Sommer

Engineered Rubber Products

John G. Sommer

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Introduction to Design, Manufacture and Testing

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Preface and Disclaimer

The successful manufacture of engineered rubber products is complicated. It involves different disciplines, materials, and types and designs of equipment. This observation is based on extensive involvement in technical activities with rubber, an in-depth review of literature that preceded the writing of this book, the many helpful comments and suggestions from colleagues, and information gained from teaching several courses in elastomer technology.

Poor communication among personnel involved in the development and manufacture of rubber products sometimes can cause problems. The intent of this book is to help improve communication among different disciplines, e.g., chemists and engineers. Using a systems approach, it is further intended to introduce chemists, engineers and others to the unique capabilities of rubber in a wide range of tire and non-tire products.

It is the author's experience derived from teaching a number of rubber-related courses over several decades that much relevant and useful rubber literature is underutilized, resulting in reinvention of the wheel. Among excellent information sources for rubber literature are the science and technology library at the Rubber Division of the American Chemical Society, located at the University of Akron; another is the Rubber Manufacturers Association located in Washington, D.C.

This book incorporates extensive bibliographies in most of its chapters. It can be read either by individual chapter of interest, or in its entirety. The reader is encouraged to obtain relevant references for further study.

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Contents

1 Introduction

The growing use of rubber in engineering applications results from its unique properties that include high extensibility, high strength, high-energy absorption, and high resistance to fatigue. Other attributes are good environmental resistance and high resilience. Engineered rubber products consist of all rubber, or rubber combined with other materials. Product complexity ranges from that of a simple rubber band to complex composites such as radial tires or rubber-metal bearings for use in aerospace applications.

Materials such as steel, aluminum, plastics, fabric, and cords are often combined with rubber to form composites. The purpose of these materials is generally to increase strength, minimize distortion, extend wear, and simplify mounting of a composite.

Rubber in a rubber-steel mechanical goods article provides flexibility, while the rigid steel provides a site for secure attachment of the composite. Composites used as mountings vary considerably in design, size and shape. Figure 1.1 shows a planar-form composite wherein the rubber bonded between rigid steel plates provides compliance in shear [1].

Figure 1.2 illustrates a tube-form composite that encloses rubber between inner and outer tubes [2]. This composite provides compliance in shear and is widely used in bushings for automotive suspension systems. These and other products require a range of manufacturing procedures.

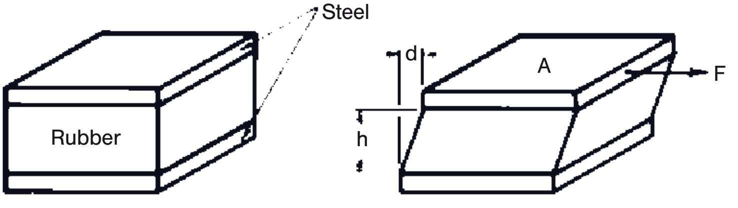

Figure 1.1 Planar-form mount with rubber bonded between rigid plates

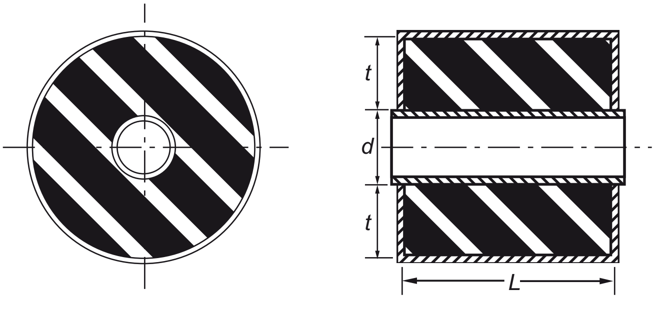

Figure 1.2 Tube-form mount

Figure 1.3 Materials and sequential steps involved in the manufacture of rubber products

Figure 1.3 lists some of the materials and sequential steps involved in the manufacture of rubber products.

The equipment used to process high-viscosity rubber compounds must be very robust to withstand the high forces involved during processing, molding, and other operations. Expensive equipment, along with a number of handling operations necessary to produce a rubber product means that rubber manufacture is both capital- and a labor-intensive. Because of these factors and increasing raw materials costs, the rubber industry is extremely competitive. Increasingly severe service demands place additional economic and technical demands on producers of rubber products.

Rubber technologists have previously concentrated on reduction of compound cost to lower product costs. Greater emphasis is now being placed on reducing product weight, reducing and even eliminating processes, and combining rigid and flexible materials in novel ways to reduce costs. These considerations apply to both tire and non-tire products.

Among factors to consider when selecting and designing products are:

- Abrasion
- Ozone cracking
- Aging
- U V exposure
- Creep
- Oil, water, and chemical resistance
- Color
- Acid and chemical resistance
- Tensile and tear properties
- Low temperature flexibility
- Permeability
- Dynamic properties
- Electrical properties
- Modulus and hardness

Modulus among materials, defined as the ratio of the applied stress (force/unit area) to the corresponding strain (change in length/original length), varies substantially. High-modulus materials such as steel strongly resist deformation, while low-modulus rubber materials deform easily. Table 1.1 lists modulus values for steel and rubber, materials that are frequently combined to form a wide range of useful rubber-metal composites [3].

Table 1.1 Typical Modulus Values for Steel and Rubber

Modulus	Steel (MPa)	Rubber (MPa)
Young's	203,000	6
Shear	79,300	1.5
Bulk	159,000	1100

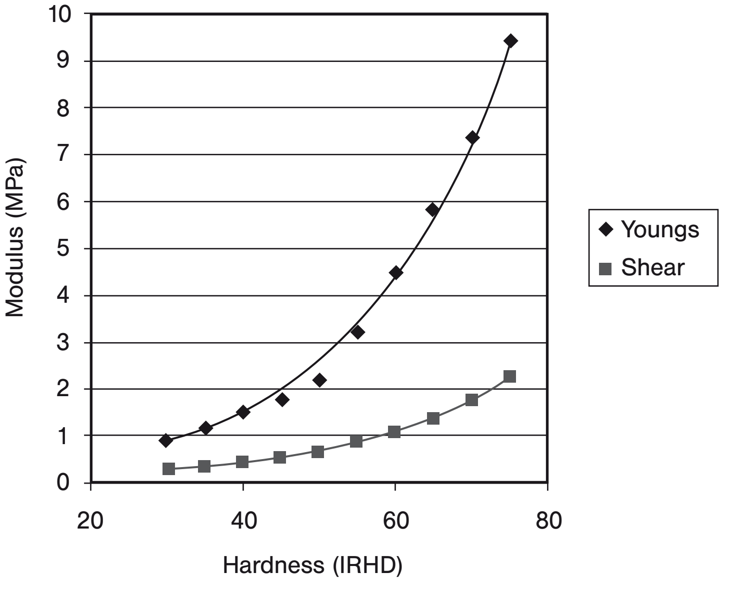

Figure 1.4 Young's modulus and shear modulus as a function of International Rubber Hardness Degrees (IRHD)

Figure 1.4 shows Young's modulus and shear modulus for typical rubber compounds as a function of International Rubber Hardness Degrees (IRHD) [4]. Hardness, which is easily obtained, is a measure of the resistance to indentation under specified conditions. Its values are within about ±2 degrees. Shear modulus, while less easily obtained, is significantly more accurate, and is the single most useful property for engineering design. It is preferred for design calculations, especially for filled rubbers whose shear modulus values are more strain dependent.

It is useful to know not only the modulus values, but also the factors that affect modulus. Differences in forces that bind the atoms or molecules in different materials mainly account for the large differences in modulus values [5]. Very strong forces between atoms account for the high modulus of steel. Only weak forces exist between the molecules in rubber, one of the necessary conditions for rubbery behavior. Rubber is a polymer that consists of very long molecules formed from either a single monomer or from different monomers. Monomers are small molecules capable of reacting with identical or different molecules.

Table 1.2 Length changes as a function of temperature

Temperature (°C)	Length (mm)
20	163.0
35	158.5
45	155.5
48	154.0
57	151.0
61	149.0

Rubber recovers substantially to its original shape after significant deformation at room temperature, as exemplified by a rubber band that is stretched and then released. The long molecules in a relaxed rubber band are in a random coil conformation. After releasing a stretched rubber band from a deforming force, recovery occurs because the very long molecules rotate around single bonds in the rubber structure. Return of the molecules to their random coil conformation provides the driving force for the rubber band to return to its original shape.

Some rubbery behavior is counterintuitive. For example, the length of a crosslinked rubber, stretched beyond a critical amount and under a constant load, *decreases* with increasing temperature [6]. This behavior occurs because the randomly coiled molecules in relaxed crosslinked rubber have higher entropy than those in stretched rubber. Stretching decreases entropy, which is a measure of the ways to arrange the molecules when their ends are at a greater distance apart than when their ends are close together. The retractive force results from the tendency of the stretched molecules to return to their original disordered condition. Table 1.2 shows the length changes in a stretched rubber band as a function of temperature.

The terms 'rubber' and 'elastomer' are used interchangeably in this book. Originally there was only natural rubber (NR), a homopolymer formed from isoprene monomer. With the invention of synthetic rubber, the term 'elastomer' was introduced. An example of the latter is styrene-butadiene rubber (SBR), which is a copolymer formed from styrene and butadiene monomers. It is important to note that factors such as different styrene-butadiene monomer ratios and polymerization conditions produce many different types of SBR.

The molecules in polystyrene, a hard plastic, lack the capability at room temperature to rotate and impart flexibility to the polymer. To become rubbery, polystyrene must be heated to a temperature of approx. 250 °F, a temperature at which rotation about single bonds commences. At this time the softened polystyrene behaves like a rubber. Melting of polystyrene and other thermoplastics enables them to be shaped like a rubber at high temperatures, followed by cooling and hardening to form useful plastic articles.

In reverse manner, with sufficient lowering of the temperature, rotation around single bonds ceases and the rubber converts to a glass. The glass transition temperature (T_g) of a polymer is the temperature at which a rubber becomes hard and brittle, or when a hard plastic such as polystyrene becomes rubbery. Below T_g, polymers behave as glass-like solids because they lack sufficient thermal energy to overcome energy barriers.

T_g values for different elastomers range from about –40 °C to –123 °C. Most elastomers have T_g values of –50 °C or lower. However, some silicone elastomers have a T_g of –123 °C, a value that allows the silicone elastomer to remain flexible at extremely low temperatures. The excellent low temperature properties permit silicone's use in aircraft seals that operate in the extreme cold of high altitudes.

The disastrous failure of an O-ring seal on the space shuttle "Challenger" in 1986 exemplifies the importance of T_g in critical applications [7]. The seal failure was attributed to the combined effect of the relatively high T_g (–10 °C to –20 °C) of the fluoroelastomer used in the seal, and to the low temperature on the day of the launch of the shuttle. Different problems occur with seals or gaskets used on refrigerators and freezers [8]. Nanoscale silver particles, incorporated in seals and gaskets, provide anti-microbial properties that reportedly help preserve food longer.

Thermosetting elastomers (TSEs) comprise the majority of elastomers used in engineering applications; thermoplastic elastomers (TPEs) are increasing in number and use, type, and importance. In contrast to the *chemical* (permanent) crosslinks that link TSE molecules, *physical* crosslinks connect the molecules in a TPE. Hence TPEs can be heated and reprocessed much like polystyrene and other plastics, a distinct advantage for TPEs. This behavior means that TPEs can be reprocessed after reheating.

An ideal rubber can be defined as one that stores all energy during its deformation, followed by release of the energy upon release of the deforming force. But we don't live in an ideal world and there is no ideal rubber. A 'superball' displays nearly ideal behavior as it returns to nearly its original drop height when bounced. The loss in height reflects the energy lost during deformation upon impact and is a measure of damping. Damping, which refers to the energy lost during a deformation cycle, is important in many engineering applications and depends upon many factors [9].

Among these are the type of elastomer, the type and level of ingredients incorporated in the elastomer, processing conditions, and the degree to which the long molecules in an elastomer are crosslinked. Long polymer chains require only few crosslinks along their length to form a stable structure [10]. Incorporating a very large number of crosslinks results in hard rubber and associated very low extensibility. These factors play an important role in many rubber products that are designed for a range of applications.

Stress softening is another important factor in engineered elastomer products that is observed in both filled and unfilled elastomers. It reflects changes in the conformation of the long molecules in polymeric materials and permits subsequent deformations to occur more readily. Hence a rubber compound will show the highest modulus during its first strain cycle, with each subsequent strain cycle showing progressively reduced stress at a given strain (stress softening). Figure 1.5 shows this effect for a vulcanized rubber tread [11]. With a sufficient number of stress-strain cycles, an equilibrium modulus is reached.

Damping is required to varying degrees in rubber used for vibration isolation where resonance might occur, for example in an engine mount of an automobile. Suspending a mass on a rubber band and then raising and lowering the rubber band at different rates (different disturbing frequencies) serves to illustrate resonance. Resonance occurs when the disturbing frequency (f_d) equals the natural frequency (f_n) of the band-mass system. The natural frequency of a suspended mass is the number of oscillations the mass makes per second after a single impulse acts on the mass.

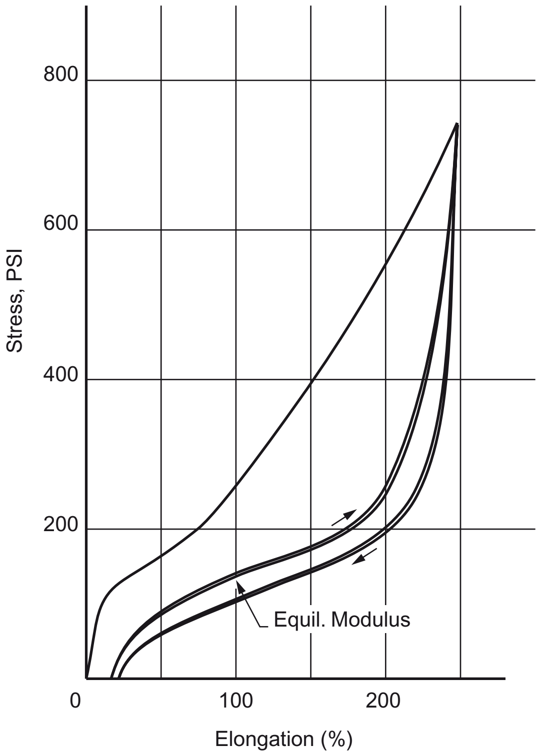

Figure 1.5 Stress softening in a vulcanized rubber tread compound

When f_d is substantially less than f_n, the disturbing motion and the mass move in unison. When f_d equals f_n, the amplitude of vibration is maximum. When f_d is substantially greater than f_n, the amplitude decreases progressively with f_d. Troops marching on a bridge illustrate this principle; they must break step to avoid exciting the bridge at its resonant frequency, a condition that could cause bridge failure.

Just as a bridge can be considered a mechanical system that can be excited, individual parts of the human body can be considered as separate components exhibiting different resonant frequencies. Long-term operation of vibrating equipment such as chain saws and pneumatic riveters can cause inflammation of muscles and tendons [12]. Rubber, widely used in this type of equipment, isolates and damps undesirable vibrations.

The above discussion deals primarily with physical issues. Equally important are the many chemical issues involved in rubber engineering. Different chemical factors are involved not only with different types of rubber, but also with the myriad vulcanization systems that crosslink (connect) the rubber molecules. The type and level of crosslinks substantially affects many important engineering properties such fatigue resistance, compression set, and resistance to degradation by heat.

Successfully optimizing these properties in engineering applications generally requires integrating the technical skills of people with different training and perspectives, e.g.,

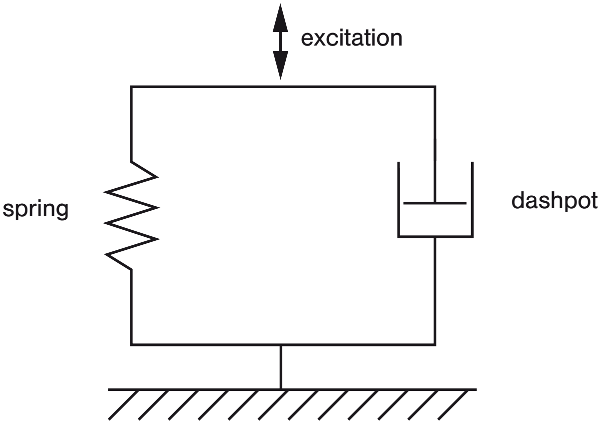

Figure 1.6 Simplified mechanical model for rubber behavior

chemists and engineers. The chemist's primary involvement is to provide rubber compositions (compounds) that will process satisfactorily and meet the material requirements for a given application or product. Engineers generally design the product and incorporate rubber materials into the design in a collaborative effort, directed toward meeting all required parameters. Successfully accomplishing these goals is often difficult, especially for complex products that are used in demanding applications.

Communication gaps sometimes occur between chemists and engineers in their efforts to develop and produce products. These partly occur because of unfamiliarity with the substantial differences in the underlying behavior of materials, e.g., those of steel and rubber. A deformed steel spring stores energy and will release nearly all this energy upon removal of the deforming force [13]. It behaves like a Hookean solid in which the deformation is instantaneous and linearly related to the deforming force. Hence, a Hookean solid shows neither rate dependence nor time dependence.

Contrasting sharply with this Hookean behavior is that of a Newtonian liquid. A Newtonian liquid shows both rate and time dependence; it has no memory and does not recover when the deforming force is removed. Rubber's response to deformation is quite complex in that it includes elements of both Hookean and Newtonian behavior. Figure 1.6 shows a mechanical model consisting of a Hookean spring and a Newtonian dashpot that approximates rubber behavior. The spring represents the element in rubber that is associated with elastic or instantaneous response; the dashpot is the element associated with time or rate-dependent (loss) response. These characteristics significantly complicate the design of rubber products.

Another factor contributing to the communication gap is the lack of elastomer information being included in the already-crammed mechanical engineering curriculum. Engineers are generally more familiar with high-modulus materials such as concrete and steel that function at very small strains in service. Young's modulus and bulk modulus successfully predict the behavior of the latter materials [14]. Increased introduction of elastomers information into engineering programs is expected to significantly improve an engineer's understanding of rubber behavior and use.

In addition to technical factors, cost remains a dominating factor as recognized early in the rubber industry by Rogers [15] who stated in 1932, "The placing of price before quality is the cause of nearly all the lurid language emanating from the engineering industry with regard to rubber". The person who specifies rubber product properties should require product quality consistent with product requirements. Too often, the specifier may overemphasize a specific property such as tensile strength that could increase compound cost and therefore raise product cost. The ultimate tensile strength can depend more upon grit content in a compound than upon the inherent compound quality [16]. Hence, performance tests are much more meaningful than other tests, such as tensile strength.

Yielding to pressure to prematurely bring a product to market can result in false economy that can lead to a less-than-desirable product design, increased manufacturing cost, and potential downstream liability costs. The General Accounting Office has noted that more than half of jury awards in product liability cases go to attorneys [17]. Liability insurance costs in the U.S. are 15 times higher than in Japan and 20 times greater than in Europe.

A rubber component should be tested in the system in which it is to function rather than to judge it on its individual properties. For example, rubber components in complex rubber structures such as tires, reinforced hose, belting, and mounts must adhere well to one another if they are to perform satisfactorily.

Steel is the most widely used metal in composites for applications that often require a unique combination of properties. Plastics are increasingly being used in plastic-rubber composites, partly because of plastic's corrosion resistance and lower density. Because the stress-strain properties of steel below its yield strength are linear, engineering design with steel is substantially easier than with elastomers.

Yield strength of steel is a term that sometimes causes confusion because of ambiguity in defining it [18]. Yield strength, measured in tension or compression, is the point at which a material will withstand a load and return to its original shape. Below this point, elastic deformation occurs. Stressing a material above its yield strength causes permanent deformation. The usual definition of yield strength is the offset yield strength, specified in the U.S. at a strain of 0.1 or 0.2% strain. Figure 1.7 shows the stress-strain curve for steel along with related terms.

Many rubber products combine the very high Young's modulus of steel (203,000 MPa) with the substantially lower Young's modulus of rubber (6 MPa). The ratio (33,833) of modulus values (see Table 1.1) in these composites results from combining rubber and steel, where the bonded rubber provides flexibility and the steel serves as a rigid member for secure attachment of the composite. In these applications, the steel reinforcements can be considered essentially non extensible.

The rubber in many products undergoes multiple stress-strain cycles at 20% and higher, for instance in engine mounts. The strain cycle for the elastomer is two orders of magnitude higher than that for the elastic region for steel. Figure 1.8 shows a stress-strain curve for a typical rubber compound.

The elongation at break shown for the elastomers in Fig. 1.9 is more than three orders of magnitude greater than the yield point of steel [19].

Although the responses shown in Fig. 1.9 are somewhat atypical of thermoplastic polyurethane elastomers, they illustrate several important features associated with stress-strain curves for an elastomer. In common with the stress-strain response for steel (Fig. 1.7), Young's Modulus (E)

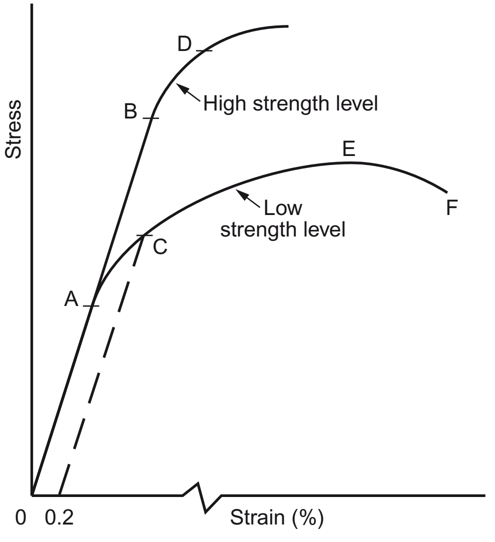

Figure 1.7 Stress strain curves for low- and high-strength steel.
Solid lines represent stress-strain curves for low- and high-strength steels, respectively; dashed line, offset at 0.2% strain for low strength steel;
(A) yield strength for low strength steel;
(B) yield strength for high strength steel;
(C) 0.2% offset yield strength for low strength steel;
(D) 0.2% offset yield strength for high strength steel;
(E) maximum yield stress for low strength steel;
(F) tensile strength for low strength steel.

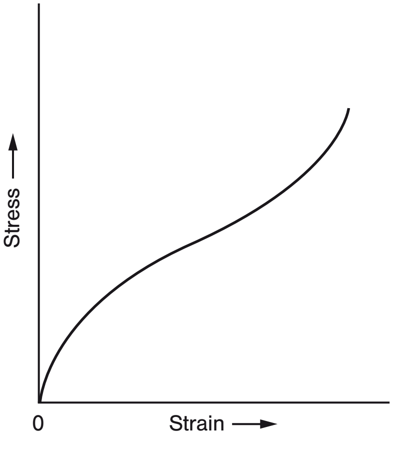

Figure 1.8 Stress-strain curve in tension for a typical rubber compound

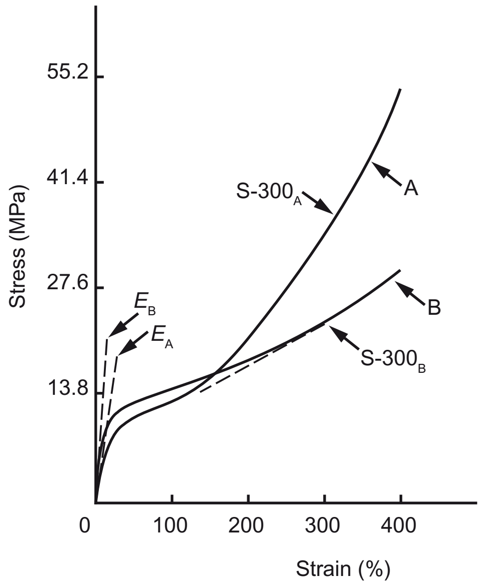

Figure 1.9 Tensile stress-strain curves for polyurethane elastomers A and B

is the slope of the dashed line drawn tangent to the curves for polyurethanes A and B. Note that the value of E_B is higher than that for E_A. With increasing strain, the curves cross at about 150% strain, and the slope for A becomes higher than that for B. At 300% strain, the stress for A (S-300_A) is significantly lower than that for B. These curves illustrate the danger in drawing conclusions based on values for S-300, tensile strength, and breaking extension.

Rubber technologists typically use the term "percent modulus" when referring to stress strain-strain properties. For example, they describe the stress required to elongate a tensile specimen by 300% as the 300% modulus. This terminology often confuses mechanical engineers because the 300% modulus is not a modulus. Rather, it is a stress at 300% strain, shown as S-300 (see Fig. 1.9). By convention, tensile stress is calculated by reference to the original (unstrained) cross section. The slope of the dashed line drawn tangent to the stress-strain curve is the modulus at 300% strain.

The higher S-300 value for compound A would imply a higher value of E. This would be problematic if A were chosen instead of B for a boot used in a constant velocity joint that rotates at high speed in a confined space in a car. High-speed rotation increases the diameter of the boot and if the boot diameter increases sufficiently, it could rub against a confining part of the car. In this application, compound B, with its higher Young's Modulus would be the compound of choice because it would stretch less during rotation.

Just because rubber ruptures at substantially higher strain than other materials doesn't mean that it should be repeatedly subjected to high strains in service. Higher strains shorten service life. This was evidenced by the use of rubber in shear as an energy absorber on an automobile bumper [20]. The shear unit absorbed energy and prevented damage to the car body during low-speed impact. The high shear strain of 250% was permitted only because the energy absorber needed to survive only a limited number of impact cycles in service before it failed.

The properties of rubber in tension are often prominently shown in data sheets for rubber. While they are of interest to the rubber compounder as an indicator of quality, their value should not be over emphasized. Because rubber is infrequently used in tension, tension properties should be of considerably less interest to designers than other properties such as shear modulus.

Shape factor (SF) is an important consideration in design of rubber products such as bridge bearings and earthquake mounts. SF, the ratio of the area of one loaded face and the total area free to bulge in a bonded rubber-metal composite, is discussed in greater detail in Chapter 5. It is preliminarily introduced here to further highlight the inherent material and behavioral differences between steel and rubber. By appropriately using the shape factor in product design, the stiffness of rubber mounts can range over several orders of magnitude.

The terms 'modulus' and 'stiffness' are sometimes confused. Modulus is a *material* property [21]. Stiffness, in contrast, depends upon *both* modulus *and* on the *geometry* of a specimen or structure. Modulus can be determined under static or dynamic test conditions. In static testing, the applied force that deforms the rubber changes at a *slow* and *constant* rate. This contrasts with dynamic testing, wherein an oscillatory applied force deforms a specimen.

The dynamic modulus will always be greater than the static modulus because all elastomers are viscoelastic, i.e., they have a viscous component that contributes to the complex modulus. The complex modulus is the vector sum of the elastic modulus (in-phase modulus) and the loss modulus (out-of-phase modulus).

This is illustrated by comparing the behavior of different-thickness strips of steel.

Figure 1.10 shows that a 0.0015-inch thick steel strip can be substantially deformed; upon release of the deforming force, the thin strip returns elastically to its original shape. A 0.025-inch thick strip of the same steel is, of course, significantly stiffer. Moderate bending of the thicker strip exceeds the steel's yield point and causes the thicker strip to remain deformed after release of the deforming force.

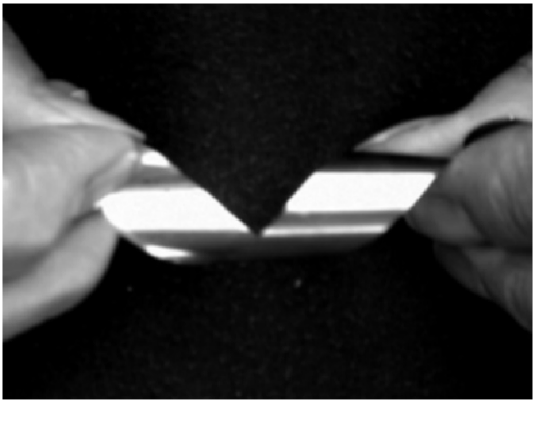

Figure 1.10 Flexibility of a 0.0015-inch thick steel strip in bending

Figure 1.11 Thermoplastic elastomer with graded thickness

Figure 1.11 shows a specimen of Santoprene® thermoplastic elastomer that was molded with increasing thickness in increments of 0.020 in. The specimen is 0.020 in. thick at its base, increasing to 0.100 in. thick at the top of the figure. Being molded from the same material, the progressive stiffness increase from bottom to top is due to the increase in thickness, again showing the expected effect of geometry on stiffness.

Damping, an important property in many rubber applications, results in the conversion of mechanical energy into heat when rubber is deformed. The warming of a rotating tire on an automobile is a familiar example. A bounced polybutadiene ball ('superball') displays little damping, while its counterpart made from butyl rubber displays high damping.

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2 Elastomers and Compounds

Environment and service conditions probably affect elastomers more than any other material. Hence the selection of the best elastomer for a given application is critical. The extremely wide range of elastomers available to the rubber technologist is both bad news and good news. Bad – because the behavior and properties of the myriad available elastomers overlap one another and complicate the choice of an individual elastomer or a blend of elastomers that will meet the requirements for a given application. Good – because the wide range of available elastomers provides the technologist with materials to meet the demands for most applications, some of which are extremely demanding.

For nearly all applications, ingredients are added to a raw elastomer and the resulting mixture is called a compound [1]. The addition of these ingredients affects not only the end-use properties but also the processing behavior of a compound. It cannot be overemphasized that one should jointly consider compounding and processing factors [2]. For instance, processing factors such as shorter mixing cycles, faster extrusion or easier demolding can offset materials costs to a degree. Specific additives for a compound can improve processing behavior, for example, specific additives can improve rates of extrusion [3].

A generic compound would likely contain at least the materials listed in Table 2.1.

After mixing, TSE compounds are shaped under pressure and heated to provide a range of mechanical, electrical, chemical, and other properties required for a given application. Properties of compounds depend markedly upon use temperature, with each compound having an allowable range of use temperatures. Progressively lower temperatures change a compound from a rubbery material to a leather-like material and finally to a glass-like material. This behavior is, of course, extremely important in applications such as seals that can be required to operate over a wide temperature range.

Compounds are designed primarily to meet specific physical and chemical requirements; however, they must also process satisfactorily by the various methods used to shape and fabricate them. For example, a compound that is designed for compression molding may not process satisfactorily by injection molding, because much more heat is generated during the injection molding process and this heat and associated higher temperature can cause scorch and shut the process down.

Table 2.1 Generic Elastomer Compound

Material	Function
Elastomer or blend of elastomers	Provide rubbery behavior to the compound
Fillers	Modify modulus and processing properties
Plasticizers	Reduce viscosity and alter properties
Protective agents	Protect compound from oxygen and ozone
Vulcanization additives	Crosslink elastomer chains

Table 2.2 illustrates an EPDM compound intended for injection molding, that is said to provide a short cure cycle time and a desirable combination of properties [4].

The EPDM in the compound, Epsyn P558, facilitates mixing and is said to provide favorable dispersion of fillers in a soft compound that has a Mooney viscosity of 35 when tested by ML 1 + 4 at 100 °C. To determine the scorch time, a higher temperature is used than that for Mooney viscosity. Mooney scorch time for the compound (MS at 121 °C) is 10 minutes to a 5-point rise. Scorch time measures the time available to process a compound before premature crosslinking occurs and inhibits or prevents rubber flow.

A brief description of materials added to the Epsyn in Table 2.2 follows:

Mistron vapor is an easy-processing mineral filler; High-Sil is a reinforcing precipitated silica filler that improves tear resistance, and Sunpar is a plasticizer. Silane improves reinforcement, and the spider sulfur prevents crystallite formation and serves to crosslink the elastomer.

Adding higher levels of low-cost fillers reduces compound costs. There is a limit to the permissible level of added fillers, because filler addition affects processing characteristics as well as the crosslinked compound properties. For example, because the level of elastomer in the compound in Table 2.3 is less than 12% by weight, the compound would not be expected to meet demanding physical property requirements.

Although end-use requirements and/or service conditions primarily dictate materials choices for a compound, processing factors also affect the type and level of materials chosen. A compounder typically first chooses the elastomers or blend of elastomers for the compound, followed by choosing fillers, and then the crosslinking or curing system [5]. Crosslinking system selection is especially important, because it significantly affects both processing and end-use properties as shown in Table 2.4 for an NR compound [6].

Table 2.4 shows that the crosslinking system significantly affects scorch time, fatigue life, and compression set, all important rubber properties. The conventional crosslinking system with the highest sulfur level provides the best scorch time and fatigue life at the expense of the highest compression set. In contrast, the EV system provides the lowest compression set but also the lowest scorch time and fatigue life. The semi-EV system provides intermediate properties. Fatigue life is especially important in flexing situations such as engine mounts and bushings. Compression set and stress relaxation properties are important in seals, especially stress relaxation. Stress relaxation is the change in stress with time for a specimen under constant force.

Table 2.4 also shows that the amount of a specific ingredient in a formulation can be quite small, e.g., 0.33 sulfur in the EV system. This small amount is difficult to weigh and disperse evenly in a compound. When the sulfur is preblended with the other curative ingredients, dispersion is more uniform but blending the ingredients can shorten scorch life relative to adding ingredients separately to the compound. Addition of special additives to the blend, e.g., phthalic anhydride, stabilized scorch time of the blend [7].

In other work, the effect of sulfur/accelerator (S/A) ratio was measured on fatigue life, crystallization, and creep in NR vulcanizates that had nearly equal S-300 values [8]. Maximum fatigue life occurred at an S/A ratio of 1.70. Temperature retraction tests indicate the greatest crystallization capability for the same S/A ratio. Creep was at a minimum at the lowest S/A ratio, a result that is consistent with the minimum number of polysulfide crosslinks.

Table 2.2 EPDM Compound for Injection Molding

EPsyn® P558	150
Mistron Vapor	120
High-Sil 233	10
Sunpar 2100	25
Zinc oxide	5
Silane A-189	1
Spider Sulfur	1
Additional ingredients	12.5
Total	324.5

Table 2.3 Low Cost EPDM Molding Compound

Epsyn® 5508	100
N550 Black	150
Whiting	225
Austin Black	200
Circosol 4240 oil	190
Zinc Oxide	5
Stearic Acid	1
Sulfur	1
Accelerators (combined)	5
Total	877

Table 2.4 Crosslinking Systems in NR

Crosslinking system	Conventional	Semi-EV*	EV*
Ingredients			
Sulfur	2.5	1.2	0.33
CBS accelerator**	0.5	1.8	3.0
TMTD accelerator	**		2.0
Properties			
Mooney scorch time, t_5 at 120 °C, min.	18.5	16	8
Fatigue life, k_c	162	120	50
Compression set, %	31	18	15

* EV-Efficient vulcanization system

** See Appendix 2 for description

A patent describes vulcanizable diene rubber compounds wherein processing safety can be maintained over a range of sulfur contents [9]. It suggests the use of this technology for improving rubber molded goods, particularly tire components.

Scorch time is also an important factor with peroxide-cured rubber [10]. Generally, sulfur-cured rubber compounds have more available options for controlling scorch time than do peroxide-cured rubber compounds. One of the newer concepts for scorch control with peroxide-cured rubber involves the use of a combination of a bis-maleimide type coagent and a sulfur donor such as dipentamethylene tetrasulfide. This combination is said to produce good physical properties.

The conventional crosslinking system (Table 2.4) with its high sulfur level favors the insertion of polysulfide crosslinks (three or more sulfur atoms) in the elastomer matrix [11]. Polysulfide crosslinks can interchange during flexing of a vulcanizate and improve fatigue life. The EV system favors the insertion of monosulfide crosslinks that are more thermally stable and improve compression set. Sulfur can also react with single rubber molecules to form intramolecular ring structures that disrupt crystallinity in an NR network. Lower crystallizing capability reduces fatigue life.

While other compounding ingredients are also important, elastomers, curing systems, and fillers are the most important. Fillers, depending on their particle size, level of addition, and other factors increase compound viscosity. Too-high filler levels render a compound non-processible. Fillers also increase hardness and modulus of compounds. A high-hardness compound that may be compression molded easily will likely be unsatisfactory for injection molding. Hence, the compound composition should not be separated from the process.

These factors, while important with lower cost compounds, become extremely important with specialty elastomers like fluoroelastomers. Because some of these fluoroelastomers offer unique chemical resistance and other desirable s properties, they command prices that at times have been higher than gold on a weight basis [12].

Increasingly difficult requirements are being legislated for vehicles [13]. Some fluoroelastomers for fuel-systems must seal for 15 years/150,000 miles without leaks and stay within fuel permeation limits even at operating temperatures above 150 °C. They must also resist fuel and alcohol blends, “sour” gasoline, and biofuels. When fluoroelastomer O-rings replaced other O-rings exposed to chlorinated slurry at 180 °C, they significantly reduced plant shutdowns.

The availability of thousands of elastomers and ingredients provides a compounder with an extremely large number of choices and increases the difficulty in choosing elastomers. The availability of an ingredient under as many as twenty different trade names further complicates the issue. For this reason, a compounder should think, not in terms of trade names, but in terms of the chemical composition of the ingredients and their potential reactions. With some ingredients, this is not possible because the manufacturer of the ingredient does not disclose the composition of the ingredient.

Rubber compounding is a highly varied activity in several aspects. Tire compounders generally deal with a relatively small number of compounds that are mixed in extremely large volumes. They will thoroughly investigate the effects of only a small change in the recipe for a tire compound, because a large number of test miles that may have to be run on the tire before the effects of the changes become evident. A tire compounder often specializes in one component of a tire, for example, the tread or the sidewall.

In contrast to tires, the same level of activity is generally unjustified with non-tire compounds used for mechanical goods because of the substantially reduced volumes of compounds produced. An exception would be the design of compounds for low volume, high-cost elastomer articles used in critical applications such as aerospace. The mechanical goods compounder must usually deal with many more compounds than the tire compounder, especially where a number of mechanical goods are produced in the same manufacturing plant with only a limited technical staff.

When there is an opportunity for producing a new product, technical specifications generally help promote communication among the design engineer, the rubber manufacturer, and the purchaser of rubber components. In defining product requirements, the designer needs to find a balance between under-and over-specifying. Under specifying is likely to compromise the suitability or quality of the product, while over specifying generally leads to increased costs and longer delivery times. It cannot be overemphasized that specifications should be definitive, *and realistic*. For example, there is anecdotal evidence of having specified Shore A hardness to within a tenth of a point, a value that greatly exceeds the capability of both the measurement instrument and the operator making the measurement.

Attempts have been made to improve the accuracy of the Shore durometer by mounting it on a stand and applying it to the test piece using a constant force applied at a constant rate. Also, modern digital readouts may be used to reduce operator error in reading the dial gauge. However, these modifications come at the expense of limited portability of the instrument.

Several different organizations facilitate the writing of specifications for materials and associated requirements for elastomer-related applications. Standard specifications facilitate the materials and design process and promote communication among those involved. Examples follow:

- ASTM (American Society for Testing and Materials)
  Provides classification of rubber materials and test methods for numerous automotive and mechanical goods applications
- SAE (Society of Automotive Engineers)
  Provides test methods and other information primarily relevant to automotive applications
- RMA (Rubber Manufacturers Association)
  Provides production tolerances and design considerations for rubber products fabricated using methods such as extrusion, molding, lathe cutting, etc.

It should be emphasized here that both a tire and a non-tire product is basically a system that involves three main factors: a compound, a process, and a design. These three factors are interactive. For example, it may be possible to manufacture a rubber extrusion to given dimensional tolerances from a harder rubber compound, but not a softer one; the harder compound will be more dimensionally stable during the extrusion process. Likewise, the successful molding of components containing an undercut depends upon the type of compound used. Articles containing an undercut, illustrated in the next chapter (Fig. 3.14), generally can be removed from their mold if they posses good hot-tear strength and the undercut is not too deep. Hence, it is important to consider both compound and design and view the manufacture of a rubber article as a system.

Compounders have recognized for some time the value of statistical methods in the design of experiments. DOE has significantly aided the compounding of elastomers as it has many other technological areas. Screening experiments can establish significance of variables and their relative importance. The DOE approach is generally more effective than doing experiments one at a time [14]. Selecting and performing an experiment design reduces the number of experiments required to achieve optimum results. However, effective use of DOE requires good judgment in selecting the factors to be studied in combination with an effective design. The author has found that initially running small designs, selecting the most relevant factors from these, and then combining these selected factors in subsequent designs is effective, especially in an industrial environment.

R. J. DelVecchio has provided a useful primer for DOE [15]. Computers and statistical software enable technologists to work much more efficiently in establishing structure-property relationships [16]. Most responses were found to be linear; however, some more complex phenomena such as fatigue required interaction terms to properly deal with them.

DOE and desirability methodology can be combined to specify final properties to optimize a product [17]. The combination can be used to:

- find a producible compound that might be considered outside the typical limits of compounding,
- reformulate products using new materials that could reduce costs and improve processing, and
- design new compounds that minimize or eliminate the need for testing (using the DOE data base).

The following examples illustrate the successful use of DOE in the development of a of rubber products. DOE was effectively used to design and optimize compounds for injection-molded air ducts for automobiles [18]. The DOE method significantly reduced the time to develop the product and it provided a useful database for subsequent work. This thorough study considered not only compounding factors, but also molding and other processing factors.

A DOE study of the dynamic properties of fluid-filled engine mounts considered variables such as orifice size, damping-fluid viscosity, and fluid-track length [19]. Results showed the importance of a decoupler in the design and they identified factors important in controlling static and dynamic properties of a mount.

A DOE study established the effect of compounding ingredients on the post-vulcanization bonding of elastomer to metal [20]. The series of regression equations developed related compounding variables and rubber physical properties. The study concluded that the failure mechanism between post-vulcanization bonding and vulcanization during bonding appeared to be fundamentally different.

DOE established compounding effects on physical properties and rubber-metal adhesion [21]. The results established that the accelerator type affected properties most, indicating that the type and distribution of crosslinks might be more important than crosslink density. Further, even subtle changes in compounding ingredients could affect a wide range of properties that included processing, aging and adhesion.

Safety considerations influence compounding and other issues. A VOC (volatile organic compound) compliant flock adhesive was developed for EPDM weather strip to meet the requirements of the 1990 clean air act [22]. Variables that were examined included: corona-treated or abraded EPDM, temperature of applied adhesive, and extruder temperature during shaping of the weather strip.

Formation of nitrosamines is another safety issue in compounding [23]. Regulations in Germany allow no more than 2.5 μg/m^3 emission of nitrosamines between vulcanization and warehousing and U.S. automobile manufacturers have issued strict regulations concerning nitrosamines. With over 300 nitrosamines listed as suspected or known carcinogens, the rubber industry continues to address them as a safety issue. Accelerators are now available that are said to be nitrosamine free [24].

It was mentioned earlier that elastomers could be broadly classified as thermosetting (TSE) or thermoplastic (TPE). Because TSEs comprise the majority of elastomers used in engineering applications, they will be discussed here in greater detail. TSEs are classified as either general-purpose or as specialty elastomers, with emphasis on the latter. Natural rubber (NR), styrene-butadiene rubber (SBR), and polybutadiene rubber (BR) are three general-purpose elastomers used in very large quantities in both tire and non-tire products, but mainly in tires. The unsaturation in their backbones makes them subject to rapid attack by oxygen and ozone. In the absence of a protective agent (antioxidant) they can rapidly oxidize as shown in Fig. 2.1 [25].

The figure shows that higher aging temperatures shorten initiation time for weight gain (oxidation) in unprotected BR and high temperatures increase the rate of oxygen reaction. The oxidation rate approximately doubles for each 10 °C increase in temperature [26]. The equilibrium weight gain is about 24 weight percent for the three different aging temperatures. Analytical tests confirmed that reaction with oxygen accounted for the substantial weight gain. Raw elastomers are typically supplied with an antioxidant and compounders usually incorporate additional antioxidant(s) that prevents or slows oxidation and protects the compound. At a weight gain of about 24%, the BR hardened significantly.

Rubbers with an unsaturated backbone (containing double bonds in backbone), such as BR and NR, typically show poorer aging resistance than those with a saturated backbone such as

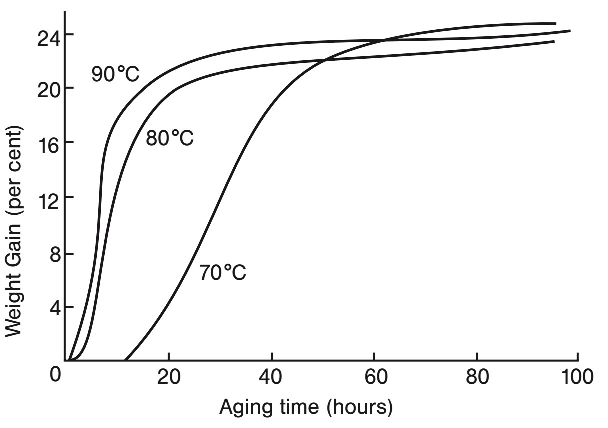

Figure 2.1 Weight gain of unprotected BR aged at 70 °C, 80 °C, and 90 °C

Table 2.5 Effect of Test Conditions on Fatigue Life of an NR Gum Vulcanizate

Strain cycle [%]	**Fatigue life** [**kilocycles**]
0–250	12
50–250	~13,000
0–240	13

EPDM. Even though EPDM has excellent inherent aging resistance because of its saturated backbone, antioxidants can improve its heat and oxidation resistance by protecting it from the harmful effects of heat and oxygen.

In contrast to the behavior of the BR, oxidatively aged NR vulcanizates can either increase or decrease in stiffness, depending on aging temperature [27]. At an aging temperature of 50 °C, stiffness increased; at an aging temperature of 110 °C, stiffness decreased. At 90 °C, stiffness remained relatively constant. Relative rates of chain scission and crosslinking account for the observed behavior. Ozone, as well as oxygen, is a problem for rubber.

Ozone, even at concentrations of only several parts per hundred million, attacks unprotected general-purpose elastomers. If the elastomers are slightly strained, cracks form on the elastomer surface that can potentially lead to product failure. Incorporation of an effective antiozonant at an appropriate level in a compound inhibits or prevents ozone cracking. Application of a coating on rubber that crosslinks at room temperature can also impart ozone resistance [28]. Potential additional advantages for coating are: improved cosmetic appearance using colored coatings and oil and solvent resistance.

Both NR and its synthetic counterpart, polyisoprene (IR), are strain-crystallizing rubbers that impart outstanding fatigue resistance to rubber articles. They are very strong even in the absence of reinforcing fillers, because the crystallites that form in them on stretching act to inhibit crack propagation. The minimum strain experienced by NR during its strain cycle significantly affects its fatigue life [29]. Table 2.5 illustrates this behavior.

The incorporation of reinforcing filler is necessary to strengthen a non-crystallizing rubber such as SBR. To be significantly reinforcing, fillers must be small (less than 1 μm in size) [30]. Small-particle fillers, because of their large surface area, interact with SBR and increase its strength by more than 10-fold. Crystallites that form in stretched NR reinforce it. Hence, a stretched NR rubber band is strong (self reinforcing), while a gum SBR rubber band is weak unless it is reinforced with filler. Although general-purpose elastomers effectively meet the properties required of many elastomer products, they are deficient in some areas that require special properties.

A number of specialty elastomers available to compounders overcome some of the deficiencies of general-purpose rubbers. These deficiencies include poor resistance to oil and fuel, high-temperature aging, and poor flexibility at extremely low temperatures. Table 2.6 lists a few specialty elastomers along with associated properties:

The elastomers shown in Table 2.6 are all TSEs that require crosslinking to attain useful properties. TPEs do not. This and other behavioral differences account for differences in their mixing and processing requirements.

Table 2.6 Specialty Elastomers and Associated Properties

Isobutene-isoprene rubber (IIR)	Good aging resistance because of its low unsaturation. Also low gas permeability, and high damping characteristics
Acrylonitrile-butadiene rubber (NBR)	Resistance to solvents. Increases in acrylonitrile/ butadiene ratio improves solvent resistance but reduce low-temperature flexibility
Hydrogenated acrylonitrile-butadiene rubber (HNBR)	Improved high-temperature aging resistance resulting from reduced unsaturation. Good solvent resistance
Ethylene-propylene-diene-monomer rubber (EPDM)	Excellent resistance to aging because of saturated EP backbone. Pendent unsaturation provides sites for crosslinking
Polychloroprene rubber (CR)	Swelling resistance to solvents is intermediate between NBR and general-purpose elastomers. Superior aging and ozone resistance relative to general-purpose elastomers
Chlorosulfonated polyethylene (CSM)	Good weathering resistance and flame-retardant properties
Silicone rubber (many types, properties, and designations)	Excellent low-temperature flexibility, and high-temperature aging resistance
Fluorocarbon rubber (many types, properties, and designations)	Excellent high-temperature properties and chemical resistance

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3 Compound Mixing and Processing

The manufacture of elastomer products involves a wide range of factors that include the selection of materials, the mixing of these materials to form compounds, and finally the conversion of these compounds into elastomer products. Raw materials that arrive at the manufacturer of rubber articles require a number of subsequent processing steps to convert them into articles that will have the properties required for their intended service.

For TSEs, processing primarily involves mixing, shaping, and forming chemical crosslinks; for TPEs, processing primarily involves heating pellets to convert them into a hot melt and then shaping and cooling the hot melt to form physical crosslinks. It is important that these processing procedures be appropriate to the product and properly controlled.

Other substantial differences between TSEs and TPEs are the necessary steps required to effect good adhesion in bonded products. TSEs and the adhesives used to adhere them to a substrate contain unsaturation that functions as crosslinking site. Hence, during bonding, only limited crosslinking (scorch) is allowed in either the TSE or the adhesive. Final crosslinking must occur between adhesive and compound prior to an unacceptable degree of scorch.

TPEs, in contrast, rely on raising their temperature sufficiently to convert them to a melt, followed by cooling that returns the original TPE properties. They are now adhered to a wide range of plastics and other materials to provide myriad composites [1]. Additionally, they are being used to encapsulate glass and form a seal in automotive applications. Use of lower TPE melt temperatures and pressures helps avoid glass breakage.

Chapter 2 was concerned mainly with materials and compounding. Also of importance is processing because of its interdependency with materials and compounding. For example, the incorporation of smaller particle size fillers in a compound generally affects several properties. Smaller filler particles increase viscosity and that in turn increases temperatures during mixing and the likelihood of scorch.

The effect of processing variables on static and dynamic rubber properties has been the subject of many studies. It was pointed out in one dynamic properties study that the process of mixing is one of the most important, but also one of the most variable and intangible in rubber technology [2]. For instance, the number of passes of a compound through a mill was shown to affect dynamic properties, especially the dynamic spring rate. Other variables shown to be important were molding and storage time of vulcanized specimens.

Viscosity, a measure of resistance to flow of a rubber material, significantly affects processing behavior. The ingredients incorporated in a rubber material during mixing further affect viscosity and therefore processing behavior. Added fillers, especially those having a small particle size, rapidly increase compound viscosity and, at too high a filler content, render the compound non-processible. Appropriate amounts of plasticizer and other ingredients result in a compound with desirable processing behavior along with the requisite properties for the intended service application. Health and safety considerations now restrict the use of highly aromatic tire extender oil (plasticizer) in tires [3].

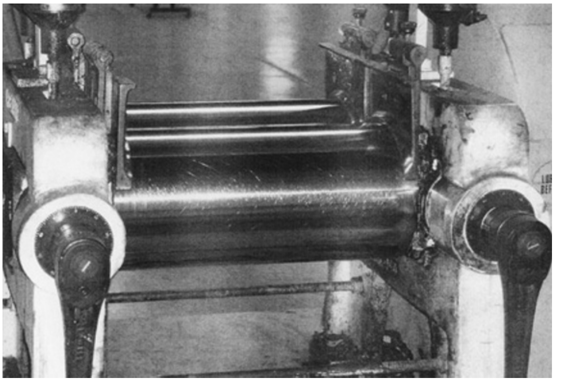

Figure 3.1 Laboratory rubber mill (Courtesy University of Akron Polymer Training Center)

Some types of rubber that offer a unique combination of vulcanized properties may present processing difficulties. HNBR is an example that shows excellent heat and oil resistance but its high viscosity can cause molding and other problems. Newer versions of HNBR with lower viscosity have demonstrated a desirable combination of good injection molding characteristics, scorch safety, and fast cure times [4].

In addition to materials effects, mixing and other processing steps can similarly affect compound properties. Smaller particle fillers increase hardness and modulus; improved dispersion of fillers during mixing can have the same effect. Hence, a compositional factor and a mixing factor can have the same effect, emphasizing the importance of jointly considering compound and process.

Mixing equipment, such as mills and internal mixers, must be robust to withstand the high stresses it is subjected to during operation. Rubber mills (Fig. 3.1) are used for both mixing and for subsequent forming of compound into sheets.

Dusting is a problem with the fine particle fillers used extensively in rubber compounding. Improvements have been made in the cleanliness of large scale mixing operations, e.g., for tires, where large amounts of fine particle size carbon black are handled [5]. Mechanical and pneumatic handling systems have mainly replaced the bags formerly used to contain black. They are used in combination with effective dust collection systems to significantly improve cleanliness in the mixing area.

Figure 3.2 shows two different internal mixers: one with intermeshing rotors (Intermix®), the other with tangential rotors (Banbury®) [6].

The rotors in both machines counterrotate to produce extensive (distributive) and intensive (dispersive) mixing. Materials added to the mixing chamber via the hopper fall into the mixing chamber and the rotors blend them within the chamber. Mixer rpm should be adjusted to yield the highest quality product in the shortest period of time.

Hardened coatings on the surfaces of internal mixers minimize wear, especially wear by compounds that contain abrasive fillers. A thermocouple(s) in the chamber monitors the temperature during mixing; energy input and mixing time can be used to monitor mixing progress.

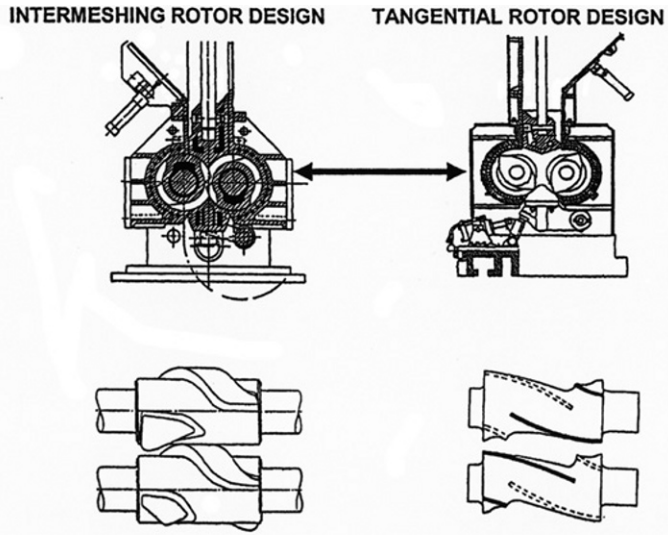

Figure 3.2 Internal mixers; left: intermeshing rotor design; right: tangential rotor design (Courtesy Farrel Corporation) [6]

Rotors in the machines shown in Fig. 3.2 differ substantially in both design and operation. In the intermeshing-rotor machine (Intermix), the rotors interlock in a manner similar to intermeshing gears. Because of this, the rotors on the Intermix must operate at the same rpm.

This contrasts with the Banbury (tangential rotor design) wherein the rotors operate at different speeds because the rotors do not intermesh. Mixing in the Banbury occurs mainly *between the rotor tips and the mixing chamber*. Both mixer types are used for medium-viscosity rubber compounds for general rubber goods, and for thermoplastic elastomer applications [7]. Additionally, the Intermix is used for low temperature compounding, applications requiring extremely high quality, and single-step mixing applications. The Banbury is used for high-volume mixing, multiple step mixing applications, especially for the final mix of high-viscosity compounds.

Current Intermix machines maximize heat transfer from the rubber to the metal surfaces of the mixing machine. The most current Banbury machines incorporate high efficiency cooled rotor tips, a ram-position indicator, and either a pneumatically or hydraulically actuated ram. The hydraulically actuated ram is said to efficiently transfer pressure to the batch during mixing. Pressure is important because it can affect the intensity of shear mixing. The ram-position indicator shows the position of the ram or plunger in the hopper of the mixer. It monitors ram height and is useful for optimizing batch weight for both the Banbury and the Intermix.

Heat exchange fluids, such as water with a viscosity of 10^{-2} poise, flow in the channels of internal mixers to remove the excess heat generated by rubber compounds during mixing. Laminar flow of Newtonian fluids occurs in circular tubes when the Reynolds number (Re) is less than about 2100; turbulent flow occurs when Re exceeds about 4000 [8]. Turbulent flow is desired in cooling channels to maximize the rate of heat transfer and Eq. 3.1 shows the parameters that determine Re.

$$\mathrm{Re} = \frac{d\,V\,\rho}{\mu} \tag{3.1}$$

Where:

Re = Reynolds number (dimensionless)
ρ = density of the fluid
d = inside diameter of the tube
V = average fluid velocity
μ = viscosity of the fluid

Although there are literature references to turbulence occurring in high-viscosity elastomers, the occurrence is highly improbable [9], or never happens [10]. A simple calculation shows that Re for typical elastomers is less than one, a value at least several orders of magnitude lower than that required for turbulent flow.

Compounds typically are dropped from internal mixers onto the counter-rotating rolls of a rubber mill. Excess rubber remains above the rolls before it is squeezed between the rolls to form sheets for subsequent handling. The nip is the gap between rolls where rubber forms a sheet on either the front or back roll. A skilled mill operator can manipulate factors such as roll temperature and roll speed ratio (when available) to favor the rubber staying on either the front or back roll.

It is extremely important to keep a mixed compound clean, especially compounds that are flexed in service, such as bushings. Silica particles with a diameter range of 0.003 to 0.079 in. were added to an NR bushing compound and the fatigue life was measured [11]. The largest particles reduced fatigue life by 26% compared to the control that contained no added particles.

Rubber compounds can be cleaned by straining them through a fine-mesh screen in an extruder [12]. Straining can be done immediately after mixing with a combined extruder-gear-pump combination, prior to extruding compound through a separate extruder-gear-pump combination, or during extrusion behind the extrusion die.

The Mooney test described by ASTM D 1646 is widely used to measure the viscosity of either raw or compounded rubber [13]. Its test time of about five minutes is an advantage; however, determining viscosity at only a single deformation rate is a disadvantage. In the Mooney test, a roughened disc rotates at a shear rate of about 1 s^{-1} in a mass of compound at a temperature of 212 °F; the resulting Mooney value is a measure of viscosity and is a well-established measurement.

Rubber compounds experience a multitude of deformation rates during processing operations such as mixing, extrusion and molding. For a better assessment of processing behavior over a range of deformation rates, a capillary rheometer can be used. This test is significantly more complicated and costly than the Mooney test and is therefore used more for research and development activities.

A compound must remain in a flowable condition during processing operations. After too long a time at high temperature during processing, a thermosetting compound will crosslink (scorch) and stop flowing. If this happens, the scorched compound must be removed from the process equipment and fresh compound introduced. Calendering, extrusion and molding are discussed next.

3.1 Calendering

Calendering is a processing operation that primarily produces rubber sheets of a controlled thickness and it is also used to coat textiles or other materials. The number of rolls on a calender and their geometric arrangement primarily defines the type of calender. Three-roll calenders commonly have the axes of their rolls arranged either vertically or offset; four-roll calenders have the axes of their rolls offset. Three-roll calenders are more commonly used for non-tire compounds; four-roll calenders for tire compounds [14].

3.2 Extrusion

The extrusion process involves transporting unvulcanized rubber through an extruder to a die where the rubber exits the extruder with the desired cross-section or profile over its entire length [15]. To attain the desired dimensional stability and other properties, TSE extrudates must be heated and crosslinked into their final shape after exiting the die; TPE extrudates, in contrast, must be cooled to attain geometric stability after extrusion. Problems with dimensional stability are generally associated with softer rubber compounds.

Long rubber articles of uniform cross section are typically manufactured by extrusion. These can be simple like tubing, or complex like door seals for automobiles [16]. By splicing lengths of extrudate of uniform cross section, extruded seals for automotive doors and trunks are formed. Figure 3.3 shows that a separate molding operation can then form molded corners that join the extruded lengths. This procedure allows for joining extrudates with different cross sections and precludes the need for molds with a large surface area.

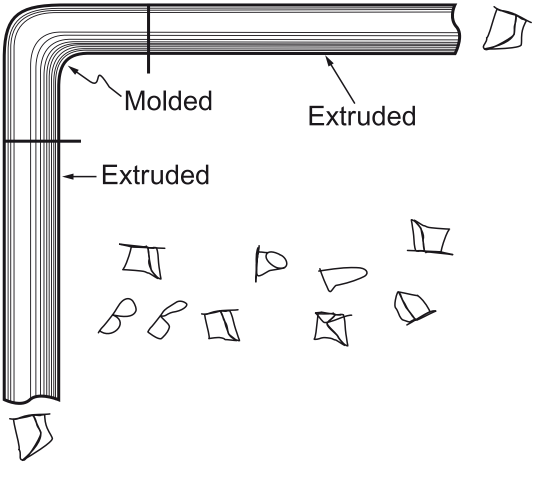

Figure 3.3 Extruded door seals joined by an injection molded corner

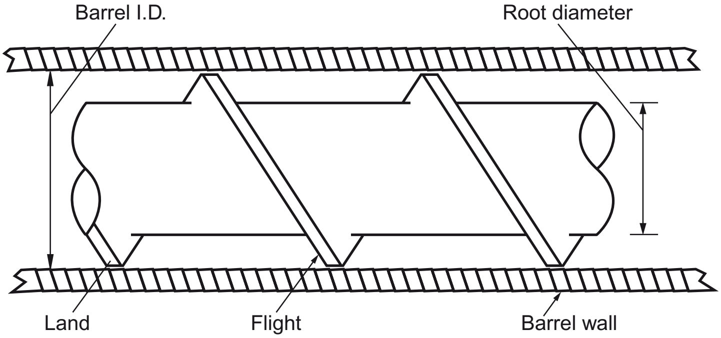

Figure 3.4 Cross-section of a screw in the barrel of an injection-molding machine

An alternative process eliminates the need for molded corners by creating a flow imbalance behind the extruder die plate [17]. By doing this, rubber exiting one side of the die opening moves faster than the other, thus forming small- and large-radius corners at specific locations on the extrudate. These corners are less-labor intensive to manufacture and are more aesthetic than those formed by molding in a separate operation.

Extrusion may be an intermediate or a final shaping operation. For example, rubber is often extruded in the form of strips that are subsequently used to supply compound to an injection-molding machine. The injection-molding machine then processes and shapes the final product. In contrast to this intermediate extrusion operation, wide rubber sheets are extruded for use as roofing, mainly on commercial buildings. Calendering is an option to produce sheet-form material.

An alternative to extruding strip for subsequent processing in an injection-molding machine is to cut and stack strips from milled sheets. Newer automated processes have removed much of the labor formerly required for this operation [18]. Prior to automation, four human stackers and one trucker were required. Now, one operator monitors the operation and loads and unloads pallets of strip rubber [19].

During extruder operation, the rotating screw in an extruder pulls in rubber strips and conveys the rubber along the barrel to the extruder die, where the extruded rubber finally exits the extruder in the desired shape. Feed strips with a consistent width and thickness must be fed into the extruder at a constant rate to obtain extrudates with close dimensional tolerances. The hopper on the extruder must be designed to uniformly feed strips to the screw. Figure 3.4 illustrates the screw in its barrel and identifies important screw features.

The flights on the screw and the inner barrel surface form a channel for rubber to flow into the die. The channel is the space bounded by the flight surfaces, the bore of the barrel, and the root diameter of the screw [20]. Minimal clearance between the land and the bore is required to generate high pressures during extrusion. Too-high pressures impose undesirably high forces on the extruder heads and die mounts.

Tapering (streamlining) the entry to an extruder die head eases flow into the die and prevents build-up of compound behind the extruder die, see Fig. 3.5. This feature is especially important for compounds with a short scorch life to avoid formation of cured compound behind the extruder die.

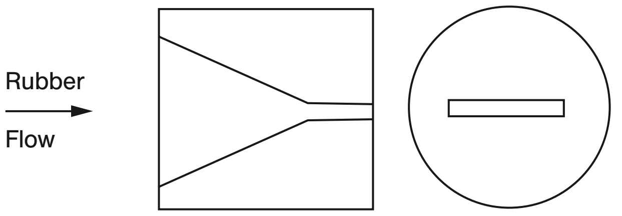

Figure 3.5 Tapered entry into extruder die to avoid scorched compound at die entry

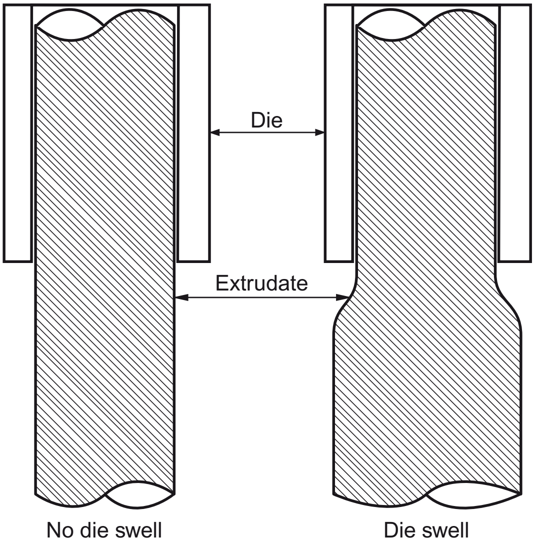

Figure 3.6 Die swell in an extrudate

Figure 3.6 shows that an extrudate will always be larger than the die dimensions due to die swell. Extrudate swell (die swell) occurs because elastically stored energy in the extrudate is released when the extrudate exits the die [21].

Key dimensions of extrudates can be measured using on-line profile gauges that incorporate lasers. A typical laser line sensor can measure dimensions of calendered sheet as well as extruded rubber [22]. The cross-section of the die and that of its extrudate often differ sharply, depending on the viscoelastic nature of the rubber compound that is extruded.

Techniques available to alleviate some extruder problems include: face-relieved dies that help fill thin edges, avoidance of local velocity minimums in thin regions adjacent to thick regions, and elimination of tearing [23]. Either the back or the front face of a die may be relieved. Back-face relief involves removal of metal from the upstream die face; it favors uniform velocity at the die exit but tends to cause rubber to flow from the thin sections of the die into thick sections. Front-face relief involves removal of metal from the downstream die face; it biases rubber flow toward the thin outside die edge as rubber flows from high to low pressure.

Extruders for TSE are either of the hot-feed or cold-feed type [24]. With hot-feed extruders, the original extruders, pre-heated rubber from a rubber mill was used to feed the extruder. Hot feed extruders typically have relatively large screw depths and short length/diameter (L/D) screw ratios that range from about 3 : 1 to 8 : 1. Higher L/D ratios provide more residence time to heat the rubber and to develop more pressure during extruder operation.

Pins in cold-feed extruders distribute the flow of the compound during extrusion while maintaining acceptable temperatures [25]. Cold-feed pin extruders represent state-of-the-art for production of extruded profiles for passenger car tires. The pins, which project through the extruder barrel, have a 1 mm clearance between their base and the core of the screw. Interrupted screw flights provide clearance between pins and the rotating screw.

Screw design for cold-feed extruders is more critical then for hot-feed extruders, because the cold feed extruder must plasticize (soften) a rubber compound in addition to compacting the rubber and pumping it to the die. This leads to greater heat generation during operation that must be controlled to avoid scorch. The maximum permissible extrusion temperature limits the extrusion output.

Favoring the cold-feed extruder is the short time between the ambient-temperature compound entering the extruder and its exit from the die.

Higher-viscosity compounds are being used in some applications such as treads for truck tires [26]. Standard cold-feed extruders may not be able to process these compounds at the desired throughput. Hence, hot-feed extruders with preheated compound can be used advantageously.

The ability to produce extruded rubber products at any desired practical length at relatively high throughputs is a significant advantage for the extrusion process. Minimal tooling costs are another advantage of extrusion relative to molding.

3.3 Molding

Molding, a major shaping operation in the rubber industry, is used to produce a wide range of tire and non-tire products whose weight ratios range over about 10^{10}. At one end of this range is a micro O-ring; at the other is a giant tire for earth moving equipment. As one would expect, many different types of molding equipment, molding materials, and molding methods are required to produce this range of products.

Figure 3.7 depicts the molding method as a function of in-mold time and viscosity. Some methods tend to be specific to a given material, e.g., reaction injection molding (RIM) and liquid injection molding (LIM) [27].

Polyurethane materials are available over a very wide range of viscosity range, from pourable to millable. Representing the pourable materials and processes are RIM (reaction injection molding) and LIM (liquid silicone injection molding). In-mold times for RIM and LIM are significantly shorter than those for hand-cast polyurethane. The materials molded by RIM and LIM crosslink much more rapidly than hand-cast or machine-cast materials. This feature positions RIM and LIM in the bottom left area of Fig. 3.7.

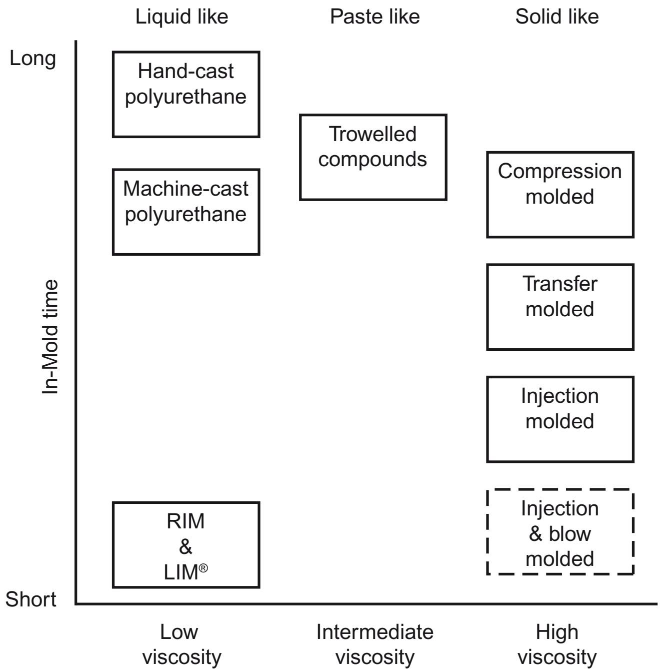

Figure 3.7 Molding method as a function of in-mold time and viscosity: —— identifies TSE molding methods; – – – identifies TPE molding methods

Paste-like (trowellable) TSEs are intermediate-viscosity materials used only infrequently in molding applications. They have a viscosity similar to that of toothpaste and house caulk and tend to trap air. Expelling this trapped air is generally more difficult than for either lower- or higher-viscosity materials. Air is buoyant enough to rise to the surface of materials with sufficiently low-viscosity, as exemplified by gas bubbles that escape from a soft drink. Air in a high-viscosity material escapes because of high stresses developed during molding, wherein *higher* viscosity generally favors air expulsion.

Application of intermediate-viscosity materials using a caulk gun or by hand trowelling is advantageous in some applications, e.g., solid rocket chambers can be lined with a special elastomer composition to protect the chamber from the extremely high temperatures resulting from burning propellant. Sheets of high-viscosity TSEs can be molded in place in smaller chambers. For very large rocket chambers, an alternative application method is required as described in Chapter 7.

Attention today focuses mainly on the molding methods for the high-viscosity materials shown in the right column in Fig. 3.7, because these methods are the most widely used methods in the rubber industry. While high-viscosity TSEs continue to be the major-use elastomers, TPEs are growing at several times the rate of TSEs and are therefore rapidly increasing in importance. First considered here is TSE molding. The three major methods for molding TSEs are compression, transfer, and injection molding (Fig. 3.7). Injection-compression and injection-transfer represent combinations of these methods that are not further discussed here.

3.3.1 Compression Molding

The mold in Fig. 3.8 shows a rubber preform positioned in its mold cavity before the mold closes. Leader pins in the mold engage their respective bushings during mold closure. While the mold shown in this figure contains only one cavity, multiple cavity molds are more commonly used and some may contain 1000 or more cavities.

The molding sequence consists of placing a preform in the cavity of an open mold, followed by mold assembly. The assembled mold is then placed in a press that applies the necessary force to squeeze the preform and configure it to the mold cavity. The volume of the preform in the mold exceeds the cavity volume and the excess compound is squeezed past the land (Fig. 3.9) into the overflow groove – also called a flash groove. The land is the small area of a mold surface bordering a mold cavity.

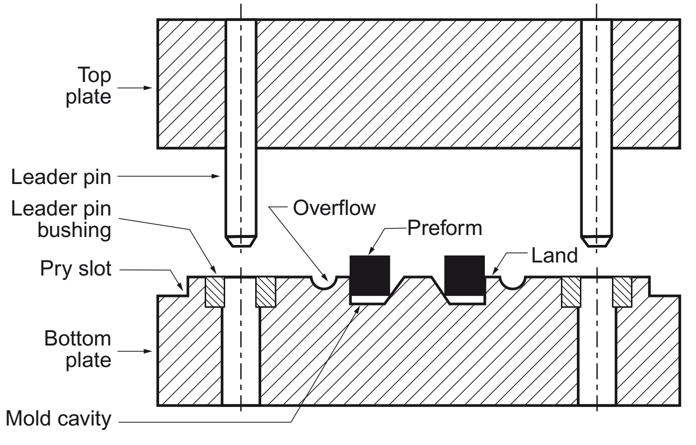

Figure 3.8 Open compression mold showing a rubber perform positioned in its mold cavity before closing the mold

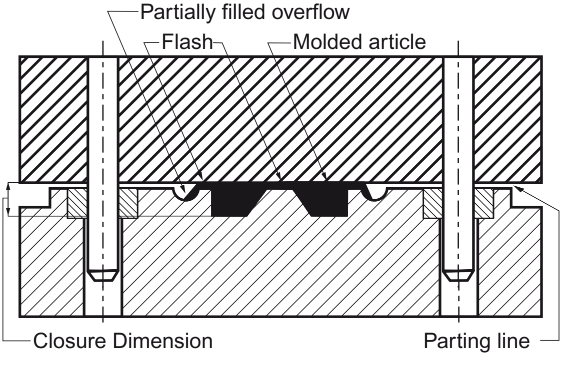

Figure 3.9 Closed compression mold showing partially filled overflow

It is undesirable for the excess compound to exit the mold cavity and completely fill the overflow groove during compression molding. The reason is that the compound flowing past the overflow boundary causes a reduction in molding pressure and represents increased compound waste. Excess compound is generally removed in a post-molding operation, called deflashing.

In Fig. 3.9 compound has flowed into, and partially filled, the overflow groove of a closed compression mold. Design of overflows significantly affects molding operations. Figure 3.10 depicts several overflow cross sections that differ from the semicircular overflow depicted in Fig. 3.9.

Increasing the depth of the semicircular overflow ('a' in Fig. 3.10) increases overflow volume without altering the land width. The increased volume in 'a' is obtained without changing the area of the overflow at the parting line. This permits placing cavities closer together and thus allows for higher volumes in overflows. The deeper overflow has two disadvantages: one is the increased difficulty in removing cured compound from deeper overflows; the other is the reduction in mold wall stiffness adjacent to the land. This lower stiffness increases deformation in the mold wall that reduces mold robustness.

The tapered wall ('b' in Fig. 3.10) overcomes the latter objection because the wall for 'b' is stiffer than that for 'a'. Also, removal of compound from tapered overflow 'b' is easier than that for 'a', but machining the tapered overflow increases mold costs and requires more spacing between cavities relative to 'a'.

Overflow 'c', with its trapezoidal configuration is also stiff relative to 'a'; varying the width of its base adjusts overflow volume and this is an advantage for thin mold plates. A disadvantage is the tendency for the corners in the grooves to become fouled with compound. Fouling is generally more severe in molds with sharp corners than in those with a radius in their corners.

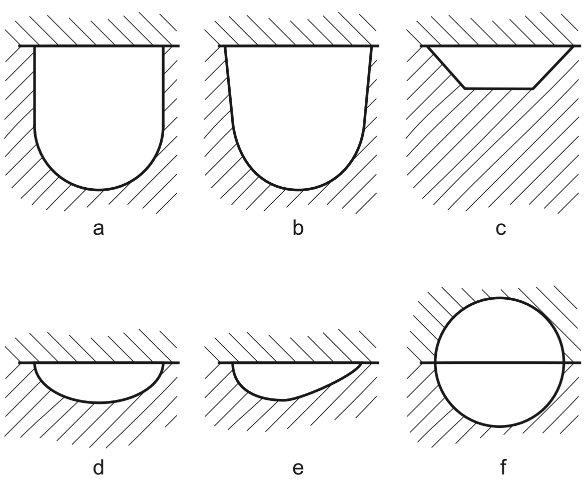

Figure 3.10 Overflow cross-sections:
(a) deep semicircular; (b) deep and tapered semicircular;
(c) trapezoidal; (d) reduced depth; (e) teardrop; (f) full round

If the overflow depth ('d' in Fig. 3.10) is less than the radius of the forming tool – commonly a ball end mill – then depth critically affects land width. For equal land widths, wall stiffness for 'd' is greater than that for 'a'. The radius of 'd' must be increased substantially to provide the same overflow volume as 'a'.

Teardrop overflow 'e' in Fig. 3.10, a variant of 'd', is initially shaped with round-ended tool. After reaching the desired depth, additional machining changes the former round section area to a teardrop shape. The radius side of overflow 'e' is positioned away from its cavity. While the teardrop increases cavity wall stiffness, it also results in higher machining costs and wider cavity spacing.

A full round overflow ('f' in Fig. 3.10) is an alternative to the semicircular one in Fig 3.8. It provides greater overflow volume per unit area of mold plate surface and thus permits closer cavity spacing. The projected area of a round overflow is 0.71 times that of its semicircular counterpart with an equivalent cross-section. This means that there is a decreased tendency for compound in the round overflow to separate mold plates if the overflow were to completely fill and pressurize the overflow cavity.

Leader pins are unnecessary for molds that do not require alignment between the top and bottom plates, e.g., Figs. 3.8 and 3.9. This contrasts with Fig. 3.11, where engaged leader pins and bushings align core and cavity.

Mold plates must securely anchor leader pins and bushings to their mold. Leader pins should terminate in a through hole rather than a blind hole to facilitate their repair and replacement. They should be appropriately dimensioned and hardened to withstand the stress and wear during subsequent mold-assembly and also during mold closing and opening in service. Leader pin diameters should be a minimum of 0.875 in. Of course mold size and other factors affect this diameter.

A two-plate mold can be used for shallow molded articles that do not require alignment between plates. A three-plate mold is usually necessary for deep articles to facilitate removal of the molded article from its cavity.

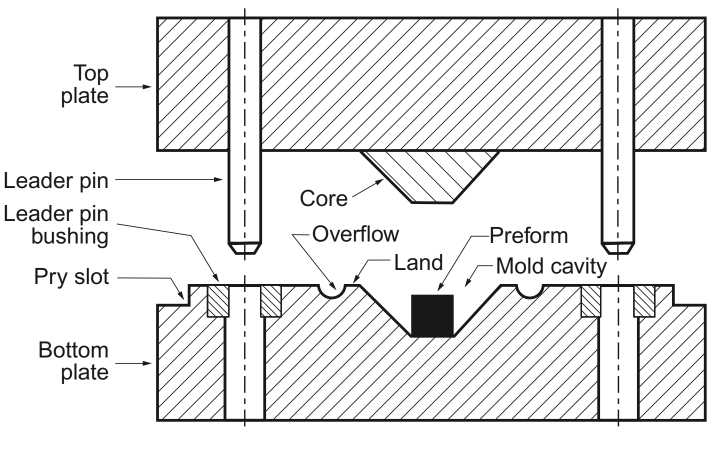

Figure 3.11 Open compression mold with a core in the top plate

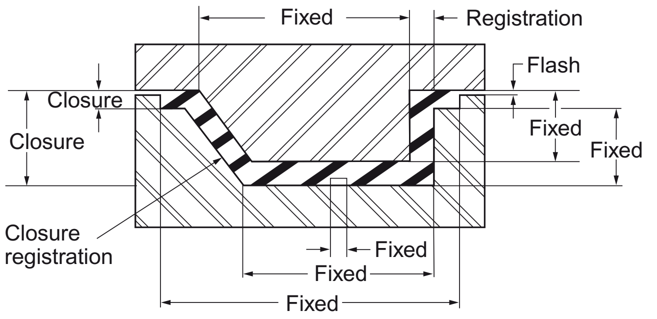

Figure 3.12 Molded product showing the effect of flash thickness variations on fixed- and closure-dimensions (from RMA Handbook, 6th edition, with permission)

Excess rubber at the parting line is often removed by tumbling molded articles against one another at cryogenic temperatures to deflash them; alternatively plastic or metal particles may impact and break away brittle flash. A number of considerations are important in cryogenic deflashing and chief among these is the preferential stiffening or embrittlement of the flash relative to that of the molded article. Being thinner, the flash cools and becomes brittle first and is therefore more prone to rupture at low strain when impacted by another molded article or by particles. This selective embrittlement favors rupture of flash adjacent to the surface of a molded article, as intended.

Compression molded articles differ from their transfer- and injection-molded counterparts in several ways, an important one being flash. Thicker flash typically results from compression molding than with the other methods, because the rubber preform enters an open mold during compression molding. By transfer and injection molding, rubber enters a closed mold. Figure 3.12 shows two important dimensions for molded articles: fixed dimensions and closure dimensions [28]. Flash thickness variations affect closure dimensions, but not fixed dimensions.

Flash thickness of compression-molded articles, which varies in the direction of mold closure, depends on factors such as compound viscosity, cavity complexity, preform shape, and the available mold-closing force. It does not vary for fixed dimensions. The Rubber Manufacturers Association (RMA) provides a guide for specifying dimensions for molded rubber products. It specifies dimensions as a function of product thickness and allowable flash thickness in the closure direction for different dimensional tolerances. Tolerances are provided over a range of product thickness from 0 to 160 millimeters for the four different tolerance designations; tolerances can be calculated for the three least-critical designations for product thickness greater than 160 mm.

Thick flash is useful with some molded articles such as those shown in Fig. 3.13. Demolding the articles individually requires significantly more time than removing them as a sheet. Connecting articles with flash allows their removal as a sheet, saving time. When this is done, the design engineer should specify the maximum flash thickness allowable without impairment of product function. A die, with its cutting edges shaped to conform to the molded product at the parting line, can subsequently cut individual articles from the sheet. This technique, of course, becomes less attractive with expensive compounds because flash is often discarded.

Figure 3.13 Removal of molded articles from a multi-cavity mold as a sheet

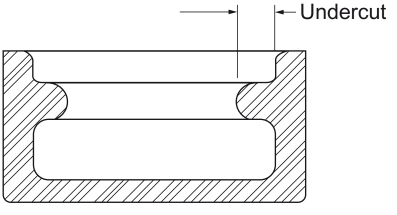

Figure 3.14 Undercut in a mold that makes demolding more difficult

Connecting articles with flash can be an advantage for another reason. Some molded articles contain a deep undercut that makes demolding more difficult (Fig. 3.14). However, molded rubber brake pads for automobiles use an undercut to a functional advantage.

The pads are stretched over a metal brake pedal during installation and upon relaxing, the pad engages the edge of the pedal for retention. Although this undercut is useful for retention purposes, it makes demolding of individual pads difficult. This difficulty is significantly reduced when thick flash connects the pads so they can be removed as a sheet and subsequently separated by cutting with a die. Moderate undercuts can generally be incorporated in molds without the need for sliding cores or split molds. Incorporating a radius in an undercut aids the removal of trapped air and eases demolding.

Times for compression molding are long, because a rubber preform, usually at ambient temperature, is placed in a hot mold cavity and subsequently heated to mold temperature. Long times are needed to raise the temperature of a thick preform to mold temperature. Theory predicts that the time required to heat an elastomer to given temperature is proportional to the square of the conducting path length. Comparison of theory and experimental results shows good agreement [29].

For a molded article with a given thickness, crosslinking time required for compression molding is generally longer than that for transfer and injection molding. Several factors account for this. By compression molding, elastomer generally enters the mold cavity at a temperature lower than that for transfer and injection molding. More work is done on a compound during transfer and injection molding and this work results in additional heating of the compound along with an associated increase in its temperature. In addition, temperatures used for transfer and injection molding are typically higher than those used for compression.

These factors account for the shorter in-mold times for transfer and injection molding (Fig. 3.7), with times for injection molding being the shortest. In-mold times for TSEs molded by the above three methods are all relatively long because of the time needed to both raise the temperature of a TSE and then crosslink it.

3.3.2 Transfer Molding

Compression and transfer molding have some features in common. Both use leader pins and bushings to align mold plates. Because transfer molds generally contain more components (plunger, pot and cavity plate) than compression molds, alignment of components in transfer molds requires additional consideration.

During transfer molding, a plunger squeezes compound between the bottom of a transfer pot and the plunger (Fig. 3.15) in a manner similar to the squeezing of the preform that occurs during compression molding.

Additional squeezing conforms the compound to the pot configuration, after which compound flows through the sprues to fill the mold cavity as shown in Fig. 3.16.

After curing, opening of the mold, and removal of the molded article from its cavity, the cured pad is removed from the transfer pot. Pry slots ease separation of the upper and lower cavity plates. Flash formed in tear-trim grooves is more easily removed than flash formed in overflow grooves. Flash grooves, typically located concentric with and outside tear trim grooves, are not shown in Fig. 3.15 or 3.16. Transfer molding offers advantages and disadvantages relative to compression.

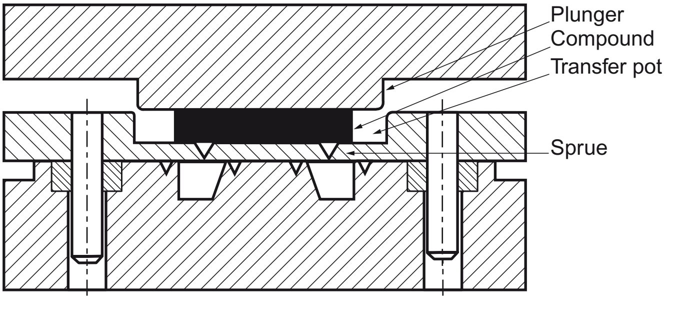

Figure 3.15 Compound in a transfer pot before closing mold

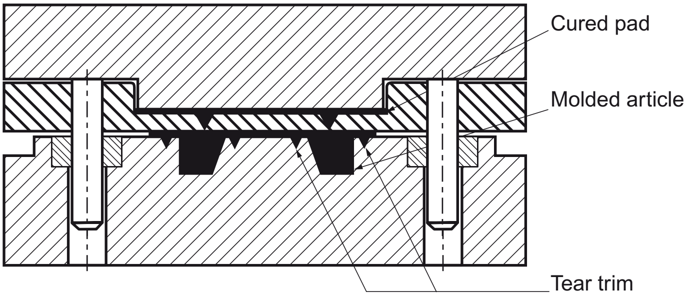

Figure 3.16 Cured pad in a transfer pot after closing mold

First the advantages: Inserts in transfer molded articles are better retained in their intended position than those for compression molded articles. This occurs because the inserts in a transfer-molded cavity are fixed in position in a closed mold when the compound enters the mold cavity via the sprue(s). Flowing compound in a compression mold can dislodge inserts and cause mold damage. Transfer-molded articles with complex shapes generally mold with less difficulty than counterpart compression moldings and a single pad in a transfer pot can service many cavities.

Transfer molding favors reduced flash thickness. It also presents a fresh rubber surface to adhesive-coated inserts in the mold, favoring good adhesion. A single preform provides compound to multiple cavities in a transfer mold. Variations in preform volume affect transfer-molded article volumes less than compression-molded article volume. A major advantage of transfer molding is the viscous heating and the associated temperature increase that occurs as compound flows through sprues at higher shear rates.

Disadvantages for transfer molds are their greater complexity and cost relative to compression molds. Maintenance costs are generally higher for transfer molds, e.g., because of pot-plunger wear. The need for compounds to flow through sprues generally makes transfer molding less tolerant of high-viscosity compounds. Heat transfers ineffectively from the top platen of a curing press to the bottom of the transfer pot, because heat must pass through the compound (preform) in the pot. The compound crosslinks in the pot and is typically discarded unless a mold design is used that avoids curing it.

A patent [30] describes the use of a heat-resistant insulation plate that provides temperature control for cold transfer molding which circumvents the curing of the preform in the pot. Figure 3.17 shows an insulating plate (76) located between the transfer pot and upper cavity plate. This plate is intended to maintain the compound in the transfer pot at a temperature sufficiently low so that compound remains uncured after completion of a molding cycle and can be used for the next molding cycle.

The apparatus for cold transfer molding shown in Fig. 3.17 incorporates a combination of features: compression springs (24) that help separate plunger and pot plates upon mold opening; stripper bolts (22) that limit the downward travel of the plunger plate; a series of bores (78) that contain inserts that convey elastomer from the pot to the mold cavity (52); insulation (76); a hinged (56) mold. The rubber insert shown in Fig. 3.18 (left) represents an article molded in the apparatus of the previous figure.

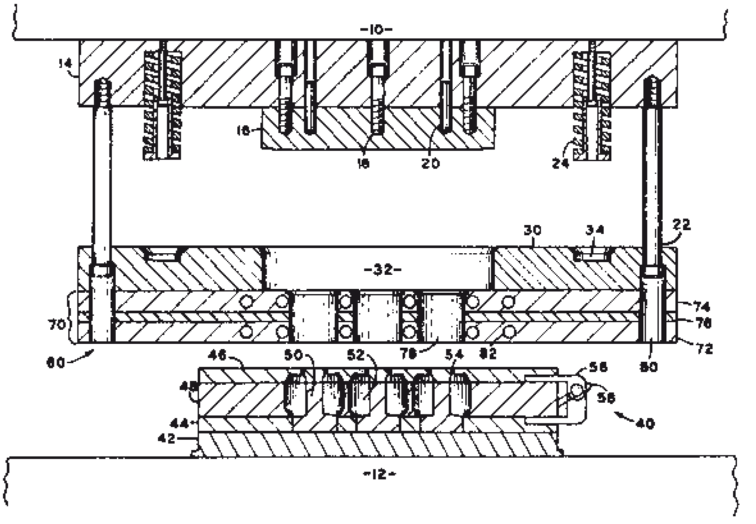

Figure 3.17 Cold-transfer molding apparatus

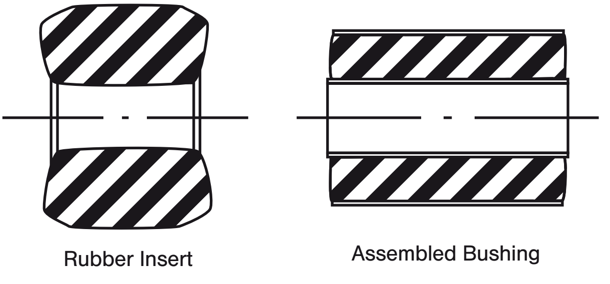

Figure 3.18 Molded rubber insert (left);
assembled bushing showing inner and outer metal sleeves (right)

Metal sleeves are located on the inner and outer surfaces of the assembled transfer-molded bushings insert as shown in Fig. 3.18 (right). The assembled bushing can be formed by squeezing a cured rubber insert between inner and outer metals during a post-molding operation, or by molding and bonding uncured rubber in place.

Curing presses provide the substantial force necessary to close molds and to maintain closure during compression and transfer molding. Although either mechanical or hydraulic presses can provide this force, hydraulic presses are much more commonly used. Figure 3.19 illustrates a four-post molding press typically used for compression and transfer molding. A press with a 26-in diameter ram, powered by 2000-psi hydraulic pressure, provides a closing force of 531 tons. The trend is toward higher hydraulic pressures of 3000 psi. The posts on curing presses must resist static forces in addition to the dynamic force caused by bumping a mold to expel air.

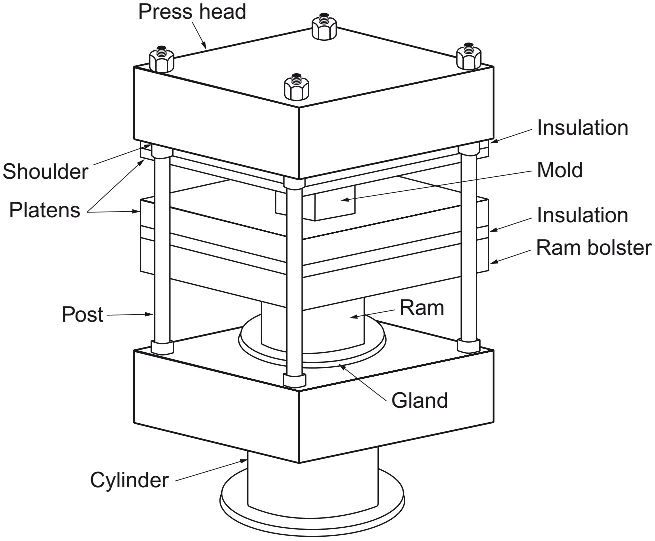

Figure 3.19 Hydraulic four-post molding press

The mold in Fig. 3.19 is purposely shown undersized to emphasize the likelihood of damage during press closing. The platens of most curing presses that have been used in production have many indentations caused by excessive localized pressure. These indentations reduce the area available for conductive heat flow from platen to mold and thus decrease heat transfer.

Ideally, the periphery of a mold in its press would remain within the confines of the press ram to minimize platen deflection. In practice, mold boundaries typically extend beyond the ram diameter. This results in uneven pressure between platen and mold; pressurized compound in the mold tends to open the mold and cause flash, especially at the mold corners. Use of mold plates with a sufficient thickness helps minimize this problem.

Injection molding of thermosetting elastomer (TSE) is typically much more demanding of material, process, and design than are compression and transfer molding. Because temperatures are much higher for injection molding than for compression and transfer, injection molded TSE compounds usually require longer scorch times. Injection molds require high quality steel to withstand the high temperatures and pressures they encounter during their molding cycle. Some of the major differences between transfer molding and injection molding are:

- Degree of sophistication and automation of the injection method
- Reserve of plasticized warm or hot rubber available for injection
- Ability to inject a compound at a temperature approaching mold temperature

Additional considerations include: the need for relatively high volume production to offset increased machine and mold costs, shortened time schedules for designing and building molds, communication difficulties between mold builders and molders, and increasingly sophisticated machining capabilities. Molders prefer mold builders who can receive drawings by computer-aided design (CAD). Differences among computer programs can cause problems.

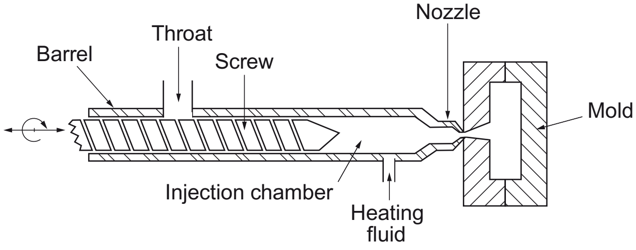

Figure 3.20 Reciprocating screw machine for injection molding

The right combination of injection molding machine, mold, rubber compound, and product design improve both productivity and quality. Machines have evolved over time and Fig. 3.20 shows a reciprocating screw machine.

The reciprocating machine incorporates a screw that functions as both screw and ram. The rotating screw pulls compound into the barrel and transports it to the injection chamber. Heat from working of the compound in the barrel, plus heat transferred from heat transfer fluid in the barrel, increases compound temperature. During the molding cycle, the screw progressively moves to the left as the rubber strip is pulled into the throat. This action provides the volume of rubber needed in the injection chamber for subsequently filling the mold cavity. The rate at which the screw retracts during rotation depends on the amount of force resisting its rearward axial movement, referred to as backpressure.

Backpressure raises torque on the screw and increases the amount of work done on the compound, thus increasing compound temperature. Low-viscosity rubber compounds generally have an increased tolerance for higher backpressure relative to their high-viscosity counterparts. Excessive backpressure can cause scorch problems in high-viscosity compounds.

Retraction progressively decreases the length of the screw that works the compound and this action results in the occurrence of an uneven temperature profile along the axis of the barrel. Hence, compound that subsequently enters the mold is not at a uniform temperature. After sufficient compound accumulates in the injection chamber for the volume required to fill the cavity, the screw stops rotating, moves forward and forces compound from the barrel into the mold. Hence, the screw in the reciprocating machine acts as both a screw and a ram.

Clearance between screw and barrel of the reciprocating screw machine is greater than the clearance for the coaxial machine shown in Fig. 3.21. The latter machine can be cleaned relatively easily and it provides high injection pressures. Retraction of the screw-barrel unit allows for easier compound changes and accessibility for maintenance. Because of these and other advantages, this arrangement is widely used today.

In operation, the barrel and screw act as a unit and engage the barrel. The rotating screw conditions compound and forces it through the nozzle into the holding chamber. After a sufficient volume of compound to fill the mold cavity has accumulated, screw rotation stops, the screw-barrel unit advances and forces compound into the cavity.

Of the several different forms of compound are used to feed injection machines – strip, granulated, and powder – strip is the dominant form. Output temperature of the extrudate is affected by several factors, including evenness of the cross-section of the strip. This is

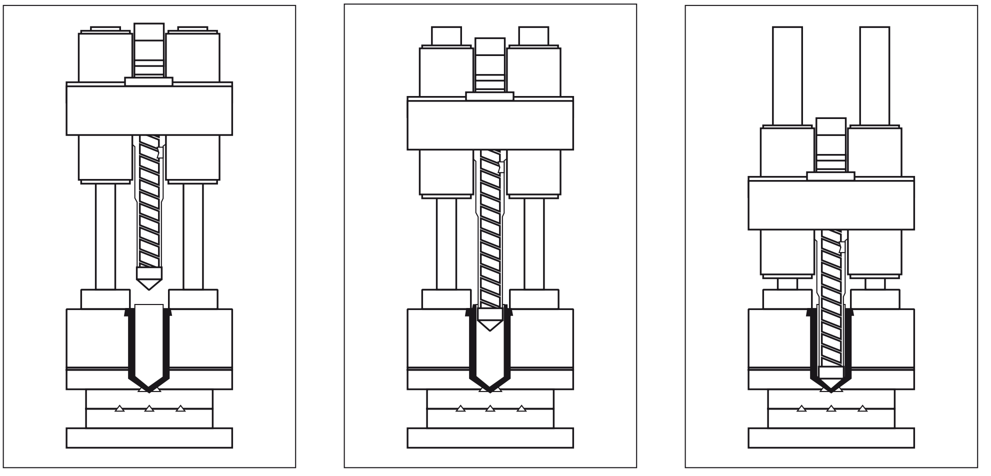

Figure 3.21 Coaxial arrangement of the injection screw and barrel

unfortunate because controlling cross-section dimensions requires a more expensive strip preparation process. Granulated and powdered compounds, especially soft ones, share a tendency to agglomerate. Although dusting the surface of these helps reduce agglomeration, it can cause other problems. Compounds with high glass transition temperatures such as NBR are generally less problematic.

Compound that exits an injection-molding machine enters a sprue that then branches into a distribution system as shown in Fig. 3.22. It flows first into a primary runner, then into secondary runners, through drops, and finally through the gates to form molded articles. The runner system can be compared to that of a water distribution system for a municipality, where water flows from a large main (comparable to the sprue) to a smaller main that feeds a neighborhood (primary runner), to pipes that feed individual homes (secondary runners), to pipes in homes that feed faucets (gates). Ideally, adjustable gates in injection molds would control elastomer flow, just as faucets control water flow in a home.

TSE molds incorporate either hot- or cold-runner systems. Compound in a hot runner system crosslinks during the molding cycle, while that in a cold runner system does not – at least not intentionally. Cured compound in a hot runner is generally discarded as scrap but it is sometimes ground into small particles for incorporation into fresh compound for subsequent use. The scrap resulting from a hot runner system is a major disadvantage, because it incurs costs, not only for the actual loss of the compound value, but also with costs for disposing of the runner scrap.

The ideal runner systems would fill all mold cavities simultaneously so that the resulting molded articles would have the same state of cure. A balanced runner system is a necessary – but insufficient – condition to meet this objective. Gate design and other factors such as compound temperature significantly affect flow behavior and therefore production rate of molded articles.

While runners can be designed scientifically, most often they are designed based on the mold designer's experience, because available time is often inadequate for the more thorough scien-

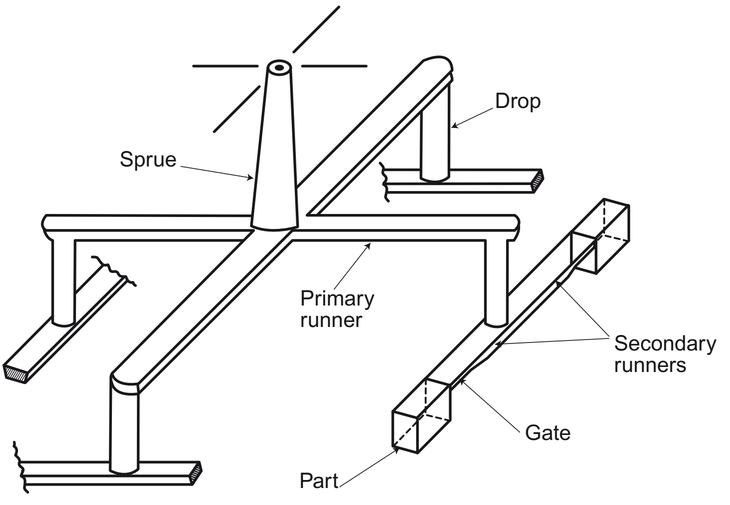

Figure 3.22 Schematic of a runner system for an injection mold

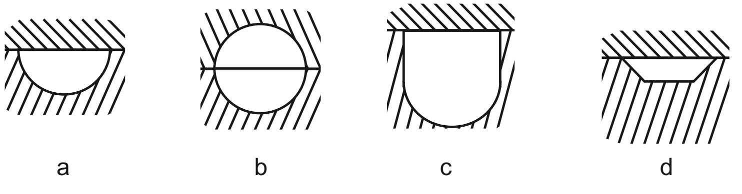

Figure 3.23 Runner cross-sections:
(a) semicircular; (b) circular; (c) modified semicircular; and (d) trapezoidal

tific approach. Mold designers frequently fabricate an injection mold with undersized runners, make a few trial moldings, and then make modifications such as increasing the runner cross section as required to fill all cavities. Figure 3.23 illustrates cross sections for several runner channel designs.

Different runner cross-sections offer relative advantages and disadvantages. The semicircular channel shown in 'a' is machined in only one mold plate, e.g., with a ball-shaped end mill. This approach does not require accurate alignment of mold plates. The cured runner is relatively easily released and removed from its semicircular channel. Circular runner 'b' in Fig. 3.23 requires machining and accurate alignment of two mold plates. Modern machining techniques facilitate obtaining the required alignment. Round runner 'b' is usually more easily removed than 'a', its semicircular counterpart.

Since modified semicircular runner 'c' is deeper, this runner releases with more difficulty than runners 'a' or 'b'. Because runner depth in 'c' exceeds its diameter, for the same projected area, it provides a greater runner volume than 'a'. This feature can be used to advantage where clamp force is marginal, because the increased volume is obtained without requiring increased clamp force to keep the mold closed. That is, the force tending to open the mold caused by pressurized elastomer in runner 'c' is independent of runner depth.

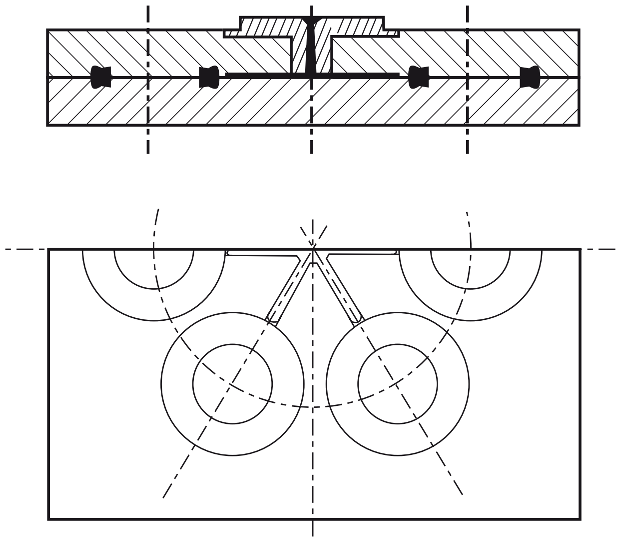

Figure 3.24 Two-plate mold for curing ring shaped articles

If a too-thin mold plate prevents machining the desired runner volume with circular runners, trapezoidal channel 'd' can be used. The desired volume can be obtained by making multiple passes with a tapered end mill to control the width of the channel. A disadvantage of 'd' is the tendency for runners cured from weak compounds to tear during runner removal because of the sharp corners in the base of the trapezoid. In addition, there is a tendency for increased mold fouling in these corners. Rounding of the corners in 'd' alleviates both these problems.

Hot runner systems can be incorporated in either two- or three-plate injection molds. Figure 3.24 illustrates a two-plate design where compound flows from the injection nozzle into the six runners and then through the gates into the mold cavities. After the cavities are filled, the compound will crosslink in the gates first, because gate thickness is substantially less than that of the runners. Here, low thermal diffusivity is used to advantage because the compound in the gates, being thin, crosslinks first and seals the cavities. Since the gate area is very small, the molded articles separate easily from the runners at the gate.

Simplicity and lower cost are advantages for a two-plate, relative to the three-plate mold shown in Fig. 3.25, where compound flows from the sprue to the drops that in turn feed the individual cavities.

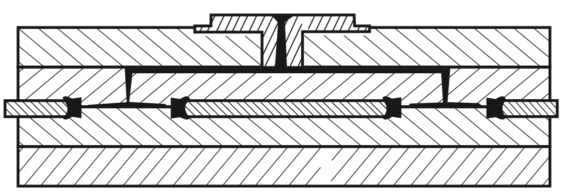

Figure 3.25 Three-plate mold for curing ring shaped articles

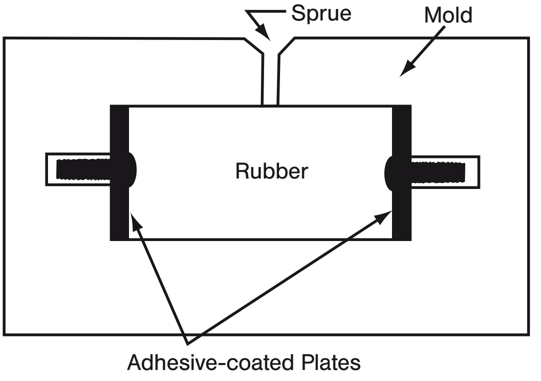

Figure 3.26 Cross-section of an injection mold for a mount showing the adhesive-coated metal plates in place

The above discussion considered molds in which the runners cure. In a cold-runner mold the runner temperature is typically maintained at about 80 °C, a temperature below that necessary to crosslink compound in the channels during the anticipated mold cycle time. Scorch characteristics of the compound of course mainly determine this temperature. This feature is especially important when molding expensive compounds, as it essentially eliminates runner scrap. A disadvantage is that cold runner systems are more complex and expensive than hot runner systems.

When molding adhesive-bonded articles, it is important to locate the sprue or gate such that the rubber entering the mold does not impinge directly upon the adhesive surface. In Fig. 3.26, the central location of the sprue avoids wiping or scouring the adhesive. Adhesives used in injection molding generally require greater resistance to scouring than do those for compression and transfer molding. An alternative to injecting compound midway between plates is to inject it through the opening in one plate, normal to the other plate.

3.3.3 Injection Molding of TPEs

Emphasis now shifts from injection molding TSEs to injection molding TPEs. There are similarities and differences among injection molding machines for TSEs and TPEs. Toggle clamps, which provide for rapid operation, are most frequently used for injection molding TPEs and other thermoplastics because TPE cycle times are much shorter than those for TSEs. Hence, times for clamp opening and closing need to be much shorter than those for TSEs. Figure 3.27 shows the screw, barrel, and hopper regions of a TPE machine.

TPE pellets are fed into the hopper located to the top right of Fig. 3.27, where they then fall into the opening between screw and barrel. Because the hot barrel heats the hopper region, cooling of the hopper may be necessary to prevent feeding problems caused by premature softening and massing of the pellets in the hopper region. The pellets enter the feed zone, where screw flights are deepest. The rotating screw transports them to the compression zone, where flight depth decreases. Here, the temperature of the pellets increases rapidly because

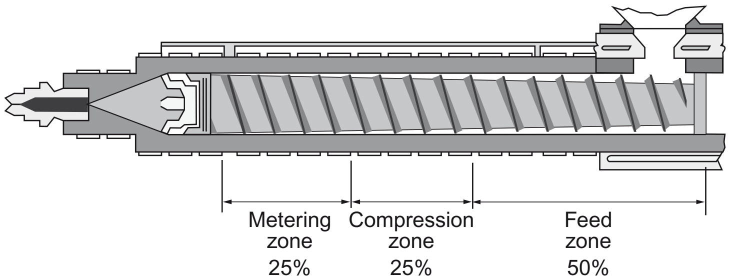

Figure 3.27 Horizontal in-line injection molding machine showing the hopper, feed-, compression-, and metering-zones

of the heat provided by the hot barrel and the mechanical work imparted by screw rotation. The metering zone is intended to melt residual solid TPE and to increase melt temperature uniformity prior the melt entering the nozzle.

The screw in the reciprocating machine in Fig. 3.27 functions as both a screw and a ram, with action similar to that for injection molding TSEs. The screw progressively moves to the right as TPE pellets fall into the feed zone. This action provides the needed volume for accumulating sufficient melt in front of the screw tip to fill the mold. The rate at which the screw retracts during rotation depends on the amount of force resisting retraction, referred to as backpressure.

Backpressure raises torque on the screw and increases the amount of work done on the melt by the screw, work that is converted to heat and increases compound temperature. Excessive backpressure causes undesirably high temperatures. Screw retraction progressively decreases the length of the screw working the compound. This action results in an uneven temperature along the axis of the barrel, with the first pellets entering the hopper receiving the most work and therefore attaining the highest temperature increase. After sufficient melt accumulates in the injection chamber for the required shot volume, the screw stops rotating and forces melt from the barrel into the mold. Hence, the screw in the reciprocating machine acts as both a screw and a ram.

TPE molded articles become dimensionally stable after hot melt cools to a sufficiently low temperature in a mold cavity. In-mold times (Fig. 3.7) for TPEs are short, because TPE molded articles require only the formation of *physical* crosslinks during cooling of hot TPE in a mold. Thin cross sections of most TPE articles require only a relatively short time to cool the hot melt in its cavity, resulting in short molding cycles. Among molding methods for TPE, injection molding dominates.

TPEs are often molded in the as-received form (most often pellets) from the TPE manufacturer. Other materials might be added to a TPE to color it, or to reduce the cost of the resulting compound. In contrast, compounds for TSE molded parts require at least the incorporation of a crosslinking system to obtain useful properties. Nearly all TSEs are compounded with fillers, plasticizers, and other ingredients to the extent that weight of these added materials frequently is several times that of the weight of the original TSE as shown in Tables 2.2 and 2.3. In contrast, substantially fewer additives are incorporated TPEs and their lower filler content results in higher TPE shrinkage.

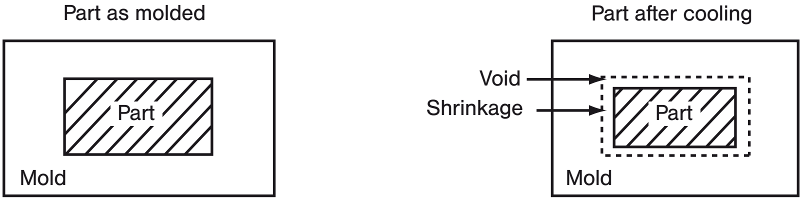

Figure 3.28 Mold shrinkage caused by cooling the melt in its mold cavity

After injection, the hot melt shrinks in the cool mold cavity. Shrinkage, the difference between the dimensions of a mold cavity and the molded product at room temperature, causes a void to form between the molded article and the surface of the mold cavity as shown in Fig. 3.28. The cooled melt forms an exterior skin that envelops residual molten TPE in the cavity.

Increased holding pressure introduces additional melt into the molded article and forces the cooled melt against the cool cavity wall until the gate freezes. After the gate freezes, increased pressure becomes ineffective, because cooled TPE blocks the gate. After removal from its mold, the molded article shrinks further as it cools. Within a given class of TPEs, shrinkage depends on a specific grade or compound. For most Santoprene TPVs, mold shrinkage ranges from 1.4 to 5%, with softer grades showing slightly higher shrinkage [31]. Thick-walled articles show higher shrinkage, thinner-walled articles lower shrinkage.

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4 Testing and Properties

ASTM tests are among the most widely used in America. Many of these, although recognized as national standards, are not permanent documents. They are drawn up by consensus among leading experts of the day and are periodically revised as necessary.

Tests that yield data for engineering design should be distinguished from those that provide quality control information. The latter establish that a material has the same batch-to-batch properties, as measured by the method being used. Ideally, design data and quality control data would be equivalent in usage. Unfortunately, this is not so.

Tests useful for generating design data (e.g., shear modulus measurements) are often regarded as too difficult or tedious and consequently are rarely used on a routine basis. Indeed, most of the standard test methods adopted by the rubber industry are quality control tests that yield data that don't directly relate to performance. While quality control tests are important, they are inadequate substitutes for tests that yield data useful for design.

Engineers familiar with tensile strength may not realize that tear strength is likely more relevant to failure modes for some rubber products such as engine mounts [1]. Generally, tensile and tear tests correlate poorly. Component testing is necessary to ensure that predicted and actual performance correlate. This is especially critical where a rubber component, e.g., a seal, is expected to perform satisfactorily over a 20-year period in a severe environment [2].

Physical tests are important when specifying rubber components. The designer needs to communicate to the component manufacturer the rubber material to be used and the properties expected of the finished component. This takes the form of a technical specification that normally defines acceptance criteria based on a number of standard physical tests. In establishing a specification, the designer should bear in mind the precision (or more often the lack of precision!) of the physical tests being used. ASTM has made a policy of including statements in its standard test methods giving guidance on the normal within-laboratory and between-laboratory variation of test results.

Test results obtained from specimens using special test slabs prepared in the laboratory should be distinguished from specimens cut from a finished rubber article [3]. In preparing specimens from finished rubber articles, buffing is generally preferred for preparing soft rubber compounds, splitting for harder ones. Additionally, factory-processing conditions seldom exactly duplicate those by small-scale processing in the laboratory. Good dispersion of fillers is typically harder to achieve with large factory mixers than with small laboratory mixers.

Further, production mixed batches reach higher mixing temperatures than laboratory mixed batches. It therefore is prudent to experimentally verify that results from the two different types of test specimens are comparable when quantitative comparisons are needed. Tensile strength and elongation at break obtained from test pieces cut from a finished component are often about 10% lower than results from specially prepared test slabs. For this reason, some specifications provide for lower test requirements when test pieces are cut from finished components.

Users of test methods should also be aware of the variation in test results as a function of time. For example, crosslinking does not stop precisely at the time a compound is removed from a curing mold. It continues as the rubber cools down to ambient temperature, and the crosslinking that occurs during cooling may be a large fraction of the total crosslinking for large molded articles that cool slowly.

Although design engineers may use Young's modulus and/or shear modulus in their calculations, these are not common parameters in the rubber industry. Young's modulus can be estimated by hanging weights on a long strip of rubber and measuring the resulting elongation with a cathetometer [4]. Alternatively, Young's modulus can be estimated by compressing a cylinder of rubber between flat, parallel platens lubricated with an inert material such as silicone fluid.

Hardness is traditionally used as a substitute for modulus and as a convenient means of classifying rubber vulcanizates. This practice is so entrenched that there is no ASTM method for the determination of shear modulus, even though shear modulus is of considerable value to the engineer.

Special procedures have been developed to test rubber, because it is a complex material with unique properties. Test results obtained on rubber in the laboratory are considerably more dependent on test conditions than tests on metals [5]. The current chapter deals with the testing of both unvulcanized rubber and vulcanized rubber – discussed first is unvulcanized rubber.

4.1 Measuring Viscosity and Scorch

Viscosity and scorch characteristics are especially important properties of rubber compounds. The Mooney viscosity test, described by ASTM D 1646, determines viscosity of both raw and compounded rubber at a test temperature of 212 °F [6]. A metal disc (rotor) rotates in the rubber as shown in Fig. 4.1. Roughened surfaces on both the platens and the rotor minimize slippage between rubber and platens as the disc rotates.

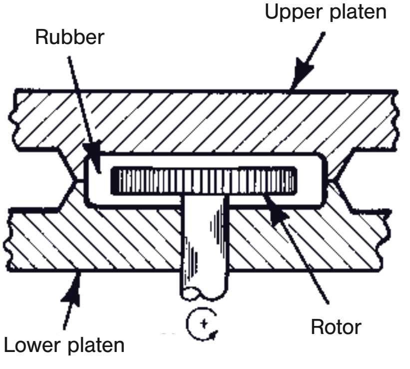


Figure 4.1 Mooney viscometer platens and rotor

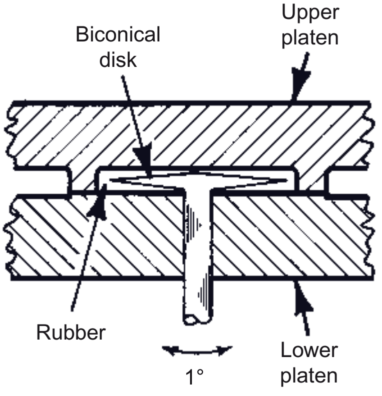


Figure 4.2 Platens and biconical disc of an oscillating disc rheometer

A smaller rotor at a higher temperature, typically 250 °F, is used in the same instrument to determine when scorch occurs. The scorch test measures the onset of crosslinking and the resulting scorch value indicates whether there is sufficient time to complete the necessary processing operations before crosslinking impedes flow of the compound. Because the rotor rotates continuously, this test can measure only the very early stage of crosslinking. Beyond this stage, the results become meaningless because crosslinked compound tears, as it can no longer flow. This is not a problem with the oscillating disc rheometer (ODR).

The ODR incorporates a biconical rotor (Fig. 4.2) that oscillates at a small strain, typically ±1°, as described in ASTM D 2084. The crosslinked rubber accommodates this low strain level without rupture.

The ODR determines the properties of *un-crosslinked*, *partially-crosslinked*, and *fully-crosslinked* compounds. The moving die rheometer (MDR) developed subsequent to the ODR eliminates the rotor, because its lower biconical platen oscillates with respect to its stationary upper biconical die. Better temperature control results from this arrangement relative to instruments containing a rotor.

Another instrument, the rubber process analyzer (RPA) further improved testing. Like the MDR, the RPA is a rotorless rheometer that measures rubber properties before, during, and after crosslinking and it retains the operating characteristics of the MDR. These characteristics include easy loading and unloading of rubber specimens for testing, a significant advantage relative to the capillary rheometer. The RPA can measure properties over a range of temperatures, frequency, and strain and then compile the resulting data in a straightforward manner.

The above rubber tests (Mooney viscosity, Mooney scorch, hardness, tensile tests, etc.) have served the rubber industry for many years; they suffer from several deficiencies, including undesirably long times for test results to be completed before batches of rubber can be released to production. Also, test results are less relevant to service conditions than desirable.

A newer instrument, called a production process analyzer (PPA), is said to combine the capabilities of several different test instruments into one [7]. It functions as a raw rubber tester, a processibility tester for mixed compounds, an advanced cure meter, and a mechanical tester for cured dynamic properties. In operation, a factory operator places a test sample in the PPA, pushes the start button, and then receives a go, or a no go, signal as to the suitability of the tested sample. This capability is said to significantly facilitate manufacturing.

4.2 Hardness

Focus now shifts to the testing of vulcanized rubber specimens and products. Among the most used – and sometimes misused test – is rubber hardness, a measure of the resistance to indentation under specified conditions (ASTM D 2240). Different instruments are available to measure different hardness ranges. Not unexpected, there are advantages and disadvantages to hardness testing.

The instruments that measure hardness are relatively inexpensive and measurements can be made on moderately irregular surfaces [8]. The dominant advantage is the ease with which hardness can be measured with a hand-held instrument. Disadvantageous are the erratic results that occur when measuring irregular surfaces.

Micro hardness testers are available that read on the Shore A scale. They use different indenters under reduced loads in order to limit the indenter penetration into the test piece, thus permitting the testing of samples thinner than the recommended 6 mm. These micro-hardness testers are usually calibrated against a conventional durometer.

More importance is often assigned to hardness values than is justified, as the measurements may bear no relation to the ability of rubber product to perform their intended function. For this reason, compression-deflection tests are occasionally substituted for hardness tests to obtain more relevant data. Compression-deflection and other stress-strain properties are now considered.

4.3 Stress-Strain Properties

4.3.1 Uniaxial Deformation

This term refers to deforming rubber on a single axis, for instance in compression or tension. When rubber is stretched, tests are typically called 'tensile tests.' Tensile tests provide a fingerprint, so to speak, of a rubber compound and indicate whether the compound contains the desired amounts and types of ingredients or whether cure conditions were satisfactory. From a single test, one can obtain stresses at different elongations, typically 100 and 300% elongation, elongation at break, and stress at break. Data obtained in this manner are widely used for quality assurance and specification purposes.

ASTM D 412, the dominant method for determining rubber properties in tension, uses a dumbbell specimen. An alternative is a ring-shaped specimen. Many rubber products undergo repetitive stress-strain cycles in service, e.g., motor mounts, tires, and suspension bushings. Tensile tests are generally run on compounds for these and other products without prestretching tensile specimens. Prestretching changes tensile stress-strain properties and the amount of change depends upon the nature of the compound.

Ring specimens are usually cut from a flat sheet by a rotating cutter mounted in a drill press. Alternatively, they may be cut from tubes on a lathe using a dilute soap solution to lubricate the blades during cutting. A pair of fixtures each consisting of a 4.75 mm spindle mounted on bearings holds the ring specimens in the tensile testing machine. In addition, the surface of the spindle is lubricated with a material that does not affect the rubber. The lubricant facilitates slip between spindle and the rubber specimen and thus helps to equalize the stresses in the rubber on either side of the spindle.

A significant disadvantage of the ring specimen is the occurrence of unequal states of strain on the inside and outside circumference of the ring. The inside is more highly strained than the outside and the state of strain in the portion of the ring in contact with the spindle is quite complex. As a result, the tensile strength observed with ring specimens is usually lower than with dumbbells.

On the other hand, the use of ring specimens is favored in some countries for the simplicity of test operation that facilitates automation. Installation of the test specimen in the grips can hardly be simpler and there is no need for an extensometer, because the extension can be calculated from the grip separation. The cut ring specimen is advantageous when testing at non-ambient temperatures, for example in an environmental chamber. O-rings of an appropriate size also may be used as the test specimen.

While the design engineer considers tensile properties of rubber to be of relatively little use, a compounder uses tensile properties to both indicate and control quality. A design engineer should avoid placing too much emphasis on the tensile strength value of a compound as the criterion for compound selection.

For vulcanizates containing reinforcing fillers (Fig. 4.3), properties can change significantly upon repeated stretching, with the greatest change occurring during the first cycle. This means that stress-strain behavior of a product in service can be quite different from results indicated by single-cycle tensile testing. Prestretching affects unfilled vulcanizates to a lesser extent.

A wide range of factors affects dynamic property test results. These include the rubber compound, the type of test specimen, specimen conditioning, test method, etc. Factors like these were included in an extensive examination of dynamic properties using an experiment design [9]. It was concluded that a wide variety of instruments in combination with several types of test specimens could provide better measurement of dynamic modulus than of dynamic loss factor. The latter is subject to greater scatter as well as to greater sensitivity to the test method.

Load-deflection requirements for a product with a specified static load-deflection characteristic shall supersede a specified hardness. The load-deflection response should be stated on the drawing and be agreed upon between customer and rubber manufacturer [10]. Some rubber products require a wide tolerance for dynamic properties that is a function of hardness and rubber wall thickness. For example, a product with a Shore A hardness above 65 and a wall thickness less than 6 mm (0.25 in.) requires a tolerance as large as ±26%.

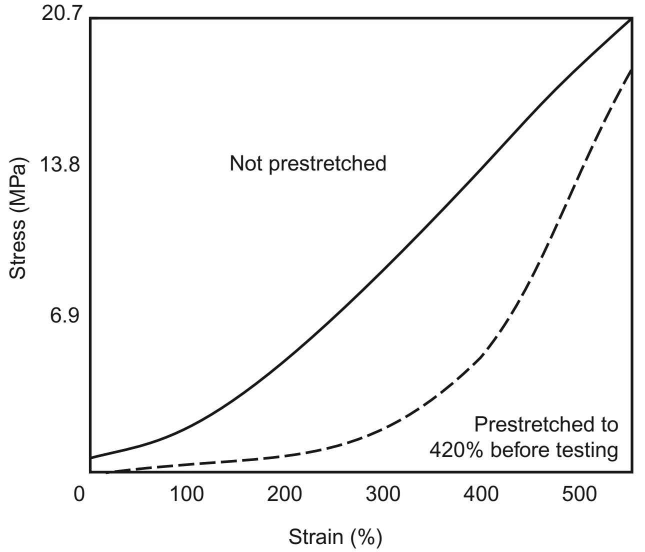


Figure 4.3 Stress-strain response for carbon black reinforced vulcanizate

4.3.2 Biaxial Deformation

Breaking stress and breaking elongation in equibiaxial stress are often significantly greater than those in uniaxial tension [11]. The lack of a preferred direction for crack growth probably accounts for this behavior. An inflated test specimen provides one means to obtain biaxial tension data. Another means is the squeezing of a flat rubber sheet between metal plates, where boundary conditions are very important, as shown in Fig. 4.4.

Modulus (slope of the compressive stress-deflection curve) is significantly higher for both the adhered specimen and the one contacting sandpaper. Use of lubricants, graphite or petrolatum, between the rubber and the metal plate results in lower modulus values, caused by slippage at the interface. Thus, proper control of boundary conditions is necessary to obtain meaningful compression-deflection properties of rubber.

ASTM D 575 describes a method for running compression-deflection properties of rubber, a method wherein geometry is extremely important. The term 'shape factor' (SF) is frequently used to describe geometry. By definition, SF is the ratio between the area of one loaded face and the total area free to bulge. This definition is of course limited to specimens where there is no – or virtually no – slippage at the interface with rubber. Hence, it applies to the curves identified 'adhered' and 'sandpaper' in Fig. 4.4. Figure 4.5 illustrates shape factors over a range of 0.25 to 10.0.

Figure 4.6 shows compressive stress vs. strain as a function of SF over the range of 0.25 to 6.0 for a 70 Shore A hardness compound. At an SF of 6.0, a small compressive strain of 2% is associated with a compressive stress of 7.5 MPa (1088 psi). A strain of about 42% is required to reach the same stress at an SF of 0.25. Hence, even a limited SF range causes large differences in stress-strain behavior in compression.

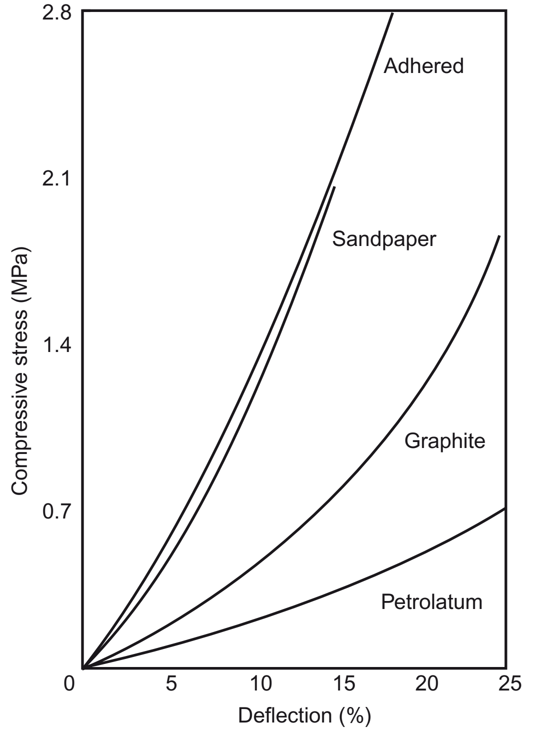


Figure 4.4 Compressive stress vs. deflection behavior for different boundary conditions

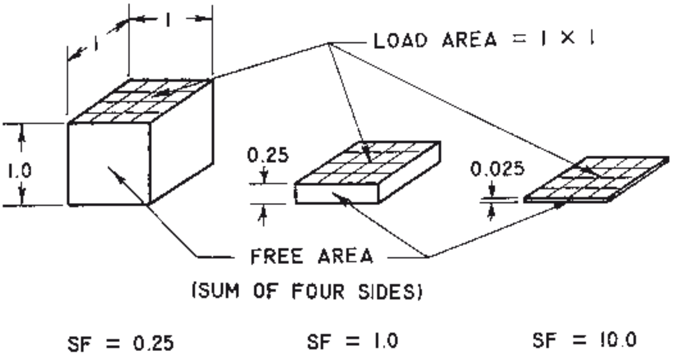


Figure 4.5 Rubber specimens with different shape factors

When SF is low, compression-deflection behavior relates mainly to rubber properties such as hardness and stress at 100% elongation. But when the SF is high, it is the SF that dominates compression-deflection behavior. Hence, rubber products with very high compression stiffness can be made from very soft compounds by using a high SF in their design. If their SF is sufficiently high, compressive stiffness approaches that obtained under triaxial compression.

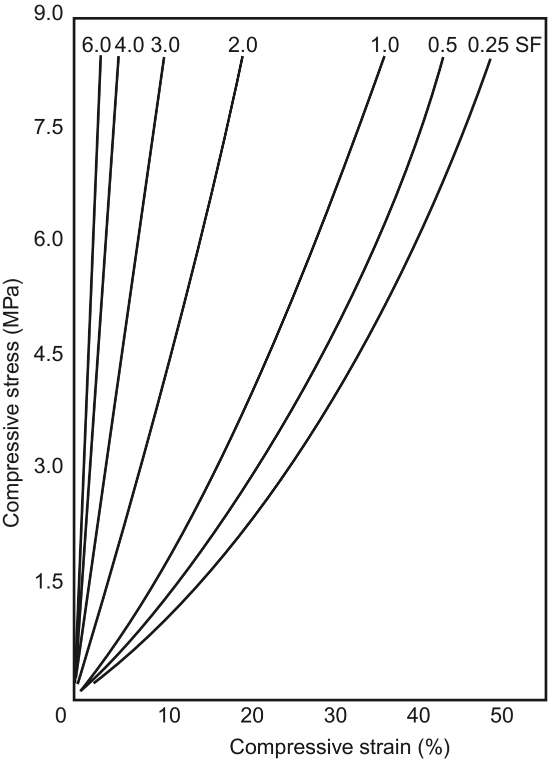


Figure 4.6 Compressive stress vs. strain for a shape factor (SF) range of 0.25–6.0

4.3.3 Triaxial Deformation

Triaxial compression (hydrostatic compression), as shown in Fig. 4.7, occurs when compressive force is applied uniformly to all surfaces of a rubber specimen. Under this condition, rubber volume decreases but its shape remains unchanged. In uniaxial tension, in contrast, shape changes with virtually no change in volume. The arrows in Fig. 4.7 indicate the direction of the applied force. For triaxial compression, high force applied uniformly over the surface of the rubber decreases volume only slightly.

Equation 4.1 defines the bulk modulus (B) as the ratio of the hydrostatic pressure to volume strain for a specimen under hydrostatic compression.

$$B = \frac{\text{Hydrostatic pressure}}{\text{Volume change per unit volume}} \tag{4.1}$$

Figure 4.7 schematically illustrates triaxial compression and uniaxial tension. Because of the extremely high value of B for rubber, about 2 GPa, a hydrostatic stress of 1 MPa reduces the volume of the rubber block by only about 0.5%. The same stress in uniaxial tension

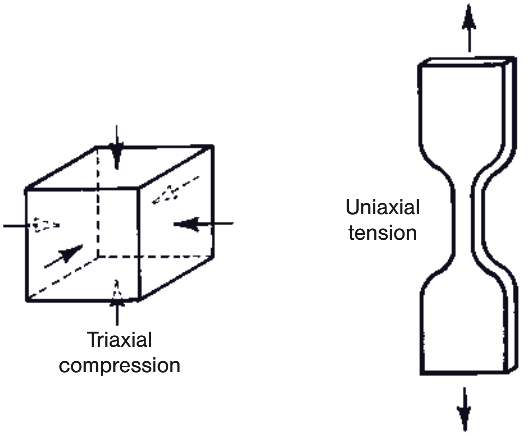


Figure 4.7 Schematic showing triaxial compression and uniaxial tension

elongates a tensile specimen by about 100%. Hence, equivalent but different types of stress cause a 2000-fold strain ratio for the specimens subjected to uniaxial tension or triaxial compression.

The different mechanisms involved in triaxial compression and uniaxial compression account for this large ratio. High stresses squeeze rubber molecules closer together during triaxial compression, but only slightly reduce volume. In uniaxial tension, stress changes conformation of rubber molecules rather than changing volume. Only low stress is required in uniaxial tension to change conformation, accounting for the large differences observed. Cross-sectional area in a stretched tensile specimen decreases to accommodate the increase in length at virtually constant volume.

Poisson's ratio (ν) is the negative transverse strain divided by the axial strain in the direction of elongation [12]. The value of ν for gum rubber is approximately 0.5, that for common steel is 0.27. The effect of shape affects these two materials substantially differently. For instance, the effect of change in shape can raise rubber's compression modulus by more than two orders of magnitude; the effect of change in shape for mild steel can raise its compression modulus by no more than about 30% above its Young's modulus [13].

The value of ν for cork, near zero, explains why it is much easier to press a cork into a wine bottle than a rubber stopper. This behavior occurs because the cork cross-section remains essentially unchanged upon pressing a cork into a bottle; a rubber stopper bulges when pressed, making entry more difficult. The most successful synthetic rubber stoppers to date have been EVA and compounds based on SEBS [14].

Cork can partner with rubber in composites [15] that have a Poisson's ratio of approximately zero. The cork, which contains about ninety percent air, is elastic and imparts good resistance to compression set of the composite. Because of this, the composite finds use as oil seals in diesel and gasoline engines.

Equation 4.2 shows the relationship among the bulk modulus (B), Young's modulus (E), and the Poisson ratio (ν). This equation is strictly valid only at small strains, where many materials can be treated as obeying the classical theory of elasticity.

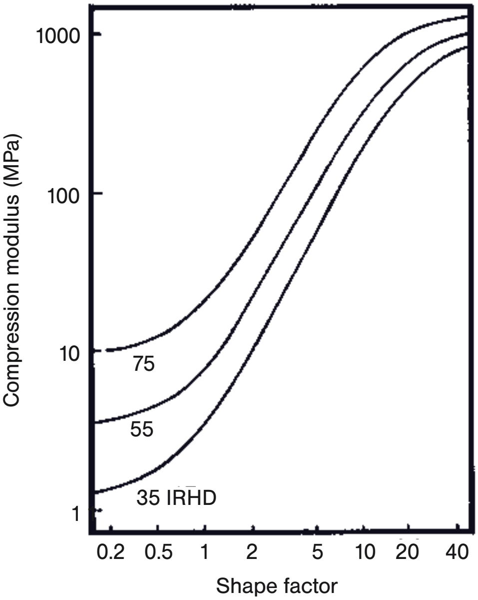


Figure 4.8 Compression modulus as a function of shape factor for three different hardness rubber compounds

$$B = \frac{E}{3\,(1 - 2\,\nu)} \tag{4.2}$$

Figure 4.8 shows the sharp dependence of compression modulus on shape factor for three different hardness NR compounds over a wide range of shape factors. Hardness is in units of International Rubber Hardness Degrees (IRHD), approximately equivalent to Shore A hardness units.

For the three different hardness compounds, compression modulus increases sharply with increasing shape factor. For the 35 IRHD compound, compression modulus increases by almost three decades over the total shape factor range. Hence, extremely stiff composites can be fabricated from soft rubber compounds by appropriate design as will be seen in Chapter 7.

4.3.4 Triaxial Tension

The poker chip specimen described in Method A of ASTM D 429 approximates triaxial tension (Fig. 4.9). A thin rubber specimen is bonded to threaded metal plates. A tension force applied to the plates results in the formation of stresses in the central portion of the rubber that approximate triaxial tension.

Cohesive failure in the rubber results from a small cavity that forms and expands in the central region of the specimen under negative pressure. Outwardly directed tension causes negative

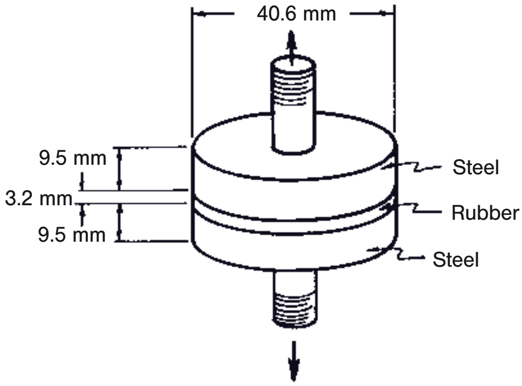


Figure 4.9 Bonded rubber-steel specimen for adhesion testing

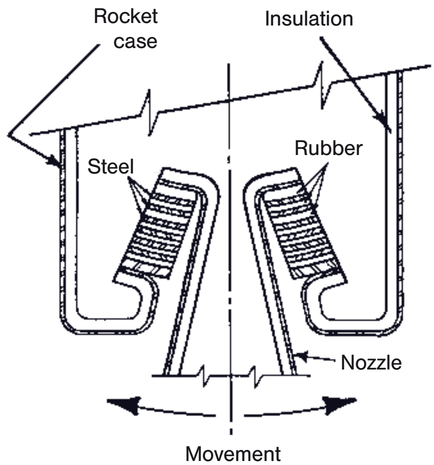


Figure 4.10 Laminated steel-rubber bearing composite that permits nozzle movement

pressure associated with elastic instability similar to that observed during inflation of an ordinary balloon [16]. Based upon FEA, Yeoh suggests potential improvements in the D 429 specimen for examining fatigue failure near bonds [17]. A spherical substrate would replace one flat metal face opposite a conical face.

The need to limit triaxial tension was demonstrated by a laminated steel-rubber bearing for a rocket motor nozzle (Fig. 4.10). One end of the bearing was attached to the lower portion of a rocket case, the other attached to the nozzle [18]. The bearing, which consisted of rubber (NR) bonded to annular shaped steel elements, permitted the nozzle to move with respect to the rocket case and thus steer the rocket.

The method used for testing bearings in uniaxial tension for quality assurance purposes places the rubber in the bearing under triaxial stress. Because the rubber in the bearing is very low modulus, it is especially prone to failure in the triaxial strain mode. The bearing failed as a result of testing and a large number of pockmarks or voids were observed on the surface of the failed rubber. These voids might result from gases trapped during molding of the bearing or from cavitation that occurred during testing.

To establish the failure cause, D 429 specimens were prepared using a rubber compound that was identical to the one used in the bearing. The rubber in one half of these specimens was cut through with a sharp knife; the other were half tensile tested. No voids were observed in the rubber that was cut through; many voids were observed on the failed surfaces that were tested. It was therefore concluded that cavitation caused void formation during triaxial tension testing.

This example demonstrates the importance of proper design, selection of a test method, and subsequent interpretation of test results. The weakness of the bearing in triaxial tension in this application is of less importance, because the bearing is not usually placed in triaxial tension in service. The soft rubber performed satisfactorily in compression because of its high shape factor.

Theory predicts that the hydrostatic stress at cavitation in triaxial tension is about 2.5 times the shear modulus [19]. Experimental data indicate that, for thickness/diameter ratios of 0.025 to 0.05, the hydrostatic stress at cavitation is about six times the shear modulus. Relatively small oscillating tensile stresses can cause rapid fatigue failure in high capacity laminated bearings.

Figure 1.1 earlier illustrated a single-lap simple shear specimen, both relaxed and with an applied shear force. The rubber is adhered to steel plates. Rubber height is h and its surface area is A. Application of a force (F) to the plates moves the top steel plate by a distance (d). Equation 4.3 shows that the shear modulus (G) is the ratio; shear stress/shear strain [20].

$$G = \frac{F/A}{d/h} \tag{4.3}$$

This simple shear specimen tends to rotate during testing, thus causes testing difficulty. Use of a double lap shear specimen (ASTM D 945) eliminates this difficulty, but there are difficulties clamping the specimen during testing. The quadruple lap specimen, described in International Standards Organization ISO 1827–1976 (E), overcomes these objections. Shown in Fig. 4.11, it is mounted in a test machine by a pin through the holes in the center plates [21]; a force (F) is then applied axially to these plates as indicated by the arrows in the figure.

During testing, the center plates are free to move axially and the outer plates are free to move transversely. At high strains the rubber thins significantly. Different thickness rubber can be molded between plates to simulate various applications in shear. In most shear applications, shear strain is sufficiently low to be in the linear stress-strain region of the curves in Fig. 4.12.

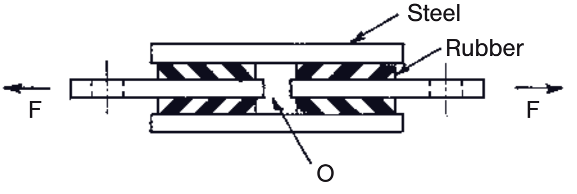


Figure 4.11 Quadruple-lap shear specimen

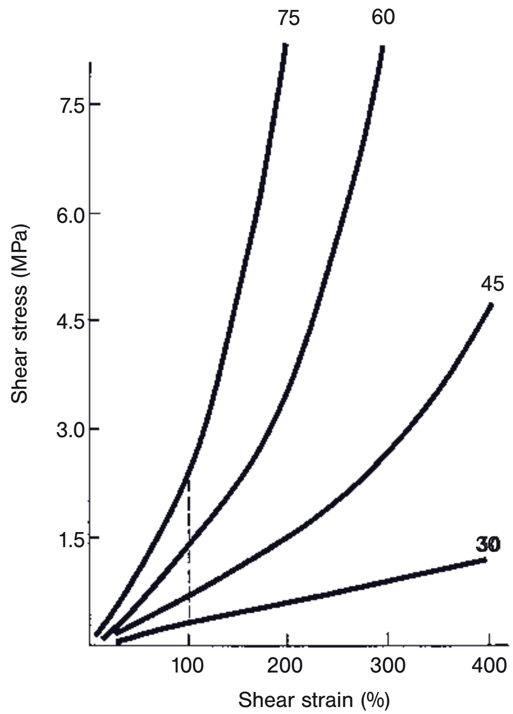


Figure 4.12 Shear stress vs. shear strain for Shore A hardness of 30, 45, 60, and 75

For soft rubber with a Shore A hardness of 30 or 45, the linear region extends to about 100% strain [21]. For harder rubber of 60 or 75 hardness, departure from linearity occurs at lower strains of about 50%. Typically, shear strain in rubber products is limited to about 75% maximum. But it may be higher for products that do not require a long service life.

Although shape only moderately affects shear modulus, it significantly affects compression modulus; high shape factors can produce extremely high modulus in compression as discussed earlier. These features permit unique combinations of rubber properties to be used advantageously in laminated rubber-metal products such as bearings for rockets and for bridges.

The stiffness of rubber components depends much more on their geometry and boundary conditions relative to other engineering materials [22]. This behavior results from the bulk modulus of rubber being two to three orders of magnitude greater than the shear modulus (see Table 1.1).

There are several methods available to measure tear resistance of rubber because of its importance in engineering applications. ASTM D 624 mentions that tear values obtained by a particular test are only a measure of tear resistance by that specific test. The tear values obtained do not have direct relation to the behavior of rubber products in service. However, tear strength is more relevant to the failure modes likely to occur in a product such as an engine mount [23]. Tear tests available now are more fundamentally based than the well-established ASTM methods. A wide range of stress distribution during test is a feature common to tear specimens.

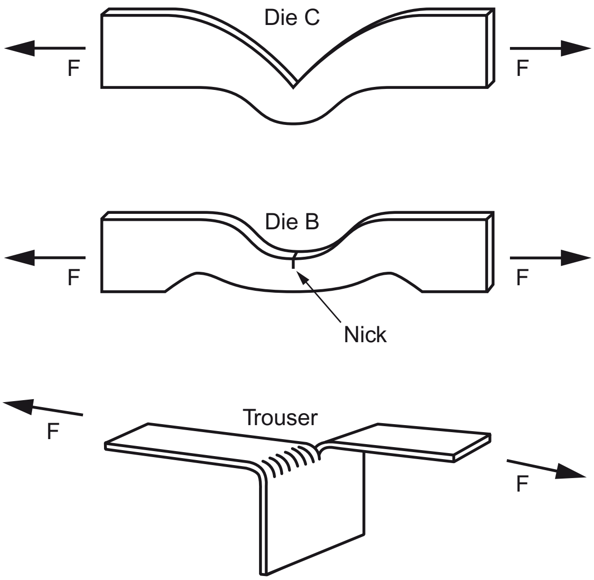


Figure 4.13 Die C, die B, and trouser tear specimens showing direction of applied force (*F*)

Figure 4.13 depicts three types of tear specimens: die C, die B, and trouser tear respectively. Arrows indicate the direction of the applied force. The die C (angle) specimen is not nicked before testing, while the die B specimen is nicked. The angle in the die C specimen and the nick in the die B specimen serve as stress risers during testing. Both of these specimens store energy in their stretched legs as they are elongated. Hence, the tear strength values obtained are the sum of both the energy to stretch the specimen and the energy to tear it. As a result, these two specimens will yield higher apparent tear values than the trouser tear specimen.

With the trouser tear specimen [24], only limited stretching occurs in the specimen tabs or legs and the energy needed to do this is relatively low. The energy associated with this limited stretching is subtracted from the total to permit calculating the tearing energy (T) in units of kN/m or lbf./in. Widening the legs or reinforcing them simplifies the calculation of T that physically is the energy required to create new surfaces during tearing.

4.4 Viscoelastic Properties

Viscoelasticity can be defined as a combination of viscous and elastic properties in a material. The relative contribution of each depends on factors that include time, temperature, stress, and strain rate. Creep, stress relaxation and set are important manifestations of the viscoelastic behavior of rubber.

4.4.1 Creep

Creep refers to the increase in deformation of rubber under a constant force; it can be measured in tension, compression, or shear. The creep arising from the viscoelastic nature of rubber is proportional to the logarithm of time. It is known as primary creep since it predominates at short times. Secondary creep may be physical or chemical in origin.

4.4.2 Stress Relaxation

Stress relaxation is the decrease in stress with time at a constant deformation. ASTM D 1390 measures it in compression using a specimen typically compressed 25%. Measurements like these are useful in understanding rubber properties in sealing applications, e.g., gaskets. Chemical relaxation dominates at high temperatures and long times [25]. It usually occurs as a linear function of time. Less dominant physical relaxation occurs approximately as a linear function of logarithmic time.

Automotive timing belts, engine mounts and seals represent products where stress relaxation measurements can facilitate development of novel or improved materials for products.

4.4.3 Compression Set

Compression set occurs in rubber placed under prolonged compression and the extent of set depends on a number of variables [26]. ASTM D 395-98 describes methods for testing under either a constant force (method A) or a constant deflection (method B) for specified temperatures and times. The residual deformation of the test specimen is measured 30 minutes after removal from the test device. The more common method B measures set under constant deflection, partly because it requires simpler equipment than that for method A.

A common misconception is that the lower the compression set the better the rubber, and there is a tendency to write specifications that permit very little set. It is possible to achieve quite low values of compression set by over-curing the rubber. But over-cure adversely affects other physical properties such as strength, flex, and ageing resistance. Hence, a low compression set compound is not necessarily a better material. The rubber technologist has the difficult task of balancing these different properties so as to obtain the best combination of properties.

Although the compression set test is usually performed at elevated temperatures to shorten test time, it sometimes is done at very low temperatures to study crystallization behavior in crystallizing rubbers such as NR. Elevated test temperatures are also used to study the aging behavior of rubber.

4.5 Dynamic Properties

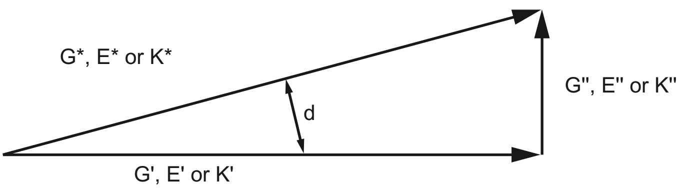
The functioning of many rubber products critically depends on proper development and control of dynamic properties. Figure 4.14 describes dynamic property terms along with their units of measurement [27]. Stiffness may be described by spring rate (K). The hypotenuse of the vector triangle represents the complex modulus or stiffness in Fig. 4.14. It can be divided into elastic (spring) and viscous (damping) components as represented by the other two sides of the triangle.

The damping coefficient (C) describes the dissipation of energy per cycle, wherein a perfectly elastic material would have a C value of zero. Various combinations of the terms in Fig. 4.14 describe a given rubber compound and the choice of terms depends partly on the method of testing and the application. Automotive engineers, generally concerned with a specific rubber assembly, usually use the terms spring rate and damping coefficient. Materials specialists, in contrast, generally describe dynamic behavior of a given rubber in terms of dynamic modulus and spring rate.

Figure 4.15 contrasts the static and dynamic behavior of a preloaded cylindrical rubber specimen. The line drawn tangent to the force-strain curve at a preload of 150 lb. is taken as the static spring rate (K_s). The complex dynamic spring rate (K^*) is always greater than K_s because of the viscoelastic nature of rubber.

Vibration in a body may consist of a periodic displacement, a random displacement, or short-term shocks. High-energy absorption and low resilience are needed for shock attenuation [28]. The simplest form of periodic motion for a body with a single degree of freedom system is movement about a reference position such that a sinusoidal curve can represent the displacement.

Servohydraulic testers are frequently used to produce the large forces that are usually required for dynamic testing. Although expensive, they provide in a single device the capability for high force, large displacement, and typical frequencies up to several hundred Hz. A number of errors can occur when testing compounds at high frequencies [29]. The test machine and/or the fixtures used to secure test specimens can induce these errors. Machine-induced errors



	Complex	Elastic	Viscous
Shear modulus, PSI	G*	G'	G"
Young's modulus, PSI	E*	E'	E"
Spring rate, LB/IN	K*	K'	K"

Damping coefficient, C = K"/2πf (lb.s/in.)
where f = frequency (Hz)

Figure 4.14 Definition of terms for dynamic properties [27]

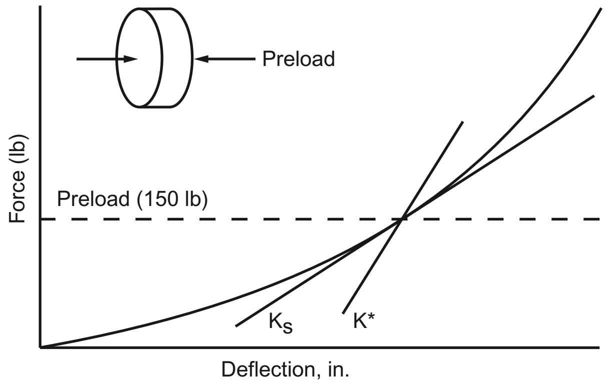


Figure 4.15 Comparison of static (K_s) and complex dynamic spring rates (K*) [27]

include non-linearities in the servo-loop and those associated with transducers. Fixture-induced errors include changes in data caused by specimen end effects and superimposed loads due to the mass of the fixture and specimen.

Dynamic testing, mostly done in the uniaxial mode, is also done in multiaxial modes [30]. Multiaxial testing modes include orthogonal axial-torsion, and orthogonal biaxial torsion; both these modes place special requirements on the reaction frame and control system. As an example, a multi-axis machine can test engine and suspension mounts [31]. The vertical axis can provide up to 30 kN for static loads, 20 kN for dynamic loads, and a displacement capability of up to 50 mm. A horizontal actuator can provide up to 15 kN for static loads and 10 kN for dynamic loads, with displacements up to 100 mm. A bed-plate weighing 5 t provides the weight needed for testing to frequencies to 220 Hz.

Broadly examined, factors controlling dynamic properties fall into four categories: composition, processing, design (product size, shape, and configuration), and testing (strain rate, strain magnitude, and temperature) [32]. Figure 4.16 shows the effect of strain and temperature at 20 Hz on the elastic component (G') of shear modulus for black-filled NR compound. The figure shows the simultaneous decrease in G' as strain and temperature increase. The decrease in G' is quite significant over the range of variables shown. It depends on filler type, level, and other factors.

The complex modulus (G^* or E^*) is the vector sum of the elastic and loss modulus; the complex spring rate (K^*) is the vector sum of the elastic and loss spring rates. For engineered structures or components, the damping coefficient (C) is often specified, as given by Eq. 4.4.

$$C = \frac{K''}{2\,\pi\,f} \tag{4.4}$$

where K'' is the loss spring rate and f is the test frequency in Hz.

Design also plays a role in damping. For example, constrained layer damping can be used for vibration and noise control. A rubber layer between metal plates forms a composite. Flexing the composite places the rubber damping layer in shear and damps the composite. Damping is an important property in many rubber applications, e.g., in rubber used for simulating necks

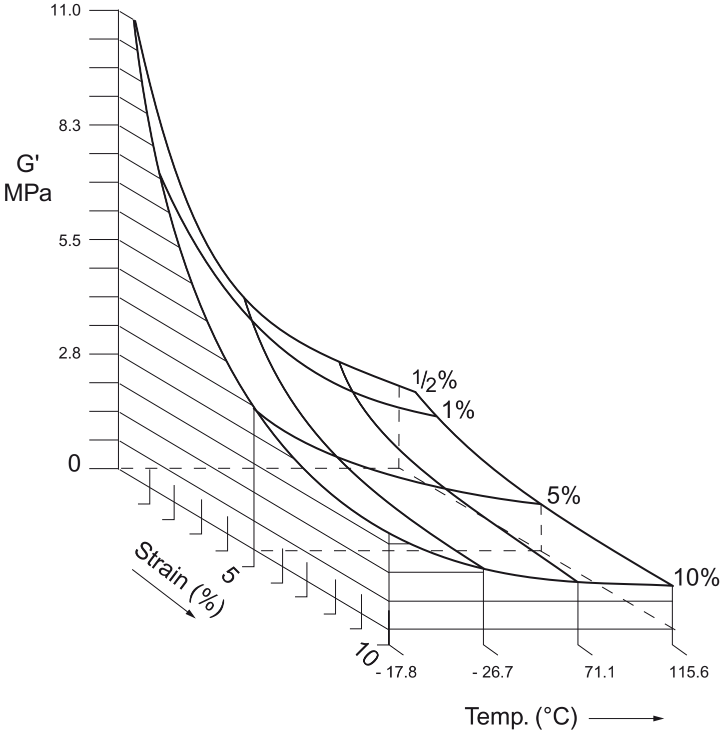


Figure 4.16 Elastic shear modulus (*G*′) for a black-filled NR compound as a function of strain and temperature at a frequency of 20 Hz [27]

in test dummies [33]. The neck consists of three steel universal joints pinned into aluminum discs with shaped rubber discs around the joints. An IIR compound with a Shore A hardness of 48 resists motion at each joint during deformation of the assembly. The neck simulation provides a mathematical model that compares human response to dummy response.

An inflatable rubber unit acts as an intelligent traffic hump that is intended to overcome the many disadvantages of traditional traffic-slowing methods. It is fitted with an air valve that controls air escape as a vehicle passes over it [34]. Both large and small vehicles deflate the unit as they pass over it, depending on their speed. When vehicles pass over it slowly, the valve opens. For vehicles traveling at higher speeds, the valve remains closed so that the hump represents an obstacle.

4.5.1 Fatigue and Cut Growth

Rubber fails in fatigue from the growth of one or more cracks that develop during repeated flexing. The cracks develop from small flaws during repeated rubber deformation. Crack growth, which occurs slowly at first, may increase rapidly as crack size increases. In severe cases, a crack propagates completely through a rubber article.

Cut growth measures the increase in length of a deliberately introduced cut while repeatedly deforming the rubber. Generally, this cut is much larger than the natural flaws (approx. 0.002 in. in size) in rubber. Flaws caused by nicks, surface irregularities, cut edges, undispersed particles, etc. are generally much larger.

If the flaws that cause local stress concentrations in rubber are large enough, they can cause failure in a single deformation cycle (tensile failure). These concentrations can greatly exceed the overall yield stress of the rubber [35]. With typical cut-growth tests, the cut-growth per cycle is relatively small, because stress is relatively low. Hence, fairly long times are required to obtain cut-growth data, because crack length increases only slightly per deformation cycle.

Fatigue and cut growth merit considerable attention, because many rubber products are repeatedly flexed in service, e.g., tires. When rubber deforms at constant amplitude, in some applications the modulus of the rubber is important, because the modulus affects the energy available to propagate cracks. For a constant amplitude cycle, higher modulus reduces strain during the deformation cycle. Hence, fatigue test methods should be considered in terms of the end-use application. Non-uniform strain cycles, varying temperatures and test frequencies further complicate testing.

The DeMattia machine bends a rubber specimen (150 mm long by 24 mm wide by 6.4 mm thick). ASTM D 430 (method B) describes its use for crack initiation or fatigue testing. ASTM D 813 describes its use for crack growth tests, wherein a dominant flaw of controlled size is placed in the groove of the test specimen prior to testing. The resulting data can be reported in several ways by this standard.

4.5.2 Tensile Failure

In contrast to the progressive failure that occurs during fatigue, tension failure occurs in a single cycle. Flaws initiate failure and affect failure properties as shown by a comparison of die-cut and molded tensile specimens [36]. Molded specimens consistently produced higher tensile strengths than die cut specimens and data for the molded specimens were more uniform. Die cutting apparently produced flaws on specimens with cut edges.

4.5.3 Hysteresis and Resilience

Hysteresis in the bulk of a specimen is defined simply as the energy lost when a specimen is deformed and then released [37]. It results from internal friction and is evidenced as heat. Hysteresis is commonly measured as a temperature increase in a flexed specimen (heat buildup) as described in ASTM D 623.

Resilience is the ratio of energy output to energy input in a specimen after the specimen has recovered from the deforming force. The energy to deform a specimen is therefore equal to the sum of the energies for hysteresis and resilience. Among methods to determine resilience are:

- Bashore resilience (ASTM D 2632), wherein a guided plunger falls freely onto the horizontal surface of a rubber specimen;
- pendulum rebound, wherein a free-swinging pendulum impacts the vertical surface of a rubber specimen.

Because rubber is viscoelastic, resilience measurements are sensitive to temperature.

4.5.4 Abrasion

Abrasion consists of the rupture of small particles of rubber under frictional forces as sliding occurs between a rubber surface and a substrate under a variety of conditions. A tire tread can abrade as it scrubs over a road surface at different speeds while under a heavy load.

Laboratory tests to estimate abrasion properties of rubber involve producing relative motion between rubber surfaces and an abrasive. Two examples are ASTM methods D 1630 and D 2228. By D 1630, a rubber test piece presses against a rotating cylinder that is covered with abrasive paper. This method is primarily used to determine the abrasion of soles and heels of footwear. Because some rubber compounds tend to clog the abrasive paper, a suitable suction device or air pressure may be used to remove the abraded particles.

The Pico abrader (ASTM D 2228) handles abraded particles differently. Dust is applied between two rotating knives that abrade the surface of a rubber test specimen and prevent the abraded rubber particles from sticking to one another. The wear-resistant tungsten carbide knives have a specified geometry. The Pico abrader reasonably predicts tire performance, shows good agreement both within and among laboratories, and is therefore a popular instrument.

Abrasion of sandblast hose is different, because the hose transports lightweight particles that impact the hose surface at high speed. An NR gum hose resists abrasion by the sand particles, but tends to build a static charge, because it is an excellent electrical insulator. Incorporating a conductive carbon black in the hose increases hose conductivity and dissipates the charge.

4.5.5 Friction

Rubber does not obey the classical law of friction that states that the ratio between frictional force and normal load is a constant called the coefficient of friction (μ). For rubber, μ decreases with increasing normal pressure. Another difference is stick-slip that occurs when friction decreases rapidly as velocity increases. The associated changes in force – often rapid – complicate interpretation of friction measurements.

Boundary conditions at a sliding rubber interface significantly affect frictional behavior, as was shown earlier in Fig. 4.4. Hence, experimental conditions must be carefully controlled to obtain reproducible friction measurements. Friction properties for rubber range widely. For tires, high friction levels are needed to provide good directional control for vehicles; low friction levels are needed for water-lubricated rubber bearings.

By ASTM E 303, a rubber specimen attached to the base of a pendulum (Fig. 4.17) is made to slide across a test surface as the pendulum swings. The degree of swing after sliding determines the friction [41]. The portability of this instrument is an advantage and it allows friction measurements to be made against both wet and dry surfaces.

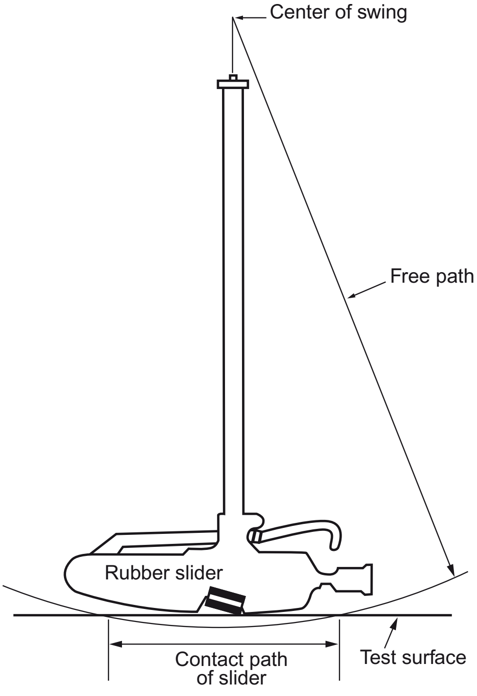


Figure 4.17 Schematic of British portable skid tester (after ASTM E 303)

4.6 Other Rubber Properties

4.6.1 Effect of Test Temperature

Rubber is typically tested at room temperature because of ease of its testing and prevalent use at or near room temperature. Tests at low and high temperatures are also necessary because rubber is also used in products over a range of temperatures. Rubber articles on airplanes must function at the low temperatures associated with high altitude. Change in hardness (ASTM D 2240) with temperature is frequently measured, as this test is both simple to conduct and convenient. Brittleness is relevant to some rubber products that can be tested by ASTM D 746.

The unusual effect of high temperature on cured rubber can be demonstrated with an ordinary rubber band. The band is suspended from a hook and a weight is hung onto the lower loop in the band. Upon heating the band, the weight rises because the higher temperature increases the modulus of the rubber, a behavior known as the Joule effect. This behavior has practical implications, for example in a moderately stretched O-ring that acts as a seal on a rotating shaft. The O-ring tends to contract and grab the shaft more tightly as temperature increases. If it grabs the shaft too tightly, it can overheat and ultimately fail.

4.6.2 Conductivity

A malfunction detector for thermal insulation in a large solid rocket motor required maximizing the difference in electrical conductivity between two rubber compounds [38]. The detector was designed to detect impending failure of thermal insulation in the rocket motor. By appropriate compounding, the electrical conductivity of the conductive compound was made $4.7 \cdot 10^{10}$ higher than that of the non-conductive compound. Conductive TSE compounds have been used for many years in electrostatic shielding applications. Conductive TPE is now available for applications requiring conductivity [39].

Conductivity in tires is important for several reasons [40]. It played a roll in the buildup of a static charge in tires that ignited fuel fumes during refueling. A large recall (2.3 million) was made to retrofit an additional grounding element in a fuel filler neck.

Other conductivity problems included excessive radio static and shocks experienced by tollbooth operators upon collecting tolls.

4.6.3 Adhesion

Adhesion is very important consideration when combining rubber with a range of substrates to form composites such as rubber-textile, rubber-plastic, and rubber-metal. Examples are tires, hose, belting and bridge bearings, products that are discussed in greater detail later. Because adhesion reliability is paramount in different physical and chemical environments, a number of different tests have been developed to approximate adhesive behavior. Two of these tests are considered here.

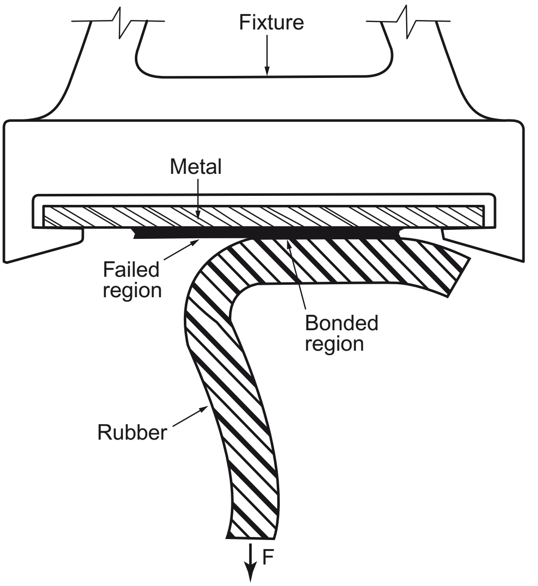


Figure 4.18 Fixture for testing adhesion of rubber in 90° peel, after ASTM D 429 (method B)

The adhesion specimen (Fig. 4.9) used in Method A of ASTM D 429 was discussed earlier under triaxial tension. By contrast, in method B of D 429, rubber is bonded to a metal strip and subsequently peeled from the strip using the fixture shown in Fig. 4.18.

During the test, rubber is peeled from the metal at approximately right angles, because the fixture rotates about a pin that holds the fixture in the test machine. As the rubber is peeled, the peeling force (*F*) often varies substantially and rapidly. Although minimum force and maximum force can be reported, average force is most often reported.

4.6.4 Permeability

Permeability is an important property, because rubber is often used in sealing applications, e.g., to contain a gas or a liquid for long periods. Permeability tests measure the ease with which a gas or liquid passes through rubber. It is important to establish equilibrium flow when measuring this property. The concentration gradient of a material (gas or liquid) provides the driving force for permeation, which consists of the fluid going into solution on one side of the rubber, diffusing through the rubber, where it evaporates on the other side. Solubility and diffusion rate are two important characteristics of a permeating fluid.

ASTM D 814 can be used to measure permeability of liquids in rubber of moderate thickness; ASTM D 815 can be used to measure permeability of hydrogen gas through rubber.

4.7 Deterioration

Rubber encounters a number of service conditions in various applications that deteriorate rubber properties at different rates and to different degrees. Conditions include exposure to weather, ozone, radiation, flame, high and extremely high temperatures.

4.7.1 Weather

The change in rubber properties with outdoor exposure varies significantly and depends on exposure conditions. In some locations, intense sunshine and high temperatures mainly deteriorate rubber; in others, ozone might be the major cause of deterioration. Chief among laboratory tests to measure deterioration and simulate weathering under controlled conditions is ASTM D 750.

This test exposes a stretched or relaxed specimen to light richer in ultraviolet than sunlight, but otherwise similar to sunlight. The exposure deteriorates the specimen and causes flaws on the specimen surface that cause a decrease in breaking elongation and tensile strength. When conducting this test, a reference specimen should be included to make the results more meaningful. For an overall assessment of weathering, specimens are often exposed to varying climactic conditions, e.g., in the south and southwest.

4.7.2 Ozone

This unstable gas occurs generally in the atmosphere at extremely low concentrations of the order of several parts per hundred million (pphm). Even these low concentrations can cause cracks in stressed rubber that form at right angles to the direction of applied stress. ASTM D 1149-78 now expresses ozone concentrations as ozone partial pressure, rather than as pphm, where standard partial pressure is 50 MPa. The use of ozone partial pressure takes into account atmospheric pressure fluctuations.

The most harmful condition occurs just above the critical stress level (about 0.06 MPa or 8.7 psi), corresponding to a critical strain of about 3%. Deep and widely separated cracks form just above the critical stress level and these are more likely to cause product failure than small cracks. Increasing stress or strain favors the formation of smaller and more frequent cracks.

Ozone cracks are unable to penetrate very far in large rubber components such as bridge bearings, because they soon encounter compressive rather than tensile stresses. Thus, ozone cracking is less of a problem for rubber articles that are used in compression. Nevertheless, it is good practice to avoid ozone cracking by using protective waxes and/or antiozonants in the rubber compound, as ozone cracks are unsightly and can initiate fatigue crack growth that ultimately can lead to failure.

4.7.3 High-Energy Radiation

Rubber used in nuclear reactors and nuclear submarines requires resistance to gamma radiation that can increase hardness and modulus. For rubber that predominately crosslinks during irradiation, a 100 megarad radiation dose approximately doubles or trebles the original S-100 value. ASTM D 1672 measures the resistance of polymers to high-energy radiation. A nuclear power cable is an example of a rubber component with both radiation- and flame-resistance [42]. Physical properties of EPDM insulation used in a cable changed only slightly after 10^7 rads. The cable showed good flame-retardant properties when tested by horizontal and vertical flame tests.

Resistance of industrial wire and cable to heat is also of interest [43]. An Arrhenius plot was used to generate data relevant to the characterization of flex wires at 150 °C. Insulation based on newer elastomers such as CPE, EVA, EPDM and TPE/TPV has largely replaced insulation based on NR, SBR, IIR, and CR. The newer elastomers provide improved chemical, electrical, mechanical, thermal and weathering properties.

Stress and aging can cause wire insulation to crack [44]. A self-healing additive for wire insulation contains reactants in the form of microcapsules. Cracking causes the microcapsules to release the reactants and heal the wire or cable.

4.7.4 High Temperature

Rubber test specimens and components are frequently aged at high temperatures to increase their rate of deterioration, thus shortening test times. The temperature selected depends on a number of factors that include:

- Oxygen availability
- Specimen size and shape
- Rubber backbone (saturated vs. unsaturated)
- Air velocity across rubber surface during aging

Because of these factors, tests should include a control specimen with known performance characteristics. Two tests frequently used for aging are ASTM D 573 and ASTM D 865. Test D 573 compares the degradation resistance of different vulcanizates that are heated in air at atmospheric pressure. Property changes with time such as tensile and elongation are determined. A potential problem with D 573 is the transfer of volatiles (especially antioxidants) from one vulcanizate to another during aging.

Another problem is the lack of control of all the aging factors during the oven-aging process [45]. Control of the air velocity across specimens is important, because it affects the air boundary layer thickness and therefore the aging rate. ASTM D 865 avoids this problem by aging each specimen in its own container, each with its own air circulating system. Firmer conclusions can be drawn from the latter test that prevents volatiles from transferring from one specimen to another. Rubber stability largely influences the selection of an accelerated test temperature and a typical temperature for NBR and SBR is 100 °C.

4.8 Rubber Ingredient Compatibility

This is an important consideration in both unvulcanized and vulcanized rubber materials. A compounding ingredient will bloom to the surface of a rubber compound when its solubility limit is exceeded. Bloom can cause problems such as poor adhesion, a sticky surface, and poor tack. Tack is the ability of two materials to resist separation after contacting one another under light pressure [46]. It is necessary to insure that the many components of a green tire will hold together before molding and vulcanization.

In addition to tack, body plies in radial tires must have good green strength so that plies will not split during either the second stage expansion or the tire molding process [47]. Green strength of a rubber is its resistance to deformation and fracture before vulcanization.

When tack is deficient, wiping the un-crosslinked rubber surface with an appropriate solvent can increase tack by plasticizing the rubber surface. Sufficient time must be provided for the solvent to evaporate if porosity is to be avoided in the rubber during vulcanization. This effect [48] was shown for NBR rocket insulation whose tack was increased by wiping an NBR compound with MEK (methyl ethyl ketone) solvent. Drying times of less than about 25 minutes caused poor ablative performance of the insulation and caused it to warp during subsequent testing with an oxyacetylene torch.

Stability of rubber products is especially important for products used in safety-related applications. Failure of rubber O-rings used in fire-sprinkler heads resulted in a recall of more than 35 million heads dating back to the mid-1970s [49]. It was found that the O-rings' performance could degrade over time due to corrosion, salt, sediment, or other contaminants.

Corrosion inhibitors are used to protect metal in oil-field operations [50]. It is ironic that these inhibitors, while protecting metal, were found to accelerate the degradation of rubber seals. Other seal environments are quite hostile. Perfluoroelastomer seals in a turbofan engine must resist chemical degradation from lube oil in addition to enduring temperatures up to 550 °F [51]. Compared to prior fluoroelastomers, perfluoroelastomer increased seal life more than 250% and eliminated 10,000 hours of unscheduled maintenance.

Kitchen faucet deck plates, typically made from a TSE, required a sealant to form a watertight barrier [52]. A deck plate now incorporates a TPV lip seal that forms a watertight barrier between the faucet and counter top and it eliminates the need for a sealant.

Some O-ring compounds are designed to swell slightly in service to seal effectively. Often, the ratio of fluid to rubber is quite high. Yet for an automotive engine mount, the volume ratio of fluid to rubber is quite low, as only a few drops of engine oil might contact an engine mount. This small amount of oil is unimportant, even though the oil may be very compatible with the rubber mount. NR engine mounts are well known to operate successfully in an oily environment for long time periods.

Another factor with mounts is the penetration rate, which is affected by factors such as temperature and fluid viscosity. Figure 4.19 shows the time to penetrate 5 mm for different penetrating fluids with different viscosities [53]. Engine oil required approximately 6 months to penetrate 5 mm. However, thick grease such as Vaseline might require as much as 50 years. ASTM D 471 is widely used to determine both swelling and deterioration properties of rubber caused by exposure to liquids.

Low molecular weight fluids in prolonged contact with rubber can either swell or harden rubber [54]. Excessive swelling or hardening degrades performance that can eventually lead to product failure. Campion has reviewed the durability of elastomers that are used in severe fluid applications such as offshore oil production [55].

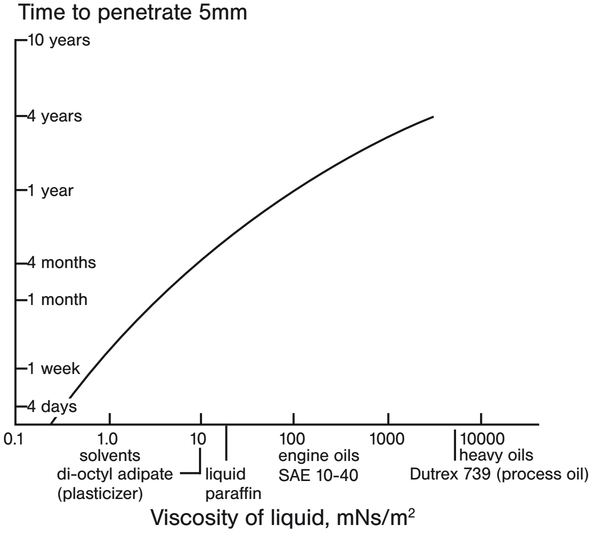


Figure 4.19 Relationship between viscosity and penetration time

4.9 Electrical Properties

Rubber used in electrical applications often requires a demanding combination of properties. Requirement combinations can include specific mechanical properties, along with ozone and aging resistance. Table 4.1 lists selected electrical properties and their associated test methods.

An extensive list of references for electrical applications is appended to ASTM D 150.

Table 4.1 Electrical Properties and Test Methods

Resistance and conductivity	ASTM D 257
Dielectric strength	ASTM D 149
Dielectric constant and power factor	ASTM D 150

4.10 Non-Destructive Testing

Non-destructive testing (NDT) methods detect and measure discontinuities or anomalies in materials, components, and assemblies. They do this without impairing the serviceability of the object tested. For example, tires are tested using NDT methods such as infrared, holography, shearography, microwave, and ultrasonic testing. These are powerful tools to evaluate the durability of radial tires [56]. On-line, non-contacting, laser-based sensors can identify and measure deformities in tires such as dents, bulges, and depressions on tire sidewalls [57]. Some sheet-of-light sensors have a measurement width exceeding 300 mm [58].

Infrared measurements can detect hot spots on rotating tires. Holography and shearography can detect belt edge separations in tires that have been placed in a vacuum chamber. Belt edge separations are very important, because they are said to be the most common durability failure mode of a radial tire [59].

Proper identification of in-process compounds, as well as finished rubber articles, is important. For example, a fluoroelastomer (Tracer VITON® T-1) will initially fluoresce a light blue color until exposed to a high temperature post oven cure, where the temperature triggers a change in fluorescence [60].

4.10.1 Testing and Computers

Computers are increasingly used in a myriad of operations associated with rubber product manufacture, e.g., product design, compound analysis, and testing. They have replaced many laborious operations such as data recording from experiments and subsequent data analysis by hand. These advantages plus lower computer costs will insure increasing computer use in rubber testing activities.

Ideally, rubber properties determined in the laboratory would correlate directly with properties determined for the same compositions in end-use or service applications. Unfortunately, lack of correlation, often the rule, is the likely reason that ASTM methods such as D 865 (accelerated aging in heat) are considered comparative only. Even so, laboratory tests can provide preliminary data that can later be used to control properties of rubber compositions for end-use products.

Only a few of the many reasons for the lack of correlation among laboratory properties and service properties are considered here. Laboratory test specimens often consist of only rubber. Many end-use products are complex composites of rubber with other materials, such as fabric and metal. Common examples are tires and hose. The design of these products and end-use conditions might affect product performance more than the rubber compounds used in them. For example, considerably higher stresses might occur in service than the stresses that occur in testing laboratory specimens.

Conditions experienced in service might not occur in the laboratory, e.g., antiozonants are commonly added to rubber compounds to provide protection from ozone attack. These compounds tested at high ozone levels in the laboratory where they are not exposed to acid rain as might occur in outdoor service. Acid rain [61] is a potentially important variable because it can leach antiozonant (generally these are alkaline). Hence, a factor not included in the laboratory test can reduce ozone resistance and cause product failure.

Another problem with determining rubber properties is hysteresis, which causes increased temperature in flexed rubber articles. Some rubber properties change significantly with temperature changes. Carried to an extreme, hysteresis can cause premature failure of a rubber article and it might even cause failure by a mechanism different than the one that determines the life of the article in service. For example, a laboratory abrasion test can be made so severe that the high temperature caused by abrasion results in failure.

Properties of full-scale tires are generally determined using indoor laboratory tests because test conditions can be carefully controlled – an obvious advantage. A disadvantage is absence of a variety of conditions that might occur in service such as different climactic conditions, rain, snow, and variations in road surfaces. For these reasons, outdoor testing is required to finally approve tire functionality and durability.

Sometimes properties measured in the laboratory correlate excellently with those measured in service. For example, settling (creep) of a building mounted on natural rubber bearings closely followed the predicted creep obtained from short-term laboratory tests [62]. Improved correlation is expected in the future with further advancements in testing. This chapter comprises an incomplete listing of rubber properties. Wood lists a comprehensive compilation of rubber physical constants and properties for unvulcanized and vulcanized rubber [63].

Ideally, the design-engineer-compounder team would prefer to produce rubber products with the best possible properties. Most of the compounds used in these products are based on sulfur crosslinking systems. Product performance often depends strongly on crosslink density (the degree of vulcanization). This behavior is observed in Fig. 4.20, where fatigue life is seen to peak at low crosslink density, where friction coefficient is very low [64].

Hence, the combination of best fatigue life and lowest friction coefficient cannot be obtained at a single crosslink density, so the rubber technologist must select the best compromise. Fatigue life demands on some rubber products are extreme. For instance, a silicone rubber keyboard can accumulate more than two million cycles during its lifetime [65].

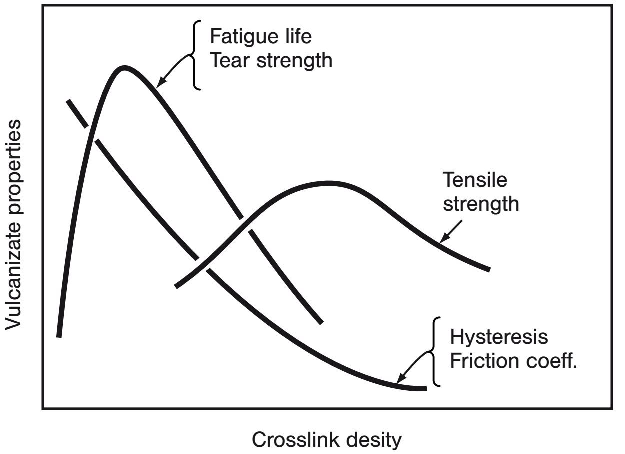


Figure 4.20 Several important vulcanizate properties as a function of crosslink density

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5 Product Design

Rubber products must be designed to withstand a range of demanding requirements in service that include a tolerance for a range of stress and strain values. Hence, allowable limits for stress and strain are a major consideration for design engineers for both tire and non-tire products. Rubber products are normally subjected to fairly small deformations that rarely exceed 25% in extension or compression, or 75% in simple shear [1]. Table 5.1 provides some additional guidelines:

Table 5.1 Guidelines for Stress and Strain Limits

Limits	Reference
15% in compression, 50% in shear for typical hardness springs	[2]
For soft rubber vulcanizates, maximum shear rarely exceeds 100% and is normally less than 50%	[3]
Maximum working stresses in rubber rarely exceed 1000 psi and are usually 50–100 psi	[4]
Mean strains of less than 20% are most common in springs	[5]
Approximately 25 psi is considered the design limit for stress applied in shear	[6]
Generally accepted limit in compression is about 250 psi but stresses as high as 500 psi have been used	[7]

Because a number of factors determine the limits shown in Table 5.1, there is no universal agreement on allowable stresses and strains. Many codes limit the allowable stress on a rubber bearing to about 1000 psi (7 MPa) [8], a value chosen because of the allowable stress on concrete. Many years later, some of these codes still dominate. Other applications, such as helicopter rotor bearings, encounter stresses that range between 5000 and 10,000 psi (34 MPa and 68 MPa) [9].

The need for early design discussions between the purchaser and fabricator of rubber products cannot be overemphasized. Here, design is considered a part of the total product system that consists of design, compound, and process. The following two examples illustrate the need for a systems approach.

A lack of discussion in the early stages of a product design caused serious problems for a purchaser of a rubber band that was to act as a friction drive in a cassette [10]. An antioxidant used to protect a conventional rubber band bloomed to the surface of the rubber band. The bloom reduced the coefficient of friction of the rubber band and rendered the band unacceptable for use as a friction drive.

Another problem occurred with a baby bottle nipple that turned purple after immersion in a sterilizing hypochlorite solution. It resulted from a reaction between the antioxidant and derivatives formed during curing of the rubber nipple and the hypochlorite. An alternative compound for this application could have prevented this problem.

The design of rubber products involves using numerous principles and guidelines, test methods, some of which are general, while others are product-specific. Of general interest are the stresses and strains that occur in products. Table 5.1 lists some requirements from several sources. The requirements for some unusual applications specify strains significantly greater than those shown in Table 5.1.

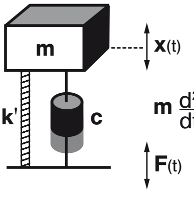
An impact absorber earlier used on Ford automobile bumpers experienced shear strains up to 250%, a strain that greatly exceeded the normal working strain for rubber [11]. It used NR in shear to absorb impacts up to a speed of 8 km/h. Because the absorber was required to experience a total of only about ten impacts in service, the high shear strain level proved acceptable. A center channel in the mount permitted the use of bumper jacks that accepted impacts at angles. These data and those in Table 5.1 emphasize the need to consider *all aspects* of a product when selecting a material and design.

Of the myriad rubber products made, several of these are further discussed in the following.

5.1 Mountings

For a rubber mounting to behave as a spring, it must be able to change shape. A successful mounting design involves consideration of clearances, avoidance of excessive local stresses and mount instability, inclusion of metal inserts, and tolerances. The designer must provide adequate clearance around mountings to prevent damage to supported equipment while the mount is undergoes extrusions about its static positions. Simplified theories assume that a mount system operates with a single degree of freedom during oscillation, i.e., on either the vertical, longitudinal, or transverse axis. Figure 5.1 illustrates the simplest form of periodic motion for a body with only one degree of freedom [12].

During operation, the mass moves vertically about a reference position such that the displacement can be represented by a sinusoidal curve [13]. The associated equation that relates the displacement (x) with time (t) is a function of the exciting force (F), the mass (m) of the body under consideration, the spring rate (k), and the damping coefficient (c) of the support for the body. Maximum motion of the body occurs when the angular frequency approximately equals the quantity $(k'/m)^{0.5}$. This frequency, known as the resonant frequency, represents the condition where vibration becomes most objectionable.



$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + k'x = F_{(t)}$$

Figure 5.1 Approximate behavior of a rubber mount [27]

Real vibrating bodies are concerned with six degrees of freedom: vertical, longitudinal, transverse, pitch, roll and yaw [14]. Mounts can be designed to provide combinations of stiffness and damping in various directions, e.g., soft in all directions, soft in two directions and stiff in one, stiff in two directions and soft in one, stiff in two directions translationally and soft torsionally. A patent describes an elastomeric isolator (Fig. 5.2) with six degrees of freedom [15].

Multiple-degree-of-freedom rubber bearings are critical component parts of offshore drilling rigs in the North Sea [16]. The rigs must accommodate sway, surge, yaw, heavy pitch, and roll experienced by a free-floating vessel. The number of degrees of freedom of motion influence the clearances required during mount operation. Spring-mass systems are frequently described by the transmissibility curve shown in Fig. 5.3.

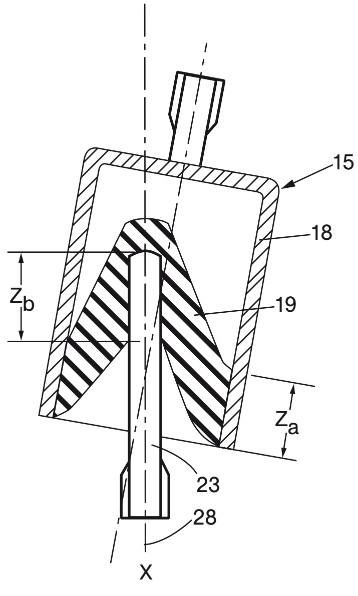


Figure 5.2 Elastomeric isolator with six degrees of freedom

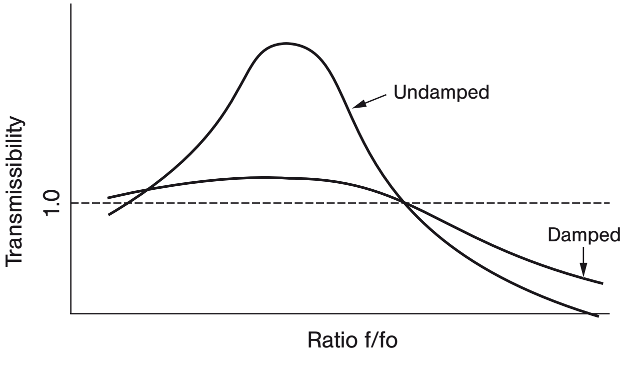


Figure 5.3 Effect of damping on transmissibility [27]

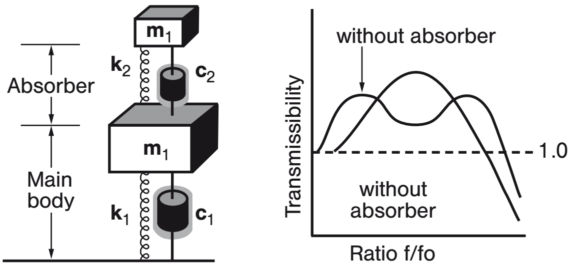


Figure 5.4 Transmissibility with a damped vibration absorber [27]

One of the assumptions in classical vibration isolation theory is that the structures on either side of an isolator are rigid. Although real-world structures are not absolutely rigid, the concept of transmissibility is generally useful. Transmissibility is described as the difference in vibration amplitude across an isolator [17]. It is the ratio output to input of either force or displacement and is plotted (Fig. 5.3) against the ratio of forcing frequency (f) to the natural frequency (f_o) [18]. Mounts should be designed to provide a resonant frequency considerably lower than the lowest frequency of the forcing frequency. Where this is not possible by changing mass or spring rate, one can increase damping in the rubber (dashpot effect) or use a dynamic vibration absorber (Fig. 5.4).

Damping converts mechanical energy to heat and mainly affects the system response at or near resonance. In contrast, in the isolation region (frequencies above $f / f_o = 2^{0.5}$) the magnitude of the force transmitted from equipment to its support is reduced. The vibration absorber shown in Fig. 5.4 consists of a damped spring-mass system (absorber) attached to the main body. Designing a vibration absorber requires that k_2 (loss modulus of the absorber) and c_2 (damping coefficient of the absorber) be held within narrow limits. This is required to tune the frequency of the absorber to the range of frequencies of interest in the main body (m_1). An important example of this technique is designing rubber engine mounts to help control vibrations in an automobile body.

Because engine, car, and drive components can pass through resonances in automobiles that cannot be altered, dynamic absorbers are used [19]. For example, a crankshaft may be the main spring-mass system with the absorbing mass being a torsional vibration damper. The main mass-spring system might be the car body, with the engine serving as the absorber to control shake.

Designing to obtain the needed k and c values is the principal task of the design engineer and the materials specialist. This task must be accomplished while working within engineering constraints concerned with assembly, geometry, size, and cost. Additionally, the manufacturing process must then be carefully controlled to hold these parameters within acceptable limits.

Figure 5.5 illustrates the effect of damping on isolation and transmissibility (T) as a function of frequency ratio [20]. It shows pronounced transmissibility increases in T for values of f / f_o of about one (the magnification region). Passing through resonance where $f / f_o = 1$ can cause damage, especially in an undamped system. For example, after starting a car engine, or turning it off, f / f_o goes through the resonant frequency.

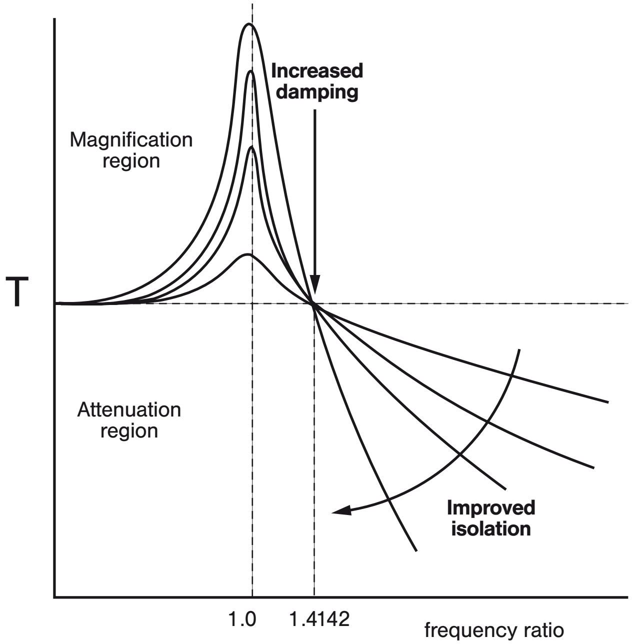


Figure 5.5 Damping vs. isolation

In an undamped or lightly damped system, severe excursions of the engine occur if the engine frequency does not pass quickly through resonance. Increased damping minimizes this problem but creates another, namely reduced isolation at higher frequencies that occur at highway speeds. Low transmissibility values are desired at highway speeds so that vehicle occupants experience minimum engine vibration. Hence, the designer must compromise engine mount design in the low-and high-frequency range.

As a general rule, excessive stresses should be avoided, because they can ultimately lead to product failure. Minimizing high stress is especially important for bonded rubber products, where very high stresses can occur at the rubber-metal interface. Incorporating radii and fillets (Fig. 5.6) minimize stress concentrations at the edge of these composites [21].

The compliant nature of rubber makes it the ideal material to combine with high modulus materials such as steel to produce mounts with a wide range of stiffness and damping that can be directionally controlled for different applications. Next discussed are rubber-metal mounts and their associated deformation modes. Shown in Fig. 5.7 is a design for seismic applications

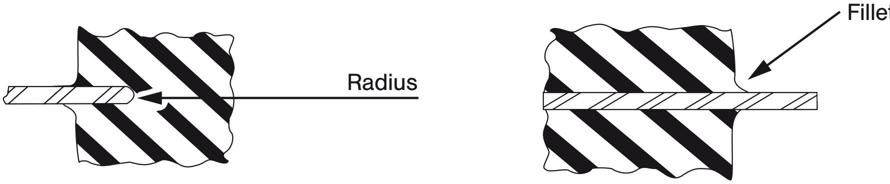


Figure 5.6 Radius or fillet in rubber and metal to reduce stress concentrations [21]

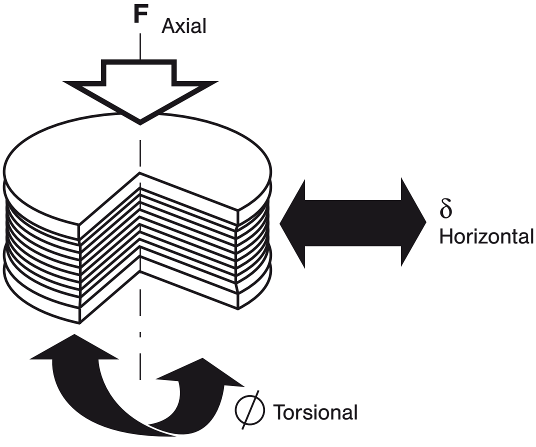


Figure 5.7 Axial compression with two shear modes [22]

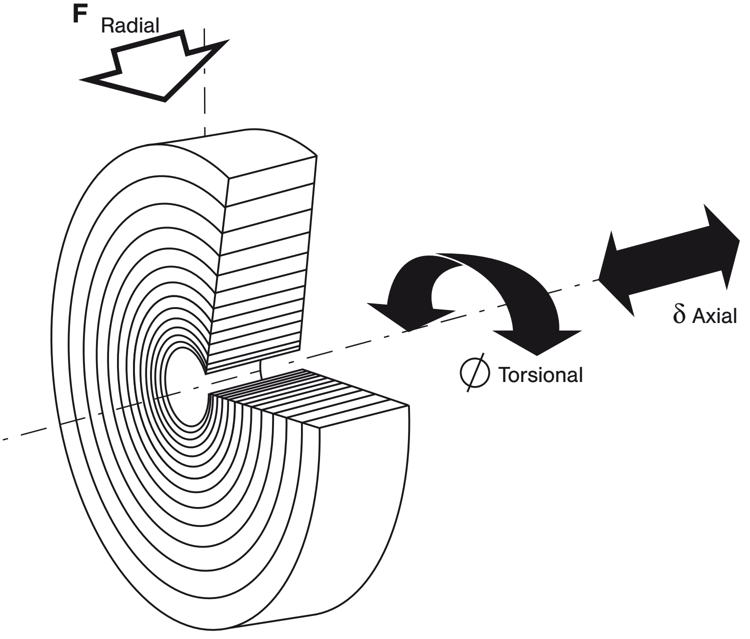


Figure 5.8 Radial compression with two shear modes [22]

and bridge bearing pads [22]. This design supports high compressive loads while providing soft, lateral (shear), and torsional characteristics. Although the article shown is round, square and rectangular products are more common in the construction industry.

Figure 5.8 shows another design with a high-shape factor that places the rubber in compression radially. Shear modes are torsional and axial.

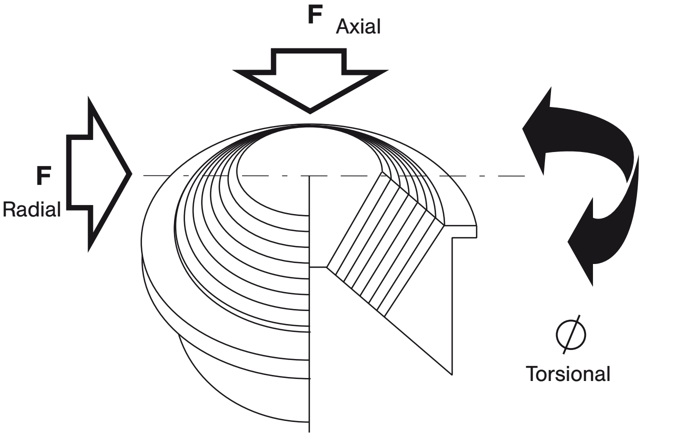


Figure 5.9 Radial and axial compression with one shear mode [22]

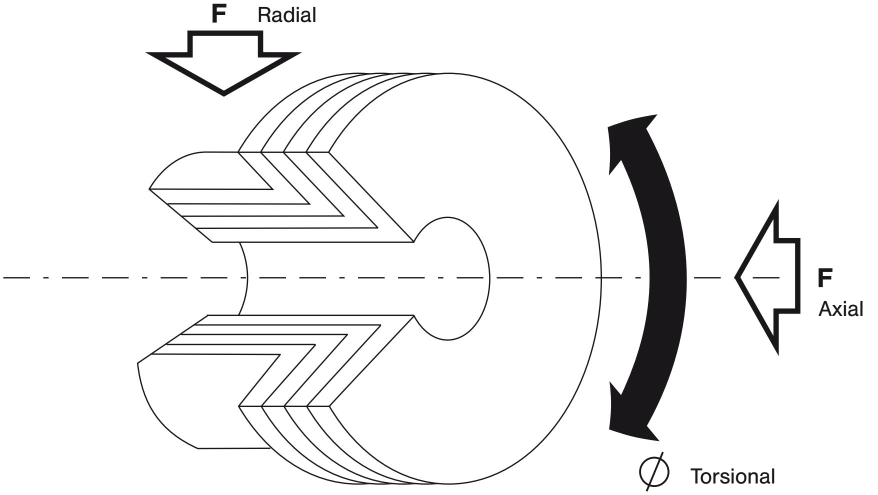


Figure 5.10 Radial and axial compression with one shear mode [22]

The conical design in Fig. 5.9 provides high axial, yet low torsional stiffness. Bearings like this are used in the rapid transit and railroad industry.

The bearing in Fig. 5.10, a variant of the one in Fig. 5.9, possesses some characteristics similar to those for the Fig. 5.9 bearing. It produces very high radial and axial-load stiffness, but is soft in torsion.

The spherical bearing design in Fig. 5.11 provides high stiffness in the axial direction while allowing the bearing to deflect in three shear modes – yaw, pitch, and roll. This type of bearing is widely used on solid rockets, earlier shown in Fig. 4.10.

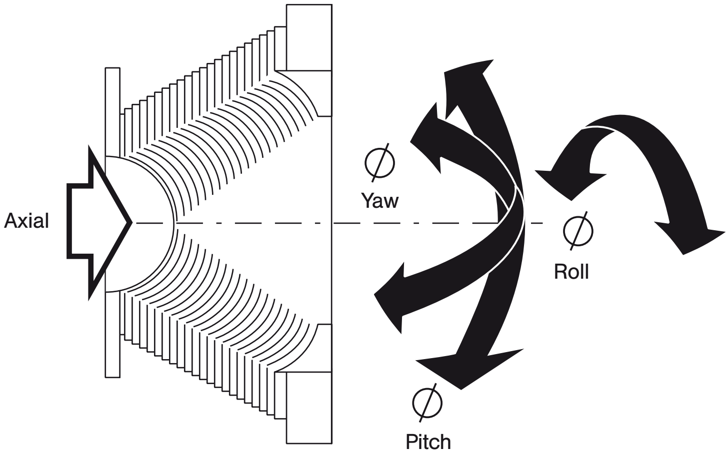


Figure 5.11 Axial compression with three shear modes, yaw, pitch, and roll [22]

Elastomers can be bonded between the outer steel ring and an inner steel ring of a ball bearing to give reduced axial vibration, radial vibration, and airborne noise [23]. Additionally, the rubber in the bearing accommodates greater misalignment.

A damped drawbar used for towing a trailer represents another use of rubber in shear [24]. Rubber, sandwiched between outer and inner steel tubes, attenuates noise, shock, and vibration during towing (Fig. 5.12). A hitch pin acts in conjunction with ovate holes in the inner tube, providing a mechanical fail-safe feature.

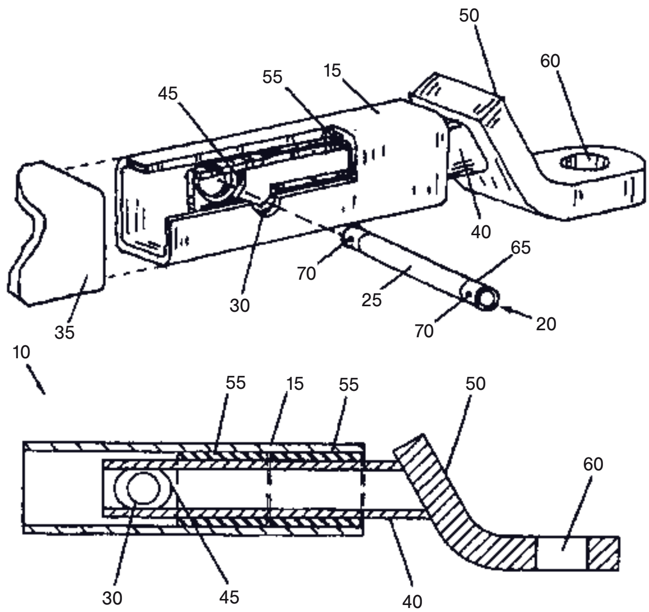


Figure 5.12 Rubber-isolated tow hitch drawbar

5.2 Hose

As with other composite rubber products, operating conditions mainly determine hose design, and call for a collaborative effort between a design engineer and rubber chemist. The engineer mainly determines the type, or types, of reinforcement based on an analysis of operating temperatures, pressure requirements, and externally applied forces [25]; the rubber chemist mainly provides the proper compounds for the tube and cover based on factors such as the material to be conveyed, adhesion requirements, and the operating temperature.

Hose is basically a flexible conduit that is designed to contain and convey fluids and solids, e.g., sandblast hose, or to transmit energy as hydraulic or pneumatic pressure. It can be broadly classified as non-reinforced or reinforced, with emphasis here on reinforced hose. The latter is basically constructed from three primary components, an inner tube, a carcass, and an outer cover. Each component is designed to meet specific performance requirements and operating conditions directed toward providing good service life.

The inner tube must withstand low temperature and remain flexible, withstand high temperature with acceptable deterioration, provide fluid compatibility, and be smooth surfaced to insure good flow. A wide range of elastomers with different properties helps meet these objectives.

The carcass should reinforce, be strong, and prevent the hose from bursting under positive pressure, or collapsing under negative pressure. Reinforcement materials consist of braided, knitted, or spiral-wound natural or synthetic yarns and fibers, metal wires, or combinations of these materials. A description of machines that apply different types of reinforcement is described in a review of hose reinforcing machines [26]. The type of reinforcement and hose construction largely determine hose resistance to stresses caused by internal and external pressure, bending, and even torsion. Reinforcement influences specific properties such as dimensional stability, elongation, and strength.

The braid in braided hose is a continuous sleeve of interwoven single or multiple strands of yarn or wire that spirals around the inner hose structure in both directions in addition to being interlaced [27]. At an angle of 54° 44′ (neutral angle) between strands of reinforcing material in the hose braid, a hose changes neither in length or diameter under pressure.

The neutral angle occurs when the resultant of the hoop force and the end force is at an angle equal to the braid angle [28]. Hose will expand in diameter and contract in length under pressure with decreasing braid angle and increasing strand pitch. It will increase in length and decrease in diameter under pressure with increasing braid angle and decreasing strand pitch. This behavior is approximate in actual hose because the neutral angle cannot be exactly maintained, and some stretch occurs in reinforcing materials during processing. For some applications, the braid angle can be designed to produce a change in length to improve retention of a hose coupling [29].

Non-reinforced hose that bursts under pressure fails circumferentially rather than axially. This occurs because the circumferential stress in the tube wall is twice that in the axial direction. This behavior is relevant to pressurized vessels. Very long cylindrical pressure vessels are made in courses and subsequently riveted together along their axis to obtain the desired length. The joints at the junction of the courses are called girth seams. Heads are attached to the end courses by girth seams [30]. Since the girth seam is stressed only half that of the longitudinal seam, joined longitudinal seams require more rivets than girth seams.

Reinforcing material in a hose does not necessarily need to be continuous. Hose compound containing short fiber reinforcement can be extruded in a manner that controls fiber orientation [31]. An advantage claimed is the elimination of braiding and knitting. Another advantage is the elimination of the need for a mandrel [32]. Air cleaner hoses have been made in production using this technology.

The outer cover on a reinforced hose protects the carcass from abrasion, corrosion, oils, and weathering. It also provides a site to mark a hose with information, e.g., for its intended service. Rubber hose is used in diverse applications, each with unique service requirements. Hose manufacture consists of forming a cylindrical tube, over which reinforcement and a cover are applied. Uncured hose often needs support to maintain the proper internal diameter and dimensional tolerances during processing. The RMA Hose Handbook [33] describes the three principal manufacturing methods for manufacturing hose: non-mandrel, mandrel, and flexible. Regardless of the manufacturing method, the finished hose must tolerate the smallest anticipated bend radius without overstress. Mandrel lubricants, available to facilitate hose fabrication, must not affect the hose material [34].

Different industries, e.g., the mining industry, require varied hose designs [35]. Within the industry there can be many sub-categories, such as:

- Hydraulic
- Fire suppression/mine spray
- Water suction/discharge
- Air breathing
- Rock dust

Hose service conditions are constantly pushed to their limit in automobiles. Under-hood temperatures, already high and detrimental to rubber components, continue to rise and place increasing demands on hose and other rubber components. For instance, some automotive hose is expected to perform continuously at 175 to 185 °C and intermittently to temperatures as high as 190 to 200 °C. Hose may need to function with different fuels, such as gasoline, diesel, biodiesel and 'sour gas' – while being required to meet reduced permeation rates.

Proper selection of a curing system and protective agents can significantly increase hose life [36]. Reduction or elimination of elemental sulfur in sulfur cure systems or the use of peroxide curing systems can improve heat resistance. Special attention must be given to peroxides because of their interaction with many antioxidants.

Automotive radiator hoses are of special interest, because electrochemical reactions can cause them to fail prematurely [37], e.g., EPDM hoses developed large cracks after relatively short periods in automotive service. A galvanic cell produced voltages generated by interaction among the engine coolant – typically an ethylene glycol water mixture – and metals such as aluminum and steel. Cracks developed in the inner hose layer and propagated into the hose body, where rapid hose failure subsequently occurred as coolant weakened the fabric reinforcement. Development of new compounds greatly alleviated this problem. Bayne provides a guide for selecting coolant hose for vehicles [38].

A radiant snow-melting hose resulted in a substantial lawsuit [39]. A multi-million-dollar settlement involved owners and former owners with this type of hose installation. A study examined the effect of heat and heat-transfer fluid on hose failure [40]. A proper fluid both scavenges trace metals and inhibits the growth of microorganisms.

A thermoplastic hydraulic hose incorporated TPV for the cover and the intermediate layers for a tubing assembly [41]. A thin layer of an impact-modified polyamide 6 or a pure polyamide 6 resin provided resistance to hydraulic oil migration and weeping. This fluid-resistant layer was co-extruded with a nylon bondable TPV that demonstrated excellent adhesion to polyamide materials in the melt phase. No weeping of hydraulic oil occurred after testing at 100 °C. Small-scale tests can shorten development time and predict field performance without requiring fabricating a full-scale hose [42].

Hose on vehicles connects the filler neck and the fuel tank, as well as serving to extract fumes from the fuel system [43]. Among specifications for these hoses are fuel permeation, burst strength, and low temperature resistance. Hose to meet these requirements consists of four layers of different elastomers, reinforced with aramid cord. Caution must be exercised when combining elastomers and plastics in a product, because materials can migrate. For instance, a plasticizer can migrate from a rubber compound into a plastic and cause problems.

A fuel hose with low permeation characteristics is constructed from six different layers: cover, reinforcement, tie layer, barrier layer, and an FKM inside veneer that can be made optionally conductive [44]. Several extruders arranged in sequence produce the different layers in the multilayer composite. The expensive FKM barrier is typically extruded as thin as possible to reduce cost; it must be sufficiently thick to meet performance requirements. Original physical properties and combined fluid and heat resistance needs generally define performance requirements. Other requirements, e.g., low temperature and burst pressure, are often specified for the finished product.

Fluorosilicone turbocharger hoses must meet increased operating temperatures and the effects of more aggressive engine oils [45]. Silicone rubber is now displacing the acrylic rubber in many of these applications. Aramid fabric provides hose strength, while the silicone rubber protects the fabric and provides flexibility over a wide temperature range. Silicon-based textiles that harden instantly under stress are now available to provide impact protection at the point of contact [46].

A carbamide solution transported by hoses is used to help transform nitrogen oxides (NO_x) into steam and hydrogen during truck operation [47]. Because this solution freezes at relatively high temperatures (–11.5 °C), a heater wire incorporated in the hose prevents the solution from freezing, thus allowing the hose to operate at low temperatures.

Plasticizers, which improved the low temperature properties of IIR-based hose and other mechanical rubber articles, reduced the ozone resistance of the articles [48]. Effective antiozonants incorporated in the IIR hose cover imparted the required ozone resistance.

Although the objective of most hose manufacturers is to make a leak-free product, leaky hoses are purposely manufactured [49]. The leaky hoses incorporate fine black granules obtained from ground tire scrap that is bonded with polyethylene and subsequently formed into hose for soaking gardens and lawns.

Brake-by-wire systems [50] are now challenging conventional automotive brake hose directed toward improved safety. Electronic-assisted braking could reduce stopping distances by up to a third, thus significantly reducing accidents such as rear-end collisions. Changing to the new system could eliminate conventional components from a vehicle: hydraulic fluid, master cylinder, brake hose, and vacuum booster pump.

5.3 Belting

Conveyor belts are a major segment of rubber belting. They consist of rubber-coated, fiber-reinforced belts that are supported and driven by rollers [51]. The rollers are generally coated to increase friction and to reduce abrasion, noise, and build-up of dirt. Tension, driving forces, geometry, and material properties of the belt and rollers affect the pressures and shear stresses in the rubber layer. Abrasion due to slip is proportional to belt pressure to the power of 1.5–3.

Belt service requirements range widely. High-performance compounds are required for severe mining conditions [52]. These include compounds for conveyor belt construction, idler rolls, mill liners and lifter bars, and extra-heavy-duty cable jackets. Operating temperature of a conveyor belt that transports hot materials is of special interest [53]. For example, the top surface of a belt conveying hot clinkers varied between 171 and 227 °C. Controlling the temperature at which hot material is initially dumped and subsequently transported can extend belt life. If a power failure occurs, hot material is removed as quickly as possible to increase belt life.

Wide conveyor belts that ride on pulleys must be sufficiently flexible in the transverse direction to form a trough for conveying material. Some steel-cord reinforced conveyor belts are huge, as long as eight miles and weigh 1300 tons [54]. Conveyor belts and V-belts must resist elongation in the longitudinal direction.

While an ordinary surface has two sides, a Möbius strip has only one side. This feature has been used in a conveyor belt for hot material wherein a face-reversing twist about the longitudinal axis of the belt alternately inverts the belt faces presented so that the belt wears equally on both sides [55]. This 'face-reversing twist' about the longitudinal axis is the subject of a patent [56] that describes alternately inverting the faces of a belt carrying hot material.

Conveying of grain presents special problems with static electricity and associated static ignition [57]. Use of carbon black in the belt compounds increased electrical conductivity and thus reduced this hazard. A test for flammability of conveyor belts involves holding a stationary belt in contact with a rotating drum until the belt breaks without producing any flame or glow [58]. Properties such as heat resistance of 170 °C and excellent non-stick properties can be incorporated in a conveyor belt [59].

5.4 Constant Velocity Joint (CVJ) Boots

The change from rear wheel drive to front wheel drive on automobiles necessitated the use of constant velocity joints (Fig. 5.13), a type of universal joint that transmits power through angles of about 6 to 10 degrees [60]. Earlier joints operated at a lesser angle, typically four degrees. The input and output shafts of constant velocity joints transmit power through an internal member that exactly bisects the two shafts. This feature reduces angular acceleration of the intermediate shaft member to zero and eliminates vibration.

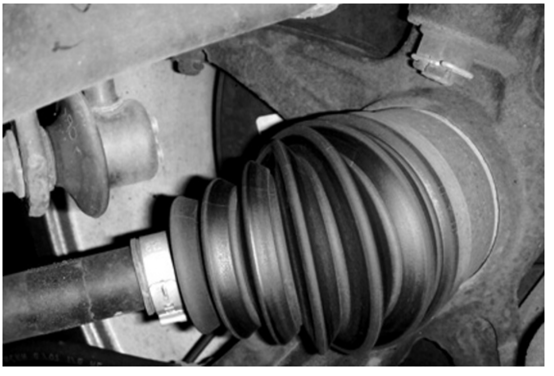


Figure 5.13 CV joint boot installed on an automobile

During operation, CVJ boots (seals) flex constantly to accommodate vertical movement of the suspension and the turning motion of the wheels. They retain lubricants and prevent entry of road debris, water, and other contaminants into the boots. Lubricants can aggravate the situation by leaching antiozonants and antioxidants from the boot compound and thus place considerable demands on both the rubber compound and the boot design. CVJ boots operate in one of the most demanding environments of any rubber component on a vehicle [61]. The convoluted shape of CVJ boots minimizes stretching while providing stability at high speeds. Excessive stretching must be avoided because it necessitates greater clearance dimensions to avoid contact between the rotating boot and its surroundings.

The compound in CVJ boots must meet a number of requirements that include: resistance to ozone and oxidation attack, acceptable low temperature and flex properties, and compatibility with the lubricant. CR served successfully in a number of CV joint applications, but increasing demands required alternative elastomers. For example, silicone rubber might be required for a boot located close to a catalytic converter. Exhaust hangers located near a catalytic converter may also require rubber with high temperature resistance [62].

Replacement of CVJ boots is expensive because it requires the disassembly of the CV joint. Split boots permit replacement without requiring disassembly [63]; design changes such as increased rotating angle have made it more difficult for the split boots to meet durability requirements. A steering-knuckle boot is an early example of a split boot for a military truck (Fig. 5.14) that incorporated a zipper at the split line [64]. It permitted much more rapid boot changes.

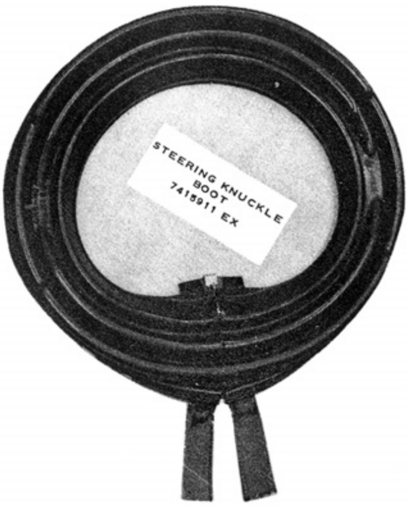


Figure 5.14 Steering knuckle boot for a military truck

5.5 Mounts and Bearings

5.5.1 Shape Factor

Shape factor (SF) is a very important factor in the design of the myriad types of rubber-metal bearings that include bridge and earthquake mounts, axial bearings, radial bearings, spherical sandwich bearings, and spherical tubular bearings [65]. These have the general advantage of providing substantially different spring rates along different axes. For example, a bridge bearing is extremely stiff in the vertical direction, much softer in the horizontal direction.

5.5.2 Bridge Bearings

Stiffness change in a bridge bearing with aging is a concern, just as it is with any rubber product in long-term service. The average shear stiffnesses of two bridge bearings in service in England for 38 years was only 7% greater than the stiffness observed for an original prototype [66]. Tests on rubber specimens prepared from a sectioned bearing showed acceptable tensile properties in the bulk of the aged bearing.

This favorable aging behavior is partly due to the relatively high shape factors, typically about six, for bridge bearings [67]. The high shape factor minimizes the exposure of the interior rubber to oxygen and ozone, thus favoring a long bearing life.

A bridge bearing is designed to support the substantial weight of a bridge with minimum deflection in the load-bearing direction. Steel plates bonded (Fig. 5.15) to elastomer [68]

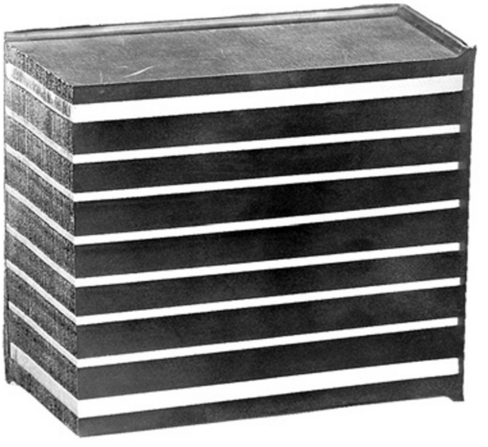


Figure 5.15 Section from a bridge bearing showing steel plates bonded to rubber

provide very high stiffness in a direction perpendicular to the plane of the plates. In the horizontal direction, low bearing stiffness is desired to minimize transfer of stress from the bridge to the bridge support structure, e.g., a concrete column. Atmospheric temperature variations cause changes in bridge length that are accommodated in shear by the bearing.

In addition to acting as a spring, the rubber in the bearing protects the steel from corrosion [69]. Increasing the outer thickness of rubber considerably increases fire resistance of a bearing. Cutting an opening completely through a bridge bearing lowers shape factor, because the opening provides a region for the rubber to squeeze from in between the reinforcing plates.

Adhesion of rubber to the steel plates essentially prevents shrinkage of the rubber in the plane of the rigid plates. Hence, nearly all shrinkage occurs in the vertical direction, namely perpendicular to the plane of the plates. Because of this, a designer must account for this anisotropic shrinkage in mold design calculations.

5.5.3 Earthquake Bearings

Structures have a natural frequency like a tuning fork. Bridge bearings essentially function under static forces (very low frequency), while earthquake bearings function under dynamic forces during an earthquake. Unfortunately, the bandwidth of earthquake frequencies corresponds to the natural frequency of many structures. Rubber earthquake bearings, placed between a structure and its support, isolate the structure and offer protection [70]. An effective earthquake bearing decouples a structure from the horizontal components of earthquake ground motions.

Sufficiently flexible earthquake bearings (essentially springs) greatly reduce the transmission of vibration from the source to the supported structure [71]. The spring does not absorb the energy of the exciting frequencies as is sometimes thought. Rather the mount mismatches the frequencies of the source and the receiver. In addition to accommodating movement, earthquake mounts provide a much lower natural frequency that avoids resonant conditions. The bearings must be sufficiently soft in shear to yield a horizontal natural frequency that is substantially below the earthquake frequency. Additionally, bearing vertical stiffness must be sufficiently high to prevent rocking of the structure during an earthquake.

Earthquake bearings, similar in construction to the bridge bearing shown in Fig. 5.15, might contain up to fifteen layers of rubber. Equation 5.1 relates the horizontal natural frequency (f_h) of a structure on its mount to the mass (m) of the structure supported by the bearing; k is the horizontal dynamic stiffness of the bearing [72].

$$f_h = 1/2\,\pi\,\sqrt{k/m} \quad (5.1)$$

f_h is chosen to be sufficiently below the dominant earthquake frequencies to obtain good attenuation. Dominant earthquake frequencies typically range from approx. 1.5 Hz to 8 Hz for rock or firm soil sites. Hence, a mounting frequency of about 0.5 Hz is typically chosen for the mounted structure. Rubber earthquake bearings reduce the forces on a medium-rise building in rock or firm soil regions by about tenfold [73]. Soft-soil locations reduce mount effectiveness [74].

A laboratory test successfully predicted the long-term creep of building mounts [75]. Design engineers are confident that data like these can predict creep after 100 years to within an accuracy of 6 mm. Creep in mounts for buildings is important because uneven settling of a building on mounts could lead to structural damage.

5.5.4 Testing and Quality Control

Organizations like ASTM and The Society of Automotive Engineers (SAE) provide a number of test methods that help in the development and characterization of products. These methods provide a universal language for communication between manufacturers and users of rubber products. Other organizations, e.g., Rubber Manufacturers Organization (RMA) provide principles and guidelines for the design and use of a range of rubber products. Included in the handbook is information on molded, extruded, lathe cut and cellular products [76].

The handbook provides engineers with a uniform procedure for describing product requirements using process symbols, charts, and definitions [77]. This approach favors understanding by those involved in the manufacturing process. Different product types, e.g., molded vs. extruded, use different manufacturing techniques. Quality control is addressed in a separate chapter of the handbook. It is important to specify only the required level of quality in a product to keep costs down.

The handbook describes different levels of dimensional control in descending order: "A1" high precision, "A2" precision, "A3" commercial, and "A4" basic. It further describes these levels as a function of fixed and closure dimensions, and of product size. Figure 3.12 illustrated fixed and closure dimensions.

Drawing designation "A1" defines a high precision rubber product that typically requires an expensive mold, fewer cavities per mold, costly in-process controls, and costly inspection procedures. An "A1" classification may not apply to some rubber types, e.g., those requiring

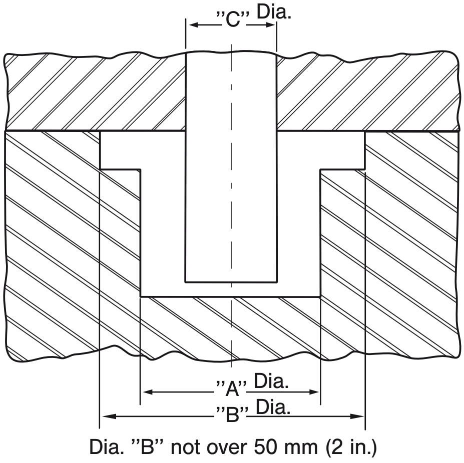


Figure 5.16 Illustration showing concentricity (reprinted from RMA Rubber Handbook, 6th edition, with permission)

a post cure. "A2" classified products will usually require careful inspection. Most rubber products are usually specified "A3". Designation "A4" applies to products requiring some dimensional control.

Because rubber product dimensions change with temperature, measurement temperature should be specified for products with critical dimensions. The time required to stabilize the product at the measuring temperature should also be specified. For products that change dimensions with moisture content, relative humidity and stabilization time should also be specified. RMA provides additional information on conditioning and methods of measurement. Other factors for consideration by the design engineer are concentricity, squareness, flatness, and parallelism.

Concentricity, the total indicator reading (TIR), relates two or more circles or circular surfaces that share a common center as shown in Fig. 5.16. It is the total movement of the hand of an indicator set to record the amount that a surface varies from concentricity. Diameters formed in the same mold plate will be concentric within 0.25 mm TIR.

The wheel shown in Fig. 5.17 specifies both concentricity and wobble, where wobble is the movement of a surface that is not intended to be parallel to the TIR axis of rotation. For example, a 75 mm (3 in.) diameter wheel would be expected to be concentric within 0.75 mm (0.030 in.), TIR and wobble within 0.75 mm (0.030 in.) TIR.

A general design principle that is seldom achievable is to make the stresses uniform throughout a rubber product [78]. More realistically, one can design to avoid excessive stress that could initiate failure. For example, a rubber block bonded to metal that is placed under compression can develop very high shear stresses at its edges due to barreling of the rubber.

Although rubber can be extruded and molded into complex shapes, it is best to design rubber articles as simply as possible. Avoid projections, overhangs, undercuts, and complex shapes as much as possible, because they increase mold and trimming costs, are difficult and costly to mold, and often increase reject rates. Review designs early with the intended product

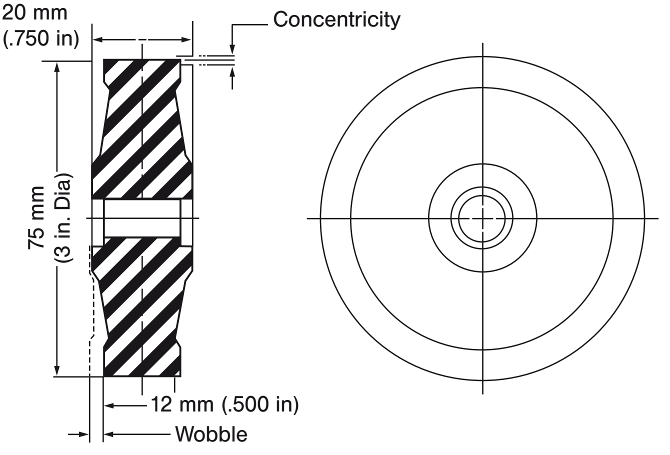


Figure 5.17 Concentricity and wobble in a wheel
(reprinted from RMA Rubber Handbook, 6th edition, with permission)

manufacturer, who can often suggest alternative approaches that reduce costs and/or improve product performance.

Locate mold-parting lines (see Fig. 3.9) to minimize air entrapment, to reduce mold-fabricating costs, and to provide for easy removal of the molded article. Ideally, parting lines are located in a plane.

Because of rubber's flexibility, draft in molds is usually unnecessary. However, draft is desirable for some soft thermoplastic rubbers; it is recommended for harder rubber, and is needed for hard rubber. Increasing draft and decreasing the depth of undercuts eases removal of molded articles from their molds.

Flat and angular surfaces are more economical than curved surfaces, because they ease mold fabrication. For rubber products that are strained in service, radii on both internal and external corners of rubber parts will generally improve fatigue life. Provide a radius on the corners of metal or other rigid materials that contact rubber. Wall thickness should be as uniform as possible to minimize crosslinking time for TSEs and cooling time for TPEs.

The smoothness of both a mold surface and the rubber compound affect the appearance of a molded article. For critical surfaces such as automotive fascia, surface appearance is especially important, because the surface of the molded fascia essentially mirrors the mold surface. Ingredients in a rubber composition, wax for example, can migrate to an initially glossy surface and dull it. The method used to remove flash can also affect appearance of a finished product. For instance, hand-trimming flash generally does not affect surface appearance, but tumbling may cause a dull surface.

Shrinkage that occurs with both TSEs and TPEs varies with different types of elastomer and the manner in which they are formulated. It very significantly affects mold design and becomes especially problematic when it is non-uniform. For rubber compounds containing oriented and bonded fiber, shrinkage is lower (Fig. 5.18) along the fiber axis. Shrinkage is higher perpendicular to the fiber axis, because the fiber does not constrain shrinkage in this direction.

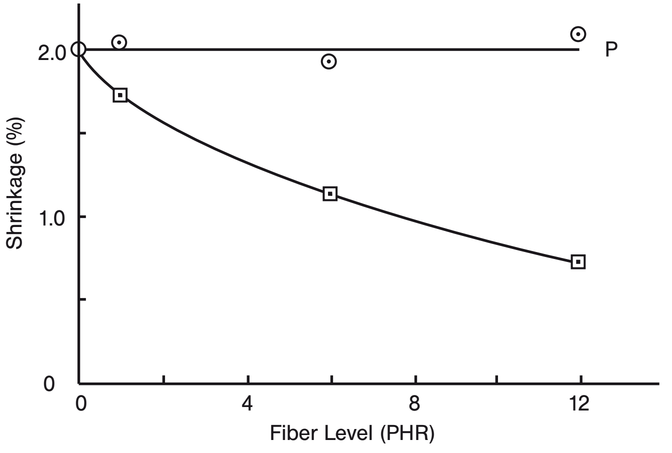


Figure 5.18 Effect of oriented fibers on the shrinkage of a rubber compound along (A) the fiber axis, and perpendicular (P) to the fiber axis

Only a 5° deviation from optimum orientation reduces the load-carrying ability in a fiber-rubber composite by 50% [79]. Ideally, fibers in a rubber product would be aligned with the stress to support the maximum load per fiber. Doing this reduces the amount of fiber required. This technology is finding use in turbocharger hoses.

Adhesion is important in silicone rubber switches coated with polyurethane [80]. Silicone (hydrophobic) will not adhere to polyurethane (hydrophilic), because of their substantially different polarities, unless the silicone surface is treated with plasma. Plasma treatment produces a high-energy surface on the silicone that facilitates good bonding of the silicone to a polyurethane top coating.

Temperature is critical in 2-shot injection molding of a TSE and a TPE when fabricating a Vamac (rubber)-polyamide (plastic) composite [81]. It must be carefully controlled to effect chemical adhesion between the two polymers. The polyamide, which is processed at about 280 °C, will freeze as the temperature falls from 240 °C to 220 °C. It must be at about 80 °C before it is overmolded with Vamac. As the Vamac cures, temperature between it and the polyamide is about 150 °C.

General guidelines are provided for overmolding TPVs [82]. Also included are recommendations for draft angles, wall thickness, undercuts and ribs, radii and fillets, hinges, surface texture, and appearance.

A handbook provides additional guidelines for the design of rubber parts [83]. For example, when bonding attachments to other materials to form a composite, keep rubber thickness as uniform as possible to minimize the potential for stress concentrations. Also, remember that rubber encapsulating a metal insert will shrink non-uniformly and cause distortion of the rubber surface.

Figure 5.19 shows rubber bonded in the cavity of a metal plate [84]. Sufficient height must be provided for grinding of this composite for it to have a flat surface. Sketch 1 shows the concave surface caused by volumetric shrinkage of the rubber; Sketch 2 shows the flat surface obtained after grinding.

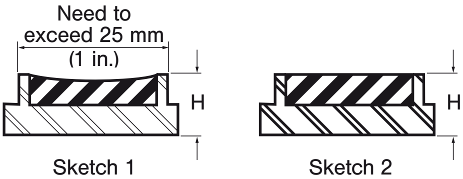


Figure 5.19 Flat rubber surface obtained by grinding
(reprinted from RMA Rubber Handbook, 6th edition, with permission)

Holes can be incorporated in rubber articles for attachment purposes or for some other function. They can be formed during molding or in a post-molding operation, e.g., by die cutting, or with a laser to produce holes as small as 0.15 mm (0.006 in.) diameter to provide an opening in baby-bottle nipples [85]. Holes should be as shallow and wide as is consistent with product requirements. Through holes are generally preferable to blind holes, because the pins that form them during molding can be anchored at both ends, making the pins less susceptible to bending during molding. This is especially important for thin pins.

Holes with their axis in the mold closing direction are preferred, because they avoid the need to incorporate retractable pins in a mold. Allow sufficient wall thickness around holes used for mounting to prevent the rubber article from tearing from the hole. Maintain hole-to-hole and hole-to-edge spacing adequate to prevent tearing. Spacing equivalent to one-hole diameter is generally considered sufficient.

Design attachments directed toward keeping rubber thickness as uniform as possible [86]. Angled inserts can be embedded in rubber products to form rubber-metal composites. During molding, flowing rubber will likely wipe adhesive from the top of the embedded insert.

Cutting rubber articles to length on a lathe from an extruded tube lowers the cost of fabrication for some rubber articles [84]. The upper illustration in Fig. 5.20 shows square-cut articles of different lengths; the lower illustration shows angle-cut articles, some of which have 'V' grooves cut in them.

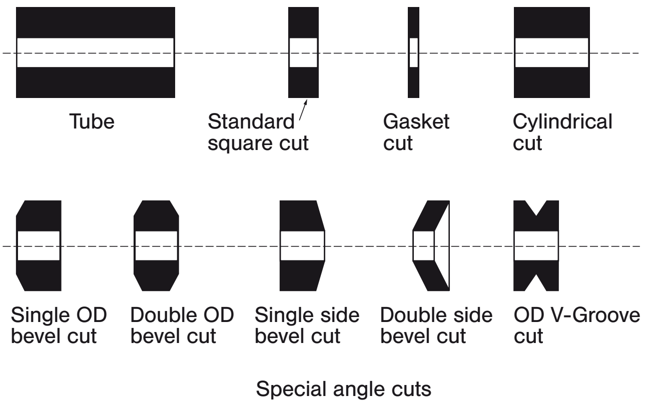


Figure 5.20 Lathe-cut articles from an extruded rubber tube
(reprinted from RMA Rubber Handbook, 6th edition, with permission)

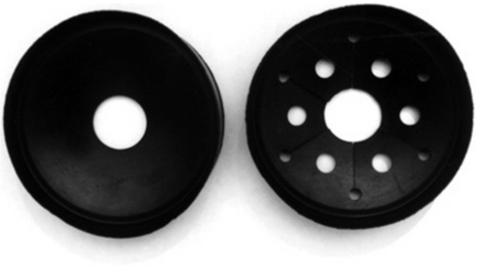


Figure 5.21 Diaphragm as molded (left); diaphragm after die cutting (right)

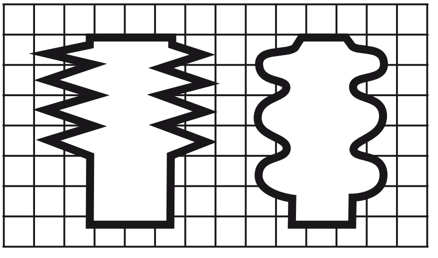


Figure 5.22 Bellows with sharp (left) and rounded (right) convolutions

Another alternative to molding a rubber article in its finished form is the post-molding operation shown in Fig. 5.21. The diaphragm could be molded in its final form by placing pins and knife-like inserts in the mold that would form the desired holes and slits. However, this would require an expensive mold. An alternative is to die cut the molded diaphragm to form the intended openings.

Providing generous radii in the walls of bellows (Fig. 5.22) facilitates demolding, reduces stress concentrations during flexing, and thus improves flex life [86]. Design guidelines are provided for convolute design for TPV tubes, ducts, and bellows [87].

Flash or feather edges on a molded article are problematic, especially thin rubber flash that tends to stick to the surface of an article. Avoid feather edges by designing the edge of the article to be 1/32 in. minimum.

The rubber earplugs shown in Fig. 5.23 illustrate a balance that was obtained among several factors [88]. They are soft (20 Shore Diameter), have high tear strength, low scrap, short cycle times, and avoid mold fouling. Using Shin-Etsu KE2004-20 silicone, the desired material and processing properties were obtained without having to redesign the mold, which would have cost $70,000 to $100,000.

Figure 3.9 showed the flash that is typically formed at the edge of a molded rubber article. The rubber that flows beyond the outer edge of the cavity is called flash extension and Table 5.2 provides RMA drawing designations for the various amounts of flash extension. Closure tolerances normally include variations in flash thickness [89].

Figure 5.23 Very soft silicone rubber earplugs

Table 5.2 Drawing Designation for Flash Extension (RMA Handbook, 6th edition)

Drawing Designation	
T .00 mm	(T .000) No flash permitted on area designated. (Standard notation regarding other surfaces must accompany this notation.)
T .08 mm	(T .003) This tolerance will normally require buffing, facing, grinding or a similar operation.
T .40 mm	(T .016) This tolerance will normally require precision die trimming, buffing or extremely accurate trimming.
T .80 mm	(T .032) This tolerance will normally necessitate die trimming, machine trimming, tumbling, hand trimming, or tear trimming.

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6 Use of Computers and FEA with Rubber

The rubber industry is among the many industries that computers have revolutionized. Computer use includes computer-aided design (CAD), computer-aided manufacturing (CAM), and finite element analysis (FEA). They have greatly improved efficiency in many areas, in addition to making possible the analysis of complex structures using FEA. Their use is not without potential problems. Inexperienced engineers may use software and databases without questioning their validity [1]. With proper use, computers and effective software have contributed immensely to the rubber industry.

Good communication among all involved in handling and processing CAD-related data and information is necessary to insure project success [2]. To favor this outcome, guidelines have been provided that include:

- checking CAD data for correctness and completeness so that projects move through engineering and manufacturing in an orderly manner
- complete dimensioning and tolerancing of prints
- assuring CAD data are compatible among those involved

FEA, used successfully for many years in the analysis of metal articles, received slower acceptance in the rubber industry, because its application to rubber is more problematic [3]. The non-linear response of filled rubber compositions and their dependence on time and temperature makes the analysis of rubber much more complex relative to metals. Both 2D and 3D FEA modeling approaches are used.

Considerable effort has been directed toward modeling and simulating polymer molding processes. These efforts have resulted in finite element analysis (FEA) programs that have generally found wider application with thermoplastics than with thermosetting elastomers. Several reasons account for this. Plastic articles are molded in much larger volume than elastomers, favoring faster amortization of the cost of simulation software. Also, hard plastics and TPEs are generally molded using pellets that often receive little or no modification before being converted into product. In contrast, TSEs are converted into complex compounds wherein the TSE usually comprises less than half the weight of the final compound.

Plastics and TPEs are generally supplied with relevant material parameters, e.g., viscosity vs. shear rate and temperature, required for molding simulations. TSEs, in contrast, require that these parameters be determined for each compound and this determination adds cost and typically lengthens time for mold design and delivery. Further, the potential occurrence of scorch with TSEs significantly complicates modeling simulations. Both proprietary and commercial programs have been developed to simulate injection molding of TSEs.

The following examples demonstrate the application of FEA to product analysis and design for specific rubber products. Selection of the method depends on the complexity of the article being molded and the manner in which the geometry will be used in the design cycle. The analysis by 3D involves creating a virtual object by dividing up an article into very small units, followed by analyzing these individual small units that leads to information on the complete article [4].

FEA is considered eminently practical since problems with incompressibility and large deformation appear to have been largely solved, often with experimental validation [5]. It is a powerful resource for design and analysis of rubber components and it appears that rubber technology has yet to realize the full capability of FEA.

Among the many methods for solving complex design problems with elastomer products, FEA is now considered the most accurate, comprehensive, and versatile. A numerical approach is used to evaluate design concepts for rubber products by predicting the internal stress and strain distributions that are difficult to measure experimentally. FEA by the finite element method (FEM) can more realistically represent geometry, loads, and boundary conditions of rubber and composite rubber products. Further, FEA reduces the need to build expensive product prototypes and therefore reduces costs. The several steps necessary to conduct analyses of elastomer structures by FEA include:

- Define the model for FEA
- Characterize the elastomer stress-strain behavior
- Solve the problem by use of a finite element code

The use of FEA is now commonplace and a several commercial codes are available such as MARC®, ABAQUS®, and ANSYS® [6]. Software availability and low-cost computing power have facilitated FEA becoming a standard tool, even in relatively small rubber companies with limited resources [7].

Factors contributing to increased use of FEA are:

- Lower computing costs
- Effectiveness in solving large deformation problems in elastomer products
- Lower cost relative to earlier design methodologies

Because of the large and nearly elastic deformation capability of elastomers relative to higher modulus materials, new models were required to mathematically describe elastomer behavior. Unfilled, crosslinked elastomer compounds that operate well above their T_g can be considered to behave hyperelastically and they can be modeled by means of strain energy functions. Most vulcanizates contain fillers that complicate the analysis.

In conducting FEA, triangular or quadrilateral elements divide a structure into elements that are joined at their intersection to form nodes. The joined elements form a mesh or grid, wherein the nodes are free to move in different directions. Deflection, pressure, friction, etc. describe the boundary conditions. It should be recognized that computer modeling accounts for only a limited number of factors and cannot consider all potential environments, interactions, and aging effects. FEA still needs considerable expertise to use [8]. Care is necessary when creating a mesh for the stress analysis of rubber because individual elements can become very misshapen as the model distorts [9]. Further, hysteresis and creep behavior of rubber limit the analysis of rubber by FEA.

The above considerations aside, FEA is a widely used technique to analyze rubber structures [10]. In addition to yielding accurate information such as stiffness predictions and stress analysis, FEA can address internal heat generation due to mechanical loading, cure state analysis, and fatigue life analysis. Fatigue life analysis considers a failure that propagates from a local point of high stress. Stiffness is an easier problem because all elements contribute in a global manner.

FEA is increasingly used in the rubber industry to solve technical problems, e.g., to predict fatigue failure and to develop products. Finney describes its application to a range of rubber products that include positive-drive timing belts, dock fenders, boots, bumpers, laminated bearings, down-hole packers, O-rings and hose [11]. Discussed below are additional examples and areas of the application of FEA:

6.1 Compounding

6.1.1 Vulcanization

Transient, thermal-diffusion FEA [12] can simulate the cure of a rubber article. It differs from low strain linear FEA, because it requires the running of analyses at small time intervals. The cure accumulated at each of the nodes of the mesh can be integrated with respect to time by including a suitable function in the FEA program.

6.1.2 Compound Development

Experiment design facilitated optimization of FKM recipes that met multiple, often competing requirements [13]. It assisted compound development through increased understanding of the effect of input variables, e.g., the effect of compound ingredients on outputs such as physical properties.

Different classes of accelerators were compared in model butyl and bromobutyl rubber compounds [14]. Zinc dibutylphosphorodithionate was examined in a three-variable, central composite experiment design. The investigation provided a basis for further examining non-nitrosamine cure systems.

6.2 Stress in a Dumbbell Tensile Specimen

Rubber tensile specimens (ASTM D 412-87) are used extensively for product development and in quality assurance activities. Fig. 6.1 shows a tensile specimen at zero elongation (dashed line) and 112% elongation [15]. Material properties for a natural rubber gum compound were used and the specimen was characterized by FEA using a proprietary code and a non-linear model.

One would expect the maximum stress to occur in the narrow cross-section of the specimen, namely the central portion. However, the analysis showed that the stress is significantly higher

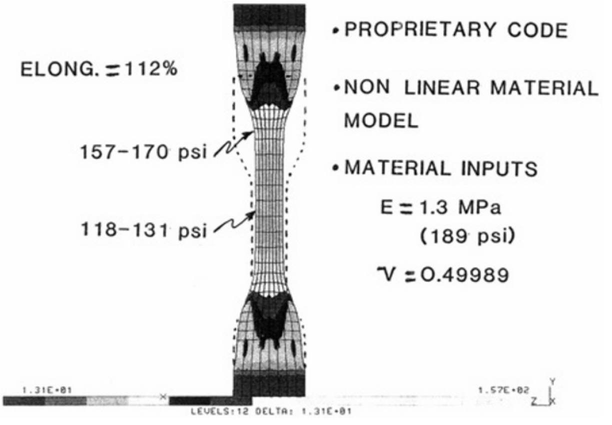

Figure 6.1 FEA of an ASTM dumbbell specimen using material properties for an NR gum compound as inputs

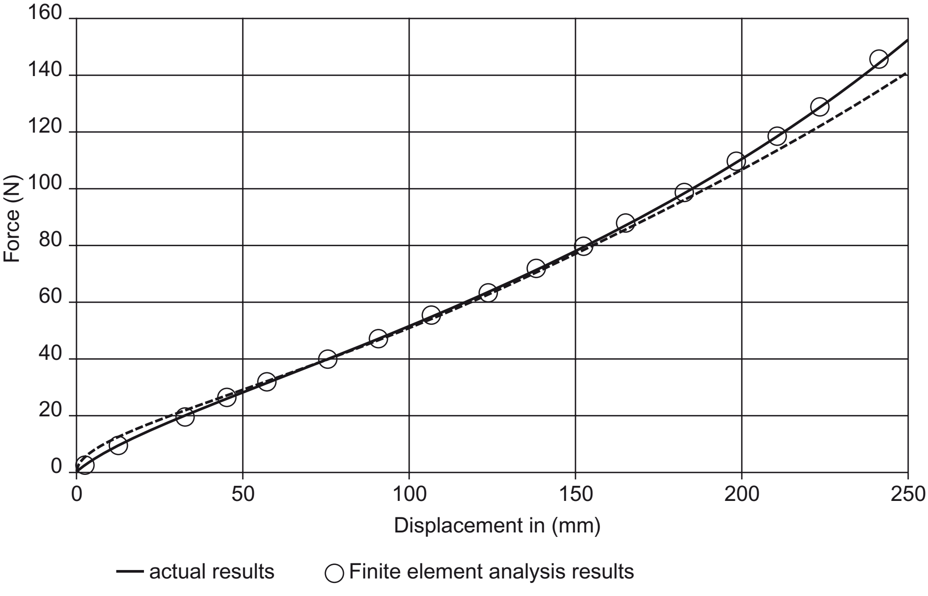

Figure 6.2 Force-displacement plots for actual and FEA characterizations of dumbbell specimens

in the region where the narrow section transitions into the wider sections. Were it not for flaws in the specimen, breakage would occur in these wider areas.

In other work, dumbbell test specimens that were stretched to break were modeled by FEA [16]. Figure 6.2 compares FEA results with actual tensile test results.

Excellent correlation is seen between FEA predictions and actual results.

6.3 FEA and Thermal Considerations

It is difficult to obtain uniform crosslinking throughout the cross-section of a large rubber article because of rubber's low thermal diffusivity [17]. Heat applied to the outside surface of rubber in a curing mold first raises the temperature of the rubber in contact with the mold. Temperature then progressively increases through the rubber toward the center of the rubber part. After completion of the curing cycle and removal of the article, the article continues to cure from the inside out, driven by the higher internal temperature.

Computer code was developed to predict temperature profiles and variations in crosslinking as a function of time of a tire in its mold [18]. Comparison of predicted and experimental results confirmed validity of the mathematical model and the 3D code.

6.4 Resistance of Rubber to Small Indentations

FEA was used to examine the resistance of rubber blocks to small indentations for a wide range of block dimensions [19]. Results agreed well with available analytical solutions. In other cases, stiffness followed simple empirical functions of the rubber block dimensions that should be useful for design purposes.

6.5 Use of FEA in Various Application Areas

Tires

A study established the ability of FEA to predict the oxidation of tires in accelerated oven testing [20]. A model successfully predicted experimentally determined crosslink density evolution in the belt-skim and wedge regions. Comparative simulation results for aging rates in different regions of a tire suggest that 60 to 70 °C is a reasonable temperature range for oven testing.

Finite element modeling (FEM) successfully simulated the joining of a tire carcass and the tire belts during tire building [21]. The method detected points where different layers in the tire cross-section have a tendency to separate. It distinguished behavioral differences between different tire types and was useful in practical problems with tire manufacture.

During tire molding, a rubber bladder positioned inside a tire provides the pressure that forces a tire against its mold. In doing this, the bladder can stretch more than 100% [22]. MARC was used to analyze the curing process and to determine how contact occurs at the tire-bladder interface. Two different bladder shapes and two different inside tire profiles determined the magnitude and uniformity of the interfacial pressures.

Determination of meaningful compound properties and their use in FEA is more complicated than in other areas of rubber technology. Four typical tire compounds containing carbon black filler were tested using uniaxial tension in addition to more complicated test methods [23]. It was concluded that Yeoh's proposed cubic strain energy function derived from uniaxial tension data can be applied to predict uniaxial compression and pure shear data. This approach was considered a quick and inexpensive method to produce a good database of material properties.

An experimental design to study belt edge separation in steel-belted radial tires included factors such as temperature, time, partial pressure of oxygen, and antioxidant level [24]. Experimental results established that the first three factors are critical external factors that affect belt edge separation. Crack growth mechanisms for the belt edge were established for tires tested in the laboratory and on road wheels.

FEA, considered crucial to simulating the behavior of new tire designs, has been used for some thirty years on whole tires. [25]. More recently, molecular modeling is being considered on a significantly smaller scale to establish the interaction between a carbon black particle and a single polymer chain. Additionally, software has been developed to predict acoustic resonance within a tire under real driving conditions. FEA has also been used to model tire traction under various road conditions [26].

Testing established the material properties of several different types of rubber [27]. All test results were verified using MSCMarc2005 FEA software in terms of the Mooney-Rivlin and Ogden models, both well known as rubber material constitutive models.

Air Ducts

This extensive project, which jointly considered materials, processing, and design, effectively used design of experiments [28]. The convoluted ducts, used under hood in automobiles, were ten inches in length and about three inches in diameter. The CSM elastomer used in the ducts evolve small amounts of sulfur dioxide that can attack molds during curing. Chromium plating on the molds minimized this problem; however, stainless steel molds proved better for long runs. Compound development using a DOE approach reduced development time and produced a database useful for future work.

The final compound demonstrated improved processing properties. Special attention was given to both wall design and thickness of the ducts, which must not collapse when operating under vacuum in service.

Belting

Dalgarno, in an extensive review of power transmission belt performance and failure, points out that material property descriptions are critical to successful finite element analysis [29]. The most common FEA approach considers the elastomer compound, the fabric, and the cord as individual linear elastic material elements that make up a composite belt.

Rubber Bumpers

A rebound bumper for an automotive suspension system was analyzed using the large-scale finite element program, ANSYS [30]. The program provided the design engineer with a method to examine both material and design changes. Comparison of theoretical and experimental data showed excellent correlation.

Elastomer Bearings

Strains in high-capacity laminated bearings were obtained using Stress

Analysis of Rubber Laminated Structures (SARLASS) [31]. Maximum compressive strains and compression induced strains occurred in the rubber layers near the large end of helicopter bearings. Crumbling indicated failure of rubber in compression and rubber that was squeezed out indicated compression-induced edge shear. Bearing redesign significantly reduced strains, improved performance, and resulted in a bearing that could perform without failure.

A meshless formulation was applied to a contact analysis for assembled rubber metal bushings [33]. The approach taken was considered very useful for analysis of bushings and other structures that undergo extreme deformation. The meshless method with fewer degrees of freedom provided the same accuracy as that of a much more refined finite element model.

FEA results, compared with published analytical expressions for a range of bushings, showed results for torsional and axial stiffness agreed reasonably well [34]. However, existing analytical solutions predict values that are incorrect for both conical and radial stiffness. It was concluded that a single measure of shear modulus taken over the correct strain range sufficiently characterizes elastomer behavior.

Marine riser flexjoints consist of joint flanges and a central housing [35]. They are used in drilling operations beneath the sea, support enormous loads, and require angular cocking and torsional motion capability. The Texgap84 program used to analyze the flexjoints used as inputs: shear modulus, bulk modulus (commonly assumed to be 200,000 psi), component geometry, and boundary conditions.

Helicopter Bearings

A number of rubber-metal bearings are used in the V-22 Osprey tiltrotor aircraft [35]. FEA established stress distributions in rubber and metal components that resulted in improved bearing life predictions and also in improvements in manufacturing cost and product quality.

Rubber Mounts

CAD was combined with the ABAQUS FEA program to determine strain energy density concentrations for a suspension mount for a heavy truck [36]. The mount, which consisted of a column of equally spaced plates and rubber, was adjusted until FEA results showed acceptable stress levels thought the mount.

Ten different models for a suspension strut mount could be examined in a day and a half using 2-D FEA [37]. These were followed by a complete 3-D model for the whole mount that incorporated all the refinements and reduced the maximum principal stress by a factor of 2.5. The activity resulted in a 15 to 20-fold increase in mount life.

The rubber in tube-form suspension mounts for automobiles deforms when under axial, conical, or torsional loading in service [38]. Axial loading permitted the use of standard axisymmetric load elements that significantly reduced the need for computer resources. Good agreement was obtained between axisymmetric and 3D analyses.

Silentblocs are tube-form bushings widely used in the suspension systems of automobiles [39]. An attempt to use a linear isotropic material model with a 0.48 value for Poisson's ratio failed because of numerical instability. The incompressible elements successfully predicted the stress distributions of the rubber insert in the assembled configuration. A second design of the bushing provided a more even stress distribution and increased fatigue life.

Dock Fender

One type of dock fender is a large block of rubber that is designed to buckle at a large compression load and thus absorb the energy of a ship striking the dock [40]. Analysis of the buckling characteristics of a fender showed excellent agreement with experimental data.

Engine Mounts

Engine mounts that deform in shear or compression offer the advantage of providing different spring rates in two perpendicular directions, and a third stiffness in the vertical direction [41]. Dynamic and static spring rates of engine mounts determined by FEA can establish the effectiveness of a specific design in isolating vibrations caused by engine idle, engine bounce, and other undesirable modes of engine vibration

Analyses were directed toward reducing vibration that occurred at idle speeds of about 600 rpm [42]. The first of two options to reduce vibration was to decrease fore and aft dynamic spring rate, an option not selected, because it increased vibration during vehicle acceleration and deceleration. The second option involved the use of a liquid-filled engine mount on the right side.

Two-dimensional plane strain conditions were used in the analysis of engine mounts [43]. Rubber legs on the mount that transmitted engine weight and vibration from the inner metal to the outer metal box were modeled using incompressible elements. FEA identified and located high stresses and predicted crack formation locations.

Human Exposure to Vibration

A human body was modeled as a simplified mechanical system represented by a series of springs and dashpots [44]. Distinct resonances occurred with different body parts, e.g., the hips, shoulders, and head, when excited in the 3 to 6 Hz region. In another example, space crew's eyeballs wobbled to the extent that they experienced difficulty in reading instruments during launching of spacecraft orbital flights. A 50-Hz vibration in the launch vehicle caused the problem [45].

Conveyor Belt Splices

To simulate a conveyor splice, specimens were prepared that consisted of four steel cables extending from one end of an elastomer block and one single center cable extended from the other end [46]. Based on experimental work with these specimens and additional work, it was concluded that FEA could be a useful tool for conveyor belt design.

Windshield Wiper Blades

FEA was used to design windshield wiper blades to predict the contact angle for a given applied load and coefficient of friction [47]. A 2D analysis of different sections allowed new designs to conform to proven characteristics and to permit adjusting length and width trimming operations.

Another FEA analysis of windshield wiper blades assumed frictionless sliding of blades [48]. During sliding, the top surface was fixed and attached to the finite element model at the top of three nodes and the model demonstrated that nonlinear FEA could be effectively used as a design tool.

Air Spring

Some axisymmetric rubber components can be analyzed using a 2D analysis rather than a 3D analysis [49]. An example is a thin-walled, reinforced rubber air spring, which was analyzed using shell elements that assume plane stress conditions. The 2D representation reduces the model size so that even a small workstation could run the analysis in only several minutes.

Automotive Door Seals

FEM, used to analyze the complex geometry of automotive door seals, provided useful insights and increased efficiency in seal-section design [50]. It was concluded that FEM provides the flexibility that is difficult to obtain by other methods.

Automotive Window Seals

Special seal software shortened the time required to design automotive components [51]. It simulated the operation of a window seal and significantly shortened the product development cycle for a glass run channel fabricated from thermoplastic rubber for a midsize vehicle. It shortened the time to evaluate design concepts and obtain an optimal design.

PC-based seal analysis software produced better seal designs and significantly shortened the lead time to produce final window seals [52]. A CAD system modeled the geometry of the seal and the surrounding sheet metal and the resulting data were imported into EASi-SEAL, a program that supported the design of multi-hardness seals.

Radial Lip Seals

Automotive engines and transmissions must retain radial lip seals in their housings if they are to perform satisfactorily [53]. FEA examined the interference between the seal O.D. and the housing I.D. It predicted the highest compressive stress occurred along the seal-to-bore interface and the calculations proved superior to calculations based on press-fit and thermal-expansion.

FEA attributed the successful operation of a radial lip seal to factors that included the mechanical strength of the rubber and the service conditions [54]. The analysis further indicated that seal formulation was consistent and that material contamination or degradation did not play a role in the observed failures.

Dishwasher Seal

Seal design modifications included elimination of the wall below the sealing lines, adding beads, and redesigning cleats [55]. Material testing and computer analysis, which took three weeks, resulted in a seal that incorporated 25% less rubber.

Keyboard Spring

Dome-shaped elastomer articles serve as springs on keyboards that must snap through their skirt when pressed [56]. It is desirable that the springs click when pressed. Abaqus software was able to solve this difficult problem. The software produced plots of stress upon key depression.

Buckling or surface folding, or a stiffness mismatch, is generally indicative of a potentially poor spring design that can lead to fatigue problems [57]. Peak strains for spring designs were found to be less than 70%. Combining FEA with the full continuum-constitutive-boundary formulation can successfully solve problems associated with buckling and postbuckling of elastomeric structures.

Hose

FEA use to examine stresses in hose greatly reduced the need for testing of hoses that transferred oil from a seabed to tankers and it significantly replaced traditional empirical methods [58]. It also resulted in reduced design time, improved hose reliability, higher burst pressures, and improved performance in dynamic fatigue tests.

Inflatable Dams

Inflatable dams have often been cost effective for temporarily or permanently blocking a water channel [59]. FEA helped to model dams and provide data from a scale model that confirmed the validity of the computer model. Engineers were able to bring within normal limits the reinforcing cord stress of the fabric in the dam.

Inflatable Beams

These can be inflated on site to replace bridges that enemy action might have destroyed [60]. They function in a manner similar to a pneumatic tire in that a high-modulus cord is prestressed by a pressurized flexible rubber matrix. Aramid cord, applied in three directions in the composite, makes the beam resistant to forces in bending, torsion, and compression.

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7 Non-Tire Products

The rubber industry produces myriad products that can be broadly classified as either non-tire or tire. Tires are discussed in the next chapter. Many of these products are complex and incorporate a number of materials and are fabricated by various techniques. Common to both tire and non-tire products is the need for good adhesion between components.

7.1 Adhesion

Adhesion among materials (rubber, metal, fabric, plastic, etc.) is important for satisfactory product performance, especially for products that undergo high stress. A number of compounding factors affect the level of adhesion [1]. These include: elastomer type, process oil, antidegradants, and cure systems. Since rubber co-vulcanizes with adhesives or adjacent rubber compounds, it is important that the rubber be scorch-free prior to bonding. A study concluded that the curing system in a rubber compound significantly affects adhesion [2]. Curatives can migrate from a rubber compound into an adjacent layer, e.g., the dip that coats a cord, and increase the curative concentration in the dip at the compound-dip interface.

Some bonded products can be released from their mold only with difficulty. Removal of a bonded article from its mold can cause excessive force at the bond line and result in a flaw [3]. This flaw can propagate and potentially cause a product to fail. Because bond strength at molding temperature is generally less than that at use temperature, relevant temperatures should be used when testing for adhesion.

Figure 7.1 shows the effect of test temperature on bond strength for an NBR compound tested in 90° peel over a test temperature range of 73 to 400 °F [4]. The higher temperature decreased bond strength by more than an order of magnitude. Among other process factors that can adversely affect adhesion is oil in air lines used to spray adhesives [5].

Numerous commercially available adhesives successfully meet the bonding requirements of most manufactured products. These can be supplied as water- or solvent-based systems, with the latter consisting of small dispersed particles (micelles) that coalesce on drying to form a bonding layer [6]. Adhesive coat thickness for primers typically ranges from 7 to 13 µm, the thickness for cover coats is typically 20 µm [7]. Rougher surfaces require more adhesive agent to ensure that the peaks are covered.

A commercial adhesive may be unavailable for some specialty applications. An example is a polysulfide-epoxy trowelable compound that bonded to prevulcanized NBR to form a composite. The composite was used as thermal insulation in a solid rocket at a service temperature of 5000 °F [8]. Testing the bond quality between the trowelable compound and the NBR required use of the special adhesion specimen shown in Fig. 7.2.

An epoxy adhesive bonded the prevulcanized NBR to the steel specimen and the trowelable insulation that filled the 'V' groove bonded to the NBR. During testing, force applied to the

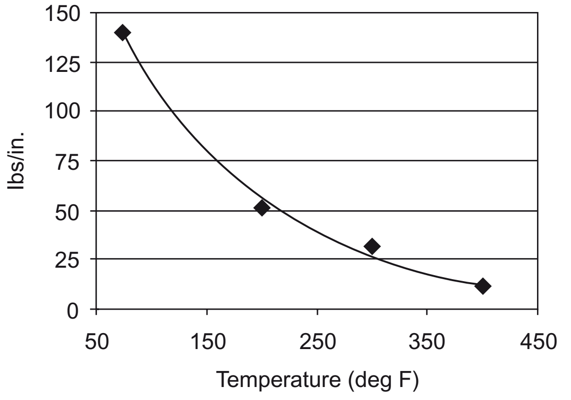

Figure 7.1 Effect of test temperature on bond strength (90° peel)

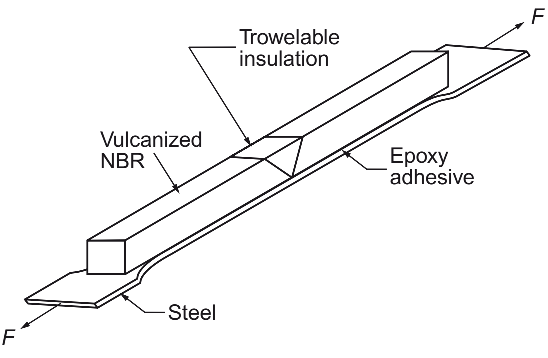

Figure 7.2 Schematic of composite specimen designed to test adhesion

steel specimen stretched the composite to simulate the strain level experienced by the rocket case upon ignition of the propellant. Test results showed that adhesion between the vulcanized NBR and the trowelable insulation was adequate.

Lesser demands are ordinarily placed on adhesives than those described in the above example, especially with respect to temperature. While either prevulcanized or unvulcanized rubber can be adhered to a wide range of materials, the bonding of unvulcanized rubber is most common. Higher bond values are generally obtained with unvulcanized rubber. Good practices must be conducted in either case to maximize adhesion. Unvulcanized rubber is often bonded to steel. A typical procedure for bonding rubber to steel using a two-coat adhesion system during compression molding is described in the following [9]:

- Clean the steel surface, either by chemical or mechanical means
- Apply a suitable metal primer to the steel surface
- Apply an adhesive to the dry surface of the metal primer
- Place the rubber against the top coat and bond the assembled components using heat and pressure

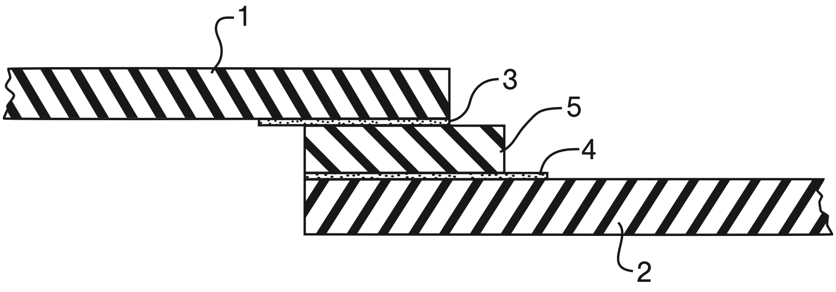

Figure 7.3 EPDM roofing membrane bonded with seaming tape:
1, 2 membrane; 3, 4 primer; 5 seaming tape

Blasting with grit is a common mechanical means to clean the surface of metallic materials [10]. It is simple to perform and provides a good surface for bonding. The first step is to provide an oil- and oxide-free surface for bonding, obtained by vapor degreasing or alkaline cleaning of a steel part to remove drawing oils and organic contaminants. Blasting with steel shot or aluminum oxide follows this step. Then, the metal may be again vapor degreased or alkaline cleaned to remove contaminants that could have deposited on the metal surface from the blasting material.

The pH of the vapor degreasing solvent should be monitored to avoid the build-up of acidic residues [11]. Use of a primer with either grit blasting or phosphatization substantially improved environmental resistance. However, compound variation can negate this effect [12]. Technologists should review the literature available from manufacturers of commercial adhesives to maximize success in bonding.

Rubber (mainly EPDM) in sheet form is widely used as roofing on structures, mainly commercial buildings. Adhesives or seaming tapes can join rubber sheets to form a waterproof seal. Figure 7.3 shows the sheets joined by a seaming tape [13]. The tape is a lightly crosslinked blend of butyl rubber and a polyisobutylene that can exhibit a peel strength of 2.5 pounds per lineal inch at about 158 °F. Adhesion tests are run at higher temperatures to approximate the temperature of a sun-heated roof.

TPO roofing, more recently available in 10-foot wide sheets, can be self-adhered [14]. Bonding is done by heat welding to form very strong seams [15].

7.2 Hose and Belting

Hose and belting represent bonded rubber products that are generally reinforced. Hose serves as a flexible connection means in modern engineering to transmit large forces or convey fluids at high pressure. The yarns and fabrics used to reinforce hose and belting must adhere well to rubber in addition to meeting other requirements. Table 7.1 lists several product types along with their requirements and representative reinforcing materials [16].

Table 7.1 Yarn and Fabric Requirements for Different Products

Product	Product requirement	Reinforcement
Air conditioning hose	Resistance to chemicals, high pressure	Aramid
Hydraulic hose	High tenacity	Aramid, PVA
Power transmission belt, timing belt	High tenacity, low elongation	Glass

Hose can serve a secondary function, e.g., damp vibration and noise from a power steering pump [17]. Complex rubber composites are increasingly being fabricated for a range of applications [18]. In addition to adhesion among components in composites, other important factors are:

- Differential coefficient of expansion among components
- Different relaxation behavior during dynamic stressing
- Local states of tension at interfaces

7.2.1 Hose

The RMA Hose Handbook describes many types of rubber and plastic materials, fibers, reinforcing cords, and manufacturing and vulcanization methods [19]. It lists elastomers such as CR, NR, IIR, NBR, FKM along with some of their properties, such as resistance to solvents, ozone, and aging. Plastics used in hoses include nylon, polyethylene, polyvinylchloride, polyester and fluorocarbon. Fibers include cotton, rayon, glass, nylon and polyester.

Different types of rubber compounds respond differently to various fluids. Ideally, a hose would tolerate a range of fluids while maintaining acceptable swelling characteristics and other properties [20]. For example, one hose can handle not only biodiesel fuel but also ethanol and gasoline [21]. The cover on the latter hose resists degradation from fuel blends and also resists abrasion. The hose inner tube helps resist swelling, softening, and cracking that may be caused by alternative fuels. Helix wire reinforcement reduces risk of hose collapse for hose used under vacuum.

Turbocharger hoses are required to operate under increasingly harsh chemical environments, in addition to higher temperatures and pressures [22]. To meet these demanding requirements, hose typically consists of a layered construction that can incorporate several different rubbers, e.g., a fluoroelastomer liner and a silicone cover. Single or multiple layers of a high-temperature fabric such as aramid reinforce the hose assembly.

A number of fabric weaves are available to meet specific hose requirements. Reinforcing wire is used in a range of hydraulic and industrial hose to satisfy high-pressure requirements. Even cotton fabric can impart substantial resistance to high pressure as evidenced by an air brake hose that withstood 900 psi pressure [23]. Other hose properties of importance include flexibility, bend radius, and electrical resistance.

A patent describes the construction of vehicle brake hose [24]. Figure 7.4 shows multiple-layers consisting of an inner tube, first and second reinforcing layers, an adhesion layer, and an

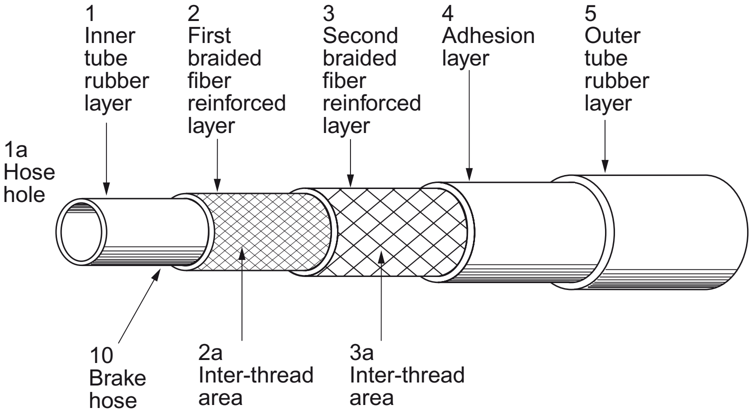

Figure 7.4 Brake hose construction for a vehicle

outer-tube rubber layer. An adhesion layer bonds the first and second braided fiber reinforcing layers to the outer tube rubber layer.

Hose should be capable of conforming to the smallest anticipated bending radius without becoming overstressed [25]. Static wires and conductive rubber components are used in some hose to dissipate electrical charges that could be hazardous around flammable liquids. In contrast, non-conductive hose is used around power lines for reasons of safety. It is critical that hose in these specific applications be identified appropriately.

The three principal methods of manufacturing hose are: non-mandrel, flexible mandrel, and rigid mandrel. Non-mandrel hose, formed by extruding a tube and cover without a mandrel for support, is generally used at working pressures of less than 500 psi.

Flexible-mandrels are used to manufacture hose with more accurate dimensions. They can be fabricated from rubber, sometimes with a wire core to minimize distortion.

The rigid-mandrel method is used for larger size hose when flexible mandrels become difficult to handle. Rigid cores are usually aluminum or steel.

7.2.2 Belts

These can be broadly classified as V-belts and conveyor belts. V-belts transmit power or motion between V-shaped sheaves [26]. They provide dependable service life, are an economical means to vary speed ratios of motion devices, and they require only low maintenance. Different V-belt designs are described in the following:

- Ribbed belts that have fabric-faced V's, V's reinforced with short fiber that are subsequently ground, and V's that are molded with short fiber flock on their face.
- V-belts with a cut edge.
- V-belts that are wrapped with one or more layers of fabric.

Variable-speed V-belts for snowmobiles place severe demands on belt design that differs substantially from those for most industrial belt applications [27]. Aggressive snowmobile riding twists the frame and causes significant component misalignment.

Twelve essential properties are considered necessary to meet the original criteria for automotive timing belts [28]. Among these are: flex crack resistance, hardness at low and high temperature, and heat and ozone resistance. It was concluded that an HNBR compound exhibited the best overall properties that are required for high operating temperatures in a modern automobile. Timing belts containing HNBR must operate satisfactorily at temperatures up to 140 °C and resist the effects of motor oils and fuel [29]. Higher operating temperatures are projected. A popular construction consists of a glass-fiber reinforcing layer and a nylon friction face. Glass fiber replaced the steel in CR belts used earlier because of its longer flex life.

V-belts, cured under tension that approximates the tension experienced in service, provide tighter dimensional control [30]. Rotary vulcanization is said to aid V-belt quality. Factors occurring during V-belt processing can significantly affect adhesion of RFL (resorcinol formaldehyde latex) treated cords [31]. For example, RFL treated cords exposed for only two days to ultraviolet rays retained only about 20% of their original adhesion value.

Serpentine belts have essentially replaced V-belts in automotive applications wherein a single serpentine belt replaces several V-belts, resulting in reduced weight [32]. A serpentine belt, driven by a crankshaft pulley, drives accessories such as the alternator, air-conditioner compressor, and the power steering pump. Projections on the timing belt register with corresponding depressions in the crankshaft pulley and accessories, an important feature for timing belts. Failure of a timing belt can cause loss of synchronization between valve and piston motion, with catastrophic results [33].

Rubber belts used in aircraft recorders must function over a wide temperature range because they can experience temperatures as low as –55 °C, and as high as 71 °C [34]. Silicone rubber belts meet these requirements along with stress relaxation requirements [35]. Equations provide information for sizing pulleys for belts and for O-rings that serve as belts [36]. O-rings are especially useful for light drives, because they are readily available in a wide range of sizes.

Conveyor belts are the most economical means of transportation over long time periods, especially when compared to other means such as truck transportation [37]. They are used extensively in mining operations to convey materials and minerals. Changes in reinforcement – from rayon in the 1950s to nylon in the 1960s – improved belt durability and extended belt life. The fiber or fabric reinforcement in these belts provides the strength necessary to transmit power to drive the conveyor and support the load on the conveyor belt [38]. Polyester's high strength-to-weight ratio and nylon's good fatigue resistance, make these fibers particularly suited for a wide range of belts.

Conveyor belt characteristics vary widely. A belt used in coal-mining operations in England is 6.5 miles long, four feet wide, and 1 inch thick [39]. Among safety concerns with conveyor belts in mining operations are belt slippage and flammability. A stringent test in the UK requires that a stationary belt be held in contact with a rotating drum until the belt breaks without it producing flame or glow [40]. Full-scale burning tests that involve burning wood under a belt are required for new belts [41]. CR in belts is said to be preferred because of its inherent flame retardancy.

Rubber used in conveyor belts for the tar-sand mining in Canada has special demands placed on it [42]. It must resist swelling by the tar sands and possess good low temperature properties – two properties that are difficult to achieve in the same compound. Low acrylonitrile NBR provides the desired combination of properties.

7.3 Mountings, Bearings, and Bushings

7.3.1 Mountings

Natural rubber is widely used in mountings because of its unique combination of properties. It provides high strength, outstanding fatigue resistance, high resilience, low sensitivity to strain effects in dynamic applications, in addition to good resistance to creep [43]. It is among the few elastomers that crystallize upon straining, a phenomenon that contributes to its high fatigue life and its high strength without the need for reinforcing fillers. Hence, NR compounds can exhibit a combination of low modulus, high strength and fatigue resistance, and very low damping.

Engine mounts operate in increasingly hostile environments, e.g., engine temperatures are reaching 130 °C near the catalytic converter on an automobile, and even higher temperatures are anticipated [44]. Higher temperatures necessitated the use of expensive silicone rubber in selected automotive engine mounts [45]. Decreasing space for ventilation and heat shields cause further temperature increases in engine mounts.

Service temperature can vary both among and within mounts as evidenced by an engine mount that failed on the author’s station wagon. Shore A Hardness measurements on the failed mount ranged from 70 to 88, with the highest value occurring in the rubber nearest the exhaust manifold. This result indicates that different locations within the failed mount experienced substantial temperature differences. Because spark plug wires can experience different temperatures at different locations in an engine compartment, more expensive elastomers might be used for the hottest cylinders [46].

Engine mounts on jet aircraft must withstand stress from sources not experienced by automobiles [47]. For instance, engine mounts for the Cessna CJ3 aircraft had to withstand engine damage equivalent to two birds flying into an engine’s fan blade without failure.

Continuing changes in technology dictate changes in product requirements. For example, adhesion systems for automotive engine mounts formerly did not require resistance to ethylene glycol [48]. With the introduction of mounts that contain ethylene glycol in chambers to control dynamic properties, new adhesives were developed that provided the needed glycol resistance.

Some engine mounts that incorporate hydraulic fluid such as ethylene glycol have significantly reduced the compromise between engine bounce and engine isolation [49]. The mounts provide high damping at low frequencies and low damping at high frequencies. They do this by transferring a hydraulic fluid through an orifice between mount chambers that controls engine bounce [50].

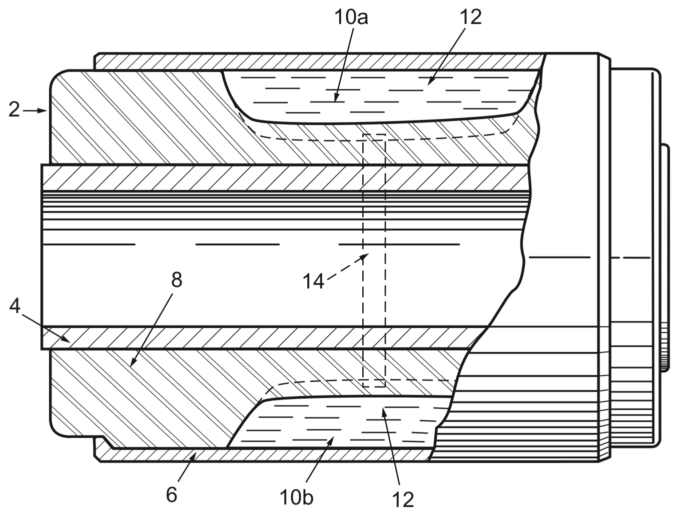

Figure 7.5 High-damping resilient rubber bushing

Figure 7.5 illustrates a bushing that transfers fluid through an orifice 14 between chambers 10a and 10b [51]. The fluid provides high damping in the radial direction. Various types of orifices or tubes can be used to vary damping properties of the bushings. The manufacture of the more complex hydraulic mounts required the development of new processes and techniques [52].

Magneto-rheological fluids encased in a shock absorber for vehicle seat damping represent another advance [53]. They consist of suspensions of minuscule magnetizable particles in oil that soften or stiffen upon reacting to magnetic fields.

7.3.2 Bearings

Suspension bushings (Silentblocs) are widely used on automobiles to reduce shock, noise, and vibration and to accommodate misalignment. They comprise a hollow rubber cylinder located between inner metal and outer metal sleeves. The rubber cylinder can be bonded in place during molding or it can be molded and then inserted between the inner and outer metal sleeves in a separate operation [54]. Figure 7.6 shows a rubber insert before and after forming the assembled bushing.

Squeezing the insert into place typically results in a about a 100% elongation of the cylinder. A strong mechanical bond is formed between metal and rubber as the rubber tries to retract upon release of the deforming force. The prestressed rubber increases the load-carrying capacity of the bushing in torsion and in the radial and axial directions.

Durability is a major performance requirement for Silentbloc bushings. Using an energy balance concept (energy available vs. energy required to extend a tear), a model was developed that agreed with tear results [55]. Silica filler is now replacing some of the carbon black typically

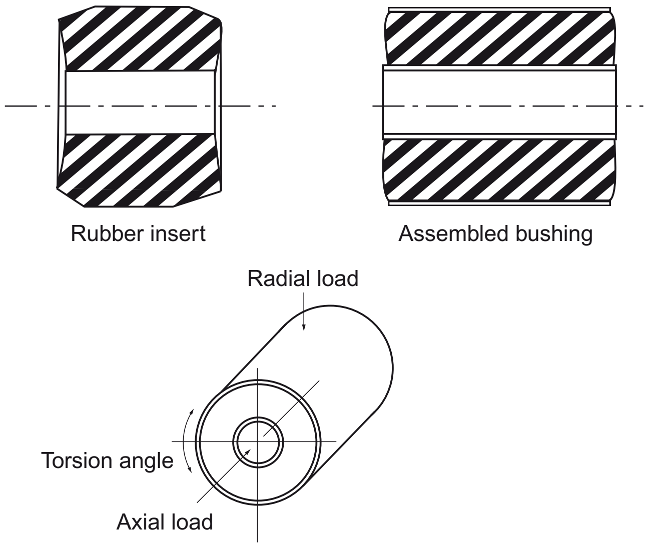

Figure 7.6 Silentbloc showing rubber bushing between inner and outer metal sleeves

used in bushings [56]. This change in materials illustrates the transfer of compounding technology from the tire sector to the non-tire sector

Certain *p*-phenylenediamine additives can cause slippage at the rubber-metal interface of non-bonded bushings and promote premature failure [57]. Hence, excessive amounts of additives that bloom to the rubber surface should be avoided.

Silentblocs have no sliding surfaces and therefore do not require protective sealing from the environment [58]. They serve as pivots and are capable of withstanding relatively high static and dynamic loads in service. The ratio of dynamic to static stiffness ranges from about 1.2 for low-damping compounds to 2.6 for high-damping compounds. Maximum oscillations are typically limited to ±40°. Smaller automobiles require bushings with lower spring rates that can be obtained by designing voids in the rubber insert. The voided inserts can be bonded to metals using a post-bonding (PV) process that minimizes deformation during the assembly process.

Elastomeric bushings experience more severe service on vehicles such as tracked military vehicles [59]. Rubber molded onto steel pins forms a bushing that is inserted into a track using about 35 to 40% compression. Bushing failure occurs on the loaded side of the bushing, with cracks initiating on the inside surface of the pin. A model was developed to predict bushing failure.

Over 30 grease fittings were needed to lubricate bearings in some early helicopters [60]. Replacement of metal bearings with elastomeric bearings represented a substantial improvement. Tiltrotor bearings replaced mechanical bearings on the V-22 tiltrotor aircraft [61]. These NR bearings must meet a range of technical demands that include: operation between –53 and +54 °C, no need for lubrication, provide a minimum service life of 2500 hours, with a duty cycle of 70% airplane/30% helicopter, and operate for 2500 hours minimum without loss of

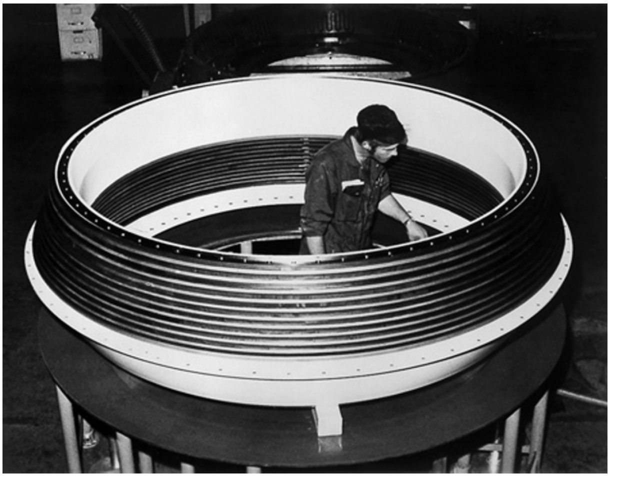

Figure 7.7 Final inspection of a rocket nozzle bearing

bond between rubber and metal. Some tiltrotor bearings incorporate 49 rubber layers bonded and vulcanized between 48 shims.

Bearing life depends on strain that is maximum at the smallest bearing diameter [62]. Since the bearing is constructed of separate layers of rubber, each layer can have a different modulus and result in a design with increased bearing fatigue life. An alternative is to vary thickness of the rubber layers. Hence, one can optimize the shape factor for each section of the bearing. However, these approaches can substantially complicate the molding of bearings.

Figure 7.7 shows final inspection of the very large nozzle bearings (rubber-metal laminate) used on solid rockets for the space shuttle [63].

Considerable attention was given to the temperature required to obtain the needed level of adhesion between the steel elements and the rubber during a 12 hour molding cycle. The 40,000-pound mold assembly was fitted with over 100 thermocouples. Flow control of the compound during molding was an especially difficult problem that was solved by providing split rings on the I.D. and the O.D. of the mold (see Fig. 7.8). The split rings allowed excess rubber to exude directly from the mold and to better control rubber distribution.

Air springs, used on a range of vehicles that include automobiles, trains, trucks, and buses, offer several advantages over steel and conventional rubber suspension systems. They are essentially reinforced bellows inflated with a gas [64]. When used in an automobile leveling system, they maintain the automobile in the intended design position independent of the load. In high-speed trains, they provide extremely comfortable rides.

In a newer process to manufacture air springs, single, separate polyamide fibers reinforce an injection-molded tube. The fibers replace the cross-ply arrangement of two layers of fabric traditionally used for reinforcement [65]. The fibers are positioned with precision in one direction only along the length of the rubber cylinder that forms the body of the spring. This construction eases expansion of the rubber tube relative to conventional fiber reinforcement. Advantages include lower weight and more compact springs.

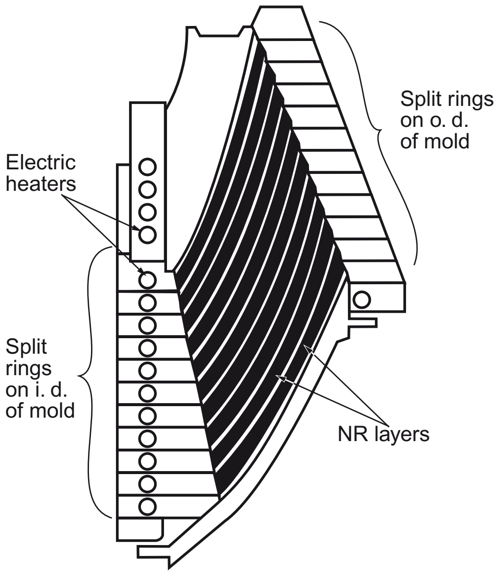

Figure 7.8 Cross-section of a rocket nozzle bearing in its mold

7.4 Energy Storage and Dissipation

Energy storage capability of materials such as a spring steel, music wire, and different types of rubber ranges widely [66]. Model airplanes that are powered by twisted strands of rubber serve as a familiar example. On a larger scale, twisted columns of rubber can store large quantities of energy for release in small vehicles such as mopeds [67]. The energy stored can be subsequently released to restart a moped. Regenerative braking is potentially applicable to larger vehicles such as garbage trucks that make frequent stops and starts [68]. It could result in significant energy savings.

Bungees (rubber ropes) are used in a variety of applications that include propulsion for test sleds and scale model vehicles [69]. Bleriot used a bungee on his monoplane when he made the first over-the-ocean flight in 1909. Bungees continue to be used today on light planes such as the Piper Cub.

A quarter-scale, rubber-band powered airplane has already flown [70]. A full-scale plane is under construction. It is to be powered by 800 each 25-foot long strands of model airplane rubber configured in a loose bundle as large as a man's thigh. The stretched bundle, expected to provide 18 horsepower, will be lubricated to prevent its self-destruction from friction.

7.5 Rolls

The roll covering handbook published by the RMA provides much information on rubber-covered rolls [71]. It describes factors that include: the elastomer used in covering rolls, associated properties, chemical and solvent resistance, factors influencing hardness, and roll cores and bearings for cores. Producers of metal sheets use rubber-covered rolls to transport metal sheet through finishing operations. The paper industry uses rubber-covered rolls in applications such as aligning web or sheet, and removing liquids by means of an active nip between rolls.

Rolls used in these myriad applications can be as soft as JELL-O or as hard as a bowling ball [72]. Resistance to abrasion and cuts and maintenance of hardness are properties of interest for rubber rolls used in the printing industry. For application at high temperatures, silicone rubber is said to offer the best resistance. Some rolls are truly massive – as large as four feet in diameter and forty feet long and they can rotate with lineal speeds up to 60 miles per hour in environments that are abrasive and caustic.

Rolls traditionally were fabricated by building up calendered sheets of rubber onto a rotating mandrel. After building the sheets to the desired diameter, rolls were ground to their final diameter. By a newer building method, rubber strips are extruded onto a rotating mandrel that moves axially [73]. Alternatively, a traversing strip of rubber can be built up on the rotating mandrel (stationary axially) until the desired thickness is obtained. The cross section of the strip that is placed onto the mandrel can be in the shape of a rectangle, trapezoid, or a parallelogram.

Modern strip building systems should be capable of applying ribbon in both directions in either a single-pass or a multiple-pass operation. Adjustable ribbon pressure during rubber application accommodates changes in wall thickness and/or mandrel diameter.

Rubber rolls were built traditionally from TSEs that required vulcanization after fabrication. Many are now fabricated from TPEs on newer machines and these will complement TSE rolls [74]. Large TPE rolls present special manufacturing problems caused by uneven cooling [75].

7.6 Seals

Rubber seals are widely used on vehicles and in myriad other applications. They must seal a wide range of fluids and operate in adverse temperature and chemical environments. The compliance and elasticity of rubber seals enable them to conform to irregular surfaces under both static and dynamic conditions. Static sealing causes a one-time deformation of a seal in contrast to a dynamic seal that is deformed frequently in service [76]. For example, a lip seal must accommodate the movement of a rotating shaft even if the motion is eccentric. Although relatively cheap, many seals find use in highly critical applications where seal failure can result in high costs and/or loss of life [77].

It is sometimes thought that lower fluid swell of a rubber seal is always preferable in a seal application [78]. Some swelling of a rubber seal in a static sealing application is beneficial

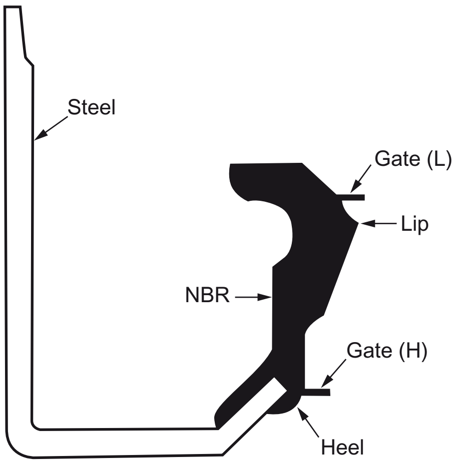

Figure 7.9 Location of heel and lip gates on a lip seal

because controlled seal swelling by a fluid increases sealing pressure. If the fluid has good low temperature properties, low-temperature resistance of the rubber compound improves as the fluid plasticizes the compound.

Location of the gates in an injection mold for lip seals can affect service behavior of seals formed in a mold [79]. Figure 7.9 shows gate locations for heel- and lip-gated seals. In tests of these seals, heel-gated seals leaked after only 15 to 18 minutes. Their lip-gated counterparts remained leak free even when tested for as long as 300 hours. Sophisticated tests run on the seals did not completely establish the cause for the observed behavior.

7.6.1 Pump Seal

A pump seal for a windshield washer formerly incorporated a two-piece assembly: a CR seal and a separate metal screen [80]. The screen was inserted into the seal in a separate operation. Changing from CR to TPE allowed a one-piece seal to be made, i.e., the screen equivalent was molded in the base of the seal. Further, the change lowered cost by more than 50%. Figure 7.10 compares the CR and TPE seals [81].

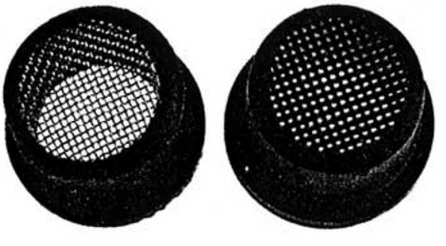

Figure 7.10 Windshield washer pump seal: CR with brass-screen insert, left; TPE, right

7.6.2 Automotive Transmission Seals

EVM vulcanizates are suitable for a range of applications, such as vibration torsional dampers, hoses, and automotive transmission seals [82]. Advantages in the latter application include excellent compression set resistance without requiring a post cure, good mechanical properties over a range of 50 to 80 Shore A hardness, a range of oil-swell resistance capabilities, with the higher vinyl acetate grades providing the best resistance. A compound based on 70% vinyl acetate EVM demonstrated the best balance between sealing force and retention force after six weeks aging in oil at 150 °C.

7.6.3 Casket Seals

One would think that rubber seals that seal tightly are desirable for all applications. Not necessarily so. In an anaerobic environment, bacteria devour soft tissue and alter the decay mechanism of a corpse. Some burial services specify that a seal not be used because a seal in a mausoleum hastens deterioration [83]. Cemeteries want air access to the casket interior.

7.6.4 Automotive Door Seals

Injection molded corners are now tightly bonded to TPV sponge extrusions for glass run channels and primary body seals [84]. Cost savings for processing are said to offset the higher cost of TPV relative to the more traditional TSE materials. Simplified fabrication and lower scrap loss for the TPV also favors lower costs. Cycle times of approx. 2 minutes for TSE corner moldings are reduced to 30 seconds when TPV is used [85]. Further, it is easier to fabricate a flash-free mold for TPV.

A patent describes an automotive door seal that is said to exhibit excellent noise insulating properties between a vehicle body and a door of a motor vehicle [86]. Figure 7.11 shows a cross-section of the seal that is said to require only a small door-closing force. The 'U' shaped channel attaches the seal to the door and the cellular bulb on the right seals against the vehicle body.

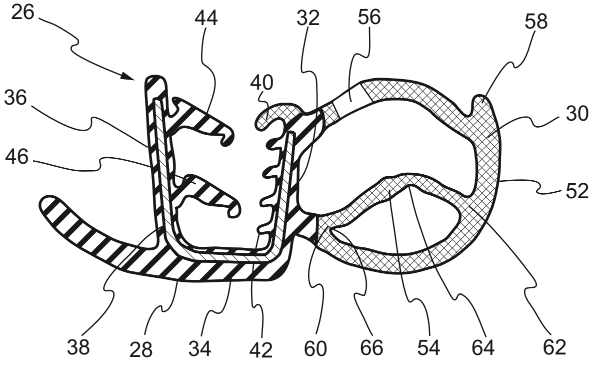

Figure 7.11 Cross-section of automotive door weather strip

Greater emphasis is being placed on the aesthetics of automotive rubber articles, such as surface appearance and seal color [87]. Exposure to sunlight can change the color of some automotive door seals; iridescence can appear in EPDM seals exposed to ozone and UV light from sunshine. Special siliceous-earth fillers incorporated in EPDM compounds are said to reduce iridescence in seals.

Colored seals offer the potential for matching seal color to the color of an automobile interior. They can be made by coloring a seal compound throughout or by coating a conventional seal (typically black) [88]. As with other automotive products, form sometimes supersedes function and results in increased inventory and cost. Coating offers the advantage of minimizing the inventory of seal compounds.

Compounding ingredients can cause undesirable discoloration and staining in seals and other rubber products [89]. Discoloration is defined as an undesirable color change that can occur in rubber compounds during processing, in the finished product during storage, and in service. Staining is the development of color or discoloration caused by a material that the rubber contacts or is close to. Compounding ingredients or their reaction products can diffuse or transfer from a rubber compound to a surface – e.g., an ingredient that diffused from the spare tire of a car substantially stained the paint in the wheel well in which it was stored.

7.7 Other Applications

Tennis Balls

Tennis ball manufacture involves three separate steps: molding hollow hemispheres (halves), pressurizing and bonding the halves at their equator to form a hollow ball, and then covering the resulting ball with fabric [90]. In step one, a tool positions accurately weighed preforms into the multiple cavities of a compression mold that then shapes the preforms into halves. After crosslinking, the flash that joins the halves facilitates their removal from the mold as a sheet. After grinding the flat equatorial surfaces of the halves, adhesive is applied to the ground surfaces.

The halves are then placed in the spherical cavities of a special mold that can be internally pressurized with a gas – typically air. The adhesive surfaces of the halves are mated and heated to bond the halves together, followed by cooling the mold. The surface of the pressurized ball is abraded, coated with an adhesive, and then covered with a fabric that is edge coated with a rubber compound. Covered balls are cured in a compression mold in the final step, taking care to orient the joints between edge-coated fabric to minimize the length of the seam at the mold parting line, i.e., the ball is inserted in the mold with seam perpendicular to the parting line.

Rubber Lining

A number of industries use rubber lining for its advantageous properties that include abrasion and chemical resistance. The mining industry employs modular rubber units in grinding mills that are said to be much easier to install than conventional steel lining [91]. Rubber lining can often be made thinner than other types of lining which results in a increased capacity in the grinding unit [92].

Other applications for rubber lining include: pipes for gravel pumps, ball mills, and linings for chemical tanks [93]. Lining, conventionally made by calendering, can also be produced by roller-head extrusion for use in tank cars [94]. The processing change from calendering to extrusion is similar to that used to fabricate flat sheets for rubber roofing.

With increased emphasis on legislation and environmental concerns, greater priority is being placed on the reduction of emission of hazardous gasses such as sulfur dioxide. Bromobutyl rubber is used to line and protect steel scrubber towers that are used to remove sulfur flue gasses [95]. Unlined steel in this application would rapidly corrode.

Expansion Joints

Pipe movement and rupture significantly increase costs during in-plant operations [96]. Fabric-reinforced rubber expansion joints accommodate pipe movement in axial compression and elongation, as well as in transverse and angular movement. Rubber expansion joints are recommended for piping systems at temperatures up to 250 °F.

Hood Stops

Screw threads are only rarely molded on conventional rubber products [97]. Adjustable hood stops on automobiles that incorporate screw threads are an exception. These hood stops, formerly made as a steel-rubber composite, are now fabricated from thermoplastic rubber (see Fig. 7.12) because they offer advantages of reduced weight and simplified manufacture.

Figure 7.12 Hood stops for automobiles

Windshield Wiper Blades

Wiper blades must conform to a windshield surface, reverse the angle of layover on the reverse wipe, and have a low coefficient of friction against glass [98]. Blades on earlier automobiles were required only to wipe a flat windshield, a considerably easier task than wiping the curved surfaces on modern automobiles. Regardless of the windshield type, low friction is desired to minimize the size of the wiper motor.

Wiper blades were traditionally made by molding, slitting a blade along its long axis to produce sharp wiping edges, and then chlorinating the slit edge to reduce the coefficient of friction. Teflon, co-extruded with NR is a newer approach to reduce the coefficient of friction [99].

Extrusion of blades is now a major fabricating method because it eliminates the need for expensive molds [100]. Wiper blades made from a synthetic alloy-grafted polymer have a hydrophobic effect that beads the water on the windshield [101]. They change the water molecule's surface tension and cause the water to form as a sheet that can more easily be swept away. Some windshield wipers now sense moisture and turn on wipers automatically.

Fuel Tanks

Technical requirements for rubber fuel tanks for fighter aircraft are especially rigorous [102]. The very low temperatures associated with high altitude stiffen the rubber used in cells that contain aircraft fuel. Embrittlement caused by low temperature, combined with a rapidly traveling bullet favor cell penetration (a 10 °C decrease in temperature is approximately equivalent to a decade increase in frequency). Hence, elastomers with good low temperature properties must be used. To prevent fuel leakage, a rubber compound that swells is included in the tank to close the opening caused by a bullet that penetrates the fuel-resistant member of the composite.

Oilfield Applications

HNBR used in oilfield applications faced problems comparable to TPE used in automobile applications, namely specifications were written in terms of a pre-determined type of material rather than for a given function [103]. HNBR's excellent resistance to high temperature and retention of physical properties under adverse conditions has resulted in its use in applications such as drilling motors, progressive cavity pumps, packers, blowout preventors, and seals for drill-bits [104].

Horseshoes

Conventional steel horseshoes can damage asphalt roads, especially during hot weather when a road surface softens. Amish farmers and mounted police in Texas use rubber-covered horseshoes to reduce road damage [105]. Figure 7.13 shows a high-mileage rubber-covered shoe that displays chunking.

Figure 7.13 Rubber covered horseshoe

Two-color horseshoes made with a thermoplastic polyurethane are now available for upscale horses [106]. Another horseshoe is constructed with a urethane base layer to provide structural support and a more flexible material for traction.

Shoes

An extensive review describes materials and processes for footwear [107]. TPEs are partially replacing TSEs that are considered superior in performance. Other materials are microcellular foam, PVC, and TPU. Using advanced machinery, it may take only 1–2 workers to operate a machine that can produce 10,000 shoes per day.

Rubber Couplings

Elastomer couplings with interchangeable flexible members accommodate misalignment between shafts [108]. They can be modified to isolate and damp vibrations, cushion shock, and even provide protection against overload. Variations include spider-, jaw-, donut-, sleeve-, and tire-couplings. Tire couplings incorporate a torus-like elastomeric unit that resembles vehicle tires, the subject of the next chapter.

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8 Tires

8.1 Introduction

When we hear the word 'tires', most of us think about the tires on our automobiles that are an indispensable product no one is particularly anxious to purchase [1]. Tires basically consist of a highly engineered and complex assemblage of components that possess a wide range of moduli. Tire types, other than automobile, include:

- Bicycle
- Truck
- Off-road
- Aircraft
- Solid
- Non-traditional

Automobile tires incorporate a combination of technical properties that include strength, elasticity, long service life, safety, traction, durability, and ride. These required properties, individually and collectively, are often achieved only with difficulty. The interdependent [2] properties of tread rolling resistance, wet grip, and wear form the so-called magic triangle. Changing one property affects the others.

Tire grip has special meaning to anyone who has skidded on a wet road. Maintaining good road contact requires that water be driven away from the tread contact area to avoid aquaplaning, wherein hydrostatic pressure builds up and reduces or eliminates control of steering and braking.

Unique treads combine compound and design factors wherein each tire has three distinct tread types for high traction on icy, snowy, wet or dry roads [3]. The center of the tread, the ice zone, incorporates a compound of rubber, glass fibers, and volcanic sand to grip icy roads. Deeply carved chutes propel water away from the tire in another part of the tread. A third portion of the tread uses reinforced rubber to improve maneuverability.

Good tire performance must be achieved with a tread contact area per tire about equal to that of only a post card [4]. Critical to good tire performance is inflation pressure, which influences tire deflection, spring rate, heat buildup, and service life. Tire over-inflation reduces contact area and increases localized wear; under-inflation causes a tire tread to bow inward in the middle, causing increased wear in the shoulder.

Halogenated butyl rubbers, widely used in tire innerliners, greatly extend the utility of butyl rubbers because they cure faster and co-vulcanize with general-purpose tire rubbers such as SBR and NR [5]. Isobutylene-based elastomers appear to have a more complex cure chemistry than do general-purpose elastomers [6]. Because they are highly saturated, ultra-fast accelerators are required to shorten cure times; some of these accelerators generate nitrosamines and are therefore not recommended. Other cure systems, such as resin and sulfur, are suggested.

Silica, replacing the conventional fillers in bicycle tires, provides maximum grip [7]. Cyclists can lean into a turn with an extra seven degrees of tilt, resulting in a substantial 40% increase in lateral grip relative to conventional racing tires. A further claim is the lowest rolling resistance of any racing tire. A disadvantage with silica is the generally higher compound cost that results from the inclusion of a coupling agent with the silica to obtain improved properties. The use of epoxidized natural rubber is said to preclude the need for a coupling agent and to simplify handling of compounds in production [8].

Pneumatic tires, constructed from many dissimilar materials, form highly complex engineering structures that are required to operate in a range of environments [9]. Automobile tires contain about twelve components, truck tires about twenty [10]. Adding to the difficulty in mixing and assembling the various materials are additional factors such as the need to meet increased demands for fuel efficiency. Factors such as tire materials, processing, and design can all interact to affect tire properties and fuel efficiency.

8.2 Materials

Each of the diverse compounds in a pneumatic tire is designed to meet specific requirements [11]. Individual elastomers, blends of elastomers, reinforcing materials (particulate and fibrous), curatives, and plasticizers contribute individually and collectively to compound properties. Examples of blends of elastomers are NR, SBR and BR used in treads; blends of NR, BR, SBR, and EPDM used in sidewalls, with the latter imparting ozone resistance. Blends of NR and BR in the range of 40 : 60 to 60 : 40 are typically used in car and truck tires to provide favorable tear and cut-growth resistance [12].

Compounds are designed to impart specific properties to a tire composite, e.g., abrasion resistance to the tread, flex resistance to the sidewall, and air impermeability to the innerliner. Interactions occur among materials that strongly affect tire performance. Examples are rubber-filler interactions in treads and crosslinking- flex life interactions in sidewalls.

In addition, for compounds to be functional, they must also process at a rate that makes them economical in an increasingly competitive market. Both mixing conditions and the sequence of adding mixing ingredients are important, as is avoiding compound contamination. The unintentional inclusion of a small amount of a highly unsaturated rubber such as NR or SBR in an IIR compound (lower unsaturation) has caused problems in many tire plants. The more highly unsaturated rubber will inhibit or prevent crosslinking in the IIR.

Foreign matter in a compound is a source of flaws that reduce vulcanizate strength. It can occur from unexpected sources [13]. For example, glass particles, cardboard, and even football tickets were found in factory-mixed compounds. The source of the foreign matter was ultimately traced to an overly zealous floor sweeper on the mixer floor who dumped his dustpan into the throat of an internal mixer, thinking it was a dustbin – a little training can go a long way.

Silane coupling agents can cause premature vulcanization [14]. Polysulfide silanes typically require several non-productive mixing steps in addition to requiring longer cure times (a non-productive step is an intermediate mixing step that does not result in a finished compound). An improved silane is said to correct these problems and to eliminate silane-derived ethanol emissions both during mixing and over the life of a tire. Highly reactive silica particles can form strong bonds with NR that lead to lower rolling resistance [15]. Blends of silica and carbon black can provide a more favorable balance between traction and wear [16].

Incorporation of 5 phr zinc oxide and 2 phr stearic acid as the activator system in sulfur-cured tire compounds has been standard practice for decades [17]. There is now pressure to reduce zinc concentrations because of environmental concerns about elevated concentrations of zinc leaching into water and harming aquatic organisms. Studies have shown that zinc oxide might be reduced by about one half without adverse effects.

8.3 Pneumatic Tires

Rubber components represent about 5% of the weight of an automobile and tires account for two-thirds of this weight [18]. The use of lighter weight steel cords and technical improvements in rubber materials have reduced tire weight by 20%.

8.3.1 Types of Tires

One of a pneumatic tire's key attributes is its ability to act as a spring and damper system that minimizes the effect of road surface irregularities over a wide range of operating conditions. Pneumatic tires can be broadly classified as bias or radial – today's major use tire. First considered are bias tires.

Bias Tires

Bias tires are still used today for trucks, trailers, farm machinery, and aircraft. Simple construction facilitates their manufacture. Their disadvantages are the heat generated between body plies during deflection in service; also, tread motion causes poor wear characteristics. Figure 8.1 illustrates construction features for diagonal bias, belted bias, and radial tires [19].

Diagonal Bias Tires

Body ply cords arranged at angles substantially less than 90° to the centerline of the tread distinguish diagonal bias tires. They extend from bead to bead, separate the innerliner from the tire sidewall and the underside of the tread.

Belted Bias Tires

These incorporate belt plies located above the body plies and under the tread. The belt plies stiffen the tire in the tread area, restrict tire circumferential expansion, and reduce tread wear. The belts restrict changes in the tire profile and reduce tread movement and improve tire durability [20].

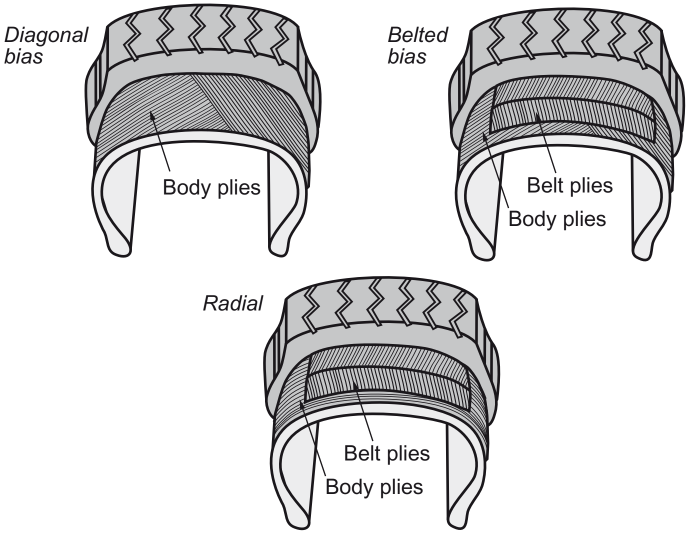

Figure 8.1 Construction of diagonal bias, belted bias, and radial tires [19]

Bias Tire Fabrication

Fabrication of the green (uncured) tire begins with the placing of a thin sheet of rubber (inner liner) onto a building drum of a tire-building machine [21]. Then subsequent components are applied, ending with the application of the tread. Pressure applied to the assembled components on the drum sticks the components together. Collapsing the drum facilitates removal of the green tire. At this stage, the assembled tire components are in the shape of an open-ended barrel.

By conventional compression molding, a rubber compound is squeezed and cured between surfaces of a rigid metal mold. This contrasts with the molding of pneumatic tires wherein a flexible bladder forms the inner tire surface and a rigid mold forms the outer sidewall and tread. Figure 8.2 shows a tire curing press and its ancillary equipment.

This figure shows an uncured tire positioned on its loading stand awaiting transport to the open tire mold by the automatic loader [21]. Hydraulic tire curing presses are replacing their mechanical counterparts because they occupy less floor space [22].

After placing an uncured tire in the lower half of the open mold, the mold is closed. Then a rubber bladder is raised from the bladder well, inserted in the interior of the uncured tire, pressurized with steam, thus forcing the green tire against the mold surfaces. Hence, the hot bladder provides heat to cure the inside of the tire while the hot metal mold provides heat to cure the outside.

Bladders require good heat aging and flex resistance at high temperatures. Inflating and deflating the bladder several times positions it in the uncured tire during the molding cycle. This action is analogous to the bumping of a curing press to expel air as described earlier for non-tire molding. After partially curing the tire, the piston returns the bladder to the bladder well, the mold opens, and the partially cured tire is placed on the conveyor shown to the right of the

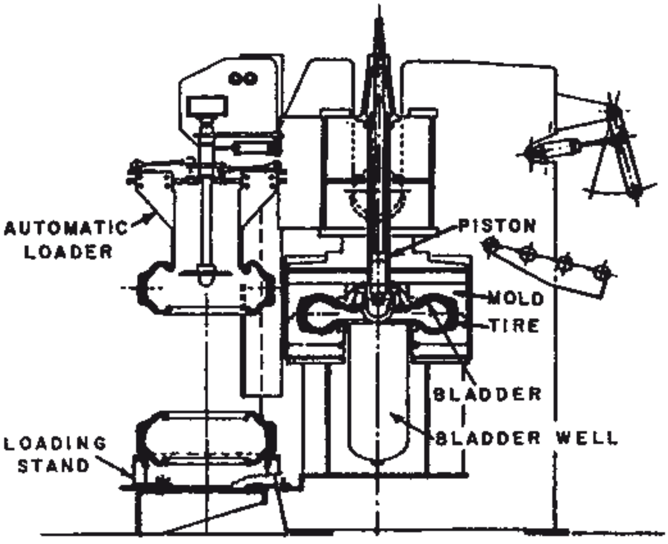

Figure 8.2 Tire curing press showing loading stand, automatic loader, bladder and bladder well (J. G. Sommer, Elastomer Molding Technology, Elastech (2003) Ch. 1)

piston. Curing continues as the tire cools outside its mold. Tires can be placed on an automatic post-cure inflator that is intended to prevent deformation in certain types of cords in cured tires. High forces associated with shrinkage of the carcass cords tend to deform a tire [23].

Comparison of Bias and Radial Tires

Figure 8.1 showed the differences in the construction of bias and radial tires. The body ply cords in a bias tire are arranged at angles substantially less than 90° to the centerline of the tread. In contrast, radial body cords are aligned at an angle of 90° to the centerline of the tread. Bias tires are more easily constructed than radial tires.

The increased stiffness from the two belt plies in a radial tire reduces tread wear and improves handling. In addition, radial tires deflect less under load, show lower heat build up and rolling resistance, along with improved performance at high speeds. Disadvantages of radial tires are increased fabrication costs and more difficult molding.

External factors, such as vehicle alignment, toe-in and toe-out, and camber affect tread wear in radial tires [24]. Separation between steel belts in radial tires can cause localized increased tread wear associated with pressurized air infiltrating the region between separated belts.

When tires fail catastrophically during operation, they can distribute a number of tire fragments on a highway [25]. These fragments can be "read" by a skilled microscopist and yield much useful information, such as rubber tear lines and other fracture topographies. Hence, the analyst can determine direction of fracture and tear propagation, making it possible to postulate modes of separation. A paper describes the use of microscopy for both tire and non-tire products [26].

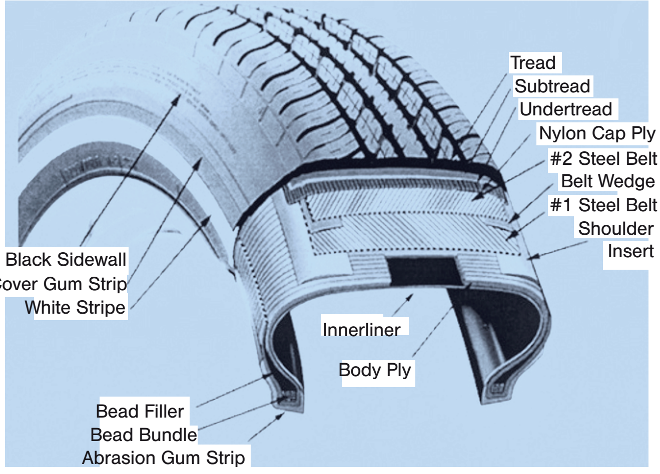

Figure 8.3 Components in a radial tire [19]

Radial Tires

A radial tire incorporates numerous materials that must be appropriately selected, combined, and processed to form intermediate components that, when joined and crosslinked, comprise the finished tire. Components must bond satisfactorily to one another to realize satisfactory performance and long service life. Materials used in this complex engineered structure must be processible and cost-competitive, while meeting many performance demands. Figure 8.3 shows the components in a radial tire [19].

Components

The ratio of Young's moduli for the materials used in a tire range in value over about 3×10^5 (Table 1.1). This large ratio makes it difficult to predict the stiffness and strength of composites prepared from them [27]. The very high modulus of the steel bead bundle provides the rigidity required to anchor a tire and its rim. The bead and the cord are the main load-carrying components in a tire. The modulus decreases through the tire section, culminating in the low-modulus tire tread where the rubber meets the road.

8.4 Tire Reinforcement

8.4.1 Bead Wire and Tire Cord

Small particle fillers reinforce a tread compound on a micro scale; bead wire and tire cord reinforce a tire on a macro scale. Both bead wire and steel cord are made from carbon steel that has been drawn and then coated to improve adhesion to rubber. Steel cords are now available with tensile strengths up to 4000 MPa and cords with strengths up to 4500 MPa are under development [28]. Increased strength will permit further weight reduction of vehicles, a much sought after target. Both cord construction and strength are important [29]. Cords constructed with sufficiently large openings allow rubber to penetrate openings and prevent localized corrosion by preventing moisture entry into a cord.

A range of polymer-based cords is available to the rubber technologist and engineer. Table 8.1 compares some of these cords and their respective characteristics [30].

Rayon is said to be the choice cord for the body of run-flat and high-performance radial tires [31].

The cords listed in Table 8.1 are treated with special adhesives to obtain the desired level of adhesion with adjacent components. For example, resorcinol-formaldehyde latex (RFL), used for many years to coat nylon and rayon, is still widely used today in the tire industry. Some general requirements for cord to rubber adhesives follow [32]:

- Provide good adhesion between cord and rubber
- Form bonds rapidly
- Provide good fatigue resistance in the cured adhesive
- Be compatible with different rubber compounds

The sulfur in the compound that encapsulates the brass coating on bead wire reacts with the coating to form a strong bond between compound and bead. Equally important are bonds between tire cord and compounds, bonds between tread and carcass, and the other components.

Table 8.1 Advantages and Disadvantages of Different Types of Tire Cords

Cord type	Advantages	Disadvantages
Rayon	Dimensional stability and heat resistance	Moisture sensitivity and cost
Aramid	Very high strength and stiffness; heat resistance	Difficult to process (cut) and cost
Nylon	Heat resistance and strength	Heat set during cooling and long-term growth in service
Polyester	High strength and low growth in service	Poorer heat resistance than rayon or nylon

Individual components in Fig. 8.3 are now discussed, moving clockwise from the bead bundle on the left. Bead bundles, formed from plated carbon steel wire that is wound into hoops, anchor an inflated tire to its rim. Flanges on the rim position and restrain an inflated tire; a central depression in the rim facilitates tire mounting and dismounting.

Damage to the bead area, which causes uneven tire rotation, can cause a slight tire wobble and alert engineers to damage [33]. A crack that forms in the bead area can progress around the tire diameter and cause air loss and other problems. Tests at higher frequencies (up to 300 Hz) can indicate the formation of bulges and cracks.

A gum chafer (not shown) provides an airtight seal and prevents wearing and cutting by the rim. The bead filler (also called the apex) is located above the bead in Fig. 8.3. Its generally triangular shape fills in the region immediately above the bead bundle and smoothes the thickness gradient above the bead bundle as the gradient progresses toward the sidewall zone [34].

Injection molding, a molding method formerly used only for non-tire molding, can form apex rings [35]. In doing this, flow length from the gate to the cavity edge was kept as short as possible. Newer technology involves a manufacturing cell that incorporates both compression and injection molding processes [36]. Treatment in a compression molding press stabilizes the bundle to prevent its distortion by high pressure during injection molding. Before the bead bundle goes to the injection press, induction heating of the bead wire cures the component from the inside out in a manner that insures that the outer edges effectively adhere to the rest of the casing. A robot picks up the compressed bead wire and transfers it to the injection press [37].

The apex provides a transition from the bead bundle to the inner body plies and the outer body plies; the latter are turned up after they are formed around the bead bundle. More than one apex can be used in a tire [38]. Bead filler hardness and height affect vehicle ride and handling characteristics. Because most of the cornering force comes from camber thrust in motorcycle tires, bead fillers with a very high hardness are used for motorsport [39]. One or more cap layers, special chafers, and flippers further increase sidewall strength.

8.5 Tire Construction

Sidewall

The tire sidewall, which protects the body plies from abrasion and impact, must also provide good resistance to flex cracking and ozone cracking. Carbon fiber (threadlike strands of pure carbon) is used in the outboard sidewall of a high-performance tire to provide stiffness for better handling [40].

Early research with antiozonants established that *p*-phenylenediamine additives in tire sidewalls provided ozone protection [41]. A sidewall may contain a white strip (white sidewall) and decorative treatments along with identifying information. Additional components can be included (not shown in Fig. 8.3) such as chippers and flippers that improve stability and handling.

Tread

The tread, which transmits steering, braking, and cornering forces to the road [42], is compounded to provide a balance among wear, traction, rolling resistance, and handling. Increased tread depth and special tread compounds help tires provide acceptable handling under dry, wet, and icy road conditions. A tread pattern can be designed to remove water ahead of the tire footprint and also to minimize tire noise for a range of road surfaces.

Attaching a double-humped strip of polyurethane foam circumferentially to the innerliner at the center of the tread is said to eliminate cavity resonance [43]. Cavity resonance is a noise of narrow frequency range caused by resonance of the air in the tire. This reference addresses other noise sources.

The small footprint on the average car tire must provide contact between the road surface and tread area adequate for acceleration, steering, and braking requirements [44]. At high speeds, some tires can increase in diameter by as much as 20 mm, thus affecting the footprint and vehicle handling [45]. A study of the paws of polar bears and geckos yielded an idea to improve road grip [46]. A tire was developed that contained thousands of pores that provided myriad edges directed toward improved road grip.

Subtread

A subtread is a thin rubber layer located under the extruded tread. It is typically a low hysteresis compound designed to reduce tire-rolling resistance and thus improve vehicle fuel economy [47]. The subtread can help fine-tune tire properties such as noise, handling and ride quality. It increases adhesion of the tread to stabilizer plies during tire fabrication and covers the ends of cut belts.

Steel Belts

The #1 and # 2 steel belts, located beneath the cap ply, stabilize the tread and provide impact resistance. Both the angle between cords in the steel belts and the belt width affect vehicle handling and ride characteristics. Quality control of belts is important and inspection systems can determine cord spacing and the occurrence of missing cords in a belt [48].

Belt Wedge

Small strips of rubber are sometimes located between #1 and #2 steel belts, near their edge. They are intended to reduce interplay shear at the belt edges during tire deflection.

Shoulder Insert

This insert, a rubber strip, separates and smoothes the contour between the #1 steel belt and the body ply.

Innerliner

A tire innerliner mainly determines the loss of inflation pressure that strongly affects tire properties, such as sidewall deflection, spring rate, heat buildup, and service life. Data from

Europe suggest that 40% of vehicles with under-inflated tires consume an additional 2.8% fuel, and waste 2.14 billion gallons of fuel per year [49]. Also, low inflation pressure is said to contribute to about 0.8% of all road deaths [50].

A tire's innerliner, typically butyl or halobutyl, is compounded to minimize pressure loss. Automobile tires ordinarily lose about 1 psi per month with the loss rate depending upon factors such as temperature, the innerliner compound and its thickness [51]. In comparison, commercial aircraft tires can lose several psi per day; space shuttle tires are limited to only about 0.1 psi loss per day [52]. Pressure in space shuttle tires for landing is 375 psi to support the high landing loads.

Separate tubes were used in early vehicle tires to retain air [53]. Their manufacture included joining an extruded tube whose ends were cut with either a butt or a lap splice. The spliced area of the tube was then place over a chilling bar at –10 °C for 7 to 20 minutes to limit strain that occurs during the subsequent splicing operation. The vulcanization cycle was typically 7 to 10 minutes at 165 °C, depending on tube size.

Halobutyl innerliners in tires provide excellent air retention characteristics [54]. Air and moisture that permeate the innerliner can diffuse into the thin carcass stock, through the belt compound, along the steel belts, and reduce tire durability. A dynamically vulcanized alloy of Exxpro specialty elastomer and nylon is said to be an alternative material to halobutyl innerliners [55]. It can be blown into films [56] and replace halobutyl rubber with a potential weight savings of 500 g per tire while still maintaining the performance of halobutyl rubber.

8.6 Component Interdependence

A spider diagram [57] illustrates the interdependence of nineteen tire properties that include handling, wet traction, ride and rolling resistance. Increased belt width improved handling and wet traction but adversely affected weight and rolling resistance. The diagram illustrates the difficulty in simultaneously optimizing a number of properties in a modern tire, one of the most underappreciated engineering structures that most of us use daily. Additional topics relevant to tire manufacture include tire load capacity, stress analysis, force and moment analysis, noise and vibration, friction and traction, rolling resistance, abrasion and wear, safety, durability, non-destructive tests, standards and specifications, and tire material recovery and reuse.

Noise is of special interest to vehicle occupants. The tire carcass can transmit structure-borne noise through the wheels and suspension and aggravate resonances in vehicle components. Road surface characteristics play a significant and interactive roll with some components. For example bead filler, which reduces noise from coarse roads, affects rolling resistance and handling.

Acoustic floor mats can also affect the noise level in the automobile cabin [58]. They incorporate crosslinked foam and crumb rubber and processing tunes the mats for each individual vehicle. The mat absorbs cabin-generated noise or the noise passes through the mat into sound-absorptive carpet.

Tire components, none of which are perfectly elastic, all contribute to rolling resistance. This resistance is very significant on tractor-trailer tires, where calculated rolling resistance is 34% of vehicle horsepower [59]. Rolling resistance contribution of different components is described as: tread 42%; belts 43%; sidewall 13%, and bead 2%. Hence, the tread and belts account for 85% of the loss.

8.7 Component Preparation and Tire Fabrication

8.7.1 Component Preparation

A number of components are prepared prior to the final fabrication of radial tires. Their preparation involves diverse processing steps that include compound mixing, extrusion, and calendering.

Mixing

Being a large volume rubber product, tire compounds are mixed in internal mixers like those shown in Fig. 3.2. Batch weights for these mixers range from 400 to 1100 pounds. After a batch is mixed, it drops from an internal mixer onto a rubber mill that then flattens the hot rubber into sheets. The sheets are cooled and stacked prior to further processing. Special release coatings can be applied to these sheets during cooling to prevent them from sticking to one another [60].

Extrusion

For many decades, hot-feed extruders served as the dominant method for extruding compound for tire profiles, wherein compound was preheated on a rubber mill prior to being supplied to the hot-feed extruder. Cold-feed extruders, in contrast, are supplied with rubber at ambient temperature, eliminating the need for the preheating step. Cold-feed extruders with pins in their barrel are currently used for passenger car tires [61]. Treads and sidewalls, extruded to the desired shape, are cut to length and then fabricated into green tires.

An alternative method involves extruding individual components that are joined immediately after extrusion – multiplex extrusion [62]. This method saves energy and results in improved adhesion between the hot components. Multiplex extrusion is done with two, three, and four extruders whose respective outputs converge at the final die.

Extruders are also used to extrude rubber compound onto bead wire using a crosshead extruder, i.e., the extruder screw is at right angles to the bead wire passing through the extruder die. After extrusion, the coated bead wire is formed into hoops for final assembly into a tire.

Calendering

Calenders form rubber compounds into sheets with an accurately controlled thickness, a feature very important for innerliners. They also apply rubber compounds to nylon cap ply fabric and steel belts. Modern calenders that incorporate improved cooling and controls are used to form profiles as well as sheet. An alternative is the use of a roller die in front of an extruder.

8.7.2 Fabrication

Radial tires can be built in two stages, wherein the tire carcass is assembled on a drum that can be rotated and collapsed to remove the partially fabricated tire. Fabrication begins with the application of the innerliner and body ply(s) that are rolled over the edges of a drum. Beads and bead filler are positioned, followed by turning the body ply(s) over the beads. Sidewall strips are then positioned against the turned-up body ply, after which the drum is collapsed prior to removal of the assembled components and transporting them to the second-stage building machine.

The belts and tread are applied on the rotating drum of a second-stage building machine that expands the carcass diameter. Stitching wheels force the various tire components together, after which the green tire is removed and stored on a rack prior to vulcanization.

Newer building machines are said to build a simple tire in less than thirty seconds with a single person operating two building drums [63]. The most complicated tires might require a separate operator for each building drum. Servomotors adjust machines for changes in tire size, with adjustments requiring only several minutes.

Figure 8.4 illustrates a green tire in its segmented mold. During the molding cycle, the sidewall sections close on another to their final position [21]. Then pneumatic or hydraulically actuated linkages move the tread segments radially inward and close the openings between the tread segments.

The photograph in Fig. 8.5 shows segments in the raised position with openings between them [21]. Upon closing the mold, the segments must move in exact symmetry with one another. Self-lubricating wear plates are used to minimize wear of sliding surfaces that are at the mold's high temperature.

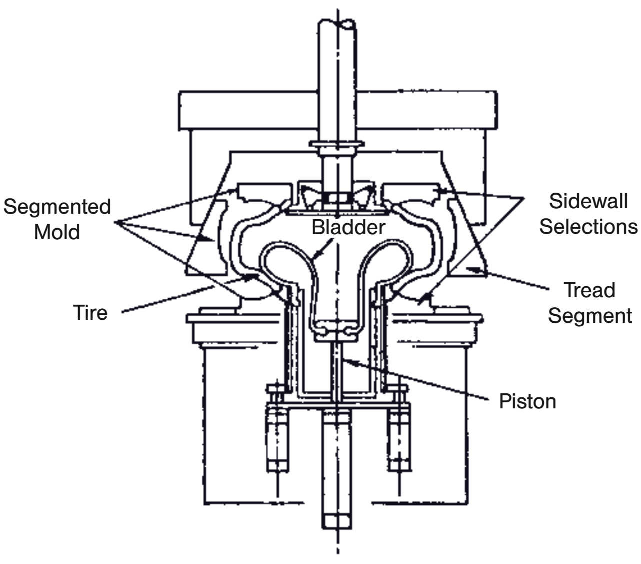

Figure 8.4 Tire curing press containing a segmented mold
(J. G. Sommer, Elastomer Molding Technology, Elastech (2003) Ch. 1)

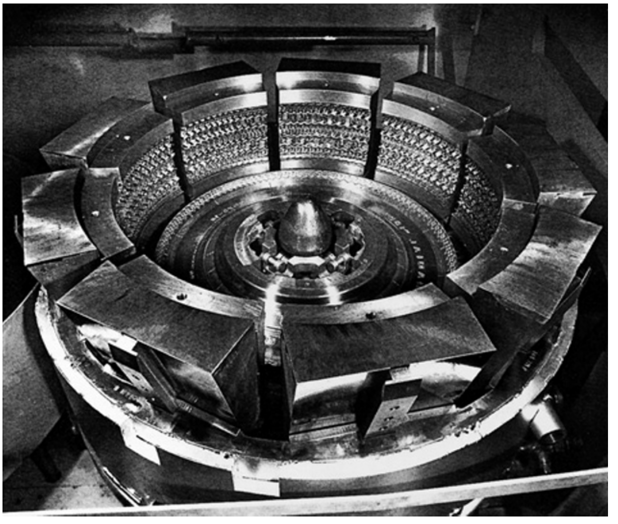

Figure 8.5 Segmented tire mold
(J. G. Sommer, Ch. 6, in "Basic Compounding and Processing of Rubber", H. Long (Ed.), Rubber Division, American Chemical Society)

Segmented molds facilitate removal of tires from their molds, especially radial tires with very stiff treads. The spaces between the segments of the open mold provide increased diametrical clearance between the outer diameter of the tire and the mold, thus ease tire removal. In contrast to a radial tire, a bias tire (less stiff) is more easily removed from its mold because it deforms more readily. In a sense, bias tires are removed from their mold, while molds are essentially moved away from a radial tire. Each mold half in a two-piece mold (Fig. 8.2) shapes a sidewall and a portion of a tread, wherein the mold parting line is not necessarily equidistant between sidewalls. In a segmented mold, separate mold parts shape sidewalls and tread.

The bladder in Fig. 8.4, when raised and pressurized to several hundred psi, forces the assembled green tire components against the surfaces of the closed segmented mold. Air trapped between the bladder and the inner liner, and in the tread and sidewall, can cause defects in a finished tire. Special lubricants and special patterns molded onto the surface of a bladder vent trapped air between the bladder and inner liner to minimize or prevent trapped air problems. Mica in the inside tire paint also facilitates venting of air. In addition, the paint between the bladder and the inside of the tire eases slippage at tire-bladder interface.

Laser systems can inspect and detect small bulges and indentations in sidewalls by profiling rotating tires [64]. Position-sensing detectors can quickly detect a bulge and other deformities on a tire rotating at 60 rpm [65]. Improved methods for manufacturing pneumatic tires have evolved over time, partially driven by the need to reduce costs.

Cost reduction can result from several areas that include savings in material costs, from the use of new materials or by substituting lower cost existing materials in a compound. A rubber compound is a very complex mixture of ingredients that can behave in a manner undetectable during testing to a specification designed to determine suitability of an alternative ingredient. Hence, testing the final product is mandatory.

Reduced processing and materials costs have become increasingly important in today's competitive tire manufacturing operations. Efforts to achieve these goals include: increasing manufacturing flexibility [66], lowering energy costs, reduced number of manufacturing steps, more effective use of floor space, and robotics. Some of these alternative manufacturing approaches are:

- Continuous Cold Compounding (C3M)
- Modular Integrated Robotized System (MIRS)
- Bridgestone Innovative and Rational Development (BIRD)
- Modular Tire Manufacturing (MTM)
- Advanced Tire Operation Module (ATOM)
- Automated Production Unit (APU)
- Integrated Manufacturing Precision Assembled Cellular Technology (IMPACT)

Continuous Cold Compounding

C3M and MIRS share some common features. Both use a small amount of floor space and begin by building tire components on a drum that remains with the tire through the curing process. Successive extruded layers partially overlap to form the desired profile. No cooling is done during production of a C3M tire in contrast to conventionally built tires. As a result, a warm tire enters the curing mold with accompanying energy savings, and the curing cycle is shorter. Rather than using bladder-applied pressure in the curing mold, an electrically heated mold closes on the tire in the C3M system.

The 26-step C3M process (depending upon the tire) is said to take 20 minutes, including a 10-minute cure cycle [67]. With C3M, three or more strips of rubber with different properties can form a tire tread [68].

Modular Integrated Robotized System

MIRS is designed for flexibility rather than for large volumes or long runs of tires [69]. It is said to reduce the number of steps in the traditional tire making process from fourteen to three steps. Micro-components produce a MIRS tire rather than a large tread and a large sidewall [70]. As a central clamp and spindle lock segments together, a barcode reader tracks the tire around the building cell. The MIRS process incorporates a series of extruders that surround a toroidal tire-building drum [71]. Extruded strips, rather than sheets of rubber, are used during fabrication and the need for monitoring personnel is significantly reduced.

Tire uniformity is said to be 30% improved relative to a tire produced on traditional equipment [72]. Another advantage claimed for MIRS is that, being modular, production can be added without the need for traditional mixing and semi-finishing lines [73].

Bridgestone Innovative and Rational Development

All stages of tire manufacturing by the BIRD system are automated, from materials processing to final tire inspection [74]. The system is said to be capable of simultaneously producing several different types and sizes of tires. A plant is expected to make 8000 units daily that will include high-performance, ultra-high performance, and large-rim, light truck, and passenger tires.

Modular Tire Manufacturing

The MTM system uses rubber compounds that are delivered to cells in strip form on pallets, while finished brass-coated wire is delivered on reels [75]. Fabric reinforcement is supplied as reels or bobbins of single dipped cord. Each cell in the system needs three people to operate it: a supervisor, an operator, and one forklift driver to relieve the other two [76]. The MTM system can produce different tires, with each having a different width, outside diameter, or cord angle without requiring changeover time [77].

Advanced Tire Operation Module

The ATOM system is designed so that no one touches the tire until the tire is cured and has undergone final inspection [78]. It is said to reduce space needs and is designed for small-lot, multi-product tires. Each tire assembly module contains twelve extruders. Belts, beads, inner plies, sidewalls, and treads are built in separate areas and the system is said to eliminate splices.

Automated Production Unit System

The APU system combines up to nine tire making steps and reduces the length of the tire production line by one third [79]. It reduces upstream production of components to a minimum. A just-in-time supply of components is provided to a building station.

Integrated Manufacturing Precision Assembled Cellular Technology

Everything from the innerliner to the apex is assembled serially while the rubber is hot using the IMPACT system, eliminating the need for tackifiers to improve adhesion [80]. Goodyear states that its system, which can be applied to almost any type tire, improves quality and reduces process steps. Each station in the system consists of a hot former, a unit similar to a two-roll mill. One roll is a simple cylinder; the other has a profiled surface. A cold-feed extruder provides compound to the unit at a volume flow rate that matches that of the component being made at a specific station.

Once laid down, components are formed into a spool large enough to build 100 or more tires. The components are then moved to a two-stage building machine and each assembly is cut to length. A typical truck-tire package made by this system is about 19% lighter than one made by more traditional assembly techniques. IMPACT is said to significantly improve positioning of components relative to conventional systems [81].

NASCAR Tires (National Association for Stock Car Auto Racing)

Demands on tires for NASCAR are severe since tires can reach temperatures as high as 270 °F during a race, although 220 °F is typical. While a passenger tire typically is designed to last for years and provide 40,000 miles of service, NASCAR tires have a maximum life spans of only about 150 miles. RFID chips carry specific information about the race tires. Embossed identification on the sidewall directs placement of tires to the left or right side. Left-side tires are smaller because they do not encounter the same high-speed stress as the right-side tires.

General Fabrication Aspects

As older tire plants close and the cost of large steam boilers for heating molds increases, the trend to electric heating will likely continue [96]. With electric heating, different portions of a mold can be heated to different temperatures so that thinner tire sections can be heated to a lower temperature than thicker sections. Electric heating also facilitates mold preheating during change of molds to accommodate a different mold size.

Repetitive cures cause molds to become dirty or fouled. A range of cleaning techniques is available to permit cleaning a mold in its curing press. One of these uses a fork lift truck to move a mold cleaning unit into the open tire mold where the unit then blasts the mold with dry ice pellets [97]. Pressurized air then blasts off the dirty and embrittled film from the mold surface. A number of other methods are available to clean curing molds for rubber, including one that uses special additives to release the fouled film [98].

8.8 Tire Aging

Oxygen present in the air that inflates tires causes the tires to age more rapidly than if an inert gas was used. For this reason, nitrogen has been used to inflate tires on race cars, large trucks, and the space shuttle to slow the oxidation rate. Nitrogen permeates rubber at only one third the rate of oxygen [82]; being dry, it eliminates the moisture typically present in pressurized air [83]. Nitrogen inflation is also being used for automobile tires as it significantly slows or even halts changes in tire properties [84].

Speeding the aging rate of tire compounds in the laboratory by increasing temperature, as with other compounds, is sometimes desirable. Caution must be exercised when doing this to avoid the occurrence of a change in mechanism that can occur over a relatively narrow temperature range. For example, at temperatures below 50 °C, degradation of a beltcoat compound was ten times faster than extrapolated values from elongation-to-break data [85].

8.9 In-Service Tire Damage and Safety

Occasional punctures and other types of tire damage are inconveniences that we tolerate for the convenience and usefulness provided by our automobiles. One would expect occurrence of this damage to be random, which it is not [86]. Rain increases the occurrence of punctures because water is an excellent lubricant for nails and other debris that puncture tires. Also, almost twice as many punctures occur in rear tires than in front tires because front tires orient debris, e.g., nails, for easier penetration into the rear tires.

Tire damaging material can come from unusual sources. Stretched rubber straps that terminate with steel 'S' hooks (Fig. 8.6) for attachment are widely used to retain cargo on vehicles. If straps break free and fall onto a roadway, front vehicle tires can roll over them and orient the hooks to puncture rear tires.

Figure 8.6 Rubber hold-down strap with 'S' hooks

Improper placement of two partially worn tires and two new tires led to accidents on wet roads [87]. Tire companies and most aftermarket providers are said to now require that new tires be placed on the rear axle when only two new tires are sold.

Tires degrade when not in service, especially in hot climates. The time tires should remain in service remains controversial, with Ford suggesting that tires generally be replaced after six years of normal service [88]. A study established that tires aged in an oven for 6 to 7 weeks at 70 °C yielded a tire equivalent to one aged four years in Phoenix, Arizona [89]. The rate of tire aging varied by more than five-fold for different brands and types of tires in the study.

Truck tires are expected to be retreaded a minimum of 3 to 4 times [90]. This expectation places considerable demands on the durability of tire compounds such as those used in the undertread, carcass and sidewall. Optimizing the heat resistance of compounds is said to improve truck tire durability.

8.10 Run-Flat Tires

There are two major types of run-flat tires:

- self-supporting tires that incorporate sufficiently stiff sidewalls to support the vehicle load after air loss;
- tires that contain a ring capable of supporting the load after air loss [91].

Other approaches include a rapid-inflate system for truck tires and multi-chamber tires. The inside of one multi-chamber tire incorporates a main chamber in the center, with sub-chambers on either side [92]. Independent control of the air pressure in each chamber is possible. A patent illustrates the release of a lubricant sealed in the chamber of a tire [93].

Run-flat tires are directed toward improved tire reliability. They are offered as an option to conventional tires on some cars and can be driven for miles after air loss. They allow the driver to delay repairing a flat until it can be done safely, not on the side of a busy highway. Run-flat tires are especially attractive for sports cars because of these cars' limited storage space.

8.11 Passenger Tire Design

8.11.1 Aspect Ratio

The aspect ratio is the ratio of a tire's section height to its section width [94]. The section height is the radial distance from the crown to the beads; the section width is the sidewall-to-sidewall dimension of an unloaded, inflated tire. Aspect ratio for early automobiles was about 100. It has decreased steadily over time and is now as low as 30, making under-inflated tires less evident.

Lowered aspect ratio increases stress in cords differently [95]. Decreases in aspect ratio caused increased stress in belt cords but decreased stress in carcass cords. Lowered aspect ratio increases the tire foot print area and thus reduces average pressure in the footprint area. Since footprint pressure correlates with hydroplaning resistance, lower aspect tires are associated with reduced hydroplaning resistance.

Tire Identification

Identifying letters, numbers, and surface decorations on molded rubber products are generally raised above the mold surface because they are most easily formed from depressions in the mold. They are widely used for identifying tires. Disposable aluminum strips with stamped identification information, placed in a mold, can form lettering (depressed rather than raised) in a rubber product.

Radio frequency identification (RFID) is a newer identification method wherein an electromagnetic pulse sent by a reader induces an electric current in a transponder or tag [99]. A difficulty with RFID tags in tires is the attenuation of the RF signal by the carbon black in a tire, making more power necessary [100]. Information stored in the tag is sent back to the reader, allowing the product to be identified, logged, and tracked with event information. This technology can also be applied to hose [101].

Another identification method uses a bar-coding system that provides all details of a compound within 20 minutes [102]. The system provides mixing information, the materials involved, related specifications, and is said to help remove variability in a compound.

Tire quality significantly depended for many years on the skills of the tire builder. In recent years, automation has reduced the number of individual components arriving at the building machine, thus improving tire quality.

Bias vs. Radial Tires

Prior to molding, a green (uncured) radial tire is shaped more like a finished tire; the preform for a bias tire is shaped more like a barrel with both ends open. Hence, molding deforms a bias tire significantly more than it does its radial counterpart.

The construction differences between bias and radial tires illustrated in Fig. 8.1 result in substantial behavioral and property differences. The sidewalls and tread in radial tires work independently of one another, because the cords in body plies and in belt plies essentially reinforce either the tread region or the body region. In contrast, in the diagonal bias tire, cord in the body plies jointly reinforces both the tread region and the body region. The radial tread deforms less in the area of ground contact and results in less heat buildup and tread wear because of reduced tread squirm [103]. Also, radial tires lower the center of gravity and their thinner sidewall transmits less shock to the rim and subsequently to the vehicle.

8.12 Truck Tires

Truck tires, classified as light, medium, or heavy duty, usually include bus tires. Their key requirements include: economical operation, longevity, and retreadability. Multiple retread capability of truck tires places longevity demands on truck tire sidewalls because the sidewall must perform adequately throughout the entire life of the tire. For example, resistance of the tire sidewall to ozone cracking is an important factor, especially with atmospheric ozone concentrations on the rise.

Inspection of tire casings by humans to determine casing suitability for retreading is limited to detection of surface imperfections [104]. Newer inspection methods include ultrasound, a technique which can detect porosity and other defects [105]. Shearography is being considered for inspecting tires suitability for retreading.

Rubber is applied to a tire casing in conventional retreading using uncured treads cut to length. Precured treads of constant curvature are an alternative and Fig. 8.7 illustrates their continuous preparation [106]. These offer an advantage over the production of flat uncured treads that are made in a discontinuous operation.

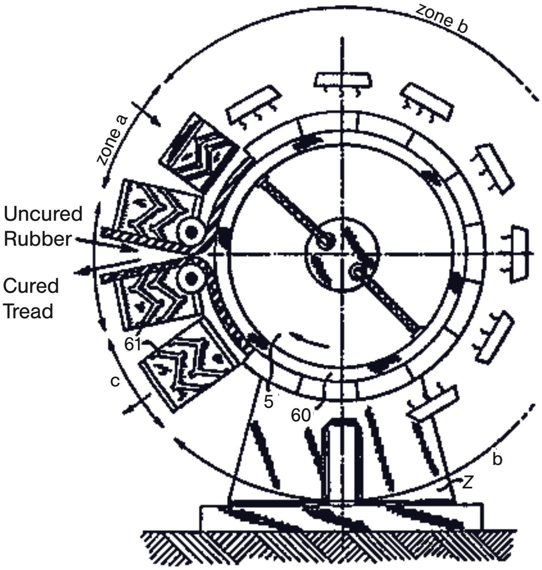

Figure 8.7 Mold for making precured treads

Full-circle treads without splices are made by injection molding for application to buffed truck tire casings [107]. Using a finite element mesh, a distribution manifold was developed and optimized by computer simulation for the injection molding operation. Rubber, heated in an extruder, is densely packed in the injection barrel and then metered and shot into a mold at pressures of 20,000 to 30,000 psi [108]. The resulting Unicircle tread is said to offer improved mileage and fuel savings.

8.13 Very Large Tires

Off-road tires often operate on uneven terrain that contains rocks and other materials that cut and bruise tires. These are as large as 15 feet in diameter, can weigh almost 4 tons, and can cost $40,000 each [109]. They include earth-moving, road-construction, and mining-vehicle tires that can require 24-hours to cure because of their thick sections.

8.14 Aircraft Tires

Aircraft tires carry extremely heavy loads for their size, but operate on relatively short service cycles. Although bias-ply tires continue to predominate [110], most new commercial aircraft are equipped with radial tires [111]. Both bias and radial tires are needed for commercial aircraft, because existing aircraft were designed for a specific tire size and type. The more costly radial tires find use in heavy jet and military jet aircraft, while bias tires are used mainly for general aviation aircraft.

Tread rubber on bias tires for a typical airliner can expand radially by as much 12% as the aircraft accelerates to take-off speed in about 34 seconds [112]. Under the same conditions, radial tires expand only about 8%, favoring longer tread life. Near Zero Growth (NZG) tires were specially developed for the Concorde supersonic airliner [113].

Jet tires used in aircraft carrier service encounter especially severe conditions [114]. They wear out 2–3 times faster than their land-based counterparts. These high wear rates are mainly caused by the maneuvering jet on the deck to get into position for take-off. Some metal plates used on the landing deck caused tires to wear out after only 4–5 landing cycles.

The very high speed capability required for Concorde tires placed severe demands on its cross-ply construction tires that contained 32 plies [115]. Although not the biggest or heaviest tires used on commercial aircraft, they had by far the highest speed rating, namely 279 mph. Concorde used only new tires even though tires on many other aircraft are routinely retreaded many times. Debris from a burst tire punctured a fuel tank and resulted in a tragic crash. Radial tires developed specifically for the Concorde reduced the burst risk.

Maximum weight of the Airbus A380 is 560 tons and in general the weight of commercial airplanes continues to increase. This weight places considerable demands on the aircraft's tires [116]. The load on an individual A380 tire is more than 33 tons at maximum load.

8.15 Solid Tires

These consist of several elements [117]: a steel element that defines the internal diameter and is used for attachment; three layers of different rubber compounds, where the outside layer is the wear layer, the intermediate softer layer is the comfort layer, and a hard compound serves as the bonding layer. Solid tires with too high spring rates are suspected of causing vibration-related health problems for long-term drivers of vehicles equipped with solid tires. An intermediate layer of a cushion gum can increase adhesion strength [118].

Injection molding of solid tires is expected to increase because of shorter molding cycles relative to compression, e.g., 24 minutes for injection vs. two hours for compression molding [119].

Both polyurethane (PU) and conventional rubber are widely used to fabricate solid tires [120]. PU tires are used in applications such as castor wheels, wheels for amusement park rides, and skate wheels. Their relatively low creep resistance at high temperatures typically limits their use to maximum temperatures of about 100–120 °C. Adhesive failure caused by high temperature can result in failure of PU wheels in service [121]. A procedure is available that predicts heat-induced failure in wheels with polyurethane treads.

8.16 Semi-Pneumatic Tires

These tires, which contain no textile or wire reinforcement, can be made from a single rubber compound [122]. Their thick walls essentially provide the required load-carrying capability in contrast to typical pneumatic tires that depend on internal air pressure to function. Semi-pneumatic tires operate at ambient pressure because air passing through a hole in their side balances internal and external pressures.

8.17 Non-Traditional Tires

Efforts are underway to replace the ubiquitous pneumatic tire. A patent [123] describes a tire that supports a load by compressing its elastomeric structure; the tire requires no internal inflation pressure. Figure 8.8 shows the continuous circumferential ribs that carry the load.

The Tweel is another non-pneumatic, single unit that could potentially replace the combined tire, wheel, and valve used in a conventional pneumatic tire [124]. Its bonded components are:

- A hub unit for attachment to a vehicle axle
- A polyurethane spoke section that is injection molded
- A reinforced tread belt
- A tread

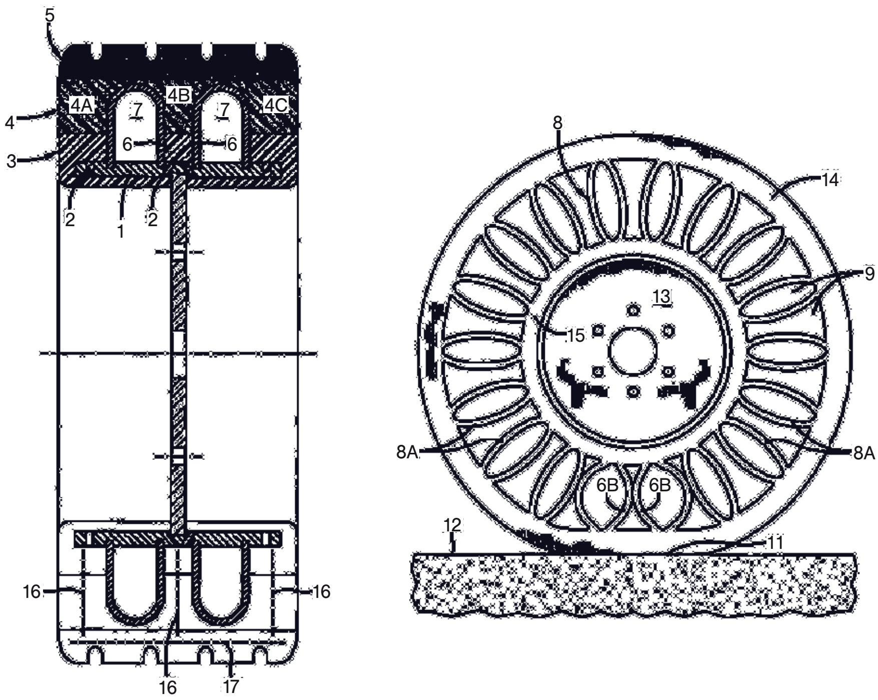

Figure 8.8 Airless tire whose ribs support the load

A rubber tread, rather than polyurethane, is needed because of urethane's poor abrasion resistance and wet friction properties [125]. Rectangular (rather than round) spokes provide five times more lateral stiffness than is provided by an equivalent pneumatic tire. Inflation pressure in a pneumatic tire is distributed uniformly throughout a tire, so increasing pressure to increase lateral stiffness also increases vertical stiffness [126]. Disadvantages for these products include noise and telegraphing of course road surfaces. These suggest that they will remain a niche item satisfactory for low-speed applications and with modest load carrying capability.

The spinning of tires on an automobile, called drifting, is a part of the racing subculture and the smoke given off by spinning tires is typically gray-white in color [127]. Tires have now been developed that liberate red smoke when spinning to add a new dimension to this activity. Dyes in the tread produce the red smoke when they reach sublimation temperature.

Colored compounds under a tire tread can be used to indicate the amount of tread wear [128]. A dual-layer tread incorporates a colored compound that becomes more evident with increasing tread wear.

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Appendix 1: Conversion Factors

To convert from	To	Multiply by
atmosphere	pascal (Pa)	$1.013 \cdot 10^5$
degree Fahrenheit	degree Celsius	*
degree Celsius	degree Fahrenheit	**
inch	meter	$2.540 \cdot 10^{-2}$
kgf	Pascal (Pa)	$9.806 \cdot 10^4$
pound force (lbf)	Newton (N)	$2.780 \cdot 10^{-1}$
lbf/in^2 (psi)	Pascal (Pa)	$6.894 \cdot 10^3$

* °C = 5/9 (°F – 32)
** °F = 9/5 (°C + 32)

Appendix 2: Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
BR	Butadiene rubber
CBS	*N*-cyclohexyl-2-benzothiazoledisulfide
CPE	Chlorinated polyethylene
CR	Chloroprene rubber
CSM	Chloro-sulfonyl-polyethylene
DOE	Design of Experiments
EAM	Copolymers of ethylene and vinyl acetate
EPDM	Ethylene-propylene-diene monomer elastomer
EPM	Ethylene-propylene monomer elastomer
EV	Efficient vulcanization
f	force
ft	foot
FKM	A specific fluoro rubber
G	Giga
GB	Gigabyte
h	hour
HNBR	Hydrogenated acrylonitrile-butadiene rubber
I.D.	Inside diameter
IIR	Isobutene-isoprene rubber
in	inch
IR	Isoprene rubber, synthetic
IRHD	International Rubber Hardness Degrees
ISO	International Standards Organization
kg	kilogram
kN	kiloN
L	length
lb	pound
lbf	pounds force
LIM®	liquid injection molding
m	meter
mbar	millibar
min	minute

mm	millimeter
MDR	Moving die rheometer
MPa	Megapascal
MSDS	Material safety data sheet
N	Newton
NBR	Acrylonitrile-butadiene rubber
NR	Natural rubber
O.D.	Outside diameter
OTR	Off the road (tires)
P	Pressure
P_L	parting line
Pa	Pascal
PBT	Polybutylene terephthalate
phr	parts per hundred rubber hydrocarbon
PP	Polypropylene
psi	pounds force/inch^2
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PVC	Polyvinyl chloride
Re	Reynolds number
RIM	Reaction injection molding
RMA	Rubber Manufacturers Association
s	second
SAE	Society of Automotive Engineers
SBC	Styrene block copolymer
SBR	Styrene-butadiene rubber
SBS	Styrene-butadiene-styrene elastomer
SEBS	Styrene-ethylene-butylene-styrene elastomer
SIS	Styrene-isoprene-styrene elastomer
T_g	Glass transition temperature
T_m	Melting temperature
TBBS	*N*-*tert*-butyl-benzothiazolesulfenamide
TBTD	Tetrabutylthiuram disulfide
TGA	Thermogravimetric analysis
TMTD	Tetramethylthiuram disulfide
TPE	Thermoplastic elastomer
TSE	Thermosetting elastomer

TPO	Thermoplastic olefin elastomer
TPU	Thermoplastic polyurethane
TPV	Thermoplastic vulcanizate
V	Average fluid velocity
VOC	Volatile organic compound
W	Watt

Subject Index