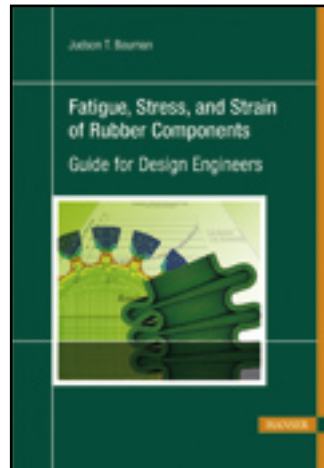


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Fatigue, Stress, and Strain of Rubber Components

Guide for Design Engineers

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2 Rubber Stress-Strain Behavior

2.1 Challenges of Rubber Behavior

There are three distinct categories of the stress-strain behavior of elastomers which make engineering design with these materials so challenging. They are: cyclic property changes, large deformation response, and non-linearity of the stress-strain curve. Most analytical work, such as finite element analysis, is aimed at the non-linear and large deformation responses. However, although the changes in behavior with cycles of load or deformation are vitally important when it comes to predicting in-service behavior, they are dealt with the least in the engineering literature.

As we will show in this chapter, a rubber test piece will change its stress-strain curve radically after the first application of load and continue to change behavior thereafter, depending primarily on the magnitude and timing of the deformations. We will refer to this category of behaviors as cyclic or time dependent properties. The second category is the large deformation response of rubber. This important behavior is seen in its soft or low modulus response to applied loads or deformations. Commonly, it is the principal reason for selecting an elastomer for a particular part or component. Non-linear stress-strain response is the third category of behaviors which challenges the design engineer.

These three categories are not the only unique features of rubber behavior, but they are the most challenging for the design engineer. Other significant characteristics have to do with temperature and immersion in aggressive fluids. Rubber typically has larger changes in stress-strain properties with temperature than other structural materials. It also is more vulnerable to deterioration of its mechanical properties in the presence of many liquids and some gases.

2.2 Characteristics of Stress-Strain Behavior

To begin explaining the various typical characteristics we will describe a simple stress-strain test, noting the special features of the response.

2.2.1 Low Elastic Modulus, High Elongation at Break, and Non-Linearity

Figure 2.1 shows the stress-strain plot of the extension of a typical elastomer tensile specimen. After considering the huge percent deformation, its most obvious feature is its

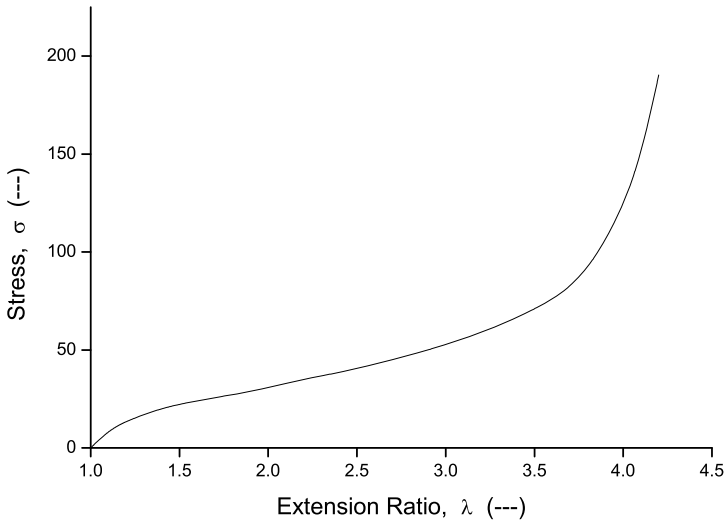


Figure 2.1 Extension of elastomer tensile specimen

non-linearity. Note that there is no constant value of the elastic modulus, i.e., $\sigma = E\varepsilon$ is only true if E is a variable. It is this characteristic that limits the usefulness of simple design equations which depend on linear behavior. Also some writers refer to the knee of the curve ($1.0 < \lambda < 1.5$) as a “yield” point; however, the elastomer response has nothing to do with the yield of metals, which requires slipping on crystalline planes.

It is instructive to note that the elastic modulus of steel is approx. 29,000,000 psi while a typical elastomer modulus is on the order of 1000 psi. Also consider that ASTM A36 steel yields at or above 36,000 psi, which corresponds to a strain of 0.12%. A typical elastomer can extend to 300% strain without rupture. These huge differences in stress-strain parameters give a rough idea of how misleading it can be to extrapolate conventional metals experience to elastomers.

2.2.2 Hysteresis

In Figure 2.2, the test machine has returned to zero stroke producing a retraction curve well below the extension. The difference in stress, $\Delta\sigma$, is hysteresis. Hysteresis is caused by internal friction, which resists both extension and contraction. Hysteresis varies with the elastomer; it is least in unreinforced natural rubber and larger in most other elastomers. It increases with the amount of reinforcing material present and with the strain rate of the test. Note that the extension curve starts above zero strain and the retraction curve likewise ends above zero strain. This is an expected response due to creep which occurs after the first extension. Creep is covered later.

Figures 2.1 and 2.2 represent the large deformation and non-linear behaviors of rubber. Many of the coefficients for design equations and constants for finite element analysis do

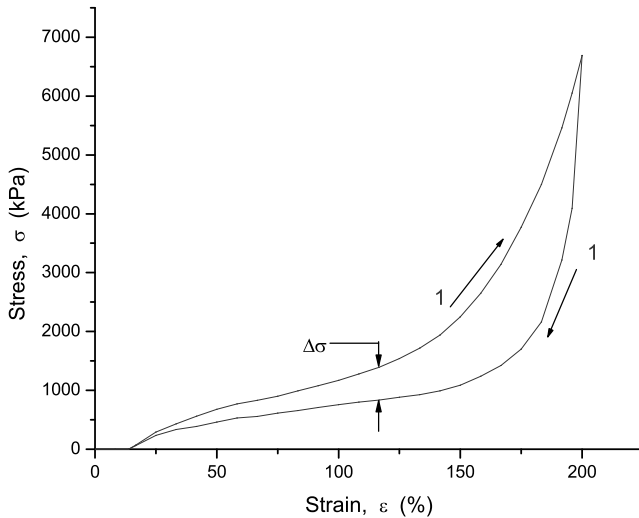


Figure 2.2 Extension and retraction of tensile specimen exhibiting hysteresis

not adequately represent the behaviors seen in Figs. 2.1 and 2.2. Particularly, the retraction curve is almost never represented in analysis. In addition, the extension curve may only be partially represented. Some models do not reflect the increasing slope above the knee and some do not even represent the knee of the test curve. So, these analytical methods are limited in what ranges of strain and stroke direction they can represent accurately.

2.2.3 Stress Relaxation

In Figure 2.3, there are two successive extension/retraction cycles taken to the same maximum stroke. The decrease in measured stress of the second cycle is due to stress relaxation. Stress relaxation is defined as a decrease in stress with time at constant deformation. In rubber, stress relaxation occurs due to the slipping of entanglements loosening the network of molecular chains so they apply less force. This action occurs under both constant deformation and cyclic deformation. The magnitude of stress relaxation effects, particularly in the first few deformation cycles, must be taken into account in engineering calculations. Stress relaxation under cyclic loading is representative of the cyclic behavior of rubber.

2.2.4 Creep

The related phenomenon of creep is also significant in elastomers. Creep is extension with time under a load. Creep, where the length of a specimen has been increased by the extension, is shown by the return stroke reaching zero stress at a positive strain. The effect

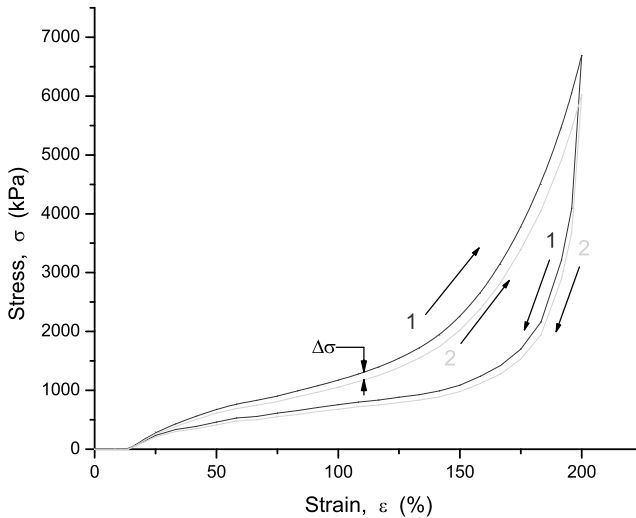


Figure 2.3 Stress relaxation

is illustrated by Figs. 2.2 and 2.3. Most rubber components are designed to avoid creep in tension or shear. In those modes, creep can easily lead to failure by rupture. The usual design approach is to pass high loads in compression.

2.2.5 Mullins Effect

The Mullins effect is perhaps the most dramatic of the effects occurring in cyclic deformation. In Figure 2.4, three extension-retraction cycles to successively higher maxima are shown. Figures 2.2 and 2.3 represented the behavior of a specimen in later cycles. Figure 2.4 represents the behavior of a specimen in its first cycle when it is freshly molded and has seen no previous deformation. Here we see the first cycle extension and retraction to a maximum of 100% strain (point A). In the second extension, the stress is greatly reduced and only turns up to meet the first curve at the maximum of the first cycle. The second extension is continued past the 100% point, where the stress remains elevated as if a continuation of the first extension. The second extension is stopped and reversed at 150% (point B). The hysteretic effect where the extension curve lies above the retraction curve can be seen here. The retraction curve, it should be noted, meets and nearly coincides with the first cycle retraction at some strain below 100%. The third extension, like the second, lies well below the first. Similar to the second, the third extension only turns up to meet the second at the second's maximum of 150%. The third extension similarly appears to be a continuation of the second cycle extension after 150%. At 200% (point C) extension the third cycle is reversed and the retraction intercepts the second cycle retraction just as the second cycle intercepted the first. For clarity in explaining the Mullins Effect, Fig. 2.4 was constructed omitting the cycle to cycle stress relaxation which

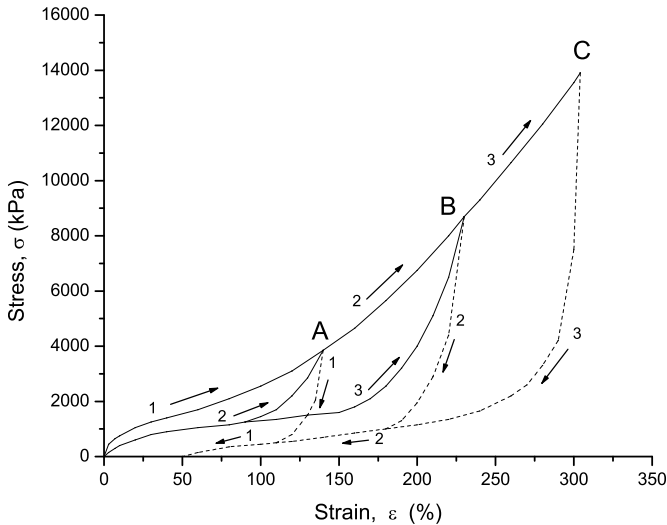


Figure 2.4 Mullins effect

occurs in both extension and retraction of an actual test. The effect of stress relaxation is covered later.

This remarkable pattern of sudden decrease in stress after the first cycle to a particular strain can be understood in terms of the rupture of the more tautly stretched chain segments during the first extension. Thus, in the second extension, at the intermediate strains, many chains are already broken and no longer resisting the extension so the stress must be lower.

As noted earlier, there is one difference between this explanation and an actual test. In practice, upon returning to the first cycle's maximum strain, the peak stress of the second cycle will be less. Likewise, the third will be less than the second at the second's maximum, and so on. Successive extension cycles to the same maximum will show a declining peak stress from cycle to cycle. In addition, the decline in stress will be seen throughout the extension and retraction cycles. This effect is due to stress relaxation. After several such cycles of declining stress the effect may seem to disappear, because its magnitude decreases as a negative exponential function. In any case, the magnitude of the stress relaxation response is much smaller than the abrupt decline from the first extension to the second caused by rupturing of the tauter polymer chains. Stress relaxation must be considered in interpreting the cyclic stress-strain response.

2.2.6 Reinforcement

Reinforcement in elastomers most often means an increase in stiffness rather than strength, although some increase in ultimate strength is usual. In a typical case, reinforcing will increase the stress in the mid-range of strain by a factor of three and increase the ulti-

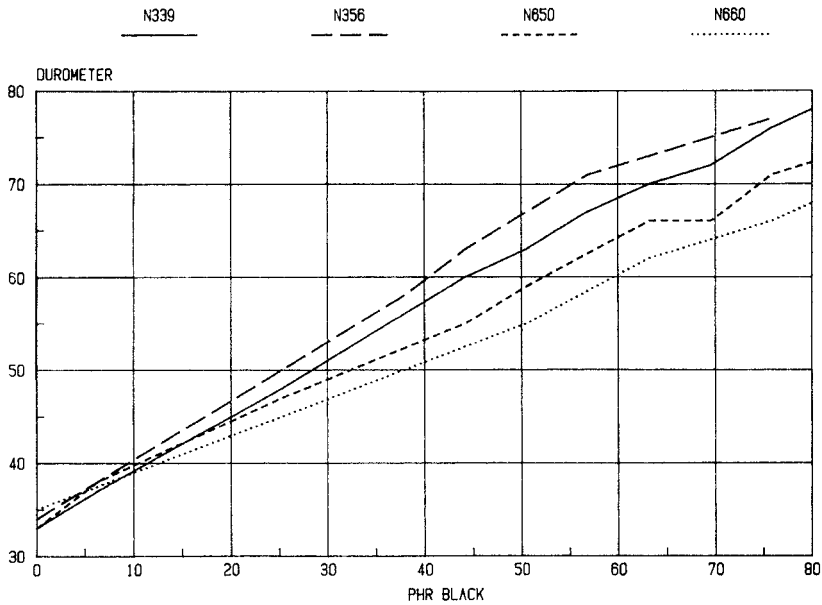


Figure 2.5 Shore A hardness as a function of carbon black loading

mate strength by only 10%. As mentioned earlier, most elastomers of interest to the design engineer are reinforced by adding fine particles to the mix before vulcanization. The most common, and the one which produces the greatest increase in stiffness, is carbon black. After carbon black, fine silica is often encountered. In some cases, inexpensive particulates, called “fillers”, are added as a cost saving measure. There is no hard line between a reinforcing particulate and a filler. Most fillers reinforce to some degree (see Fig. 2.5) and reinforcing particulates often reduce manufacturing costs. However, in design we are most interested in those which improve the physical properties.

2.2.7 Cyclic Frequency and Strain Rate

The $\Delta\sigma$ of the hysteresis loop of extension-retraction cycles to the same maximum is increased with frequency or strain rate. This phenomenon, illustrated in Fig. 2.6, is best understood as a function of strain rate. The effect is often shown in plotted data as function of frequency. But in the data, the distinction between strain rate increase and frequency increase cannot be made. Consider a sine wave strain of a particular frequency and notice that one can compute the maximum rate of change of strain by getting the slope of the curve at the zero strain. Then, if the strain amplitude is kept the same while the frequency is increased, the slope of the strain curve at zero strain must increase. In fact, there is no physical argument to show that a frequency increase separate from strain rate increase would cause an increase in the hysteresis magnitude. Whereas if the hysteresis is due to the making and breaking of the weak van der Waals and polar bonds between

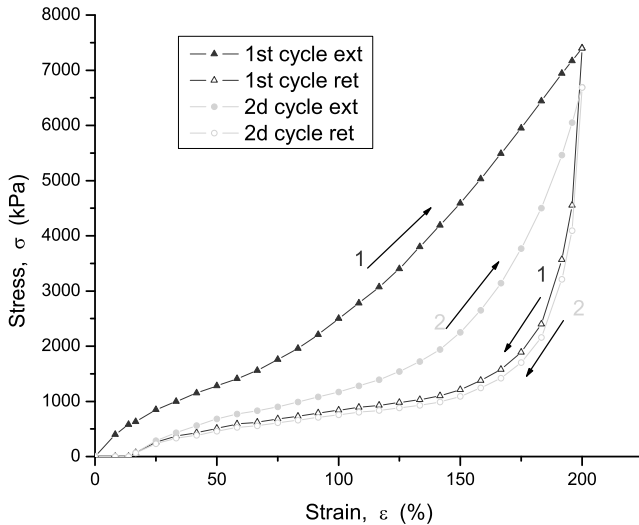


Figure 2.6 Effect of cyclic frequency or strain rate

adjacent chains, a time dependent process, then the increase of stress at higher strain rates falls into place. This explanation of the internal friction of elastomers is expanded in Chapter 3.

2.2.8 Temperature

All of the phenomena described earlier are affected by temperature. In this discussion, the effect of increasing temperature is considered separately from any chemical action associated with the temperature rise. Thus, the temperature effects considered are those which do not cause permanent degradation or change of the physical properties. Within those limits, the effects of increasing temperature are:

- Hysteresis magnitude decreases.
- Fatigue life is shortened.
- Recovery from set takes place more rapidly.
- Stress relaxation is more rapid.
- Creep is more rapid.

2.2.9 Immersion Effects

In this text we will not discuss the effects of immersion in aggressive environments in any detail. The chemical reactions between some fluids and various elastomers can have a serious deleterious effect on the elastomers' mechanical properties. These effects properly

belong in the field of chemistry. The design engineer can deal with this variable by conducting mechanical property tests in the expected operating environment. It is also possible to conduct tests where the degradation is accelerated by raising the temperature during the test and using the Arrhenius relation (see Chapter 9) to predict the decline in properties at the expected service temperature.

2.2.10 Strain Crystallization

Several elastomers exhibit crystallization at high strains. Unreinforced natural rubber is the most prominent of these. When strain crystallization occurs, the stress-strain curve steepens markedly and the ultimate failure strength is raised. Internally the long polymeric chains have been pulled into parallel alignment by the large extension so they are able to form a regular crystalline structure with adjacent chains. Figure 2.7 is a sketch showing the difference in curve shape between a crystallizing and a non-crystallizing elastomer. A group of parallel chains with van der Waals bonding between them requires the simultaneous rupture of all the chains to fail. Thus, the strength of the crystallized group is much greater than a similar non-crystallized group whose chains have slightly different extensions reaching failure load one chain at a time.

It is worth noting that strain crystallization is most prominent in particular elastomers, for example, natural rubber and polychloroprene (neoprene). Particle reinforcement reduces or eliminates the effect entirely. The effect is absent from those elastomers that have large or polar branches to the chain such as acrylo-nitriles.

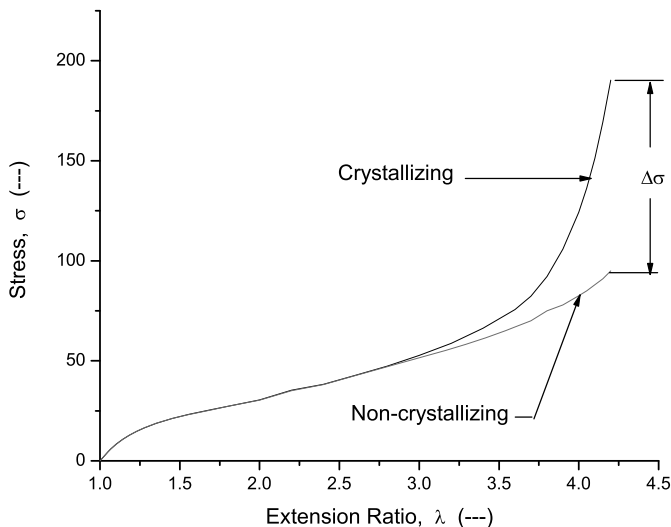


Figure 2.7 Strain induced crystallization

2.2.11 Permanent Set

A unique feature of elastomer behavior is set. Set designates a permanent residual deformation after the applied force or stroke has returned to zero. It is often difficult to measure, because the duration of the force or stroke also produces stress relaxation and/or creep. Figure 2.8 shows the stress-strain trace of a test specimen that has been extended to 100%, held there for a 30 minute period, and was then released. The specimen immediately returned to an 8% strain. Then, over a period of several hours, its length is gradually reduced to leave a permanent set of 4%.

Permanent set increases with the time in the deformed state and with the maximum deformation held. Recovery seems to be time dependent much like stress relaxation. One should expect the recovery to occur quickly for the first few seconds and continue at an ever decreasing rate.

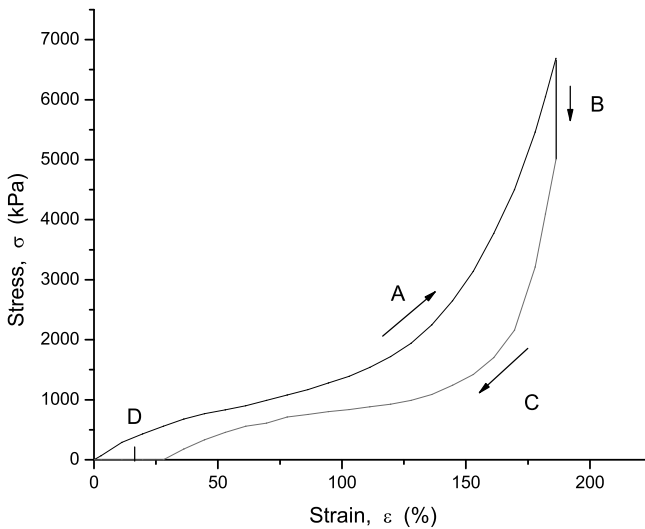


Figure 2.8 Permanent set

2.2.12 Recovery

After an initial extension of a fresh specimen, a second extension to the same strain will produce a greatly lowered stress. However, after some time (measured in hours) without further deformation, some of the lost stress will return. Recovery will not be complete because of permanent set.

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