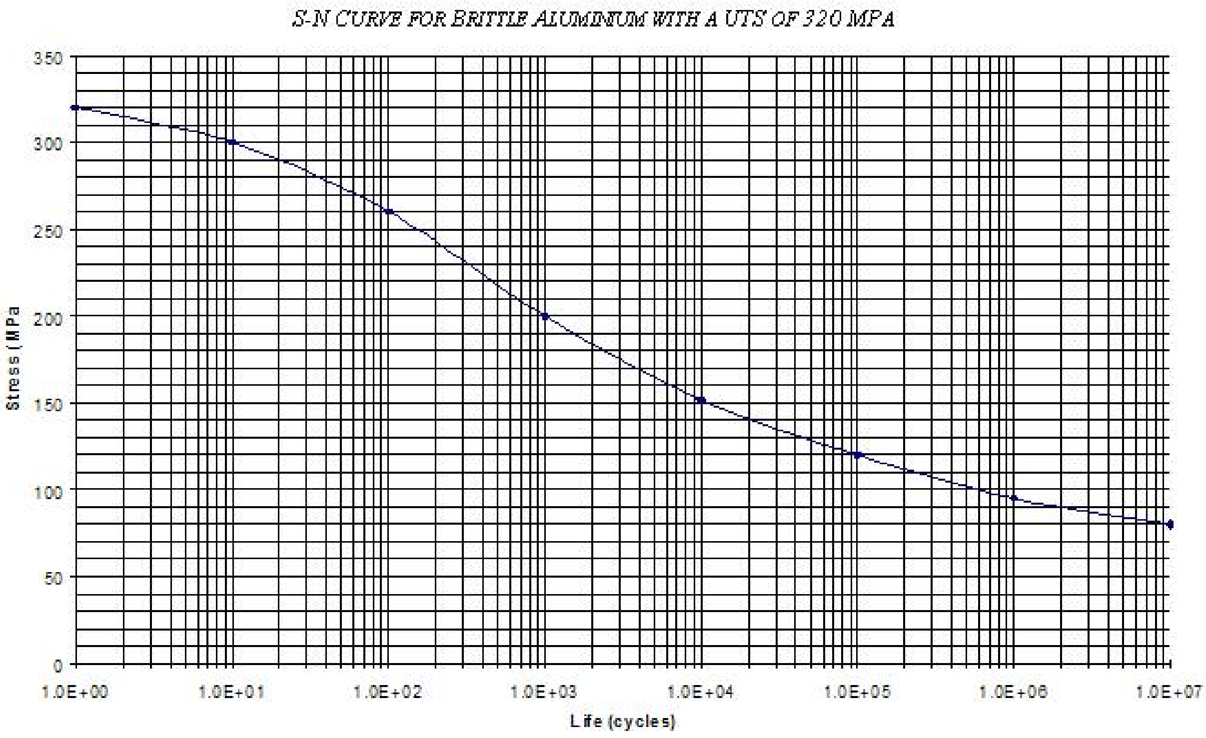
ME102: Subunit 3.3.6: Cyclic Fatigue

You are probably quite familiar with the type of fatigue that occurs when you bend, for example, a paper-clip wire back and forth a few times until it breaks. This process is an example of *low-cycle fatigue*. In general, fatigue is the failure of a material, from repeated use or stress, at a repeated stress value that is lower than that required for failure upon one exposure. Low-cycle fatigue is so called because it occurs at stress repetitions $NR < 10^3$. Another class of fatigue is termed *high-cycle fatigue*, and occurs for stress repetitions $NR > 10^3$. You may be familiar with this sort of failure if you have experienced a catastrophic breakage of a chain, belt, or connecting rod in an internal combustion engine. In other words, high-cycle fatigue occurs because of many (on the order of 10^6) low-stress loadings. You can think of this section as simply providing a review of commonly used methods for correlating data about how machines wear out.

Both high-cycle and low-cycle fatigue are examples of what is called *time-varying load fatigue.* It occurs because of the accumulated permanent structural damage, usually in the form of cracks, acquired from repeated loadings.

High-cycle fatigue usually occurs from repeated deformations in the elastic range, and loading stresses much less than the yield stress of the material. Data for this type of fatigue are commonly analyzed and presented with a stress-lifetime, or S-N, plot. Imagine doing the following experiment. Choose a range of stress values less than the yield stress of the material, and then count the number of repeated loadings at each stress value required for failure of the material. An example of such a plot is shown in the figure below. Note that the scale for NR, or Life (cycles), is logarithmic. Often, such plots may exhibit a fatigue limit; that is, there is a stress value below which repeated loadings do not cause any material damage. This phenomenon manifests as a low plateau on the right hand side of S-N plots.

Such S-N plots are useful guides for lifetime prediction. However, an important difficulty arises because the lifetime is dependent not only upon NR, but also upon the mean stress experienced during that time. For many experimental situations, the mean stress is zero; that is, the material is subject to stress reversal upon each loading. If, however, there is some significant mean stress, then time to failure can be substantially reduced. Data presentation and analysis then becomes a three-dimensional problem. It can be handled approximately by a method attributed to Goodman and Gerber, in which the allowable fluctuating stress amplitude can be expressed as $\sigma_a = \sigma_f(1 - (\sigma_m/\sigma_u)^\gamma)$, where σ_f is the allowable stress for zero-mean loading, σ_m is the mean stress for actual loading, σ_u is the tensile strength of the material, and γ is an exponent ranging from 1 (for brittle materials) to 2 (ductile materials).



S-N curve for brittle Aluminum. Note that the curve covers both low-cyle and high-cycle fatigue limits. Figure in the public domain obtained from this location and attributed to Wikipedia user BenPAllen.

Other phenomena that can be approximately accommodated by simple S-N analysis are the effects of surface finish, type of stress, thermal history, and other miscellaneous effects. These phenomena can be approximately handled by multiplicative factors that lower the S-N curve by an empirical, fractional amount.

A similar strategy can be used to predict the effects of accumulated loadings under different stress conditions. This technique is commonly known as Miner's rule.

In low-cycle fatigue, strains are typically plastic. For such situations, it is more common to correlate strain with lifetime rather than stress (as in high-cycle fatigue). This type of relationship is often called a *Coffin-Manson relation*, and can be written in a form resembling $S = k N^c$, where S is the strain amplitude, k is a constant, N is the number of strains to failure, and c is a negative exponent on the order of –0.7 to –0.5.

Several approaches have been proposed to deal with intermediate-cycle fatigue; the fundamental mathematical problem is representing the S-shaped curve in the above figure with appropriate parameters. There are clearly three regions in the curve.

In practice, the effects of cyclic fatigue can be moderated with designs that focus on two factors: keeping materials in compression as much as possible and avoiding regions of stress concentration in product design.