Accelerating Validation Testing

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Bringing new or improved products to market sooner has long been proven profitable for companies. One way to help shorten the time-to-market is to accelerate validation testing. That is, shorten the test time required to validate a new or improved product.

Fatigue testing is a common validation test that often involves long periods of time. However, the time can be shortened by an often forgotten—or unknown—concept of accumulated damage, which works especially well for mechanical components such as gears and shafts.

Accumulated damage is based on a fatigue curve for the material and Miner's rule: damage is the life already expended divided by the total life available according to the fatigue curve for the material. If one knows the accumulated damage for any test

conditions, one can use an accelerated test—higher torques or forces at faster speeds—to produce the same accumulated damage, thereby completing the test in a much shorter time.

$$\sigma = b \cdot N^m \qquad (1)$$

Where:
σ = Stress
N = Cycles
b = Coefficient
m = Exponent

For many mechanical components, fatigue curves define allowable forces, torques or stresses as a function of cycles. Many investigators have shown that power-function equations define fatigue properties for mechanical components, as shown in Equation 1, where stress is a function of cycles (Ref. 1).

A typical fatigue curve is often called an S-N curve in which S = Stress and N = Cycles (Fig. 1). Notice that it declines very sharply at the beginning and trails off at higher cycles. One could allow the curve to continue forever, which means there is always a fatigue limit to any material. Some, however, declare an endurance limit—either at one million cycles or at ten million cycles. This means there is infinite life at or below a specific stress level. Others change the curve at a specific number of cycles to reflect the realities found from testing. Whatever your experience, base your decision on actual test results.

The lower end of the curve is asymptotic to the vertical axis (approaching the vertical axis, but never getting there, even going on forever), which means, theoretically, there could be an infinitely high stress if the component does not experience any cycles. This is not physically possible in that to create stress,
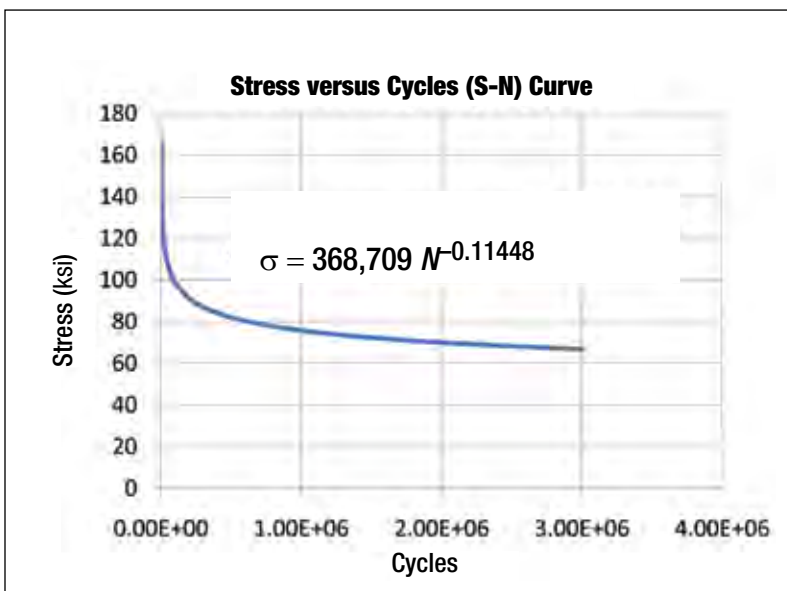

Figure 1—Typical S-N curve.

Stress versus Cycles (S-N) Curve

$\sigma = 368{,}709\ N^{-0.11448}$

a load must be applied and at least one cycle. Material has an ultimate stress level at one cycle, but it is not infinitely high. The fatigue curve, then, is limited on the lower end to the ultimate stress. To account for low-cycle fatigue, the fatigue curve is stopped at 1,000 cycles.

It may be visually easier to interpret the curve if it is plotted on log-log paper to produce a straight line, along with the limit at 1,000 cycles (Fig. 2).

The S-N curve relates life (cycles) and stress for a specific material, heat treatment, special conditioning or any other process that influences the fatigue property. Be sure to define the fatigue curve from actual test results.

Figure 3 is an exaggerated S-N curve that shows Miner's rule (Ref. 2)—linear damage accumulation—for calculating and accumulating damage. The principle may be simple—damage is cycles used divided by cycles allowable—but it is very powerful. Of course, there are other damage-accumulation techniques that readers could use if they wish. But Miner's rule will be used in this article.

If one tested a component to the stress level and number of cycles of point P1 in Figure 3, it might take longer than desired; but one can shorten the time by testing at a higher stress.

Figure 4 illustrates the concept of accelerated testing. A second point (P2) accumulates the same amount of damage as P1, meaning that P2 must be located on a curve that runs through P1 and be parallel to the original S-N curve.

The proportion of life used (damage) is the same for the two points shown in Figure 4; it just may not visually look that way because the S-N curve (straight line) is drawn on log-log coordinates.

Perhaps an example with numbers will improve clarity. The S-N curve's equation in Figures 1 and 2 will be used for the example.

Let us suppose the duty cycle requires 200,000 cycles at a stress level of 91 ksi. To complete the test in half the time (100,000 cycles), the stress must be at 99 ksi to accumulate the same amount of damage:

$\sigma(ksi) = 368,709 \, (200,000)^{-0.11448} = 91$ ksi
$\sigma(ksi) = 368,709 \, (100,000)^{-0.11448} = 99$ ksi (2)

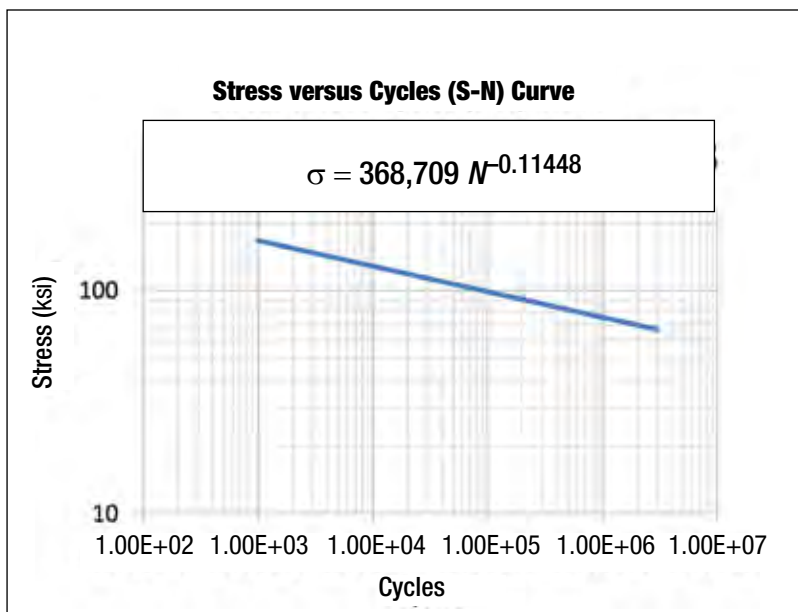The previous example is simple—i.e., one

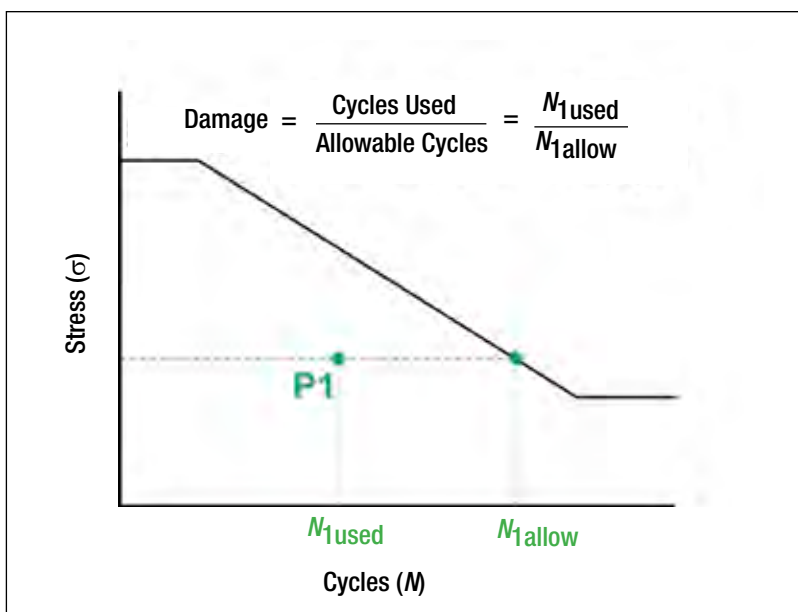Figure 2—Typical S-N curve on log-log graph.

Figure 3—Exaggerated S-N curve to illustrate damage.

point. But what if the duty cycle has many points? The same procedure is followed as shown in Figure 5.

There are five stress levels in Figure 5, so there are five different numbers of cycles to accumulate for a total of 200,000 cycles. The accelerated test in Figure 5 shows that testing for 100,000 cycles at 95 ksi accumulates the same amount of damage, which means the test time is reduced by half. Using previous equations for damage, stress (S) and cycles (N) and then re-arranging them as needed, one can

continued

make the calculations shown in Figure 5.

One can use two more relationships that are shown in Figure 6. Stress is proportional to a geometry factor, and the number of cycles equals speed X time. Although torque is used in Figure 6, force could just as easily have been used. To move from one point to another on any curve one must use the curve's equation; it shows how the derivation creates a simple method to go from one point to another on the same curve, and how one may use more common duty cycle measurements—i.e., torque (or force), speed and time.

Equation 3 shows the use of torque, geometry, speed and time to replace stress and cycles (also shown in Fig. 6) within the fatigue curve equation, where:

$$\sigma = b \bullet N^m$$

$$\text{Torque} \bullet \text{Geometry Factor} = b(\text{Speed} \bullet \text{Time})^m$$

$$(3)$$

If one wants to accelerate a gear test, for example, then one knows that the gear tooth stress equals the tooth force from the torque X a geometry factor. That relationship is well documented in technical literature such as AGMA documents (Ref. 3).

The next step is to change each duty cycle point (torque 1, speed 1 and time 1) to the test condition (torque 2, speed 2 and time 2). The derivation to achieve that change is in Equation 4:

$$\frac{T1 \bullet J = b(S1 \bullet t1)^m}{T2 \bullet J = b(S2 \bullet t2)^m}$$

$$\frac{T1}{T2} = \left(\frac{S1 \bullet t1}{S2 \bullet t2}\right)^m$$

$$S1 \bullet t1 \bullet T1^{-\left(\frac{1}{m}\right)} = S2 \bullet t2 \bullet T2^{-\left(\frac{1}{m}\right)}$$
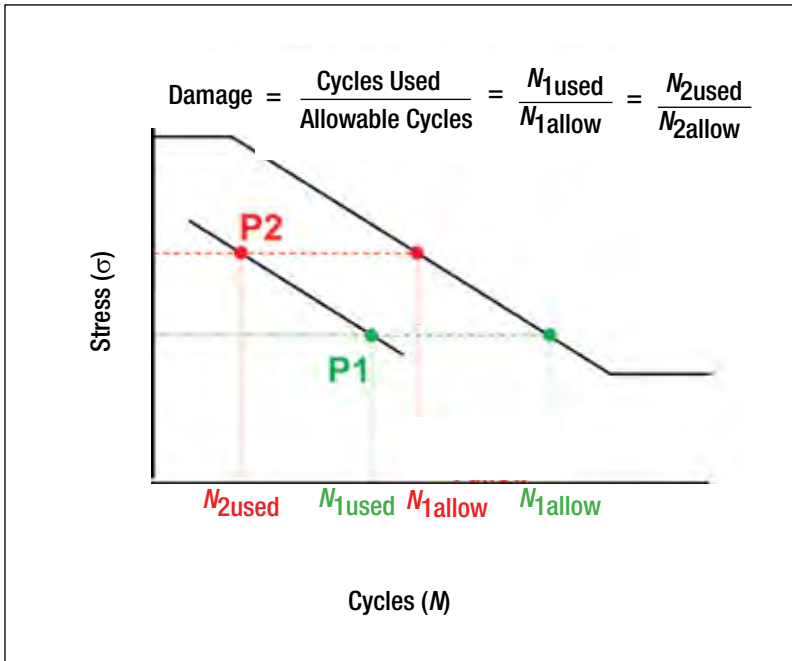
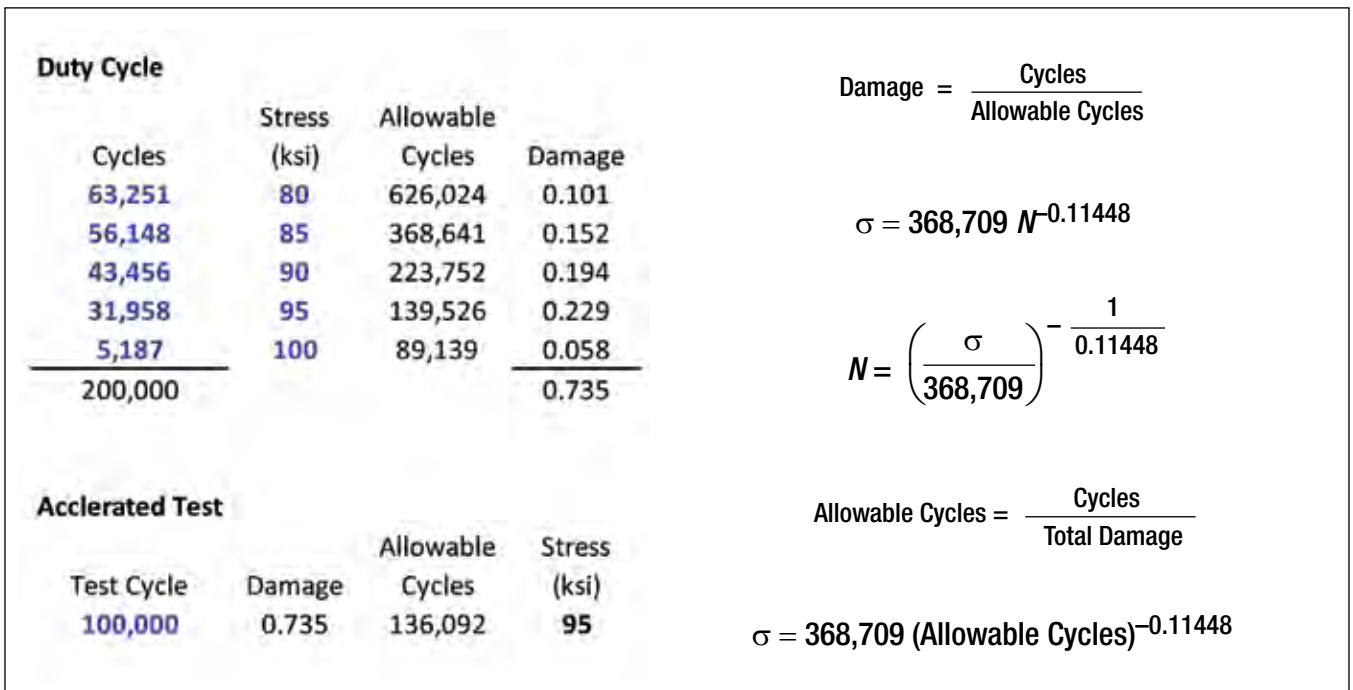$$(4)$$

Figure 4—Exaggerated S-N curve with two points.

Figure 5—One accelerated test point replaces complex duty cycle.

Where:
S = Speed (rpm)
t = time (hours)
T = Torque (lb-ft)
J = Geometry Factor
m = Exponent

When each duty cycle point is converted to the test condition, the test condition duplicates the same damage as entire duty cycle.

Figure 7 shows an example of a gear duty cycle converted to a gear test cycle. If the gears were tested according to the duty cycle, it would take 36,000 hours; but an accelerated test would only take 22.6 hours—a fantastic savings in test time.

Accelerated testing must be based on well-known fatigue (S-N) curves and test experience to assure that new failure modes would not be introduced. Without such knowledge and experience, one can introduce failure modes that would not appear in real applications or pass tests that are not related to the material's real fatigue life. However, properly used, accelerated testing can save a company time and money in getting products to market much sooner. And that means bringing in new revenue much sooner. ⚙

References:
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2. Juvinall, R.C. and K.M. Marshek. *Fundamentals of Machine Component Design*, Fourth Edition, John Wiley and Sons, Inc., Section 8.12 "Fatigue Life Prediction with Randomly Varying Loads."

3. ANSI/AGMA 2001–D04. *Fundamental Rating Factors and Calculations Methods for Involute Spur and Helical Gear Teeth*.
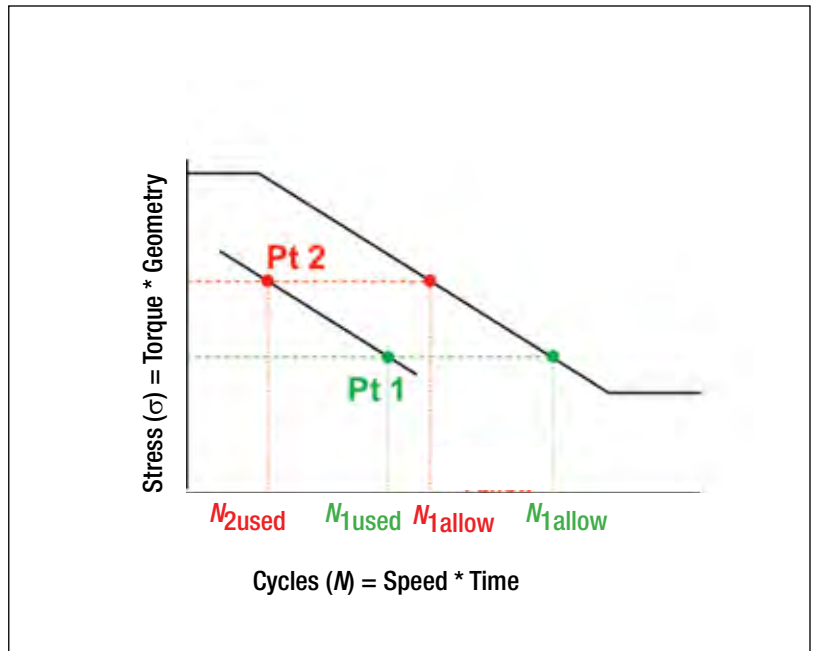
Figure 6—Moving from one point to another.
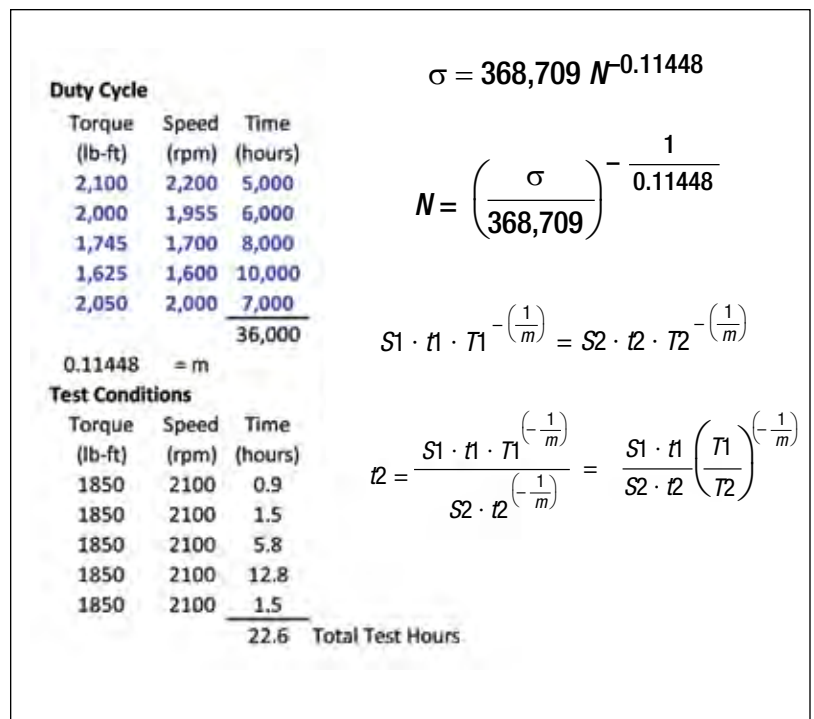
Figure 7—Example of duty cycle conversion to test condition.

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