INCREASING GEAR SET POWER DENSITY
High-strength, high-toughness steels can be used to increase power density while addressing critical components of gear set design.

INCREASING THE POWER DENSITY OF YOUR GEAR SETS allows you to develop durable gear sets with an existing design but higher horsepower and torque capabilities or with the same capacity, but reduced gear size and mass for light weighting.

Increasing power density can be achieved by addressing three critical components of gear set design: geometry, surface finish, and metallurgy. By modifying geometry, one can avoid stress concentrations arising from geometric factors. Improving surface finish through grinding, honing, or super finishing improves resistance to root-bending fatigue, pitting fatigue, and scuffing damage. The metallurgical tactics include the use of clean steels as discussed in last month’s Materials Matter column, removal of intergranular oxidation formed during heat treatment by grinding, shot peening gear roots to generate compressive residual stresses, and optimization of case depth and heat treatment.

This Materials Matter column focuses on employing affordable higher strength steels in order to increase fatigue strength, wear resistance, and resistance to bending overload damage. One of the tremendous advantages steels have over other materials is the broad range of strengths they can achieve by changing the chemistry and heat-treatment process. Finding stronger steels than those typically used for gears is not too difficult. What is challenging is getting significantly stronger steels that exhibit sufficient toughness to avoid brittle or ductile overload failures or early fatigue failures in gear sets subjected to high loads and/or transient loads. The classical trade-off in all materials is that increasing strength nearly always results in reduced toughness, but with careful design and processing, steels can achieve significant strength improvement and still display excellent toughness properties.

To assess fatigue strength and toughness, one needs only to look for commonly available data on steel properties. An engineering approximation can be made that the fatigue strength is conservatively estimated to be 50 percent of the ultimate tensile strength. And, the most common method to assess toughness is the Charpy V-notch impact toughness test. Figure 2 shows the range of estimated fatigue strengths and impact toughness combinations achievable by common gear steels (8620, 4320, 4820, 9310, 3310) and compares that to some available, patent-pending, high-strength, high-toughness gear steels. In some cases, a 50 percent increase in fatigue strength can be achieved with good, and sometimes even better, toughness than the more common gear steels.

It is worthwhile to take a moment to consider how higher strength steels further drive the need for clean steels. The AGMA Metallurgy and Materials committee has been revising the “AGMA Information Sheet 923 — Metallurgical Specifications for Steel Gearing.” The addition of a grade 4 steel for gearing has been proposed, which includes, among other details, more precise and design-relevant metrics for steel cleanness as described in the January 2017 featured article “Gear Design Relevant Steel Cleanness Metrics,” and in April 2017’s “Steel Cleanness and Why Measurement Matters,” May 2017’s “Industry Standards for Steel Cleanness,” and June 2017’s “Power Density; Why Clean Steel Matter” Materials Matter articles.

Figure 1 describes the relationship between inclusion size and steel fatigue strength based on the extensive work of Murakami and colleagues, wherein they found that fatigue strength was related to the square root area of an inclusion perpendicular to the principal stress.
direction as described by Equation 1. As steel strength is increased and gears are subjected to higher loads, the critical flaw size that limits the fatigue strength goes down. As our industry adopts higher strength steels to improve the capacity of advanced gear sets, having clean steels becomes increasingly important.

\[ \sigma_{\text{fatigue}} = \frac{1.54 \Delta K_{\text{th}}}{\sqrt{\pi \times \text{area}}} \]  

EQUATION 1

Where \( \Delta K_{\text{th}} \) is the threshold, or minimum stress intensity required for fatigue crack growth and \( \sqrt{\text{area}} \) represents the square root area of an inclusion-assessed perpendicular to the principal stress.

In order to assess the magnitude of the potential for either light weighting or increased power throughput, one needs to assess the effects of traditional versus high-strength, high-toughness gear steels on gear set design. The Technical Resource “ANSI/AGMA 2001-D04, Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth” provides a framework and the equations necessary to make such estimates. In table 4 of this AGMA resource, the allowable bending stress for grade 3 gears is listed at 75 KSI. This value also is shown as the AGMA limit in Figure 1. The allowable limit for high-strength, high-toughness steels also is shown in Figure 1 at 110 KSI. In each case, for traditional and for high-strength, high-toughness gear steels, the actual fatigue capacity may be measurably higher than these conservative limits and will be further dependent on the steel grade and heat-treatment processes selected. For the sake of illustration, the bending stress fatigue limits of 75 KSI and 110 KSI were selected for further calculations.

A generic pinion and gear set was conceived, and the calculations for this gear set were built in a spreadsheet in order to assess the magnitude of potential benefits. Figures 3 and 4 show the results of these calculations. The switch from commonly used gear steels to high-strength, high-toughness gear steels can result in a 45-percent horsepower increase in an increased through-put initiative or a 30-percent weight reduction in a light weighting initiative. When you need to design your gear sets to go beyond typical gear performance expectations, high-strength, high-toughness gear steels can help get you there. Collaboration between gear designers and materials designers will continue to drive improvements in our industry.

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Figure 3: Assuming an increase in fatigue strength from 75 to 110 KSI results in a 45-percent increase in gear set horsepower capacity. Relative horsepower capacity (as a percentage) as a function of the bending fatigue strength calculated per the AGMA 2001-D04 technical resource.

Figure 4: Assuming an increase in fatigue strength from 75 to 110 KSI results in a 30-percent reduction in gear set mass. Relative gear set mass (as a percentage) as a function of the bending fatigue strength calculated per the AGMA 2001-D04 technical resource.