Engineered Gear Steels: A Review

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The selection of the proper steel for a given gear application is dependent on many factors. This paper discusses the many aspects related to material, design, manufacture, and application variables. The results of several studies on the optimization of alloy design for gas- and plasma-carburization processing are reviewed.

Introduction

Improved performance and reliability at the lowest cost per unit of life is a goal common to all industries. It is especially true for the automotive, truck, and power transmission industries, where systems comprised of gears, shafts, bearings, springs, discs, sheaves, rollers and/or other mechanical components are being asked to deliver higher strength and greater power throughput while using smaller, lighter weight designs. The aim is to achieve some combination of weight savings, higher fuel economy, lower vehicle emissions, decreased downtime and maintenance requirements, quiet operation and design flexibility. These, in turn, provide added value in the form of improved performance, manufacturability and life cycle costs.

Comprehensive Approach

Many factors affect the ultimate performance of a component. These include raw material, design, processing/product and application variables as shown in Table 1.

Table 1—Important Variables.

Raw Materials	Design	Processing/Product	Application
Cleanness Alloy Selection Alloy Design Formability Machinability Chemistry Control Hardenability Control Strength/Toughness Fatigue Strength Inclusion Engineering Surface Quality Dimensional Quality Price/Delivery	Innate Validity Applied Stresses Residual Stresses Process Selection	Heat Treatment • Case/Core Properties • Type: carburize, nitride induction harden • IGO Control • NMTP Control Distortion Control Residual Stress Generation • heat treat • peening Geometry/Contour Control Surface Finish • grinding • polishing • superfinishing • peening Surface Treatments/Coatings	Lubricant Type • base • viscosity • temperature/oxidation stability • additives Lambda Ratio Contamination • chemical • mechanical • electrical Loading • nominal • instantaneous Modes of Damage • surface • subsurface

Optimization of the process and product for any given component is complex and requires a comprehensive interdisciplinary engineering approach. An overall concept is illustrated in Figure 1.

The base of the performance pyramid should be considered for each component in a system. A successful design depends on quality engineering within and between disciplines for any given part. The metallurgical, mechanical and tribological aspects must all be considered. Process and product factors are extremely interdependent. One begets and/or depends on the other.

When designing a component, the engineer does not simply begin in the material column and select a grade with certain attributes. Rather, several important questions must first be asked:

1. What are the application rigors the component must endure?
2. How will the part be made? How will its basic form be generated? What heat treatment will be used?
3. How will a beneficial residual compressive stress state be generated in the contact surface region—via heat treatment and/or post-heat-treatment processes?
4. What types of surface finishes and geometry (contouring) aspects will be involved?
5. What lubricants, temperatures, contaminants and loading (nominal and instantaneous) must be considered?
6. Will surface engineering capabilities (finishes, textures, coatings, etc.) be used?

These are just a few of the application questions. Many others undoubtedly should be asked. The crux is that the engineer must draw on the various disciplines to design a given component. Once the questions are answered, the materials engineer can provide a knowledge-based recommendation for the material of choice to achieve the required manufacturability, performance and cost.

System Upgrading

This approach can be sequentially applied to each component in a subassembly or full system. The engineering team can determine which component is the "weakest link." That part can then be upgraded. Obviously, some other component will then become the weakest link. By iteratively stepping through the components, the system can be continuously improved.

Most automotive transmission models will be expected to double in power throughput capacity from one useful lifetime to the next. Teamwork between the metallurgical, mechanical and

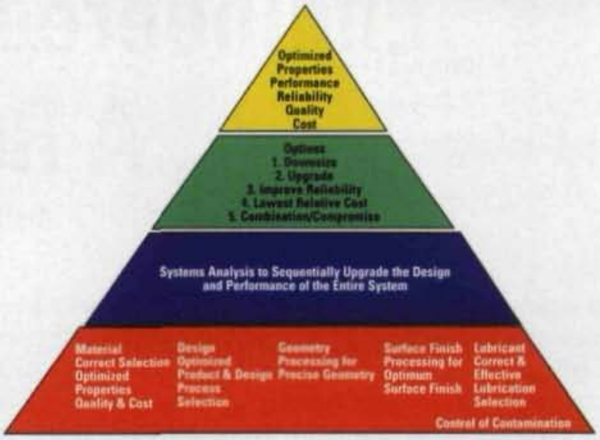


Figure 1—The Performance Pyramid. Beginning with the base (Table 1), the individual components can be optimized. Subsequently, by moving up the pyramid, a system can be optimized.

tribological team members can readily achieve such requirements—and, oftentimes, more.

Engineering Advancements

Fortunately, technical advances in each of these areas have been occurring for many years. The subsequent portions of this paper will review some of the specific improvements related to gear steels and their thermal processing.

Steel Cleanness

This factor heads the material listing because of its fundamental importance. It is the foundation upon which high performance can be built. It is generally well accepted that fewer and smaller inclusions translate to longer life relative to subsurface initiated fatigue.

Today's clean steels have resulted from many improvements in steelmaking practices. The melting furnace is basically used to provide liquid metal. Secondary metallurgical techniques in ladle refining and teeming practice have become the key elements. Important factors include degassing and deoxidation practices, temperature control, inert gas shrouding, improved refractories and the use of bottom-poured ingots or significantly improved tundish systems and large cross-section continuous casters (Ref. 1). It is especially important to prevent reoxidation during teeming/casting and any type of exogenous inclusions (Ref. 2).

Continuing advances in internal quality have resulted from the ability to accurately measure the internal cleanness over a significant volume of steel. Historical test methods, such as microscopic evaluation, magnetic particle testing and oxygen analysis, are valuable tools. But they are not capable of truly distinguishing relative differences in very clean steels. Ultrasonic testing has proven to be the critical tool. It has the ability to sample sufficient volume and the summed lengths of inclusions per unit volume can be correlated to fatigue life. This is illustrated in Figure 2, which depicts the improvements realized in rolling contact fatigue life of bearings as changes in melting practices created cleaner steels. The cleanness has been improved by four orders of magnitude while the life has improved more than two orders of magnitude.

The compositions and morphologies of any inclusions present are also important. The work by Stover and Leibensperger (Refs. 2 and 4) found alumina-type stringer oxides to have the greatest detrimental effect on contact fatigue life. Sulfides can become operative once the oxide cleanness is very good (Refs. 4 and 15). Other work (Refs. 5 and 6) is corroborative in showing lower sulfur levels and/or shape control of sulfides to be beneficial to fatigue life. These works show this is true for several types of fatigue.

While cleanness is critically important, it is crucial to recognize that cleanness alone cannot guarantee specific performance. Fatigue is a statistically-based phenomenon between competing modes of damage. If conditions such as poor/improper lubrication, contamination, misalignment, poor geometry, design or finish, etc. are present, the effects of clean steel may not be realized. However, assuming that sound engineering and manufacturing principles are followed to avoid or minimize surface-initiated fatigue modes, then clean steel is a necessity.

This is illustrated in Figure 3, which shows the interactive effects of surface finish and cleanness on gear bending fatigue. Steel A is a very clean bottom-poured material while Steel B is typical of an average bloom-cast material. This gear set was designed so the pinion would fail due to bending fatigue. The results strongly illustrate that the full advantage of clean steel can be realized when surface initiation factors are minimized (Ref. 1).

Alloy Design for Carburized Gears

Intergranular oxidation (IGO) at the surface grain boundaries is an important issue for components that are conventionally gas-carburized. It is especially important for gears. Bearing manufacturers enjoy the benefit of grinding all contact surfaces and many non-contact surfaces. As a consequence, the IGO and the usual concomitant nonmartensitic transformation product (NMTP) microstructural layer are removed; but, in gearing, the flanks and especially the roots of the teeth are often not ground.

Fortunately, two methods exist to help combat this issue in gearing: alloy design and plasma carburizing.

Alloy design can be a very effective method to virtually eliminate IGO/NMTP during conventional gas-carburizing

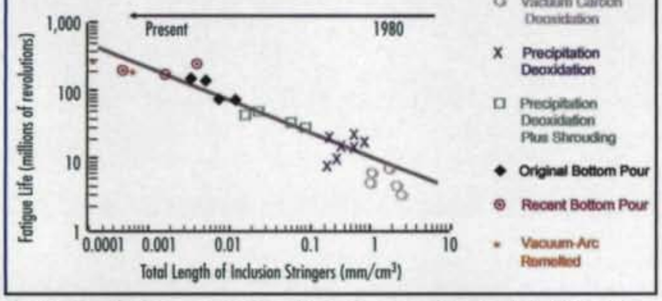


Figure 2—Cleanness and rolling contact fatigue life improvements as steelmaking practices have changed.

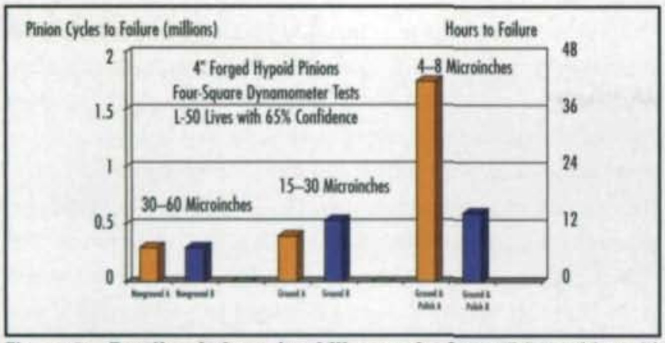


Figure 3—Bending fatigue durability results from 4" forged hypoid pinions using four-square dynamometer tests.

Table 2—Relative Oxidation Potentials for Several Alloying Elements, in Descending Order (Ref. 7).	
Greater Than Fe	Ti, Si, Mn, Cr, (Fe)
Less Than Fe	(Fe), W, Mo, Ni, Cu

Table 3—Alloying Considerations.	
Decrease	Si, Mn, Cr, Ti, P, S
Increase	Mo, Ni

(Refs. 7–14). The approach is based on the oxidation potentials of the alloying elements (Ref. 7), which are shown in Table 2.

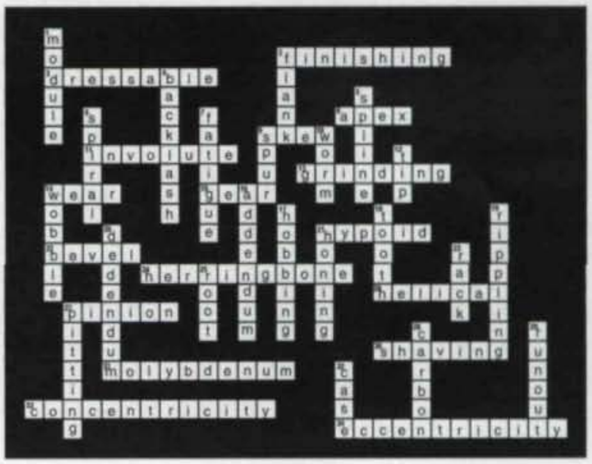
Alloying elements with affinities for oxygen greater than that of iron (Fe) can form oxides in the surface region, particularly in the grain boundaries. As a consequence, they are removed from the matrix and their hardenability effect correspondingly minimized. The oxidized layer is often confined to 10–20 microns; but, the associated NMTP layer can be significantly deeper (Refs. 7 and 13). Importantly, elements with affinities for oxygen less than that of iron are not oxidized and their hardenability effect is not lost; hence, the alloying approach shown in Table 3.

In this approach, silicon (Si) is quite important since it forms the greatest amount of oxide to the deepest depth (Refs. 7 and 13). The oxides of manganese (Mn) and chromium (Cr) form closer to the surface, with the chromium oxides being the shallowest. Many are compound oxides. Excellent descriptive work may be found in References 7, 8, 9, 11 and 12. Phosphorus (P) and sulfur (S) are controlled due to their inherent effects on toughness. Hyde demonstrated the effect of phosphorus on bending fatigue, as shown in Figure 4 (Ref. 12). Basically, it is sufficient to maintain $P < 0.015\%$, which can be readily achieved.

Sulfur is a prime example of an element where consideration must be given to all processing and product factors. For example, low sulfur is very desirable for toughness, formability, and fatigue resistance. But, higher sulfur is often quite necessary for machinability. Thus, the engineer must weigh all competing requirements when establishing an alloy approach. This is true for all the elements. All the production and application factors must be considered. If an element is lowered for one reason, but it has a decided effect on other factors, the engineer must find an approach to replace its effect.

Molybdenum (Mo) plays a crucial role. It does not oxidize

GEAR CROSSWORD ANSWERS



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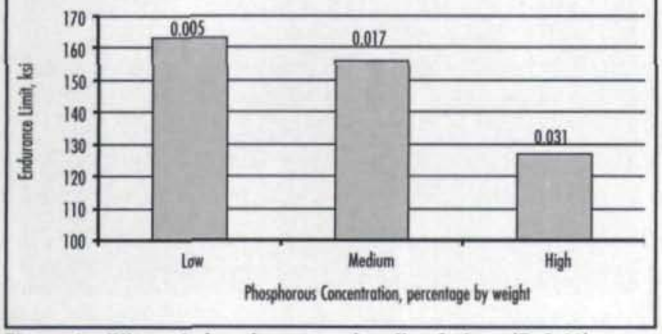

Figure 4—Effect of phosphorous on bending fatigue (Ref. 12).

Table 4—Chemical Composition of Steels in IGO/NMTP Studies.

Steel Type	C	Mn	P	S	Si	Cr	Ni	Mo
4615 Modified	0.16	0.52	0.010	0.015	0.24	0.12	1.75	0.54
8620 Modified	0.21	0.92	0.014	0.023	0.11	0.50	0.38	0.16

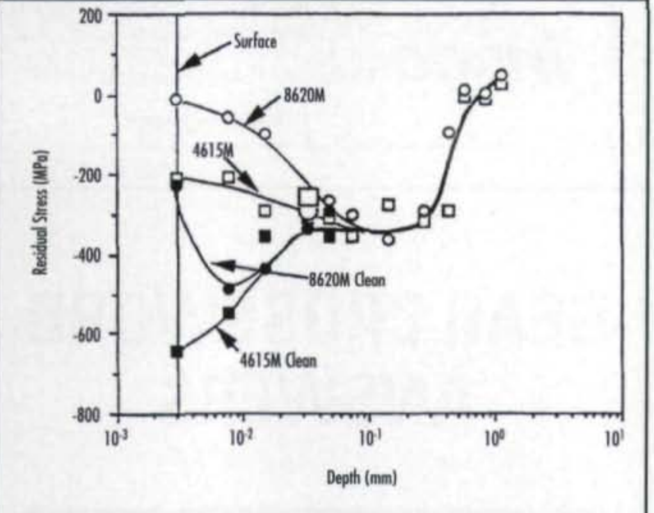

Figure 5—Residual stress distributions in the gas-carburized bending fatigue specimens, both before and after glass-bead cleaning (Ref. 9).

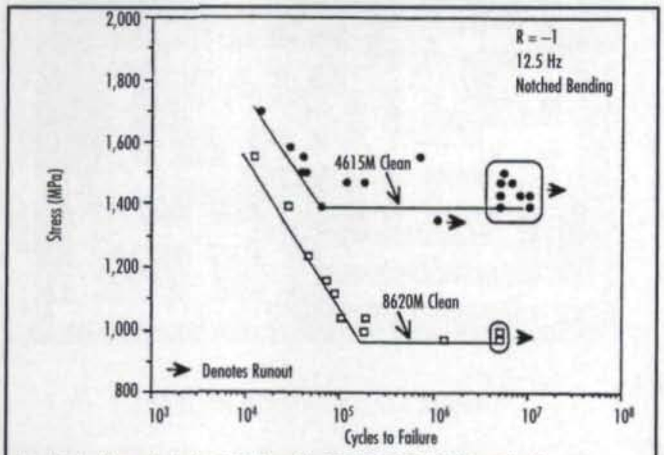

Figure 6—Bending fatigue behavior as carburized (Ref. 9).

and therefore remains in solution to maintain the surface hardenability. Importantly, it maintains the martensitic surface microstructure and beneficial residual compressive stresses. Increased molybdenum contents are required if silicon and/or manganese and/or chromium are lowered. Molybdenum plays the crucial role along with nickel (Ni)—if utilized—of replacing the corresponding hardenability loss. (It is important to note that nickel is a desirable element for both hardenability and toughness. However, its use is often minimized by request due to cost considerations.) The effect of silicon loss on hardenability is often greater than commonly expected so that molybdenum needs to be added to compensate for the hardenability loss.

The effect of IGO/NMTP has primarily been noted on the bending fatigue resistance of gear teeth (Refs. 8–15). The fatigue resistance is lowered by three main effects: a) formation and effect of the grain boundary oxides, b) a lower-strength NMTP surface microstructure, and c) a corresponding loss of surface residual compressive stresses (Refs. 8, 9, 11, 12, 13 and 14).

Bending fatigue work undertaken in References 9–11 was directed at determining the relative importance of these effects. Several of the findings are reviewed below. Each of these studies involved the same two steels: an 8620 modified (lower silicon) and a 4615 modified (higher molybdenum). Their compositions are shown in Table 4. While viable gear steels, neither is optimum to prevent all of the above effects. While newer alloy designs have proven better, the results described below remain valid and form the basis for additional work.

Both steels heat-treated very similarly. The case hardness profiles were similar, and the case microstructures were martensite with approximately 25% retained austenite. However, there were differences at the as-carburized surfaces. The 8620 modified exhibited IGO (manganese, chromium oxides near the surface; iron, silicon oxides at deeper depths) with significant corresponding NMTP formation (primarily pearlite with smaller amounts of bainite) (Ref. 9). The 4615 modified, owing to its higher silicon level, also exhibited IGO (manganese, silicon oxides) but—due to its higher levels of molybdenum and nickel—maintained the hardenability of the surface matrix and did not exhibit any NMTP microconstituents. As a result, the steels exhibited the residual stress profiles shown in Figure 5 (Ref. 9). The specimens that were glass-bead cleaned after heat treatment, were tested in four-point bending rigs devised by Ford Motor Co. personnel, described in SAE960977 (Ref. 9). The results are shown in Figure 6.

Analysis of the results by Dowling suggested the difference in endurance limits was due ≈50% to the better residual compressive stress state in the 4615 modified and ≈50% due to the lower-strength NMTP surface layer in the 8620 modified (Ref. 9). It is important to note that both steels exhibited IGO of similar depths, and thus the initiation of fatigue via this "metallurgical notch effect" is assumed to be similar. Apparently, the better residual stress state, plus higher strengths of the 4615 modified's surface, delayed initiation to higher stress levels.

These same two steels were also tested in full planetary gear sets in SAE960978 (Ref. 10). The results were similar. The 4615 modified's performance was approximately 20% higher than that of the 8620 modified's.

Plasma-Carburizing Effects

As mentioned earlier, another method of preventing the effects of IGO on gear bending fatigue is to utilize plasma-carburizing rather than conventional gas-carburizing. A third study was conducted in which the same two materials were both gas-carburized and plasma-carburized. Details are in Reference 11. The residual stress profiles of the four sets are shown in Figure 7, and the four-point bending fatigue data are shown in Figure 8. In this study, none of the specimens was glass-bead cleaned.

It is important to note: When plasma-carburized, neither steel exhibited any NMTP and only a few small oxide particles (iron, chromium oxides) were found at the very surface of the 8620 modified. As a consequence, the residual stress states and endurance limits of these two specimen sets were similar. Also, the two plasma-carburized sets were both significantly better than the gas-carburized 8620 modified (which showed significant IGO and NMTP, with a correspondingly poorer residual stress state).

The gas-carburized 4615 modified specimens still had the best residual stress condition and corresponding endurance limit. This may be the result of a thinner case depth profile in the gas-carburized 4615 modified. Researchers at Climax Molybdenum Co. (Ref. 8) have shown there is an optimum case depth to maximize the residual compressive stress state and thus maximize performance.

However, recent work at the University of Newcastle (England) found similar results between gas- and plasma-carburized specimens (Ref. 16). In addition, work by Krauss also showed differences in the bending endurance limits. Krauss' conclusions suggested a relationship to grain size and the amount of retained austenite in the gas and plasma specimens (Ref. 17). This phenomenon deserves further study.

Corroborative Studies

The IGO/NMTP studies reviewed above have been corroborated by Hyde and Irani (Refs. 12 and 13) and recently by Shaw,

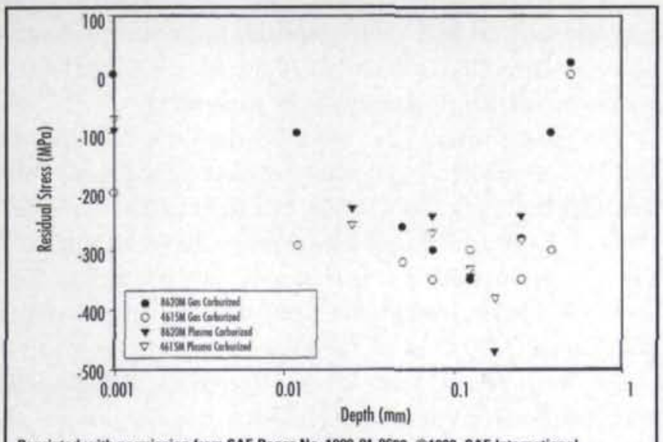

Figure 7—Residual stress data for both gas- and plasma-carburized bending fatigue specimens of both steels, 4615M and 8620M (Ref. 11).

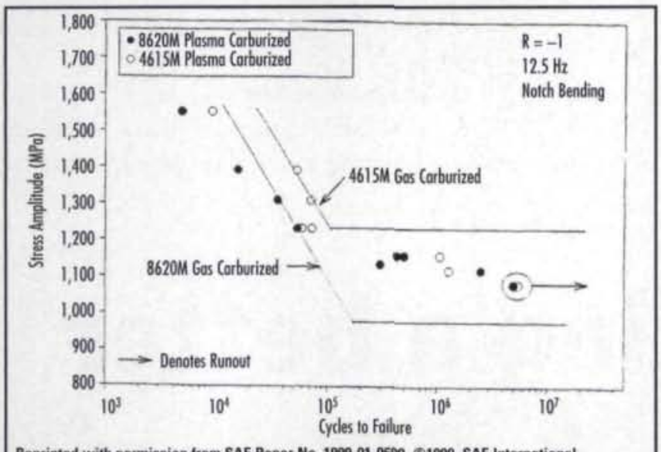

Figure 8—Bending fatigue behavior for gas- and plasma-carburized specimens (Ref. 11).

Hofmann, and Evans (Refs. 14 and 15). Both have documented the fractography of the initiation and propagation stages of bending fatigue and have studied the effects of additional residual stress enhancement (e.g., peening, grinding, superfinishing, etc.).

As Shaw and Hofmann note, "bending fatigue can be controlled through improved surface quality, steel quality, and control of the residual stress state" (Ref. 16). As this paper indicates, such aspects can be engineered via different methods. These methods allow the initial product and process designers to choose how to best produce a gear for a given application. Integrating the important variables from Table 1 with the various disciplines, the engineer can determine how the gear material and processing should be designed.

Summary

The process, product, and performance characteristics of mechanical systems' components are dependent on many variables related to material, design, process control, and application requirements. Application engineering is a complex exercise that must weigh and counterbalance many competing issues. Fortunately, today's steels and many of the processes can be engineered to achieve maximum performance. Clean steel forms the foundation upon which to build. Knowledge of the requirements for forming, machining, and heat-treat response can then be combined with manufacturing and application requirements to design the steel composition.

Details of one aspect, control of IGO/NMTP relative to bending fatigue, were reviewed. If gears are ground in the roots and on the flanks, this issue is moot. If the roots are not ground, then alloy design or plasma-carburizing is a viable solution. If the flanks are not ground, it is advisable to minimize IGO/NMTP effects as they will likely decrease contact fatigue resistance.

The use of an interdisciplinary concurrent engineering methodology and the performance pyramid, shown in Figure 1, permits individual components and/or their overall systems to be optimized relative to properties' performance, reliability, quality, and cost. ○

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