Austempered Gears and Shafts: Tough Solutions

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Definitions, Acronyms and Abbreviations

ADI: austempered ductile iron.

AGI: austempered gray iron.

Ausferrite: acicular ferrite and austenite.

Austempering: a special, isothermal heat treatment process that can be applied to ferrous materials. Austempering consists of austenitizing, followed by rapidly quenching to a temperature where the material is then transformed isothermally to form either ausferrite in cast iron or bainite in steel.

Austenite: a face-centered, cubic, non-magnetic phase found in iron and steel alloys.

Austenitizing: forming austenite by heating a ferrous alloy above its critical temperature—to within the austenite (steel) or austenite + graphite (cast iron) phase region from the phase diagram.

Bainite: an austenitic transformation product of acicular ferrite and carbide found in some steels and cast irons. Upon cooling, it forms at temperatures between those at which pearlite and martensite transformations occur.

Carburizing: the process by which the surface carbon concentration of a ferrous alloy is increased by diffusion of carbon from the surrounding environment.

Fatigue: failure of structures that are subjected to fluctuating and cyclical stresses.

Isothermal: that which is at a constant temperature.

Isothermal transformation (T-T-T or I-T) diagram: a plot of temperature versus the logarithm of time for an alloy of definite composition; used to determine when transformations begin and end for an isothermal heat treatment.

Martensite: a metastable iron phase supersaturated in carbon that is the product of a diffusionless transformation from austenite.

Residual stress: a stress that persists in a material that is free of external forces or temperature gradients.

Stress corrosion cracking: a failure that results from the combined action of a tensile stress and a corrosion environment; the corrosion environment lowers the stress levels for cracking due to tensile stress alone.

Tensile strength: the maximum engineering stress, in tension, that may be sustained without fracture.

Yield strength: the stress required to produce a very slight yet specified amount of plastic strain; a strain offset of 0.002 is commonly used.

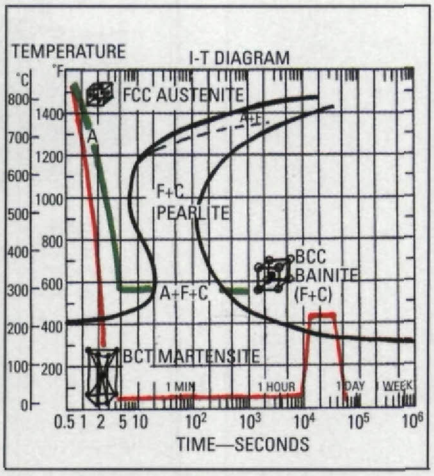

Fig. 1—Schematic I-T diagram illustrating the austempering (red) and quenching & tempering (green) processes.

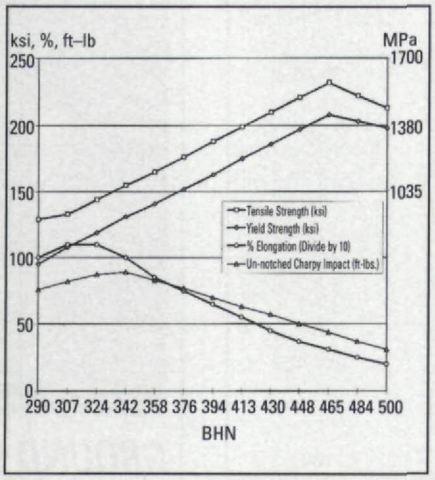

Fig. 2—Typical properties of austempered ductile iron as a function of Brinell hardness.

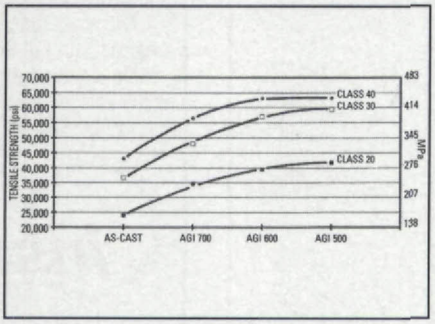

Fig. 3—Tensile strengths of austempered gray iron as a function of austempering temperature (F).

Abstract

Austempered irons and steels offer the design engineer alternatives to conventional material/process combinations. Depending on the material and the application, austempering may provide the producers of gears and shafts with the following benefits: ease of manufacturing, increased bending and/or contact fatigue strength, better wear resistance or enhanced dampening characteristics resulting in lower noise. Austempered materials have been used to improve the performance of gears and shafts in many applications in a wide range of industries.

Introduction

Austempering is a special, isothermal heat treatment process that can be applied to ferrous materials to increase strength and toughness. Figure 1 shows a schematic isothermal (I-T) diagram with both the austempering (green line) and the quenching and tempering (red line) processes outlined. Austempering consists of austenitizing, followed by rapidly quenching to a temperature in the range of 260–385°C (500–725°F), where the material is then transformed isothermally to form either ausferrite (acicular ferrite and carbon stabilized austenite) in cast iron or bainite (acicular ferrite and carbide) in steel. The quench

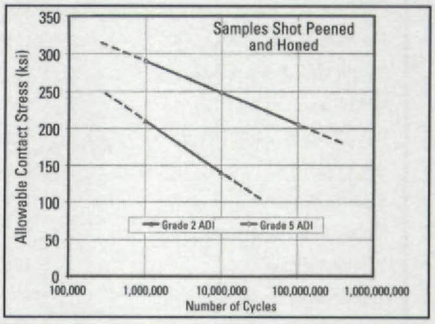

Fig. 4—Contact fatigue (90% confidence limits) from the ASME Gear Research Institute.

and temper process consists of austenitizing and then rapidly quenching below the martensite start temperature. The martensite that forms is very hard and brittle; subsequently, it must undergo a tempering step to acquire the desired combination of strength and toughness.

Because austempering is an isothermal process, it offers advantages versus quenching and tempering. Since the formation of bainite or ausferrite occurs over minutes or hours at a single temperature, distortion is minimized and cracking does not occur. Meanwhile, the formation of martensite occurs immediately as the metal temperature drops below the martensite start temperature. Because cooling is achieved at different rates in various sections, there is a non-uniform transformation, which can result in significant distortion and/or cracking.

Carbo-Austempering™ is a heat treat process used on certain steels where the surface of the part is carburized, followed by an isothermal quench at a temperature that produces a high carbon, bainitic case. When the process is applied to low-carbon steels, it results in the formation of a bainitic case and a low-carbon, tempered martensite core. For medium-carbon steels, bainite is formed throughout the cross-section of the part.

Austempered Irons

Austempering can be applied to ductile and gray iron castings to produce beneficial properties relevant to numerous applications. In the case of gears and shafts, austempering yields austempered ductile irons (ADI) and austempered gray irons (AGI) with better strength, wear resistance, and noise dampening properties than either as-cast irons or other competitive materials. As seen in Figure 2, the tensile and yield strength of ADI increases with increased Brinell hardness. The different grades of ADI—achieved through a variation in the austempering temperature and time—can create a range of properties in ADI applicable to the specific requirements of the component design, as seen in Table 1.

Figure 3 shows the relationship of as-cast gray iron to AGI as a function of austempering temperature. Increased tensile strength can be achieved by austempering gray iron at various temperatures.

Contact Fatigue. Austempered ductile iron lends itself to increased contact fatigue strength and wear resistance. Figure 4 compares the allowable contact stress behavior of ASTM Grades 2 and 5 (ASTM 1050-700-07 and 1600-1300-00). Figure 5 demonstrates that the contact fatigue properties of various grades of ADI are comparable to gas nitrided steels and competitive with carburized and hardened steel.

Figure 6 illustrates that ADI has improved abrasion resistance when compared to steels and quenched and tempered ductile iron. ADI experiences less volume loss at similar hardness levels, resulting in a component with improved wear characteristics.

Bending Fatigue. ADI also presents an increase in bending fatigue for gear applications. Figure 7 shows the comparative allowable tooth root bending stresses for ADI Grades 2 and 5. Figure 8 shows a comparison of tooth root bending fatigue in various materials. That figure demonstrates that ADI is competitive with cast and through-hardened steels. It also shows that shot-peened ADI has improved fatigue strength that is comparable to gas-nitrided and case-carburized steels. Shot peening can improve the allowable bending fatigue of carburized

Table 1—ASTM 897 Property Table for ADI

Grade	Tensile Strength (MPa/ksi)	Yield Strength (MPa/ksi)	Elong. (%)	Impact Energy (J/lb-ft)	Typical Hardness (BHN)
1	850/125	550/80	10	100/75	269–321
2	1050/150	700/100	7	80/60	302–363
3	1200/175	850/125	4	60/45	341–444
4	1400/200	1100/155	1	35/25	366–477
5	1600/230	1300/185	N/A	N/A	444–555

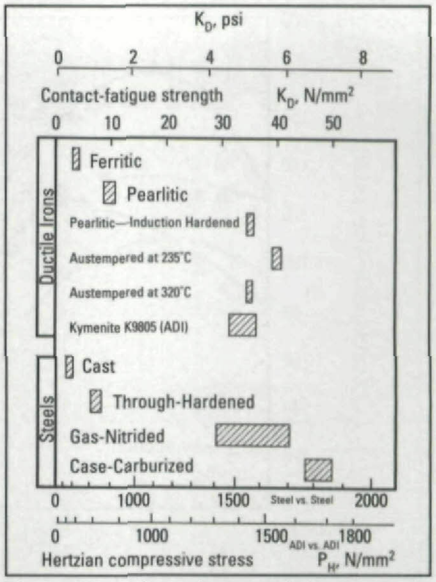

Fig. 5—Comparison of contact fatigue strengths of ADI with those of conventional ductile iron and steels used for gear applications.

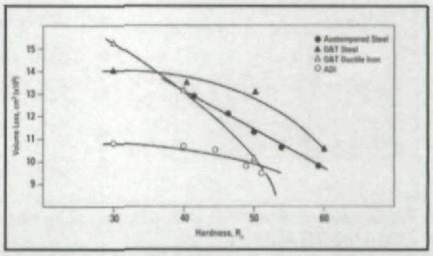

Fig. 6—Pin abrasion test, comparing volume loss at equivalent hardnesses[4].

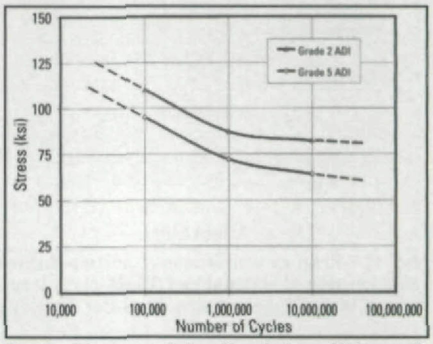

Fig. 7—Single tooth bending fatigue (90% confidence limits) from ASME Gear Research Institute.

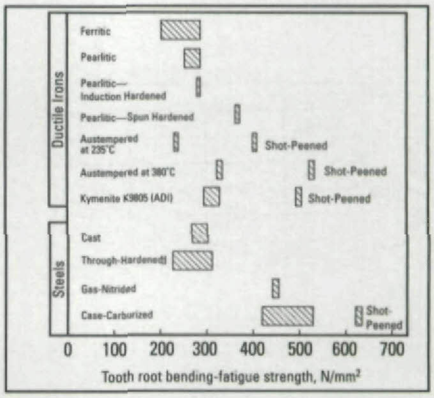

Fig. 8—Comparison of bending fatigue strengths of ADI with those of conventional ductile iron and steels used for gear applications.

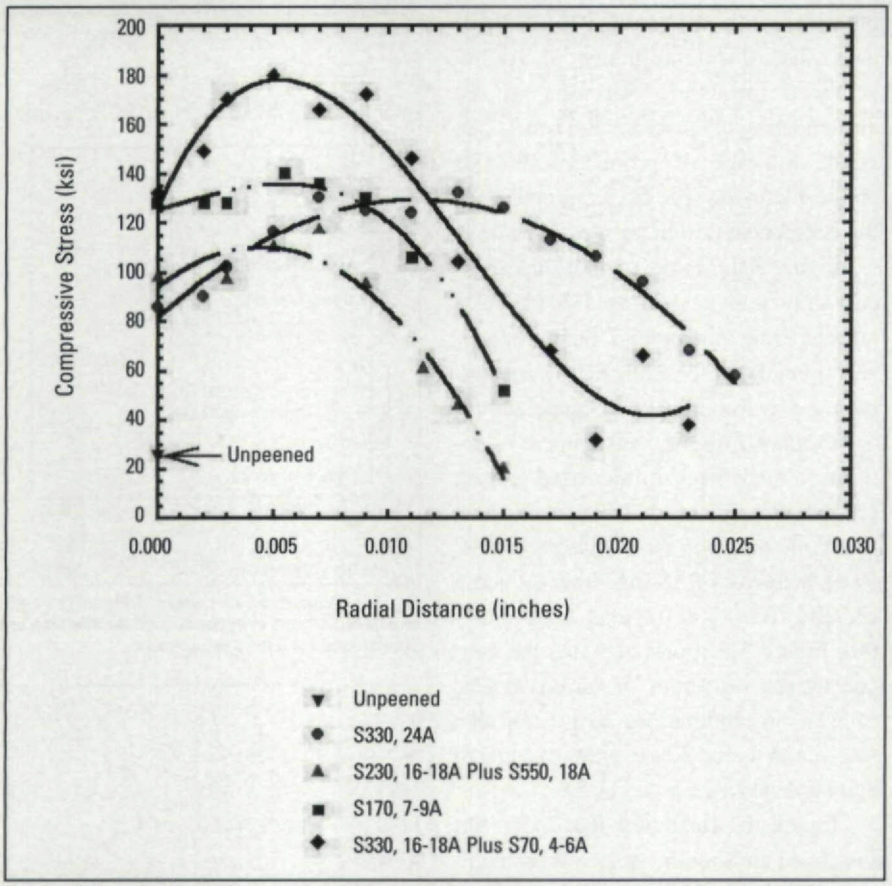

Fig. 9—Effect of various shot-peening schemes on the compressive stresses of Grade 4 (ASTM 1400-1100-01) ADI.

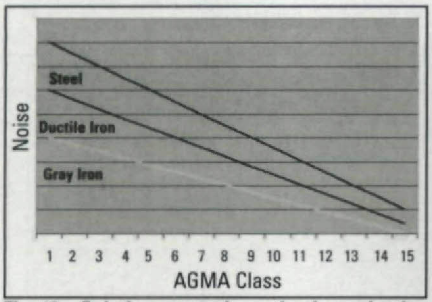

Fig. 10—Relative comparison of noise reduction as a function of material and AGMA class (courtesy of Wells Manufacturing, Dura-Bar Division).

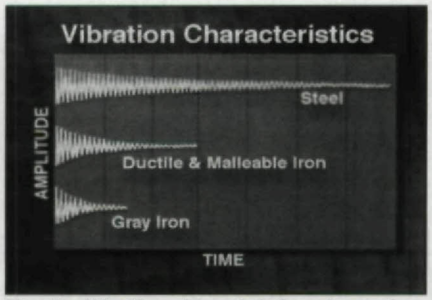

Fig. 11—Vibration characteristics of gray iron, ductile iron and steel (courtesy of Wells Manufacturing, Dura-Bar Division).

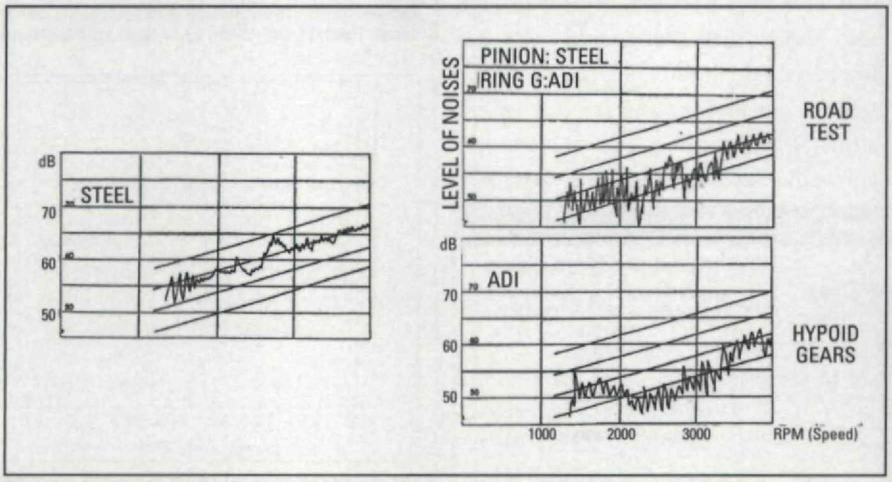

Fig. 12—Comparison of noise in hypoid gears during vehicle road tests, from the ASME Gear Research Institute Report A4001.

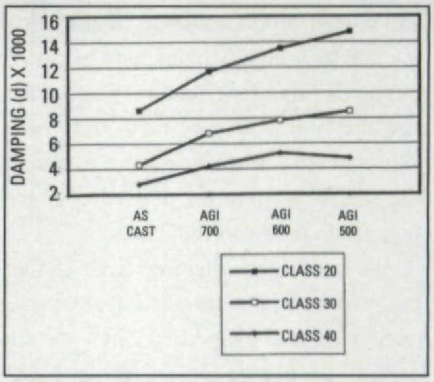

Fig. 13—Damping of austempered gray iron compared with as-cast.

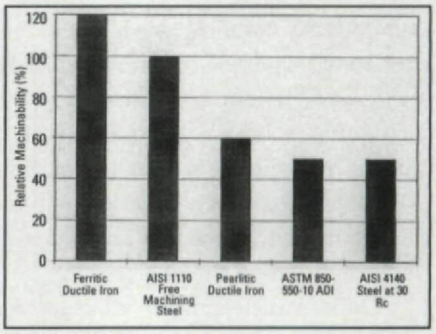

Fig. 14—Relative machinability of several ferrous materials.

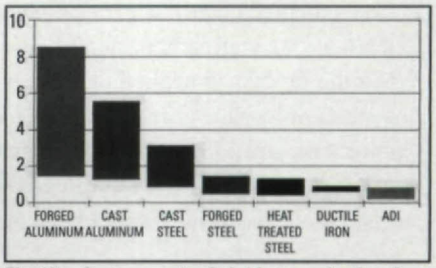

Fig. 15—Cost per unit of yield strength of various materials.

Fig. 16—ADI Hypoid Ring and Pinion Gears.

Fig. 17—ADI gear segments for a 19-foot diameter rotary railcar dumper.

and hardened steels by 30%, while it increases the allowable bending fatigue of ADI by 75%.

The bending performance of ADI can be greatly enhanced by shot peening and fillet rolling. In Figure 9, several shot-peening combinations are measured for their effect on residual compressive stresses. The as-austempered surface compressive stress observed was less than 30 ksi while the maximum shot-peened surface compression was more than 130 ksi.

Noise Reduction. ADI and AGI are not only competitive in bending and contact fatigue, but they also can greatly reduce the noise found in gears made of other materials. ADI can reduce noise by more than 2 dB compared with carburized and hardened 8620 steel gears[6].

As seen in Figure 10, gray and ductile iron are quieter than steel. That is due to the presence of graphite in ductile and gray iron, as well as the ausferrite matrix in austempered irons. The graphite nodules in ductile iron and the graphite flakes in gray iron create a dampening effect that significantly reduces vibration in those materials. That allows for the possibility that gears machined to lower AGMA classes could be as quiet as those machined to more precise grades. Figure 11 schematically shows the relative dampening characteristics of steel as compared with ductile and gray iron.

A study done on a hypoid gear set, shown in Figure 12, compares the noise of that gear set when using steel, ADI or a combination of both materials. Note the improvement in noise level when both the ring gear and pinion are made of ADI.

The austempering of gray iron also increases the noise reduction capabilities of gray iron. As seen in Figure 13, the damping characteristics of gray iron are increased when austempered, giving the higher strength AGI better noise reduction characteristics than its as-cast counterparts. In fact, an AGI with a tensile strength of nearly 60 ksi can have the noise dampening capabilities of a fully damped, Class 20 gray iron.

Manufacturability. ADI and AGI offer an opportunity for increased manufacturability of a part. Rough machining can be done prior to heat treatment. In the as-cast condition, the material is much easier to machine, resulting in a lower cost to manufacture. Though many applications can be heat treated after final machining, finish machining after heat treatment increases the strength characteristics of ADI and AGI, giving them superior fatigue strength than prior to finish machining. Figure 14 compares the relative machinability of several ferrous materials. Note that ductile iron in a ferritic or pearlitic condition is easier to machine than 4140 steel or ADI. If ductile iron is machined prior to heat treatment, one can gain the advantage of better machinability. Furthermore, machining of ductile iron, gray iron, ADI and AGI results in a compact, discontinuous chip that is easily handled and is fully recyclable. Dry machining techniques

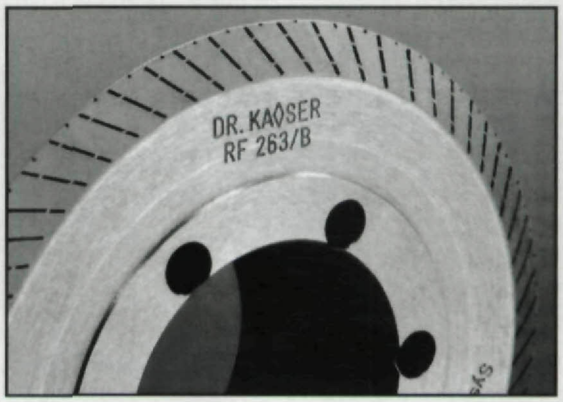

Fig. 18—ADI inboard constant velocity joint for light vehicles (Courtesy of Delphi).

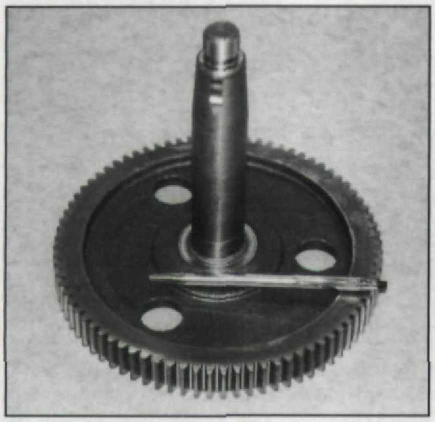

Fig. 19—ADI gear and axle for commercial lawnmowers.

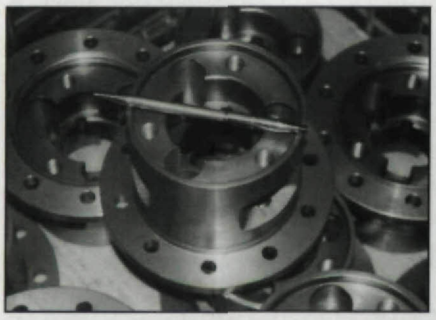

Fig. 20—ADI limited slip differential gear housing.

Fig. 21—ADI hay baler knotter gear.

can be easily applied to as-cast gray and ductile irons. The increased ease of manufacturability related to cast irons goes beyond improved machinability. Iron castings are generally nearer net shape and less expensive than steel forgings and castings. Figure 15 shows a comparison of relative material cost of different materials per unit of yield strength. Taking into account all material and processing costs, ADI and AGI are relatively less expensive to manufacture than other commonly used materials.

Another benefit of austempering is reduced distortion and the elimination of quench cracking. When General Motors Corp. switched to ADI hypoid differential gears from the traditional carburized and hardened 8620 steel process in the 1970s, the company was able to eliminate the need for press quenching.

Applications of ADI and AGI Gears

As previously shown, ADI and AGI gears have higher bending and contact fatigue strengths, improved wear resistance and reduced noise levels. Figure 16 is an example of a hypoid gear set that realized a reduction in noise when switched from a steel application to ADI.

Fig. 22—AGI gear for timing on a light vehicle engine.

Austempering can also give benefits to larger than average gear sets, such as the large gear segments shown in Figure 17. Figures 18 through 21 show various applications of ADI gears, from agricultural applications in knotter gears (Figure 21) to light vehicle applications of differential housings (Figure 20) and CV joints (Figure 18) to a gear-and-axle set used in commercial lawnmower engines (Figure 19). Figure 22 shows an AGI distributor gear used in the late 1970s.

Austempered Steels

Medium- and high-carbon steels can be successfully austempered along with powdered metal mixes that have sufficient hardenability and nearly full density. In general, the steel that is selected must have an isothermal transformation (I-T or T-T-T) diagram that exhibits the following characteristics:

1. A pearlite start time (nose) that is sufficiently delayed to avoid its formation on quenching to the austempering temperature.
2. A reasonable bainite transformation time.
3. A martensite start temperature that is low enough to allow for the formation of bainite.

Austempered steel offers several advantages when compared with conventional quenched and tempered steels. Because austempered steel is formed by an isothermal transformation, the likelihood of distortion is reduced, and the presence of quench cracks is eliminated. The bainitic microstructure produced by austempering is more wear resistant than tempered martensite, as illustrated in the pin abrasion test results of Figure 6. In addition, bainitic steels are more resistant to hydrogen embrittlement and stress cor-

Table 2—Gross and Bain Comparative Data for 0.74% C Steel Parts[7]

	Quenched & Tempered	Austempered
Rc Hardness	50	50
UTS (MPa/ksi)	1701/246.7	1949/282.7
Yield Strength (MPa/ksi)	839/121.7	1043/151.3
Elongation (% in 6 inches)	0.3	1.9
%RA	0.7	34.5
Impact* (J/ft-lb)	3.9/2.9	47.9/35.3

rosion cracking. For example, at high hardness levels (> 38 Rc), martensitic bolts are subject to stress corrosion cracking. Austempered bolts do not exhibit that behavior. For given high hardness levels (> 40 Rc), austempered parts exhibit higher strength and toughness than comparable quenched and tempered parts, as shown in Table 2.

Above a certain hardness level, the fatigue strength of conventional quenched and tempered steel drops significantly, as illustrated in Figure 23. That does not occur in austempered structures. In fact, the fatigue strength continues to increase up to the maximum bainitic hardness.

Austempered Steel Applications

There is a range of applications for austempered gears as shown in Figures 24 and 25. The gears vary in section size from the 1 mm thick wave plates pictured in Figure 24 to the large gear segments shown in Figure 25.

Powdered metal steel parts of sufficient density can also be austempered. Examples include the metal sprag races shown in Figure 26.

Austempered steel applications are not limited to gears. Output shafts are also austempered for high strength and toughness with low distortion.

Carbo-Austempered™ Steel

Low- to medium-carbon steels are good candidates for Carbo-Austempering™. Typically a high-carbon, bainitic case (50–60 Rc) is produced on a component with a lower carbon, tempered martensite core (< 40 Rc). In some instances, advantages have been realized in medium-carbon alloy steels with a high-carbon, bainitic case (45–55 Rc) on a medium-carbon, bainitic core (45–50 Rc).

Carbo-Austempering™, like austempering, is a low-distortion heat treatment process when compared with conventional carburize, quench and temper heat treatments. During Carbo-Austempering™, the transformation begins in the center, or core, of the part. That results in the formation of compressive stresses as the outside layer or case transforms last during the heat treat process. The residual compressive stresses on the surface of a Carbo-Austempered™ steel result in improved high-load, low-cycle fatigue properties versus conventional carburized and hardened steel. That is illustrated in Figure 27, which contains rotating bending fatigue curves for both Carbo-Austempered™ and conventionally carburized and hardened 8822 steel. Note the superior performance of the Carbo-Austempered™ steel in the low-cycle regime (< 10^5 cycles).

Similar results were obtained with single tooth bending fatigue testing of Carbo-Austempered™ 8620 steel. That is illustrated in Figure 28, which contains single-tooth gear fatigue curves for 8620 steel that has been both Carbo-Austempered™ and carburized, quenched and tempered. The Carbo-Austempered™ gears will carry loads up to 40% greater than their carburized, quenched and tempered counterparts in the

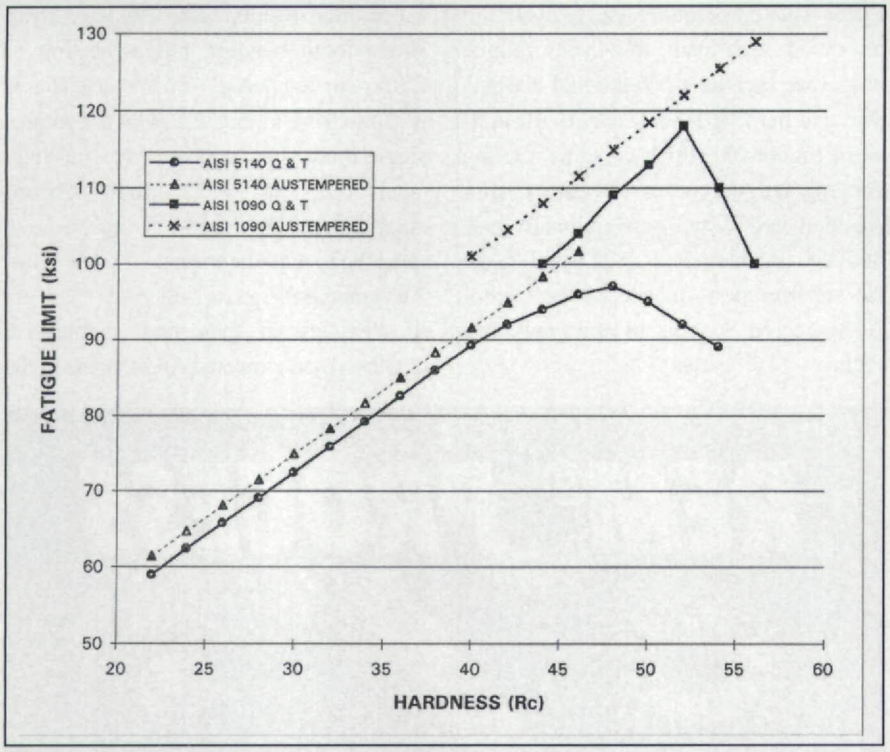

Fig. 23—Fatigue strength of bainite vs. tempered martensite.

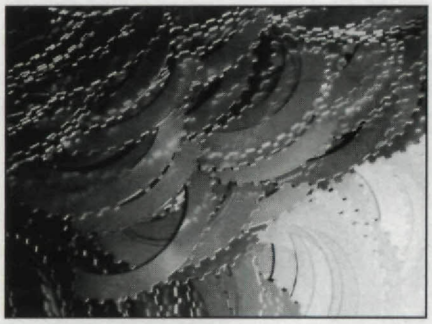

Fig. 24—Austempered steel wave plates.

Fig. 25—Austempered steel large gear segments.

Fig. 26—Austempered steel, powdered metal sprag races.

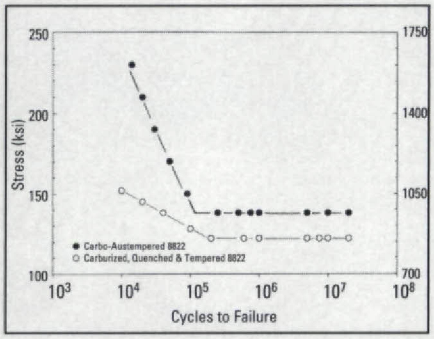

Fig. 27—Rotating bending fatigue properties of Carbo-Austempered™ vs. conventionally carburized and hardened 8822 steel.

low-cycle regime. Additionally, the Carbo-Austempered™ gears have an endurance limit that is 17% greater than the carburized, quenched and tempered gears.

Carbo-Austempered™ steels also exhibit superior toughness or impact properties in comparison with conventional carburized and hardened steel. Figures 29 and 30 illustrate such a comparison of both v-notched and unnotched impact specimens from 5120 steel, respectively. The notched impact energy of the Carbo-Austempered™ specimens is almost twice that of the carburized and hardened specimens in Figure 29. The difference in performance for the unnotched bars is significantly higher, with the average Carbo-Austempered™ impact energy being in excess of 22 times that of the carburized and hardened 5120 shown in Figure 30.

Carbo-Austempered Steel Applications

Carbo-Austempered™ components perform well when exposed to overload type conditions. Typical applications include input and output shafts (Figures 31 and 32), clutch components, starter clutches, pump shafts and gears.

Austempering—
What It Is, And What It Isn't

Austempering is a high-performance heat treatment, but it is not a panacea. The application, as with all material/process combinations, must fit. ADI makes a quiet, low-cost gear or shaft in its allowable loading range, but it will not outperform carburized and hardened alloyed, low-carbon steel in bending or contact fatigue. So, if a current product in carburized steel is failing in bending fatigue or pitting, ADI would not be a solution. However, if the contact and bending loads are in ADI's range, a considerable cost and noise advantage can be expected.

Carbo-Austempered™ steels will outperform 60 Rc carburized and hardened steels in impact and bending fatigue, but at 58 Rc maximum hardness, Carbo-Austempered™ steels are limited to slightly lower contact loads. Therefore, Carbo-Austempering™ can be used in applications where spike overloads in bending occur. At hardnesses in excess of 40 Rc, austempered, medium-carbon steels outperform through-hardened martensitic components in impact strength and notched fatigue loading. However, below 40 Rc, evidence would indicate that martensitic structures will outperform bainitic structures.

Thus, designers should use austempering (as would be the case with other material/process combinations) as one option in their design "tool kit." The designer should work closely with the material provider and the heat treater to determine if austempering would provide a benefit to his or her drive component application.

Summary

The austempering process offers the designers of gears and power transmission components a viable, cost-effective, high-performance alternative to many conventional material/process combinations. Austempering of irons and steels results in increased levels of fatigue strength, wear resistance and toughness. Benefits in the areas of noise reduction and manufacturability have also been documented.

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- General Motors Powertrain Division
- Ford Motor Co.
- Torsion Control Products
- General Motors Allison Transmissions
- Purolator
- Wells Manufacturing, Dura-Bar Division
- Auburn Gear

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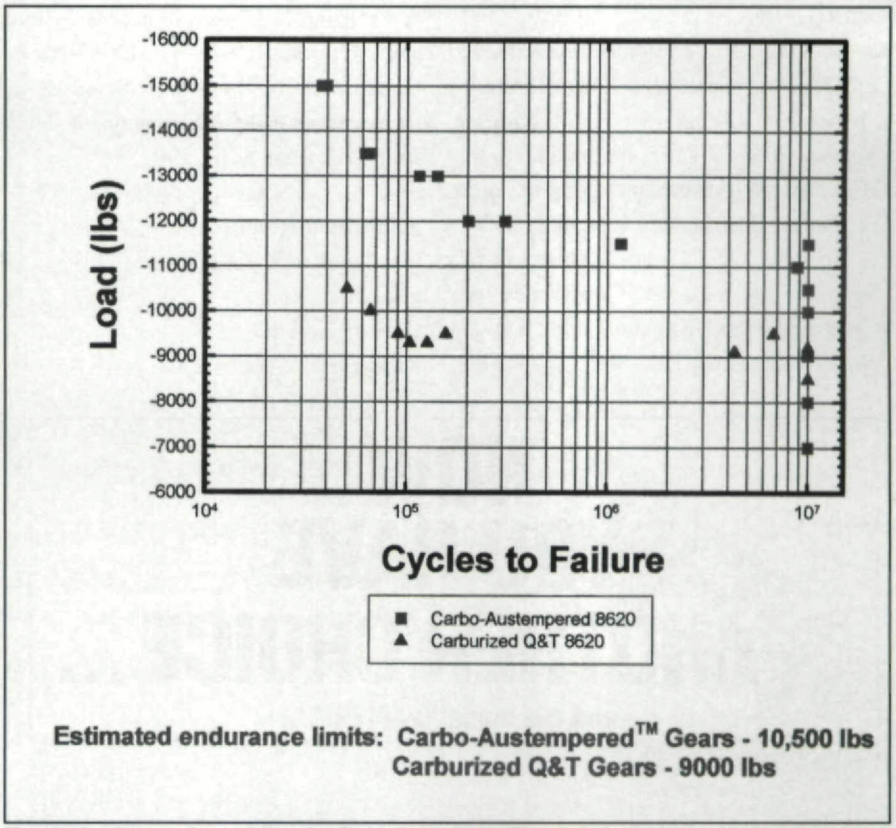

Fig. 28—Load vs. cycles to failure for Carbo-Austempered™ and carburized, quenched and tempered 8620 steel gears.

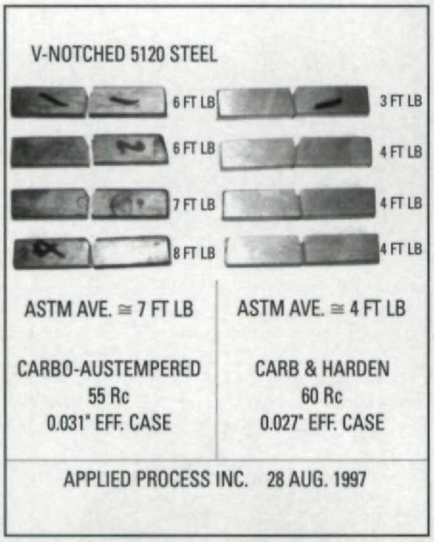

Fig. 29—A comparison of fatigue strength of V-notched Carbo-Austempered™ and carburized and hardened steel of similar hardness.

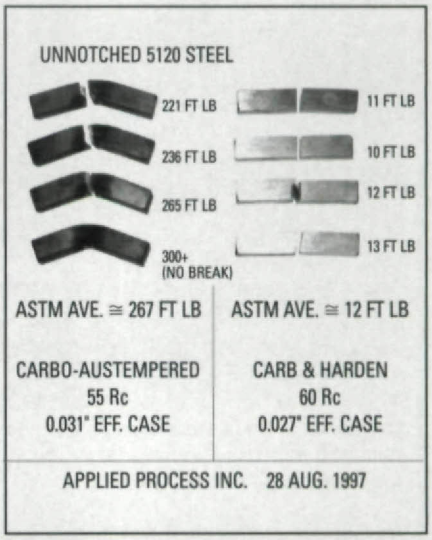

Fig. 30—A comparison of fatigue strength of unnotched Carbo-Austempered™ and carburized and hardened steel of similar hardness.

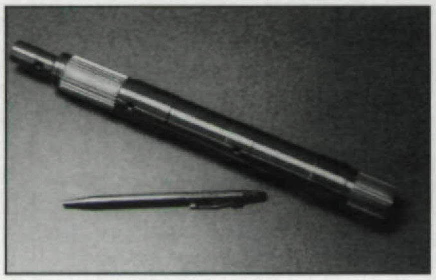

Fig. 31—Carbo-Austempered™ steel transmission output shaft for medium-duty truck and bus (Courtesy of GM Allison Transmission).

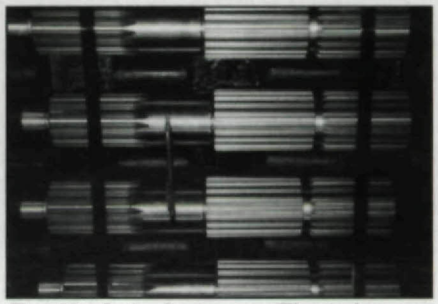

Fig. 32—Carbo-Austempered™ steel output shafts for heavy-duty automotive transmissions.

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Additional Resources

www.appliedprocess.com
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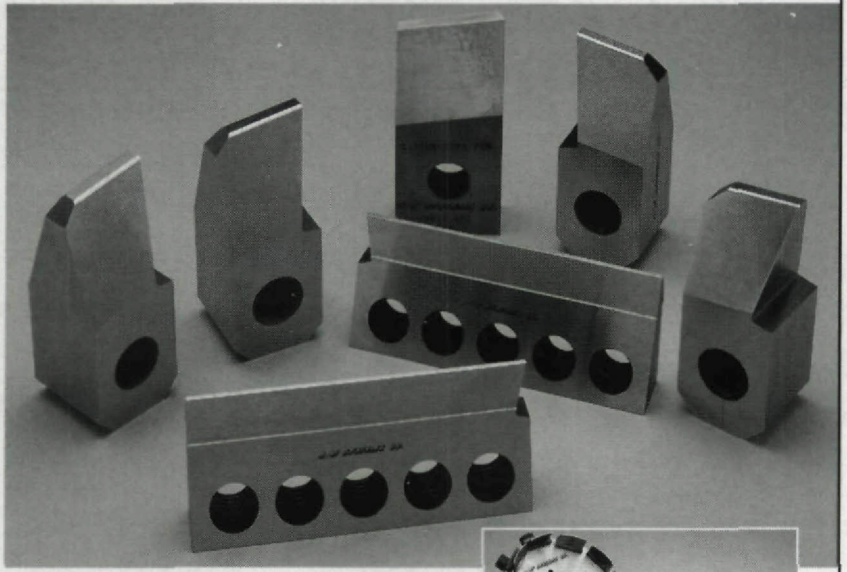
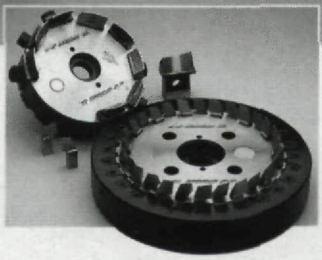
www.afsinc.org
www.asm-intl.org





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