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Austempered Materials for Powertrain Applications

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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 following benefits to producers of powertrain components such as gears and shafts: ease of manufacturing, increased bending and/or contact fatigue strength, better wear resistance and enhanced dampening characteristics resulting in lower noise. Austempered materials have been used to improve the performance of powertrain components in numerous applications for a wide range of industries, from gears and shafts to clutch plates and crankshafts. This paper focuses on Austempered solutions for powertrain applications with an emphasis on gear and shaft solutions.

Keywords automotive, carbon/alloy steels, cast irons, heat treating, machinery, material selection

1. Introduction

Austempering is an 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 (line 1) and the quench and tempering (Q&T) (line 2) processes outlined. Austempering consists of austenitizing followed by rapidly quenching to temperatures 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 Q&T process consists of austenitizing and then rapidly quenching below the Martensite start temperature. The Martensite that forms is very hard and brittle and subsequently, must undergo a tempering step to acquire the desired combination of strength and toughness.

Austempering is an isothermal process and offers advantages over Q&T. The formation of Martensite occurs immediately as the metal temperature drops below the Martensite start temperature. The surface of the part will transform before the center, so distortion and/or cracking can occur due to non-uniform transformation. This is further exacerbated by changes in section sizes. Since the formation of Bainite or Ausferrite occurs over minutes or hours at a single temperature, distortion is minimized and cracking does not occur.

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 required to produce a high carbon, Bainitic case. When this 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.

2. Austempered Irons

Austempering can be applied to both ductile iron and gray iron to produce beneficial properties. Austempered Ductile Iron (ADI) and Austempered Gray Iron (AGI) components exhibit increased wear resistance, higher strength, and better noise damping properties than their as-cast states. Figure 2 shows the relationships between Brinell hardness and tensile strength, yield strength, % elongation, and un-notched Charpy Impact energy for ADI. With an increase in hardness, the strength of ADI increases while elongation and impact strength decrease. The standard ASTM grades of ADI and their properties are listed in Table 1.

Figure 3 shows the tensile strength and yield strength of AGI as a function of hardness including the as-cast condition for Classes 20, 30, and 40 gray irons. Elongation and Charpy impact energy are excluded from this figure because they are not relevant for gray iron or AGI gear applications.

2.1 Contact Fatigue

The data for the wear properties of Austempered irons are presented for three wear conditions specific to gear wear: high stress abrasive wear, galling, and gear tooth pitting.

Figure 4 shows pin abrasion (high stress) test results for ADI and competitive materials. In general, ADI exhibits a lower volume loss for a given hardness level than Q&T steel or ductile iron. This occurs as a result of the Austenite component in the Ausferrite microstructure of ADI. When a high normal force is applied, this Austenite can undergo a strain transformation to Martensite which is an excellent wear material. The depth of this hardened layer (≈5μm) is shown in Fig. 5.

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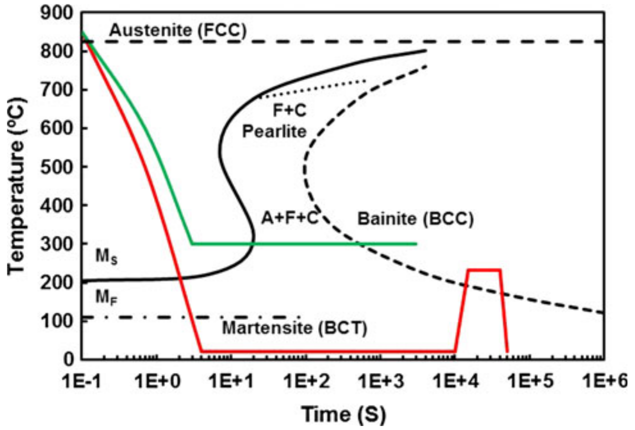

Fig. 1 Schematic *I-T* diagram illustrating the Austempering (line 1) and Quench & Tempering (line 2) Process. The basic crystal structures are in parentheses

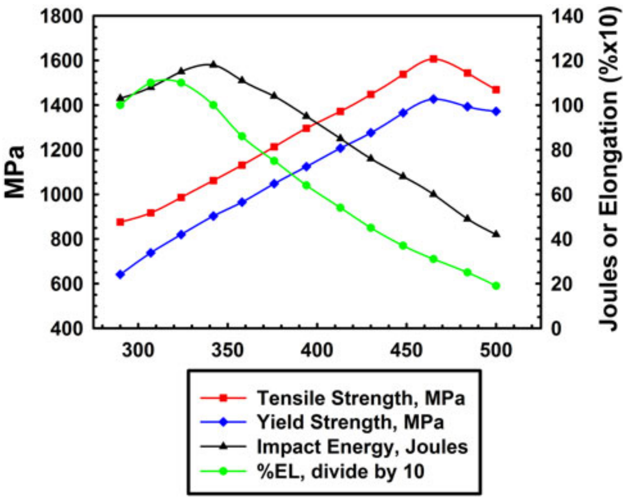

Fig. 2 Typical properties of ADI as a function of Brinell Hardness (HBW). Note: % Elongation values as plotted should be divided by 10

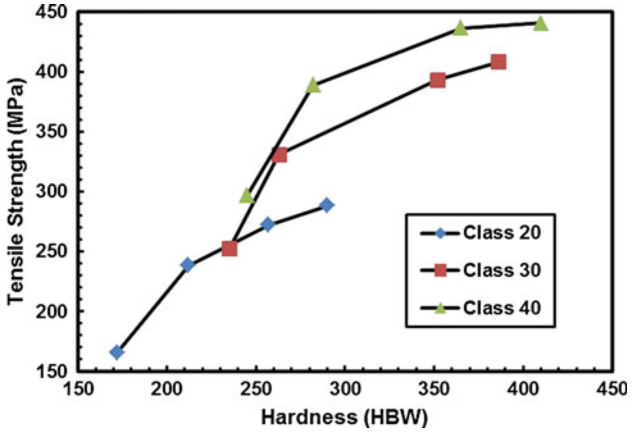

Fig. 3 Tensile strengths of Austempered Gray Iron (AGI) as a function of Brinell Hardness (HBW)

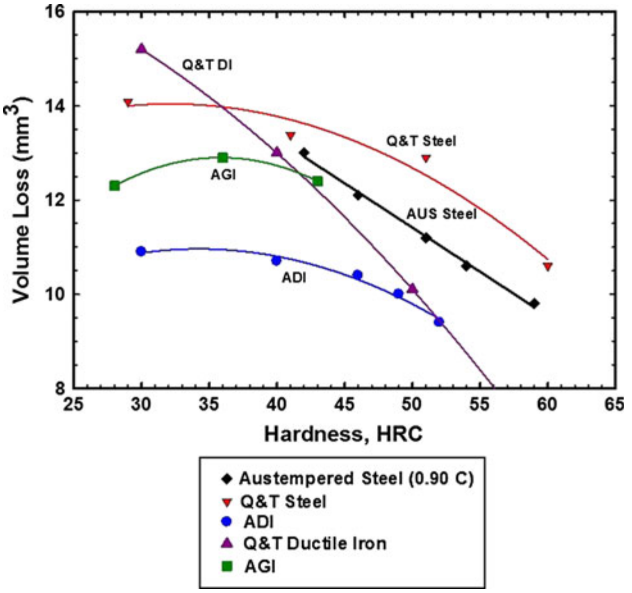

Fig. 4 Pin abrasion test results, comparing volume loss at equivalent hardnesses

Table 1 Properties of ADI per ASTM A897/A897M-06 (Ref 1)

Grade	Tensile strength, MPa/Ksi	Yield strength, MPa/Ksi	Elong, %	Impact Energy, J/ft-Lbs	Typical hardness, HBW
750-500-11 (110-70-11)	750/110	500/70	11	110/80	241-302
900-650-09 (130-90-09)	900/130	650/90	9	100/75	269-341
1050-750-07 (150-110-07)	1050/150	750/110	7	80/60	302-375
1200-850-04 (175-125-04)	1200/175	850/125	4	60/45	341 -444
1400-1100-02 (200-155-02)	1400/200	1100/155	2	35/25	388-477
1600-1300-01 (230-180-01)	1600/230	1300/185	1	20/15	402-512

Gear failure due to scuffing is defined as damage caused by localized frictional welding between two sliding surfaces (Ref 3). This is essentially a galling phenomenon. Figure 6 shows self-mated galling test results for ADI, Carbo-Austempered™ (C/A) 8620, and carburized quenched and tempered (C/H) 8620. In this study, a spike in the coefficient of friction indicates that galling has occurred. Examination of the curves in Fig. 6 illustrates that Grade 900-650-09 did not gall in this self-mated test. It is theorized by the authors that the graphite nodules in ductile iron provide a source of lubrication and, thus, increase galling resistance (Ref 4).

ADI has a Young's Modulus that is 20% lower than that of steel; therefore, ADI gear teeth conform more than steel ones. The elevated conformance of the teeth increases the area of contact and decreases the Hertzian contact stress for a given load. Figure 7 shows the allowable contact fatigue strength

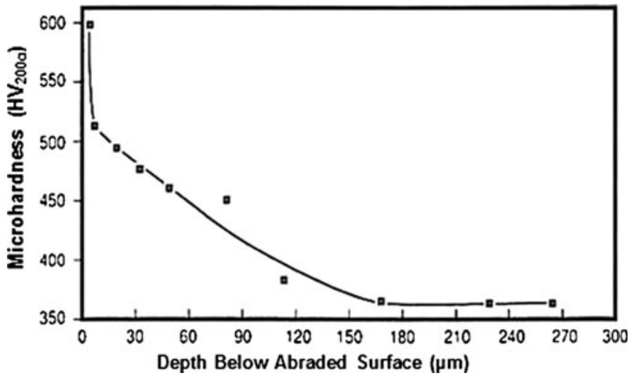

Fig. 5 Vickers microhardness profile versus the depth below the surface for Grade 1050-750-07 ADI (Ref 2)

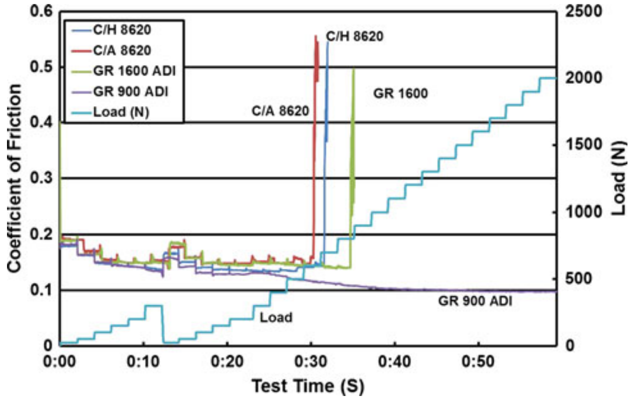

Fig. 6 Coefficient of friction versus load and time showing the galling threshold for various materials

versus hardness for ADI and competitive steel heat treat options for gear design. It shows that ADI competes favorably with through-hardened, through-nitrided, and through-induction hardened steels.

2.2 Bending Fatigue

Figure 8 shows the allowable tooth root bending fatigue strength of ADI and conventionally heat treated steels for gear applications. ADI is competitive with cast and through-hardened steels in tooth root bending. Furthermore, when shot-peened, the fatigue strength of ADI is markedly improved, allowing it to compete favorably with gas-nitrided and case-carburized steels. Shot peening can improve the allowable bending fatigue of carburized quenched and tempered steels by 30%, and up to 75% for ADI.

In Fig. 9, several shot peening combinations are measured for their effect on residual compressive stresses for Grade 1400-1100-02 ADI. The as-Austempered surface compressive stress observed was less than 207 MPa while the maximum shot-peened surface compression was more than 896 MPa. Thus, the bending performance of ADI can be greatly enhanced by shot peening and other processes such as fillet rolling that impart a residual compressive stress on the surface of a component.

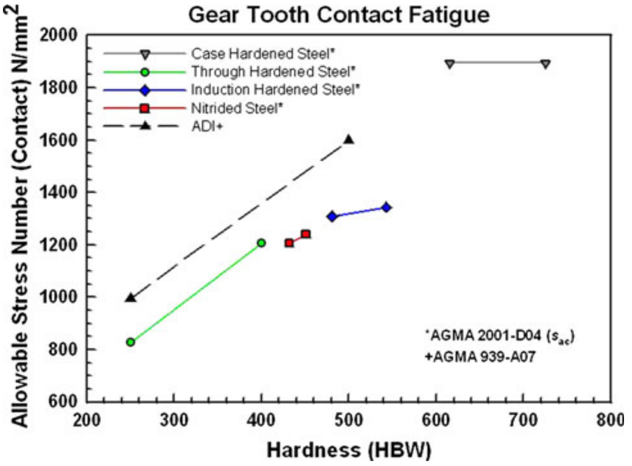

Fig. 7 Comparison of the contact fatigue strengths of ADI to various steels used for gear applications (Ref 5)

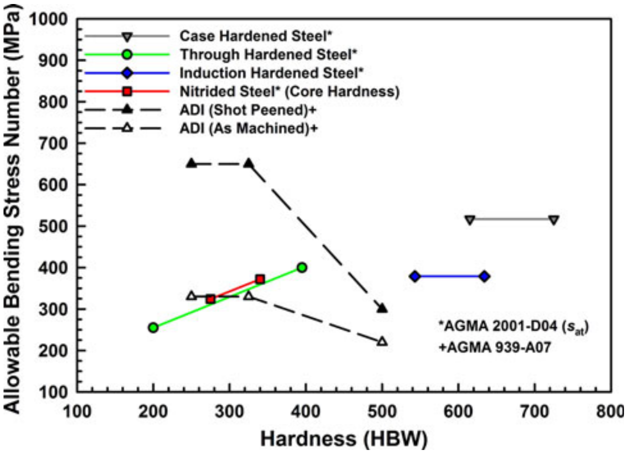

Fig. 8 Comparison of tooth root bending fatigue strength of ADI with those of competitive steels used for gear applications (Ref 5)

2.3 Noise Reduction

Cast iron is inherently quieter than steel alternatives due to the presence of graphite. Figure 10 is a schematic showing the relative damping of gray iron, ductile iron, and steel.

The finer microstructural scale of Ausferrite (versus tempered Martensite) further enhances the damping properties of Austempered irons. A study completed on hypoid gear sets, shown in Fig. 11, compares noise output for a steel gear set to an ADI gear set. This study found that a larger noise reduction could be attained with the ADI gear set. Additional research is needed to evaluate the conditions under which ADI gears are noise attenuating.

Austempering of gray iron increases the noise reduction capabilities of gray iron. As shown in Fig. 12, 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 414 MPa can have the noise dampening capabilities of a fully damped, Class 20 Gray Iron (with a UTS of 138 MPa).

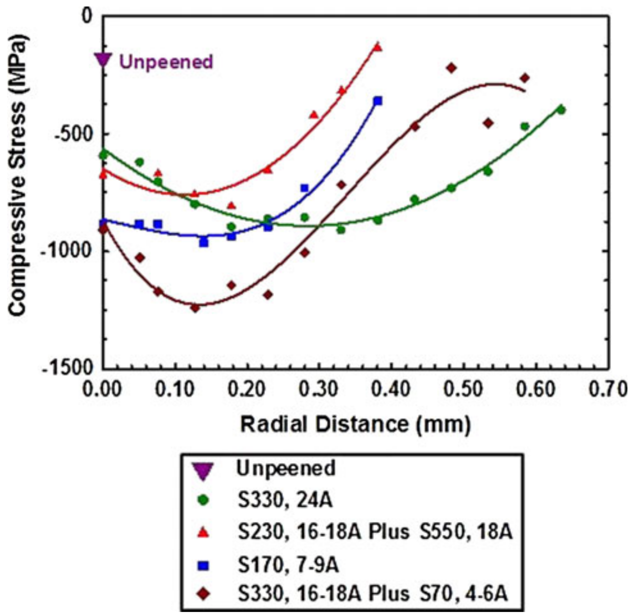

Fig. 9 Effect of various shot peening schemes on the compressive stresses of Grade 1400-1100-02 ADI (Ref 6)

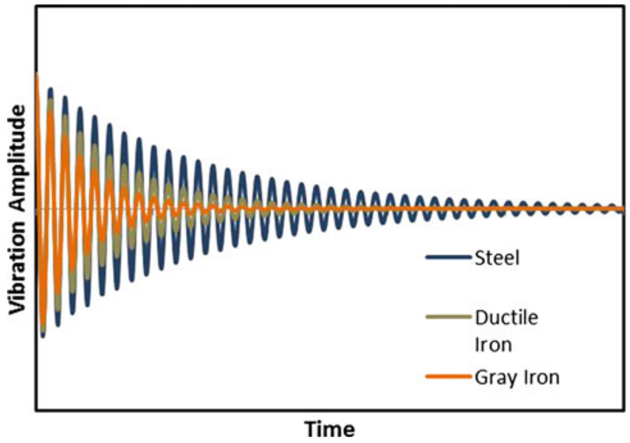

Fig. 10 Schematic of vibration characteristics of Gray Iron, Ductile Iron, and Steel

2.4 Manufacturability

ADI and AGI offer an opportunity for increased manufacturability of a component, since rough machining can be done prior to heat treatment. In the as-cast condition, the material is much easier to machine, reducing the total manufacturing cost. Though many applications can be heat treated after final machining, finish machining after heat treatment increases the strength and fatigue characteristics of ADI and AGI. Figure 13 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. 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 can be easily applied to as-cast gray and ductile irons.

In addition to the increased ease of manufacturability and improved machinability, iron castings are generally nearer net shape than steel forgings and castings. Figure 14 shows a comparison of relative material cost of different materials per unit of yield strength. When all material and processing costs are taken into account, ADI and AGI are relatively less expensive to manufacture than other commonly used materials.

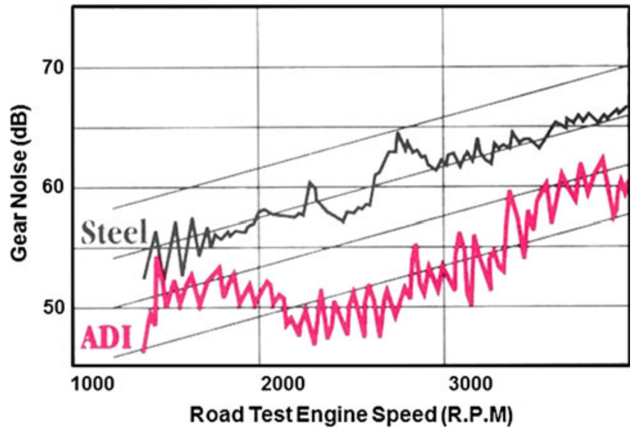

Fig. 11 Comparison of noise in hypoid gears during vehicle road tests, from the ASME Gear Research Institute Report A4001 (Ref 6)

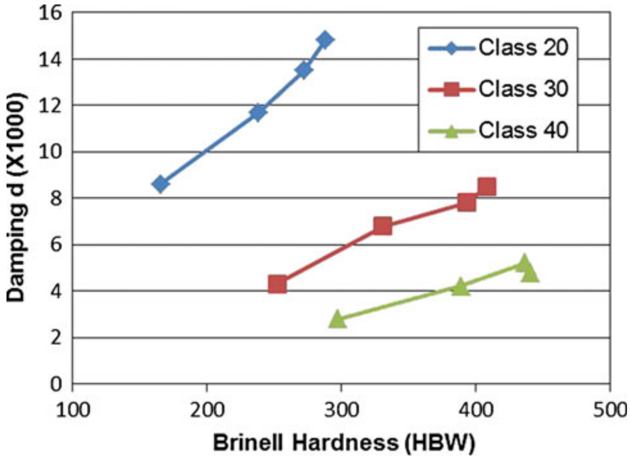

Fig. 12 Damping of Austempered Gray Iron versus Brinell hardness. Each curve represents a different base gray iron with the lowest hardness data point for each grade being the as-cast condition

The Austempering process also results in reduced distortion and eliminates the occurrence of quench cracking. When General Motors switched to ADI hypoid differential gears from traditional Carburized quenched and tempered 8620 steel process in the 1970s, they were able to eliminate the need for press quenching.

2.5 Applications of Austempered Irons

Figure 15 through 20 show ADI and AGI powertrain components that deliver decreased cost, comparable or improved mechanical properties, and increased design flexibility.

3. Austempered Steels

The Austempering heat treatment can be applied to steels providing the steel has a time-temperature-transformation diagram with the following characteristics:

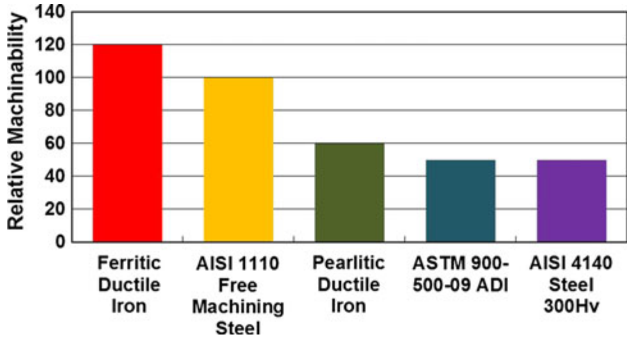

Fig. 13 Relative machinability of several ferrous materials

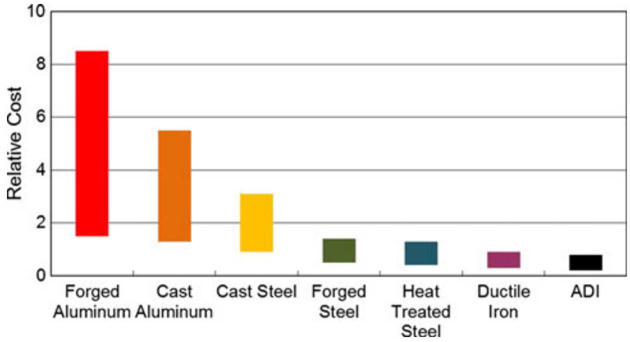

Fig. 14 Cost per unit of yield strength of various materials. Comparison based on results for the forged steel normalized to 1

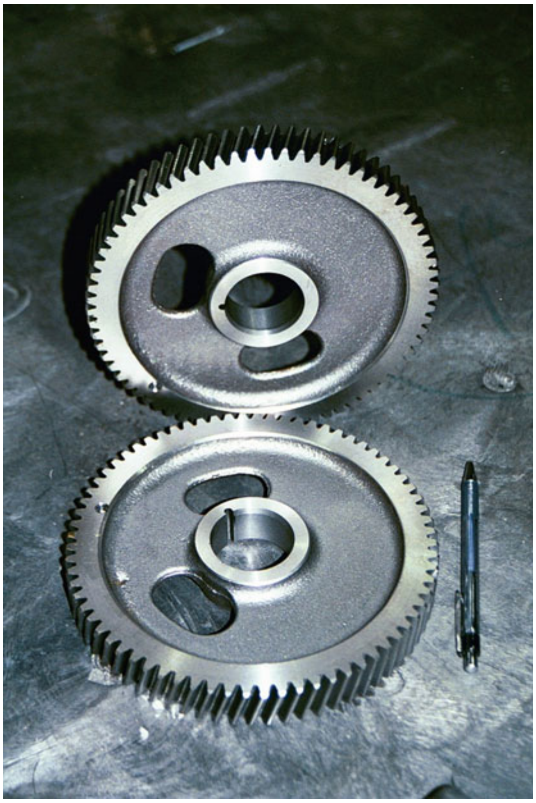

Fig. 15 ADI Diesel engine timing gears have replaced carburized Q&T gears at a cost savings for many years

Fig. 16 ADI hypoid differential gears and pinions are common conversions to Grades 1200-850-04 or 1400-1100-02 ADI

Fig. 17 A one piece ADI gear and axle for commercial lawnmower drives that replaced a three piece carburized steel assembly

Fig. 18 ADI mill gears are produced in segments and assembled post heat treatment

Fig. 19 ADI crankshafts have been used in several notable sports cars for increased fatigue strength and reduced weight and cost (Ref 7)

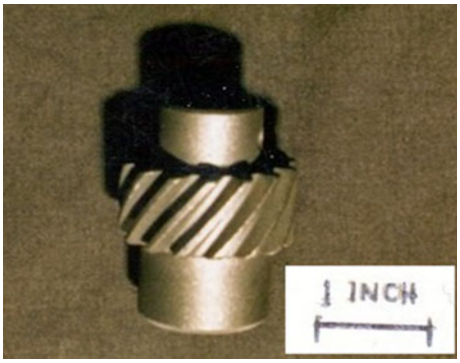

Fig. 20 AGI gear for timing on a light vehicle engine

1. A Martensite start temperature low enough to allow for the formation of Bainite.
2. Sufficient hardenability to avoid the formation of pearlite on quenching to the Austempering temperature.
3. A reasonable Bainite transformation time.

Powdered metal steels can also be Austempered if the alloy meets all of the above criteria and is near full density.

Table 2 shows the tensile and yield strength, hardness, elongation, percent reduction in area, and impact energy of Austempered 1074 and 4340 steel versus their Q&T counterparts. In this data, the impact strengths of the Austempered steels are higher than those of Q&T steels at the hardness levels tested for each alloy. Bainite exhibits higher toughness and equivalent or increased strength in certain high hardness regimes when compared to tempered Martensite. Bainitic toughness surpasses that of Martensite between 40 and 50 HRC depending on the steel alloy.

Austempered steels also exhibit higher ductility for high hardness values when compared to their Q&T counterparts. In a bend test of these two heat treatments on 1050 steel at 49 HRC, only the Austempered test piece survived (Ref 8).

Austempered steels also exhibit improved fatigue properties. At high hardness, Bainite does not exhibit a decrease in fatigue strength. In contrast, above a certain hardness level, the fatigue strength of conventional quench & tempered steel drops significantly due to a susceptibility to hydrogen embrittlement as illustrated in Fig. 21.

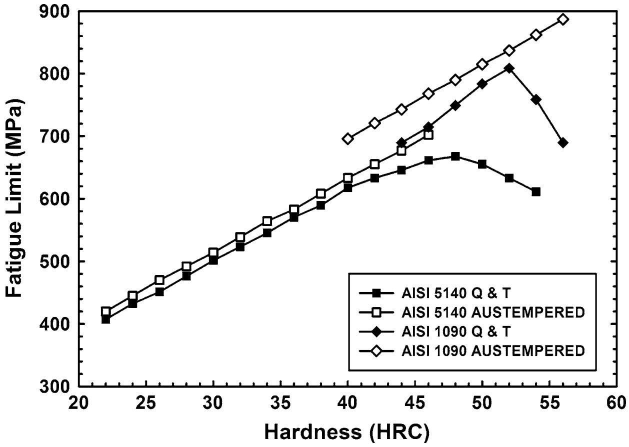

Fig. 21 Fatigue limit as a function of hardness for two different steels that have been Austempered and quench and tempered (Ref 9)

Bainite at equivalent hardness has improved abrasive wear resistance over tempered Martensite. This is an additional advantage and can be seen in Fig. 4.

In the finite life fatigue regime, Austempered steels excel over Q&T steels. Figure 22 shows stress life fatigue data for a fully reversed axial load on Austempered and Q&T 4340 steel tensile specimens. The Austempered 4340 has higher finite life strength than the Q&T 4340. The increased finite life strength makes Austempered steel output shafts ideal for occasional overload applications.

3.1 Contact Fatigue

Documentation of the contact fatigue properties of lower Bainite has been largely confined to high carbon, chromium alloyed steels that are suitable for bearing races. Certainly, this is an area that warrants further investigation.

3.2 Applications of Austempered Steel

Figure 23 through 25 show Austempered steel powertrain components.

4. Carbo-Austempered Steels™

Low to medium carbon steels are good candidates for Carbo-Austempering™. Typically a high carbon, Bainitic case (HRC 50 - 60) is produced on a component with a lower carbon, tempered Martensite core (HRC < 40). In some

Table 2 Mechanical properties of Q&T and Austempered 1074 and 4340 steels

Material	Q&T 1074	Austempered 1074	Q&T 4340	Austempered 4340
HRC Hardness	50	50	45	47
UTS, MPa/Ksi	1701/246.7	1949/282.7	1465/212.5	1605/232.8
Yield Strength, MPa/Ksi	839/121.7	1043/151.3	1340/194.3	1340/194.3
% Elongation	0.3	1.9	12.8	14.2
% RA	0.7	34.5	50.4	56.7
Impact V-Notched (J/ft-Lbs)	3.9/2.9	47.9/35.3	27.8/20.5	31.6/23.3

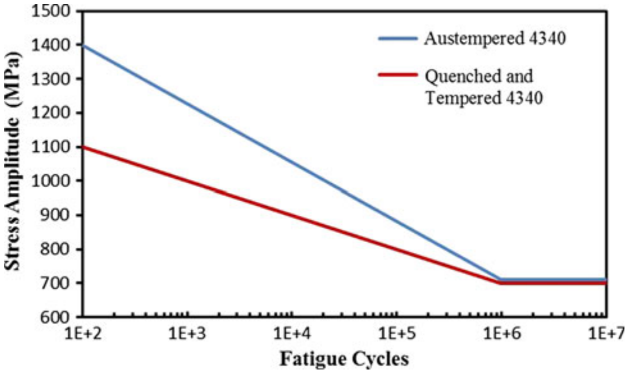

Fig. 22 Stress amplitude versus fatigue life for Austempered and Q&T 4340 steel at equivalent hardness (Ref 10)

Fig. 23 Austempered steel agricultural transmission output shafts

Fig. 24 Geared output shaft for HD Trucks

instances, advantages have been realized in medium carbon alloy steels with a high carbon, Bainitic case (45-55 HRC) on a medium carbon, Bainitic core (45-50 HRC).

4.1 Bending Fatigue

Carbo-Austempering™, like Austempering, is a low distortion heat treatment process when compared to conventional carburize quench and temper heat treatments. During Carbo-Austempering™, the transformation begins in the center or core of the part. This 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 quenched and tempered steel. This is illustrated in Fig. 26, which contains rotating bending fatigue curves for both Carbo-Austempered™ and conventionally carburized quenched and tempered 8622 steel. The surface hardness for these specimens was 58 HRC with an effective case depth of 0.76 mm (0.03 inches). Note the superior performance of the Carbo-Austempered™ steel in the low cycle regime ($<10^5$ cycles) where improvements in fatigue strength of up to 40% can be realized. This trend also occurs in tooth root bending fatigue testing. Figure 27 shows the tooth root bending fatigue life of Carbo-Austempered™ and Carburized quenched and tempered 8620 steel.

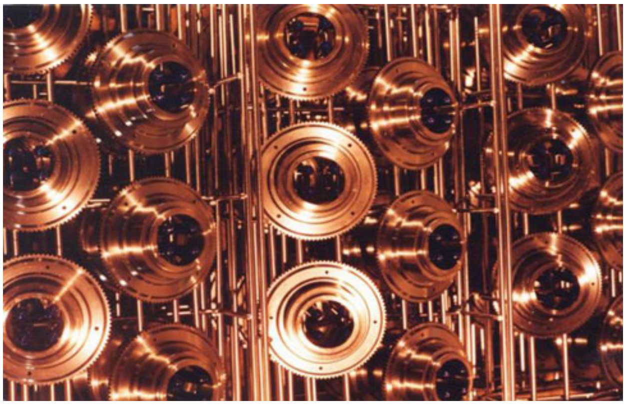

Fig. 25 Austempered steel reverse gears

4.2 Applications of Carbo-Austempered™ Steel

Figure 28 through 31 show Carbo-Austempered™ steel parts.

5. Conclusions: 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 can produce a quiet, low cost gear or shaft in its allowable loading range but it will not outperform carburized quenched and tempered alloyed, low carbon steel in bending or contact fatigue. Therefore, 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.

Below 40 HRC evidence would indicate that martensitic structures will outperform Bainitic structures. However, at hardnesses in excess of 40 HRC, Austempered medium carbon steels outperform through-hardened martensitic components in impact strength and notched fatigue loading. The reduction in distortion as compared to a Q&T or carburized Q&T shaft often eliminates the need for post-heat treatment straightening and eliminates losses due to cracking.

Carbo-Austempered™ steel will outperform HRC 60 carburized quenched and tempered steels in impact and bending

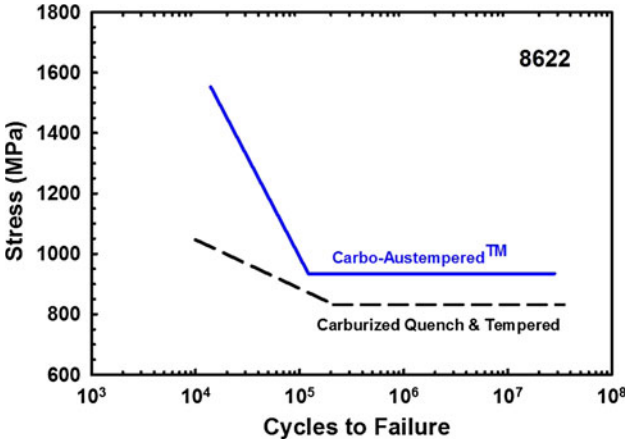

Fig. 26 Rotating bending fatigue comparison of 8622 steel that has been Carbo-Austempered™ and Quench & Tempered

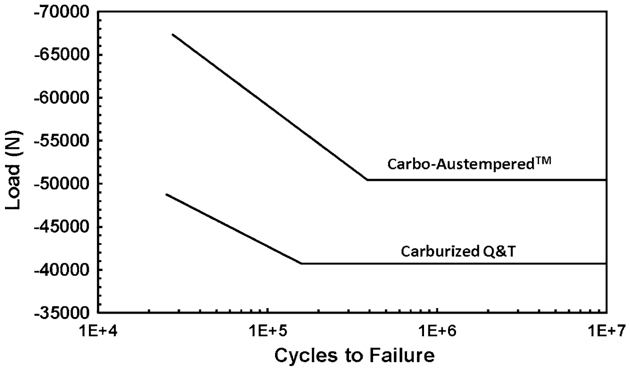

Fig. 27 Load versus cycles to failure for single tooth bending fatigue testing of Carbo-Austempered™ and Carburized Q&T 8620 Gears

Fig. 28 A Carbo-Austempered™ steel school bus transmission output shaft

fatigue, but, at 58 HRC, maximum hardness are limited to slightly lower contact loads. Therefore, applications for Carbo-Austempering™ are where spike overloads in bending occur.

Thus, one 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/her drive component application.

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.

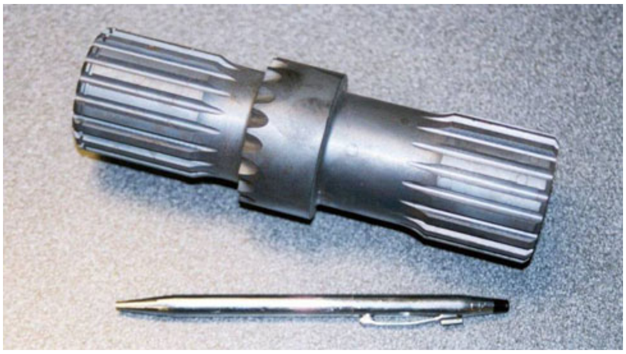

Fig. 29 A Carbo-Austempered™ steel shaft coupler for mis-aligned shafts

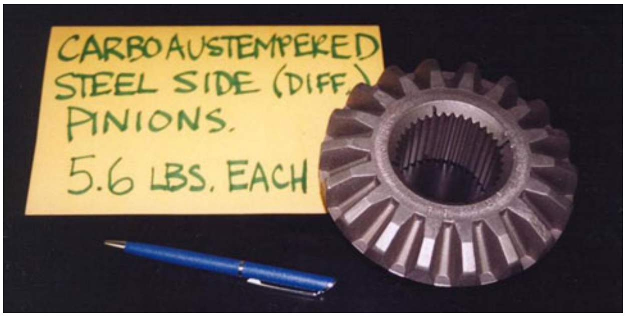

Fig. 30 Carbo-Austempered™ steel side pinions can be found in many high torque differentials

Fig. 31 Starter clutch shells in many light vehicles are Carbo-Austempered™ to withstand the high impact clattering engagement of the starter

Austempering of irons and steels results in increased levels of fatigue strength, wear resistance, and toughness. Benefits in the areas of noise reduction, manufacturability and wear resistance have also been demonstrated.

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