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Wear Properties of Austempered Ductile Irons

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ABSTRACT

Austempered cast irons have a unique microstructure (ausferrite) that provides for excellent wear properties. This paper will examine the available data in the literature on wear in several modes: abrasive wear, adhesive wear (frictional or sliding and rolling), and erosive wear. Additional wear data, including that from competitive materials as well as from private communications, will be presented along with examples of applications of austempered ductile cast irons where wear properties are of concern

INTRODUCTION

The ausferrite microstructure of austempered cast irons consists of a mix of acicular ferrite and high carbon austenite as shown in **Figure 1**. (The exception to this is the SAE J2477 Grade 750-500-11 which contains a certain percentage of pro-eutectoid ferrite). The relative amounts of ferrite and austenite present as well as the microstructural scale are dependent upon the choice of heat treatment parameters.

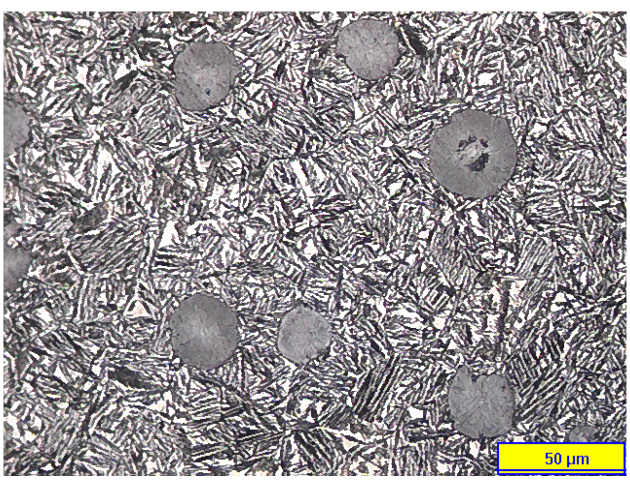

Figure 1: Photomicrograph of Austempered Ductile Iron. The ausferrite matrix typically consists of acicular ferrite (needles) and high carbon austenite (light colored phase).

The austenite component of the ausferrite is thermodynamically, but not mechanically stable. When a high normal force is applied to an austempered component, a strain-induced transformation of austenite to martensite occurs. This results in the formation of a layer of hard, wear resistant martensite that is backed by tough ausferrite. **Figure 2** shows the increase in hardness on an abraded surface of ADI that occurs when martensite is formed. This ability to form martensite is the primary reason for the excellent wear properties of austempered ductile irons.

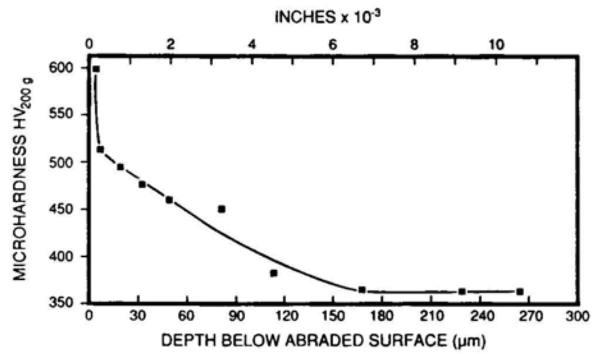

Figure 2: Microhardness as a function of depth for an abraded surface of ADI. (From Ductile Iron Data for Design Engineers.[1])

BACKGROUND

There are numerous publications in the literature that refer to the wear properties of ADI as a function of both microstructure and environment. Due to space constraints, only a selection of these papers is summarized.

Gangasani [2] investigated the friction and wear behavior of various ductile irons under dry conditions over hardened 52100 disks using a 3 pads-on-disk method. In this study, the wear loss of the materials tested was found to be related only to the starting hardness. Grade 5 ADI and Q&T D5506 ductile iron exhibited the lowest wear rates, which were approximately 9% that of D4512 ductile iron.

Gundlach and Janowak [3] studied the wear characteristics of ADI under the conditions of jaw crusher, pin abrasion and rubber wheel abrasion tests. These testing procedures simulate gouging, high stress and low stress abrasion environments, respectively. The greatest amount of work hardening occurred in the jaw crusher test where ADI outperformed Q&T steel at 515 HBW, but not as well as a work-hardened Hadfield steel (12%Mn). During pin abrasion testing, the work-hardening of ADI resulted in ADI being substantially more abrasion resistant than steels of comparable hardness. However, in a low stress environment (rubber wheel testing), the work-hardening was minimal, thus, wear resistance was proportional to the original hardness of the material.

Lerner and Kingsbury [4] reported results for ADI and competitive materials that were tested against a hardened 1045 steel shaft in rotating dry sliding conditions which best simulates the wear conditions for bushing/bearing applications. In this environment, the wear resistance of ADI was 4 times greater than that of pearlitic ductile iron, 12 times that of leaded-tin bronze, nearly 14 times that of aluminum bronze and only about 1.3 times less than that of a fully martensitic ductile iron.

Mädler [5] investigated the use of ADI as an alternative material for railcar wheels. An ADI/steel pairing for the wheel and rail was discovered to have the most favorable wear characteristics. Mass loss at higher contact forces was reduced considerably by using an ADI wheel. Her work showed that both the ADI wheel and the steel track wore less, **(Figure 3)**. This was attributed to the lubricating action of graphite, which created greater lubricity in the boundary layer between both friction partners (i.e. ADI and steel), which is missing in the pure steel pairing.

Shimizu et al. [6] completed a study on the erosive wear of ductile iron, including Grade 1 ADI. Specimens were blasted with grit at varying impact angles in order to simulate the surface damage caused by the impact of particles in either gas or liquid flow. Grade 1 ADI was found to have a maximum erosion rate when the impact angle was 40 – 60°. The erosion rate was 1/25 of ferritic ductile iron and 1/10 of pearlitic ductile iron (70% pearlite). The austenite volume in the ausferrite was measured prior to and after blasting. The initial level was 40% and it decreased to 3-5% after sandblasting, indicating that the forces applied were sufficient to transform the bulk of the austenite present to martensite on the exposed surface.

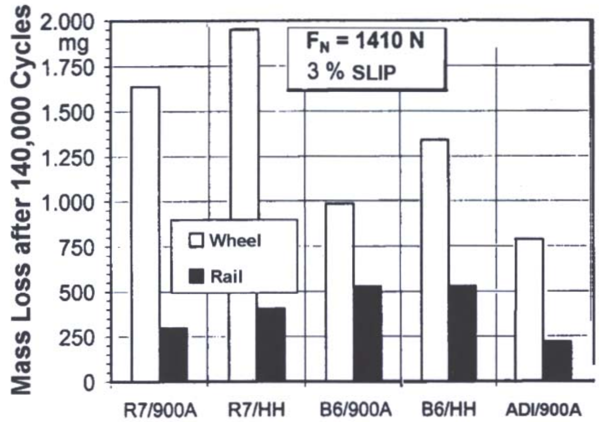

Figure 3: Mass loss after 140,000 cycles for various wheel/rail material combinations. This figure shows that both the ADI wheel and the steel track wore less than the steel/steel pairings in a test with a 1410N normal force and 3% slip. (From Mädler)

Observations from the Literature

All of the testing that has been completed to document the wear properties of ADI can be separated into two basic types of environments: (1) environments with stress levels high enough to cause the surface to work-harden or to allow for the austenite within the ausferrite to transform to martensite and (2) environments with stress levels insufficient to allow for the formation of martensite.

EXPERIMENTAL PROCEDURE

Wear testing has been completed in both high stress and low stress environments for a variety of austempered ductile irons and competitive materials. High stress testing was done utilizing the pin abrasion testing method per ASTM G132-96(2001). Low stress testing was completed using both the wet sand/rubber (WSRW) wheel method per ASTM G105-02 and the dry sand/rubber wheel method (DSRW) per ASTM G65-00.

RESULTS

Pin abrasion test (high stress environment) results are shown in **Figure 4** for a number of cast irons, austempered ductile irons, steel and abrasion resistant irons. Several observations can be made from this data:

- The curves for austempered irons are relatively flat, indicating that the material loss is insensitive to hardness. This is a result of the austenite to martensite transformation on the surface of the test piece.
- In a high stress abrasion environment, ADI, CADI, Ni-Hard Grade 2 and abrasion resistant

(AR) irons have better abrasion resistance than austempered and Q&T steel.

- The abrasion resistance of ADI can be further improved by the addition of carbides or using CADI. The volume of material lost is dependent on the volume fraction of carbide present, with higher carbide volumes resulting in better abrasion resistance.
- The best abrasion resistance is exhibited by the AR irons. However, CADI and Q&T ductile iron can rival the performance of some of these irons.

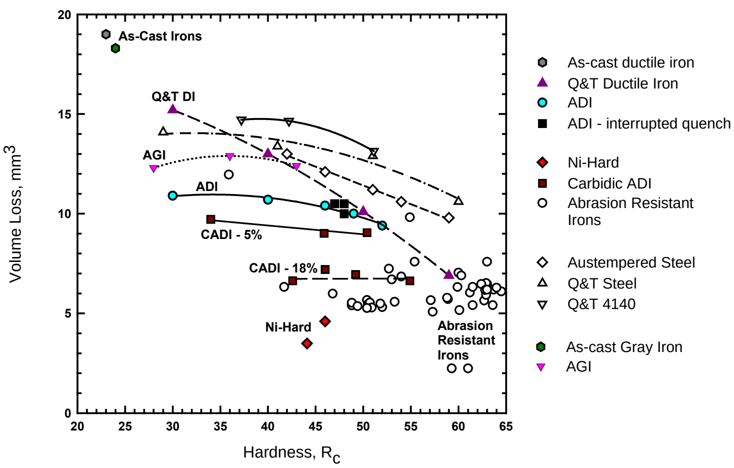

Figure: 4 Pin Abrasion Data for various cast irons, austempered ductile irons, steel and abrasion resistant irons. Abrasion resistant iron data from the Abrasion-Resistant Cast Iron Handbook. [7]

Wet sand/rubber wheel (low stress environment) results are shown in **Figure 5** for austempered ductile irons and competitive steels. Because the data overlaps in some instances, only the regressions lines for each data set are present in this figure. (See the Appendix for a plot containing all of the data points.) Dry sand/rubber wheel (low stress environment) results are shown in **Figure 6**.

Observations from **Figures 5** and **6** include:

- The curves for the austempered irons have a steeper slope than those from the pin abrasion testing. This likely occurs because the normal forces applied in the WSRW and DSRW testing were insufficient to initiate the austenite to martensite transformation.
- In these testing modes, the abrasion resistance is dependent on the bulk hardness of the material. This was confirmed for dry rubber wheel testing by Gundlach and Janowak. [3]
- The abrasion resistance of ADI can be improved by the addition of carbides i.e. CADI, with the higher carbide volumes exhibiting lower material loss.
- The best performance was obtained from a carburized and hardened 8620 steel in WSRW testing. Testing of competitive materials in a DSRW environment is in progress.

It should be noted that the relative magnitudes of the volume loss for WSRW and DSRW testing are different in **Figures 5** and **6**. This occurs because the hardness of the rubber wheels that are utilized for DSRW and WSRW testing is different, depending on the test method. A harder rubber wheel was used for the DSRW testing, hence the reporting of larger volume losses. As a result, readers are cautioned to use this data to compare materials tested within the same mode, but not compare the volume losses from one test method to another.

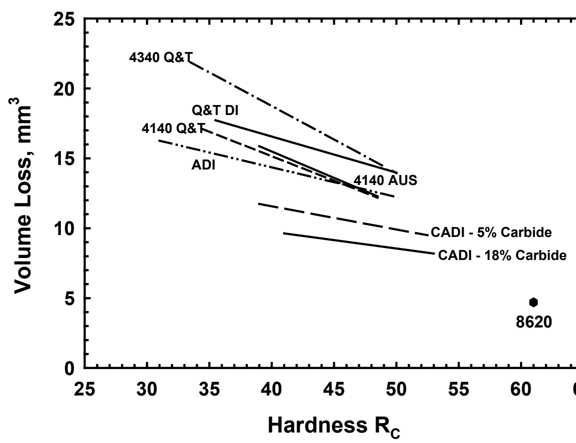

Figure 5: Wet Sand/Rubber Wheel Abrasion results for various ductile iron, austempered ductile irons and steel.

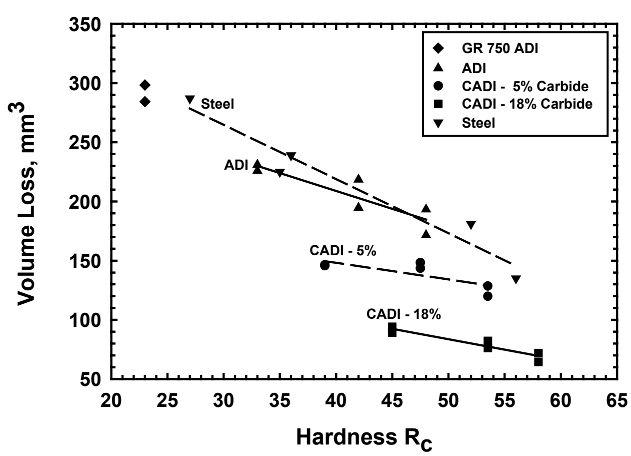

Figure 6: Dry Sand/Rubber Wheel Abrasion results for various austempered ductile irons and steel.

PRACTICAL APPLICATION OF ADI ENGINEERED COMPONENTS IN WEAR APPLICATIONS

Most of the earliest applications of ADI were related to wear resistance. Today, ADI has found application in most durable goods industries and into products ranging from bulldozers, to automobile camshafts, to power tools, to engine timing gears, to dry cleaning conveyors.

ADI has been found to be the cost effective answer for many applications but has proven insufficient in others. For example, GM Powertrain (L4 engine in the 1980's) and CWC Textron (Viper engine since 2000) have found that selectively hardened cam lobes perform adequately at contact loads below 240,000 psi, but contact loads above that result in component pitting in high-cycle applications. Engine designers utilizing the 240,000 psi limitation have adjusted either the spring rate of the roller or sliding followers to accommodate the material and millions of engines operate today with ADI camshafts.

Gear wear is a combination of rolling and sliding contact. While ADI is an excellent candidate material for gears, it is limited to rolling/sliding contact loads below those allowed by the suggested formula below:

$$\sigma_{H\ Limit} = (2.45 \times (\text{Hardness HBW}) + 376\ ) / 6.895$$

This equation was developed using ASME Gear Reseach Institute data for ADI gears [8] and has been proposed to both the AGMA Helical Gear Rating and Mill Rating Committees.

The designer that understands these limitations can develop product to take advantage of the performance characteristics of ADI.

Wheelebrator Inc. [9] found in a study that ADI is adequate in chain conveyors but the material is outperformed by manganese steel in blast cabinet housings and white iron in vanes and liners. A comparative test performed by the authors between high-chromium white irons, ASTM 897 ADI Grade 230-185-01, and a 10% carbide ADI is shown in **Figure 7.** In this application, the shot literally rolls down the face of the vane with very little normal force, thus, the strain-induced transformation to martensite does not occur.

A study performed by the University of South Australia in the Golden Grove Quarry (South Australia) [10] showed that scraper teeth made out of ADI wore 13% less than their commercial steel counterparts when alternated with steel teeth on a working scraper that was tested by moving rock in an operating quarry.

Several applications follow with the anecdotal information that surrounds them.

Figure 7. In a side-by-side test of shotblast vanes, high-Cr white iron (top left) out performed CADI (bottom left). In a similar test on a different machine, high-Cr white iron (top right) outwore an ASTM A897-03 Grade 230-185-01 ADI (bottom right). Notice the wear pattern of the ADI in the absence of carbides.

AUTOMOTIVE CAMSHAFT

Automotive engine camshafts of the type shown in **Figure 8** need to be able to resist high rolling contact loads and the adhesive wear (pitting) conditions that result. Most ADI camshafts in use today are selectively Austempered using either induction or flame heating of the lobes followed by an Austemper quench to produce a cam surface hardness of up to 500 HBW. Millions of camshafts of this type are being produced annually. [11]

Some work has been done, to date, on CADI camshafts (both in chilled iron and Carbidic throughout), but as of this writing no production examples exist.

Figure 8: Typical ductile iron automotive camshaft.

FINAL DRIVE GEAR FOR AN OFF-HIGHWAY UTILITY VEHICLE

The gear shown in **Figure 9** is a ductile iron gear austempered to ASTM A897 Grade 175-125-04 ADI. It is machined in the relatively soft, as-cast condition and then Austempered. The Austempering growth is allowed for in the prior machining so that the gear grows into dimensional tolerance during heat treatment. The competitive material process combination for this application would be machining from alloyed steel forgings or bar stock followed by carburizing and hardening or induction hardening after machining.

Figure 9. This is the final drive gear for an off-highway utility vehicle. It is austempered to grade ASTM A897-03 175-125-04 after machining. [12]

SUSPENSION BRACKET FOR A HEAVY TRUCK

The ADI suspension spring bracket shown in **Figure 10** is designed to sustain the dynamic structural loads of a truck suspension while resisting the high normal force, sliding wear of the spring-on-bracket interface. Before ADI, most truck suspension brackets were either flame hardened ductile iron or steel weldments. The mode of failure of those locally Martensitic hardened components was either wear, or fatigue failure in the heat affected zone adjacent to welds, or hardened areas. Aluminum has not proven to be particularly successful for these types of brackets because it lacks resistance to sliding wear.

Figure 10: A heavy truck suspension bracket made of ASTM-A897-03 Grade 130-90-09 ADI (~300 HBW). [12]

TIMING GEARS FOR DIESEL ENGINES

The timing gears shown in **Figure 11** have been in continuous production since the mid-1980's. They replaced carburized and hardened low carbon, Cr-Mo steel at a significant cost savings. While ADI gear teeth can only sustain about 80% of the maximum contact loads of carburized steel, in most gear designs the allowable contact stress of ADI is sufficient. An, because of its lower modulus, the ADI gear tooth complies, creating a larger contact surface for a given load, thus reducing the actual contact stress Furthermore, the graphite nodules in ADI gears produce a quieter gear that aids the designer in addressing NVH issues.

Figure 11: Diesel engine timing gears made of ASTM A897-03 Grade 230-185-01 ADI (approximately 480 HBW) [12]

SPROCKET FOR CONSTRUCTION EQUIPMENT

The sprocket shown in **Figure 12** replaced induction hardened ductile iron. The through-hardened ADI structure provides superior toughness and wear resistance. Austempering does not embrittle the teeth as does induction hardening. Furthermore, the ADI sprocket is through hardened giving it wear resistance and strength throughout, while the induction hardened sprockets are hardened only on the teeth.

Figure 12: The sprocket shown in this figure replaced an induction hardened sprocket. The ASTM A897-03 Grade 150-110-07 sprocket teeth wear comparably to their induction hardened counterparts but they are much tougher and not subject to breakage. [12]

SUMMARY

ADI is a competitive material for many wear applications. However, it exhibits its best wear properties in conditions where the normal forces engaging the component are high enough to initiate the Martensitic strain transformation that give the structure a hard surface layer. In conditions where the normal force is lower, ADI's wear resistance is proportional to its bulk hardness as are the competitive steel and iron materials. ADI and CADI can be very competitive to other as-cast and heat treated steels but carburized and hardened steels, manganese steels and some abrasion resistant irons may outperform ADI in some applications. The use of ADI in a specific application must be considered as one option, amongst others.

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ADDITIONAL RESOURCES

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