JMEPEG (1998) 7:48-52

Wear Resistance Properties of Austempered Ductile Iron

Y.S. Lerner and G.R. Kingsbury

(Submitted 21 May 1997; in revised form 13 June 1997)

A detailed review of wear resistance properties of austempered ductile iron (ADI) was undertaken to examine the potential applications of this material for wear parts, as an alternative to steels, alloyed and white irons, bronzes, and other competitive materials. Two modes of wear were studied: adhesive (frictional) dry sliding and abrasive wear. In the rotating dry sliding tests, wear behavior of the base material (a stationary block) was considered in relationship to countersurface (steel shaft) wear. In this wear mode, the wear rate of ADI was only one-fourth that of pearlitic ductile iron (DI) grade 100-70-03; the wear rates of aluminum bronze and leaded-tin bronze, respectively, were 3.7 and 3.3 times greater than that of ADI. Only quenched DI with a fully martensitic matrix slightly outperformed ADI. No significant difference was observed in the wear of steel shafts running against ADI and quenched DI. The excellent wear performance of ADI and its countersurface, combined with their relatively low friction coefficient, indicate potential for dry sliding wear applications. In the abrasive wear mode, the wear rate of ADI was comparable to that of alloyed hardened AISI 4340 steel, and approximately one-half that of hardened medium-carbon AISI 1050 steel and of white and alloyed cast irons. The excellent wear resistance of ADI may be attributed to the strain-affected transformation of high-carbon austenite to martensite that takes place in the surface layer during the wear tests.

Keywords abrasion wear test, abrasive medium, austempered ductile iron, austenite, coefficient of friction, countersurface material, martensite, rotating dry sliding test, stress-affected phase transformation, wear behavior

1. Introduction

Austempered ductile cast irons (ADIs) constitute a new family of engineering materials that can be successfully used in many applications requiring high strength combined with relatively high impact toughness and ductility (Ref 1-4). ASTM designates five grades of ADI that, depending on the heat treatment parameters, have the mechanical characteristics shown in Table 1.

Typically, the austempering process consists of two sequentially performed heat treatment operations:

- *Austenitizing:* preheating to 840 to 930 °C (1550 to 1700 °F) and holding at this temperature for a period of time necessary to produce austenite
- *Rapid cooling* to 220 to 440 °C (430 to 750 °F) and *isothermal holding* at this temperature to produce a specific microstructure called ausferrite (Ref 5) with a desirable austenite/ferrite ratio

Recent studies (Ref 5-8) have shown that this new family of engineering materials also offers great potential for cast parts in applications involving impact loads combined with wear. Wear commonly is classified according to its three major modes (Ref 9, 10):

- *Adhesive (frictional) wear* (sliding and rolling) caused by contact with another metallic surface
- *Abrasive wear* caused by contact with metallic (shots, swarf) or nonmetallic abrasive (sand, coal, cement, slag, etc.) materials
- *Erosion wear* caused by impact of dispersed particles in flowing fluids or gases

Y.S. Lerner, University of Northern Iowa, Cedar Falls, IA 50614-0178, USA; and **G.R. Kingsbury,** Lyndhurst, OH 44124, USA.

Abrasive wear takes place in agriculture machines, coal pulverizing equipment, slurry pumps, and so on. Erosion wear may be combined with localized abrasive wear—for example, at bends and valves in pneumatic conveying systems in coal pulverizing equipment, and in pump impellers. Reference 11 reports on erosive wear tests performed on ADI, ferritic ductile iron (FDI), and pearlitic ductile iron (PDI) using a shot blast machine. The erosion rate in ADI was about 10 times less than in PDI and 25 times less than in FDI, showing that ADI has greatly superior erosion resistance. This fact was attributed to the transformation of retained austenite to martensite that took place in ADI.

The study outlined in Ref 12 employed a rubber wheel abrasion test, similar to ASTM G 65-94, in a silica slurry and a reciprocative pin abrasion test on abrasive cloth to rank a series of alloyed ADI (1.5% Ni + 0.3% Mo) austenitized and austempered at different temperatures. Under some specific abrasive

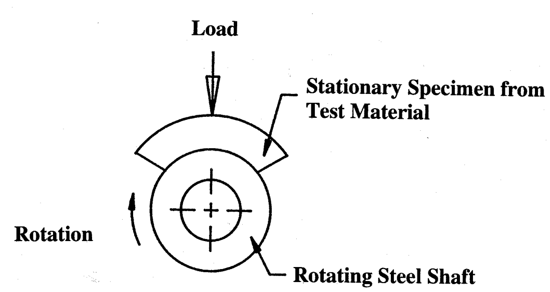

Fig. 1 Schematic of dry sliding wear test

wear conditions, the wear resistance of ADI was substantially greater than the wear resistance of steels of comparable hardness. Again, this was attributed to the work hardening of the austenite in the ADI microstructure. Data in Ref 5 and 8 showed that in pin abrasion wear tests, ADI with a hardness of 30 to 52 HRC can provide an equivalent level of abrasion resistance to both austempered and quenched and tempered steels at a lower hardness level.

As the preceding literature review shows, most studies of ADI wear resistance have been based on abrasive wear tests, which are far from typical conditions for most industrial components. Furthermore, many industrial application (e.g., railroad shoes, conveyers for abrasive ores, and pump bearings) involve adhesive (frictional) wear—that is, rotating dry sliding wear. In many cases this type of wear is combined with abrasive wear. Dry sliding wear takes place not only in different types of brakes, but also in lubricated bearings, particularly at start-up, when under high local loading a satisfactory oil wedge cannot be ensured. Lack of data comparing the wear performance of ADI with that of alternative materials under these specific conditions has kept the field of ADI applications from expanding.

Another factor restraining the ADI market is that the published data are related primarily to the austempering process parameters rather than to the standard ADI grade designations. This can be confusing to the designer, who may not have a metallurgical background and may not be able to interpret the published information with confidence. This study investigates the potential of standard ADI grades as dry sliding wear-resistant and abrasive wear-resistant materials for cast parts, in comparison with commonly used wear-resistant alloys.

2. Experimental Procedures

Two standard grades of ADI deemed most suitable for these applications were selected and tested to develop the necessary information. Heat treatment parameters and various properties for the ADIs and other tested alloys are given in Tables 2 and 3.

2.1 *Rotating Dry Sliding Test*

The aim of these tests was to simulate the dry sliding wear mode that is typical for bushing/bearing applications that involve a relatively high *PV* factor, where *P* is working pressure on the bearing and *V* is surface velocity (Ref 13, 14). During the rotating dry sliding test (Fig. 1), a stationary block made from test material was held under a working pressure of 7.5 MPa against a rotating steel shaft at a surface speed of 0.31 m/s for 2 h. The shaft, made from quenched 1045 steel (48 to 52 HRC), was 30 mm in diameter and 10 mm wide. The running-in period for the various materials ranged from 10 to 15 min, until consistent friction coefficient values were obtained.

Table 1 ADI grades and properties
According to ASTM Standard A 897M-90 (metric) and A 897-90 (English)

Grade	Minimum yield strength, MPa	Minimum yield strength, ksi	Minimum tensile strength, MPa	Minimum tensile strength, ksi	Minimum elongation, %	Minimum unnotched Charpy, J	Minimum unnotched Charpy, ft · lbf	Typical Brinell hardness, HB
850/550/10	550	80	850	125	10	100	75	269-321
1050/700/7	700	100	1050	150	7	80	60	302-363
1200/850/4	850	125	1200	175	4	60	45	341-444
1400/1100/1	1100	155	1400	200	1	35	25	388-477
1600/1300/...	1300	185	1600	230				444-555

Table 2 Heat treatment, matrix microstructure, and hardness of materials tested under conditions of rotating dry sliding wear

Index	Material	Heat treatment	Metallic matrix(a)/hardness
1	DI, grade 100-70-03	Normalized	Pearlitic, 3-7% ferrite, 255-271 HB
2	DI (4% Si)	Normalized	Pearlitic, 2-5% ferrite, 265-271 HB
3	DI (0.7% Mo)	Normalized	Martensitic, 10% acicular, 453 HB
4	DI (0.4% Si, 0.4% P)	Normalized	Pearlitic, phosphide eutectic, 273-281 HB
5	DI (4.7% Si)	Normalized	Pearlitic, 10% ferrite, 302-311 HB
6	ADI, grade 175/125/4 (alloyed with Mo and Ni)	Austenitized at 900 °C (1650 °F) for 2 h, austempered at 300 °C (570 °F) for 2 h	Ausferrite, 42-44 HRC
7	Nitrided DI	Heated in a dissociated ammonia atmosphere for 16 h at 550-560 °C (1020-1040 °F)	0.25 mm (0.01 in.) nitrided layer, including 0.08 mm (0.003 in.) with nitride particles (550-650 HV) and a nitrogen-rich austenitic underlayer (300-350 HV)
8	Quenched DI	Quenched in water, tempered for 1 h at 220-240 °C (430-465 °F), cooled in air	Martensitic, 48-50 HRC
9	Aluminum bronze (9% Al, 4% Fe)	As cast	123-127 HB
10	Leaded-tin bronze (4.5% Pb)	As cast	115-121 HB

(a) Graphite nodularity in all DI samples was not less than 80%.

In this test, the wear behavior of both the test material and the countersurface was measured. This was done because in real bearing/bushing applications the countersurface material significantly affects net system operation performance.

Three duplicate tests were conducted for each test material. Different types of DI, including ADI and nitrided DI, were tested in comparison with aluminum and leaded tin bronzes. Detailed descriptions of the tested materials are given in Table 2. Surface roughnesses of the test blocks and test shafts in the range 0.10 to 0.15 μm were obtained after final machining and fine grinding. The coefficient of friction (f) values were calculated as the ratio of the measured friction force value (F) to the test load (W):

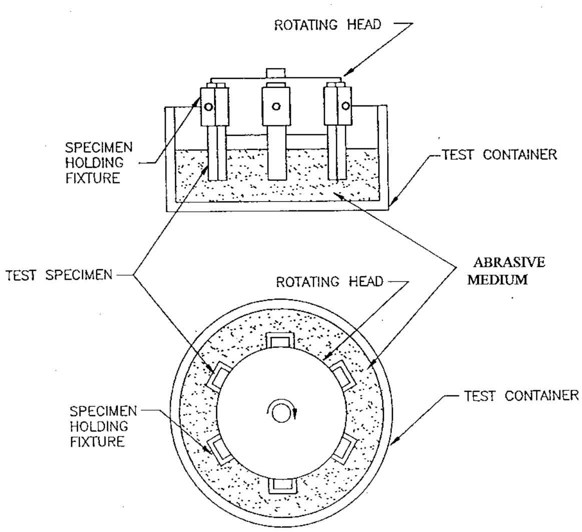

Fig. 2 Schematic of abrasion wear test

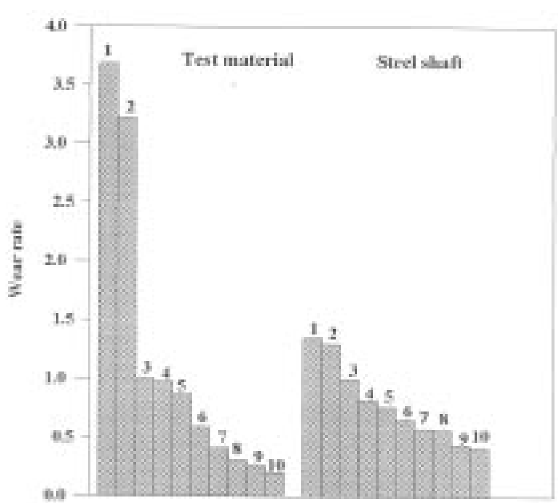

Fig. 3 Wear resistance of materials in rotating dry sliding test. 1, aluminum bronze; 2, leaded-tin bronze; 3, PDI, grade 100-70-03; 4, DI (4.0% Si); 5, DI (4.7% Si); 6, DI (4.0% Si, 0.4% P); 7, nitrided DI; 8, DI (0.7% Mo); 9, ADI, grade 175/25/4; 10, quenched DI

$$f = \frac{F}{W}$$

Wear resistance was determined from the loss in weight. The wear rate (R) of the test material, as well as the steel shaft, was calculated as a ratio of weight loss of the test material or the corresponding steel shaft to the weight loss of the reference material (unalloyed pearlitic DI, grade 100-70-03) and its corresponding steel shaft.

2.2 *Abrasion Wear Test*

This test, schematically illustrated in Fig. 2, was developed to simulate the conditions of erosion wear combined with localized abrasive wear—typical, for example, for bends and valves in pneumatic conveying systems in coal pulverizing equipment, slurry pumps, and pump impellers. Table 3 lists heat treatment parameters and hardnesses for the tested materials. Specimens were prepared in the shape of rectangular bars measuring 25 by 75 by 10 mm (1 by 3 by 0.4 in.). The holding fixture was designed to hold six specimens. Three similar specimens made from the reference material were alternated with three test specimens, and an average wear rate was calculated for each material. In order to accelerate wear and create more local stress by the impeller effect, the test specimens were held in the fixture at a 30° angle.

The test cycle consisted of rotating the specimens fixed on the rotating head at a speed of 1000 rev/min inside the container—filled with an abrasive medium (alumina sand with a particle size of approximately 2 mm—for 15 h. The rate of wear was determined as the ratio of weight loss of test material to the weight loss of reference material (quenched and tempered AISI 1050 steel). Fresh alumina particles were used for each test.

3. Results and Discussion

3.1 *Rotating Dry Sliding Test*

The data in Table 4 characterize the wear behavior of investigated materials when tested against hardened 1045 steel shafts in rotating dry sliding tests. Figure 3 shows the relative wear resistance of test materials and their countersurfaces. In these wear tests, unalloyed pearlitic DI grade 100-70-03 was used as the reference material. Relatively high wear was exhibited by the bronzes: compared to the reference material, the wear rate of aluminum bronze was 3.6 times greater and leaded-tin bronze 3.2 times greater. The wear of steel shafts running against the bronzes could not be determined accurately because of transfer and adhesion of bronze material to the shaft surfaces.

Wear of pearlitic DI grade 100-70-03 was improved by alloying with additions of 4 to 4.7% Si and with 4% Si + 0.4% P. Nitriding of DI and alloying with 0.7% Mo reduced its wear factor to 0.416 and 0.309, respectively, but caused a disproportionately higher shaft wear factor: 0.57 and 0.58, respectively.

Quenched DI with a fully martensitic matrix microstructure slightly outperformed ADI. The wear rate of ADI was only about 1.3 times less than that of quenched DI, with no significant difference in the wear of the steel shaft. Most importantly, the wear rate of ADI was about 25% that of pearlitic DI grade 100-70-03, with corresponding steel shaft wear of less than 50%. Excellent wear resistance of ADI and its countersurface combined with their relatively low friction coefficient points to the potential for practical applications involving this wear mode.

3.2 *Abrasion Wear Test*

Data from these tests can be used to rank materials according to their resistance to abrasive wear. The results in Fig. 4 indicate that unalloyed white cast iron exhibited only 7 to 8% less wear than the quenched and tempered AISI 1050 medium-carbon steel reference material. The wear rates of Cr-Ni gray cast iron and 12% Cr white cast iron were very similar, at 0.8 to 0.84 times that of the reference material. The wear rate of quenched DI was much superior, at 0.58 times that of the reference material. However, ADI and AISI 4340 steel exhibited the lowest abrasion wear rates, at around 0.5 times that of the reference steel.

3.3 *Practical Application Potentials*

Results from this study demonstrate the superior wear resistance of ADI compared to many conventional wear-resistant alloys. This resistance can be explained by the stress-affected phase transformation of high-carbon austenite to martensite in a matrix of acicular ferrite that takes place during the tests (Ref 15). In wear processes that involve reasonably severe applied forces, the surface that is in contact with the abrasive medium or with a countersurface undergoes plastic deformation, which accelerates this phase transformation and amplifies the ADI wear resistance.

It should be emphasized that this process takes place only at the surface, while the core metallic matrix continues to be relatively soft and ductile. This dual microstructure can be compared to that obtained after surface hardening of austenitic steel containing 12 to 14% Mn.

Presented here are potential wear applications in which ADI may be considered as an alternative material to:

- Alloyed and unalloyed steel castings and forgings that are used under abrasive wear conditions. ADI may permit an 8 to 10% reduction of part weight and cost, because ADI cast-

Table 3 Heat treatment, hardening method, and hardness of materials tested under conditions of abrasive wear

Index	Material	Heat treatment	Hardness, HRC
1	AISI 1050 steel (medium carbon)	Quenched and tempered	48-52
2	AISI 4340 steel	Quenched and tempered	50-52
3	Gray cast iron (0.8% Cr, 3% Ni)	As cast	46-50
4	Cast iron (12% Cr)	As cast	45-47
5	Unalloyed white cast iron (CE = 3.8%)	As cast	48-50
6	Quenched DI	Quenched in water, tempered for 1 h at 220-240 °C (430-465 °F), cooled in air	48-50
7	ADI, grade 200/155/1 (alloyed with Mo and Ni)	Austenitized at 885 °C, (1625 °F) for 2 h, austempered at 280 °C (535 °F) for 3 h	47-49

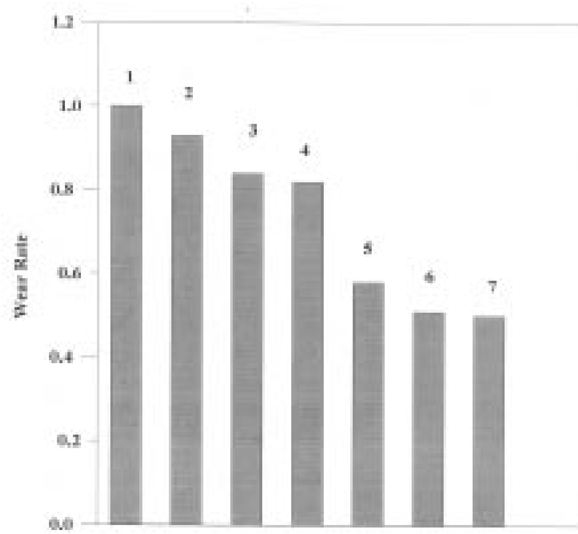

Fig. 4 Wear resistance of materials in abrasive test. 1, quenched and tempered medium-carbon 1050 steel; 2, unalloyed white cast iron; 3, gray cast iron (0.8% Cr, 3% Ni); 4, white cast iron (12% Cr); 5, quenched and tempered DI; 6, ADI, grade 200/155/1; 7, alloyed steel 4340

Table 4 Wear rate and coefficient of friction of materials tested against hardened 1045 steel rings in dry sliding tests

		Wear rate, g/h		Wear factor		
Index	Material	Test material	Steel shaft	Test material	Steel shaft	Friction coefficient
1	PDI, grade 100-70-03	0.2940	0.1000	1.0	1.0	0.472
2	DI (4% Si)	0.2890	0.0820	0.98	0.82	0.478
3	DI (4.7% Si)	0.2560	0.0460	0.87	0.76	0.497
4	DI (4% Si, 0.4% P)	0.1740	0.0360	0.59	0.66	0.484
5	Nitrided DI	0.1223	0.0573	0.416	0.58	0.524
6	DI (0.7% Mo)	0.091	0.0589	0.309	0.57	0.482
7	ADI, grade 175/25/4	0.0788	0.0440	0.268	0.44	0.436
8	Quenched DI	0.061	0.0420	0.207	0.42	0.437
9	Aluminum bronze (9% Al, 4% Fe)	1.082	+ (increment)	3.68	…	0.457
10	Leaded-tin bronze (5% Sn, 4.5% Pb)	0.9594	+ (increment)	3.22	…	0.331

ings are approximately 8 to 10% lighter than steel parts with equivalent or better service performance.

- White iron castings in applications requiring both wear resistance and high impact toughness. ADI may enable significant cost reduction with better service performance.
- Bronzes and pearlitic DI in rotating dry sliding wear applications, typical for bushings/bearings used at a relatively high *PV* factor and in a dirty environment, where reliable fluid lubrication is not ensured. ADI may lower cost, while giving better service performance.

4. Conclusions

In the dry sliding wear mode, ADI wear resistance was nearly four times greater than PDI grade 100-70-03, more than 12 times that of leaded-tin bronze, and nearly 14 times that of aluminum bronze. Only quenched DI with a fully martensitic matrix exhibited slightly greater wear resistance than ADI. Steel shaft wear with both quenched DI and ADI was correspondingly low.

In abrasive wear tests, ADI exhibited wear resistance that was equivalent to that of AISI 4340 steel, almost twice less than that of hardened and tempered AISI 1050 carbon steel, and significantly greater than that of white and alloyed cast irons.

The superior wear resistance of ADI may be attributed to the transformation of high-carbon austenite to martensite that takes place in the surface layer during the wear tests. The wear data developed in this study may be extrapolated to practical wear systems that are generally similar to the dry sliding and abrasive wear regimes of the tests.

References

1. *Ductile Iron Handbook,* American Foundrymen's Society, 1992
2. *Ductile Iron Production,* QIT America, 1992
3. Y.S. Lerner, A.G. Miroshnichenko, R.L. Snezhnoy, and N.I. Vinogradova, Development of Austempered Ductile Iron for Gears, *Russ. Cast. Prod.,* No. 10, 1985, p 4-7
4. Y.S. Lerner, S.L. Burakov, V.V. Barsukov, F.I. Kreis, and V.I. Efimov, Applications of Ductile Irons in Farm and Tractor Machinery, *NITRACTORMASH,* Moscow, 1980
5. B.V. Kovacs, Austempered Ductile Iron: Fact and Fiction, *Mod. Cast.,* March 1990, p 38-41
6. K.L. Hayrynen, ADI: Another Avenue for Ductile Iron Foundries, *Mod. Cast.,* Aug 1995, p 35-37
7. J.R. Keough, An ADI Market Primer: Part 1, *Foundry Manage. Technol.,* Oct 1995, p 28-30
8. J.R. Keough, An ADI Market Primer: Part 2, *Foundry Manage. Technol.,* Nov 1995, p 27-31
9. *ASM Handbook,* Vol 18, *Friction, Lubrication, and Wear Technology,* ASM International, 1992
10. M.H. Jones and S. Douglas, *Industrial Tribology,* Elsevier Science, Amsterdam, 1983
11. K. Shimuzu, T. Neguchi, T. Yamaguchi, and T. Kamada, Basic Study on Erosive Wear of Ductile Iron, *AFS Trans.,* Vol 102, 1994, p 285-289
12. R. Gundlach and J. Janowak, Process Overview of Wear and Abrasion Testing, *Proc. 2nd Int. Conf. Austempered Ductile Iron,* University of Michigan, 17-19 March 1986, p 23-30
13. Y.S. Lerner, Wear Resistance of Ductile Irons, *J. Mater. Eng. Perform.,* Vol 3 (No. 3), 1994, p 1-6
14. Y.S. Lerner, Ductile Iron Use in Machine Tool and Hydraulic Components, *Foundry Manage. Technol.,* Aug 1995, p 108-115
15. J.R. Laub, Cast Austempered Ductile Iron for High Strength and Long Wear, *Adv. Mater. Process.,* Vol 145 (No. 2), 1994, p 12-15