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FRICTION AND WEAR CHARACTERISTICS OF DUCTILE IRON IN DRY SLIDING CONDITIONS.

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ABSTRACT

There could be a number of situations where ductile iron parts might be rubbing against hardened steel parts under dry conditions for part of the time or all the time. Using laboratory methods, the wear and friction characteristics of ADI, Q & T, ductile iron, and as-cast ductile irons were evaluated.

A multi-specimen wear testing equipment capable of continuously monitoring applied torque, specimen temperature and ambient temperature was employed in the laboratory testing. The specimen holder was of the type called 3 pads-on-disk. The wear patterns of these different types of ductile irons were compared and presented in the form of graphs. Also the friction coefficients under these different material combinations were evaluated. The friction coefficients continuously changed with the time of testing and a typical graph is presented in this paper. An analysis of the results is also presented.

INTRODUCTION

In most of the mechanical assemblies there are some moving parts and some stationary. As a result of this there is a continuous relative sliding action in these mechanical devises. Frictional forces in these sliding surfaces result in wear. Friction and wear is not an intrinsic property of any material but it is a system property. The best way to study the process, therefore, is by actual observation of an assembly in the field run. However, the time of such testing would be long. Designers may like to see some relative behavior of the materials under laboratory conditions, which are for most of the time accelerated to yield quick results. One has to be real careful in interpreting and applying these results in the practical situations. One such method could be dry sliding of one test material over another test material under controlled pressure and sliding velocity. Keeping all these limitations in mind the objective of the work reported in this paper was to find out the dry sliding wear and dry frictional behavior of various continuously cast ductile iron samples over hardened 52100 steel disks when relatively lower loads are employed. This paper reports a part of the larger on-going wear and friction investigation program at Wells Manufacturing Company.

BACKGROUND

Ductile iron had been replacing several steel parts in the machinery since last 50 years. Besides mechanical properties the wear resistance of ductile iron was also of great interest to many investigators. Based on actual application the test procedures were designed or adopted by investigators. The range of ductile irons investigated include the as cast materials, as cast alloyed ductile irons to various grades of austempered ductile irons (ADI). Janowak et al [1] described the type of metal matrix obtained in ADI by various austempering temperatures. Comparative studies made by Liu et al [2], and Riposan et al [3], involving flake graphite cast iron, CG iron and nodular graphite ductile iron also placed ductile iron high from wear resistance point of view. A number of research workers took special interest in ADI. Zhou et al [4] studied wear resistance of different ADI components and concluded that the wear resistance is closely related to the amount of ausferrite. Gundlach et al [5] concluded from their tests that during the abrasion tests (jaw crusher) the surface of ADI samples got work hardened and thus better wear resistance was realized. Mayr et al [6] and Bing-Qing et al [7] also concluded that the stress induced martensite formation was there in ADI. Schissler [8] studied ADI using abrasion wear testing methods. Schissler concluded that the amount of retained austenite in their tests influenced the wear of the ADI surfaces. Prasanna et al [9,10] using a wet grinding type testing equipment on ADI samples concluded that ADI when austempered at a temperature in the range of 240 C to 280 C yielded best wear resistance results. Cast iron is widely used in conditions of dry-sliding wear in which two metallic surfaces are in rubbing contact. Examples include brake drums, brake discs, and clutch plates [11]. The cast irons were evaluated for wear under laboratory conditions as well as field-testing. Different types of ductile irons were tested but most of the time investigators were looking at the ADI for improved wear characteristics. The tests were conducted using extremely higher friction forces or impact forces. No detailed analysis of the friction coefficients during the testing had been reported. Based on this information it is thought that planning of tests using 3 pads-on-disk adapters, a relatively new test procedure for this purpose, could yield information beneficial to evaluate ductile iron test materials in laboratory conditions. The dry test conditions could be selected with relatively lower forces and study the effect of this combination on wear and friction characteristics. Presented investigation was on ductile irons of different matrices obtained by as cast and heat treatments. The information generated was on wear and friction coefficients under dry conditions.

DUCTILE IRON MATERIAL UNDER INVESTIGATION

Continuous casting of ductile iron bars proved to be outstanding in manufacturing shrinkage free and consistent quality bars. Continuous cast bars are relatively free from many types of inclusions. The soundness of these bars is unsurpassed by any other type of casting process.

Continuous casting of ASTM A536-84 grades 65-45-12 and 80-55-06 ductile irons is very much feasible and a number of customers use these products as some components in their hydraulic, agricultural, automotive and earthmoving machine assemblies. Therefore, these two grades were selected for investigating wear and friction behavior under laboratory conditions. The as-cast bar size of 80-55-06 grade (5506 DI) was 5.500" and of 65-45-12 grade (4512 DI) was 4.000".
The as-cast chemistries of the material are given in the **Table 1**. The sulfur and Mn levels were lower and 5506 grade ductile iron was obtained by using some alloying with elements such as Cu and Sn.

The pad samples that were used in the wear and friction testing were prepared from 8" length bar samples taken from single continuous cast bar of 6' length.

The as -cast un-etched and etched microstructures of the 4512 DI and 5506 DI samples were examined and found to be possessing better than 90 % nodularity . The average pearlite contents in the matrix of 4512 DI and 5506 DI were about 30 % and 67 % respectively.

The bars used for making various pad samples were heat-treated. The 5 % nital etched microstructures of these heat-treated pads (ADI, and Q & T) are given in the **Figures 1 to 4**. ADI treatments resulted in coarse to fine ausferrite structure as given in the **Figures 1 to 3**. The tempered martensite structure could be seen in **Figure 4**. The microstructures were taken from pad s used in preparation of test samples.

For the purpose of testing the pads samples of 4512 DI and 5506 DI have varying levels of pearlite. Also by heat-treating to ASTM A897-90 ADI grades 1, 3 and 5 samples got different amounts of bainitic ferrite and carbon saturated stable austenite in the metal matrices. The tempered martensite is another matrix in the samples that we are interested in evaluating in the wear tests. The material mechanical properties such as hardness and tensile, yield and elongations (4512 DI & 5506 DI) are given in **Table 2**. The test bars were taken from the continuously cast bars.

Samples from these materials were used to heat treat to get different matrix conditions for evaluation. The samples were taken from approximately mid-radius of the cast bar. The samples were then rough turned to required diameter before sending to appropriate heat treatment. The samples were subjected to the heat treatments as given in **Table 3**. Resulting hardness values were also recorded in the **Table 3**. These samples were used to make pads of 3/8" diameter and 0.101" thick. Material used for the disks in the testing was 52100 steel, which was austenetized at 1650 F and quenched and tempered to a hardness of about 60 Rc.

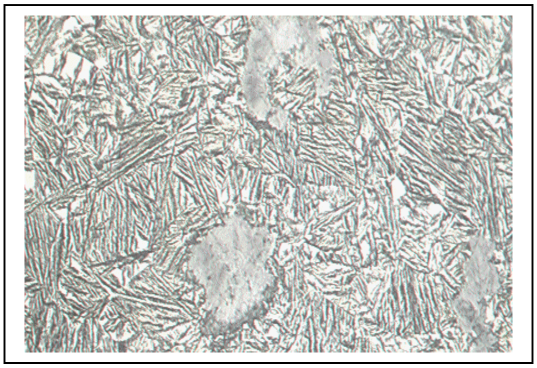

Figure 1: ADI Grade 1, Etched, 500x

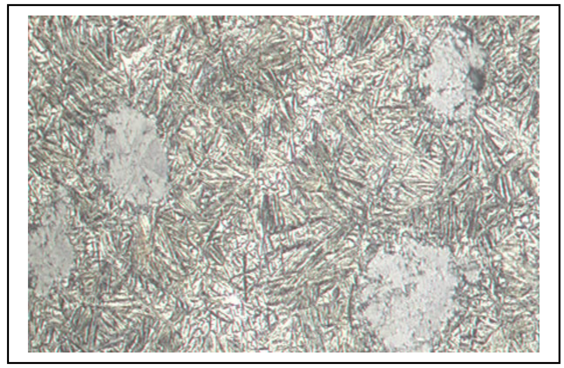

Figure 2: ADI Grade 3, Etched, 500x

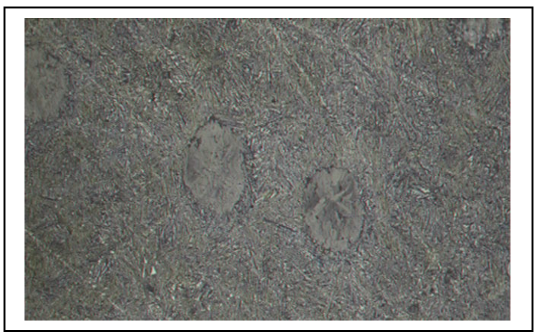

Figure 3: ADI Grade 5, Etched, 500x

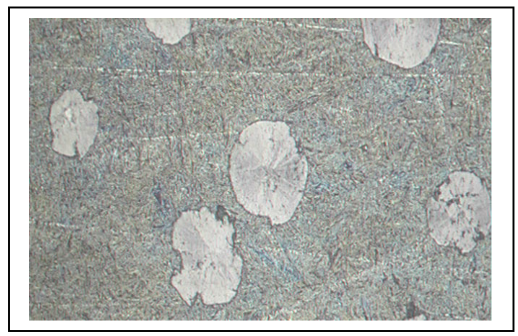

Figure 4: Q & T DI, Etched, 500x

Table 1: As cast chemical composition of 65-45-12 and 80-55-06 grades.

Element	4512 DI wt %	5506 DI wt %	Element	4512 DI wt %	5506 DI wt %
Carbon	3.57	3.38	Copper	0.022	0.058
Silicon	2.46	2.47	Vanadium	0.004	0.004
Manganese	0.23	0.20	Tin	0.009	0.041
Nickel	0.013	0.009	Titanium	0.015	0.011
Chromium	0.029	0.027	Phosphorus	0.029	0.029
Magnesium	0.033	0.027	Sulfur	0.008	0.008
Molybdenum	<0.005	<0.005	Aluminum	0.011	0.011

Table 2: Mechanical properties of as cast 65-45-12 and 80-55-06 grades.

Material Grade	BHN Edge	BHN Center	Tensile, psi	Yield, psi	Elongation, %
65-45-12	170	178	78,200	48,400	16.0
80-55-06	238	242	100,800	59,300	10.0

Table 3: Heat treatment conditions and final hardness.

HEAT TREATMENT	AUSTENITIZING TEMP (F)/DURATION	QUENCHING TEMP (F)/DURATION	HARDNESS Rc
4512 DI ADI GRADE 1	1634 / 74 MINUTES	729 / 85 MINUTES	26
4512 DI ADI GRADE 3	1634 / 74 MINUTES	603 / 159 MINUTES	38
4512 DI ADI GRADE 5	1634 / 74 MINUTES	481 / 240 MINUTES	45
5506 DI Q & T	1650 / 120 MINUTES	WATER QUENCHED TEMPERED AT 500 F	55

WEAR TESTING MACHINE AND THE TEST PROCEDURE

For the wear test in the laboratory a multi-specimen test machine was used. The machine has the capability to run from 9 to 7200 rpm with various pulleys. The loads on the samples could be up to 807 lb and the specimen could be maintained if necessary at higher temperature (up to 300 F) with appropriate fluid surroundings. The sample loading table and spindle could be seen in the **Figure 5**. The machine is equipped with data acquisition system which could be made to obtain the specimen temperature, temperature of the surrounding chamber, torque, rpm and time values at every 2 seconds duration or any higher durations as desired. A continuous display of these values is also there on the control panel. The panel displaying the test parameters is shown in **Figure 6**.

Figure 5: Multi-specimen testing machine

Figure 6: The Control Panel

Figure 7: Samples and Sample adapter

For the current laboratory wear testing a 3 pads-on-disk adapter was used. The pads, pad- holder, and a disk are shown in the **Figure 7**. In a given test 3 pads of 0.375" diameter and 0.101" thick are mounted in a rotating upper adapter at a position 0.75" on a radius.

This is equivalent to using three samples for testing on almost similar conditions (counter surface, temperature and lubrication / no lubrication etc.) The lower disk specimen is a stationary one. The material for this disk could be same as pads or any other counter faces that need to be evaluated for friction and wear with respect to the pad material.

In the present investigation the pads were made out of 4512 DI as cast, 5506 DI as cast, 4512 as cast ductile iron heat treated to ADI grades 1, grade 3, and grade 5, and 5506 DI as cast which was Q & T heat treated. In these experiments the disks used were only made from Q & T 52100 steel. The pads and the disks were ground to size and the starting surface finish was uniform as given in the typical measurements using a Federal Pocket Surf Indicator. The pads measured a surface roughness of Ra 10 to 15 micro inches and the disks measures a radial surface roughness, Ra of about 32 to 48 micro inches and tangential roughness of about 42 to 54 micro inches.

The test conditions were as followed: No lubricant was used and no external heating was employed. The machine has the capability to measure the temperatures of the disk and the surroundings. Several trial tests were conducted with different loads and rpm to get test parameters that yield measurable values and tests could be conducted in the laboratory without undue noise and vibration. Some trials were made using deionized water, a smear of oil on the surfaces of pads etc. Finally dry test condition under a fixed weight of 5 lb was selected as this test procedure gave adequate measurable wear rates. A predetermined load of 5 lbs was employed through out the testing. The leverage was 2 and as that resulted in a thrust of 10 lb. Also the rpm was kept constant around 100. The data such as the time, torque, and temperatures (disk and surrounding the adapter) were periodically measured (every 20 seconds interval) and put into a data acquisition system. Single test duration was for 12,000 revolutions (approximately 2 hours). At the end of the test, machine stops automatically. At that time the adapter was taken out, the pads and the disk were cleaned of the debris, and the pads and disk were weighed using a high precision balance with least weighing capacity of 1/10th of a mg. The debris was also collected from the table at the end of each test. The color of the debris collected was red and it was a powder. Obviously it looked like an iron oxide as reported in the literature in similar situations [2]. All the data pertaining to these tests were saved in a DAS file for analysis. For any 3 pad sample set, this testing was repeated 12 times to cover a total of over 144,000 revolutions.

The wear data were assessed with respect to revolutions of the spindle. Each pad covered a distance of 4.71" per revolution. The data obtained was over 12,000 revolutions (approximately 2 hours duration), so that amounted to a distance of 4,710 feet. The testing machine could be programmed to stop automatically after 12,000 revolutions of the spindle. At the end of each test the samples were taken out and weighed after cleaning. Weight loss was recorded for each of the run. For each combination of materials twelve runs were made. The results of these tests were then analyzed to find out the wear loss by weight and by volume and also to find out the variation of friction coefficients during the tests.

EXPERIMENTAL RESULTS

At the end of 12 run test procedure the pads were examined using optical microscope, stereomicroscope and SEM. One of the pad was cut into half and the section and the remaining semi - circular surface were mounted and polished to examine the microstructure of the wearing surface and its cross section. **Figures 8 to13** show etched microstructures of all these sectioned mounts. The surfaces of pads were examined using Hitachi S3500 N Scanning Electron Microscope. The wear morphology of worn surfaces was examined at 400x or higher magnifications and given in **Figures 14 to 19**.

The weight loss data of each pad and each disk was recorded for every run and data over twelve runs were presented as volume loss for each material combination. A typical graph for 4512 DI is given in the **Figure 20**. These are the graphs generated using the weight loss information.

DAS provided information on the torque during the tests. Torque and the direct thrust on the samples (10 lb) that will help calculate the friction coefficients. The frictional coefficient, **f**, was calculated as a ratio of (**Ff/Fn**), Where **Ff** is frictional force calculated using the geometry of the test set up and the torque and **Fn** is the normal force which was kept at 10 lbf in all of these experiments. The frictional coefficient values were averaged over a small periods of time (moving average) to suppress noise in the DAS. A typical plot of the friction coefficients in various runs (against cumulative revolutions) of ADI Grade 5 sample set is given in **Figure 21**.

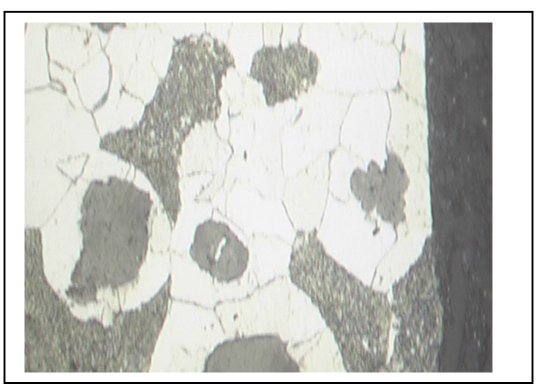

Figure 8: 4512 DI, etched, 500X

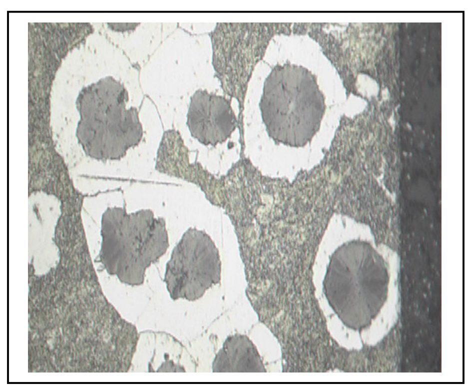

Figure 9: 5506 DI, Etched, 500X

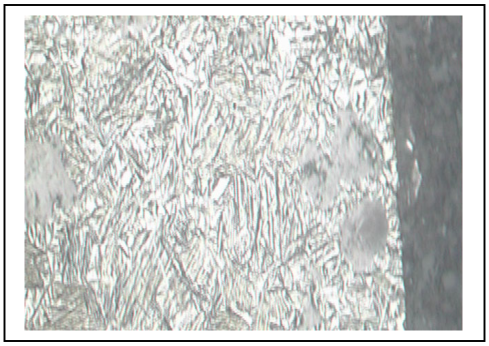

Figure 10: ADI Gr 1, etched, 500X

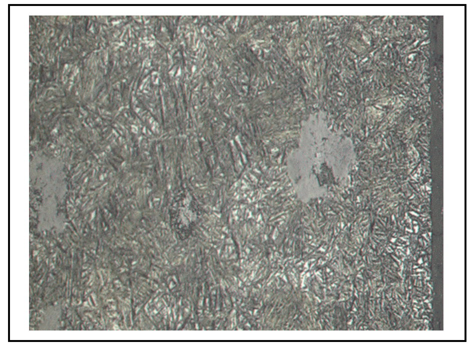

Figure 11: ADI Gr 3, etched, 500X

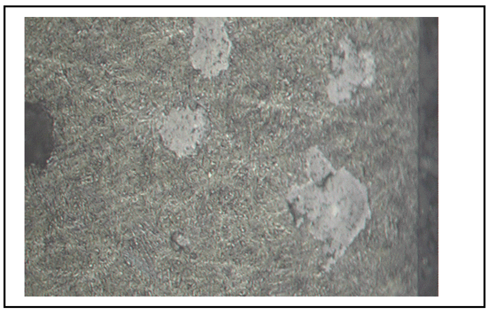

Figure 12: ADI Gr 5, Etched, 500X

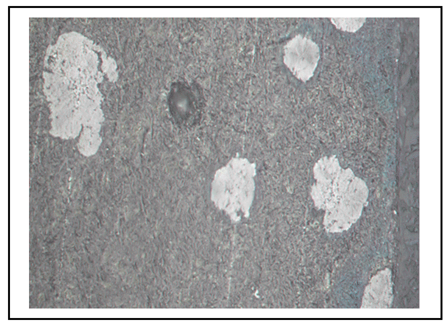

Figure 13: DI Q & T, Etched, 500X

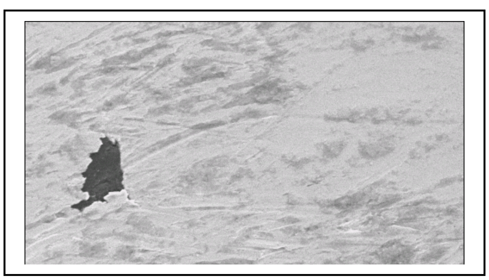

Figure 14: 4512 DI, SEM, Surface, 800x

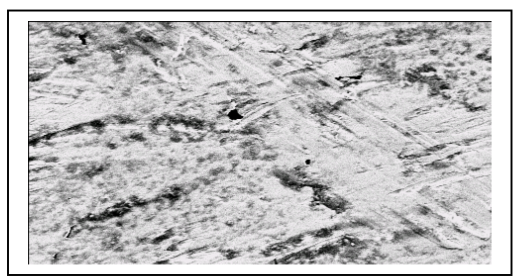

Figure 15: 5506 DI, SEM, Surface,400x

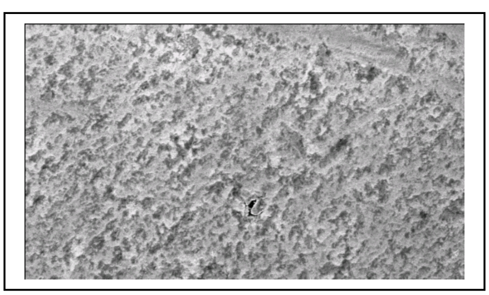

Figure 16: ADI G 1, SEM, P. Surface, 800x

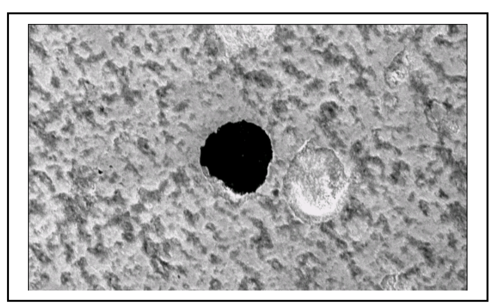

Figure 17: ADI G 3, SEM, Surface, 400x

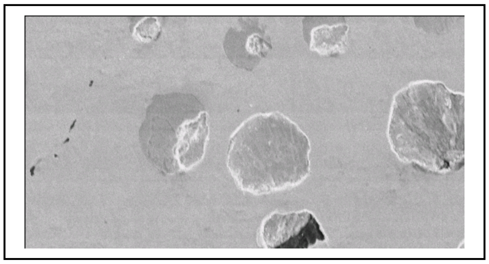

Figure 18: ADI G 5, SEM, Surface, 400x

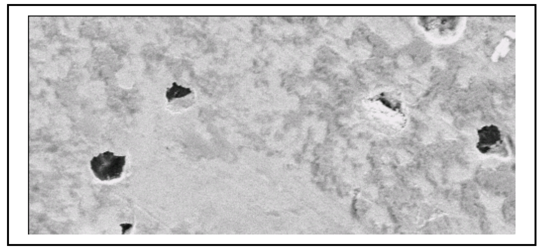

Figure 19: DI Q&T, SEM, Surface, 400x

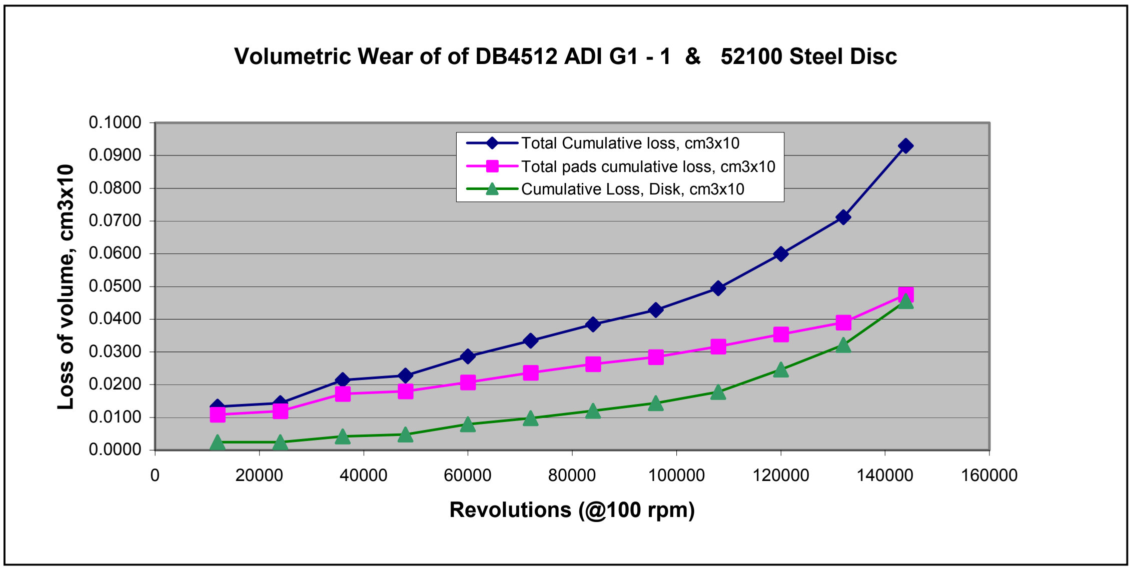

Figure 20: The volume loss of 4512 pads and 52100 steel disk over 12 runs

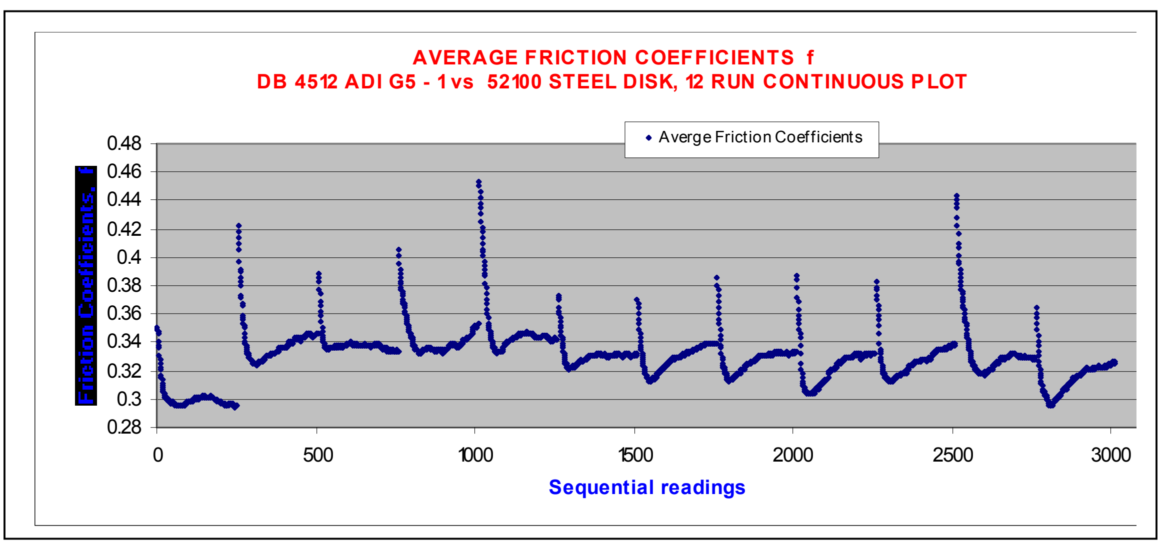

Figure 21: The frictional coefficients of ADI Grade 5 vs. 52100 steel over 12 runs

DISCUSSION

During the tests the three pads were constantly rubbing against the surface of the disk at an average surface velocity of 37.3 fpm. The design of the adapter was such that the debris produced during the rubbing action was less likely to be caught in between the pads and the disk. However, one of the mechanisms involved could be abrasive wear even though the pressure between the pads and the disk was only 30 psi and the surface velocity was only about 37 fpm. Abrasive wear occurs when hard protuberance (asperity) on the surface of a material or a hard particle entrapped between surfaces plastically deforms or cuts a surface as a result of motion. Adhesive, fatigue and oxidation mechanisms could also play a role in the wear of surfaces that are pressed together, and have a relative motion [12]. From the debris collected it was clear that there is some amount of oxidation of the surface that is taking place and the abrasive wear constantly exposes virgin metal surface for further oxidation. The loss of weight information was converted into volume loss because of the use of different materials for pads and disks (it was assumed that the pads of ductile iron had a density about 7.1 g / cm3 and disk of steel had a density of about 7.8 g / cm3). The volume loss curves were derived from the weight loss information. These curves give cumulative volume loss information over 12 tests of a given sample combination. A comparison graph of the cumulative volume loss of pads over 12 tests of all samples is given in the **Figure 22**. As expected wear of 4512 DI was higher than others.

Two runs in the beginning could be removed from analysis to accommodate running-in wear. In the second running-in period wear of ADI G3 was higher than ADI G1. There are still ten two hour runs remaining to analyze. The average wear of these ten runs could be compared to see relative wear of these materials. Comparison purpose the wear of 4512 ductile iron pads was taken as a base. The relative wears of the rest of materials is presented in the **Figure 23**. Wear ratio of 5506 DI was 89 % of the wear experienced in the case of 4512 DI. ADI grades 1, 3, and 5 had a relative wear of 18, 14 and 9 % respectively. The wear ratio of Q & T ductile iron was on the lower end (8 %). This is in line with the starting hardness values of ADI grades. In this test there is no evidence of work hardening of retained austenite in the ADI grade 1 as reported by other workers [6,8]. This may be due to the absence of excessive stresses causing deformation of the surface layers. Microstructures, at 500 magnification, given in the **Figures 8 to 13** do not indicate any surface material deformation including the graphite nodules. The test load was thus insufficient to cause that type of extensive deformation. This was in line with the test objective.

However, a very thin layer of surface in the case of ADI grade 1 might have gone through some transformation as it could be assessed from the surface coefficients of friction. The coefficients of friction in the case of ADI grade 1 were similar to DI Q & T material. The grand average values (average of the average values of all runs) of the friction coefficients were presented in the

Figure 24. ADI grades 3 and 5 had lesser values (0.35 & 0.44 respectively) than ADI grade 1 and Q & T grade. In the case of ADI Grade 1 there might be a thin layer of retained austenite transforming to martensite and it could be sensed by the observation of frictional coefficients only (072 & 0.78).

In general the hardness measurements on the pads were a little higher (Rc) than at the starting time as given in **Table 4**. This may also be due to general work hardening of the surface of pads due to deformation of a very thin layer that could not be seen in ordinary optical microscopy. The average disk temperatures that were monitored during the tests are given in the **Table 5.** The temperatures did not exceed 44 C. From this observation it was clear that there was no excessive heating of the pads during the tests. It's also clear from the values that the mechanical properties are unlikely to be affected by these temperatures.

Table 4: Hardness of pads after wear testing.

Material	ADI Grade 1	ADI Grade 3	ADI Grade 5	DI Q & T
Hardness, Rc	31.5	41.5	49.0	55

The surface SEM wear morphologies presented in the **Figures 14 to 19** indicate extensive abrasive wear patterns on the 4512 DI and 5506 DI. However, the surface abrasive marks were relatively lesser in ADI grades and Q&T sample. In fact in the latter samples the graphite nodules could be seen clearly without any smearing over it.

Table 5: The average temperature of the disk (last 10 runs).

Material	4512 DI	5506 DI	ADI G1	ADI G3	ADI G5	5506 Q&T
Avg. C	39.3	39.8	42.8	34.7	32.2	43.5

To see if there was any martensitic transformation of retained austenite, the ADI Grade 1 pad was selected for further analysis. The pad's cross-section was checked for micro hardness. Micro hardness measurements were made in three planes, one along the rubbing surface, second at the mid-section and third parallel and close to the other side of the pad.

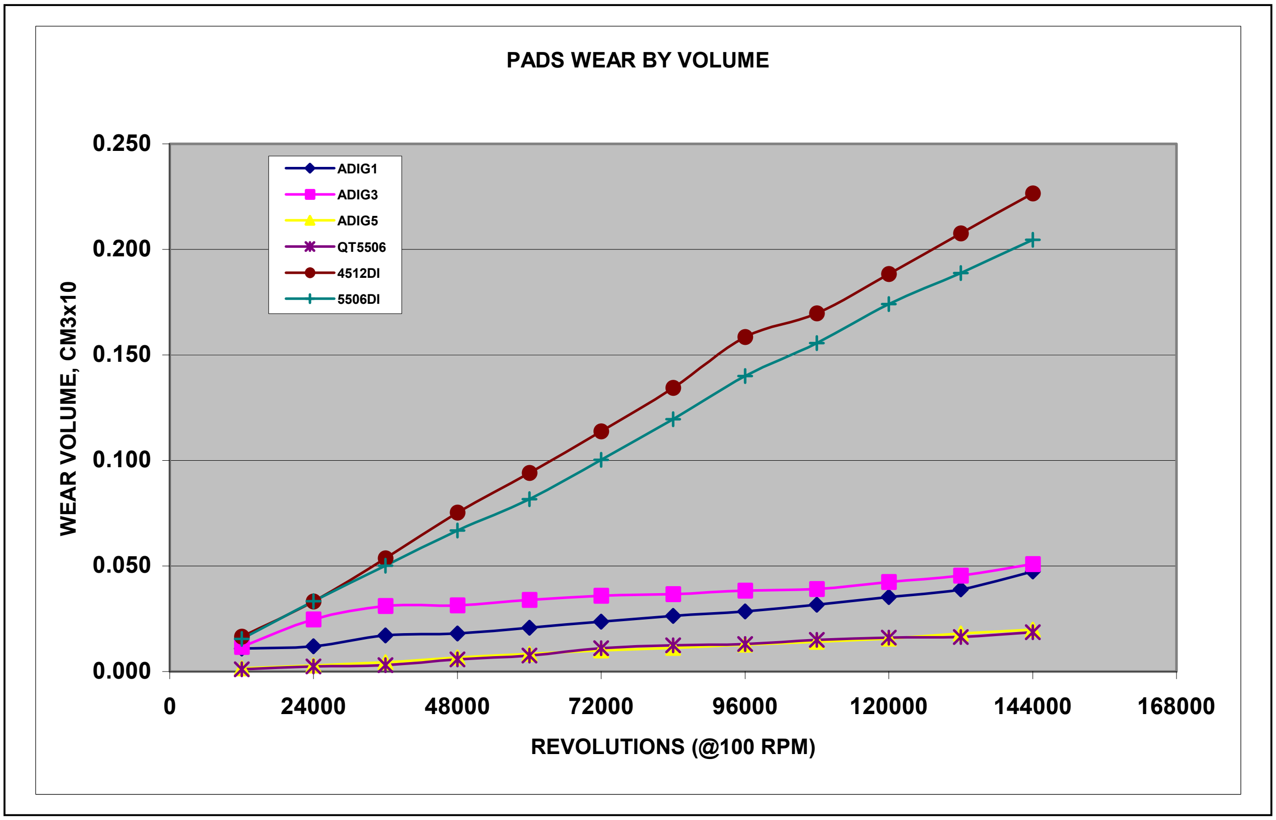

Figure 22: Wear of Pads by volume of all materials tested using dry sliding test method.

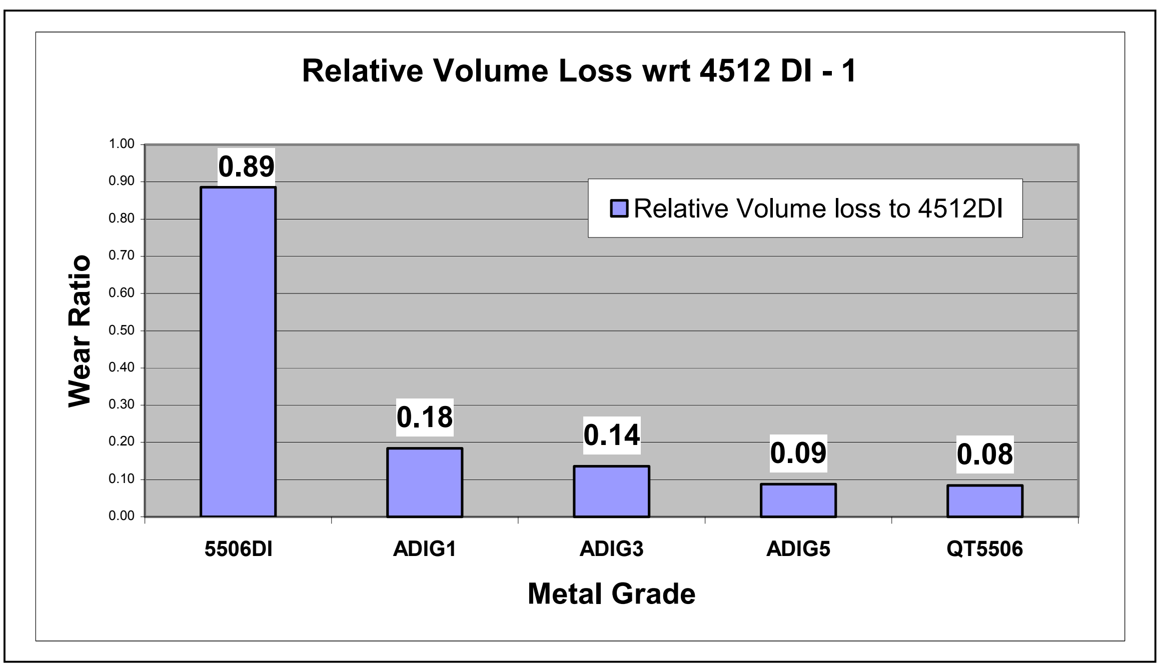

Figure 23: Wear ratios of different pad materials

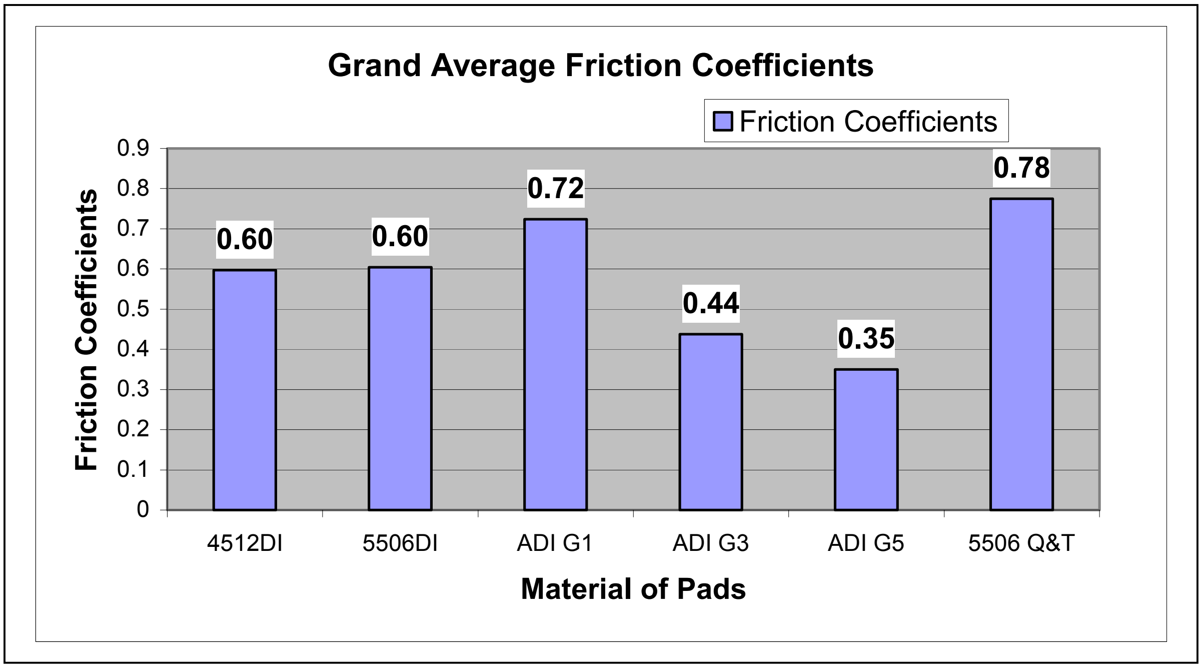

Figure 24: Friction coefficients of different pad materials vs. 52100 steel disks.

The readings are given in the **Table 7.** The results were not significantly different to indicate that the retained austenite close to the rubbing surface was transformed into martensite. A number of investigators in the earlier works indicated that possibility [6,8]. That might be true only when higher amounts of deformation were employed. In these tests the wear of the pads was in accordance with the starting hardness of the pads.

The wear rates were calculated for all the sample materials that were tested based on last ten run averages. These values are given in terms of volume loss, cm3 x 100 per 5280 feet (one mile) of rubbing. **Table 6** gives the wear rates. Least wearing materials were ADI grade 5 and Q & T ductile irons.

Table 6: The wear rates of the ductile iron materials tested.

Material	4512 DI	5506 DI	ADI G1	ADI G3	ADI G5	Q & T DI
Wear rate, cm3x100/mile	0.217	0.192	0.040	0.029	0.019	0.018

Table 7: Micro hardness, (HV), ADI Grade 1 Pad, 500 gram test load.

Reading no.	Before testing	Near Test Surface	Mid-Section	Near the Other Side
1	335.1	417.0	457.5	342.2
2	383.8	432.5	326.3	335.7
3	391.7	421.5	348.2	440.0
4	369.4	307.0	384.6	335.7
5	404.9	390.1	417.9	270.1
6	322.7	401.5	355.0	315.0
7	326.9	320.3	425.1	303.7
8	310.4	419.7	300.4	390.9
9	390.1	319.7	303.1	442.9
10	371.6	227.0	409.2	331.9
Average	360.7	375.2	350.8	372.7
Stndev	33.80	51.17	56.71	54.36

SUMMARY

Ductile irons as cast and heat treated were evaluated for wear and frictional characteristics using a 3 pads-on-disk test method. The following main conclusion are drawn from the work:

1) 3 pads-on-disk method, a relatively new method, could be used to evaluate friction and wear behavior of materials under dry conditions using lower applied stresses at the interfaces of the rubbing surfaces.
2) When interfacial pressures are relatively lower the wear loss of material is related only to the starting hardness of the samples. No extensive evidence of martensite formation was seen in ADI grade 1 samples.
3) Oxidational wear was present when dry wear tests in atmosphere were conducted besides abrasive and probably adhesive wears.
4) The wear rates of ADI grade 5 and Q & T ductile iron pads under these conditions were only about 9 % of the wear rates of 4512 DI pads.

ACKNOWLEDGEMENTS

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Author also thanks Mike Anderson and his colleagues of Falex Corporation for their advise during development of test procedure.

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