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Wear Resistance of Ductile Irons

Y.S. Lerner

This study was undertaken to evaluate the wear resistance of different grades of ductile iron as alternatives to high-tensile-strength alloyed and inoculated gray irons and bronzes for machine-tool and high-pressure hydraulic components. Special test methods were employed to simulate typical conditions of reciprocating sliding wear with and without abrasive-contaminated lubricant for machine and press guideways. Quantitative relationships were established among wear rate, microstructure and microhardness of structural constituents, and nodule size of ductile iron. The frictional wear resistance of ductile iron as a bearing material was tested with hardened steel shafts using standard test techniques under continuous rotating movement with lubricant. Lubricated sliding wear tests on specimens and components for hydraulic equipment and apparatus were carried out on a special rig with reciprocating motion, simulating the working conditions in a piston/cylinder unit in a pressure range from 5 to 32 MPa. Rig and field tests on machine-tool components and units and on hydraulic parts have confirmed the test data.

Keywords

abrasive-contaminated lubricant, alloying and inoculation, bursting tests , ductile iron, endurance tests, frictional wear, microhardness of structural constituents, nodule size, reciprocating sliding wear, rotating sliding testing, static and pulsating pressure testing, wear rate

1. Introduction

DUCTILE iron offers a unique combination of mechanical and service properties (Ref 1, 2). Ductile iron castings have replaced high-tensile-strength iron, forgings and steel castings in a variety of applications (Ref 3-6). This study was undertaken to evaluate the wear resistance of different grades of ductile iron as alternatives to high-tensile-strength alloyed and inoculated gray irons and bronzes for machine-tool and high-pressure hydraulic components.

One of the major determining factors in materials selection for industrial machinery components is wear resistance (Ref 7, 8). High-pressure hydraulic parts must be made from materials that possess a combination of wear resistance, hydraulic soundness, and high bursting pressure resistance (Ref 9, 10).

The objectives of this study were to:

- Evaluate the wear resistance of ductile irons under typical conditions of reciprocating sliding wear with and without

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Table 1 Heat treatment/surface-hardening method, metallic matrix, and hardness of tested materials

Material	Heat treatment or surface-hardening method	Metallic matrix	Hardness, HB(a)
Ductile iron grade 100-70-03	Normalizing	Pearlitic, 2-5% ferrite	255-271
Ductile iron grade 80-55-06	Normalizing	Pearlitic-ferritic (20-25% ferrite)	235-255
Ductile iron grade 80-60-03	As cast	Pearlitic-ferritic (25-30% ferrite)	229-255
Ductile iron grade 70-50-03	As cast	Pearlitic-ferritic (30-40% ferrite)	207-235
Gray iron grade 30	As cast	Pearlitic	197-207
Gray iron grade 35 inoculated with 75% FeSi	As cast	Pearlitic	217-229
Gray iron grade 40 alloyed with Cr, Ni, and Mo	As cast	Pearlitic	235-255
Ductile iron alloyed with 4% Si	Normalizing	Pearlitic	265-271
Ductile iron alloyed with 4% Si + 0.4% P	Normalizing	Pearlitic, phosphide eutectic	273-279
Ductile iron alloyed with 0.5% P	Normalizing	Pearlitic, phosphide eutectic	263-271
Ductile iron alloyed with 4.7% Si	Normalizing	Pearlitic, up to 10% ferrite	302-316
Ductile iron alloyed with 0.06% Sn	Normalizing	Pearlitic	255-263
Ductile iron alloyed with 1% Cu	Normalizing	Pearlitic	281-285
Ductile iron alloyed with 0.6% Mo	Normalizing	Martensitic, 10% acicular structure	441-455
Ductile iron alloyed with 0.9% Mo	Normalizing	Martensitic, 10% retained austenite	514-521
Nitrided ductile iron	Heating in a dissociated ammonia atmosphere for 16 h at 550-560 °C	0.25 mm nitrided layer, including 0.08 mm with nitride particles and a nitrogen-rich austenitic underlayer	550-650 HV (particles) 300-550 HV (underlayer)
Quenched ductile iron	Quenching in water, tempering for 1 h at 220-240 °C, and cooling in air	Martensitic	48-50 HRC
Ductile iron with globular pearlite	Normalizing; spheroidization annealing	Globular pearlite	235-241
Leaded tin bronze	As cast	Chemical composition: 5% Sn, 4.5% Pb	115-121
Aluminum bronze	As cast	Chemical composition: 9% Al, 4% Fe	123-227

(a) Brinell hardness unless otherwise noted

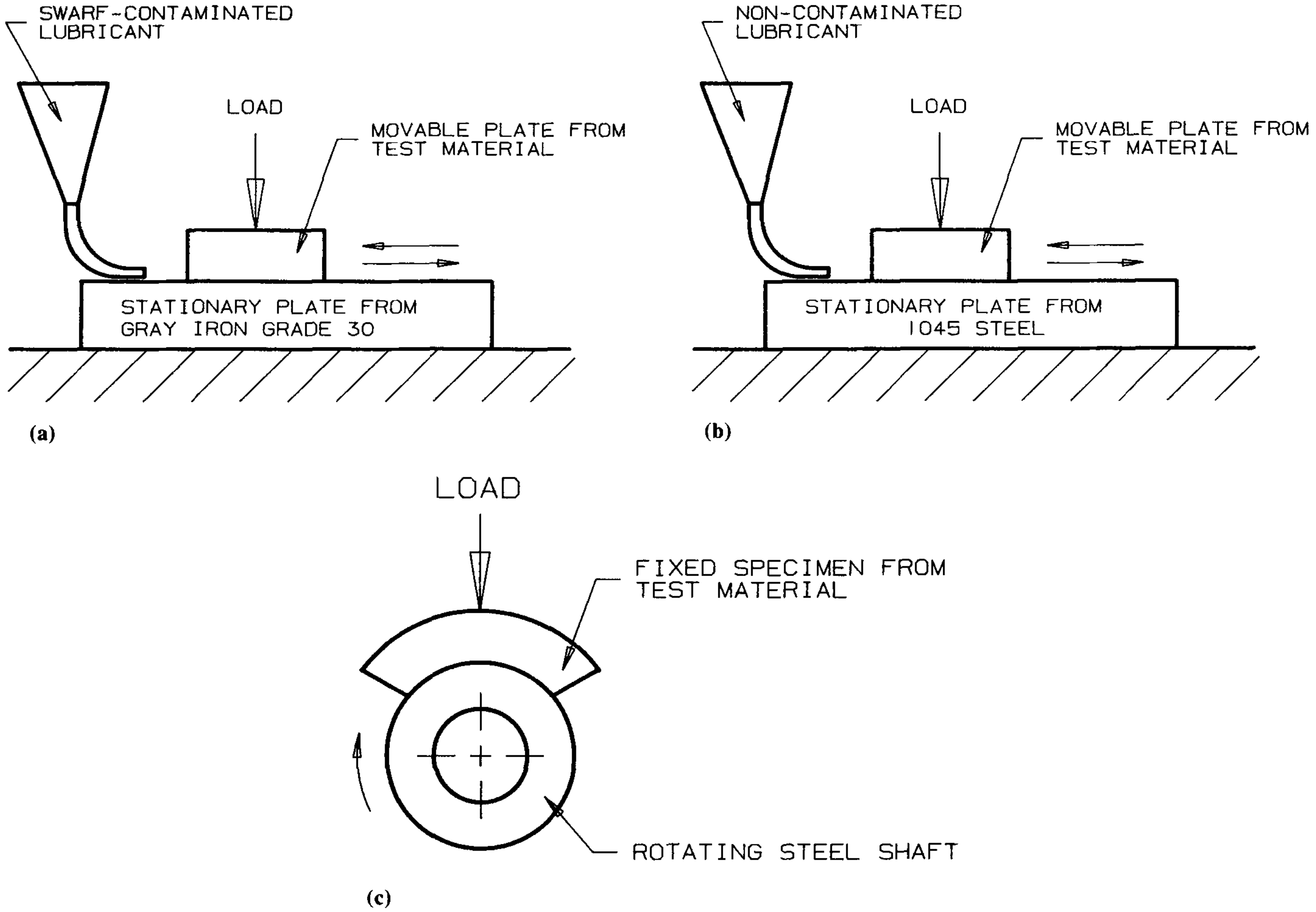

Fig. 1 Schematic of laboratory apparatus used for sliding wear tests. (a) Reciprocating wear with abrasive-contaminated lubricant. (b) Reciprocating wear with noncontaminated lubricant. (c) Bearings for continuously rotated shafts

abrasive-contaminated lubricants for machine and press guideways
- Investigate potential applications for ductile iron as a bearing material for steel shafts under continuous rotating sliding wear
- Study the potential use of ductile iron as an alternative material for high-pressure hydraulic components

2. Experimental Procedures

Table 1 lists the tested materials, along with their heat treatment or surface-hardening methods, microstructure, and hardness. Figure 1 schematically illustrates the laboratory apparatus used for wear tests. Each material was tested three times. The wear rate value shown below for a given material under each set of test conditions represents the mean value. Reciprocating sliding wear tests were conducted with abrasive-contaminated lubricant (Fig. 1a) and with noncontaminated lubricant (Fig. 1b).

Reciprocating wear tests with abrasive-contaminated lubricant were designed to simulate typical working conditions of reciprocating sliding wear for machine-tool components and presses. The bottom flat specimen 1 was made from the material to be tested and was clamped stationary. The test material was prepared in the form of rectangular plate machined from 50 mm (2 in.) thick bars. The upper movable specimen also had a flat surface and was made from gray iron grade 30. Both specimens were ground to a surface finish of 0.56 to 0.88 µm. Tests were carried out at a specific load of 2.0 MPa and a sliding speed of 0.06 m/s for a testing period of 60 min. The lubricant was prepared by adding cast iron swarf crushed to 0.05 to 0.1 mm size to industrial oil SAE-20 in a ratio of 1:10. Wear measurements were made using an optical depth gage, and the wear rate, W, was recorded as:

$$W = \frac{\Delta H}{T}$$

where ΔH is linear wear in millimeters and T is the testing period in minutes. As can be seen, the wear rate is proportional to the actual linear wear of the tested iron; therefore, a lower value implies greater wear resistance.

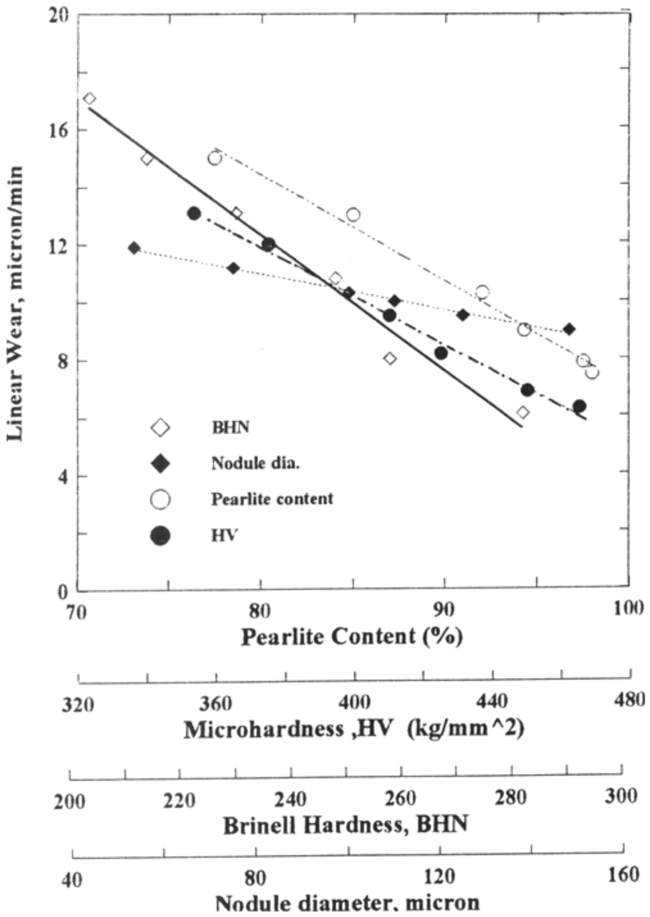

Fig. 2 Influence of pearlite content, pearlite microhardness, Brinell hardness, and nodule diameter on the wear resistance of ductile iron in reciprocating testing with abrasive-contaminated lubricant

Reciprocating wear tests with noncontaminated lubricants were carried out at a specific pressure of 6 MPa and a sliding speed of 0.45 m/s over a period of 8 h. The ductile irons, gray iron, and leaded tin bronze were tested against plates of normalized 1045 steel (207 HB), and the rate of wear was determined from the loss in weight.

Rotating sliding testing with lubricant (Fig. 1c) were carried out with rotary motion between a stationary shoe held under a load of 7.5 MPa and a quenched 1045 steel shaft (48 to 52 HRC) rotating at a surface speed of 0.31 m/s for 20 h. Wear resistance was evaluated from the loss in weight.

3. Results and Discussion

3.1 *Reciprocating Wear with Abrasive-Contaminated Lubricant*

Studies of the influence of microstructure and microhardness on wear resistance showed (Fig. 2) that the pearlite content and its microhardness, along with the Brinell hardness of the bulk iron, directly influence wear rates. Thus, raising the pearlite content from 85 to 98% lowers the rate of wear by a factor of 1.7. As the pearlite microhardness is raised from 350 to 465 HV, the rate of wear decreases by a factor of 2.5. The influence of graphite nodule diameter on the rate of wear is less pronounced, but increasing the nodule diameter from 50 to 140 μm lowers the wear rate by a factor of 1.3.

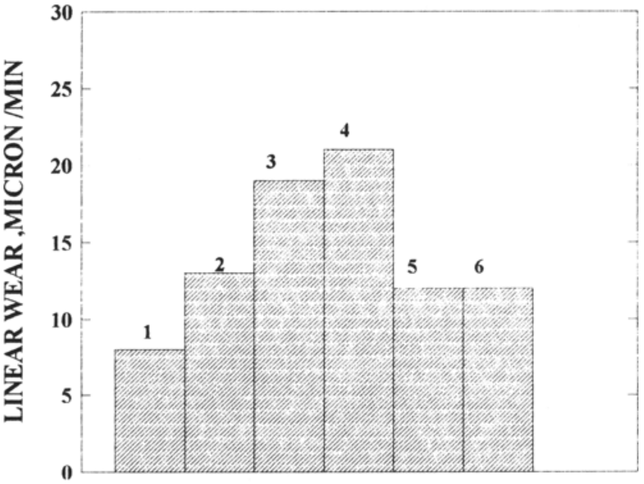

Fig. 3 Wear rates for ductile and gray irons in reciprocating testing with abrasive-contaminated lubricant. 1, ductile iron grade 100-70-03; 2, ductile iron grade 80-60-03; 3, ductile iron grade 70-50-03; 4, gray iron grade 30; 5, gray iron grade 35 inoculated with 75% FeSi; 6, gray iron grade 40 alloyed with chromium, nickel, and molybdenum

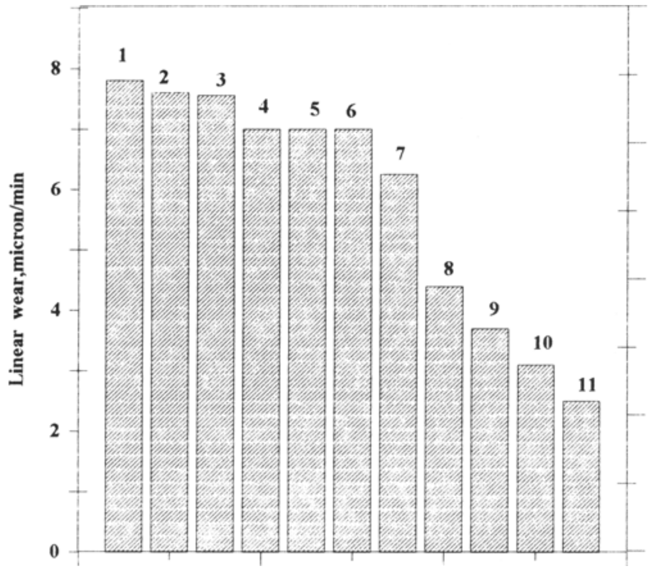

Fig. 4 Effect of alloying and surface hardening on wear of ductile irons in reciprocating testing with abrasive-contaminated lubricant. 1, grade 100-70-03; 2, containing 0.06% Sn; 3, containing 4% Si; 4, containing 4% Si and 0.4% P; 5, containing 0.5% P; 6, containing 4.7% Si; 7, containing 1% Cu; 8, containing 0.6% Mo; 9, nitrided; 10, containing 0.9% Mo; 11, quenched

The wear resistance of gray and ductile irons under conditions of semiabrasive reciprocating testing is presented in Fig. 3. As can be seen, pearlitic ductile iron grade 100-70-03 was found to have 2.5 times the wear resistance of gray iron grade 30 and 1.5 times that of both inoculated gray iron grade 35 and

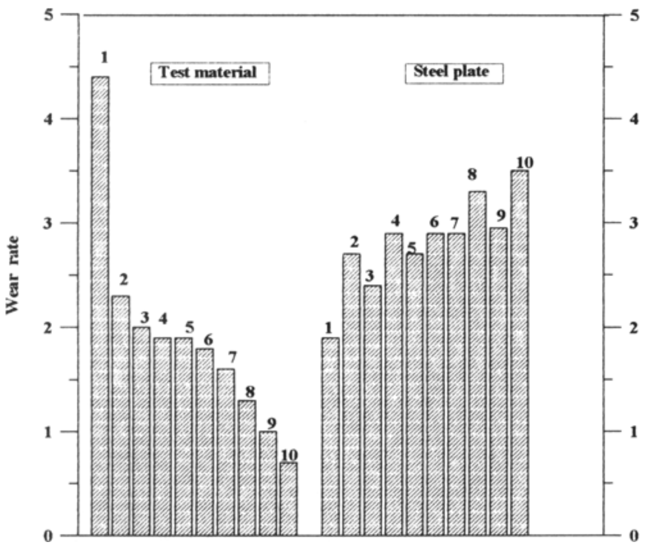

Fig. 5 Wear rates for ductile irons, gray iron, and bronze in lubricated reciprocating sliding testing. 1, gray iron grade 30; 2, leaded tin bronze; 3, ductile iron grade 100-70-03; 4, ductile iron containing 4% Si; 5, ductile iron containing 0.5% P; 6, ductile iron containing 4% Si and 0.4% P; 7, ductile iron containing 0.06% Sn; 8, ductile iron containing 1% Cu; 9, ductile iron containing 4.7% Si; 10, ductile iron containing 0.6% Mo

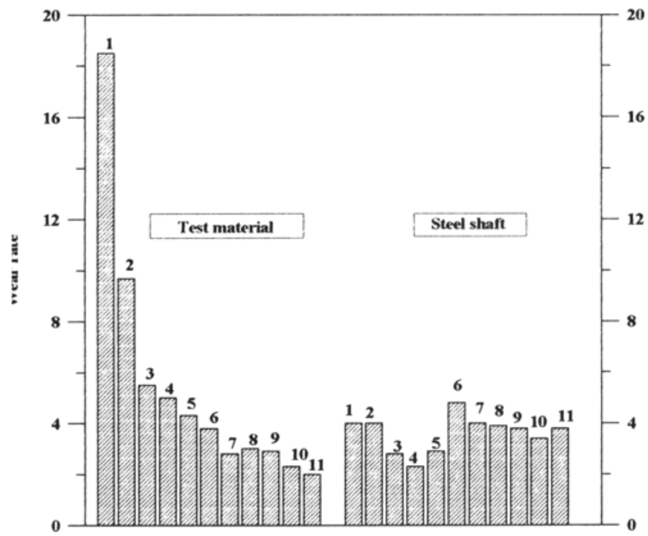

Fig. 6 Wear rates for ductile irons, gray iron, and bronze in rotating sliding testing with lubricant. 1, gray iron grade 30; 2, ductile iron with globular pearlite; 3, aluminum bronze; 4, ductile iron grade 100-70-03; 5, ductile iron containing 4% Si; 6, ductile iron containing 4.7% Si; 7, ductile iron containing 1% Cu; 8, ductile iron containing 0.6% Mo; 9, nitrided ductile iron; 10, ductile iron containing 0.9% Mo; 11, quenched ductile iron

gray iron grade 40 alloyed with chromium, nickel, and molybdenum. Ductile iron grade 80-60-03, with a pearlitic-ferritic metallic matrix, has 1.7 times greater wear resistance than gray iron grade 30 and almost the same wear resistance as both inoculated gray iron grade 35 and alloyed gray iron grade 40. Ductile iron grade 70-50-03 is more wear resistant than gray iron grade 30, but less so than grades 35 and 40. The pearlitic ductile iron grade 100-70-03 exhibited significantly smaller linear wear than any of the other ductile iron grades or high-strength gray irons in this test. Gray iron grades 35 and 40 exhibited wear at a roughly comparable rate.

Figure 4 illustrates the effect of commonly used alloying elements and surface treatment methods on ductile iron wear resistance under the same conditions. These results are shown in comparison with pearlitic ductile iron grade 100-70-03. As can be seen, wear resistance increases slightly when silicon content is increased up to 4.7% or 0.5% P is added.

The best wear resistance was exhibited by hardened ductile iron and ductile iron alloyed with 0.9% Mo. Their wear resistance is approximately 2.8 to 3.5 times greater than unalloyed pearlitic ductile iron grade 100-70-03.

Nitrided ductile iron eventually wears rapidly, because the layer that contains nitride particles is shallow and when removed exposes a transition layer of low wear resistance. Ductile irons are superior to gray irons in wear resistance under this type of wear because their metallic matrix structure is stronger and the graphite inclusions are nodular.

3.2 *Reciprocating Wear with Noncontaminated Lubricant*

Figure 5 shows wear rates for test materials and corresponding steel plates. As can be seen, under given test conditions the wear resistance of ductile irons, combined with low to moderate wear of steel plates, is enhanced by the addition of different alloying elements. Alloying with 1% Cu lowers the rate of wear by a factor of 2 and alloying with 0.6% Mo increases wear resistance by a factor of 3. Unalloyed pearlitic ductile iron grade 100-70-03 is more wear resistant than pearlitic gray iron grade 30 or leaded tin bronze.

3.3 *Rotating Sliding Testing with Lubricant*

Figure 6 compares the wear resistance of test materials and corresponding steel shafts under the given test conditions. Alloying with silicon has a positive influence on ductile iron wear resistance, but it is recommended only for static load conditions because it drastically reduces impact toughness. Alloying with 1% Cu also improves wear resistance and does not cause brittleness. Ductile iron with 0.9% Mo wore at the same rate as nitrided and quenched ductile iron.

These results indicate that by proper selection of alloying additions and surface treatment methods, ductile iron can be used as a bearing material for components with high local loadings.

4. Ductile Iron for Hydraulic Parts Applications

A special study was conducted to determine the specific properties of ductile irons that are essential for their use as alternatives to high-strength inoculated and alloyed gray irons and bronzes for hydraulic parts applications.

Test pieces and hydraulic components cast in various ductile and gray irons were compared for bursting resistance, wear resistance, and hydraulic soundness. The castings were poured in both sand and permanent molds. Soundness tests were carried

Table 2 Recommended ductile iron for hydraulic parts applications

Castings group	Working conditions of components	Typical representative castings	Recommended grade of ductile iron
A	Exposed to wear conditions and >30 MPa pressure	Distributor bodies; rotors, liners, and bushes for piston, axial-, and radial-piston pumps and hydraulic motors	80-55-06 100-70-03
B	Not exposed to wear, pressure >30 MPa	Pump and hydraulic motor bodies; end covers; distribution, monitoring, and regulating apparatus	60-40-18 65-45-12

out under static and pulsating pressure in a special testing apparatus. A flat specimen made from tested iron was placed in the pressure chamber and the internal pressure raised in 2 MPa steps until leakage appeared on the specimen surface. The quantitative soundness index was defined as the critical pressure divided by the plate thickness.

It was established by these tests that permanent-mold ductile iron castings are 20 to 30% higher in hydraulic soundness than sand castings of the same grade. The improvement is associated with the superior feeding conditions during accelerated solidification. All test results on the various ductile iron grades cast by the same process under different loading conditions were 2 to 2.5 times higher than those for gray iron class 35 castings.

Wear tests on test pieces and castings for hydraulic equipment were carried out on a specially designed rig with reciprocating motion, simulating the working conditions in piston/cylinder units in which the gap between the working surfaces contains a fluid lubricant film. The rate of wear was determined by measuring the lubricant leakage rate through the gap. Oil pressures of 2 to 30 MPa were used for specimens of ductile iron grade 80-55-06, cast iron grade 30, and aluminum bronze.

At 5 to 10 MPa, the ductile iron and aluminum bronze were roughly comparable in wear resistance to gray iron. The scuffing resistance of cast irons is proportional to their pearlite content and microhardness. A steady reduction in the coefficient of friction is observed when ductile iron is paired with quenched steel grade 1045 under copious lubrication conditions.

Bursting tests were carried out on distributor bodies made from ductile iron grade 80-55-06 and gray iron grade 40. Oil was forced into the bodies under pressure while they were clamped between gasketed end plates secured together by tie-bolts. The pressure was gradually raised until signs of failure appeared. The distributor bodies in gray iron grade 40 failed at 100 to 110 MPa, whereas the ductile iron grade 80-55-06 bodies sustained greater than 150 MPa.

Endurance rig tests were carried out under the limiting permissible working conditions using distributor bodies. The test rig maintained cyclic working conditions with a cylinder pressure of 32 MPa, with the control solenoid adjusted to reciprocate the main slide valve at one cycle every 2 s. The degree of wear was evaluated from the variations in dimensions and in leakage rates before and after the test period.

The test rig was dismantled periodically for visual observation of the running-in behavior and the degree of wear. No failures were encountered within the 6×10^{-16} cycle endurance tests. These results showed that the hydraulic components made from ductile iron had a 50 to 100% longer life than those made from gray iron grade 40.

Pump valve boxes cast in gray iron grade 30 and ductile iron grade 80-55-06 were tested for 500 h with 50 MPa pressure, rising to 70 MPa for 5 s after each 20 h period. The gray iron specimens failed after only 30 to 40 h, whereas those made from ductile iron grade 80-55-06 remained in working order after the full 500 h.

On the basis of these results, two main groups of typical components for hydraulic apparatus and high-pressure hydraulic equipment have been earmarked for production in the various ductile iron grades, with recommended microstructural and soundness requirements, as a basis for drawing up industrial specifications and standards (Table 2). They both include hydraulic soundness requirements, but differ in that group A specifies microstructural requirements (>70% pearlite) while group B specifies high-strength and ductility requirements.

Results of this study have been successfully employed for mass-produced machine-tool and hydraulic components in the various grades of ductile iron, with recommended chemical compositions and microstructures.

5. Conclusions

A comprehensive study involving different wear test methods has been conducted to evaluate the wear resistance of ductile irons in comparison with high-strength gray irons and bronzes. Quantitative relationships have been established between the rates of wear and the microstructures that result from alloying or surface treatment methods.

Under some wear conditions, ductile iron can be substantially more wear resistant than high-strength gray irons and bronzes. Ductile iron is recommended as a material for machine and press guideways, as a bearing material for components with high local loading, and for hydraulic components exposed to wear conditions and hydraulic pressures of more than 30 MPa.

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