Tribological Behaviour of Si-Cu-Mo-Ni Alloyed Austempered Ductile Iron

Rajendra M. Galagali, R. G. Tikotkar

Abstract**—**Ductile iron samples alloyed with 2.5% Si, 0.78% Cu, 0.421% Mo and 0.151% Ni were austempered at 345 °C and 380 °C for 150 and 180 mins and then tested for wear strength. Ductile iron was also included in the study for comparison purposes. A pin-on-disc machine was employed for wear study. The investigations were carried out for a speed of 3 m/s, under the contact load of 29.43 N with varying sliding distances ranging from 1000 m to 5000 m. The experimental outcome indicates that ADI austempered at 345 °C is more wear resistant than the one austempered at 380 °C. Also for only a sliding distance of 3000 m, both exhibited almost same wear resistance. SEM analysis indicates running sliding marks more or less parallel to one another. Spalled layers and large voids which resemble delamination were observed on worn surface of ADI380. This indicated the occurrence of severe wear. Dark patches observed indicate oxidized surface.

Keywords**—**Austempered ductile iron, coefficient of friction, dry sliding wear, sliding distance.

I. Introduction

Austempered Ductile Iron (ADI) is exhibited as an excellent engineering material with strength, toughness and ductility. Austempering heat treatment brings in balanced mechanical properties [1], [2]. The material is relatively inexpensive [3]. The selection of heat treatment temperatures and times are based on desired microstructure and properties. ADI undergoes two stage reaction process during the cycle of heat treatment [4], [5]. ADI is finding its place in the manufacture of automotive components and machine parts such as camshafts, bearings and timing gears subjected to severe service conditions [6]-[9]. It is also used in the production of jaw crusher components, impact plates, hammers, excavator teeth, rolls and drills [10]. Undesirable ausferrite structure appears as specific ferrite clusters in the matrix, if the silicon is above 3.5% [11].

Heat treated ductile iron forms different grades of ADI. There are six grades of ADI as per ASTM A897/897M-06 (2011) [11]. The minimum properties to meet each grade are listed in Table I. The relative proportions of austenite and ferrite in the ausferrite microstructure are dependent on the austempering heat treatment parameters. The parameters decide the range of properties of ADI [19].

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TABLE I
Grades and Properties of ADI as per ASTM A897/897M-06 (Reapproved 2011) [1], [11]

Grade	Former designation	Tensile strength (MPa)	Yield strength (MPa)	Elong. (%)	Impact energy (J/lb-ft)	Typical hardness (HBW)
750-500-11 (110-70-11)		75 /110	500/70	11	110/80	241-302
900-650-09 (130-90-09)	Grade 1	900/130	650/90	9	100/75	269-341
1050-750-07 (150-110-07)	Grade 2	1050/150	750/110	7	8 /60	302-375
1200-850-04 (175-125-04)	Grade 3	1200/175	850/125	4	60/45	341-444
1400-1100-02 (200-155-02)	Grade 4	1400/200	1100/155	2	35/25	388-477
1600-1300-01 (230-185-01)	Grade 5	1600/230	1300/185	1	20/15	402-512

Austempering consists of two sequentially performed operations [11].

1. *Austenitizing*: Preheating to 840 to 930 °C and holding at this temperature for sufficient time to produce austenite.
2. *Rapid cooling*: To 220 to 440 °C and isothermal holding at this temperature to produce a specific microstructure called ausferrite with a desirable austenite/ferrite ratio.

Recently, several attempts have been made to investigate the tribological behaviour of ADI. Prado et al. [12] reported on the variation of the wear resistance of ADI with austempering temperature under dry roll-sliding conditions. Shimizu et al. [13] compared the erosion characteristics of ADI with that of ferritic and pearlitic irons. A comparison of the abrasive wear behaviour of ductile iron with martensitic and austenitic matrices was reported by Luo et al. [14]. The present paper attempts to compare the dry sliding wear behaviour of ADI austempered at 345 °C and 380 °C for 150 and 180 mins. resp.

II. Experimental Procedure

A. Materials

DI with the chemical composition shown in Table II was produced in a commercial foundry using 500 kg medium frequency induction furnace. Specimens with dimensions ϕ10 mm and length 30 mm were machined from the cast test bar in shell mould. Some specimens were subjected to austempering heat treatment to produce ADI.

TABLE II
Chemical Composition of DI (Wt%)

C	Si	Mn	P	S	Mg
3.52	2.5	0.161	0.037	0.014	0.054

The first ADI was austenitised at 870 °C for 90 min. and austempered in salt bath at 345 °C for 150 min. It is designated as ADI345. The second ADI was austenitised at 870 °C for 120 min and austempered in salt bath at 380 °C for 180 min. It is designated as ADI380. Some DI samples were also involved in the study for comparison purposes. The austempering time selected was such that the specimens were in the heat treatment processing window where the resultant ADI would be expected to exhibit the best combination of mechanical properties [15]. Fig. 1 indicates a typical austempering cycle.

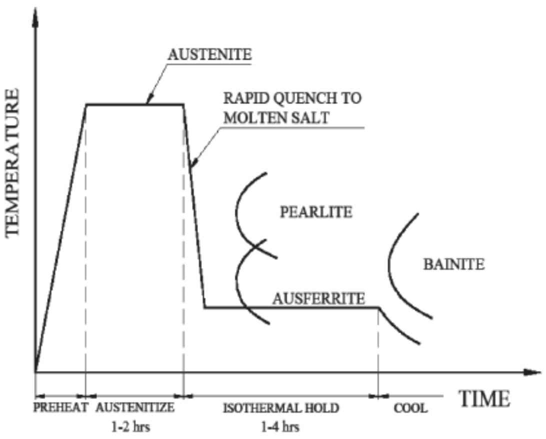

Fig. 1 Schematic diagram of ADI processing steps [11]

B. Wear Testing

The dry sliding wear tests were carried out using a pin-on-disc apparatus, at room temperature and at a relative humidity between 28 and 37%. The pins, with a diameter of 10 mm, were made by ADI and the counterface disc was EN-32 steel disc with 65 HRC. The sliding surfaces had an initial roughness of R_a=0.5 μm. Tests were conducted at room temperature with applied load of 29.43 N, sliding speed of 3 m/s for various sliding distances from 1000 m to 5000 m. The weight loss was determined as a function of sliding distance to a precision of 0.1 mg. The obtained values were converted into wear volumes by considering a density of 7.1 g/cm^3. At least three tests for each experiment were carried out to minimise the experimental error. During each test, the evolution of the friction coefficient and of the pin temperature was also recorded. For the temperature measurements, a chromel-alumel type thermocouple was placed in a hole (with a diameter of 0.8 mm) at a distance of 8 mm from the sliding surface. The average surface temperature was then obtained by considering a linear heat flow and using the approach developed by Ashby et al. [16] and Zhang and Alpas [17]. Information on the wear mechanisms was obtained by examining the worn surfaces by scanning electron microscopy.

III. Results and Discussion

In Fig. 2, experimental steady state wear rates of DI, ADI345 and ADI380 are reported as a function of sliding distance. In agreement with [18] wear rates are found to increase with sliding distance. It is observed that ADI345 is more wear resistant than ADI380. At a sliding distance of 3000 m both ADIs exhibited almost the same wear rate. The gap between the two wear rates is maximum at 1000 m and 5000 m. ADI380 exhibited linear wear rate from sliding distance 2000 m to 4000 m. ADI345 showed almost linear wear rate from 1000 m to 3000 m and 3000 m to 5000 m.

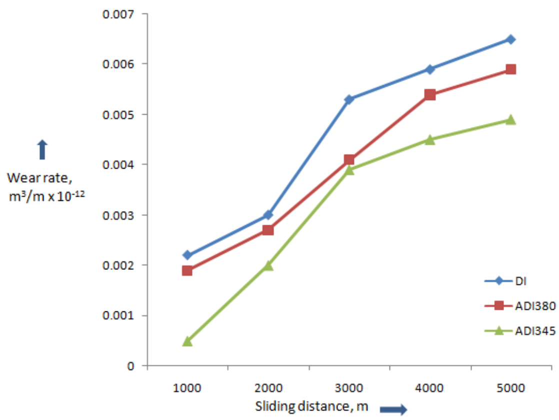

Fig. 2 Experimental wear rates as a function of sliding distance

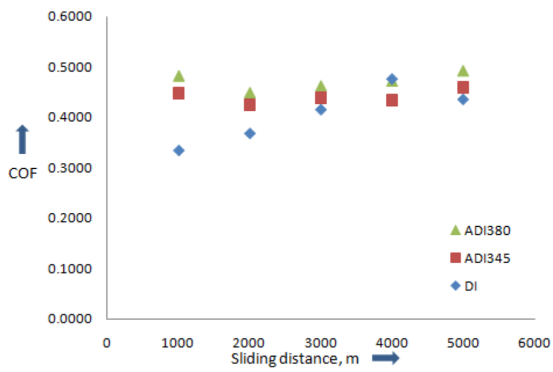

Fig. 3 COF as a function of sliding distance

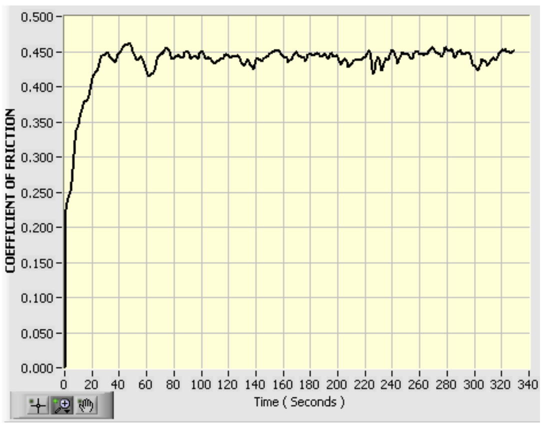

Fig. 4 COF as a function of time

In Fig. 3, the steady state coefficient of friction (COF) is reported as a function of sliding distance. The steady state was reached after about 500 m of sliding distance on an average. COF is seen to increase for DI with sliding distance till 4000 m and falls for 5000 m. COF for ADI380 is more at 1000 m, falls at 2000 m and then increase thereafter. There is continuous fall and rise of COF for ADI345. Fig. 4 shows COF as a function of time.

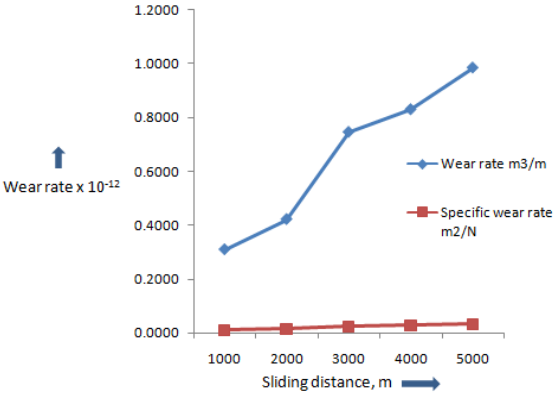

Fig. 5 Wear rate and specific wear rate of DI

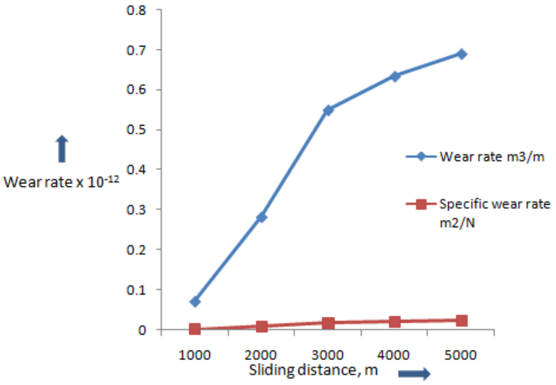

Fig. 6 Wear rate and specific wear rate of ADI345

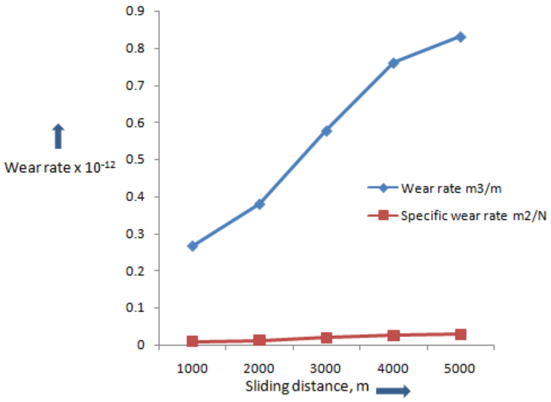

Fig. 7 Wear rate and specific wear rate of ADI380

Figs. 5-7 indicate the relation between wear rate (m^3/m) and specific wear rate (m^2/N) for the three materials under study. The gap between the two is minimum at a sliding distance of 1000 m and maximum for 5000 m. The specific wear rate is almost linearly increasing for the three materials chosen for study.

The scanning electron microscopic images of both ADIs are shown in Figs. 8-11. The wear scars morphology of ADI345 and ADI380 are shown in Figs. 10 and 11. Both scars show similar morphology. Running sliding marks more or less parallel to one another were observed on the micrographs. Dark patches scattered on the surface are also seen. Cleaning the worn surface in running water did not remove these patches. Dark patches may indicate oxidised surface. Spalled layers and large voids which resemble delamination were observed on worn surface of ADI380. This indicated the occurrence of severe wear. Graphite nodules appearing on surfaces of both ADIs were appeared to be plucked out during sliding. Oxide smeared on graphite nodules got flaked. Perhaps the oxide chips are the major cause of abrasion commonly observed in unlubricated conditions. Non-continuous oxide films were formed and displaced giving rise to metal-metal contact. This results in plastic yielding and subsequent delamination during which COF is high and falls when oxide is formed. This could be the reason for the sinusoidal variation of COF.

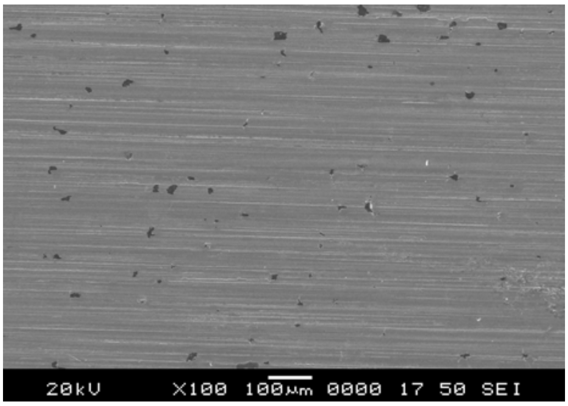

Fig. 8 SEM image of ADI345

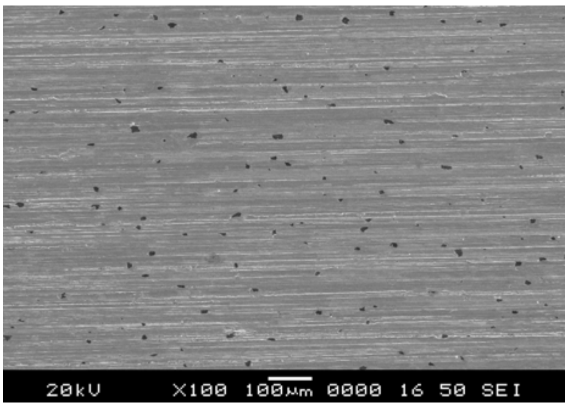

Fig. 9 SEM image of ADI380

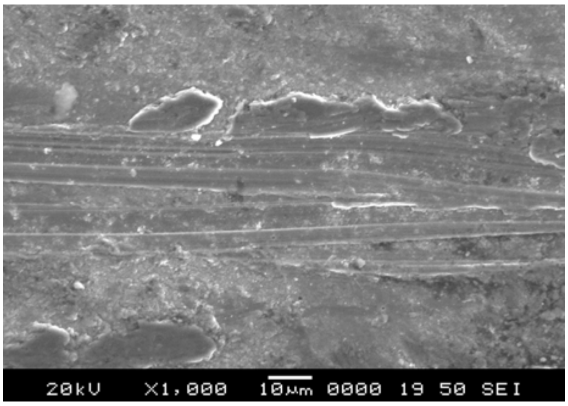

Fig. 10 SEM image of worn surface of ADI345

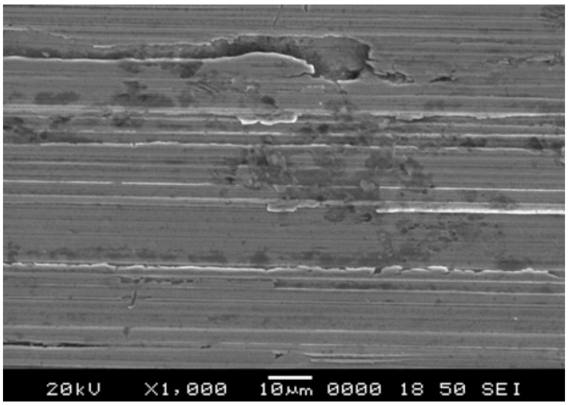

Fig. 11 SEM image of worn surface of ADI380

IV. CONCLUSIONS

The following conclusions can be drawn from the obtained results;

1. ADI345 is more wear resistant to ADI380 indicating that increased austempering temperatures decrease the wear resistance of material. For a sliding distance of 3000 m both the materials exhibited same wear rate. Linear wear rate was exhibited by ADI380 for sliding distance of 2000 m to 4000 m.
2. COF of ADI380 is more compared to ADI345 for all sliding distances.
3. The gap between wear rate and specific wear rate increased with the sliding distance.
4. Wear occurred by plastic yielding and oxidation accompanied by delamination. Running sliding marks more or less parallel to one another were observed on the micrographs.

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