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INFLUENCE OF HEAT TREATMENT ON FRICTION AND WEAR OF DUCTILE IRON: ROLE OF CHROMIUM AND NICKEL

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ABSTRACT
In the present work the effect of heat treatment on friction coefficient and wear of ductile iron containing chromium and nickel was investigated. Heat treatment processes applied in the present work were normalizing, compressed air quenching, oil quenching, water quenching, and austempering. The tribological behaviour of the tested specimens was evaluated by scratch test through measuring scratch width, friction coefficient and hardness.

The experimental results showed that the highest hardness values of GGG 60 were displayed by test specimens quenched in water and air. Friction coefficient of as-cast DI displayed the highest values. Oil and water quenched test specimens showed the lowest friction coefficient. Minimum wear was displayed by test specimens quenched in oil followed by that quenched in water. Cr-DI showed significant increase in hardness after heat treatment processes. Maximum hardness was displayed by water quenched specimens (600 H_v). Specimens quenched in oil displayed the lowest friction coefficient, where the highest value did not exceed 0.2. Oil, water and compressed air quenched specimens showed the lowest wear. Finally, heat treated specimens of Ni-DI showed significant increase in hardness. Normalized specimens displayed the lowest values of friction followed by oil, water and compressed air quenched specimens. Normalized as well as oil, water and air compressed quenched test specimens of Cr-DI and Ni-DI showed reasonable values of friction coefficient and wear which recommend them for wide application.

KEYWORDS
Friction, wear, hardness, scratch test, ductile cast iron, copper, molybdenum, heat treatment.

INTRODUCTION
Cast irons are ternary alloys of Fe + C + Si [1]. The addition of silicon is found to allow the formation of graphite more easily, particularly its formation from the liquid. Perhaps it might be more correct to say that the addition of Si makes it more difficult to form Fe_3C. The size and the number of graphite nodules formed during solidification

are influenced by the amount of carbon, the number of graphite nuclei, and the choice of inoculation practice, [2]. Normal graphite-containing ductile iron has 10 % less weight than steel of the same section size. The graphite also provides lubricity for sliding friction, and the low coefficient of friction permits more efficiently running gears.

Increasing the range of carbon content 3 to 4% enhance the tensile strength but has negligible effect on elongation and hardness, [3]. Carbon should be controlled within the range of 3.6 - 3.8% except when deviations are required to provide defect free casting. Austempering of various Al content ductile irons at 350 ◦C for times up to about 100min produced microstructures containing high percentages of bainitic ferrite with a stable high-carbon enriched retained austenite and the amount of martensite decreases with increasing isothermal transformation time, [4, 5]. At short austempering time carbides could not be detected in the microstructures for Al alloyed iron and the matrix of iron consisted of aggregated layers of carbide-free bainitic ferrite and high-carbon retained austenite. It is believed that the strong effect of Al graphitization helped to suppress formation of the carbides.

Ductile cast irons are primarily heat treated to create matrix microstructures and associated mechanical properties not readily obtained in the as-cast condition, [6]. As-cast matrix microstructures usually consist of ferrite or pearlite or combinations of both, depending on cast section size and/or alloy composition. Limitations of this process are similar to those of steel and include problems with distortion and quench cracking. The mechanical properties of ductile irons are controlled by the volume fracture and distribution of matrix phases and microstructures, [7]. In the newly developed ductile cast iron with dual matrix structure, the structure consists of ferrite, and martensite or ausferrite (bainitic ferrite and high carbon austenite), which is called Dual Matrix Structure (DMS). This new material meets requirements for good toughness and higher ductility in some automobile components. For austempered DI, austenitic-ferritic volume fraction (AFVF) increased with increasing partial austenitizing temperature, [8]. The tensile strength increased while ductility decreased with increasing the AFVF.

Specimens austenitized at 850 °C have microstructures containing a high volume fraction of pro-eutectoid ferrite, some acicular ferrite, and high carbon austenite. An increase in austenitization time and decrease in austenitization temperature could render ADIs more erosion resistant because the final matrices consist of more ferrite and contain less carbon, [9]. The microstructure of specimens austenitized for 15 min at 850 °C contains some acicular ferrite, high carbon austenite, and a large volume fraction of proeutectoid ferrite. The properties of ADI can be varied by changing the austempering temperature. A lower transformation temperature produces a fine, high strength, wear-resistant structure, [10]. A higher transformation temperature results in a coarser structure that exhibits high fatigue strength and good ductility. With long austempering times the high-carbon austenite precipitates *X*-carbide at the ferrite–austenite boundaries, [11]. The formation of bainite does not result in any catastrophic change in properties but produces a gradual deterioration with increasing time of austempering. Surface treatment is a subject of considerable interest at present because it seems to offer the chance to allow improved components with idealized surface and bulk properties, [12]. There are many competing processes for heat treatment ranging

from the lower power-density processes of flame, induction, and tungsten inert gas arc welding (TIG) to high power-density processes of laser and electron beam.

Laser treatment of cast iron or steel generally results in a typical melt profile consisting of melt and transformed zones, [13]. The microhardness of the layers reveals a gradient variation along the cross section of the LSA layers. A surface exposed to a nitriding medium will generally form two distinct layers, [14]. The outside layer is called white (compound) layer and its thickness generally ranges between zero and 25 µm. Underneath the white layer there is a diffusion zone. The properties of these layers depend on the type of basic material and its original pre-process hardness.

Boronizing, which is conventionally carried out by holding the materials at 700 -1100 °C in a boron-rich environment for diffusion of boron atoms into the material in order to form a boride layer, is very attractive thermochemical surface treating technique for ferrous alloys, [15]. Boride layer formation enhances tribological performance by providing high surface hardness and low friction coefficient. Moreover, it considerably improves corrosion resistance of ferrous alloys. The wear resistance after conventional boronizing was about three times than that of the a ustempered state of GGG-40 grade ductile iron. When the successive heat treatment procedure including boronizing and austempering was applied, further increase in the wear resistance (about two times of the boronized state) was achieved. Boro-tempered ductile Iron is a process in which, the samples boronized for 1–3 h and then tempered between 250 and 350 °C for 1 h, [16]. The boride layer is formed by boro-tempering heat treatment on the ductile iron and its micro-hardness is in the range of 1654– 1867 HV.

A comparative study, [17], for the dry friction and wear characteristics of five kinds of cast irons (flake graphite cast iron, spheroidal graphite cast irons, ADI) under the conditions of high sliding speeds and high contact pressures were experimentally examined. It was found that, [18], in the specimens with dual matrix structure, for any combination of martensite and proeutectoid ferrite volume fractions and tempering period, the amount of tensile strength and ductility can satisfactorily be optimized. Ductile iron with dual matrix structure exhibits much greater ductility than conventionally quenched + tempered ductile iron. The wear resistance depended on matrix structure and its hardness. The large ausferrite volume fraction with higher hardness resulted in lower weight loss, [19]. At the lower applied load, the specimens with the high nodule count were exhibited lower wear rate than those having the low nodule count, while at the higher loads wear resistance was weakened with increasing the nodule count, [20]. 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.

In the present work, the effect of heat treatment on friction coefficient, wear and hardness of ductile iron containing chromium and nickel was investigated.

EXPERIMENTAL

The test specimens of ductile iron of rectangular cross section of 10 × 15 mm and 25 mm in length were tested. Table 2.1 shows the chemical composition of the tested materials. Tested materials were ductile irons (GGG 60) of pearlitic structure with low percent of ferrite. Chromium and nickel were added to ductile iron; they will be referred in text as Cr-DI and Ni-DI.

Test specimens were subjected to heat treatment processes (normalizing, compressed air quenching, water quenching, oil quenching, and austempering) in order to have ductile irons with a wide range of properties and structures. The electrical lab furnace was used to austenitize tested specimens at 900 °C for 2 hours. Austenitizing temperature and time were selected carefully to ensure austenite transformation and carbides breakdown as much as possible together with avoiding grain growth. Austenitizing was followed by cooling in different media. The first was normalizing by cooling specimens in still air, where, cooling rate was relatively high to form pearlitic structure and prevent ferrite formation. The second was quenching in water, oil, and compressed air. The third was austempering carried out using hydroxide salt bath composed of 40 % sodium hydroxide and 60 % potassium hydroxide. For this composition of salt bath, melting point was about 160 °C and range of use was 180 - 350 °C. Specimens were austempered at 300 °C for 1 hour, 2 hours, and 3 hours.

Table 2. 1 Chemical composition of ductile iron specimens.

GGG 60									
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
3.15	2.33	0.602	0.0337	0.0081	0.0708	0.0076	0.0369	0.0115	0.0271
Cu	Nb	Ti	V	W	Pb	Mg	As	B	Fe
0.228	0.0017	0.0121	0.0109	0.0501	0.033	0.0389	0.0052	0.0001	93.38
Cr-DI									
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
3.45	2.63	0.595	0.0349	0.0106	1.04	0.0164	0.0389	0.0127	0.028
Cu	Nb	Ti	V	W	Pb	Mg	As	B	Fe
0.0803	0.0042	0.0158	0.0128	0.0588	0.005	0.0424	0.0058	0.0001	91.92
Ni-DI									
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
2.89	2.39	0.554	0.0307	0.008	0.268	0.0032	2.66	0.0106	0.0266
Cu	Nb	Ti	V	W	Pb	Mg	As	B	Fe
0.0757	0.0019	0.019	0.011	0.0509	0.003	0.0398	0.0042	0.0001	90.97

Scratch tester shown in Fig. 1 was used. It consisted of a rigid stylus mount, a diamond stylus of apex angle 90° and hemispherical tip. The stylus was mounted to the loading lever through three jaw chuck. A counter weight was used to balance the loading lever before loading. Vertical load was applied by weights of 5, 10, 15, 20, 25 N. Scratch resistance force was measured using a load cell mounted to the loading lever and connected to display digital monitor. The test specimen was held in the specimen holder which mounted in a horizontal base with a manual driving mechanism to move specimen in a straight direction. The scratch force was measured during the test and used to calculate friction coefficient. The test was conducted under dry conditions at

room temperature. An optical microscope was used to measure scratch width with an accuracy of ± 1.0 μm.

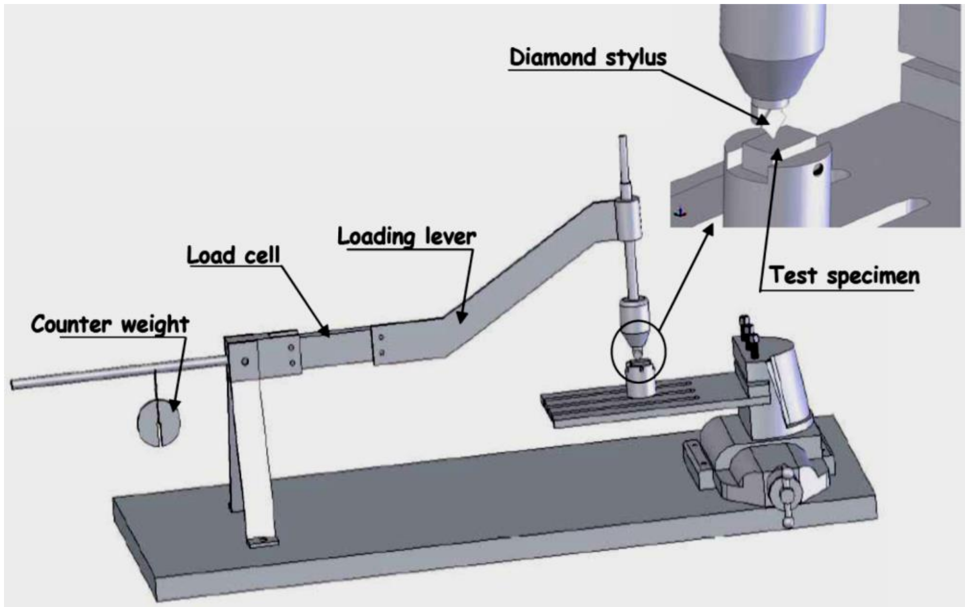

Fig. 1 Arrangement of scratch test rig.

RESULTS AND DISCUSSION

Hardness of GGG 60 is shown in Fig. 2. Hardness of normalized and compressed air quenched specimens was 300 and 306 H_v respectively. The highest hardness values were displayed by test specimens quenched in water and air. Normalizing involved the austenitizing of ductile iron, followed by cooling in air. As-cast ductile iron casting was normalized to break down carbides and increase hardness and strength.

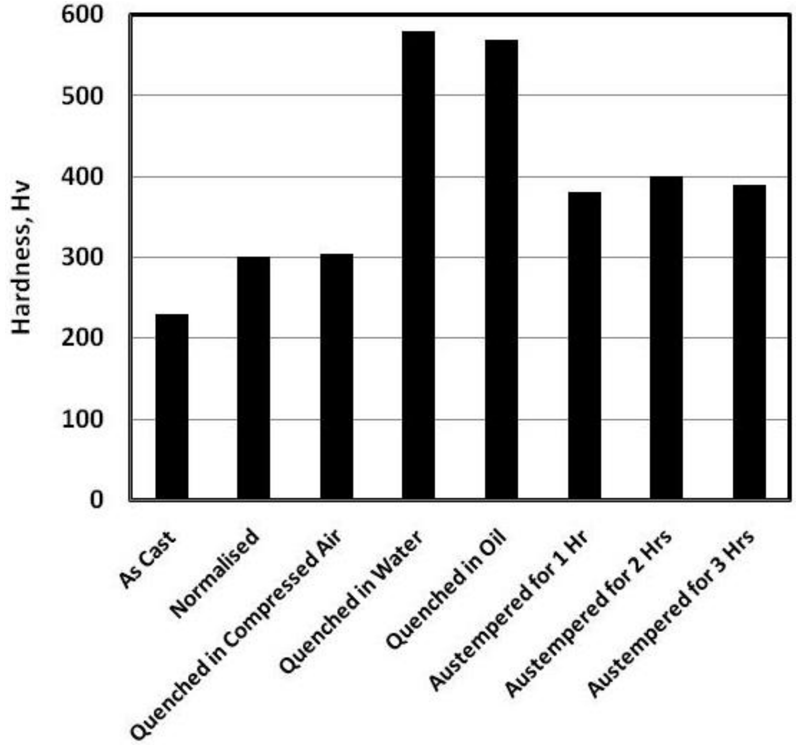

Fig. 2 Hardness of GGG 60 after heat treatment.

Friction coefficient of GGG 60 is illustrated in Figs. 3 and 4, where as-cast DI displayed the highest values. Oil and water quenched test specimens showed the lowest friction coefficient. This trend might be from the increased hardness of the treated surface which enabled it to resist the penetration of the stylus tip into the scratched surface. As for austempered specimens the lowest friction coefficient was displayed by test specimens austempered for 3 hours.

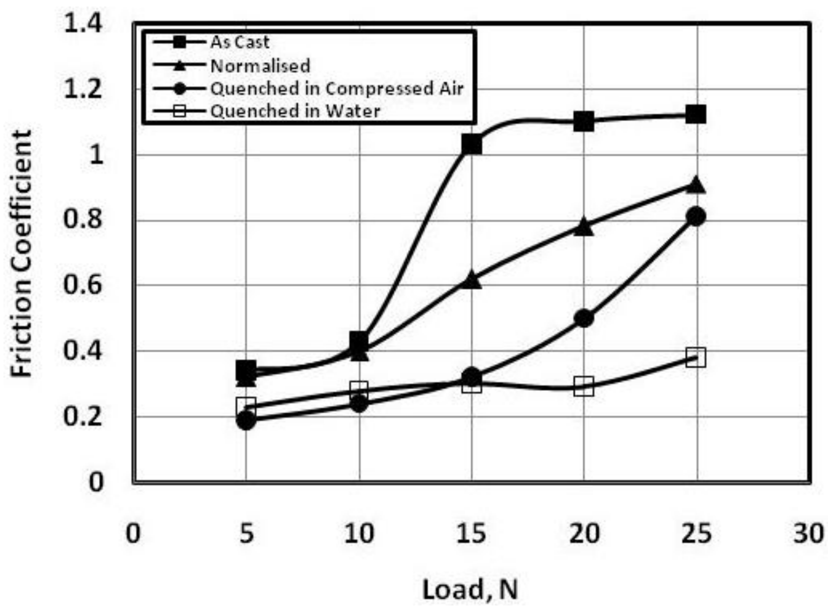

Fig. 3 Effect of heat treatment on friction coefficient of GGG 60.

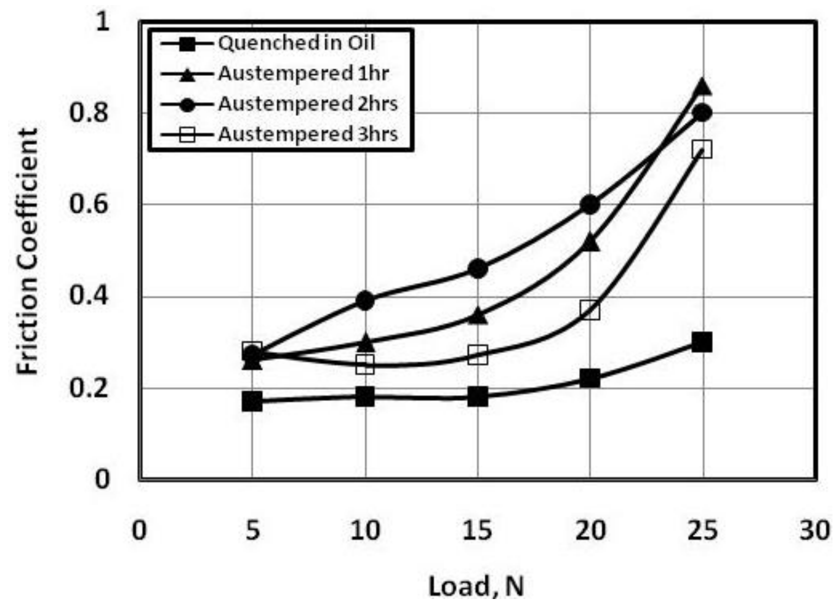

Fig. 4 Effect of heat treatment on friction coefficient of GGG 60.

Wear of GGG 60 is shown in Figs. 5 and 6. Generally, Wear increased with increasing applied load. Minimum wear values were displayed by test specimens quenched in oil followed by that quenched in water. Test specimens austempered for 3 hours represented the lower wear than that displayed by the austempered for one and two hours.

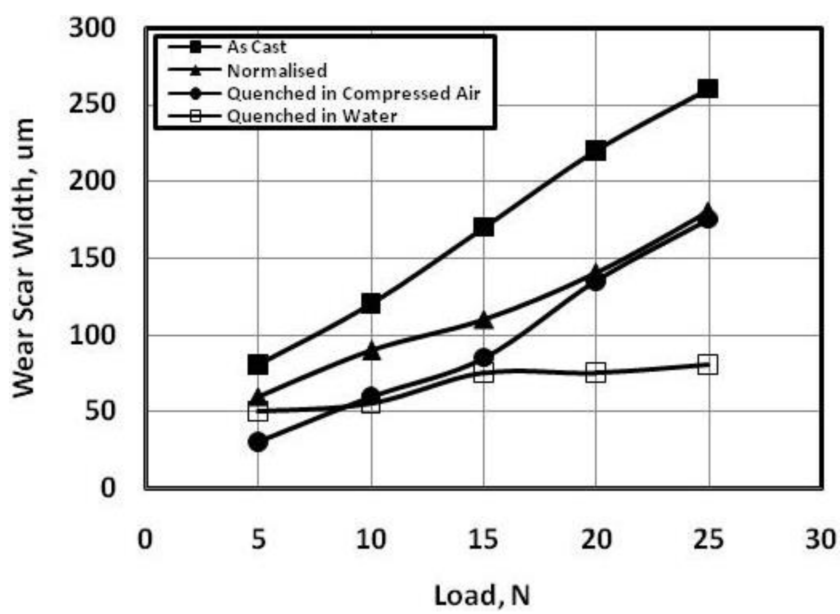

Fig. 5 Effect of heat treatment on wear of GGG60.

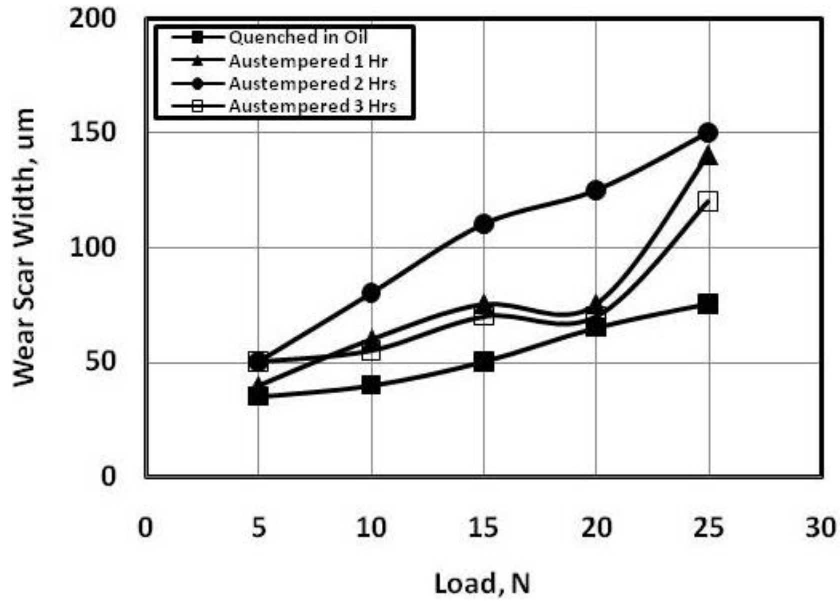

Fig. 6 Effect of heat treatment on wear of GGG60.

Hardness of Cr-DI after heat treatment is shown in Fig. 7. Cr-DI showed significant increase in hardness after heat treatment processes. Normalizing process produced the lowest increase in hardness from 295 H_v to 368 H_v. Hardness of quenched specimens by compressed air (588 H_v) exceeded the hardness of quenched ones in oil (560 H_v) and approached the hardness of water quenched specimens (600 H_v).

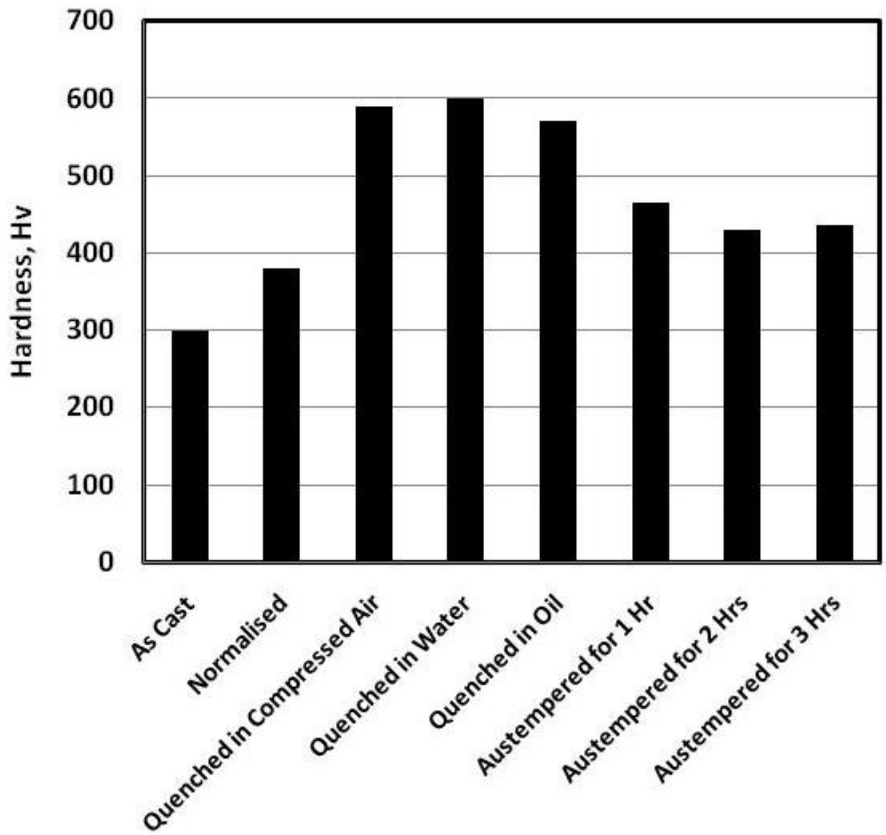

Fig. 7 Hardness of Cr - DI after heat treatment.

Effect of heat treatment on friction coefficient of Cr - DI is shown in Figs. 8 and 9. Specimens quenched in oil displayed the lowest friction coefficient, where the highest value did not exceed 0.2. Specimens quenched in compressed air and water showed low values of friction coefficient. This behaviour might be attributed to the increased hardness observed for heat treated test specimens, Fig. 7. Compared to GGG 60, no enhancement was observed for the values of friction coefficient.

Figures 10, and 11 show wear of Cr-DI. Oil, water and compressed air quenched specimens showed the lowest wear. This observation indicated significant improvement in wear resistance in comparison to as-cast specimens. Austempered specimens for 3 hours showed quite good wear resistance although that their hardness was lower than that observed for quenched test specimens. Wear displayed by specimens quenched in oil was lower than that shown by GGG 60. Test specimens quenched in oil can be recommended to be used in application due to their relatively low values of friction and wear.

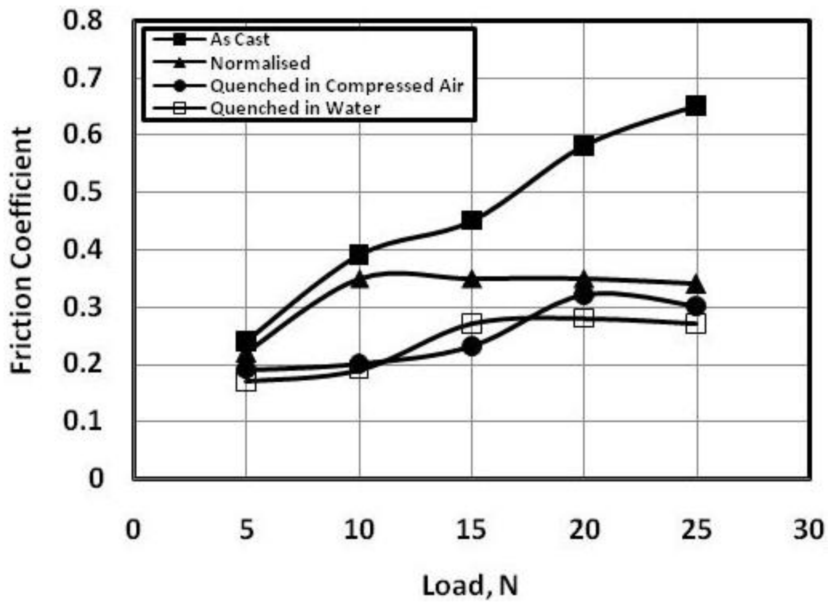

Fig. 8 Effect of heat treatment on friction coefficient of Cr - DI.

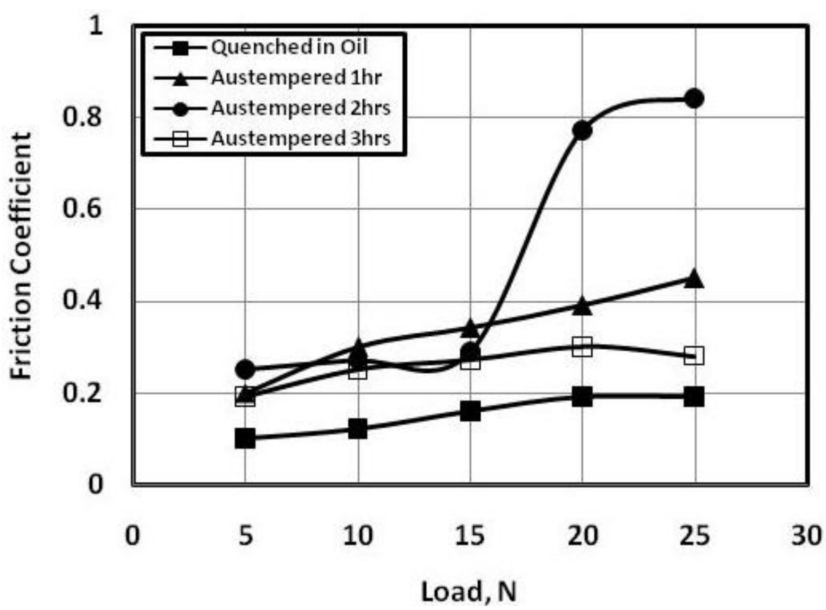

Fig. 9 Effect of heat treatment on friction coefficient of Cr - DI.

Heat treated specimens of Ni-DI showed relatively higher hardness than as-cast specimens, Fig. 12. A significant increase in hardness was produced by normalizing process (460 H_v). Hardness of quenched specimen by compressed air (520 H_v) approached the hardness of oil quenched specimen (531 H_v) and water quenched specimen (540 H_v). Hardness of austempered specimen followed by air cooling (409 H_v) exceeded slightly hardness of that austempered and cooled in water (400 H_v).

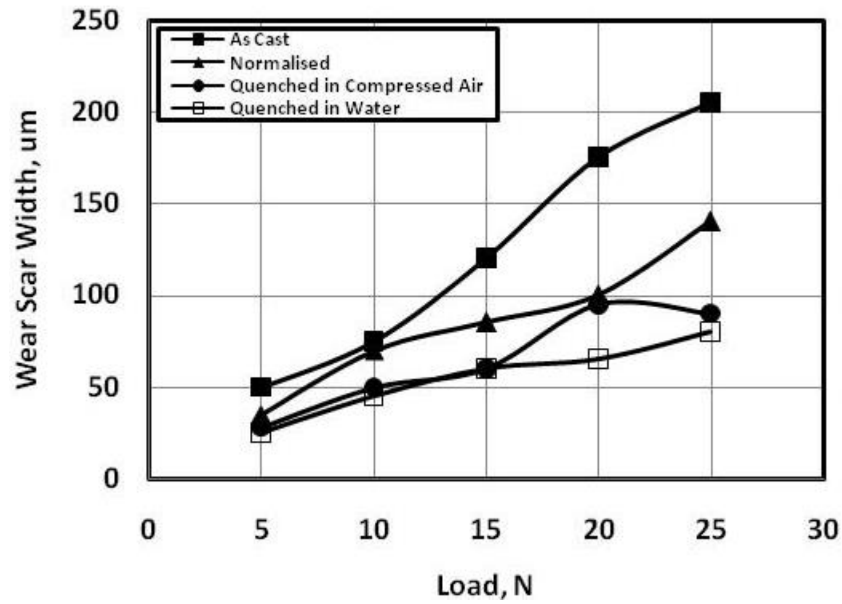

Fig. 10 Effect of heat treatment on wear of Cr - DI.

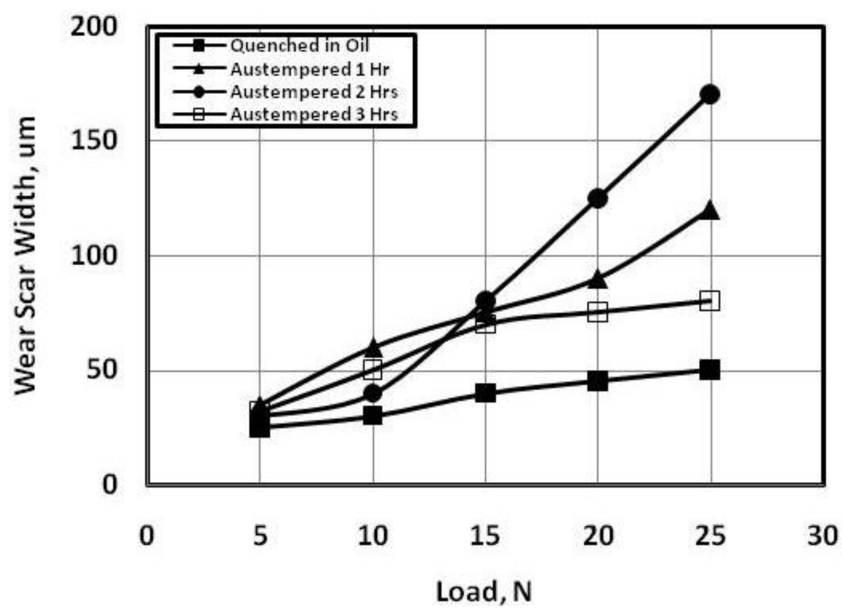

Fig. 11 Effect of heat treatment on wear of Cr - DI.

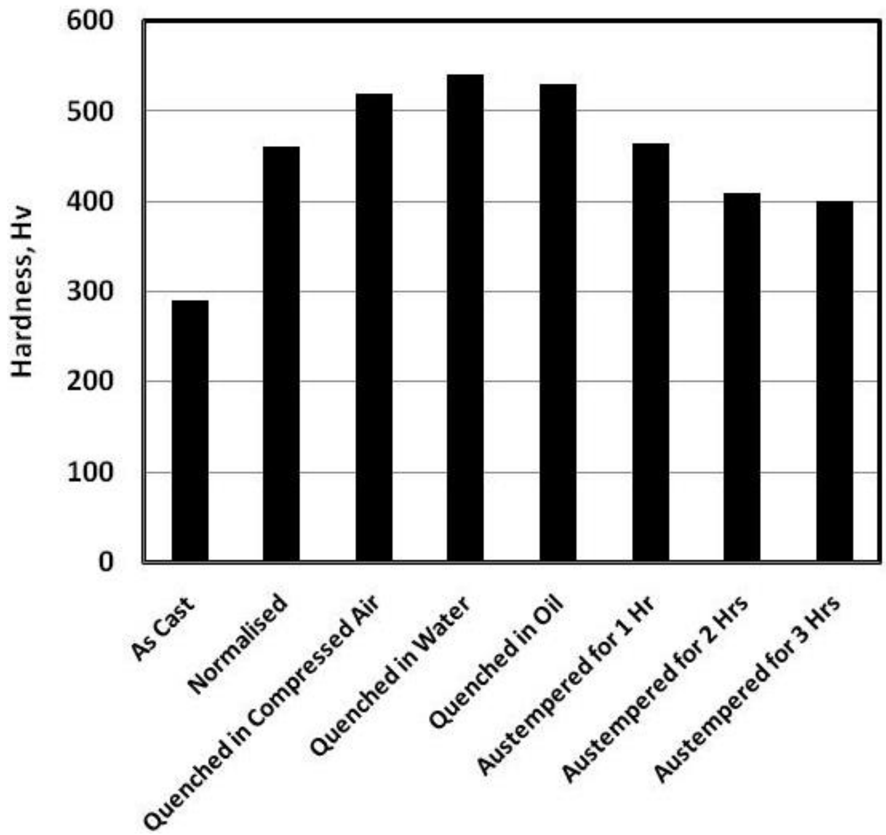

Fig. 12 Hardness of Ni - DI after heat treatment.

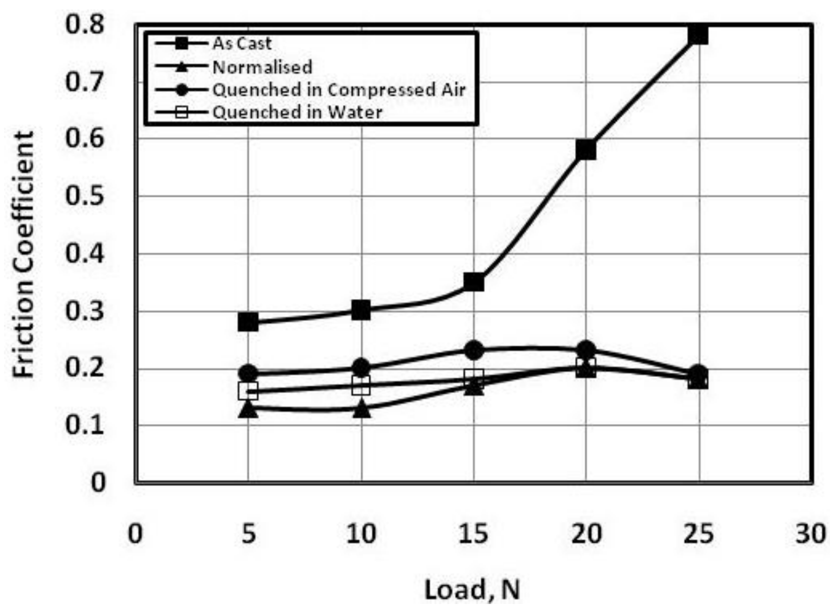

Fig. 13 Effect of heat treatment on friction coefficient of Ni - DI.

Effect of heat treatment on friction coefficient of Ni-DI is shown in Figs. 13 and 14. Normalized specimens displayed the lowest values of friction followed by oil, water and compressed air quenched specimens. As-cast specimens showed an increasing trend of friction with increasing load, while heat treated specimens were not influenced by load.

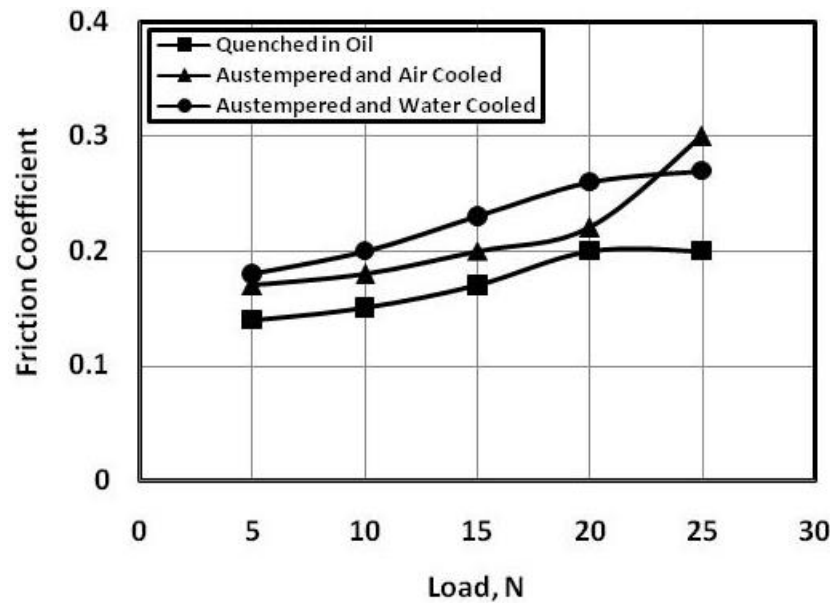

Fig. 14 Effect of heat treatment on friction coefficient of Ni - DI.

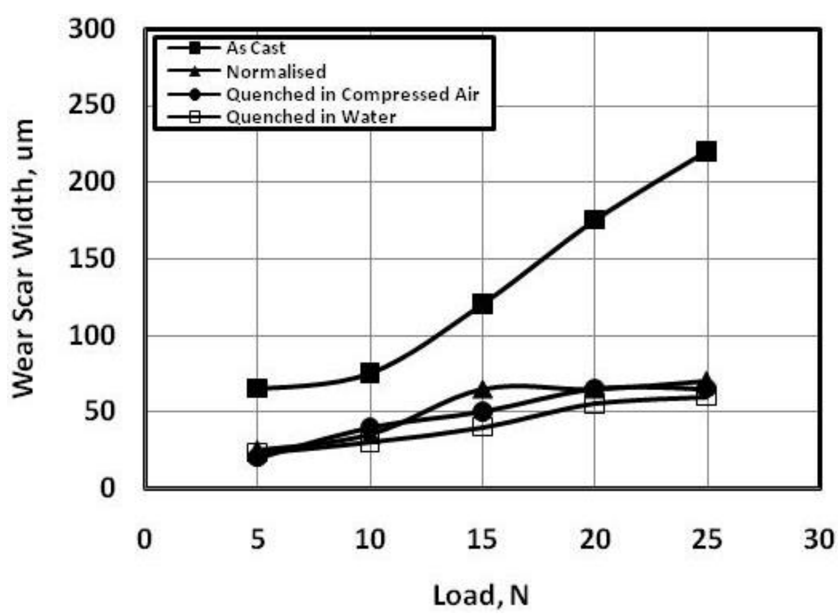

Fig. 15 Effect of heat treatment on wear of Ni – DI.

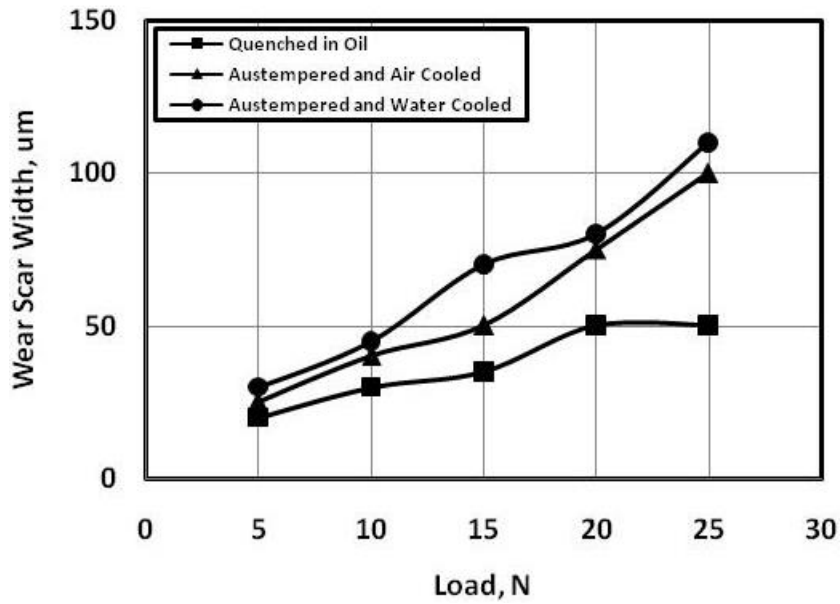

Fig. 16 Effect of heat treatment on wear of Ni – DI.

Wear resistance displayed by oil, water and compressed air test specimens significantly increased, Figs 15 and 16. . Wear resistance of austempered specimens followed by air cooling was better than that observed from austempered ones followed by water cooling. As observed for Cr-DI test specimens, normalized as well as oil, water and air compressed quenched test specimens of Ni-DI showed reasonable values of friction coefficient and wear which recommend them for wide application.

CONCLUSIONS

1. The highest hardness values of GGG 60 were displayed by test specimens quenched in water and air. Friction coefficient of as-cast DI displayed the highest values. Oil and water quenched test specimens showed the lowest friction coefficient. Minimum wear was displayed by test specimens quenched in oil followed by that quenched in water.

2. Cr-DI showed significant increase in hardness after heat treatment processes. Maximum hardness was displayed by water quenched specimens (600 H_v). Specimens quenched in oil displayed the lowest friction coefficient, where the highest value did not exceed 0.2. Oil, water and compressed air quenched specimens showed the lowest wear. Test specimens quenched in oil can be recommended to be used in application due to their relatively low values of friction and wear.

3. Heat treated specimens of Ni-DI showed significant increase in hardness. Normalized specimens displayed the lowest values of friction followed by oil, water and compressed air quenched specimens. Normalized as well as oil, water and air compressed quenched test specimens of Ni-DI showed reasonable values of friction coefficient and wear which recommend them for wide application.

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