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INFLUENCE OF HEAT TREATMENT ON FRICTION AND WEAR OF UNALLOYED DUCTILE IRON

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ABSTRACT
Ductile iron is cast iron in which the graphite is present as spheres (nodules). This produces material which has high strength, ductility, thermal shock resistance, and wear resistance with good castability, damping capacity, machinability, and self lubricating as a combination of steel and cast iron properties. Previous works showed that the main factor affecting the mechanical properties of ductile iron is structure. Ductile iron structure is controlled by alloying elements or heat treatment or both.

In this study the effect of heat treatment on friction coefficient and wear of unalloyed ductile iron was investigated. The 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 and calculating friction coefficient as well as hardness.

Baesd on the experiments carried out in the present work, it was found that heat treatment of unalloyed cast iron improved the hardness, wear resistance and reduced friction coefficient. Besides, quenching ductile irons in water and oil caused the highest increase in hardness and wear resistance and recorded the minimum values of friction coefficient. Good increase in wear resistance and reduction in friction coefficient were displayed by austempering ductile irons.

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

INTRODUCTION
Cast irons are ferrous alloys which contain carbon contents in the 2-5% range, well above the normal carbon contents of steels, [1]. The other critical alloying element in cast irons is silicon, which is present at concentrations between 1 and 3%. Cast irons are ternary alloys of Fe + C + Si [2, 3]. 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, [4]. 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 affect on elongation and hardness, [5]. 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, [6, 7]. 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, [8]. As-cast matrix microstructures usually consist of ferrite or pearlite or combinations of both, depending on cast section size and/or alloy composition. Lighter castings made of alloyed iron may be martensitic or may contain an acicular structure after normalizing. The most common method to strengthen ductile iron is quench and tempering. The process is similar to that used for steel, [9]. 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, [10]. 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, [11]. The tensile strength increased while ductility decreased with increasing the AFVF.

The average austenite volume fraction of austenite, its carbon content, and the size of bainitic ferrite also increase with increasing austempering temperature, [12]. The influence of austenitizing temperature on the impact properties of samples solution treated between 850 and 1000 °C for 180 min and austempered at 360 °C for the same time period has been found that, impact energy values fall slightly as the solution treatment temperature increases from 850 to 950 °C and more rapidly with further increase in austenitizing temperature, [13]. 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, [14]. 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, [15]. 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, [16]. 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, [17]. 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.

Induction hardening consists of rapid heating of the thin surface layer above the transformation temperature at which the metal matrix will be transformed to austenite and subsequent cooling of the workpiece produces a martensitic microstructure of great hardness in the thin surface layer, [18]. Induction heat treatment has the ability to limit the heated surface area and depth of hardening only to the areas where the metallurgical changes are desired. Both the abrasive wear resistance and residual compressive stresses in the specified areas of the part increase by localized induction hardening. The remaining parts of the workpiece are unaffected by the process. By surface hardening and microstructural modification in the DCI roll irradiated with high-energy electron beam, the tempered bainitic matrix was changed to a mixture of martensite, austenite, and ledeburite by electron beam irradiation, [19]. Graphites were partially or completely dissolved depending on heat input and their size.

Laser treatment of cast iron or steel generally results in a typical melt profile consisting of melt and transformed zones, [20]. The predominant structure in the melt zone was ledeburite with some undissolved graphite spheroids Multicarbide reinforced DI surface composite layers were successfully fabricated by LSA using a continuous wave (CW-CO_2) laser and a pulsed Nd:YAG laser, [21]. 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, [22]. 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, [23]. 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 austempered 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, [24]. 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.

Consequent to welding, rise in temperature results surface fusion which make it possible for carbon atoms from ductile iron and chromium atoms of electrode react profusely to form hard carbide phases, [25]. As a result of this, hard carbide phases (Fe, Cr)$_7$C$_3$ and (Fe, Cr)$_3$ C established at the interface. The wear rate was lower in thin-coated specimens than in uncoated or thick-coated ones.

A comparative study, [26], 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, [27], 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, [28]. Studies of the influence of microstructure and microhardness on wear resistance showed that the pearlite content and its microhardness, along with the Brinell hardness of the bulk iron, directly influence wear rates, [29]. Thus, raising the pearlite content from 85 to 98% lowers the rate of wear by a factor of 1.7. 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, [30, 31]. 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 unalloyed ductile iron was investigated by scratch test through measuring scratch width and calculating friction coefficient.

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. A spectrometer, model SPECTROLAP, was used for chemical analysis. Tested materials were unalloyed ductile iron (GGG 40, and GGG 60). The scope of tested material selection is to cover most structures of ductile iron in as-cast state and after heat treatment processes. GGG 40 has ferritic with little pearlitic structure and GGG 60 has pearlitic structure with low percent of ferrite.

Test specimens were subjected to heat treatment processes (normalizing, compressed air quenching, water quenching, oil quenching, and austempering) in order to achieve 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, the 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 is about 160 °C and range of use is 180 - 350 °C, [53, 54]. Specimens were austempered at 300 °C for 1 hour, 2 hours, and 3 hours.

Table 2.1 chemical composition of ductile iron specimens

Material No. 1: *GGG 40*									
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
3.6000	2.8000	0.4180	0.0335	0.0028	0.0400	0.0042	0.0394	0.0014	0.0233
Cu	Nb	Ti	V	W	Pb	Mg	As	B	Fe
0.0838	0.0008	0.0083	0.0103	0.0205	0.0030	0.0400	0.0055	0.0001	94.0500
Material No. 2: *GGG 60*									
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
3.1500	2.3300	0.6020	0.0337	0.0081	0.0708	0.0076	0.0369	0.0115	0.0271
Cu	Nb	Ti	V	W	Pb	Mg	As	B	Fe
0.2280	0.0017	0.0121	0.0109	0.0501	0.0030	0.0389	0.0052	0.0001	93.3800

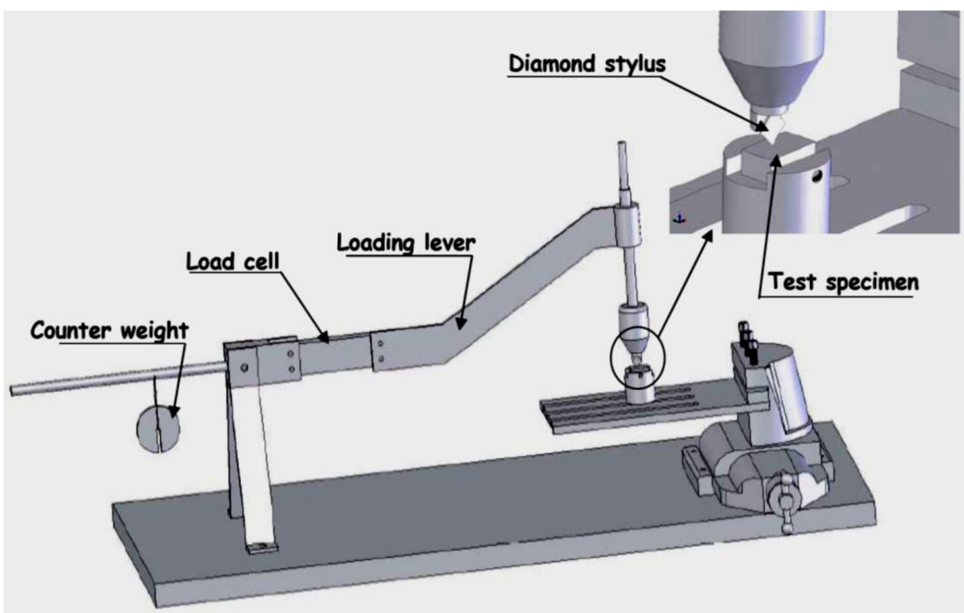

Fig. 1 Arrangement of scratch test rig.

Scratch tester shown in Fig. 1 was used. It consists 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 chunk. 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 is measured using a load cell mounted to the loading lever and connected to display digital monitor. The test specimen is held in the specimen holder which mounted in a horizontal base with a manual driving mechanism to move specimen in a straight line. The scratch force was measured during this test and used to calculate friction coefficient. This test is conducted under dry conditions at room temperature. An optical microscope was used to measure scratch width. Brinell hardness test was carried using Proceq hardness tester model EQUOTIP2.

RESULTS AND DISCUSSION

Heat treatment of ductile iron is used to have the desired properties for the wide range of applications. In this study, the hardness and tribological properties of the tested materials were changed widely. In general, quenching ductile irons in water and oil produce maximum hardness and wear resistance and minimum friction coefficient.

Figure 2 shows the hardness of GGG 40 ductile iron in as-cast state and after various heat treatment processes. Increase in hardness of normalized specimen (255 HB) appears is noticed but that still represented the minimum improvement in hardness of GGG 40. Test specimens quenched by compressed air showed significant hardness increase, while that quenched in water displayed the highest hardness values, followed by tests specimens quenched in oil. As for the austempered test specimens, hardness decreased for one hour cooling in air then slightly increased with increasing the cooling time to 2 hours.

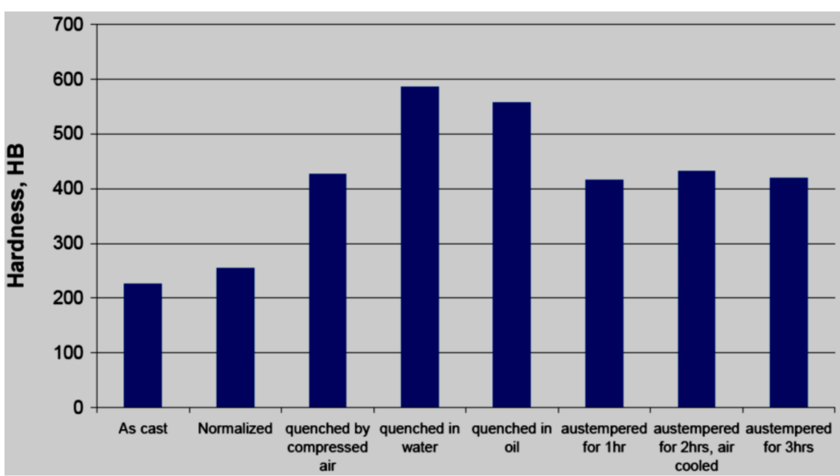

Fig. 2 Hardness of GGG 40 after heat treatment.

The hardness of GGG 60 is shown in Fig.3. Hardness of normalized and compressed air quenched specimens was 300 and 306 HB respectively. The highest hardness values were displayed by the test specimens quenched in water and in air. The hardness of the austempered test specimens of GGG 60 showed relatively lower values than the measured for GGG 40. Normalizing involves the austenitizing of ductile iron, followed by cooling in air. An as-cast ductile iron casting is normalized to break down carbides and increase hardness and strength. Normalizing is sometimes followed by tempering to relieve residual stresses. Tempering after normalizing is also used to obtain high toughness and impact resistance. The objective of austenitizing is to produce an austenitic matrix with as uniform carbon content and to break down primary carbides.

Oil is preferred as a quenching medium to minimize stresses and quench cracking, but water or brine may be used for simple shapes. The formation of low carbon martensite will cause reduced distortion and cracking in complex castings during quenching and, when tempered, low carbon martensite has toughness superior to both tempered high carbon martensite and normalized microstructures.

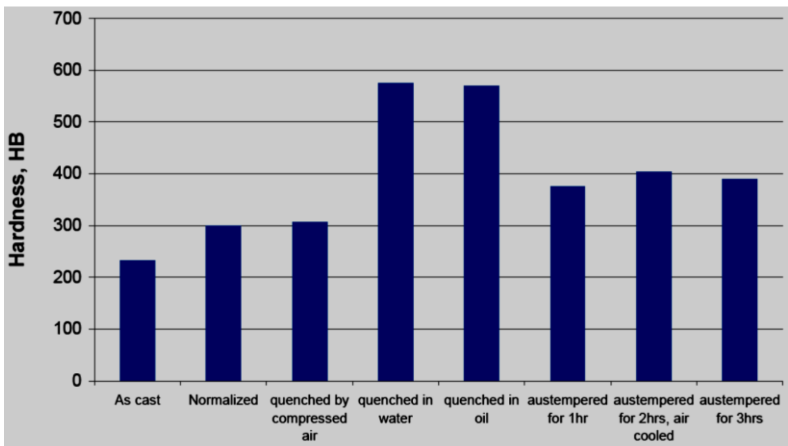

Fig. 3 Hardness of GGG 60 after heat treatment.

Friction coefficient of GGG 4 is shown in Fig. 4, where as cast DI showed the highest friction values followed by normalized, air quenched and water quenched DI. Friction coefficient significantly increased with increasing applied load. The increase of friction coefficient was related to the depth of stylus in the wear track. As the hardness of the tested materials increased the depth of stylus tip into the scratched materials decreased.

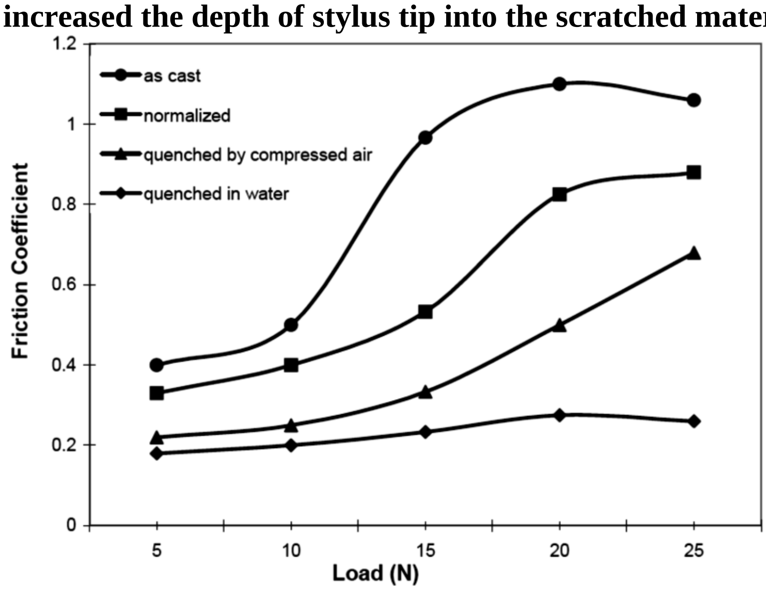

Fig. 4 Friction coefficient of GGG – 40.

Oil quenched and austempered (2 hours) test specimens showed the minimum friction coefficient, Fig. 5. Friction coefficient slightly increased from 0.18 to 0.25 as the applied load increased from 5 to 25 N. austempered test specimens (1 and 3 hours) showed an increasing trend of friction coefficient.

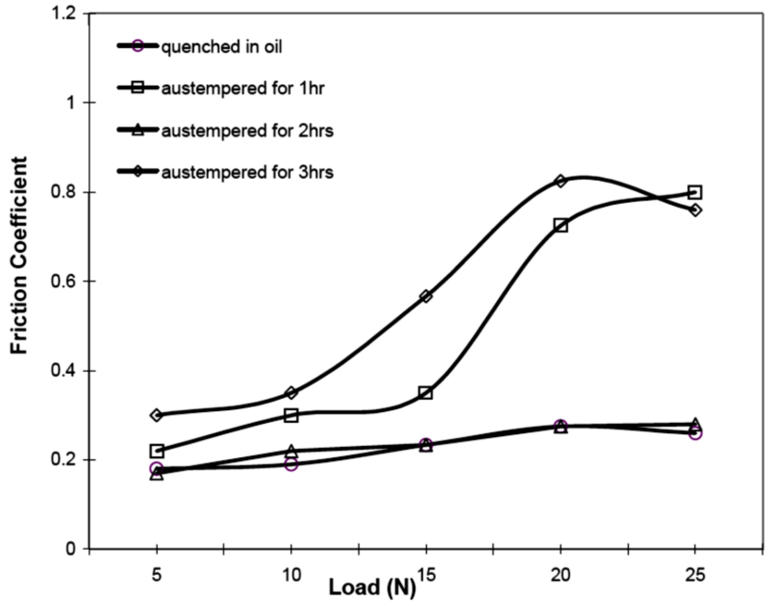

Fig. 5 Friction coefficient of GGG – 40.

Wear of GGG 40 is shown in Figs. 6 and 7. Wear significantly increased with increasing applied load. As cast DI specimens showed the highest wear followed by the normalized, then air quenched, oil and water quenched test specimens. Austempered test specimens (2 hours) showed reasonable wear resistance among the other two austempered test specimens (1 and 3 hours.) Based on the results of hardness, friction and wear, it can be observed that there was correlation among those three parameters. The superior wear resistance of DI might be attributed to the transformation of high carbon austenite to martensite that takes place in the surface layer during the wear tests. The wear resistance depended on matrix structure and its hardness. Studies of the influence of microstructure and microhardness on wear resistance showed that the pearlite content and its microhardness, along with the Brinell hardness of the bulk iron, directly influenced wear rates. Thus, raising the pearlite content lowered the rate of wear.

Friction coefficient of GGG 60 is illustrated in Figs. 8 and 9, where as cast DI displayed the highest values. Similar to the behaviour of GGG 40 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.

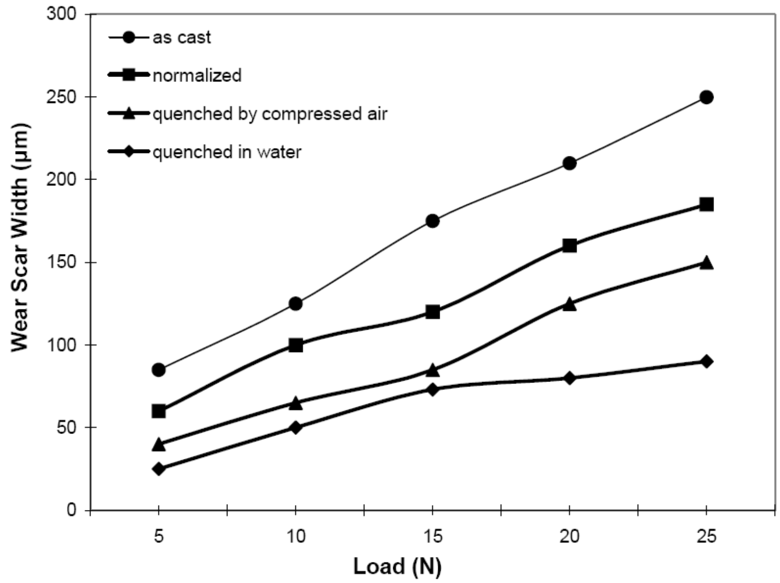

Fig. 6 Wear of GGG - 40.

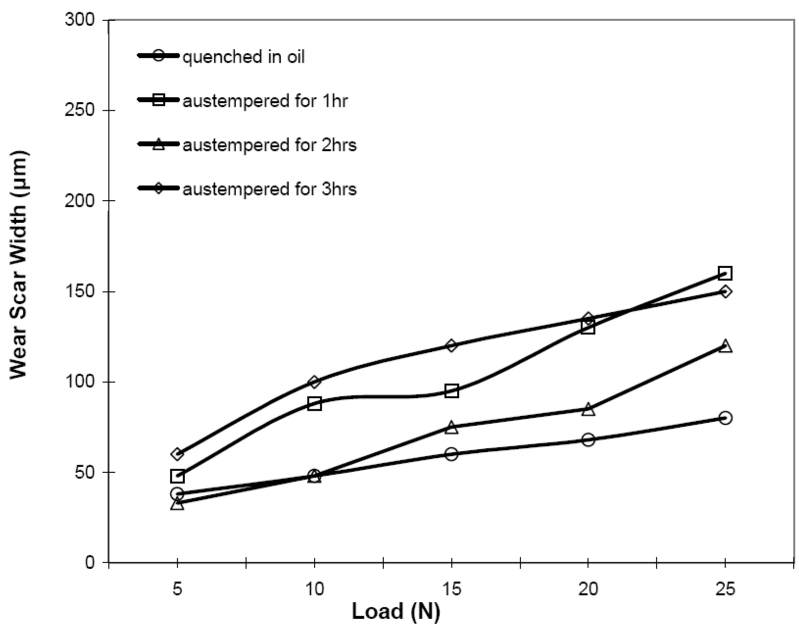

Fig. 7 Wear of GGG - 40.

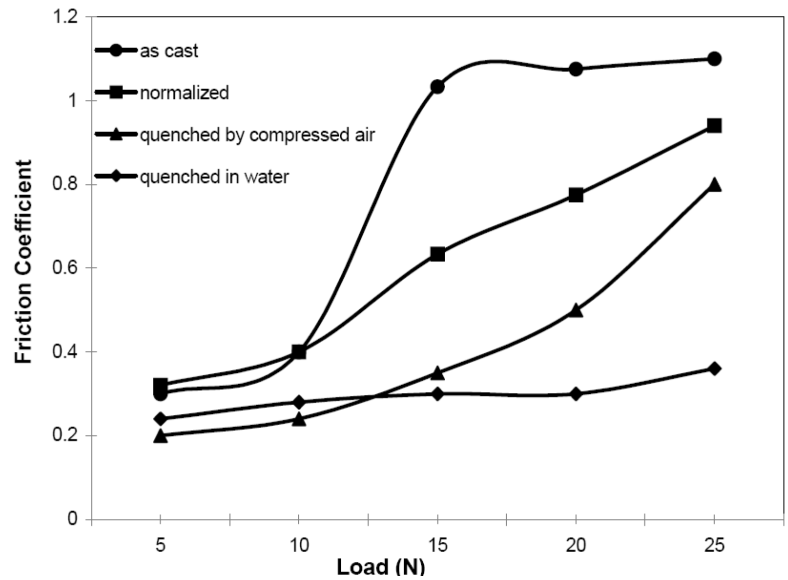

Fig. 8 Friction coefficient of GGG 60.

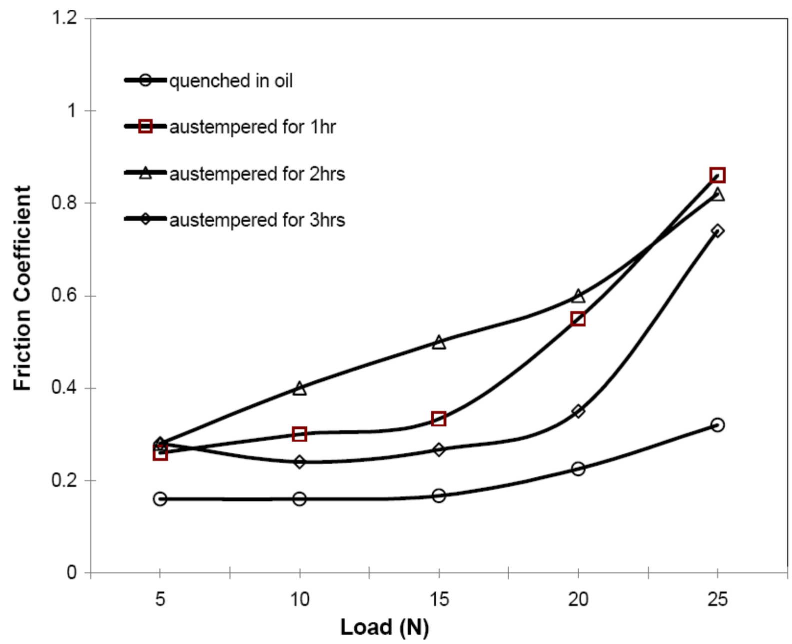

Fig. 9 Friction coefficient of GGG 60.

Wear of GGG 60 is shown in Figs. 10 and 11. Generally, Wear increased with increasing applied load. The 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.

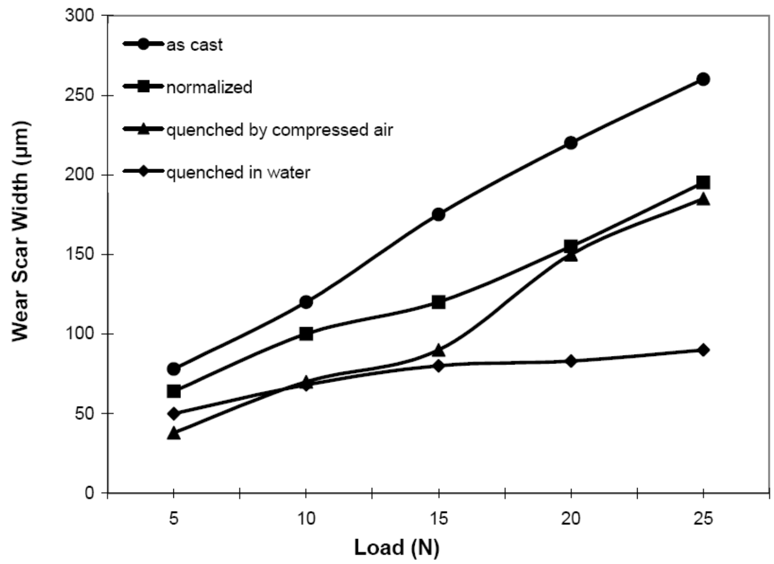

Fig. 10 Wear of GGG 60.

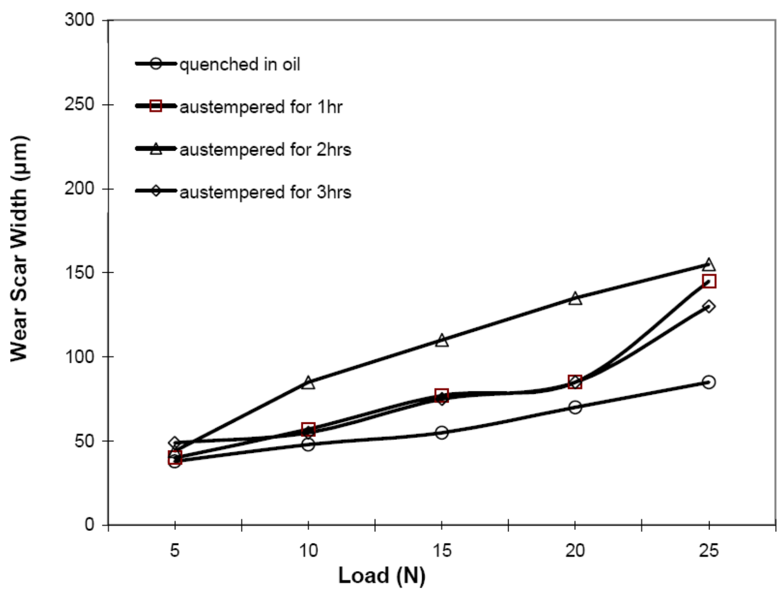

Fig. 11 Wear of GGG 60.

CONCLUSIONS

From the present investigation on the effect of heat treatment on friction coefficient and wear of unalloyed ductile iron, the following conclusions can be obtained:

1. Friction coefficient as well as wear increased with increasing load.

2. As the hardness increased, friction coefficient and wear decreased.

3. The highest hardness of the heat treated GGG 40 was displayed by specimens quenched in water followed by that quenched in oil.

4. As cast materials represented the highest friction coefficient.

5. The highest wear resistance and lowest friction coefficient were observed for specimens of highest hardness, such as water and oil quenched test specimens.
6. Austempered test specimens displayed quite good wear resistance and low friction coefficient

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