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RESEARCH

Effect of Heat Treatment on the Abrasive Wear Behavior of High Chromium Iron under Dry Sliding Condition

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A B S T R A C T

The effect of heat treatment on the abrasive wear behavior of high chromium cast iron (NF253AHT) under dry sliding condition has been investigated. Rectangular cross sectioned samples of the alloy were produced by sand casting. After casting, the samples were machined to equal dimensions of 50 mm x 15 mm x 10 mm and heat treated by annealing, hardening and tempering. Abrasive wear tests were carried out on the samples using the pin-on-disc wear test. The tests were carried out under restricted values of speed, load and time. Within this limit, the hardened sample displayed a superior wear resistance, while the annealed sample displayed the weakest wear resistance. A graphical model (wear map) displaying all the wear regimes of the alloy, which may serve as a wear predictive tool was subsequently developed from the results of the wear tests. With the exception of the as-cast and annealed specimen, all other specimens (hardened and tempered) have functioned adequately in wear prone environment, but with different degree of effectiveness. Hence, the hardened and tempered samples can be used in shot blast equipments and in the grinding of minerals.

1. INTRODUCTION

The abrasive wear of materials is of technical and economic importance [3]. It has been already recognized as one of the most potentially serious tribological problems facing the operators of many types of plants and machinery; several industrial surveys have indicated that wear by abrasion can be responsible for more than 50 % of unscheduled machine and plant stoppages [1].

In view of this, newer materials that may adequately function in wear prone environments have been developed [1–8]. High Chromium cast irons within the range of 22 % - 30 % wt of Chromium content have known to posses a very good sliding wear resistance. Their good abrasive wear resistance is a direct consequence of the presence of M_7C_3 – type carbide, also present in the iron matrix. The Chromium carbide Cr_7C_3 alone has a hardness of 1200 HB while that of the matrix is about 200 HB, thus giving a bulk hardness of about 600 HB in the as cast condition. The hardness of the matrix can be increased by an appropriate heat treatment (i.e. hardening by quenching), and this will further increase the wear resistance of the alloy. The potential for chromium to be used in wear prone applications has been discovered long time ago; consequently, the binary chromium alloys have been explored with Titanium, Zirconium, Hafnium, Niobium and Tantalum, individually. Each of these alloys has been subjected to abrasive wear test and it was discovered that the wear rate of all the alloys decreased as the content of alloying element in each of the materials increased up to their solubility limit [4]. Taking into account the theoretical expression for the wear rate, as suggested by Archard [11];

$$Q = \frac{KW}{H} \tag{1.0}$$

where Q is the volume loss of the abraded material per unit sliding distance, K is the wear coefficient, W is the applied normal load and H is the hardness of the abraded material, the volume of removed material from a body during wear, is inversely proportional to the hardness of the material [9].

The high Chromium cast irons have relatively excellent abrasive wear resistance due to their high hardness; however, their susceptibility to brittle fracture has limited their application in environments where percussive conditions exist [3]. Two contradictory properties of the chromium cast iron i.e. high hardness and low toughness may be reconciled by a grain refinement and the uniformity in the distribution of the carbide phase in the austenitic or its transformed matrix [3]. For this reason, in the present study, annealing, hardening and tempering have been carried out on individual specimen of high Chromium cast iron NF253AHT; aside from enhancing the homogeneity in the distribution of the carbide phase, it is also expected to result a variation of combination for hardness-toughness in each specimen. Each of the specimens of the alloy NF253AHT will be placed in a simulated service wear condition, involving certain values for speed, applied load and time of contact. The simulation of machine contact may be aimed at elucidating the essential physical mechanisms of surface damage and material loss, with the longer term aim of building an analytical and predictive model of the wear process [1]. The different responses of each type of the specimens made of the alloy NF253AHT are displayed in a wear map for a broader view of their wear behaviors. The wear maps will be able to provide a more global picture of how materials in relative motion behave when different sliding conditions are encountered. They also provide the relationships among various dominant mechanisms of wear that are observed to occur under different sliding conditions as well as the anticipated wear rate [8]. For each of the specimens made of the alloy NF253AHT (i.e. as-cast, annealed, hardened and tempered), the variation of the wear rate with the applied pressure have been carried out and when coupled with the developed wear maps, they will give a vivid picture of the dry sliding wear behavior of the as-cast and the heat-treated specimens of NF253AHT alloy.

2. MATERIAL AND METHOD

2.1 Material Preparation

NF253AHT grade of high Chromium cast iron has been used in this study. The alloy has a composition of 2.93 % C, 22.72 % Cr, 1.13 % Mn, 0.79 % Si, 0.34 % Ni, 0.02 % Mo, 0.02 % P and 0.005 % S; the samples were sand cast in Nigerian Foundries Limited (NFL), Otta, Nigeria, with an electric induction furnace of two tons capacity. The specimens were initially cast into dimension of 52 mm x 16 mm x 12 mm, after which they were ground into equal shapes with the dimensions of 50 mm x 15 mm x 10 mm. The raw material that was used in obtaining the alloy and the quantity added into the furnace are tabulated below (Table 1).

Table 1. Charge make-up for NF253AHT.

MATERIAL	MASS (kg)	Cr	C	Mn	Si	Ni	Mo	P	S
Returns	1000.000	11.360	1.456	0.565	0.340	0.170	0.010	0.010	-
Fe-Cr	302.930	11.36	0.038	-	-	-	-	-	-
Fe-Mn	13.230	-	-	0.430	0.000066	-	-	-	-
Fe-Si	8.880	-	-	-	0.355	-	-	-	-
Fe-Ni	4.86	-	-	-	-	0.170	-	-	-
Graphite	35.500	-	1.42	-	-	-	-	-	-
Steel	634.600	-	0.008	0.142	0.448	-	0.0095	0.0095	0.005
Total	2000	22.72	2.93	1.13	0.79	0.34	0.02	0.02	0.005

2.2 Heat Treatments

A programmable induction industrial muffle furnace of one ton capacity was used in carrying out the heat treatments of the alloy in Nigerian Foundries Limited (NFL), Otta, Nigeria. Twelve specimens were obtained from the casting, and nine of these were annealed in the muffle furnace by stepping the furnace to 300 ˚C, heating up to 750 ˚C at 75 ˚C/hr and holding for 2 hours. The annealed specimen (three pieces) were allowed for cooling in the furnace, while the six remaining pieces were charged for hardening by raising the temperature of the furnace to 1000 ˚C at 75 ˚C/hr and holding for 4 hours. Then, all six specimens were quenched with forced air, after which three pieces of the hardened specimens were tempered by heating the furnace to 680 ˚C at 75 ˚C/hr and holding for 2 hours. The temperature was subsequently brought down to ambient temperature by applying forced air.

2.3 Hardness and Impact Test

The hardness test was carried out at Nigerian Foundries Limited (NFL), Otta, Nigeria with a Universal Hardness Testing Machine. The surfaces of the specimens having the dimensions of 50 mm x 15 mm were made very flat before carrying out the hardness test and the ball indentation method was applied for the entire specimen.

The impact test was also carried out at NFL using Avery Charpy Impact Testing machine having a striking velocity of 5 m/s and a kinetic energy of 298.3 J. The specimens were given a V-notch before the impact tests was carried out.

2.4 Microstructural Examination

For the microstructural examination, the samples were cut from the as-cast and heat treated blocks. The samples were mounted with epoxy resin for an easy grinding and polishing. The samples were finally etched with a reagent containing equal volumes of HNO_3, HCI and water. Then the etched samples were examined under a CETI Metallurgical Research Microscope, which has a magnification of x100.

2.5 Sliding Wear Test

A pin-on-disc wear testing machnie was used in carrying out the wear test, varying the speed from 2.0, 2.4, 2.8, 3.2 and 3.6 m/s, and the applied loads from 6.38, 8.34, 10.30, 12.26 and 14.22 N, at a fixed time limit of 3 minutes. In order to ensure that there is an effective abrasion of the surface of the specimens, each of the specimens was subjected to sliding on emery paper (200 grit size) fixed on an aluminum wheel on the pin-on-disc machine. During sliding, the load was applied on the specimen through a cantilever mechanism and the specimen brought in intimated contact with a rotating disc with a diameter of 200 mm. The specimens were cleaned with a soft brush after each test and they weighed with a micro-balance. The wear rate was calculated using a weight loss technique and expressed in terms of volume loss per sliding distance unit.

3. RESULTS AND DISCUSSION

3.1 Microstructures

The microstructures of the samples are shown in Figs. 1a-d. Figure 1a shows a typical as-cast structure that is predominantly austenitic in nature due to the high Chromium content (22.72 % Cr). There is a non-homogenity in the distribution of the carbide phase inside the iron matrix and the carbide particles are seen to cluster, this can have an effect on the mechanical behavior of the as-cast specimens and, more importantly, on its wear pattern.

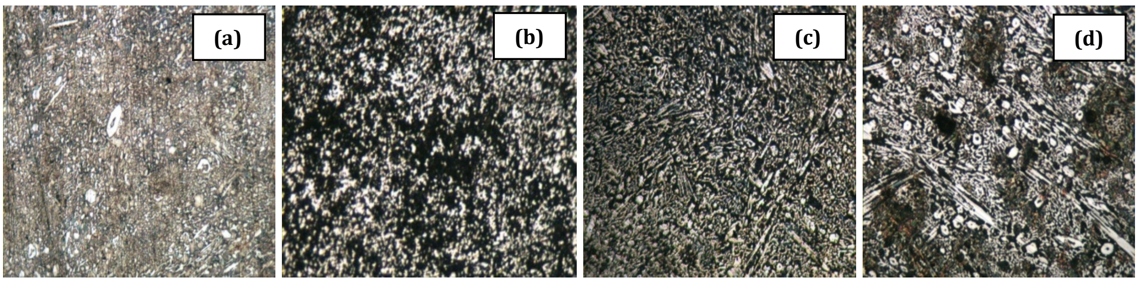

Fig. 1. (a) Microstructure of the as-cast specimen (100X); (b) Microstructure of the annealed specimen (100X); (c) Microstructure of the hardened specimen (100X); (d) Microstructure of the tempered specimen (100X).

However, the presence of a microstructure that is predominantly austenitic implies that, under the condition of severe impact stresses, the wear surface can become very hard and highly wear resistant. Due to the fact that percussive conditions do not exist in this present study, in areas where there are higher concentrations of the carbide Cr_7C_3, the as-cast specimen would display a very good resistance to wear while those areas that have a less concentration of the carbide would make the specimens to be prone to severe wear. Figure 1b showed the micrography of the annealed NF253AHT specimen.

The microstructure is essentially ferritic, with evenly disposed carbide particles. The annealing treatment has refined the grains, it induced toughness and it produced grains that have a common orientation and are strain-free. The inducement of toughness is expected to bring about a reduction in the hardness of the specimen. In turn, this is expected to negatively affect the wear pattern of the specimen [5].

Figure 1c shows the microstructure of the hardened NF253AHT specimen that is predominantly martensitic with dispersed carbides. The martensite has the BCT (body-centered tetragonal) structure that is formed when BCC (body-centered cubic) iron is forced air quenched from a temperature of 1000 °C and it has a highly distorted lattice, and the effect is to impart a very high hardness to the specimen. The presence of the martensite implies that the matrix would have a high hardness when it is combined with the hardness of the Chromium carbide particles Cr_7C_3, it would greatly increase the hardness of the specimens and also increase its wear resistance.

Figure 1d shows the microstructure of the tempered NF253AHT specimen, which is almost as that in Fig. 1c. However, the freshly produced martensite in Plate 1c has been lowered to an acceptable level where the tendency for crack generation and brittle fracture is minimized. The hardened specimen has been partially relieved of its internal stresses and, as a result, a better toughness is expected from the tempered specimen at the expense of a reduction in hardness.

3.2 Impact Test

The energy dissipated in breaking each specimen is its impact toughness. The Charpy impact test yielded to the following results: annealed specimen – 79 J, as-cast specimen – 76 J, tempered specimen – 73 J and hardened specimen – 65 J. The wear resistance is very much dependent on the specimen hardness [9], however, the toughness is also important. A good degree of toughness is desired in the materials in order to prevent cracking when they are used in an abrasive-percussive environment. The annealed specimen displayed the highest toughness (79 J) due to the reduction in lattice defects and the growth of strain-free grains caused by the recrystallization (see Fig. 1b).

The as-cast specimen displays a lower toughness than that of the annealed specimens due to defects that are naturally introduced into a cast material, i.e. point, line, planar and even bulk defects. Thus, the as-cast specimens can still be used in an abrasive-percussive environment as long as their wear resistance is high enough to ensure a very low abrasion.

The tempered specimen had an impact toughness of 73 J and this value of toughness is acceptable when it is compared to that of the hardened specimens. However, the toughness of the tempered specimen is acceptable and the material could function in a variety of environments where the percussive conditions are not excessive.

The hardened specimen showed the least toughness of 65 J. Its hardness had been obtained at the expense of a reduction in toughness.

3.3 Hardness Test

The results of the hardness test carried out on all the specimens are: annealed – 428 HB, as-cast – 590 HB, hardened – 693 HB, tempered – 619 HB. Due to the stress relief during recrystallization and grain refinement during grain growth, the annealed sample becomes soft and, thus, the hardness of the annealed alloy NF253AHT becomes reduced to 428 HB (see Fig. 1b). This reduction in hardness may seriously hamper the ability of the specimen to resist serious wear.

The as-cast specimen has an improved hardness value of 590 HB due to the presence of naturally introduced lattice defect during casting, the hardness of the iron matrix and the hardness of the carbides (M_7C_3) present within the matrix.

The hardened specimen had the highest hardness of 693 HB, as expected. This is due to the distortion of the lattice by the excess carbon trapped within the BCT structure of martensite (see Fig. 1c). At such a high value of the hardness, it follows from Archard's equation (eq. 1) that it should provide a very good resistance to wear comparatively to other specimens.

The tempering of the hardened specimen brought about a reduction in hardness to 619HB. This is due to the precipitation of excess carbon in the BCT structure of martensite as the BCT is re-converted into a BCC structure (see Fig. 1d). The excess carbon precipitates as carbides and, thus, the tempered specimen is partially relieved of the internal stress.

3.4 Wear Behavior

3.4.1 Wear Map

It is a common practice to describe the wear behavior of some alloy using a single variable. However, the wear map is a better tool that displays the wear behavior of a material as a function of two other variables (here, the sliding speed and the applied normal load). The wear maps for each type of materials are displayed in Figs. 1-4.

The volume loss was calculated from:

$$V = \frac{m}{\rho} \qquad (2.0)$$

where ρ(g/cm^3) is the density of the abraded material, m(g) is the weight loss and, V(cm^3) is the volume loss; the wear rate in mm^3/m was obtained by dividing the volume loss in mm^3 by the sliding distance in m. The density of each type of specimens was found to vary. The as-cast specimens had an average density of 8107.5 kg/m^3, the annealed specimens – 8285.7 kg/m^3, the hardened specimens – 8557.6 kg/m^3 and the tempered specimens – 7482.3 kg/m^3. The average of these densities is 8108.3 kg/m^3 and, after converting its units, it was used in obtaining the weight losses.

The wear map of the as-cast high chromium non specimen (Fig. 1) shows the wear rates of the specimen varying randomly as the applied load and sliding speed were varied. The highest rate of wear takes place under a load of 10.3 N and a speed of 2.8 m/s. The wear volume under that test conditions was 0.07 mm^3/m. This peak in wear volume is not excessive. The as-cast specimen has not performed too badly as concern the wear resistance; however, the randomness with which it behaves is a subject of interest. It displays almost "zero" wear under four sets of different test conditions: (2.4 m/s, 12.2 N), (2.8 m/s, 8.34 N), (3.2 m/s, 12.26 N) and (3.6 m/s, 6.38 N). Immediately after the display of almost "zero" wear, there is a sharp transition to severe wear. The wear behavior of the as-cast specimens is manageable, but the unpredictable nature in its wear pattern should be of concern if the alloy NF253AHT is to be deployed for use in the as-cast condition.

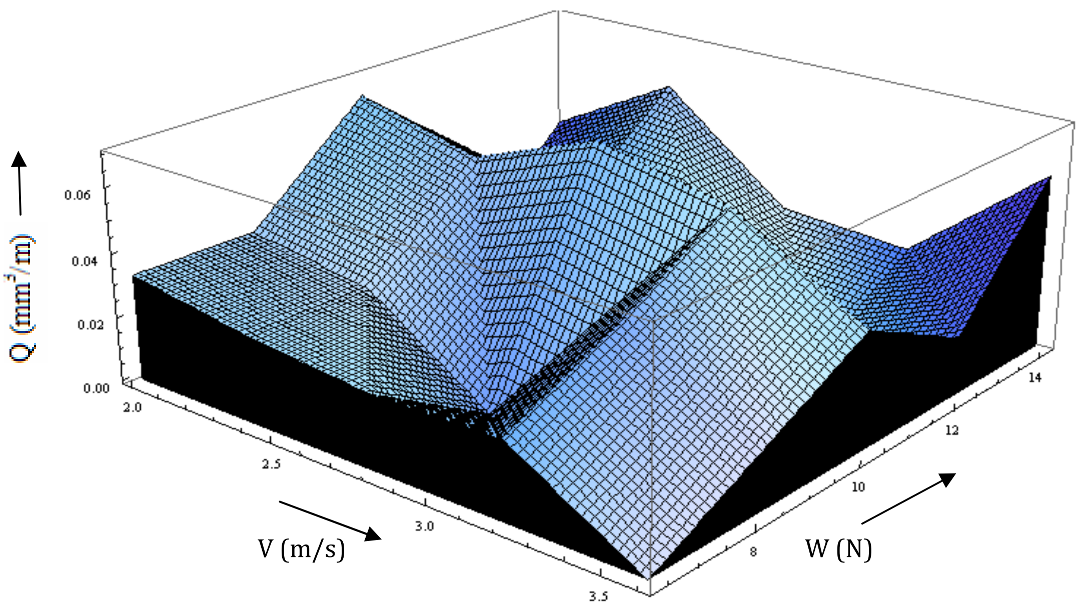

Fig. 1. Wear map for the as-cast high Chromium iron NF253AHT grade.

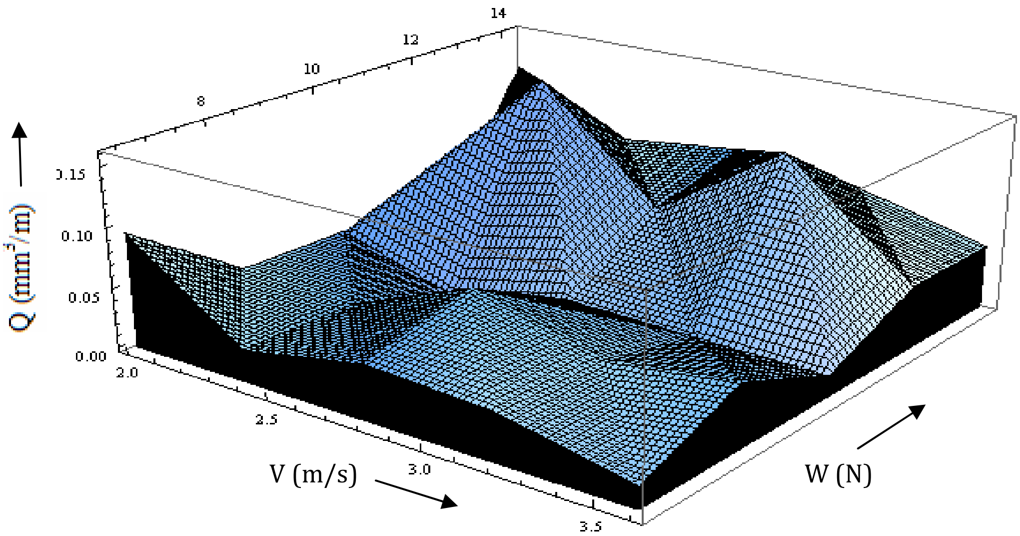

Fig. 2. Wear map for the annealed high Chromium iron NF253AHT grade.

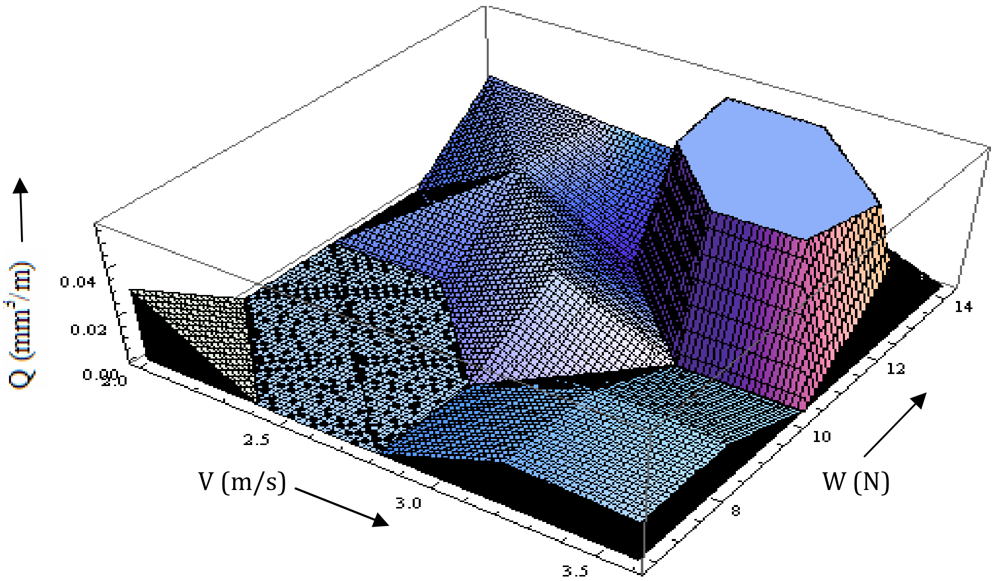

Fig. 3. Wear Map for the hardened high chromium iron (NF253AHT Grade).

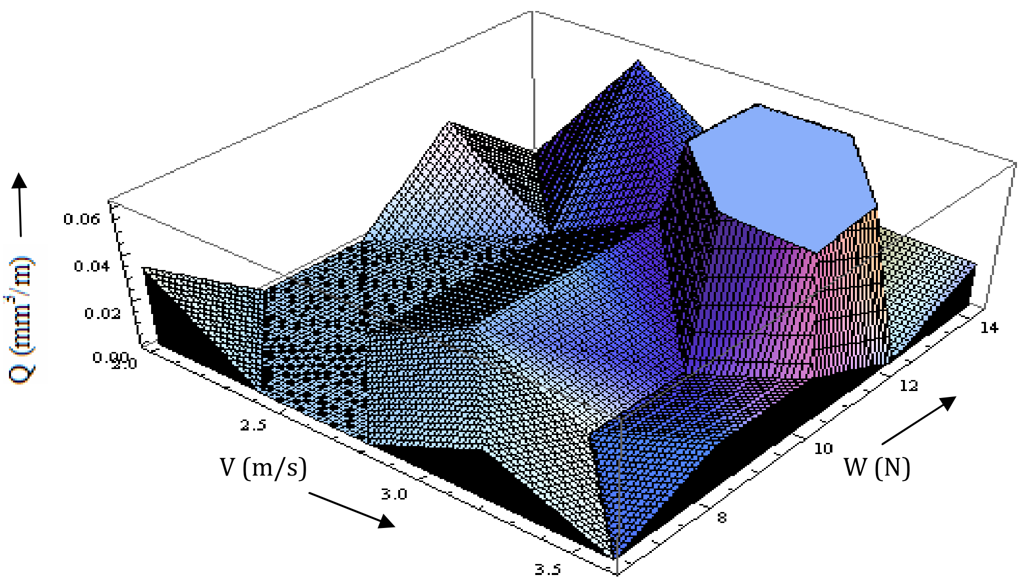

Fig. 4. Wear map for the tempered high Chromium iron NF253AHT grade.

The wear map of the annealed high chromium iron as given in Fig. 2 shows the specimens displaying the weakest resistance to wear. The highest wear rate occurred at a speed of 3.2 m/s, where the load was 12.26 N. The wear volume at that condition was 0.14 mm^3/m. This peak in the wear volume is twice than that of the as-cast specimen. The annealed specimens also displayed a random pattern of wear behavior like the as-cast specimens, but the degree of randomness is not as pronounced as that of the as-cast specimens.

For the hardened specimens (Fig. 3), the wear map shows that at lower speeds and applied loads, there was a very high resistance to wear. This case occurred at twelve sets of test conditions: (2 m/s, 8.34 N), (2 m/s, 10.3N), (2 m/s, 12.26 N), (2.4 m/s, 6.38N), (2.4 m/s, 8.34 N), (2.4 m/s, 10.3 N), (2.8 m/s, 6.38 N), (2.8 m/s, 8.34 N), (2.8 m/s, 12.26 N), (3.2 m/s, 10.3 N), (3.6 m/s, 10.3N) and (3.6 m/s, 14.22 N), respectively.

At higher values of speed and load, the wear rate of the hardened specimens increased sharply as depicted by frustum in the wear map. However, the wear volume under those conditions is very minimal when compared with other specimen. The highest peak in wear volume on the wear map of the hardened specimen is 0.34 mm^3/m. The hardened specimen thus displayed the best wear resistance as displayed on the wear map.

The wear map of the tempered specimen (see Fig. 4) is very much similar to that of the hardened specimen. It also good wear resistance at twelve sets of test conditions: (2 m/s, 8.34 N), (2 m/s, 10.3 N; 2 m/s, 14.22N; (2.4 m/s, 6.38 N), (2.4 m/s, 8.34 N), (2.4 m/s, 10.3 N), (2.4 m/s, 12.26 N), (2.8 m/s, 6.38 N), (3.2 m/s, 8.34 N), (3.2 m/s, 10.3 N), (3.6 m/s, 6.38 N) and (3.6 m/s, 12.26 N), respectively. At higher values of speed and load, the wear rate of the specimens sharply increased, however, just as in the case of the hardened specimens, the wear rate displayed is very low as compared to that of the as-cast and the annealed specimen. The highest peak in wear volume was 0.35 mm^3/m as displayed on the wear map.

3.4.2 The effect of Applied Load on Wear Severity

The wear coefficients for the as-cast and the heat treated specimens made of high Chromium cast iron NF253AHT grade have been computed from Archard's wear equation (eqn. 1) for each unique combination of speed and applied normal load (Fig. 5). The wear coefficient is an indication of the severity of wear and it provides a valuable means of comparing the severities of different wear processes.

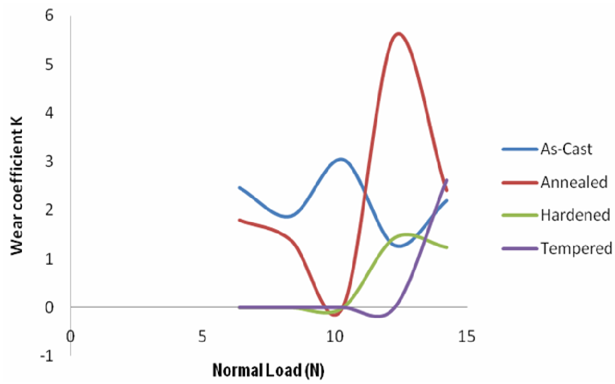

Fig. 5. Change in the wear coefficients with increasing load for the as-cast and heat treated specimen of NF253AHT.

Between 6.38 N and 8.34 N, the value of the wear constant for the as-cast specimens is high. However, the value declines when the load increases from 6.38 N to 8.34 N. This decline in wear constant value may be attributed to the clustering of the Chromium carbide particles in the iron matrix of the specimens and non-homogeneity in their distribution. Within the same range of normal load, the annealed specimens show a lower value of the wear coefficient, which declines when the load increases from 6.38 N to 8.34 N. The annealed specimen has displayed a similar pattern to the as-cast specimen. However, its values of wear coefficients were lower. This may be attributed to homogeneity in the distribution of the carbide phase in the iron matrix, but the lower value of matrix hardness has impeded the annealed sample from displaying a better wear resistance. Within the same range of load, the hardened and tempered specimens have displayed almost zero values of wear coefficient, respectively. This corresponds to the regions of less wear. The almost "zero" values of the wear coefficient may be attributed to the uniform distribution of the carbide phase combined with a matrix whose hardness has been substantially increased by heat treatment. This has resulted in the production of the martensite and the tempered martensite, respectively, and the crystal lattices of these structures are highly distorted leading to the high increase of the matrix hardness (see Figs. 1c-d).

Between 8.34 N and 10.3 N, the value of the wear coefficient for the as-cast specimens gently rises to a peak value of 3.04 at 10.3 N. This may be attributed to a region within the matrix of the specimen that is low in carbide concentration coming in contact with the abrasive within that limit. The hardness of the matrix, which is somewhat high, has restricted the as-cast specimens from undergoing severe wear. The wear coefficient of the annealed specimens within that limit has dipped to almost zero. This may be attributed to the uncovering of fresh surfaces of carbide particles that are highly resistant to wear. The hardened and the tempered specimens have both displayed almost "zero" values of the wear coefficient within this limit. The presence of martensite and tempered martensite, respectively, may said to be responsible for their excellent wear resistance, as indicated by their almost zero wear values.

Between 10.3 N and 12.26 N, the wear coefficient of the as-cast specimen dips to the lowest value of 1.28. This is further proof of the unpredictability in the wear pattern of the specimen due to a lack of homogeneity in the carbide phase distribution. Within the same limit, the annealed specimens rise to the highest peak of 5.58, evidently displaying high severity of wear, which is a direct consequence of a very soft matrix (see Fig. 1b). The hardened specimens show a rise in the wear coefficient within the same limit of 1.43 and this is the highest peak it ever attains at the constant speed of 2.4 m/s. The increase in wear coefficient may be attributed to a lack of toughness of the specimens. As particles of Cr_7C_3 are exposed to the abrasive media, they are knocked-out under testing at high speed and applied load. This leads to a loss of material from the surface of the hardened specimens [9-11]. Within the same limit of speed and load, the tempered specimens display almost zero values for the wear coefficient. It is owing to a very hard matrix of the specimens, which have been toughened by tempering, coupled with evenly dispersed Chromium carbide particles.

Between 12.26 N and 14.22 N, the values of wear coefficient of the as-cast specimens increase indicating an increase in the wear severity. The wear severity for the as-cast specimens is not excessive, however, they seem to rise and fall intermittently. Within the same limits, the values of the wear coefficient for the annealed specimen's dips, indicating a decline in the wear severity. This may be attributed to an uncovering of new specimen surface exposing fresh Cr_7C_3 particles that provide a good wear resistance to the specimen. Within these limits, the hardened specimen displays a decline in the wear coefficient, indicating a decrease in wear severity. It may be due to the discovering of fresh carbide particles that resist to the sliding wear of the specimen. It should be noticed that at the peak load of 14.22 N, the hardened sample displays the lowest value of the wear coefficient of 1.23, an indication of the lowest severity of wear at the peak load. Within the same range of loading, the values for the tempered specimen rises from almost "zero" value wear coefficient to its peak of 2.62. The increase in load on the tempered specimens may have affected their ability to maintain an excellent wear resistance.

3.4.3 Effect of Applied Pressure on Wear Rate

The term wear rate implies the rate of the material removal per unit of an exposure parameter (i.e. time or sliding distance). In the present study, the values of wear rate have been obtained per unit of sliding distance (Fig. 6). The wear rate of a material is quite different from its wear coefficient. The wear coefficient is a dimensionless quantity and it is a constant for a given set of exposure parameters.

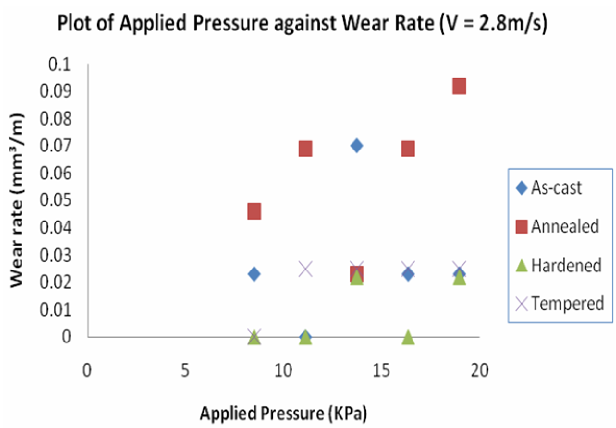

Fig. 6. The change in the wear rate of the as-cast and heat treated specimen with increasing applied pressure.

The values for the applied average pressure were obtained from:

$$p = \frac{F}{A} \tag{3.0}$$

Where p(Pa) is the applied average pressure, F(N) is the normal load and, A(m^2) is the area of the cross-section of the specimen that was subjected to wear.

Between 8507 Pa – 11120 Pa, the as-cast specimens show a dip in the wear rate, as in the case of the wear coefficient, it is owing to the non-homogeneity in the carbide phase distribution within the iron matrix. The wear rate rises steeply from pressure of 11120 Pa to a peak value of 0.07 mm^3/m at 13733 Pa then the wear rate eventually declines. A similar behavior is displayed by its wear coefficient, the annealed specimens show a high rate of wear even at the beginning of the wear test, of 0.046 mm^3/m. It also displays the intermittent rise and fall in the wear rate owing to its very soft matrix and the wearing away of a layer of carbide phase revealing fresh ones. The annealed specimens eventually peak its wear rate of 0.092 mm^3/m at the highest value of the applied average pressure of 18,960 Pa. The hardened specimen displayed its high wear resistance (almost "zero" wear rate) between 8,507 Pa and 11,120 Pa largely due to its high hardness of 693 HB. It however displays rise and fall in its values of the wear rate up to the peak of the applied average pressure. It has displayed the best wear resistance in comparison to the lot. The tempered specimens displayed almost "zero" wear only at the beginning of the test, where the applied average pressure was 8,507 Pa, due to its high hardness value of 619 HB. Its wear resistance declined after there was an increase in the applied average pressure and it continued to wear at a constant rate of 0.025 mm^3/m. Its homogeneous distribution of the carbide phase, coupled with its hard and tough matrix (73 J) is largely responsible for this constancy in the wear pattern.

4. CONCLUSIONS

From the above results and discussion, the following conclusions are done:

1. The hardened specimens have the greatest resistance to wear within the limits of speed, applied load and time for which the investigation was carried out.
2. The comparison among the wear coefficients has revealed the excessive wear rate of the annealed specimens. It also reveals the average wear severity of the as-cast specimen and the competitive wear resistances of the hardened and tempered specimens.
3. Within the limits of this investigation, the wear rate for all specimens is not directly proportional to the applied average pressure. This implies that an increase in the applied average pressure does not translate to an increase of the wear.
4. With the exception of the as-cast and annealed specimens made of NF253AHT, all other specimens (hardened and tempered) would function adequately in a wear prone environment but with different degree of effectiveness.
5. The hardened and tempered high Chromium cast iron NF253AHT can be used in shot blast equipments and in grinding of minerals.

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