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Age Strengthening of Grey Cast Iron Alloys for Machine Cutting Tools Production

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Abstract

This work was carried out with the aim of using alloying and ageing processes to develop new alloys from grey cast iron that will have optimum properties suitable for the manufacturing of machine cutting tools. Four different alloys of grey cast iron with alloying composition of Fe-3% Al-2.5% Cr-2% Mo; Fe-3% Al-2% Cr-2% Mo; Fe-3% Al-2.5% Cr-1.5% Mo and Fe-3% Al-1.5% Cr-2% Mo were produced. The chemical analysis of both as-received base metal and produced alloys was determined using Spetro-CJRO Arc-Spectrometer. The microstructural properties and mechanical properties (hardness, impact toughness and ultimate tensile strength) of the produced alloys were determined for both as-cast samples and aged samples. The results showed that the addition of these alloying elements slightly decreased carbon, silicon and phosphorus content and thereby changed the hypereutectic cast iron to hypoeutectic by reducing the carbon equivalent. Also the morphology of graphite flake was changed as a result of the formation of nitrides and carbides of different phases. The results of the mechanical properties showed that the maximum hardness values obtained for each of the four alloys produced and aged at 300˚C are 71.5 HRc, 69 HRc, 66.5 HRc and 65.4 HRc respectively. The maximum values for impact toughness obtained for each of the same produced alloys are 66 J, 63.6 J, 62 J and 60.3 J respectively. Also the maximum ultimate tensile strength values obtained for each of the alloys are 1380 N·mm^{-2}, 1311 N·mm^{-2}, 1260 N·mm^{-2} and 1190 N·mm^{-2}. Comparing the properties obtained from the produced alloys with those of the commercial cutting tools, it was found that cutting tools manufactured from these produced alloys can compete favourably with cast cobalt tool, high speed steel (HSS) and tool steel.

Keywords

Grey Cast Iron, Alloying Elements, Ageing, Cutting Tools, Microstructures

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1. Introduction

Some of the engineering materials in their natural state have little or no engineering application. They can be made to perform well in their service areas through some treatments such as alloying and heat treatment [1]. It is because of these reasons that men especially engineers, technologists and scientists will continue to interact with natural materials to alter their natural status in order to meet up some stringent conditions of service such as high-technology and advanced engineering works that are highly demanded for nowadays [2]. The materials strengthening mechanisms are accomplished by single-phase materials production, grain size reduction, solid-solution alloying, precipitation (ageing) and strain hardening [1] [3]. All strengthening techniques are aimed at restricting or hindering dislocation motion, thereby rendering a material harder and stronger. The two principal hardening reactions in heat treatment are precipitation from supersaturated solid solution and eutectoid decomposition [4].

Grey cast iron has microstructure from which different microstructures may be generated or developed by adjustment of composition and an appropriate heat treatment [4] [5]. Age strengthening of grey cast iron can occur naturally at room temperature or artificially at elevated temperature. Most grey cast iron alloys significantly respond to age strengthening and the presence of iron nitride and carbo-nitride contributes to ageing mechanism [6]. Nitrogen in excess of the stoichiometric amount to combine with strong nitride forming elements was found to be an important factor affecting the level of age strengthening [6]. When the nitrogen content is within the range of 0.015% - 0.052%, nitrogen will combine with iron or some alloying elements such as Mo, V, Al, Ti, and Cr to form chemical compounds called nitrides [7]. Anish [8] stated that the age strengthening mechanism in the grey cast iron is due to a precipitation of nitrides, carbides and carbo-nitrides in the ferrite matrix. The precipitation is in three stages: formation of interstitial atom clusters, nucleation of precipitates and growth of the precipitates [9].

Grey cast iron with addition of 0.15% - 2% chromium is used for high hardness without brittleness and high resistance to abrasion [9]. Mahran [7] investigated the tendency of the different alloying elements to form hard nitrides of the iron by precipitation. The result of his investigations showed that very high hardness can be obtained when grey cast iron alloy contains 1.5% - 2% aluminium, 1.5% - 2% titanium, 1.5% - 2% molybdenum and 2% - 5% chromium.

Cutting tools must be made of a material harder than the material which is to be cut, and the tool must be able to withstand the heat generated in the metal-cutting process [10]. Some of these cutting tools commercially available are carbon tool steel, high speed steel (HSS) and cemented carbide [10]. Others are cast cobalt alloys, ceramics, cermet, cubic boron nitride (CBN) and diamond. To produce quality product, a cutting tool must have four characteristics such as hardness to withstand abrasive force, ultimate tensile strength (UTS) to impact high stability (tools do not chip or fracture easily) even at high temperature, toughness to be able to absorb high energy and wear resistance in order to have acceptable tool life for the tool [11].

So many authors and researchers have worked on grey cast iron alloys at various levels of studies. Among them are Richards, Aken and Nicola [6] who studied age strengthening of grey cast iron for improving machinability. The result of their work showed increase in UTS and hardness from 3.3% to 13.5%. Anish [8] studied the effects of alloying elements and kinetic on age strengthening of grey cast iron. Tremendous amount of improvements in both microstructural and mechanical properties of grey cast iron alloys were recorded from their works. But there was little or no thought of utilizing this strength improvement in grey cast iron to develop new alloys for the manufacturing of machine cutting tools. Therefore, the thought of developing new alloys from the grey cast iron through alloying and ageing processes for the manufacturing of cutting tools is a welcome endeavour and development.

This work employed both alloying and heat treatment (ageing) processes to develop new alloys of grey cast iron with optimum properties suitable for the production of machine cutting tools. The alloying elements used are aluminium (Al), chromium (Cr) and molybdenum (Mo). Aluminium was selected because of its tendency to form nitride in cast iron. Chromium and molybdenum were selected because of their tendency to form and stabilize carbides [6].

2. Experimental Procedures

Alloy materials include grey cast iron scraps; aluminium ingot of 2024 series according to ASTM unified numbering system (UNS), ferro-chromium of 67% purity, ferro-molybdenum of 55% purity and nitrided ferro-manganese of 75% purity to enrich the nitrogen content of the alloy. The ranges of alloying elements used are 2.5% - 3% aluminium, 2% - 2.5% chromium and 1.5% - 2% molybdenum. From this ranges, four different alloys of grey cast iron were formulated. These include Fe-3% Al-2.5% Cr-2% Mo, Fe-3% Al-2% Cr-2% Mo, Fe-3% Al-2.5% Cr-1.5% Mo and Fe-3% Al-1.5% Cr-2% Mo.

Charge calculation was carried out to determine the amount of alloying elements in gram to be added. The formula used is as shown in equation 1 in line with the work done by Soiński and Ziółkowska [12] [13]. The calculated amount of each of the alloying elements is as shown in **Table 1**.

$$\begin{pmatrix}\text{Amount of Alloying}\\ \text{Element to be added}\end{pmatrix} = \frac{\left(\begin{matrix}\text{Required}\\ \text{Amount}\end{matrix}\right) - \left(\begin{matrix}\text{Amount in}\\ \text{the base metal}\end{matrix}\right) \times \left(\begin{matrix}\text{Total wt. of}\\ \text{the Charge}\end{matrix}\right)}{\text{Purity of the Alloying Element}} \tag{1}$$

2.1. Melting

Indirect electric arc furnace of 2 Kg capacity was used for the melting. The required quantities of the charging materials were weighed using weighing balance and charged into the furnace. Grey cast iron scraps were first charged and heated to the temperature of 1140˚C before the addition of alloy elements. Carbon (II) tetrachloride powder was added as a degasser. Nitrided Ferro-manganese (Fe-75% MnN) was added to enrich the nitrogen content of the melt as well as to neutralize the harmful effect of the sulphur [3]. Pouring was done at 1350˚C into a sand mould. The cast alloys were 12 mm diameter by 180 mm length of rods.

2.2. Ageing Treatment

During ageing, samples were heated to 900˚C, soaked for 30 minutes and transferred into salt-bath held at ageing temperature of 150˚C, 200˚C, 250˚C, 300˚C and 350˚C for forty-eight hours [1].

2.3. Tests

Tests carried out on as-cast alloys as well as aged samples are:

a) Chemical Analysis

Spetro-CJRO Arc-Spectrometer was used. Test piece whose surface was ground to ensure flatness was mounted on the sparking point of the spectrometer and the button was pressed. After 30 – 40 seconds composition was displayed on the monitor screen [14].

b) As-Cast Microstructural Analysis

Metallurgical microscope model STN 42 was used. It was equipped with a CCD camera connected to a computer for image capturing. Specimen was polished with 180, 240, 320, 400 and 600 grit paper revolving at 150 rpm for 55 seconds. They were then etched with nital (4% nitric acid and 96% alcohol) for two minutes. The microstructures and phases were estimated by visual examination and compared with AFS microstructural rating chart [14].

c) Hardness Test

Wilson Rockwell hardness tester scale C model D.G 201-1 was used. The minor load was 10 Kg and the major load was 150 Kg. The minor load was applied by placing the specimen on the anvil and moved up until specimen come in contact with the indenter. At this point, the dial gauge moved to zero graduation. Then the major load was applied. Three points hardness was measured and the average was taken [1].

d) Impact Test

Charpy method was used. Specimen of square cross-section of 10 mm by 10 mm and 50 mm long notched at the midpoint was used. Sample was placed in a vise as a beam fixed at the two ends and hit behind the V-notch by 75 Kg pendulum. The energy absorbed was read from the dial scale [14].

Table 1. Calculated amount of alloying element added.

Elements	2.5% Al	3% Al	1.5% Cr	2% Cr	2.5% Cr	1.5% Mo	2% Mo
Amount added	55.5 g	67.8 g	49.5 g	66 g	82 g	61 g	100 g

e) Tensile Test

Universal table-top tensiometer of model KPL 2000-1 with self-aligned Instron 8800 digital controlled panel was used. The dimension of the test piece was 9 mm diameter and 36 mm gauge length. The test specimen was gripped at the two ends and was pulled until fracture [1].

3. Results and Discussions

3.1. Chemical Analysis

Table 2 shows the chemical composition of the base metal (grey cast iron) and alloying elements used for this work. From the **Table 2**, it was observed that the grey cast iron contains majorly 3.60% C, 2.30% Si, 0.90% Mn, 0.20% P and 0.1% S with carbon equivalent of 4.43. It is hypereutectic because, cast iron having carbon equivalent below 4.3% is hypoeutectic while above 4.3% is hypereutectic [10]. It is a class 30 grey cast iron because the base composition to achieve a nominal class 30 grey cast iron, is 3.4% - 3.7% C, 0.06% - 0.15% S, 2.1% - 2.6% Si, 0.45% - 1.0% Mn, 0.03% - 0.2% P, 0.03% - 35% Cu and 0.004% - 0.08% Cr [8]. Ferro-chromium contains 67% Cr purity; ferro-molybdenum contains 55% Mo purity and aluminium contains 96.93% Al purity. According to ASTM unified numbering system (UNS), this aluminium belongs to 2024 series.

Table 3 shows chemical composition of the produced alloys. The addition of alloying elements (Al, Cr and Mo) have affected the chemical composition of the base metal (grey cast iron). There was reduction in the content of major nominal alloying elements of grey cast iron such as carbon, silicon, sulphur and phosphorus. The reduction of carbon, silicon and phosphorus contents lowered the carbon equivalent therefore, change the structures from the hypereutectic to hypoeutetic. This gives rise to the formation of pearlite that accommodate other phases such as nitrides and carbides [3] [10]. It is the presence of these phases in pearlitic matrix that lead to improvement in mechanical properties such as hardness, toughness, UTS and wear resistance [3]. On the addition of alloying elements, carbon was reduced from 3.60% to 3.43%. Silicon was reduced from 2.50% to 2.30% and phosphorus from 0.20% to 0.15%. With this composition, the carbon equivalent has been reduced from 4.43 to 4.25. The alloys have become hypoeutectic [15]. As-cast microstructure changed from hypereutectic to hypoeutectic with the increase of alloying element [15]. It was also noticed that the nitrogen content was increased to 0.500%.

Table 2. Chemical composition of the base materials used for the work.

Materials	Chemical Composition (%)												
	Fe	C	Si	Mn	P	S	Cr	Mo	Al	N	Cu	Ti	Mg
GCI	92.89	3.60	2.50	0.90	0.20	0.10	0.004	0.002	0.001	0.002	0.003	0.001	-
Fe-Cr	30.43	4.50	2.50	0.01	0.03	0.03	67.00	0.002	0.001	0.001	-	0.001	-
Fe-Mo	42.09	0.15	2.50	0.02	0.10	0.15	0.001	55.00	0.001	0.001	-	0.001	
Fe-MnN	15.78	0.15	1.00	75.0	0.05	0.02	-	-	0.002	8.00	-	0.001	-
Al	-	-	0.001	0.02	-	-	-	-	96.93	0.001	3.00	0.001	0.04

Table 3. Chemical composition of the produced alloys.

Alloys No	Chemical Composition (%)											
	C	Si	Mn	P	S	Mg	Mo	Al	N	Ti	Cr	Fe
1	3.43	2.31	1.041	0.15	0.102	0.02	2.000	2.990	0.50	0.004	1.510	bal
2	3.43	2.30	1.041	0.15	0.102	0.02	1.500	3.000	0.50	0.004	2.501	
3	3.43	2.30	1.041	0.15	0.102	0.02	2.000	3.001	0.50	0.004	2.010	
4	3.44	2.30	1.041	0.15	0.102	0.02	2.001	3.001	0.50	0.004	2.501	

As-Received Microstructure of the Base Metal

Figure 1 shows the micrograph of the base metal used for the work. The grain particles are mostly made up of graphite flakes in pearlitic matrix. Microstructures consist of dark graphite existing in the form of flakes, which reside inside ferrite or pearlite matrix. The micro-structure represents a typical grey cast iron with large volume of soft graphite flakes embedded in the matrix of the microstructure [16]. The phases present are graphite flakes, cementite, pearlite and ferrite.

As-Cast Microstructures

Figures 2-5 show the as-cast microstructures of the produced alloys. On the addition of alloying elements, the morphology of the graphite flakes changed. Aluminium does more of grain refinement and nitride forming while chromium and molybdenum form carbides and decrease the volume of the graphite flakes. With addition of molybdenum and chromium, hypoeutectic grey cast iron with uniform distribution of randomly graphite flakes were revealed [17]. The addition of chromium decreases the volume of the graphite flakes and formed carbides [3]. It changed the microstructures from hypereutectic to hypoeutectic and changed a ferritic matrix of partially transformed austenite to pearlitic matrix of entirely transformed martensite [17]. The beneficial synergistic effect of these alloying elements is that, addition of chromium can form very hard and brittle carbides because of

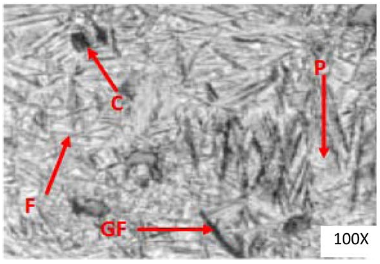

Figure 1. Micrograph of the base metal (grey cast iron). C = Cementite, P = Pearlite, GF = Graphite Flake, F = Ferrite.

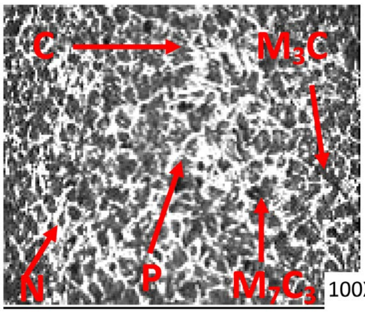

Figure 2. Micrograph of as-cast grey cast iron alloy (F-3% Al-2.5% Cr-2% Mo). C = Cementite, N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

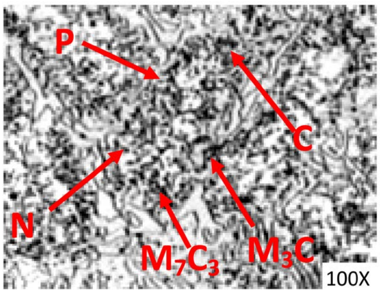

Figure 3. Micrograph of as-cast grey cast iron alloy (F-3% Al-2% Cr-2% Mo). C = Cementite, N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

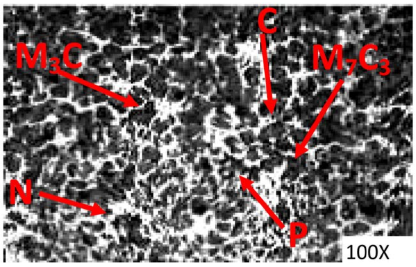

Figure 4. Micrograph of as-cast grey cast iron alloy (F-3% Al-2.5% Cr-1.5% Mo). C = Cementite, N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

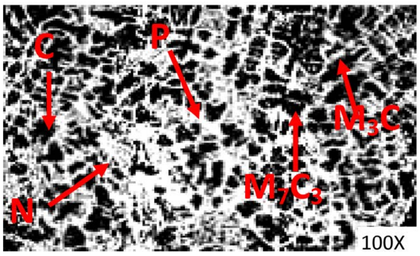

Figure 5. Micrograph of as-cast grey cast iron alloy (F-3% Al-1.5% Cr-2% Mo). C = Cementite, N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

its high chilling power [3]. Addition of aluminium and molybdenum in conjunction with chromium can neutralize this chilling power by refining carbide phases, reducing inter-carbides spacing, improving carbide morphology and distribution [18].

3.2. Microstructures of the Produced Alloys after Ageing

Figures 6-9 show the microstructures of the produced alloys after ageing treatment. There are two major types of precipitates in terms of morphology in each case. The first ones are tiny and finely dispersed precipitates which are intermingled with somehow coarse particles within the same matrix. The tiny and finely dispersed particles may likely be nitrides, specifically aluminium nitrides, iron nitrides and others that may be formed from chromium and molybdenum because all carbide formers are also nitride formers [7] [19]. The second ones are the coarse particles that are likely to be carbides formed by chromium and molybdenum and even iron. Ageing occurs by precipitation of nitrides and carbides from solid solution [7]. Molybdenum additions altered the lattice misfit between the precipitates and the ferrite matrix and also stabilized the spherical morphology of the precipitates. The segregation of molybdenum to the precipitate-matrix interface was responsible for this stabilization of these phases through changes in the interfacial energy and surface stress [15]. The addition of these alloying elements promotes the formation of nitrides and carbides of different phases such as primary carbide (M_3C), eutectic carbide (M_7C_3) and secondary carbide ($M_{23}C_6$). During ageing these phases are precipitated and evenly dispersed throughout the matrix to offer resistance to dislocation motion thereby improves the mechanical properties according to Anish [8]. The strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix through Precipitation Hardening or Age Hardening [16].

As-Cast Mechanical Properties

Table 4 shows as-cast hardness, impact toughness, UTS, and wears resistance of the produced alloys. The alloys with the compositions of (Fe-3% Al-2.5% Cr-2% Mo, Fe-3% Al-2% Cr-2% Mo, Fe-3% Al-2.5% Cr-1.5% Mo and Fe-3% Al-1.5% Cr-2% Mo have as-cast hardness of 65.1 HRc, 64.5 HRc, 60.6 HRc and 56.8 HRc respectively, as-cast impact toughness of 47 J, 42 J, 38.9 J and 38.2 J respectively, as-cast UTS of 899.1 $N \cdot mm^{-2}$, 876.5 $N \cdot mm^{-2}$, 867.4 $N \cdot mm^{-2}$, and 856.2 $N \cdot mm^{-2}$, respectively. The as-cast stress/strain curves showed only the elastic region and do not show the plastic region which is the characteristic of cast iron [3] [10].

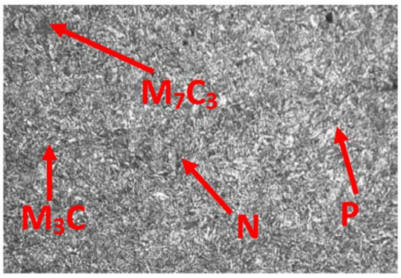

Figure 6. Micrograph of grey cast iron alloy (F-3% Al-2.5% Cr-2% Mo) aged at 300˚C for four hours. N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

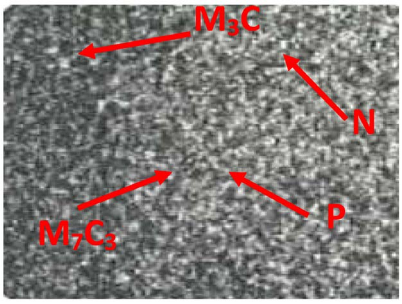

Figure 7. Micrograph of grey cast iron alloy (F-3% Al-2% Cr-2% Mo) aged at 300˚C for four hours. N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

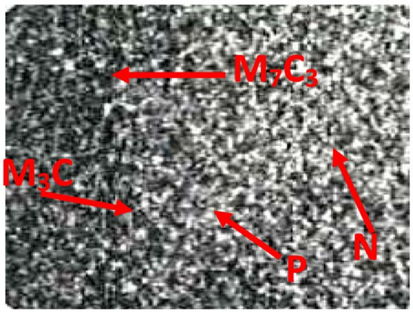

Figure 8. Micrograph of grey cast iron alloy (F-3% Al-2.5% Cr-1.5% Mo) aged at 300˚C for four hours. N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

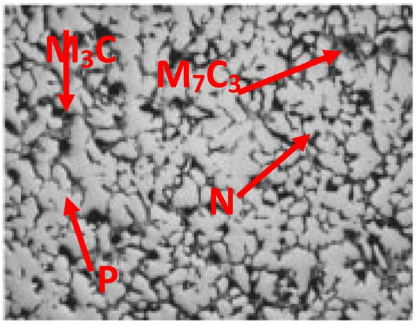

Figure 9. Micrograph of grey cast iron (F-3% Al-1.5% Cr-2% Mo) aged at 300˚C for four hours. N = Nitride, P = Pearlite, M_3C = Primary carbide, M_7C_3 = Eutectic carbide.

Table 4. As-cast mechanical properties.

Grey Cast Iron Alloys	Hardness (HRC)	Impact Toughness (J)	Ultimate Tensile Strength ($N \cdot mm^{-2}$)
Fe-3% Al-1.5% Cr-2%% Mo	56.8	38.2	856.2
Fe-3% Al-2.5% Cr-1.5%% Mo	60.6	38.9	867.4
Fe-3% Al-2% Cr-2%% Mo	64.5	42	876.5
Fe-3% Al-2.5% Cr-2%% Mo	65.1	47	899.1

3.3. Hardness of the Aged Alloys

Figure 10 shows variation of hardness with ageing temperature for the aged alloys. There was decrease in hardness values with increasing temperature at the lower ageing temperatures between 150˚C and 210˚C above which the hardness increases with increasing temperature up to 310˚C at which the maximum hardness was obtained for each of the alloys. The decrease in hardness at the lower aging temperature may be attributed to slow nucleation rate of the precipitates which delays the formation of stable phases [1] [20]. At high temperature, the precipitated particles are found at the grain boundaries while at lower temperature, the precipitate particles are located in the matrix where the entanglement to dislocation is less [5].

3.4. Impact Toughness of the Aged Alloys

Figure 11 shows the impact toughness values for aged alloys. The impact toughness increases with initial ageing temperature up to 210˚C after which there was little decrease for all the alloys. At 250˚C the toughness started increasing again. The phenomenon of increasing and decreasing of toughness is due to lower hardness values recorded at the initial ageing temperature. Where the hardness is lower the impact toughness is higher and verse versa [18]. It was observed that all the alloys respond to age strengthen as the hardness, impact toughness and ultimate tensile strength after ageing were higher in each alloy than as-cast. Addition of aluminium, chromium and molybdenum to gray cast iron has great effect on the micro-structure of gray cast iron.

3.5. Ultimate Tensile Strength of the Aged Alloys

The UTS increases with ageing temperature and reached its maximum values at the ageing temperature of 310˚C for all the alloys except alloy Fe-3% Al-2.5% Cr-2% Mo which continue to increase with the ageing temperature as shown in **Figure 12**. The stress/strain curves showed little plastic behaviours after ageing treatment compared to as cast stress/strain curves. Stress/strain curves after ageing treatment exhibit both elastic and plastic regions [8]. There is increase in hardness, impact strength, and ultimate tensile strength due to multiple precipitates of different phases with different orientations (nitrides are precipitated interstitially while carbides are precipitated substitutionally within the same matrix). These elements; aluminium, chromium and molybdenum hold carbon and nitrogen in close associations and generate internal friction which results in the substitutional versus interstitial dipoles that can strongly impede the dislocation [9].

3.6. Properties Comparison of Produced Alloys after Ageing and the Commercial Machine Cutting Tools

Table 5 and **Table 6** showed the properties of produced grey cast iron alloys after ageing and the range of properties of the commercial machine cutting tools. Comparing **Table 5** with **Table 6** show that machine cutting tools manufactured from the produced alloys will compete favourably with high speed cutting tool (HSS), cast cobalt alloy cutting tool, tool steel, and cemented carbide tools under the same condition. Wear resistance has a direct correlation with harness property of the materials since the harder the material, the high the wear resistance [11]. In terms of cost analysis, the method adopted for the production of machine cutting tools in this work is simple and less costly than the conventional methods. The grey cast iron scrap which is the major raw material in this work is easily available and cheaper compared to conventional cutting tool materials such as diamond, tungsten carbide, cobalt, high alloyed steel etc.

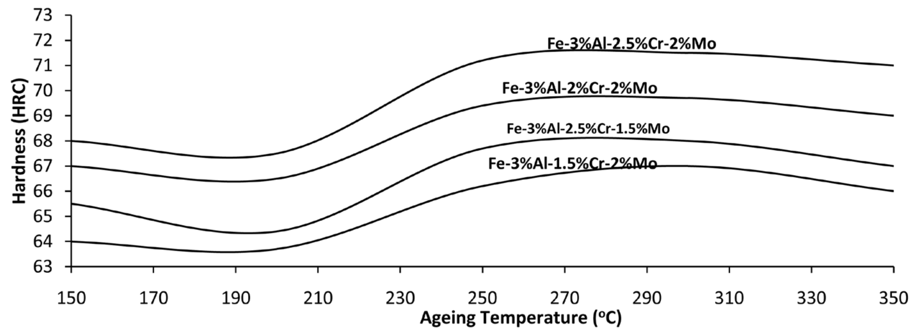

Figure 10. Variation of hardness with ageing temperature of the produced alloys.

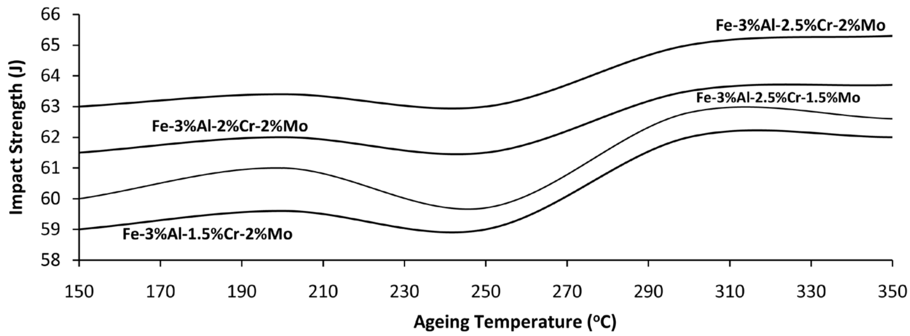

Figure 11. Variation of impact strength with ageing temperature of the produced alloys.

Table 5. Properties of the produced alloys after ageing.

S/N	Alloys	Hardness (HRc)	Impact Toughness (J)	UTS ($N\cdot mm^{-2}$)
1	Fe-3% Al-2.5% Cr-2% Mo	71.5	66	1380
2	Fe-3% Al-2% Cr-1.5% Mo	69	63.6	1311
3	Fe-2.5% Al-2.5% Cr-2% Mo	66.5	62	1260
4	Fe-2.5% Al-2% Cr-1.5% Mo	65.4	60.3	1190

Table 6. Range of properties for the commercial machine cutting tools.

Cutting Tool Materials	Properties			
	Hardness (HRc)	UTS ($N\cdot mm^{-2}$)	Toughness (J)	Wear resistance $cm^{-2} \times 10^6$
Carbon tool steel	55 - 65	1125 - 1290	46 - 50	3.0 - 5.0
High cobalt steel (HSS)	67 - 70	1130 - 1300	47 - 56	4.3 - 5.2
Cast cobalt alloys	65 - 68	1100 - 1200	54 - 60	4.8 - 5.5
Cemented carbide	86 - 90	1300 - 1400	52 - 57	4.0 - 5.7
Ceramic	87 - 93	1345 - 1450	56 - 60	5.3 - 6.0
Cermet	90 - 94	1455 - 1480	60 - 65	5.0 - 7.0
Cubic boron nitride (CBN)	91 - 95	1490 - 1500	60 - 67	6.0 - 7.5
diamond	95 - 100	1500 - 1545	56 - 70	6.5 - 8.0

Courtesy of Stephenson and Agapiou (1997).

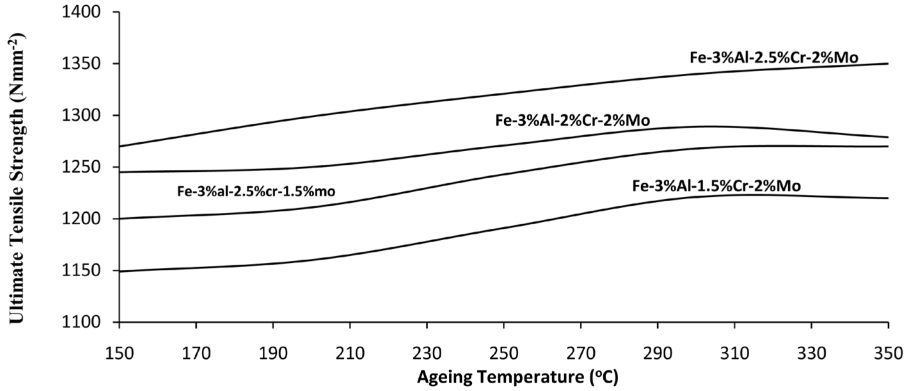

Figure 12. Variation of ultimate tensile strength with ageing temperature of the produced alloys.

4. Conclusions

The following conclusions were drawn from the research work:

1) Overall research work provided more information on the age strengthening of grey cast iron alloys.

2) The study has established the development of alloys from grey cast iron for machine tools industries.

3) Alloying and age strengthening mechanism can be used to produce alloys of grey cast iron with improved strengths that has reduced rate of tool wear.

4) Machine cutting tools can be produced locally to reduce the over dependence of the foreign ones in our machine industries which will go a long way to encourage indigenous technology.

5) It has been discovered that grey cast iron alloys containing 2.5% - 3% aluminium, 2% - 2.5% chromium and 1.5% - 2% molybdenum are suitable for cutting tools manufacturing.

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