July – August 2020
ISSN: 0193-4120 Page No. 10 - 16

Preliminary Study on Mechanical Response and Microstructural Evolution of Al-Cr Alloy under Varying Heat treatment Conditions

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Abstract

High performance materials are known to enhance the economy of production due to their ability to withstand desired engineering applications. In view of this, Al-Cr alloy with varying amounts of chromium was developed using two-step stir-casting method.The suitable volume fraction for various Al alloy and Cr combination were 99.5Al-0.5Cr, 99Al-1Cr, 97Al-3Cr and 94Al-6Cr. 99.5Al-0.5Cr alloy which relatively best mechanical properties was selected and subjected to solution heat treatment at 450°C for 20 minutes and also aged at various temperatures (120, 130, 150, 160 and 170 °C) for 45 minutes. The mechanical response (ultimate tensile strength, hardness and impact) of the as cast (un heat treated) alloys were investigated. The ultimate tensile strength (UTS), hardness and microstructure of the artificially aged 99.5Al-0.5Cr alloy were further investigated. The microstructure of 99.5Al-0.5Cr alloy was examined using Optical Microscope (OPM). Among the as cast alloys, the 99.5Al-0.5Cr alloy exhibited the highest UTS and hardness values of 106.93MPa and 58.3 Kgf/mm^2, respectively. Maximum UTS and hardness values of 123.46 MPa and 89.7 Kgf/mm^2 , respectively were obtained for 99.5Al-0.5Cr alloy at 160 °C of artificial aging, which showed that the aging effect increased the UTS, hardness and impact strength values of 99.5Al-0.5Cr alloy by15.63 , 53.90 , and 39.39%, respectively. The 99.5Al-0.5Cr alloy artificially aged at 160 °Cexhibited the highest impact strength value of 22.44 J/mm^2 among other samples. The agehardening noticed in 99.5Al-Cr0.5alloy was ascribed to the hardening effect of heat and precipitation ofintermetallic chromium as revealed bythe OPM micrograph. The outcome of this study has shown that chromium alloying element has potentials for improving mechanical properties and the benefits of aged hardening effect on Al-Cralloy can be explored for various industrial applications.

Keywords:*Al-Cr alloy, Ultimate tensile strength, Hardness, Impact strength and Microstructure*

I. INTRODUCTION

The modern evolution in the field of technology necessitates the development of advance engineering materials for diverse engineering applications, particularly in the field of aerospace, maritime, automotive and military engineering related [1, 2]. These areas require materials singularly with high strength, light weight and superior tribological characteristics. Such requirements can only be met by combining the properties of two or more alloys or alloying elements such as Al and Cr [3-5]. High-performance aluminium alloys have been the subject of intensive research in the past few years [6, 7]. Research efforts have been concentrated on the development of new compositional materials with improved properties, as well as on the

July – August 2020
ISSN: 0193-4120 Page No. 10 - 16

development of processing techniques capable of improving the behaviour of conventional alloys and producing new alloys with extraordinary characteristics [8, 9]. The major drawback of the available lightweight materials is either their limited propertiesor high production cost. Thus, continuous efforts are being made by researchers to develop new types of lightweight alloys, which are low in cost and capable of meeting properties requirements [10-12]. Nowadays, aluminum and its alloys are the most commonly used non-ferrous materials for engineering applications due to their outstanding properties such as good strength to weight ratio, excellent ductility, remarkable corrosion resistance, accessibility and low cost [13-15]. These unique properties have been further improved via the addition of other alloying elements and heat treatment [16, 17].

The inclusion of selected alloying elements such as Si, Mg, Zn, Zr, Ni and Mn in small amount to aluminum alloys have reportedly enhanced their properties and usefulness [18, 19].Some researchers have also reiterated the microstructural modifying effect, mechanical properties, formability, and corrosionresistance improvement of these alloying elements, which also combine with aluminum alloys to promote the heat-resistant and thermal stability of the resulting structure [20, 21]. Therefore, this present study examines the mechanical properties and microstructures of as cast and heat treated Al-Cr alloys. The influence of the Cr reinforcement in the Al alloy was largely exploited.

II. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1. Raw materials

Aluminium alloy was used as the base metal for the alloy. Thealloy was sourced from scraps (mostly car engine parts). This decision was intuited out of the desire to recycle aluminium waste in our environment for different engineering applications.The chemical composition of the resulting aluminium alloy after solidification of the molten scraps was determined using X-ray fluorscence machineas presented in Table 1. The chemical composition largely conformed to that of AA 1120 alloy. Chromium was procured from William Rowland Ltd, Sheffield, United Kingdom.

Table 1: Chemical composition of Al (AA 1120) alloy (wt. %)

Element	Fe	Cu	Pb	Ni	Zn	Al
wt. %	0.4050	0.8320	0.0060	0.4780	0.0045	98.1920

2.2. Casting Mould and Al - Cr alloy production process

Green sand mould containing clay as binder was used to prepare the Al-Cr alloys cast in this work. The cavities where the molten Al-Cr alloys solidify were prepared with patterns made of steel. The pattern was lubricated for good surface finish and effortless removal of the cast from the mould. The Al-Cr alloys were produced using the liquid metallurgy route (two step casting technique). The constituents were charged in the proportion shown in Table 2. Mass of Al alloyfor each of the charges was 500 g, while those of Cr ranges from 2.51 to 31.9 g. The chromium powder was preheated in a furnace at a temperature of 750 °C. To aid wettability, the aluminium alloys were also preheated at a temperature of 350 °C for 30 minutes.

Table 2: Weight percentage of Al and Cr in Al-Cr Alloys (Charge Calculations)

S/N	Al-Cr Alloy	Al alloy (%)	Cr (%)	Weight of Cr (g)
1	99.5Al-0.5Cr	99.5	0.5	2.51
2	99Al-1Cr	99.0	1.0	5.05
3	97Al-3Cr	97.0	3.0	15.46
4	94Al-6Cr	94.0	6.0	31.90

The Al alloys were positioned in crucible and placed in furnace at temperature of 780 °C using tongs. After about 20 minutes, a uniform liquefied alloy was achieved. The preheated chromium powders were then introduced into the crucible containing the liquefied Al alloy. The mixture was returned to electrical stirring furnace and reheated for 15 minutes at 300 rpm until indistinguishable molten mixture was accomplished. At the finishing stage of mixing, the furnace temperature was retained at 780 °C. Slags were removed from the molten metal and poured into the prepared mould cautiously. This was left for about 20 minutes to enable solidification and dissipation of heat from the cast. The moulds were broken to obtain the Al-Cr alloys cast, cooled at room temperature and prepared for characterisation.

July – August 2020
ISSN: 0193-4120 Page No. 10 - 16

2.3. Characterisation of the Cast Al-Cr alloy Samples

Tensile strength of samples was characterised using Universal Instron Machine. The hardness of the cast was investigated using Brinell hardness tester, while the impact strength of the various samples was determined using a pendulum-type impact strength testing machine. Six other specimens of 94Al-0.5Cralloy in as cast condition were further subjected to heat treatment at 450 ℃ for 20 minutes. They were thereafter artificially aged at varying temperature of 120, 130, 140, 150, 160 and 170 ℃, at constant holding time of 45 minutes and allowed to cool in natural air. The microstructural examinations were carried out with the aid of Optical Microscope (OPM).

2.3.1. Tensile strength test

Tensile strength test was carried out in accordance with ASTM E8. The specimens were machined using lathe machine and thereafter shaped into standard test piece size dog bone shape of diameter, gauge length and length 4.32 mm, 28.4 mm and 100 mm, respectively. One end of the specimen was fastened to the frame of the Universal Instron Machine by means of grips, while the other end was similarly fixed to the movable cross head. A steadily increasing load was applied to the specimen by pulling the hand wheel of the machine in a clockwise direction. The magnitude of the load was measured by the pointer on the load measuring unit. The yield point was measured on the pointer when the mercury stopped moving in the forward direction for a short while. On further increase of the load, the pointer got to the ultimate load and at that point, the pointer moved in the reverse direction and stopped at a point to cause a fracture of the specimen. Thereafter, the fractured specimens were arranged together and the final length and diameter of each specimen were measured. More so, the average tensile strength values were calculated.

2.3.2. Brinell hardness test

For the purpose of this test, various specimens of the Al-Cr alloys were machined to cylindrical shapes with length of 30mm and diameter 8mm. Each specimen was polished to remove any surface defects from the sand casting process. The indenter standard steel ball is of diameter 10mm and the mercury gauge was set to zero as the reference point on the Brinell hardness machine. The indenter was then pressed on the surface of the specimen by gradually applying load by rotating the hand wheel of the machine in the clockwise direction till the mercury gauge read 225 Kgf and was left on this position for about 15 seconds. The diameter of the indentation on the specimen was measured after the load and ball were removed. The hardness of the samples was obtained in accordance with ASTM A29/A29M-15. The Brinell hardness numbers of the samples were then calculated using equation 1[22].

$$\mathrm{BHN} = \frac{2P}{\pi d(d-\sqrt{(d^2-D^2)}} \qquad (1)$$

Where, d and D are the diameter of the steel ball and the diameter of indentations left by the test ball, respectively. P is the applied force on the indenter.

2.3.3. Impact strength test

Impact strength which is the capacity of material to resist or absorb shock energy before the sample's fractures was tested on each specimen in accordance with ASTM D256, after cutting them to a standard test piece size of diameter 10mm and length 120mm. A groove of 2mm was notched on each specimen to help the specimen fit into the machine. The specimens were fixed to the machine and the pendulum was allowed to fall from a fixed starting point of a known height to fracture or deform the specimen. When the pendulum was released from the maximum height position, the pointer on the scale also moved along with the pendulum and stopped, indicating the impact strength. At that point, the specimens were already fractured.

2.3.4. Metallographic examination

Metallographic assessment was done in order to investigate the microstructure of the alloys produced. Specimens for metallographic examination were highly polished and then etched with etchants (solution containing 2 % sodium hydroxide). This treatment was carried out to reveal the grain structure. Accuscope Microscope coupled with camera of magnification 400X was used for optical microscopy.

III. 3. RESULTS AND DISCUSSIONS

3.1. Ultimate Tensile strength (UTS) of Al-Cr alloy Samples

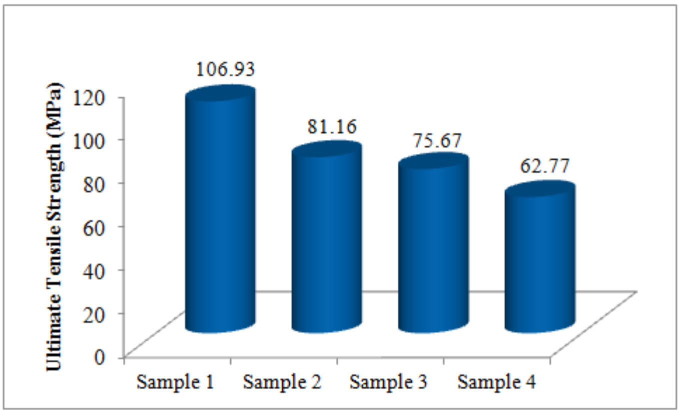

Figure 1: Ultimate Tensile Strength of as cast Al-Cr alloy samples

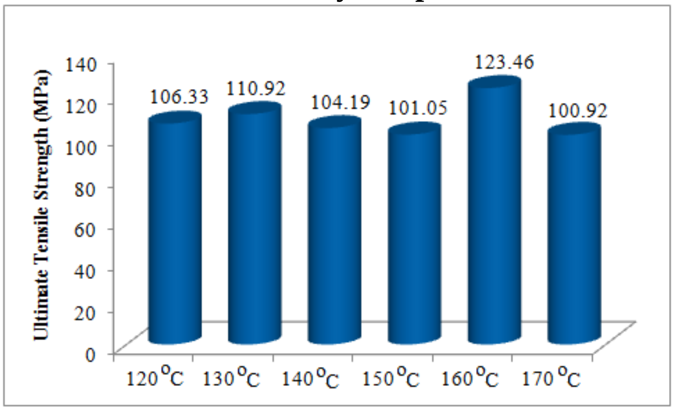

Figure 2: Ultimate Tensile Strength of artificially aged 99.5Al-0.5Cr alloy

Figure 1 describes the UTS of as cast Al-Cr alloys samples. Sample 1 (99.5Al-0.5Cr alloy) exhibits the highest UTS among the test samples and this reduce as the percentage concentration of chromium increases. The reduction in ultimate tensile strength as the concentration of chromium increase could be ascribed to the probable decline in synergy between Al alloy and the molecules of chromium [23]. The ultimate tensile strength of 99.5Al-0.5Cr alloy was 106.93 MPa while the lowest UTS value of 62.77 MPa was attained for sample 4 (94Al-6Cr alloy), despite having the largest percentage addition of chromium. This indicated that 99.5Al-0.5Cr alloy offered higher restrain to peripheral pulling compared to other samples [24, 25]. The UTS of six heat treated specimens are indicated in Figure 2. The ultimate tensile strength decreases slightly at 120 °C from 106.93 MPa to 106.33 MPa, but increased marginally by higher percentage at 130 °C. Reduced UTS was however recorded at 140 and 150 °C. The UTS value increase to 123.46 MPa at 160 °C, which represents 15.63 % increment, relative to the as cast samples. This increment is significant and makes it a reasonable material that can be exploited for advance application [25].

3.2. Brinell hardness of Al-Cr alloy Samples

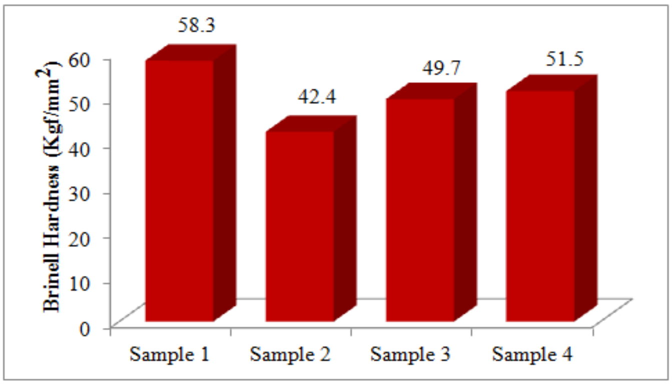

Figure 3: Brinell hardness of as cast Al-Cralloy samples

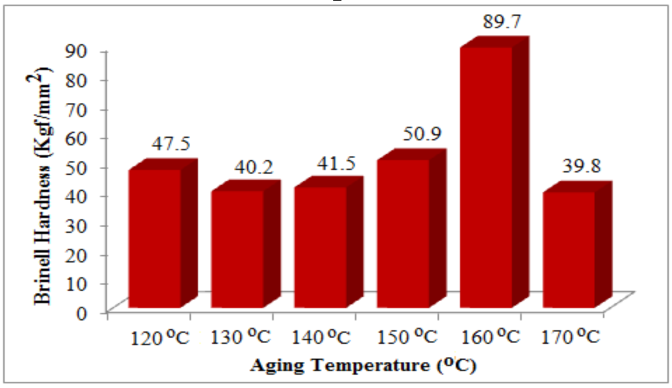

Figure 4: Brinell hardness of artificially aged 99.5Al-0.5Cr alloy

The Brinell hardness of as cast Al-Cr alloy samples is shown in Figure 3. Sample 1 (99.5Al-0.5Cr alloy) displayed the maximum hardness value of 58.3 Kgf/mm^2. The hardness value reduced to 42.4Kgf/mm^2 on the inclusion of 1% chromium into the matrix of Al alloy, but increased to 49.7 Kgf/mm^2 for 97Al-3Cr alloy and 51.5 Kgf/mm^2 for 94Al-6Cr alloy. The hardness values of as cast Al-Cralloy were generally reasonable. However, the hardness of six specimens from 99.5Al-0.5Cr alloy heat treated at 450 °°C for 20 minutes and further aged at varying temperatures of 120 , 130, 140 , 150 , 160 and 170 °C, at constant holding time of 45 minutes and allowed to cool in natural air , indicated in Figure 4 revealed that noteworthy hardness value of 89.7 Kgf/mm^2 was observed at

160 °C. The difference between the hardness value of as cast and heat treated 99.5Al-0.5Cr alloy depict 53.9 % increase. This increment underscores the significance of heat treatment and aging to which the specimen was subjected. Aging process had been reported to promote hardness due to the precipitates of alloying elements that hinder the movement of the dislocations [26, 27].

3.3. Impact Strength of Al-Cr alloy Samples

The impact strength of Al-Cr alloy samples, indicating the amount of energy each alloy sample could withstand when sudden loads were applied is shown in Figure 5. Comparing all the samples, it was observed that sample 1 (99.5Al-0.5Cr) that was artificially aged at a temperature of 160 °C was able to exhibit best ability to withstand load. The observed impact strength was 22.44 J/mm^2 as compared to the as cast form of 99.5Al-0.5Cralloy with impact strength value of 8.84 J/mm^2. 94Al-6Cr alloy displayed the lowest impact strength value of 8.30 J/mm^2, Although the influence of aging treatment on the impact of Al-Cr alloy was significant, it was however noted that all the samples were found to exhibit good impact strength due to the strengthening ability of Cr in matrix of Al alloys [28].

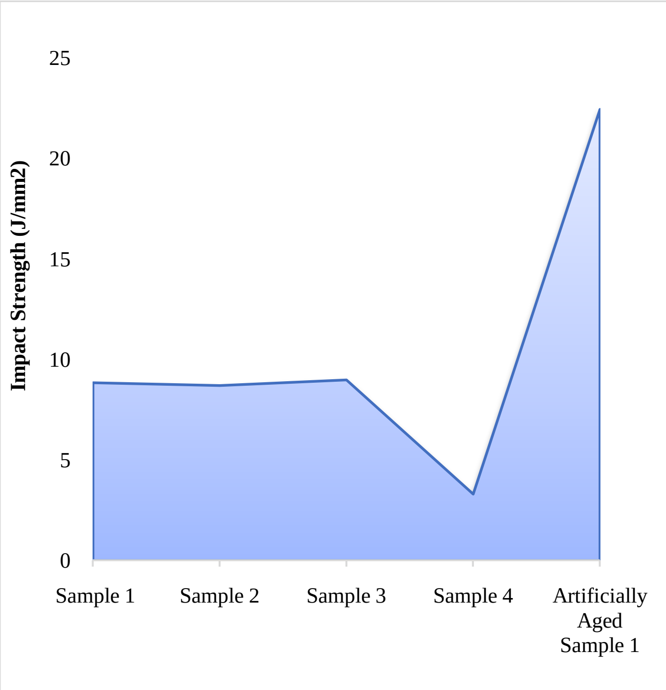

Figure 5: Impact strength of Al-Cr alloy samples

3.4. Microstructural Characteristics of Al-Cr alloys via OPM

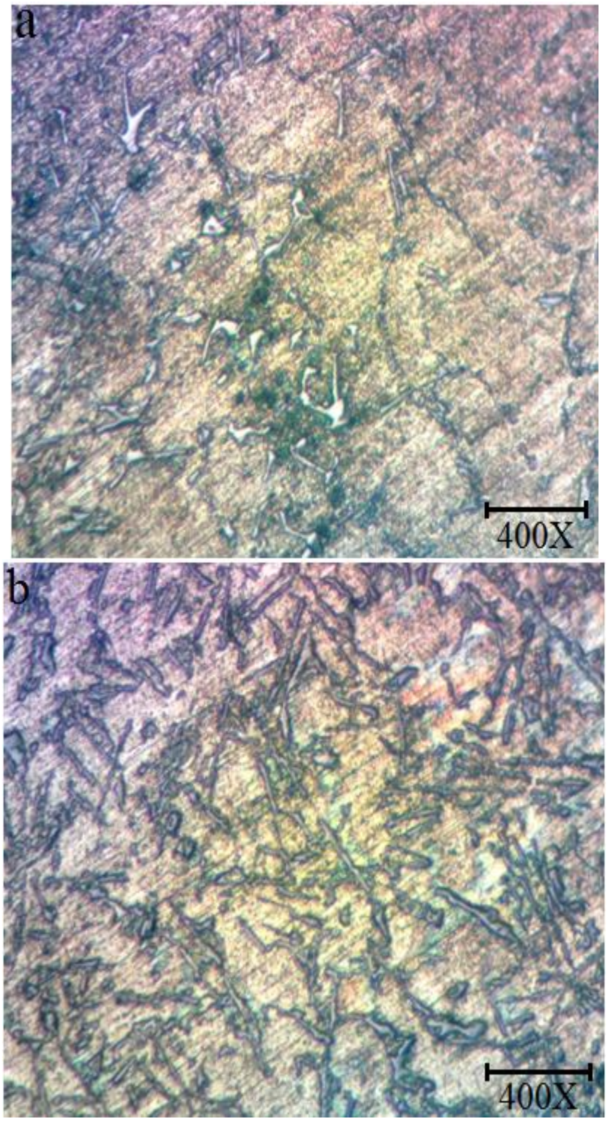

Figure 6: OPM micrograph of (a) Solution heat treated 99.5Al-0.5Cr alloy at 450 °C (b) artificially aged 99.5Al-0.5Cr alloy at 160 °C.

Figure 6 (a & b) show the OPM micrograph of solution heat treated of 99.5Al-0.5Cr alloy at 450 °C and subsequent artificially aged 99.5Al-0.5Cr alloy at 160 °C, respectively. Figure 6(b) showed rougher morphology and darker coloration than Figure 6(a). This could be attributed to the agehardening effect of heat on 99.5Al-0.5Cralloy and precipitation ofintermetallic chromium in its matrix. The porosity and clefts on the surface of Figure 6(b) could not have gone deeper due to the high hardness and tensile strength it exhibits. The appropriate interfacial bonding and reasonable grain size as revealed in the micrograph of Figure 6(b) could be the reason for the excellent mechanical performance of 99.5Al-0.5Cr alloy at the 160 °C artificial aging [29], with significantly dissimilar microstructure compared to the OPM micrograph in Figure 6(a). Micro-segregations produced when 99.5Al-0.5Cr alloy was steadily cooled after casting, was dissolved to form homogeneous phases during heat treatment operations. As a result of age hardening heat treatment, there is formation of coarse grains dispersed precipitate of Cr in the aluminium matrix while small grains of Cr phases were formed in aluminium matrix as a result of the heat treatment operation [30]. The aging precipitated phases aid the dispersion strengthening, thus improving the mechanical properties of the alloy [26].

IV. CONCLUSIONS

The influence of Cr inclusion in Al alloy and heat treatment were investigated. Al-Cr samples were characterised based on tensile strength, hardness, impact strength, and evolved microstructures. The following conclusions are drawn from this study:

- The inclusion of Cr alloying elements in Al alloys improved the performance characteristics of the alloy.
- UTS, hardness and impact strength values improved by 15.63 %, 53.9 %,, and 39.39 %, respectively when 99.5Al-0.5Cr alloy was artificially aged at 160 °C . This is an indication that artificial aging at 160 °C enhances mechanical properties of Al-Cr alloys.
- The rough morphology and dark coloration of the artificially aged 99.5Al-0.5Cr alloy at 160 °C was attributed to the hardening effect of the heat and precipitation ofintermetallic chromium in the matrix of Al-Cr alloy.

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