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Production and Characterisation of Al-Mg-Cr Alloy for Machine Tool Applications

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Abstract

Industrialisation and technological advancement are immensely influenced by materials development and innovation. Recent studies have shown that the use of some specialised alloying elements can be explored for enhancing properties of monolithic alloys. This study focuses on the production and characterisation of Al-Mg-Cr alloy suitable for machine tool applications. Al-Mg-Cr alloy was developed using sand mould and two-step stir-casting method. Chromium was added to Al-Mg alloy at varying contents of 0.5, 1.0, 1.5 and 2.0 %. Tensile tests were carried out in accordance with ASTM E8 to determine ultimate tensile strength (UTS), percentage elongation and modulus of elasticity at varying chromium contents. The evolved microstructures were examined using an optical microscope (OPM). The study revealed that the alloy containing 1.5% chromium exhibited maximum ultimate tensile strength of 135.15 MPa and percentage elongation of 3.76 %. However, Al-Mg-Cr alloy containing 1.0% chromium exhibited best combination of UTS (123.98 MPa), percentage elongation (3.32%), modulus of elasticity (12.11 GPa) and microstructural features. Five samples of Al-Mg-1.0Cr alloy were thereafter heat treated at different temperatures from 250 ˚C to 450 ˚C. The heat treated samples were also subjected to tensile tests and optical microscopy. The results were compared with the as-cast Al-Mg-1.0Cr alloy. The results showed that heat treatment of Al-Mg-Cr alloy had adverse effect on their mechanical and microstructural properties. The outcome of this study has shown that chromium as alloying element has potentials for enhancing tensile and microstructural characteristics of Al-Mg based alloys, and the benefit can be explored for machine tool applications.

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Keywords:*Alloy, Chromium, Characterisation, Microstructure and Heat treatment*

I. INTRODUCTION

Over the past few decades, production of light and strong materials has received special attention by researchers. Aluminium based metallic alloys are regarded as superior materials with advanced properties, and are actively being sought, for engineering applications [1-3]. In recent years, Aluminum base materials have gained importance in aerospace, automotive and structural applications due to their improved mechanical characteristics, light weight and good stability at any operational condition [4-6]. Other indispensable characteristics of advanced materials are high ductility, stiffness, strength, corrosion resistance and good thermal response [7]. Aluminium alloy such as Al-Si-Mg casting alloys have been widely employed in several industrial applications, such as transport and automotive field due to its exceptional castability, high elongation and considerable strength, in particular after appropriate heat treatment [8-11].

Diverse researchers have already studied the effect of alloying elements and heat treatment on properties of alloy materials [12]. Among these are the investigation of the effect of Mg content on solidification, precipitation of AlSi7Mg casting alloy and analysis of the aging behaviour of Al-Si alloys with Mg and Cu inclusion with special interest on the precipitation process. Mg and Cu were found to have enhanced the microstructure, mechanical properties and precipitation sequences [13, 14]. Similarly, the inclusion of Cr and Mn in aluminium alloys led to improvement in mechanical properties and morphology [15, 16]. Chromium is also known to improve corrosion and stress corrosion cracking of some alloys in high temperature. The Cr addition to aluminium alloy have been discovered to form compound with β (AlFeSi) into a block-shaped Al-Si-Mn-Cr-Fe-Cu phase, which improves the morphology of the Fe phase and therefore, improved mechanical properties such as impact toughness and hardness [17].Therefore, this present study is aimed to explore the use of Mg and Cr particles as alloying elements for Al 6063 alloy, and to investigate the influence of Cr particulate addition on the mechanical properties and microstructures of the developed alloys, taking into consideration the homogeneity of the reinforcement dispersion in the alloy. The significance of this research is to examine mechanical properties and microstructures of Al-Mg-Cr alloy under the influence of varying Cr additions.

II. MATERIALS AND METHODOLOGY

2.1. Materials

Aluminium 6063 alloy was used as the base metal for the alloy. The alloy was procured from NIGALEX Nigeria Limited (NNL), Lagos State. The chemical analysis was done at NNL and it is presented in Table 1. The procured Al6063 alloy was later recast into blocks as shown in Figure 1, while magnesium powder purchased from ShoCrown Laboratory Ventures, Iwo road, Ibadan and chromium procured from William Rowland Ltd, Sheffield, United Kingdom are presented in Figure 2(a & b).

Table 1: Chemical composition of Al 6063 alloy (wt. %)

Element	Si	F	Cu	Mn	Mg	Cr	Zn	Ti	Al
wt. %	0.5344	0.2041	0.003	0.0143	0.4309	0.003	0.002	0.005	98.62

Figures 1: Blocks of Al 6063 alloy

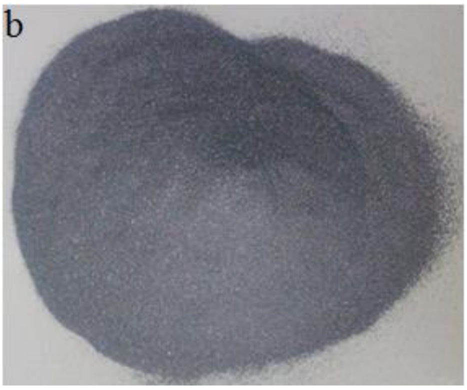

Figure 2: (a) Magnesium and (b) Chromium powders

2.2. Casting Mould and Al-Mg-Cr alloy preparation procedure

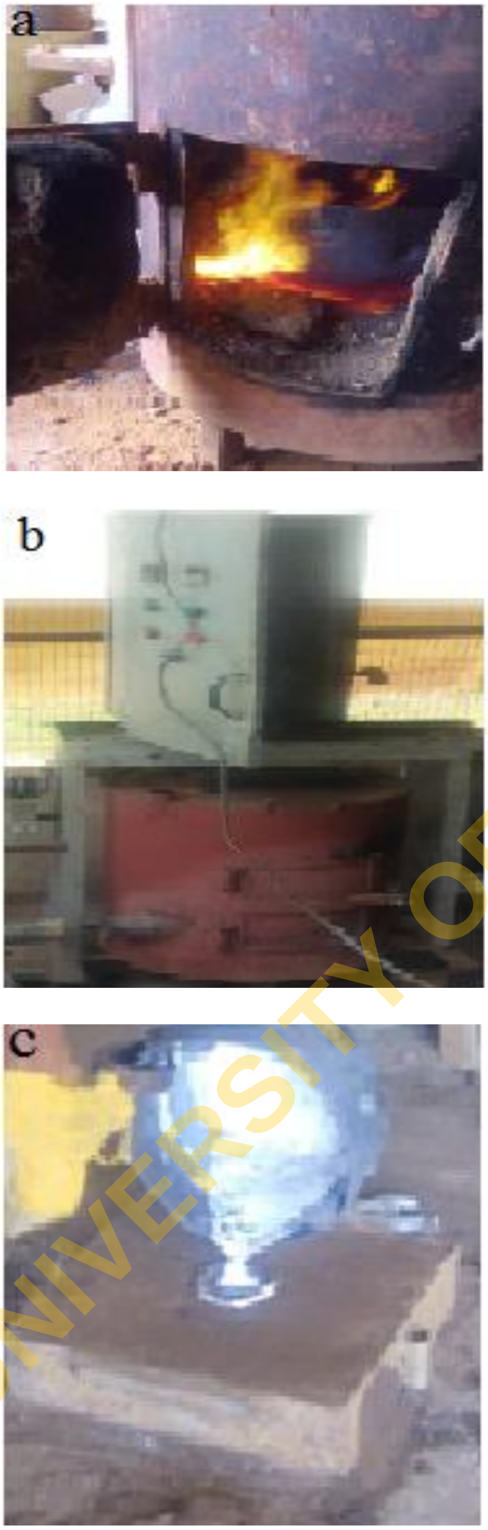

Figure 3: (a) Heating of Al-Mg alloy in the furnace, (b)Electrical stirring of the mixture and (c) Pouring of molten metal into the mould

Figure 4: (a) Al-Mg-Cr alloy cylindrical rods cast and (b) Hand wheel cast from Al-Mg-Cr alloy

In this work, the cast was prepared in a green sand mould containing bentonite (clay as binder). The cavities in which the molten material was poured during the casting process were prepared, while cylindrical and hand wheel patterns made of steel were used. The patterns were lubricated to enable easy removal from the mould and ensure a good surface finish of the casting. The Al-Mg-Cr alloy was produced using the liquid metallurgy route (two step casting technique). The constituents were charged in the proportion shown in Table 2. Mass of Al 6063 for each of the charges was 500 g, Mg was 2.5 g while Cr ranges from 0 to 10.3 g. The Chromium powder was preheated in a furnace at a temperature of 750 °C. The aluminium alloy and magnesium powders were also preheated at a temperature of 350 °C for 30 minutes to aid wettability.

Table 2: Weight percentage of Al alloy, Mg and Cr (Charge Calculations)

Samples	Al6063 (%)	Mg (%)	Cr (%)	Cr (g)
1	99.5	0.5	0	0
2	99.0	0.5	0.5	2.5
3	98.5	0.5	1.0	5.1
4	98.0	0.5	1.5	7.7
5	97.5	0.5	2.0	10.3

The Al alloy and magnesium powders were then placed in the crucible and inserted into the furnace at temperature 780 °C using tongs as shown in Figure 3(a). After about 20 minutes, a homogeneous liquid of the alloy was achieved. The preheated chromium powders were then introduced into the crucible containing the Al-Mg alloy and mixture was returned to electrical stirring furnace shown in Figure 3(b) and reheated for 15 minutes at 300 rpm until relatively homogenous molten mixture was achieved. At the final stage of mixing, the furnace temperature was maintained at 780 °C. Slag was removed from the molten metal and carefully poured into the prepared mould shown in Figure 3(c), which was left for about 20 minutes to allow for solidification and dissipation of heat. The moulds were broken to get the cast shown in Figure 4(a), cooled at room temperature and made ready for characterisation. Figure 4(b), hand wheel cast from Al-Mg-Cr cast was obtained after characterisation and volume fraction of Cr for achieving best properties was determined.

2.3. Characterisation of the Cast Al-Mg-Cr alloy Samples

Mechanical properties of the samples such as tensile strength, maximum elongation and modulus of elasticity were characterised using Universal Instron Machine. Al-Mg-1.0Cr (sample 3) had the highest number of cycles to failure when subjected to cyclic loadings. Five specimens of Al-Mg-1.0Cr alloy were further produced to carry out the heat treatment of the alloy. The Al-Mg-1.0Cr alloy casting were subjected to normalising heat treatment at varying temperature of 250, 300, 350, 400 and 450 °C, at constant holding time of 20 minutes and allowed to cool in natural air. The Metallographic examinations (microstructural studies) were carried out with the aid of Optical Microscope (OPM).

Tensile strength test

The tensile strength of the cast products of Al-Mg-Cr alloy with different compositions of chromium were characterised using Universal Instron Machine where samples were subjected to controlled tension until failure, in accordance with ASTM E8. Maximum elongation and modulus of elasticity were also determined via tensile test. The test piece was prepared based on dog bone shape, length of 100 mm and gauge length 30 mm. The cylindrical test piece section has a diameter of 3 mm. Three specimens of each sample were produced from the cast alloy and pulled to rupture. The clench region of test specimens was gripped to the jaw of the tensile testing machine and pulled by the applied force via the hydraulic drive, which was followed by the computation of average tensile strength values. Maximum elongation and modulus of elasticity were also determined via the tensile strength test.

Metallographic examination

Metallographic examination was carried out in order to characterise the microstructural phases of the alloys produced. The microstructural study was carried out with the aid of Optical Microscope (OPM) after etching the samples to mirror-like polished surface in a solution containing 2% sodium hydroxide. The OPM used is an Accuscope Microscope coupled with camera of magnification 400X.

III. RESULTS AND DISCUSSIONS

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

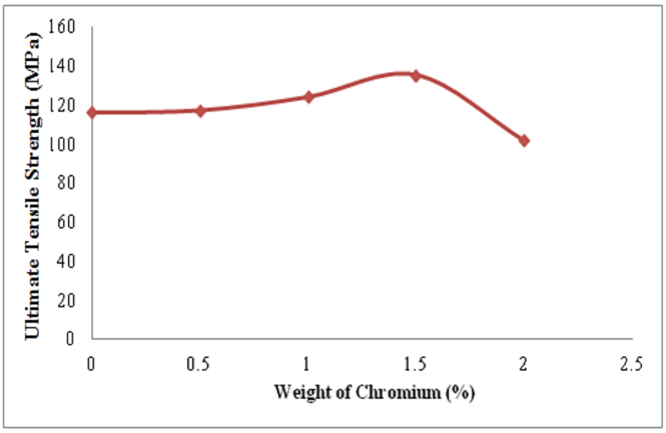

Figure 5: Ultimate Tensile Strength of un heat treated (as cast) Al-Mg-Cr alloys with varying percentage weight of chromium

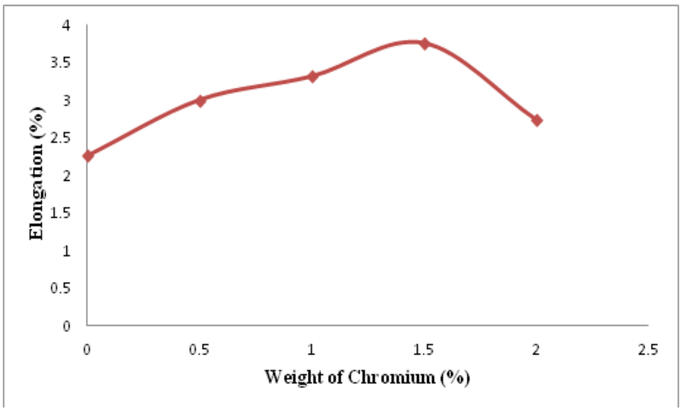

Figure 6: Maximum Elongation of un heat treated (as cast) Al-Mg-Cr alloys with varying percentage weight of chromium.

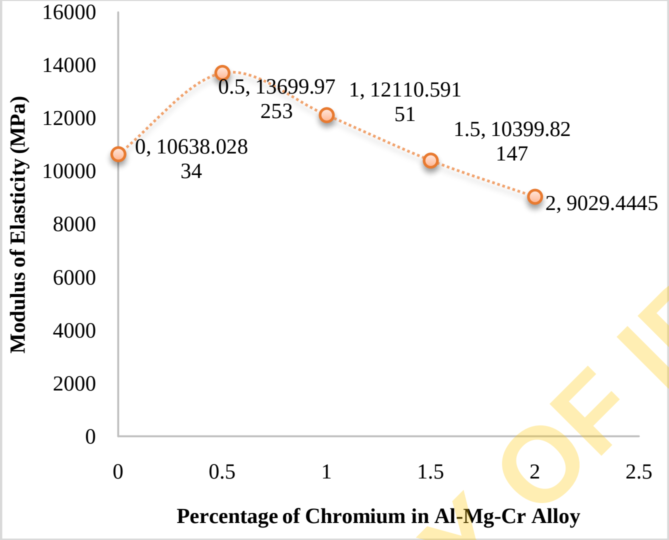

Figure 7: Effect of percentage Chromium on the Modulus of Elasticity of Al-Mg-Cr alloy.

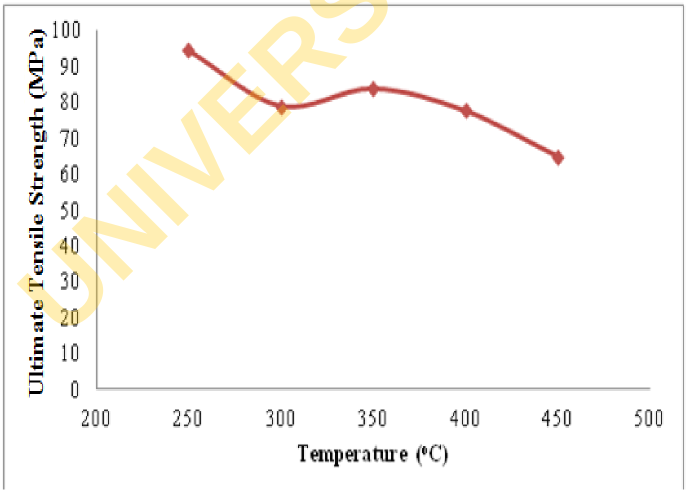

Figure 8: Ultimate Tensile Strength of heat treated Al-Mg-1.0Cr alloyat varying temperatures

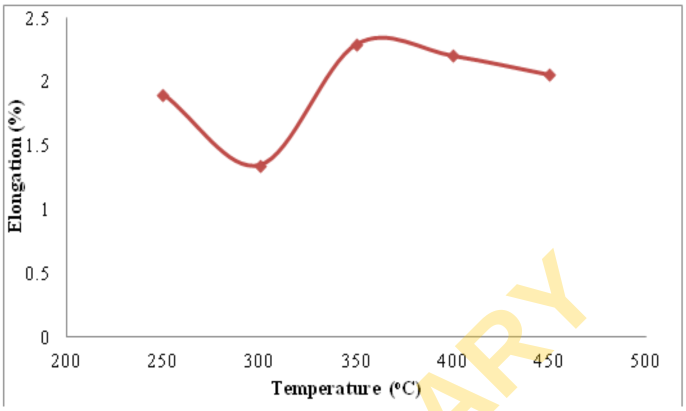

Figure 9: Maximum Elongation of heat treated Al-Mg-1.0Cr alloyat varying temperatures

The average ultimate tensile strength of as cast Al-Mg-Cr alloys at varying percentage weights of chromium is described in Figure 5. The Al-Mg-1.5Cr alloy (sample 4 with 1.5 percentage weight of chromium) exhibited the highest value of ultimate tensile strength of 135.15 MPa. The values of the ultimate tensile strength of samples 1, 2, 3 and 5 were 116.01, 117.11, 123.98 and 101.68 MPa, respectively. Expectedly, the values of ultimate tensile strength increase with the increase in the percentage inclusion of chromium. However, the lowest UTS value was recorded for samples 5, despite having the largest percentage inclusion of chromium. This behaviour could be attributed to decrease in the ductility of the Al-Mg-Cralloy in micro-levels localized near the Cr particles [18]. Comparatively, samples 3 and 4 provided higher resistance against an external pulling, which plays vital role in the fracture or failure of the alloys [19]. The Cr particles enhance the mechanical properties of the alloy, it possibly reacted with the metal matrix to reduce the void nucleation sites and also limit de-bonding of the matrix during the plastic deformation [20]. In the same vein, the maximum elongation of the un heat treated (as cast) test samples is shown in Figure 6. It is observed in Figure 6 that sample 4 (Al-Mg-1.5Cr alloy) undergo more elongation before fracture. The percentage elongation was estimated as 3.76 %. The large elongation indicates ability to absorb more energy compared to other samples before fracture [21]. The modulus of elasticity of the developed Al-Mg-Cr alloy versus the percentage weight of chromium contained in each sample is represented in Figure 7. The sample containing 0.5% Chromium attained highest Modulus of

Elasticity with 13.7 GPa. This is followed by samples containing 1% Chromium with 12.11 GPa. However, it was observed that Al-Mg-Cr alloy containing 1.0% chromium exhibited best combination of UTS (123.98 MPa), percentage elongation (3.32%), modulus of elasticity (12.11 GPa) andmicrostructural features.

From Figure 8, it was observed that the UTS of heat treated Al-Mg-1.0Cr alloy reduces drastically, compared to the as cast. The UTS values for heat treated Al-Mg-1.0Cr alloy were 94.25, 78.78, 86.64, 77.50 and 64.79 MPa for 250, 300, 350, 400 and 450 ℃, respectively. The value was minimum at 450 ℃ and maximum at 250 ℃ , all lower than 123.98 MPa (UTS for the as cast, Al-Mg-1.0Cr alloy), which indicated that the heat treated sample exhibit decrease in ductility, and as such lower load or pull that was required to cause failure, compared to the as cast sample [22]. The behaviour of this material to heat treatment could be an indication of catastrophic failure or brittle fracture at higher or uncontrolled heat treated temperature due to the reduction in plastic deformation [23]. As shown in Figure 9, reduced elongation was also observed for the heat treated (normalized) Al-Mg-1.0Cr alloy compared to the un heat treated. The maximum elongation of heat treated Al-Mg-1.0Cr alloy was 2.29 % at 350 ℃, it was 3.32 % for the as cast. Reduction in elongation after heat treatment further confirmed the reduction in the ductility of Al-Mg-1.0Cr alloy due to the probable emergence of micro void into its matrix by the heat treatment. The behaviour of the material after heat treatment is an indication that the heat treated Al-Mg-1.0Cr alloy is more prone to brittle failure than the as cast, and as such lower tensile force required for failure to take place [24].

3.2. Microstructural Characteristics of Al-Mg-Cr alloys via OPM

Figure 10: OPM micrograph of Sample 1 (Al-Mg-0Cr alloy)

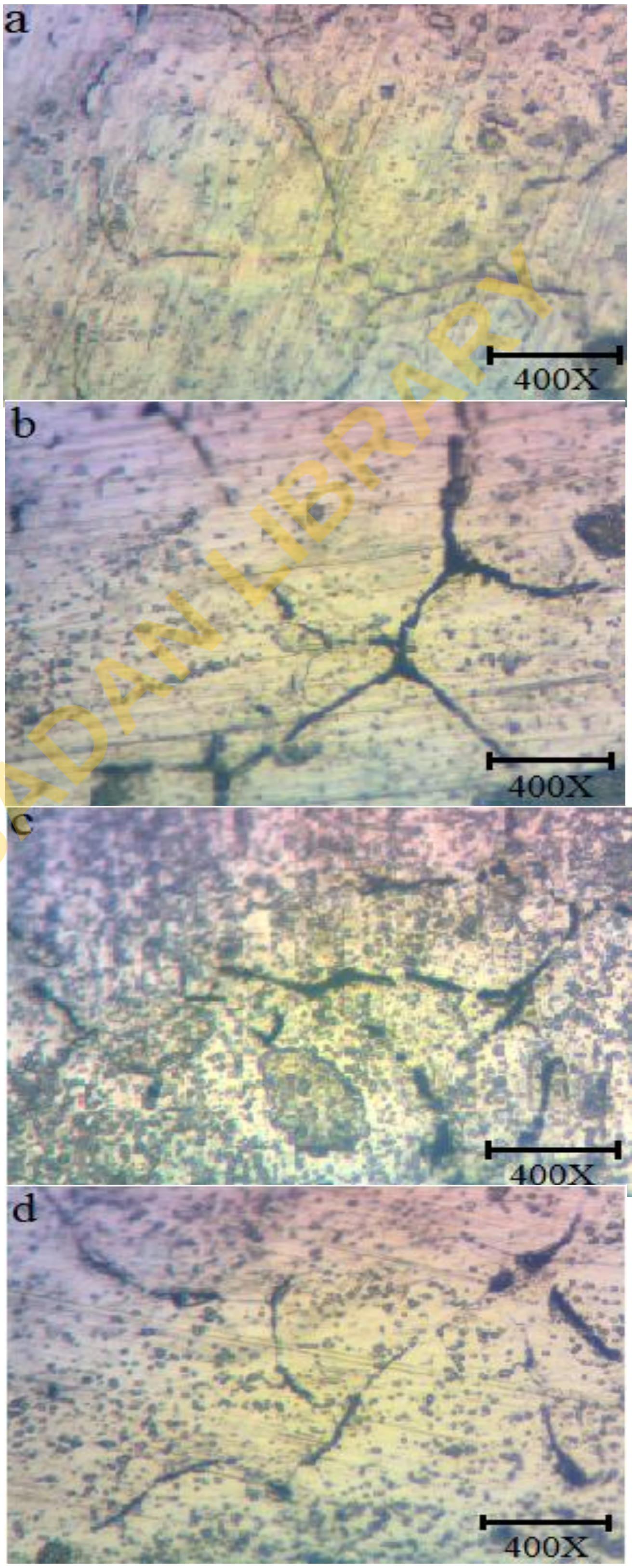

Figure 11: OPM micrograph of (a) Sample 2 (Al-Mg-0.5Cr alloy); (b) Sample 3 (Al-Mg-1.0Cr alloy); (c) Sample 4 (Al-Mg-1.5Cr alloy); (d)Sample 5 (Al-Mg-2.0Cr alloy)

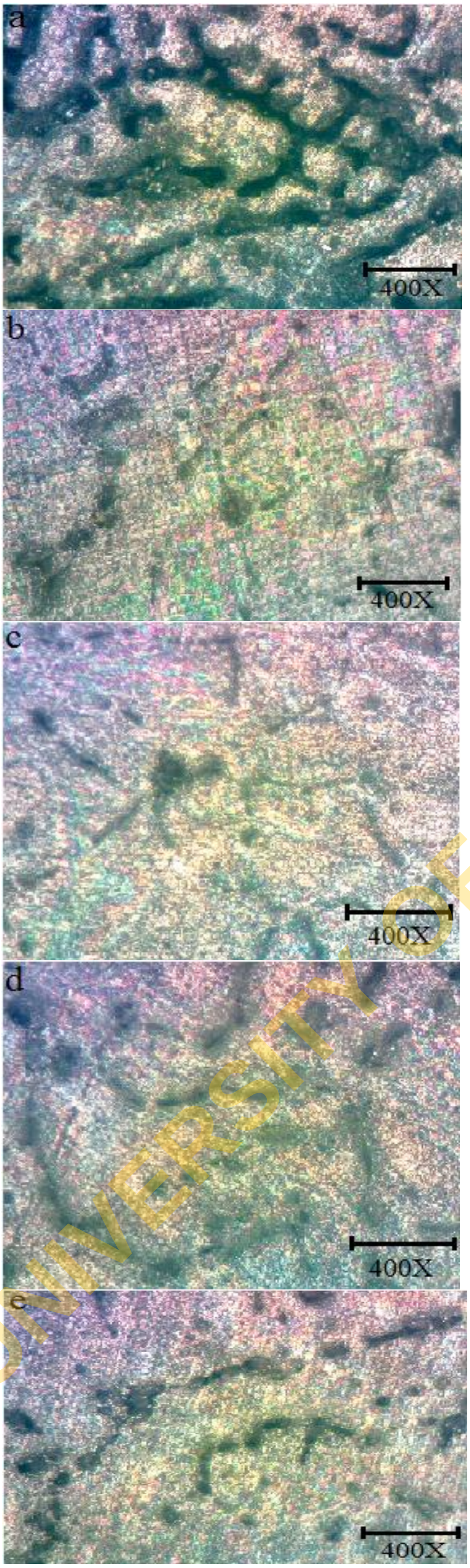

Figure 12: OPM micrograph of heat treated sample 3 (Al-Mg-1.0Cr alloy) at (a) 250 °C; (b) 300 °C; (c) 350 °C; (d) 400 °C; (e) 450 °C

The OPM micrograph of Sample 1 (Al-Mg-0Cr alloy) presented in Figure 10 revealed few porosity and cracks, and some precipitates of Mg in the casting. However, the micrographs in Figure 11 unveiled more uniform morphologies, with no appearance of porosity and cracks. The homogenous distribution of the reinforcements (chromium) was observed in the matrix of Figure 11(a-d). The relatively better morphology of Figure 11 compared to Figure 10 could be attributed to the ability of chromium to fill the micro-holes or void in the matrix of Al-Mg alloy [26]. The size of Al 6063-Mg became finer on the introduction of 0.5wt. % of Cr as shown in Figure 11a, but gets a little more coarse on the inclusion of 1.0 and 1.5 wt. % of Cr as indicated in Figure 11b and 11c. However, Figure 11d representing micrograph of 2.0 wt. %. of Cr inclusion in Al 6063-Mg revealed finer grains. The proper interfacial bonding and reasonable grain size of Figure 11b and 11c could be the reason for the better mechanical performance of Sample 3 (Al-Mg-1.0Cr alloy) and Sample 4 (Al-Mg-1.5Cr alloy) [27].

Observation from the optical micrograph in Figure 12 showed that heat treatment altered the morphology of Sample 3 (Al-Mg-1.0Cr alloy) at 250 °C. More porous morphological structure and darker precipitate was observed at 250 °C. These dark precipitates signify the possibility of irregular and randomly grains with average size in the range of 30 µm ~ 170 µm within the matrix of the alloy. However, better refinement of the grain boundaries was observed with increase in the heat treatment temperature. Relative to the as cast Al-Mg-1.0Cr alloy, no significant microstructural changes were observed in the heat treated alloy samples, an indication that the grain size has attained a saturation state.

IV. CONCLUSIONS

The effect of the inclusion of Cr in Al-Mg alloy was examined when subjected to tensile and microstructural tests. The following conclusions are drawn from this study:

1) The adoption of varying percentage weight of Cr in Al-Mg alloy matrix revealed significant impact on the performance characteristics of the alloy. Inclusion of Cr particles into the matrix of Al-Mg alloy increased ultimate

tensile strength by 16.50 % and 66.37 % increase in elongation before fracture.

2) The observed increase in percentage elongation and microstructural features unveiled addition of Cr particles in the matrix Al-Mg alloy reduced cracks and porosity due to uniform dispersion of the alloying elements along the grain boundaries and therefore exhibits potential for enhancing ductile fracture.

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