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Effect of Copper and Magnesium Stoichiometric Additions and Thermal Aging on the Mechanical Properties of Cast Aluminium Alloys

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Abstract

Objective: To study the mechanical properties of newly developed cast aluminium alloy with additions of copper and magnesium in the mole ratio of 1:1:1 of Al-Cu-Mg in as cast and thermally aged conditions. **Methods/Statistical Analysis:** For the (wt.%) selection of Cu-Mg on the basis of stoichiometric calculations, 1 unit (wt.%) of copper and 1 unit (wt. %) of magnesium were mixed in base metal liquid. Aluminium 6063 base material was heated in an electric furnace at 750°C in permanent mild steel mould preheated at 200°C in order to achieve homogenised cast alloyed ingot. **Findings:** The specimens were extracted from cast aluminium ingot for tensile and impact strength evaluation, microhardness variations and metallurgical studies in as cast and aged conditions (160°C for 5,6 and 7 hours respectively). Optical microscopy reveals increased rate of intermetallic precipitation at aged conditions which was supported by X-ray diffraction patterns. Moreover, copper and magnesium additions increased the ultimate tensile strength, impact strength and microhardness values of newly developed aluminium cast alloy in comparison with conventional Al 6063 base material. **Application/ Improvement:** Therefore, based upon the present work, it is recommended to use this ratio of copper and magnesium in aluminium base alloy in order to achieve better mechanical properties in industrial applications.

Keywords: Aluminum Alloys, Electric Furnace, Intermetallic Compounds, Solution Treatment, Thermal Aging

1. Introduction

Aluminium alloys are next to steels in use as structural metals. Its density is around 1/3 to the steel which makes its use advantageous particularly for space vehicles, aircrafts as well as many types of surface and water borne vehicles[1]. In automobiles, the components such as engine blocks, head, pistons and wheels etc. are generally aluminium based cast alloys[2]. The low cost and scenario of continuous demands for weight reduction and improvements in fuel efficiency of automobiles have increased pace of research in developing aluminium based cast alloys[3]. The Al-Cu-Mg alloys offer high hardness and strength. Its components contribute the high degree of damage tolerance[4]. The alloys of the Al-Cu-Mg system provide the basis for the development of many other important Al alloys[5]. The composition of the alloying elements and casting conditions influence the state of intermetallic phases and finally the mechanical properties of the alloy[6-8]. The first age-hardening of aluminium alloy as reported in literature was performed in year 1909 who patented duralumin of casting components containing Cu and Mg substances[9]. The steps consist of solution treatment, quenching and artificial aging. The age -hardening mechanism is responsible for strengthening. The presence of copper in Al-Si-Cu alloys leads to the formation of the Al2Cu intermetallic compounds has not dissolve during heat treatment[10-12].

The mechanism is based on the formation of intermetallic compounds during decomposition of a metastable

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supersaturated solid solution by performing solution treatment and quenching[13-17]. The copper and magnesium in combination have been used for improving the aging characteristic of the cast alloy18. Some of the investigators have taken compositions of alloying elements in weight fraction or volume fraction but in arbitrary manner. They have used design of experiments for material compositions as input parameters and different mechanical properties as responses, and finally optimum values of alloying elements are suggested for the given objective19. In place of taking the fraction of alloying element in arbitrary manner, a pattern based on stoichiometric weight fraction is explored and presented in the study. Study has been made on Al-Cu-Mg casting and results in terms of metallurgical and mechanical properties have been presented.

As per, Al-Cu-Mg alloys are in use with different ratios of addition of copper and magnesium but no work has been reported where stochiometric additions of 1:1:1 of Al:Cu:Mg was reported. Further, relation between metallurgical and mechanical properties of these aluminium alloys was not reported. Therefore, it was necessary to undertake present work in order to generate database for mechanical properties of these aluminium alloys.

2. Experimentation

2.1 Methodology

The mole ratio of Al-Cu-Mg was selected as 1:1:1 which resulted into the stoichiometric ratio of Al-Cu-Mg as 38.05-44.81-17.13. Such a high percentage of Cu and Mg cannot be a suitable condition for formation of the Al based alloy, hence 1% of wt. each of Cu and Mg as per stoichiometric ratio were taken for mixing with the base metal aluminium.

The aluminium was melted in a 2-kg capacity of graphite crucible using an electric furnace. The temperature was maintained at 750°C for half an hour, which is higher than the melting temperature of Al as shown in Table 1. The Cu and Mg in powder form were preheated at 250°C for 30 minutes and mixed in liquid aluminium metal which further stirred for five minutes at 800 rpm. The chemical compositions were tested using spark emission spectrometer analysis (Model No: Bruker Q8 Magellan, Make: Germany). The test method was used in accordance to ASTM E 415-2015 standards. Finally, metallographic and mechanical properties of the cast aluminium alloy are analysed.

The cast aluminium specimens were extracted as shown in Figure 1, polished as per standard metallographic procedure up to 3000 grit size and Kroll's etchant (Electrolyte used: Distilled water (92 ml) +Nitric acid (6ml) +Hydrofluoric acid (2ml) was applied for 15 seconds to reveal microstructure using optical microscopy[20]. The X-Ray Diffraction (XRD) technique (Make: Panalytical, Model: Xpert Pro) was used to generate spectra which showed intermetallic precipitation behaviour of cast base material and after alloying additions of copper and magnesium. Fractography studies were also performed to determine type of fractured surfaces for tensile and CVN samples of different aluminium cast ingots using Scanning Electron Microscopy (SEM) (Make:JEOL, Model:JSM-6510LV).

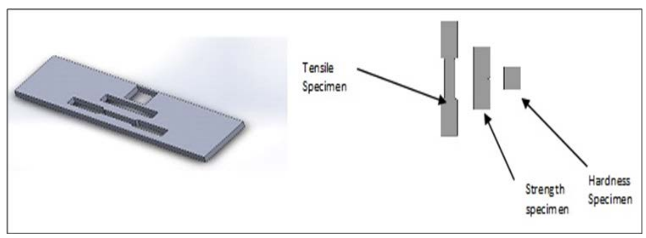

Figure 1. Schematic plan for extraction of specimens for metallurgical and mechanical testing.

Tensile specimens were tested on a servo hydraulic based digital controlled tensile testing machine of having capacity 50 kN (make: Tinius Olsen, UK, Model-H50KS) and ultimate tensile strength for base and aged cast aluminium alloys were determined. The tensile specimens were prepared in accordance with ASTM E08/E8M-09

Table1. Furnace parameters for casting of aluminium alloys

Sl. No.	Make/ Model	Furnace Temperature Maintained	Holding Time of Liquidus Aluminium at 750°C	Mixing Time	Metal Pouring Time	Thermal Aging Temperature
1.	Matrix Scientific Instruments Pvt. Ltd. Delhi	750°C	30 Mnts.	5 Mnts.	700°C	1600C

(Sub size Specimen) standard21 as shown in Figure 2. The Charpy V-notch (CVN) test was done to measure the fracture toughness of cast and cast aged material. Figure 3 showed sample for Charpy V-notch test prepared as per ASTM E23-12c standard22.The hardness measurements were taken using Brinell hardness tester23 (make-: MIRAJ, INDIA, Model:3000(O) of maximum capacity 3000Kgf. In this particular case the testing was carried out at 500Kgf load with a 5mm indenter ball. The indentation was measured in terms of BHN fore cast and aged material.

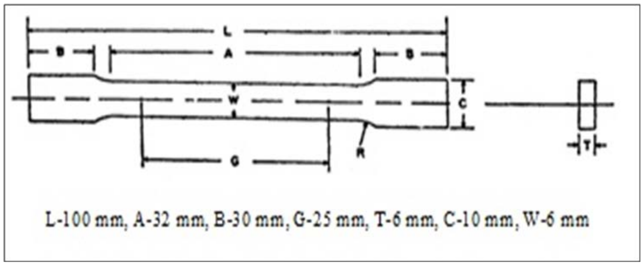

Figure 2. Dimensions of the tensile specimen as per ASTM standard.

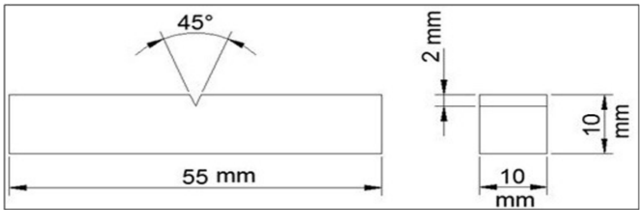

Figure 3. Schematic of the Charpy impact test specimen as per standard practice.

3. Results and Discussion

3.1 Spectro Analysis

Chemical composition of aluminium base material as purchased from local market was tested using spectrometer as shown in Table 2. Moreover, after alloying additions of copper and magnesium in aluminium matrix, chemical compositions were determined through spectrometer in as cast and aged conditions.

As evident from spectrometer analysis, on adding 1wt.% (on stoichiometric basis as mentioned earlier)

Table 2. Chemical composition of base material

Al	Cu	Mg	Si	Mn	Ni	Zn	Pb	Cr	Fe	Sn	Ti
98.78	0.0018	0.554	0.471	0.017	0.003	0.025	0.001	0.104	0.017	0.022	0.0042

Table 3. Alloying element composition in cast and aged cast base material

	Al	Cu	Mg	Si	Mn	Ni
Cast base Aluminium	**98.52**	**0.0055**	**0.329**	**0.502**	**0.181**	**0.026**
1Hrs solution Treatment & 5Hrs Aged-cast base Aluminium with 1% Cu, Mg	98.11	0.281	0.164	0.631	0.41	0.008
2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg	95.41	0.543	0.305	0.737	0.9	0.27
3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg	95.45	0.542	0.306	0.73	0.92	0.32

	Zn	Pb	Cr	Fe	Sn	Ti
Cast base Aluminium	**0.064**	**0.173**	**0.152**	**0.013**	**0.028**	**0.0065**
1Hrs solution Treatment & 5Hrs Aged-cast base Aluminium with 1% Cu, Mg	0.063	0.051	0.008	0.24	0.01	0.024
2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg	0.74	0.14	0.005	0.64	0.19	0.12
3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg	0.074	0.62	0.008	0.52	0.28	0.23

copper and magnesium in the base material, there is increase in the percentages of both alloying additions in aluminium matrix. However, there were no variation in elemental compositions when samples were aged as shown in Table 3, reduction aluminium percentage in the matrix was also noticed which is quite evident with addition of copper and magnesium.

3.2 XRD Spectra

There is formation of intermetallic precipitates on melting. Table 4 shows presence of intermetallic precipitates in cast base material and cast aluminium alloy with copper and magnesium addition in as cast and thermally aged conditions which has been observed in XRD spectra. In cast base material Al 6063, AlCu compound has less strength and $Al_{12}Mg_{17}$ compound contributes to hardness of cast alloy. However, when aging was done to 160°C, formation of Al_5Cu_6Mg sigma phase takes place which increases the tensile strength of the material. At the elevated temperature coarse precipitate AlCuMg was also formed. The aging treatment dissolves the AlCu compound and forms complex precipitate compounds which enhance the strength of the matrix. Alloyed with 1 wt % (on stoichiometric basis as mentioned earlier) of copper and magnesium, complex precipitates were observed in XRD spectra shown in Figure 4 which increases the microhardness and tensile strength of the aluminium alloys. At elevated temperature, alloyed metal matrix composite with copper and magnesium, dissolution of these complex compounds occurs and formation of coarse precipitates such as Al_2CuMg[3] and $Al_{14}Mg_{13}$ was there which enhances the toughness and strength at high temperatures. Sigma phase precipitation was noticed in as cast and aged aluminium alloyed with copper and magnesium which enhances their strength as compared to cast base material.

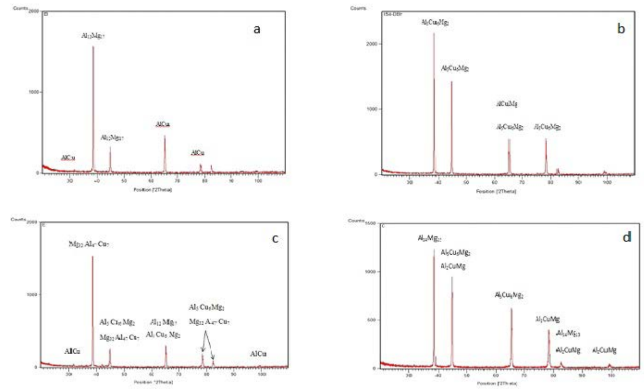

Figure 4. Intermetallic precipitate formation as per XRD diffraction patterns for: (a) Cast base Aluminium, (b)1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg, (c) 2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg, and (d) 3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg

3.3 Microstructural Studies

The photograph of microstructures of Cast base Aluminium, 1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg,2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg and 3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg are shown in Figure 5. There was negligible precipitate formation along the grain boundaries in cast base material but after aging, nucleation of precipitates at most of the grain boundaries were noticed which enhances the strength. Alloying with copper and magnesium leads to fine precipitate forma-

Table 4. Intermetallic compounds in cast and aged condition as per XRD spectra

Type of material	Intermetallic precipitate formation as per XRD spectra			
Cast base Aluminium	AlCu	$Al_{12}Mg_{17}$	-	-
1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg	Al_5Cu_6Mg	AlCuMg	-	-
2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg	AlCu	$Al_{12}Mg_{17}$	Al_5Cu_6Mg	$Al_{47}Mg_{32}Cu_7$
3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg	Al_5Cu_6Mg	Al_2CuMg	$Al_{14}Mg_{13}$	-

tion. However, as aging was done, these fine precipitates transform to coarser precipitates at high temperature and nucleation at grain boundaries were enhanced.

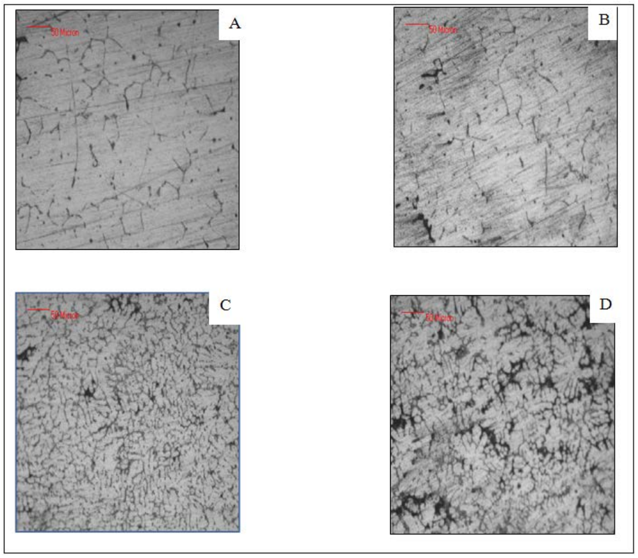

Figure 5. Photomicrographs at 200X for: (a) Cast base Aluminium, (b) 1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg, (c) 2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg, and (d) 3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg.

3.4 Tensile and Microhardness Studies

Tensile strength and microhardness values of cast metal at different stages are shown in Table 5. Their tensile fractographs are shown in Figure 6. Dimple morphology was observed in the fractographs. In cast base metal, small dimples comprising of precipitates were observed but after aging of this cast base, the small dimples coalesce together to form large dimples which contain hardened precipitates[24]. These hardened participates contribute to increase in ultimate tensile strength of the aged cast. Copper and magnesium act as inoculants when alloyed with aluminium base metal and induce grain refining in matrix by nucleating more nucleation sites for precipitation. Thus, precipitation hardening was induced in alloyed metal matrix while casting which improves the ultimate tensile strength of cast metal. As the strength increases it also increases microhardness of copper, magnesium added cast metal.

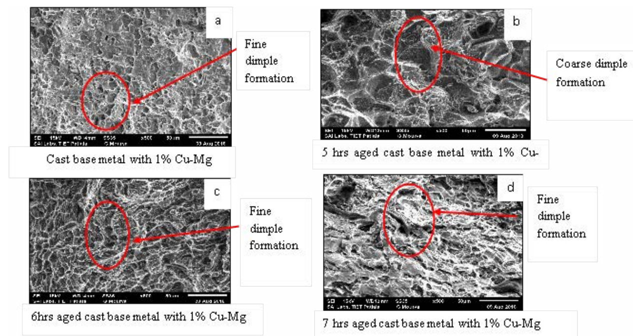

Figure 6. Tensile fractographs at 500X for: (a) Cast base Aluminium, (b) 1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg, (c) 2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg, and (d) 3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg.

3.5 Impact Studies

The results of impact strength in terms of joules of energy to estimate fracture toughness of cast materials was shown in Table 6 and their impact fractographs are shown in Figure 7. In cast base metal, dimple fracture was noticed which corresponds to ductile fracture. When alloyed with copper and magnesium, cast aluminium base metals pos-

Table 5. Microhardness and ultimate tensile strength values of cast base and metal matrix alloyunder as cast and aged condition

Sl. No.	Type of material	Area of Tensile Test specimen, mm^2	Ultimate Tensile Strength (N/mm^2)	Microhardness on Vicker's scale at load-300 gms, Time-20sec.
1.	Cast base Aluminium with 1% Cu, Mg	36	142	54 0
2.	1 Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg	36	200	83.67
3.	2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg	36	188	76.80
4.	3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg	36	173	58.30

sess very small dimples (Figure 6c) because of refinement of grain structure of base metal which ultimately improves the fracture toughness of material[19]. At thermally aged conditions, metal matrix alloyed cast metal; intermetallic precipitates as shown in XRD patterns improves significantly toughness of alloyed cast base material.

Table 6. Impact strength values of cast base and Metal matrix alloy in as cast and aged condition

Sl. No.	Type of material	Impact Strength (joules)
1.	Cast base Aluminium 1% Cu, Mg	15
2.	1 Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg	17
3.	2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg	19
4.	3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg	24

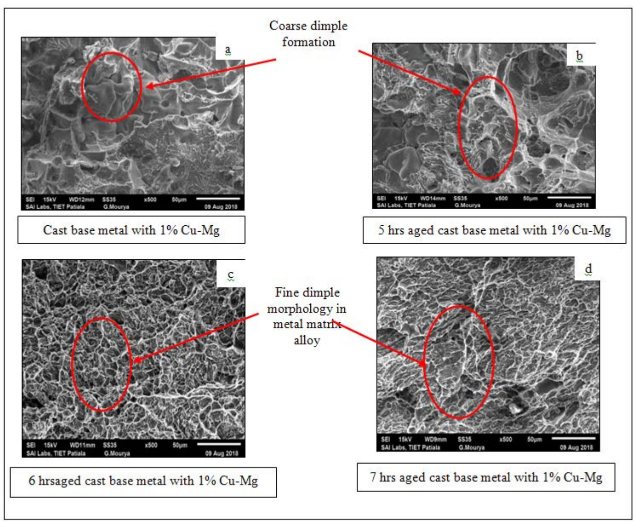

Figure 7. Fractographs of impact specimens at 500X for(a) Cast base Aluminium, (b) 1Hrs solution Treatment & 5Hrs Aged- cast base Aluminium with 1% Cu, Mg, (c) 2 Hrs solution Treatment & 6 Hrs Aged- cast base Aluminium with 1% Cu, Mg(d) 3 Hrs solution Treatment & 7 Hrs Aged- cast base Aluminium with 1% Cu, Mg.

4. Conclusion

- With increase in aging time of copper and magnesium added aluminium cast base metal, different intermetallic precipitation behaviour was observed as compared to cast base metal in as cast condition as observed from XRD studies,
- Owing to increased intermetallic precipitation at aged conditions as revealed by optical microscopy, significant improvement in mechanical properties was noticed viz. ultimate tensile strength, impact strength and microhardness, and
- Further, ductile fracture with dimple formations was observed in all specimens.

5. Acknowledgements

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