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Mechanical Properties of Stoichiometrically Developed Al-Cu-Mg Cast Alloy Under Controlled Environment

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Present study was carried out to investigate the mechanical properties of newly developed cast aluminum alloy with addition of copper 1.0 % (at.) and magnesium 1.0 % (at.) in the mole ratio of 1:1:1 Al-Cu-Mg. The selection of Cu-Mg on the basis of stoichiometric calculations, 0.55 (at. %) of copper and 0.21 (at. %) of magnesium were mixed in liquid aluminium base material, which was prepared in electric furnace. The melt was held at 750 ºC with alloying additions of copper and magnesium for about 5 min to ensure complete homogenization. Further, this liquidous aluminium metal matrix was stirred at 500 rpm for 5 min and poured at 700 ± 10 ºC in permanent mild steel mould at 200 ºC in order to achieve as-cast alloy. Solution treatment at 500 ºC for 1 h and thermally aged at temperature 160 ºC for 5 h was exposed. The effect of solution and thermal aging temperature on metallurgical morphology and the role of intermetallic compounds on mechanical properties of as-cast alloy have been studied. The optical microscopy and scanning electron microscopy equipped with energy dispersive spectroscopy were used to identify the intermetallic phases and formation of different precipitates was studied by using X-ray diffraction. The improvement in ultimate tensile strength and hardness values have been reported.

Keywords: Aluminum alloys, Mechanical properties, Solution heat treatment, Thermal aging, Intermetallic compounds.

INTRODUCTION

Aluminum 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, wheels, *etc*. are generally aluminum 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 aluminum 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 Al-Cu-Mg provides the basis for the development of many other important Al alloys [5]. The first age-hardening of aluminum alloy was performed by A. Wilm in year 1909 who patented duralumin of casting components containing Cu and Mg substances [6]. The steps consist of solution treatment, quenching and artificial aging. The age-hardening mechanism is responsible for strengthening. The mechanism is based on the formation of intermetallic compounds during decomposition of a metastable supersaturated solid solution by performing solution treatment and quenching [7,8].

The composition of alloying elements and casting conditions influence the state of intermetallic phases and finally the mechanical properties of alloys [9]. The copper and magnesium in combination have been used for improving the aging characteristic of the alloys. Some 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 objective.

In place of taking the fraction of alloying elements in arbitrary manner, a pattern based study on stoichiometric weight fraction is explored and presented in the paper. Investigations have been made on Al-Cu-Mg casting and results in terms of metallurgical and mechanical properties are presented.

EXPERIMENTAL

Methodology: Initially to start with the mole ratio of Al-Cu-Mg were selected as 1:1:1, which results into the stoichiometric ratio of Al-Cu-Mg as 23.496-55.338-21.165. Such a high percentage of Cu and Mg cannot be a suitable condition for formation of the Al based alloy, hence 1 (at. %) each of Cu and Mg as per stoichiometric ratio were taken for mixing with the base metal [9].

A graphite crucible of 2 kg capacity was used in electric resistance furnace, and the melting temperature was kept at 750 ºC [10] for 5 min. The Cu and Mg as decided above were preheated at 200 ºC for 30 min and mixed in liquidous aluminium metal and stirred for 5 min. The melts were hold at 730 ºC for about 30 min [11] to ensure complete homogenization and poured after degassing into a permanent mould. It refines the microstructure of metallic material which change the morphology and distribution of intermetallic particulates to enhance the mechanical properties of as-cast aluminium alloy. The mechanical tests which include tensile test, microhardness measurement and Charpy V-notch (CVN) tests were performed to obtain cast alloy. Finally, metallographic and mechanical properties of the as-cast alloy have been analyzed.

Metallographic tests: The cast specimens were polished as per standard metallographic procedure by using emery paper of progressive finer grades 400, 600, 800, 1000, 1200, 1500, 2200, 2500 and 3000 grit size with single disk machine. They were polished with alumina powder to obtain a mirror like surface by solvyt polishing cloth and continue water supply. Kroll′s etchant [distilled water (92 mL) + nitric acid (6 mL) + hydrofluoric acid (2 mL)] was applied for 15 s to reveal microstructure. Optical microscopy was used to capture microstructures of as-cast and thermally aged aluminium alloys and their photographs taken with the magnification × 200. Fractography was done to determine type of fracture for tensile and CVN samples using scanning electron microscopy JEOL (JSM-6510LV).

Mechanical properties: Tensile specimen samples 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 as-cast alloy and thermally aged cast base alloys was determined. The tensile specimens were prepared in accordance with ASTM E08/E8M-09 standard. The Charpy V-notch (CVN) test was done to measure the fracture toughness of as-cast and aged as-cast. The sample for Charpy V-notch test was prepared as per ASTM E23-12c standard .The micro hardness measurements were taken by using Vickers micro hardness tester (make: Shimadzu, Japan, Model: HVM-2T) of maximum capacity 2 kg. The testing was carried out at 300 g load with a dwell of 20 s.

RESULTS AND DISCUSSION

Spectro analysis: The chemical compositions were tested as per ASTM E 1251-17a using spark emission spectrometer analysis (Model No: LMF_01, Spectromaxx, Germany). The chemical compositions of as-cast alloy and thermally aged alloy were tested using spectrometer and shown in Table-1.

The chemical composition on as-cast with solution temperature 500 ºC for 1 h with 1 % Cu, Mg and aged as-cast alloy, temperature 160 ºC for 5 h with 1 % Cu, Mg spectrometer analysis on addition 1.0 (at. %) copper and magnesium in the base material, there is significant changes in chemical composition of as-cast alloys were observed.

X-ray diffraction: The X-ray diffraction technique was used to show different intermetallic precipitate formations in as-cast and thermally aged alloy which has been observed in XRD spectra (Fig. 1). In as-cast base aluminium alloy, AlCu compound has less strength and Al_2Cu compound contributes to hardness of as-cast alloy. However, when aging was done to 160 ºC, formation of Mg_2Si, sigma phase takes place which increases the tensile strength of material (Table-2). At the elevated temperature coarse precipitate Al_2CuMg was also formed. The aging treatment dissolves Al_2Cu compound and forms complex precipitate compounds which enhance the strength of matrix.

The complex compounds occur and formation of coarse precipitates such as Al_2CuMg and Mg_2Si, 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.

Optical microscopy: The microstructure consists primarily of a dendritic morphology with dendritic α-Al arms, Si-rich platelets, Al-Cu phases and Fe-containing intermetallic compounds. The photographs of microstructure of as-cast aluminium, aged as-cast base aluminium, as-cast aluminium with 1% Cu, Mg and aged & as-cast aluminium with 1 % Cu, Mg are shown in Fig. 2. There was negligible precipitate formation along the grain boundaries in as-cast aluminium 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 formation. However, as aging was done, these fine precipitates transform into coarser precipi-

TABLE-1
ALLOYING ELEMENTS COMPOSITION (wt. %)

Stage of as-cast alloys	Al	Cu	Mg	Si	Mn	Ni	Zn	Pb	Cr	Fe	Sn	Ti	V
SHT at 500 °C 1 h, As-cast alloy with 1 % Cu, Mg	97.73	0.3235	0.6129	0.484	0.0110	0.0023	0.0065	0.0045	0.0027	0.655	0.0045	0.1438	0.0079
TAG at 160 °C 5 h, As-cast alloy with 1 % Cu, Mg	97.66	0.3302	0.6679	0.495	0.0111	0.0023	0.0068	0.0046	0.0028	0.690	0.0042	0.1344	0.0075

SHT = Solution heat treatment; TAG = Thermal aging

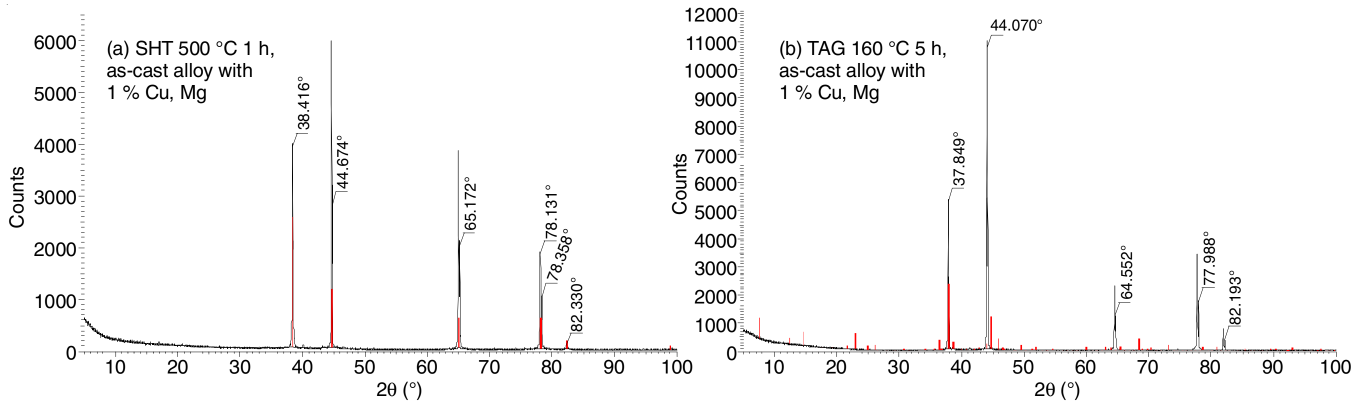

Fig. 1. Intermetallic precipitate formation as per XRD diffraction patterns for (a) SHT 500 °C 1 h, as-cast alloy with 1 % Cu, Mg (b) TAG 160 °C 5 h, as-cast alloy with 1 % Cu, Mg

TABLE-2
INTERMETALLIC COMPOSITION OF THE OBSERVED PHASE

Composition corresponding to solution treatment at 500 °C for 1 h			Composition corresponding to aged temperature at 160 °C for 5 h		
Element	Weight (%)	Atomic (%)	Element	Weight (%)	Atomic (%)
Mg K	0.68	0.77	Mg K	0.73	0.82
Al K	97.19	98.32	Al K	96.42	97.95
Cu K	2.13	0.91	Cu K	2.85	1.23
Totals	100.00		Totals	100.00	

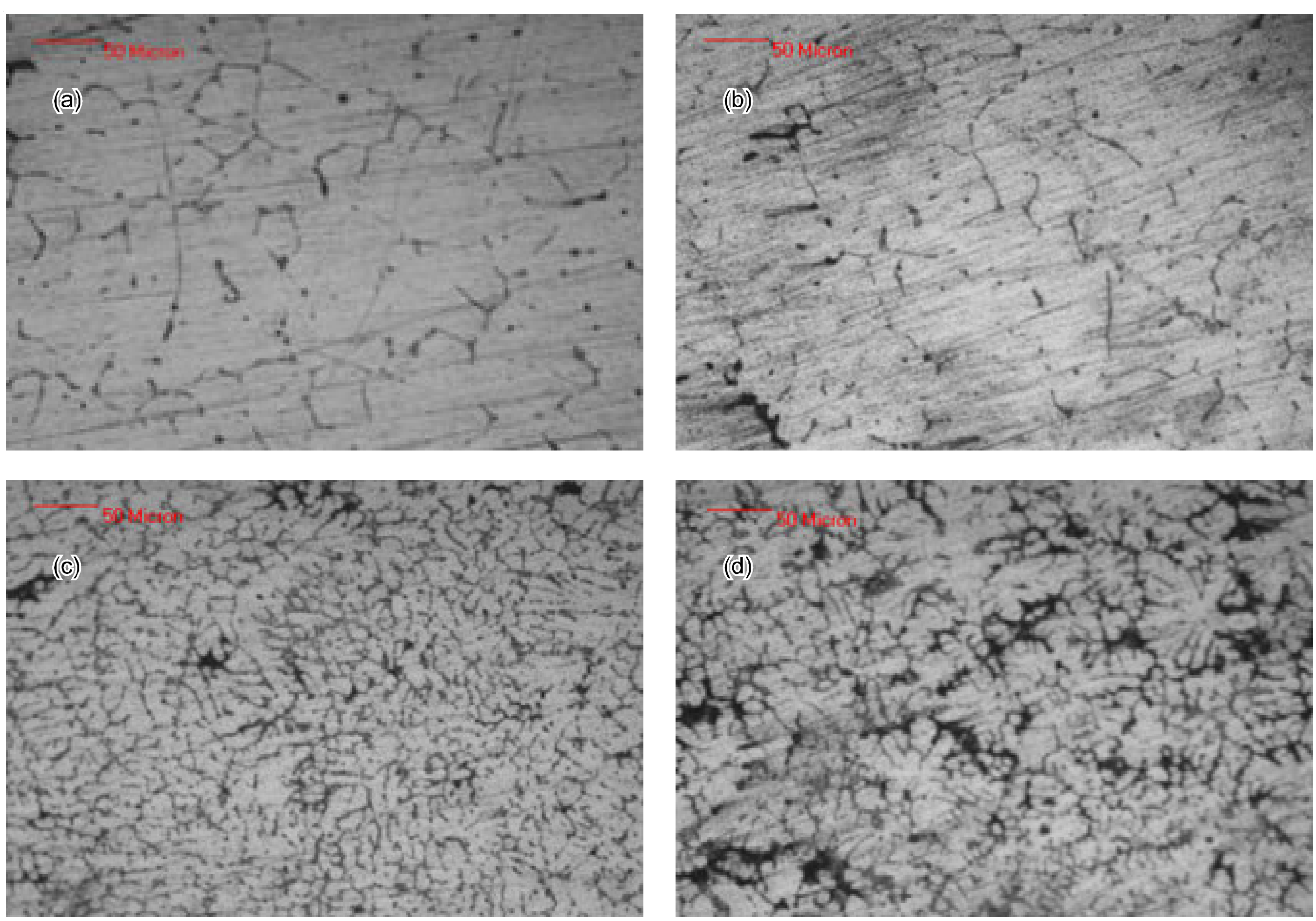

Fig. 2. Photomicrographs at 200X for (a) SHT 500 °C 1 h, as-cast alloy (b) TAG 160 °C 5 h, as-cast alloy (c) SHT 500 °C 1 h, as-cast alloy with 1 % Cu, Mg and (d) TAG 160 °C 5 h, as-cast alloy with 1 % Cu, Mg

tates at high temperature and nucleation at grain boundaries were enhanced.

SEM-EDS: The Fe SEM-EDS samples were analyzed for as-cast solution at 500 ºC, 1 h and as-cast, aged temperature

160 ºC, 5 h. Magnesium has revealed that peaks for each elements were deducted and compounds formed in the alloy during solidification are "Chinese Script", intermetallic phase, AlCu, Al_2CuMg, and Mg_2Si (Fig. 3).

Tensile and microhardness studies: Tensile strength and microhardness values of as-cast metal at different stages are shown in Table-3. It can be seen that the hardness of alloy increased obviously at the aged conditions due to nucleation and growth

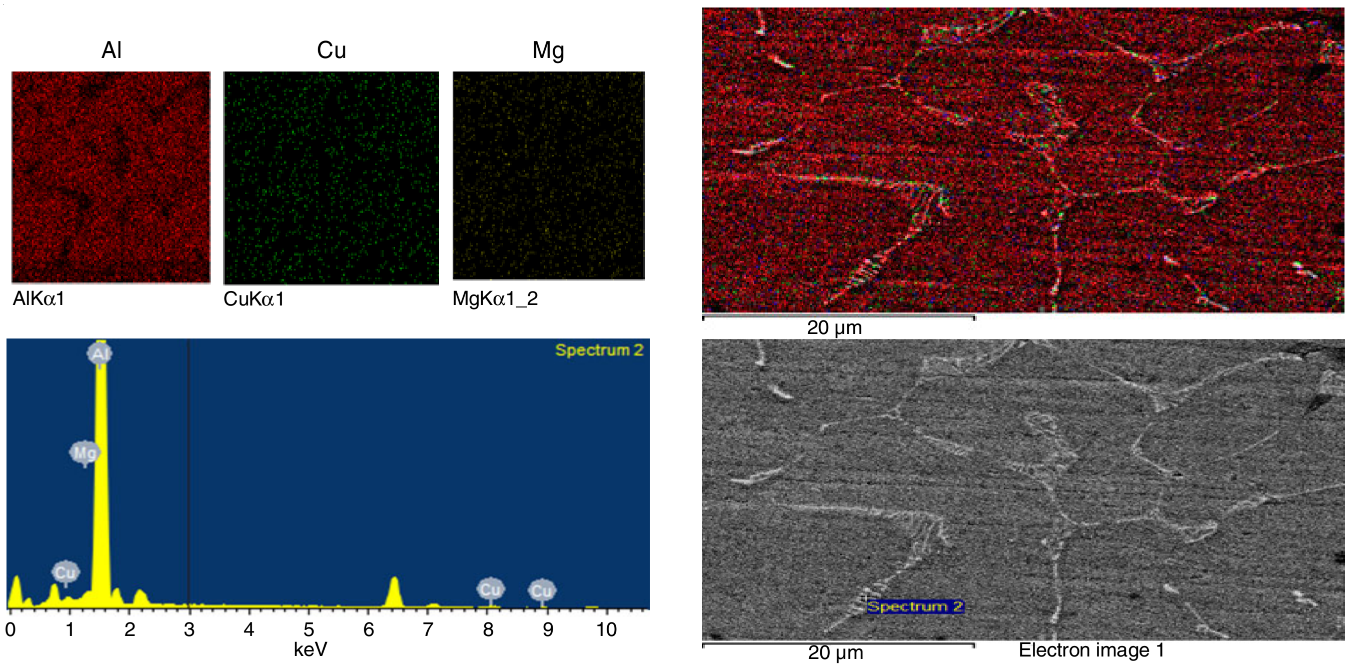

Fig. 3a. SEM micrograph, EDS mapping and measurement of chemical composition corresponding to solution treatment at 500 °C, 1 h

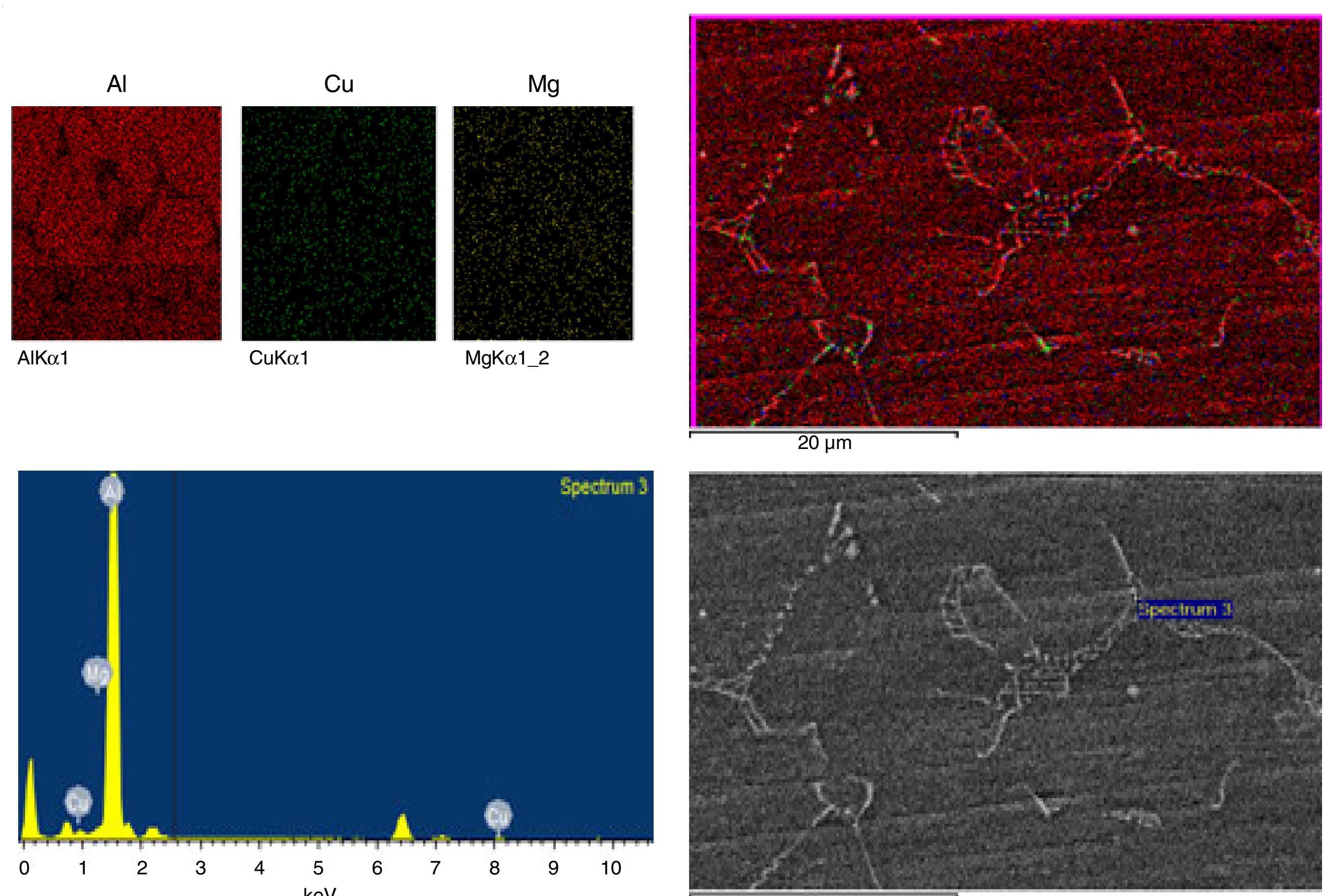

Fig. 3b. SEM micrograph, EDS mapping and measurement of chemical composition corresponding to aged temperature at 160 °C for 5 h

TABLE-3
MICROHARDNESS AND ULTIMATE TENSILE STRENGTH VALUES

as-Cast alloy stage	Area of tensile test specimen (mm^2)	Ultimate tensile strength (N/mm^2)	Hardness on Brinell (BHN) at load: 500 kgf, time: 30 s
SHT at 500 °C 1 h, as-cast alloy	36	132	33.50
TAG at 160 °C 5 h, as-cast alloy	36	132	33.50
SHT at 500 °C 1 h, as-cast alloy with 1 % Cu, Mg	36	140	37.70
TAG at 160 °C 5 h, as-cast alloy with 1 % Cu, Mg	36	192	44.90

SHT = Solution heat treatment; TAG = Thermal aging

of the aging precipitates. The dimple morphology was observed in the fractography. In as-cast base metal, small dimples comprising of precipitates were observed but after aging of this as-cast base, the small dimples coalesce together to form large dimples which contain hardened precipitates. 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 positions for precipitation. Thus, precipitation hardening was induced in alloyed metal matrix while casting which improves the ultimate tensile strength of cast metal. The resulting improvement of mechanical properties after heat treatment is correlated to the intermetallic phase and the precipitation hardening as previously reported.

Impact studies: The results of impact strength in terms of joules of energy to estimate fracture toughness of cast materials are given in Table-4 and their impact fractography is shown in Fig. 4.

In cast base metal, dimple fracture was noticed which corresponds to ductile fracture. When alloyed with copper and magnesium, cast aluminium base metal possess very small dimples because of refinement of grain structure of base metal which ultimately improves the fracture toughness of material.

TABLE-4
IMPACT STRENGTH VALUES OF SHT AND TAG AS-CAST ALLOY CONDITIONS

As-cast alloy stage	Impact strength (joules)
SHT 500 °C 1 h, as-cast alloy	15
TAG 160 °C 5 h, as-cast alloy	15
SHT 500 °C 1 h, as-cast alloy with 1 % Cu, Mg	20
TAG 160 °C 5 h, as-cast alloy with 1 % Cu, Mg	9

SHT = Solution heat treatment; TAG = Thermal aging

Conclusion

When copper and magnesium were added in as-cast base aluminium alloy, the elemental change in wt. % were noticed. These elements enhance intermetallic precipitate formation at the grain boundary of cast base aluminium alloy. So, significant improvement in mechanical properties were observed in copper and magnesium alloyed as-cast alloy and thermally aged conditions. This is because of both intergranular and

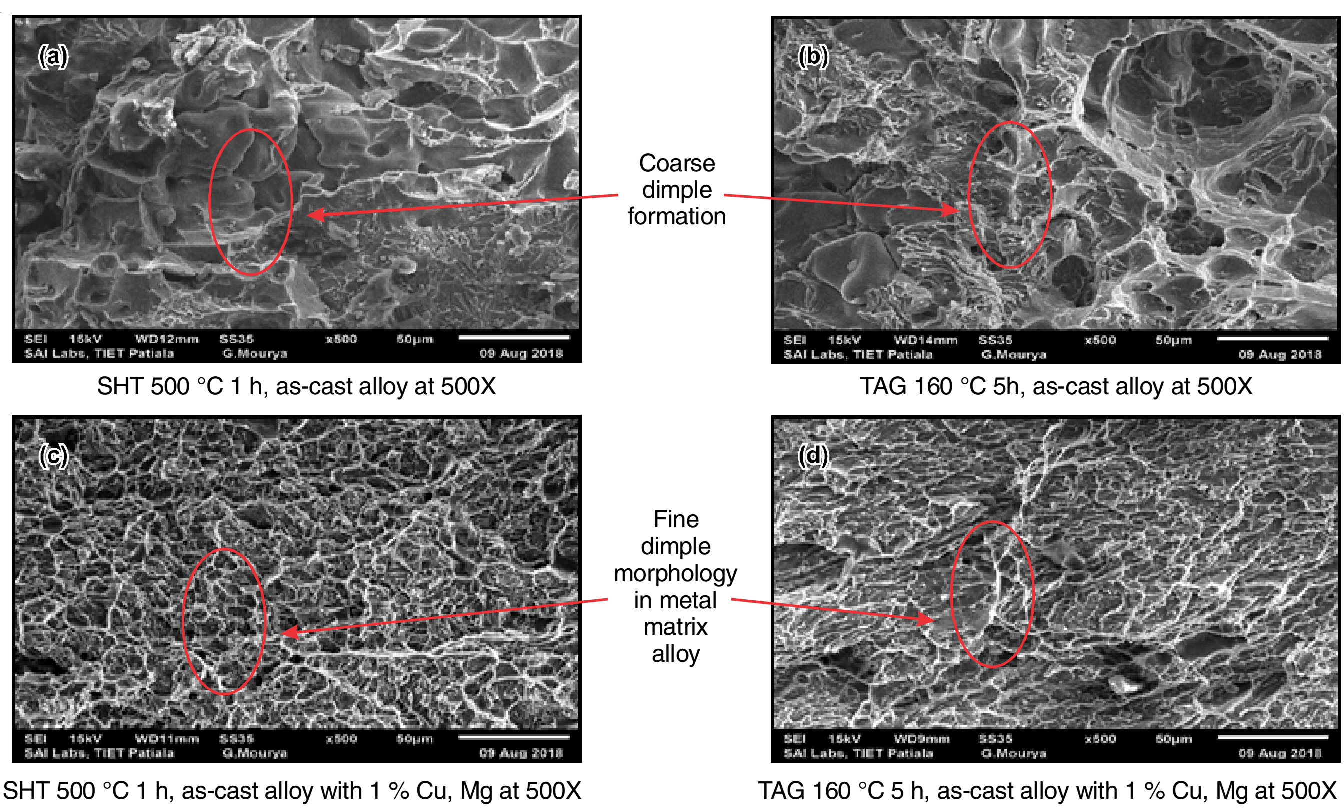

Fig. 4. Impact fractography at 500X for (a) as-cast aluminium, (b) TAG 160 °C 5 h, as-cast alloy (c) SHT 500 °C 1 h, as-cast alloy with 1 % Cu, Mg and (d) TAG 160 °C 5 h, as-cast alloy with 1 % Cu, Mg

transgranular fine dimples formation and increased nucleation of precipitates in aluminium alloy.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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