Experimental Analysis of Mechanical Properties of Aluminum Alloy LM-4 by Variation of Copper Content

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Abstract - *Copper is the only material that is having greatest impact of all alloying elements on the strength and hardness of aluminum cast alloys. Cu improves the machinability of aluminum alloys by increasing the hardness, making it easier to generate small cutting chips and fine machined finishes. On the other side, copper generally reduces the corrosion resistance of aluminum. Copper is generally used to increase the tensile strength and hardness through heat treatment. It also reduces the resistance to corrosion and hot cracking, or hot tearing.*

In this work, emphasis is given on the influences of copper in aluminum alloy LM-4. A total five alloy were made with variation of copper in the composition of 5%, 7%, 9%, and 11% using die casting process and their mechanical properties were calculated and analyzed. Tensile test bar was tested at room temperature. The ultimate tensile strength was increased with increase in copper content. The maximum ultimate tensile strength was obtained in LM-4 at 11% of copper.

Key Words: Aluminium Alloy, Copper, Tensile Strength, Hardness, Impact Strength

1. NTRODUCTION

The effect of Mg/Si ratio and Cu content on the stretch formability of aluminum alloys of the series 6xxx by using scanning electron microscopy (SEM), hardness tests, forming limit diagram measurements and tensile tests. It was found that the formability of Al–Mg–Si alloys decreases due to a decrease in the work hardening and strain-rate hardening capability, with the increase of Mg/Si ratio. It also have been investigated that with the addition of Cu improved the work hardening capacity, but slightly decreases the strain-rate hardening potential [1].The Aluminum alloys with silicon as a major alloying element are a class of alloys, which are the basis of many manufactured castings. This is mainly due to the outstanding effect of silicon in the improvement of casting characteristics, combined with other physical properties, such as mechanical properties and corrosion resistance [2]. The relationship between room temperature (RT) and high temperature fatigue behavior of A354 and C355 alloys and their micro structural features, in particular, secondary dendrite arm spacing (SDAS) and intermetallic compounds. The micro structural analyses and rotating bending fatigue tests emphasized that (i) SDAS influenced room temperature fatigue behavior of the peak-aged A354 and C355 alloys, while its effect on the overaged alloys at high temperature was negligible; (ii) fatigue cracks nucleated mostly from large inter metallic compounds; (iii) at room temperature, C355 alloy was characterized by higher fatigue strength in comparison to A354 alloy [3]. The Silicon is present as a uniformly distributed fine particle in the structure. However, when the primary silicon appears as coarse polyhedral particles, the strength properties decrease with increasing silicon content, but the hardness goes on increasing because of the increase in the number of silicon particles [4]. A linear single variable model for precipitation heat treated Al-Zn-Mg-Cu aluminum alloy hardness and yield strength described. Based on the major alloying elements and the strengthening precipitate compositions, a concept model was developed. A Refined composition model was subsequently developed to account for the effect of minor alloying (Mn) and impurity elements (Fe, Si). The model was also valid refined composition for predicting yield strengths of Al-Zn-Mg-Cu-Zr aluminum alloys [5].Activation energy for recrystallization on homogenized samples which were rolled up to the maximum possible reduction in area (~75% by iso conversion methods using differential scanning calorimetry data, whereas, stored strain energy was determined by X-ray diffraction analysis. It was analyzed that for the same sample the activation energy for recrystallization interrelated well with the stored energy by optical and transmission electron microscopy, Micro structural evolution was also analyzed. The cry rolled annealed sample showed an improved yield strength with a reasonable ductility. The YS found to be 10 times higher than that of the cast homogenized sample. This is attributed to the recovery of low angle grain boundaries, increasing grain boundary spacing, formation of nano twins and decrease in the dislocation density without any recrystallization [6].Al-Si alloys find wide application in the marine, electrical, and automobile and aircraft industries because of high fluidity, low shrinkage in casting, high corrosion resistance, good weld-ability, easy brazing and low coefficient of thermal expansion [7]. This Al-Cu phase diagram shown only goes up to ca 60%, by weight, of Copper and is “split” at around 54wt%Cu by a particular phase. This "split" means that the two parts of the diagram must be considered separately. The diagram up to the 54% point is very similar to the "standard" phase diagram. The eutectic composition is at 33%Cu/67%Al, and the T_e is ca. 550 K. A 25%Cu/75%Al composition is known as a hypoeutectic alloy A 36%Cu/64%Al composition is correspondingly called hypereutectic [8].

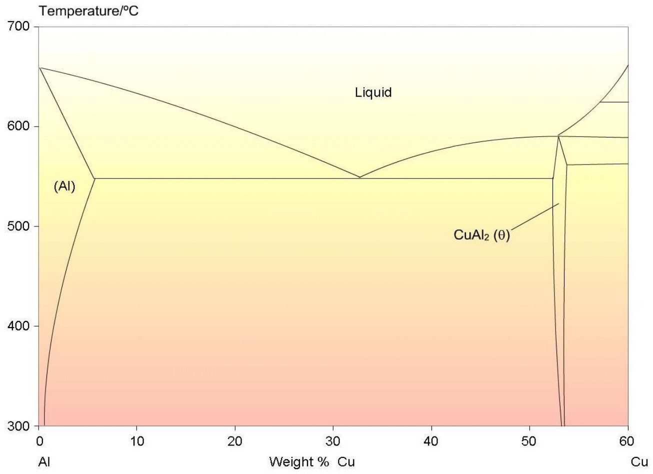


Figure 1: phase diagram of Aluminum-Copper [8]

The influence of the Si content of the aluminum alloys on their wear resistance has been well documented and eutectic alloys are reported to have better wear resistance than those of hypoeutectic and hypereutectic composition. Manganese is also able to change the morphology of the iron-rich phases from platelets to a more cubic form or to globules. These morphologies improve tensile strength, elongation, and ductility [9]. The effect of five different heat treatment methods as peak aging (T6), over aging (T74), high temperature and subsequently low temperature aging (HLA), retrogression and raging (RRA) and double retrogression and raging (DRRA) on strength, fracture toughness and microstructure of 7N01 aluminum alloys by by optical microscopy (OM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). The strength and fracture toughness of the five samples are tested. The results showed that 7N01 Al-alloy treated at T6 condition has high strength but low fracture toughness. Compared with T6 treatment, T74 and HLA treatments increase the fracture toughness by 67% and 90% respectively, while the strength decrease by 9% and 17%. RRA process which improves the fracture toughness without sacrificing strength, was a proper treatment method for 7N01. The fracture toughness of DRRA treated alloy was much lower than that of RRA. Quantitative analysis through TEM images showed that the heat treatment affects the mechanical properties of 7N01 Al-alloy highly through changing the precipitates in grains and on grain boundaries [10]. The relation between ageing and retrogression temperatures on Al 6061 alloy on hardness and ultimate tensile strength (UTS) was studied. It was found that higher UTS and hardness were obtained at elevated ageing, retrogression temperatures, and lowest retrogression time. Alloy ultimate tensile strength has been improved by controlling these parameters, showing a reduction in time consumption during the thermal treatment. A relationship has been established between UTS, hardness, and time/temperature for ageing and retrogression regimes by multiple linear regression method. For optimized ageing temperature and retrogression time- temperature, in order to obtain both specific UTS and hardness, this correlation can be used [11]. Aluminum and aluminum alloy are gaining huge industrial significance because of their outstanding combination of mechanical, physical and tribological properties over the base alloys. These properties include high specific strength, high wear and seizure resistance, high stiffness, better high temperature strength, controlled thermal expansion coefficient and improved damping capacity [12]. Several methods for estimating fatigue properties of wrought aluminum alloys from simple tensile data or hardness was discussed. Among them, Park-Song modified Mitchell's method provided the best estimation results in low fatigue life regime [13]. The presence of additional elements in the Al-Si alloys allows many complex intermetallic phases to form. Copper is a potent precipitation-strengthening agent in aluminum. Cu additions up to about 5% lead to alloys with high strength and good toughness when subject to natural or artificial aging. The addition of Cu increases considerably the strength of Al–Si alloys, due to precipitation of dispersed Al_2Cu (θ) phase during aging. The strengthening contribution from precipitation is typically a function of both precipitate size distribution and volume fraction [14].

The scanning electron microscope (SEM) microstructures of the five samples of 6351 aluminum alloy with different contents of copper with 400x magnification as shown in Fig. 2. Porosity in aluminum alloys is classified into two kinds: (i) macro porosity (~1–10 mm), which is mainly comprised of massive shrinkage cavities, and occurs in long-freezing range alloys, caused by failure to compensate for solidification shrinkage, and (ii) micro porosity (~1–500 μm), distributed more or less homogeneously, due to the failure to feed inter dendritic regions, and the precipitation of dissolved gases (i.e., gas porosity). In all aluminum alloys samples investigated was observed the two types of porosity like marked in yellow arrows in Fig. 2 [15].

The mechanical properties of aluminum, nylon, GFRP, aluminum-GFRP composite & aluminum-nylon composite were found by using experimental method, The deflection of aluminum composite beams is less than that of pure material beams, the natural frequencies of pure materials (GFRP & Nylon) are larger than those of composite beams made by them if nylon is taken as synthetic fiber with Al, but if GFRP is taken then its deflection is found to be increased when compared to pure GFRP. So, nylon suits good to make composite beam with Al as compared to other synthetic fibers like GFRP [16, 17].

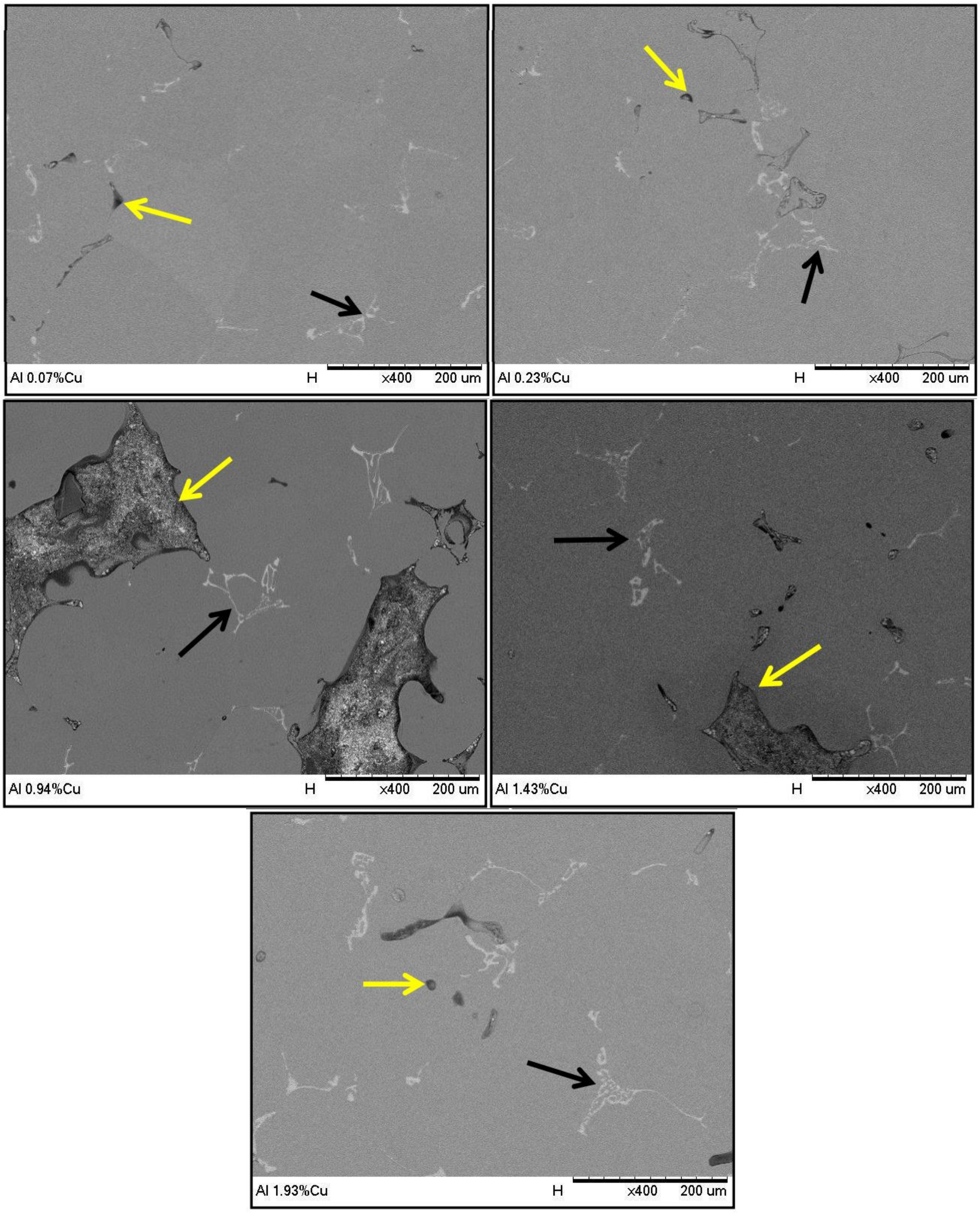


Figure 2: Microstructures of the 6351 aluminum alloy samples with different copper content; porosity (yellow marked); Al(MnCuFe)Si constituent (black marked) [15]

The addition of copper as main alloying element (mostly range 3–6 wt. %, but can be much higher), with or without magnesium as alloying constituent (range 0–2 %), allows material strengthening by precipitation hardening, resulting in very strong alloys. Also the fatigue properties are very good for this series. Copper tends to precipitate at grain boundaries, making the metal very susceptible to pitting, intergranular corrosion and stress corrosion [18]. Up to 12 wt. % copper the strength of the alloy can increase through precipitation hardening, with or without the presence of Mg; Hardening is achieved through the precipitation of Al2Cu or Al2CuMg intermetallic phases during ageing which leads to strengths second only to the highest strength 7xxx series alloys [19]. The influence of Ni on the overall properties of thin film, composition of Al–Cu–Ni which was deposited by thermal evaporation. The chemical composition was detected by energy dispersive X-ray spectroscopy and showed a compositional spread of approximately 20 at. % Ni. Decreasing the Ni content in the Al–Cu–Ni thin films resulted in an increased grain size and characteristic surface microstructure evolution. Chemical dissolution experiments have shown that Ni is enhancing the chemical stability of Cu, excepting inside the compositional region between 7 and 13 at% Ni [20]. The ultimate tensile strength of the alloy improved as compared to LM 12, the solidifications temperature for Al- Alloy reduces and this is an important factor to consider which temperature the heat treatment not should exceed. When increase the silicon content then the melting point of aluminum alloy is decreases whereas fluidity was increases [21, 22]. The hardness measurements to characterize the early stages of precipitation in three Al–Mg–Si alloys with different Cu contents (Al–0.51 at.% Mg–0.94 at %Si, with 0.01 at.%, 0.06 at.%, or 0.34 at.% Cu) at a range of single and multi- stage heat treatments to evaluate the changes in precipitation processes. Three ageing temperatures were investigated, 298 K (natural ageing), 353 K (pre-ageing) and 453 K (automotive paint-bake conditions). The Cu content had significant effects on the microstructural evolution within the alloy. Formation of clusters which can act as precursors of elongated precipitates during paint-baking was found to be enhanced with increasing Cu content. This improved the paint-bake hardening response and mitigated the deleterious effects of natural ageing [23]. The effect of Mg level on the microstructure and mechanical properties for die-cast Al – Si – Cu alloys under the as cast, the solutionised, and the solution and aged conditions was investigated. It was found that the Mg additions resulted in an effective strengthening to the alloy under both the as-cast condition and the solution and aged condition showed by SEM and TEM analysis. In the die-cast Al–Si–Cu alloys, the lamellar and blocky Al2Cu (Si) were formed overall the experimental alloys, but the irregular Al-Cu-Mg-Si intermetallic were emerged when Mg content was higher than 0.32wt%. The addition of Mg offered extra strengthening after the solution and ageing. Mg content can be controlled at a level up to 0.73wt% for increasing the strength with acceptable ductility under as-cast and heat treatment conditions [24]. The deformation behavior of an aluminum–lithium alloy heat treated to different tempering conditions at high strain rate in compression using a direct impact Hopkinson Pressure bar was investigated. Detailed microstructural investigation was carried out using electron back scatter diffraction and bulk crystallographic texture was determined using X-ray diffraction. The naturally aged sample showed less propensity to adiabatic shear band formation and therefore, highest toughness, compared to artificially aged samples. This can be attributed to higher resistance to instability by prolonged strain hardening from dislocation– precipitate interaction in the underage sample compared to peak and over aged samples under dynamic loading conditions. The single stage peak-aged sample provides the best combination of high toughness with stable microstructure amongst the differently aged samples [25].

2. EXPERIMENTAL PROCEDURE

2.1 Casting

For casting process different metals such as alumimium, copper, magnesium, silicon, iron, manganese, nickel, zinc lead, tin, titanium was melted one by one according to there melting points i.e metal with highter melting point was melted first and so on. A specimen (casted product) was obtained by the combination of all these metals.

The amount of heat that must be removed from a casting to cause it to solidify is directly proportional to the amount of superheat and the amount of metal in the casting, or the casting volume. Conversely, the ability to remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted and the insulating value of the mould. These observations are reflected in Chvorinov's Rule, which states that t_f, the total solidification time, can be computed by

$$t_f = \mathrm{C}\left[\frac{\mathrm{V}}{\mathrm{A}}\right]^{\mathrm{n}}$$

Where V is the volume of the casting, A is the surface area, C is the mould constant, n is a constant, which varies from 1.5 to 2.0 (2 in Chvorinov's work).

The total solidification time is the time from pouring to the completion of solidification and mould constant C depends on the characteristics of the metal being cast (its density, heat capacity, and heat of fusion), the mould material (its density, thermal conductivity, and heat capacity), the mould thickness, and the amount of superheat. Chvorinov's rule is one of the most useful guide to the students of foundry engineering. It provides a powerful general method of tackling the feeding of castings to ensure their soundness and producing castings with improved structure and properties. Since a feeder and a casting are both within the same mould and fill with the same metal under the same conditions, Chvorinov's rule can be used to ensure that the casting will solidify before the feeder by designing a feeder with a higher modulus than the casting. Different cooling rates and solidification times can produce substantial variation in the resulting structure and properties. For instance, die casting, which uses metal moulds, has faster cooling and produces higher-strength castings than sand casting, which uses a more insulating mould material.

Derivation of Chvorinov's Rule has analyzed the heat transfer within a theoretically infinite mould filled with liquid metal and suggested that the distance travelled by the solidification front, x [26]

$$x = \eta\sqrt{\mathrm{t}}$$

Whereη is a constant (cm $s^{-1/2}$) and t is the solidification time (s). Schwartz also suggested that, for one dimensional heat flow, the temperature at the mould/metal interface, T_i , is assumed to be constant and can be calculated as

$$T_i = \frac{T_m}{1+\sqrt{\frac{b_m}{b_s}}\,erf\left(\frac{\eta}{2\sqrt{\alpha_s}}\right)}$$

Where Tm is the melting temperature (°C) (assuming no solidification interval), b_m and b_s are the heat diffusivity of mould and solidifying metal (cal cm^{-2} s^{-1} C^{-1}), and αs is thermal diffusivity of solidifying metal (cm^2 s^{-1}). The diffusivity is often measured as the product of KρC, where K is thermal conductivity (Cal cm^{-1} $s^{-1}C^{-1}$).and C is the specific heat (Cal g^{-1} C^{-1}).

The heat diffusivity ratio is small for sand moulds, and hence Ti is lower than Tm by only about 2%. Therefore, the amount of heat lost from the solidified layer would be negligible, and the surface temperature of metal in sand castings will not depend on the actual shape of the casting. Chvorinov proceeded to show that the solidification time of castings poured with no superheat can be expressed as [26]

$$t = \frac{\pi}{4b_m}\left\{\frac{L\rho_1}{T_m+T_0}\right\}^2\left(\frac{V}{A}\right)^2$$

In this work the tensile test at room temperature was conducted on a standard universal testing machine using ASTM code D638-02 a (Type-I) [27] as shown in Fig.3

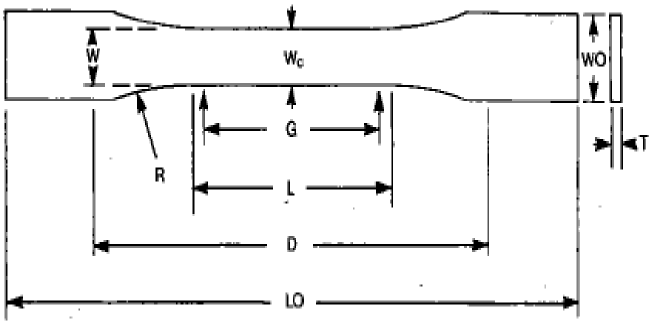
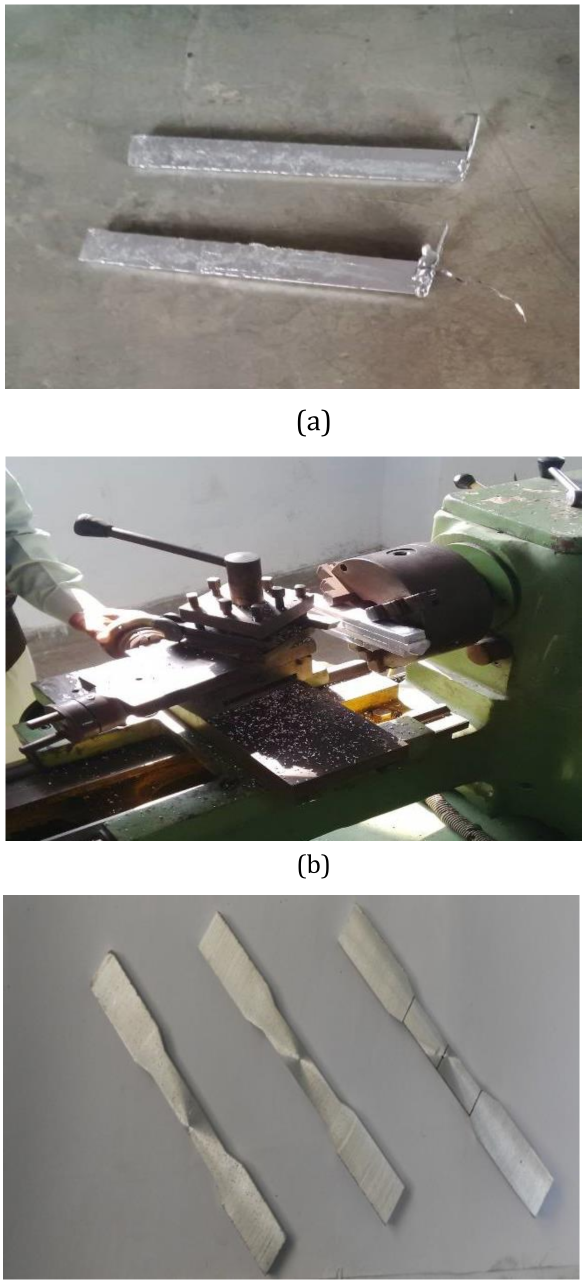


Figure 3: Drawing of Test Specimen [27]

Table 1: Dimensions of Test Specimen [27]

Specimen Dimension in (mm)			
Dimension (See Drawing)	Thickness 7 mm or Less		Over 7 to 14 mm
	Type-I	Type-II	Type-III
W- Width of Narrow section	13	6	19
L-Length of narrow section	57	57	57
WO-Width over all	19	19	29
LO Length over all	165	183	246
G-Gage length	50	50	50
D-Distance between grips	115	135	115



(a)

(b)

(c)

Figure 4 (a) Unfinished tensile specimen, (b) Machining of the specimen, (c) Final tensile specimen

3. RESULT AND DISCUSSION

3.1 Tensile Strength

The engineering stress-strain curve for pure Aluminum specimens with an enlarged scale, shows the strains from zero to specimen fracture. Here it appears that the rate of strain hardening diminishes up to UTS (Ultimate Tensile Strength).Beyond UTS, the material appears to strain soften, so that each increment of additional strain requires a smaller stress. [17]. Fig. 6 shows the stress strain curve for aluminum alloy LM-4 with variation of copper content from

5-11%. The tensile strength values lie in the range of 158.41 MPa to 234.31 MPa at room temperature.

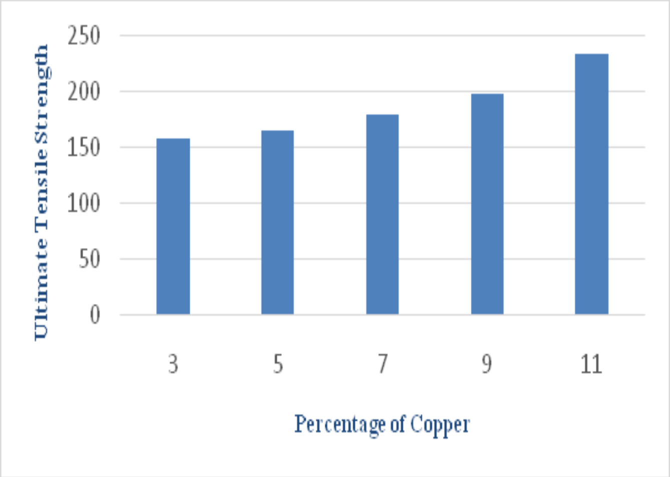
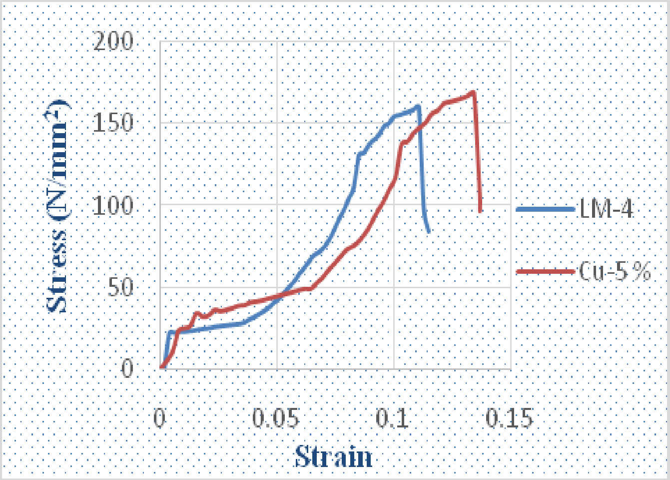
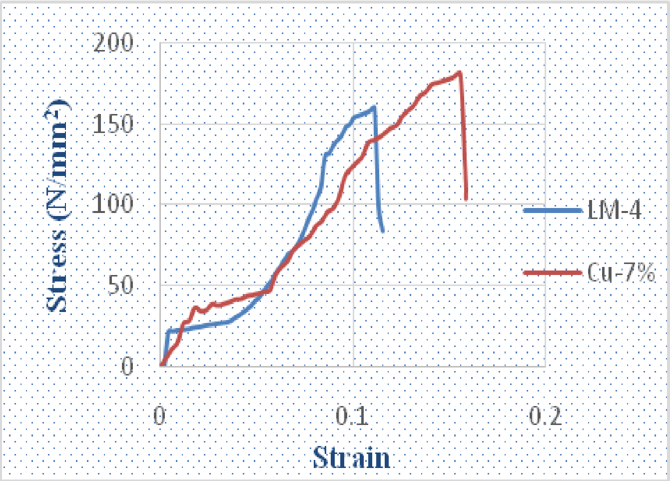


Figure 5: Ultimate tensile strength of aluminum alloy with variation of copper content

It was observed that increase in tensile strength attributed to the dissolution of the Cu rich intermetallic phase particles, mainly the Al_2Cu phase during solution treatment. It also resulted in solid solution hardening (the process mainly responsible for the observed increase in strength). The value of ultimate tensile strength of cast aluminum alloy are higher than the base aluminum alloy LM-4



(a)



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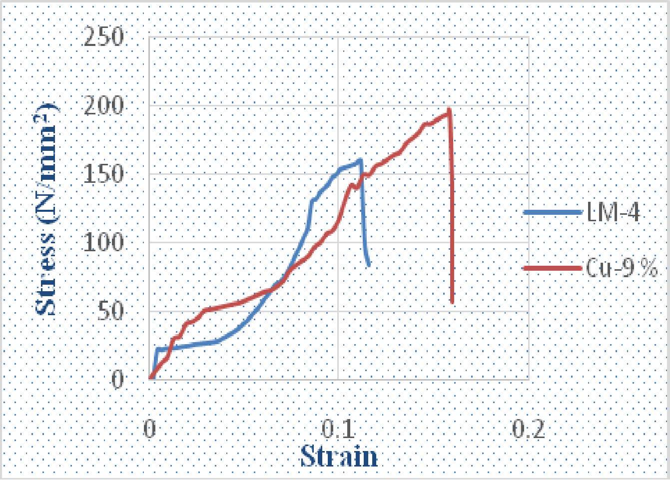
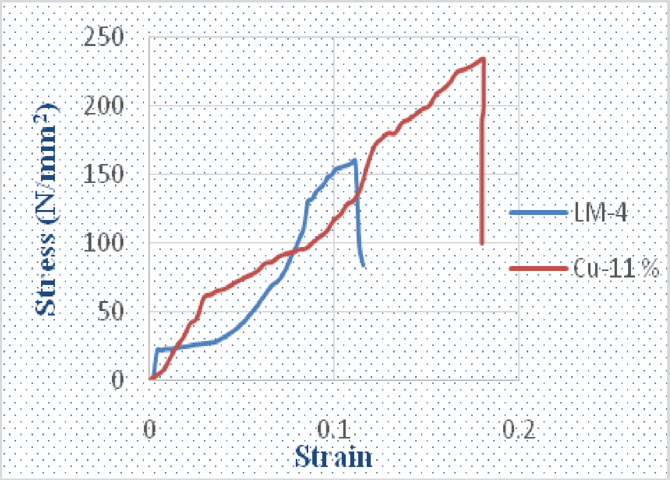


(c)



(d)

Figure 6: Comparison of LM-4 with (a) LM-4 with Cu-5%, (b) LM-4 with Cu-7%, (c) LM-4 with Cu-9%, (d) LM-4 with Cu-11%

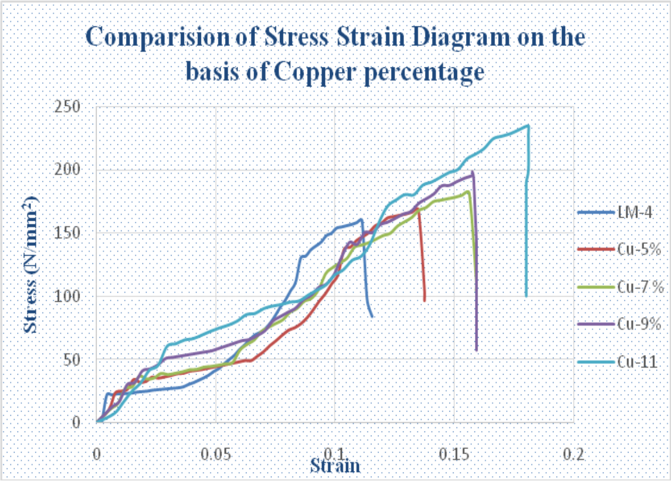
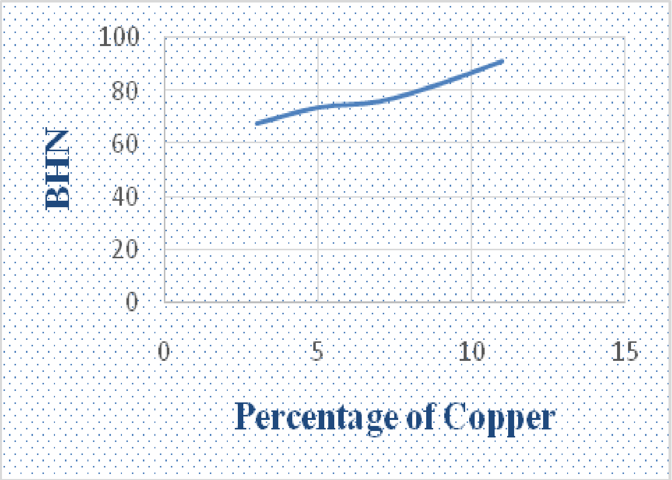


Figure 7: Combined Comparison of aluminum alloy LM-4

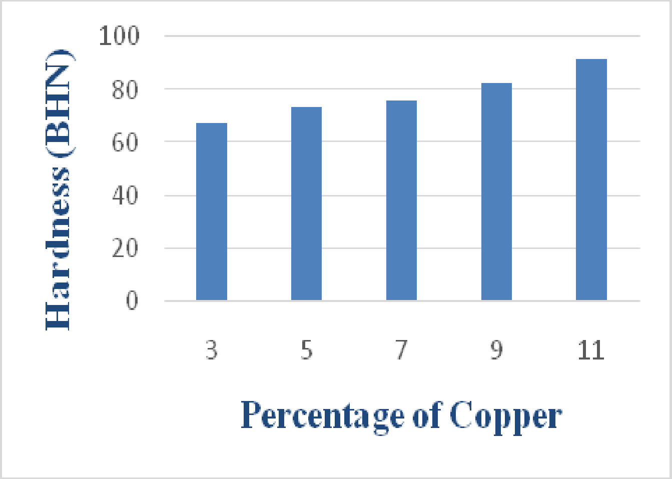
The improvement of tensile strength of cast aluminum alloy LM-4 with variation of Cu (5-11%) in comparison to base alloy is shown in Fig. 7. The aluminum copper alloy was successfully synthesized by the die casting method. Mixing of copper and aluminum particles lead to the cluster formation and hence resulted in the formation of improved alloy.

3.2 Hardness Test

Some alloys may improve their strength and hardness by the formation of uniformly small dispersed particles within the original matrix when the solidified alloy is subjected to heat treatment. These particles are called second phase particles and the strengthening achieved through the precipitation of these particles is known as age hardening. These precipitated particles strengthen the heat treated alloys by blocking the movement of dislocation. Al-Cu alloys are suitable for casting, as these alloys can be heat treated and can be age hardened [28, 29].



(a)



(b)

Figure 8: (a), (b) Hardness of aluminum alloy with variation of copper content

Fig. 8 (a & b) elucidate the variation of copper content on the hardness of cast aluminum alloy. It may be observed that hardness of cast aluminum alloy was increased with increased in copper percentage, the highest hardness value was obtained in cast Al-Cu-11% is 91.32 BHN whereas the minimum hardness was obtained in base aluminum alloy LM-4 .

3.3 Impact Test

Toughness is the ability of a material to absorb energy and plastically deform without fracturing. Impact test is a method for evaluating the toughness of engineering materials. The notched test specimen is broken by the impact of a heavy pendulum or hammer, falling at a predetermined velocity through a fixed distance.

Table 2: Impact testing result

Material	Dimension (mm)	Energy in (Jules)
LM-4	55x10x10	2
LM-4 (5% Cu)		2.5
LM-4 (7% Cu)		3
LM-4 (9% Cu)		4
LM-4 (11% Cu)		4.5

The Charpy test is performed by preparing the specimen as per IS: 1757 standard. The impact results are shown in table-2 and Fig. 10. It was found that the LM-4 with Cu 11% absorbed more energy than the other cast aluminum alloy because it contains less amount of aluminum.

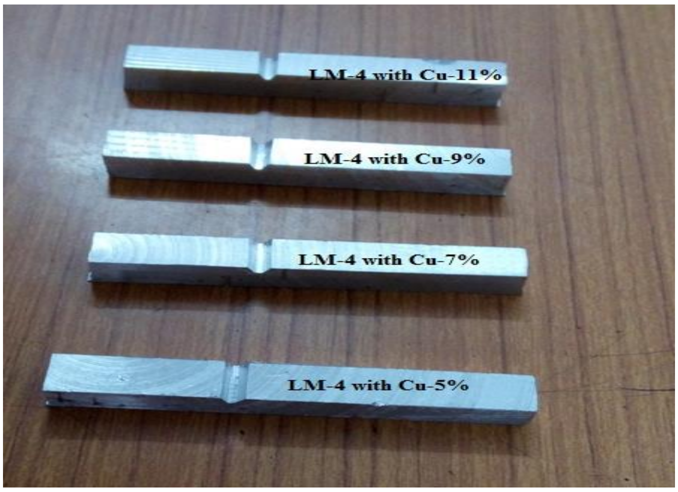


Figure 9: Impact Test Specimen

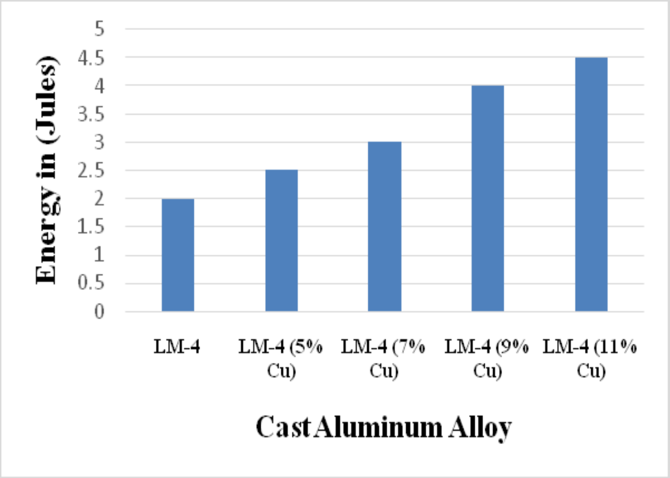


Figure 10: Variation between Energy and Cast Aluminum alloy

4. CONCLUSION

The mechanical properties of aluminum alloys LM-4 with variation of copper concentration were achieved using experimental method. The influence of copper concentration on mechanical properties of aluminum alloy LM-4 have been studied. Based on Mechanical testing, the following conclusion were observed.

- Increase in the copper concentration, increased the ultimate tensile strength.
- The Maximum ultimate tensile strength was 234.31 N/mm^2 in 11% of copper concentration in LM-4
- The Minimum ultimate tensile strength was obtained 158.41 N/mm^2 in base aluminum alloy LM-4.
- Further addition of copper, leads to the reduction of solidification temperature of aluminum alloy LM-4.
- Hardness was improved when concentration of copper increased, maximum hardness was obtained in LM-4 with 11% copper concentration.
- It was found that the LM-4 with Cu 11% absorbed more energy than the other cast aluminum alloy because it contains less amount of aluminum.

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