Influence of Magnesium on Mechanical Properties and Microstructure of Pure Aluminium

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***Abstract* :** This paper deals with the influence of alloying with Magnesium of Pure Aluminium on their microstructure and Mechanical Properties. The additional level of magnesium is 2.5, 4.5, 6.5& 8.5 weight percent. The presence of Magnesium performed two types of event in liquid Aluminium. One of these is solid solution strengthening which is confirmed by the hardness & Tensile Testing. Another one is the formation of intermetallic phases like Al3Mg2 (β - Phase) by a eutectic reaction. As the amount of Mg increases Intermetallics of Al-Mg (β - Phase) is increases in developed alloy. These intermetallics are located at the grain boundary and pushed towards the grain boundary during solidification which is confirmed by Microstructural Analysis with the help of optical microscopy and Scanning electron microscopy. Grain size measurement was also carried out to understand the grain refining effect of Mg. Mg addition showed remarkable grain refinement from grain size no 1 to 6. As Magnesium content increases hardness and tensile value is increasing up to 4.5 wt% Mg after that large amount of β - Phase is formed which is brittle in nature which quite reduces hardness and tensile value.

Keywords: Al-Mg Alloy, Microstructure, β - Phase, Tensile strength, Hardness, Grain Size.

1. Introduction:

Aluminium (Al) is second most overflowing metallic element from the earth. Aluminium and its alloy is comprehensively used as an engineering material because of its eccentric properties like light weight, good strength, formability, weldability and excellent atmospheric corrosion resistant. [1] The perticular elements added as alloying in aluminium are copper, magnesium, manganese, silicon and zinc. Depending on Alloying elements and tratment performance Aluminium alloy chiefly classified as cast and wrought , both of the classification are further subdivided into the groups heat-treatable alloys and non-heat-treatable alloys. [2]

From All wrought alloys, Aluminium -Magnesium(Mg) alloys (5xxx series) are most widely used in sports industries, Automobile Industries, Aerospace industries as they possess a good combination of mechanical properties and specially high strength to weight ratio. [3], [4] Magnesium notably improve the Tensile strength of Pure aluminium without unreasonably reducing the ductility. [4],[5] Magnesium is a chief alloying element in the 5XXX series of Aluminium alloys & these alloy are falling down in non heat treatable alloys category so principal event for strengthan the alloy is by solid solution strengthening and by restrict the grain growth [6],[7]. Mg has maximum solid solubility in an aluminium matrix which is 16.26 atomic weight percentage around 450^{o} C that is at eutectic temp and Eutectic reaction (I) as shown below involves the formation of aluminium solid solution (Alpha solid solution) and intermetallic compound of Al-Mg (beta phase).[8-10]

Liquid Aluminium → Alpha solid solution + Al_3Mg_2 (β - Phase) .... (I)

The equilibrium solid phases of the Al-Mg system consist of the face-centered cubic (Aluminium) solid solution and the second one is the close-packed hexagonal (Magnesium) solid solution. The compound of these two phases having approximate chemical composition Al_3Mg_2 has a complex FCC structure. [10]

Magnesium plays a key role in precepitation hardening by creating Guinier - Preston (GP) zones and precipitates. These precepitates restrict the disocation motion and changing the aluminium lattice by internal strain. Hence, provide strength to the alloy .The raising amount of Mg not only accelerated precipitation but also raising the amount of precipitation within the grains.[12-16] the possible ageing sequence is as follows. [17], [18]

Supersaturated solid solution → intermediate phase β '→ equilibrium phase β (Al_3Mg_2).

During Solidification, this phase is concentrated at the grain boundary. [3], [6], [15] Mg gives the grain refining effect in aluminium alloy. This remarkable grain refinement is observed as a result of Magnesium distribution at the grain boundary area. [19], [20]

Generally, Magnesium is added around 3-8%, which exhibit good mechanical properties, beyond 8% higher porosity was observed & dendrite structure also observed which reduces mechanical properties.[3],[17] This research article focuses on optimum Magnesium addition for good mechanical properties.

2. Experimental Details.

Aluminium alloys containing 2.5, 4.5, 6.5 and 8.5% Magnesium were prepared from 99.8% Pure Aluminium wire and 99.9% Magnesium Ribbon. Melting practice is carried out in an electric resistance furnace As shown in fig 1 with the help of graphite crusible. In which Aluminium is charged and after getting a processing temperature of around 720 ^{o}C, the addition of Magnesium in a range of 2.5%, 4.5%, 6.5% and 8.5% is carried out in a bath of liquid aluminium. Drossing and Degassing were carried out for better melting practice. To achieve uniform distribution and good properties stirring of the molten mixture is carried out and then the molten mixture is poured into a permanent metallic die made-up of mild steel containing 5 cast rods having 15 cm height & 2.5 cm diameter of each as shown in fig 2(a). After cooling & solidification casting is removed as shown in fig 2(b) then sampling was accomplish for various charectrization.

Chemical analysis of developing alloy was carried out with Bruker Q4 TASMAN advanced CCD based optical emission spectroscopy according to ASTM E1251:2017. Hardness testing acomplished by Brinell hardness tester at 250 Kg load using a ball indenter according to IS 1500 (Part 1): 2013. Tensile testing accomplished by a universal testing machine. Specimen Size for tensile testing is as shown in fig 3 The microstructure is developed by conventional metallography practice according to ASTM E407-07(2015) and was observed using Olympus GX-41 optical microscope and JEOL 5610 LV Scanning Electron Microscope with Energy Dispersive Spectroscopy (EDS) at different magnifications on 0.5%HF etched Surface. Grain Size Measurement is cacomplished by Optical microscope according to ASTM-112-13 practice. X-Ray Diffraction (XRD) with Pan Analytical X'pert Pro Machine is carried out for phase identification.

Fig.1 Elecrtric resistance furnace with controll unit.

Fig.2 (a) Metallic Die (b) Casting after solidification

Fig.3 Size of Tensile specimen

3. Result & Discussion

3.1 Chemical Analysis

The chemical composition of the developed alloy was listed in Table 1. Chemical aanalysis by Spectroscopy and EDS both confirms the recovery of Mg in developed alloy and taking an average of both the results for consideration. Some heavy elements like Si, Cu, and Fe were also present in minor quantities. Required amount of Mg is present for the formation of Al-Mg intermetallics.

Table 1. Chemical Composition of Aluminium (Al) - Magnesium (Mg) Alloy

Elements (%)	Pure Al	Al + 2.5% Mg	Al + 4.5% Mg	Al + 6.5% Mg	Al + 8.5 %Mg
Mg	0.001	2.461	4.537	6.305	8.794
Si	0.056	0.090	0.084	0.086	0.082
Zn	0.010	0.047	0.054	0.009	0.070
Fe	0.127	0.128	0.182	0.149	0.154

Cu	0.006	0.017	0.003	0.006	0.007
Al	99.78	96.87	94.74	93.08	90.47

3.2 Microstructural Analysis

By adopting a standard metallographic procedure polished samples were prepared for the observation. This observation was performed by optical microscope and scanning electron microscope. The typical Microstructure of pure aluminium and aluminum containing 2.5 wight percent Magnesium, 4.5 weight percent Magnesium, 6.5 weight persent Magnesium and 8.5 weight persent Magnesium are shown in Fig.4 which was taken by optical microscope and Fig 5 which were taken by scanning electron microscope.

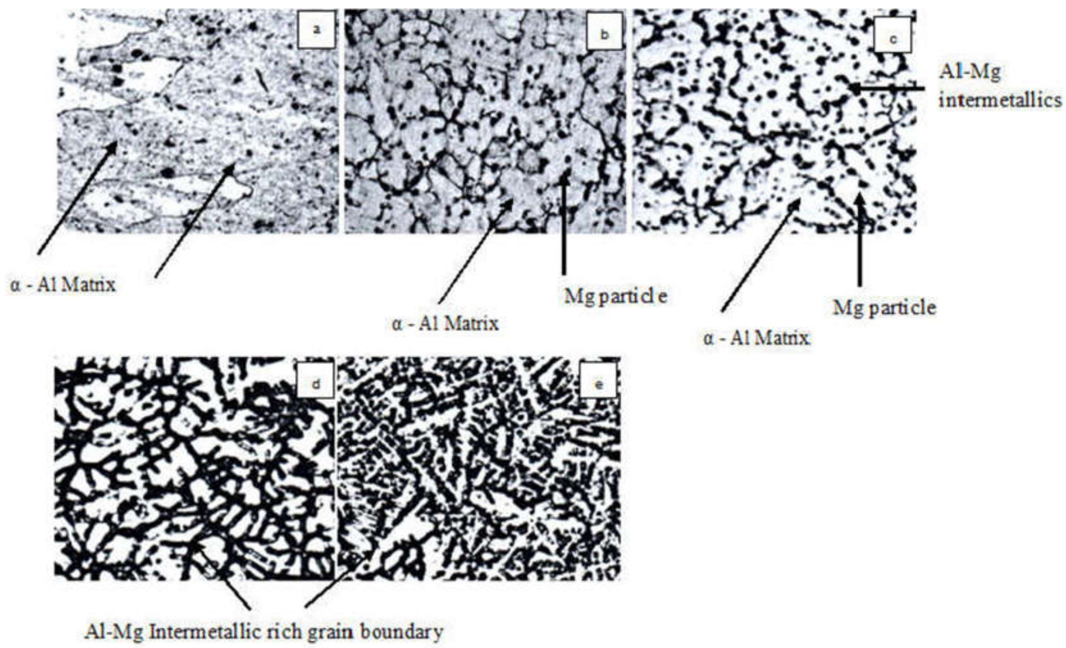

Fig.**4** Microstructure of (a) Pure Aluminium (b) Aluminium with 2.5% Magnesium (c) Aluminium with 4.5% Magnesium (d) Aluminium with 6.5% Magnesium (e) Aluminium with 8.5% Magnesium at 400X.

According to binary phase diagram of Aluminium Magnesium system, in the microstructure two phases will presence one is a solid solution of Aluminium i.e. α aluminium and another is an intermetallic compound of aluminium and magnesium i.e. β phase (Al_3Mg_2) which is form by eutectic reaction. This β phase is generally concentrated on the grain boundary. Fig 4 (a) Shows Microstructure of pure aluminium without the addition of magnesium containing only an aluminium matrix. Fig 4(b) shows the presence of Magnesium in a small dark circle and also at the grain boundary. In fig 4(c) presence of Mg in a small dark circle and also β phase presence at grain boundary were observed.

As the amount of Magnesium increases the clustering and gathering of Mg and the formation of Al-Mg Intermetallics increases. Due to that the thickness of grain boundary increases and also the network of grain boundary increases. This can be shown in fig 4 (d) and fig 4(e). As magnesium percentage increases microstructure changes from coarse grain to fine grain.

SEM images also indicate the presence of magnesium and α- aluminium matrix. The dark black portion shows the presence of magnesium and the grey portion was α - aluminium matrix. In fig 5(a) and 5(b) magnesium is in the form of the dark black circle and also some white small circle is observed; these are due to heavy elements present in raw material. As the magnesium content increases grain boundary formations increase as observed in fig 5(c) and 5(d). At a higher level of magnesium clustering of intermetallics of Al-Mg is observed in the dark portion as observed in fig 5(e).

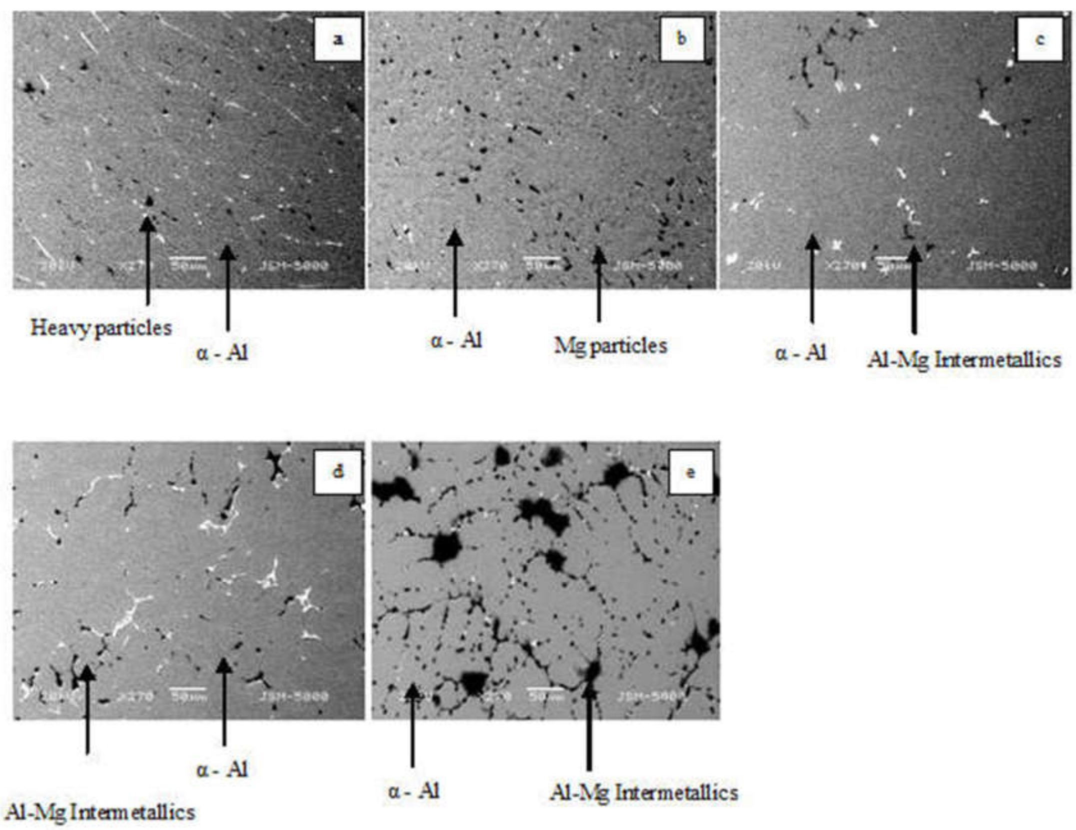

Fig.**5** SEM images of (a) Pure Aluminium (b) Aluminium with 2.5% Magnesium (c) Aluminium with 4.5% Magnesium (d) Aluminium with 6.5% Magnesium (e) Aluminium with 8.5% Magnesium at 270X in back scattered mode.

3.3 Xrd Analysis

The XRD was carried out using Cu as the anode material with a k-alpha wavelength of 1.54060 Å to characterize various phases present in the alloy. The scan range was 10° to 110°. Phase analysis of pure aluminium (A), Aluminium with 2.5% Magnesium (B), Aluminium with 4.5% Magnesium. Aluminium with 6.5% Magnesium (D), Aluminium with 8.5% Magnesium (EE) shows in fig 6.

Table **2**. Values of 2θ and d-spacing for pure aluminium and aluminum containing 2.5 weight percent Magnesium, 4.**5 weight** percent Magnesium, 6.5 **weight persent Magnesium** and 8.5 **weight persent** Magnesium.

Plane	Pure Al		Al+ 2.5% Mg		Al+ 4.5% Mg		Al+ 6.5% Mg		Al+ 8.5% Mg	
	2θ	d	2θ	d	2θ	d	2θ	d	2θ	d
(1 1 1)	38.4460	2.33959	38.2897	2.34877	38.2499	2.35113	38.1844	2.35501	38.0183	2.36492
(2 0 0)	44.6903	2.02612	44.5261	2.03321	44.4432	2.03681	44.3792	2.03960	44.2102	2.04700
(2 2 0)	65.0656	1.43236	64.8209	1.43718	64.7691	1.43820	64.6503	1.44056	64.4436	1.44468
(3 1 1)	78.1835	1.22160	77.9498	1.22468	77.7216	1.22770	77.5438	1.23007	77.3834	1.23222

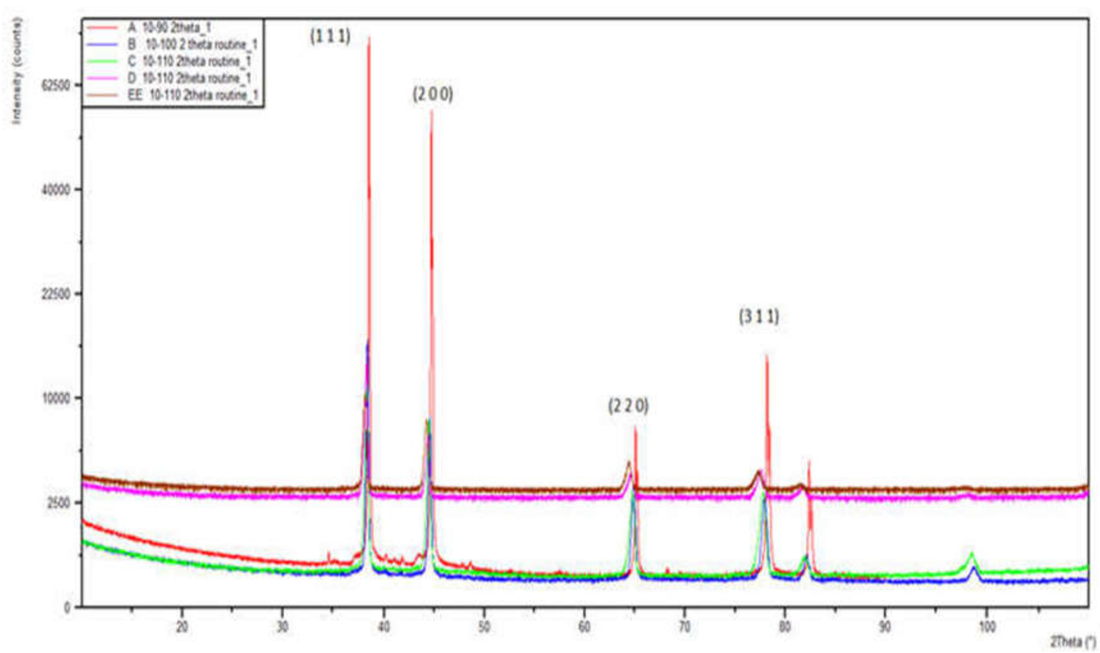

Fig.**6** XRD pattern of (A) Pure Aluminium (B) Aluminium with 2.5% Magnesium (C) Aluminium with 4.5% Magnesium (D) Aluminium with 6.5% Magnesium (EE) Aluminium with 8.5% Magnesium

All the alloys show α-Aluminium phase but as the Mg content, increasing intensity of the α-Aluminium phase is changing as shown in table 1. The peak of all planes shifted towards the left as the Mg content increases and also the area and height of the peak is changed as compared to the pure aluminium pattern which confirms the presence of Mg. Here, Peak for the beta phase is not observed may be due to less alloying element. [21], [22]

3.3 Hardness Measurements

Hardness testing was acomplished by a Brinell hardness tester at 250 Kg load for pure aluminium and aluminum containing 2.5 wight percent Magnesium, 4.5 weight percent Magnesium, 6.5 weight persent Magnesium and 8.5 weight persent Magnesium. BHN value of all developed alloy reported in fig 7. The result shows a continuously increasing hardness value compared to pure aluminium. This was observed due to precipitation hardening and formation of the secondary particles during solidification which promotes the hardening process and a remarkable change in hardness is observed. [3], [22], [23]

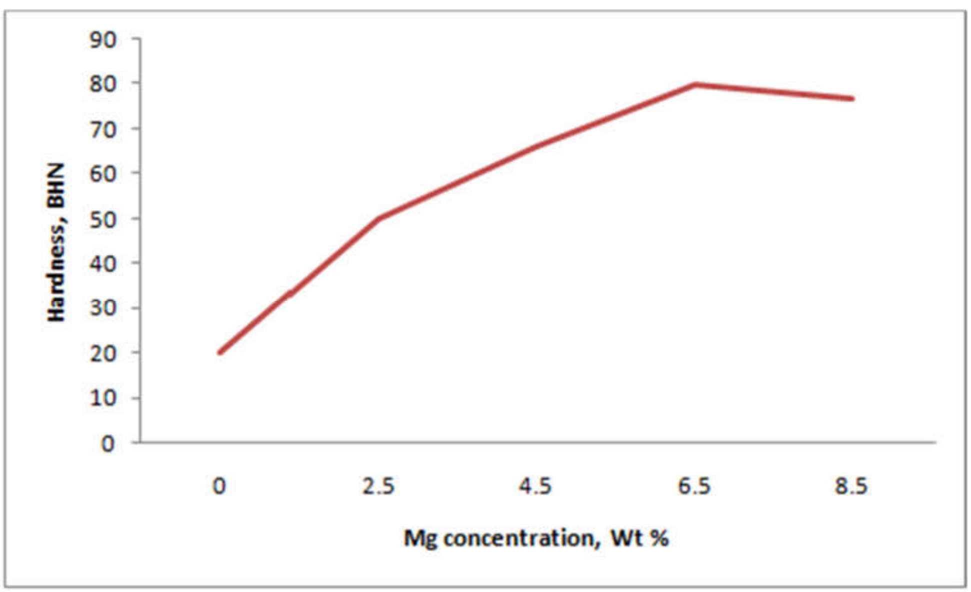

Fig.**7** Hardness value for Developed Alloy

3.4Tensile Testing

Tensile testing was acomplished by Universal Testing Machine at 250 kg load and observation is reported in fig 8.

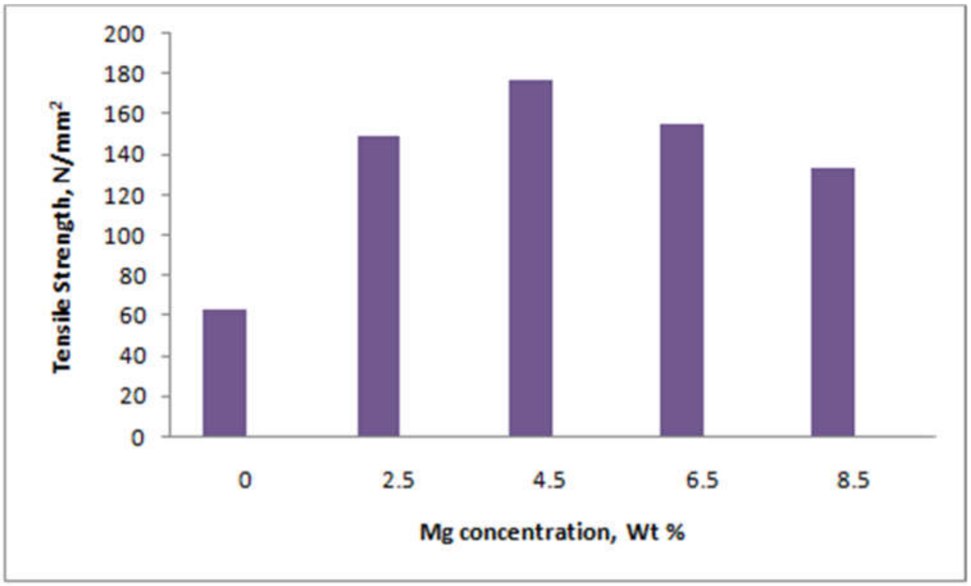

Fig.8 Tensile Strength of Developed Alloy

From the result and observation opines that as the amount of Magnesium increases, the tensile value increases. Magnesium gives rise to formation of intermetallics compounds and these phases improve the strength of the pure aluminium by solid solution strengthening. These phases are generally located at the grain boundary. As the concentration of Mg is increased grain boundary thickness is increased. This makes the grain boundary brittle and weakens so at higher levels of Mg a slight reduction in strength is observed. [3], [22], [24]

3.5 Grain Size measurement

Average ASTM grain size number is measured with the help of optical microscope, all result are reported in Table 3

Table **3** Average ASTM grain size number of pure aluminium **and aluminum** containing 2.5 **wight percent** Magnesium, 4.**5 weight** percent Magnesium, 6.5 **weight persent** **Magnesium** and 8.5 **weight persent** **Magnesium.**

Sr.No	Alloy	Average ASTM grain size number
1	Pure Aluminium	1

2	Pure Aluminium + 2.5% Magnesium	5
3	Pure Aluminium + 4.5% Magnesium	5-6
4	Pure Aluminium + 6.5% Magnesium	6-7
5	Pure Aluminium + 8.5% Magnesium	6-7

From observation it has been noted that as the amount of Magnesium increases the grain size number increases. Generally Magnesium and its intermetallics is gathering next to the grain boundaries or on the grain boundary and act as network former and reduce grain size. Mg acts as a grain refiner and after addition of magnesium Microstructure of pure aluminium changes non uniform to uniform with equiaxed grain. [18]

4. Conclusion

From all the observations and results,

i. Magnesium successfully added by conventional melting practice in pure aluminium.
ii. Magnesium profoundly affects the properties of pure Aluminium.
iii. Magnesium and its intermetallics uniformly distributed at the grain boundary upto 4.5% Magnesium after that clustering of intermetallics at the grain boundary was observed. For the reason the grain boundary was infirm and detoriate the mechanical properties.
iv. Magnesium content increases hardness value increases 4 fold and optimum hardness observed at 6.5% Mg.
v. Tensile strength is increases 3 fold and optimum tensile strength is observed at 4.5% Mg.
vi. Aluminium 4.5 % mg shows good combination of mechanical properties.

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References

1) Elwin L. Rooy, “ASM Metal Handbook Properties and Selection: Non- Ferrous Materials and Special Purpose Alloys", ASM International, Vol.02, pp. 17-44, 1992.
2) Nafsin, N., & Rashed, " Effects of Copper and Magnesium on Microstructure and Hardness of Al-Cu-Mg Alloys", International Journal of Engineering and Advanced Technology , Vol.02, pp. 533–536,2013.
3) Panchal, H. N., & Rao, V. J. (2019). Influence of Mg on Micro-Mechanical Behaviour of as Cast Al–Mg System. Physics of Metals and Metallography, 120(9), 881–887. https://doi.org/10.1134/S0031918X19090126
4) Lucky Agrawal, Rakesh Yadav, and Abhished Sexena, Effect of magnesium content on the mechanical propertiesof Al–Zn–Mg alloys,” Int. J. Emerging Technologies 3 (1), 137–140 (2012).
5) Sidney H Avner , Introduction to physical metallurgy ,1997, Mcgraw hill production, , P. 481-495.

6) Vuelvas, S., Valdez, S., & Gonzalez-Rodriguez, J. G. (2012). *Effect of Mg and Sn Addition on the Corrosion Behavior of an Al-Mn Alloy in 0.5 M H 2 SO 4*. *Int. J. Electrochem. Sci* (Vol. 7). Retrieved from www.electrochemsci.org
7) Summers, P. T., Chen, Y., Rippe, C. M., Allen, B., Mouritz, A. P., Case, S. W., & Lattimer, B. Y. (2015). Overview of aluminum alloy mechanical properties during and after fires. *Fire Science Reviews*, *4*(1). https://doi.org/10.1186/s40038-015-0007-5
8) Joseph R. Davis, Introduction To Aluminum And Aluminum Alloys", ASM International, 1993, PP.30-32
9) Goel, R., Upadhyay, M., Maulik, O., Prasad, Y. V. S. S., & Kumar, V. (2014). Effect of Magnesium on Strain Hardening Response of Al-Mg- Mn based Alloys. *Procedia Materials Science*, *5*, 1241–1247. https://doi.org/10.1016/j.mspro.2014.07.435
10) George E. Totten, " Handbook of Aluminum – Physical Metallurgy & processes ", Marcel Dekker Inc, pp 120-126, 2003.
11) Murray, J. (1982). The Al−Mg (Aluminum−Magnesium) system. *Journal of Phase Equilibria*, *3*(1), 60–74.
12) Król, M., Tański, T., Snopiński, P., & Tomiczek, B. (2017). Structure and properties of aluminium–magnesium casting alloys after heat treatment. *Journal of Thermal Analysis and Calorimetry*, *127*(1), 299–308. https://doi.org/10.1007/s10973-016-5845-4
13) Schoenitz, M., & Dreizin, E. L. (2003). Structure and properties of Al-Mg mechanical alloys. *Journal of Materials Research*, *18*(8), 1827–1836. https://doi.org/10.1557/JMR.2003.0255
14) A. Barbucci, P. L. Cabot, G. Bruzzone, and G. Cerisola, "Role of intermetallics in the activation of Al-Mg-Zn alloys," J. Alloys Compd., vol. 268, no. 1–2, pp. 295–301, 1998.
15) He, J., Wen, J., & Li, X. (2011). Effects of precipitates on the electrochemical performance of Al sacrificial anode. *Corrosion Science*, *53*(5), 1948–1953. https://doi.org/10.1016/j.corsci.2011.02.016
16) Nozato, R., & Ishihara, S. (1980). CALORIMETRIC STUDY OF PRECIPITATION PROCESS IN Al-Mg ALLOYS. *Transactions of the Japan Institute of Metals*. https://doi.org/10.2320/matertrans1960.21.580
17) Caceres, C. H., Davidson, C. J., Griffiths, J. R., & Wang, Q. G. (1999). The effect of Mg on the microstructure and mechanical behavior of Al-Si-Mg casting alloys. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, *30*(10), 2611–2618. https://doi.org/10.1007/s11661-999-0301-8
18) Birol, Y. (2012). Effect of solute Mg on grain size of aluminium alloys. *Materials Science and Technology (United Kingdom)*, *28*(8), 924–927. https://doi.org/10.1179/1743284712Y.0000000024
19) El-Hadad, S., Moussa, M. E., & Waly, M. (2020). Effects of Alloying with Sn and Mg on the Microstructure and Electrochemical Behavior of Cast Aluminum Sacrificial Anodes. *International Journal of Metalcasting*. https://doi.org/10.1007/s40962-020-00483-6
20) Garcia-Garcia, F. J., Chiu, T. Y., Skeldon, P., & Thompson, G. E. (2015). Effect of magnesium and titanium on the cathodic behaviour of aluminium in nitric acid. *Surface and Interface Analysis*, *47*(1), 30–36. https://doi.org/10.1002/sia.5640
21) Kawasaki, M., Ahn, B., Lee, H., Zhilyaev, A. P., & Langdon, T. G. (2016). Using high-pressure torsion to process an aluminum-magnesium nanocomposite through diffusion bonding. *Journal of Materials Research*, *31*(1), 88–99. https://doi.org/10.1557/jmr.2015.257
22) Goel, R., Upadhyay, M., Maulik, O., Prasad, Y. V. S. S., & Kumar, V. (2014). Effect of Magnesium on Strain Hardening Response of Al-Mg- Mn based Alloys. *Procedia Materials Science*, *5*, 1241–1247. https://doi.org/10.1016/j.mspro.2014.07.435
23) Correa, R., Sánchez, H., & Calderón, J. A. (2011). *Improvement of micro-hardness and electrochemical properties of Al-4%Cu-0.5%Mg alloy by Ag addition Mejoramiento de la micro-dureza y de las propiedades electroquímicas de la aleación Al-4%Cu-0.5%Mg mediante la adición de Ag*. *Rev. Fac. Ing. Univ. Antioquia N.°* (Vol. 61). Diciembre.
24) Girisha H N, & Sharma, K. V. (2012). *Effect of magnesium on strength and microstructure of Aluminium Copper Magnesium Alloy*. *International Journal of Scientific & Engineering Research* (Vol. 3). Retrieved from http://www.ijser.org.