International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:13, No:9, 2019

Investigation of Mg and Zr Addition on the Mechanical Properties of Commercially Pure Al

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***Abstract*—**The influence of Mg and Zr addition on mechanical properties such as hardness, tensile strength and impact energy of commercially pure Al are investigated. The microstructure and fracture behavior are also studied by using Optical and Scanning Electron Microscopy. It is observed that magnesium addition improves the mechanical properties of commercially pure Al at the expense of ductility due to formation of β'' (Al_3Mg) and β' (Al_3Mg_2) phase into the alloy. Zr addition also plays a positive role through grain refinement effect and the formation of metastable $L1_2$ Al_3Zr precipitates. In addition, it is observed that the fractured surface of Mg added alloy is brittle and higher numbers of dimples are observed in case of Zr added alloy.

***Keywords*—**Al-alloys, hardness, tensile strength, impact energy, microstructure.

I. Introduction

COMMERCIALLY pure aluminum belongs to 1xxx series of aluminium alloys. It has very low strength when compared to the other series of aluminum alloys [1], [2]. Alloying elements' addition is one of the standard methods to produce superior properties of aluminum alloys which can meet a broad variety of structural applications [3]-[5]. Alloying elements when added to aluminum alloys may create property of precipitation hardening, solid solution hardening, dispersion strengthening, grain refining, modifying metallic and intermetallic phases, suppression of grain growth at elevated temperatures, wear resistance and other tribological properties. Aluminium-magnesium casting alloys have a wide range of application, especially in the automotive and ship borne industry that is directly related to their good mechanical properties [6], [7]. These alloys are differentiated by super castability and exceptional corrosion resistance due to presence of high magnesium [8], [9]. However, high strength and appropriate elongations are required of aluminium casting alloys for structural components. Grain morphology, grain size, dendrite arm spacing, second-phase particles and fine precipitates on microstructure homogeneity are critical factors affecting mechanical properties of cast parts [6], [10]-[12].

Additions of transition metals like zirconium leads to formation of $L1_2$-orderd Al_3Zr phase from the melt. It is very stable against particle coarsening. It causes additional distribution of dislocations which pin grain boundaries and inhibit recrystallization. The Al_3Zr particles form from the melt as a primary phase during rapid solidification, act as nuclei for the solidification of Al, and Zr can thus operate as grain refiner of Al [13]-[15].

Based on the above point of view, Mg is added to commercially pure Al used in this study to form the binary alloy. The other element Zr is subsequently added with Mg to study their mutual effect on the mechanical properties of cast Al at room temperatures.

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II. Experimental Procedure

The alloys studied in the work were prepared by melting commercial pure aluminum (99.7%), industrial pure magnesium (99.9%) and master alloys of Al–10% Zr. A resistance heating furnace was used for this melting and the final temperature was kept at 780 ± 15 °C. Then the melt was allowed to be homogenised under stirring at 700 °C and poured in a preheated mild steel mould (200 °C) size of 17 × 150 × 250 in millimeter. All the alloys were analysed by wet chemical analysis and spectrochemical method simultaneously to determine the chemical composition. The chemical compositions of the alloys are given in Table I. Hardness of the investigated alloys as cast state was measured with the use of Brinell hardness tester. The Brinell hardness test method consists of a 5 mm diameter steel ball subjected to a load of 250 kg sustained for 30 seconds. An average of ten concordant readings was taken as the representative hardness of a sample. Tensile testing was performed in an Instron testing machine at room temperature. The strain rate of the machine was $10^{-3}s^{-1}$. The samples were prepared to ASTM standard. Young's modulus and Strain-hardening exponent are calculated from the experimental recorded tensile value. For impact test, the sample size was 10 x 10 x 55 mm with an angle of 45° and 2 mm depth V-shaped notch. Testing was performed in accordance with ASTM E23. Tensile and Impact toughness test were determined using five test pieces for each test. The microstructural images of the polished and etched samples are observed under a Versamet-II Microscope. The fracture surfaces after tensile tested samples were carried out with a Jeol Scanning Electron Microscope, model JSM-5200.

TABLE I
CHEMICAL COMPOSITION OF THE EXPERIMENTAL ALLOYS (WT %)

Alloy	Mg	Zr	Si	Fe	Sn	Zn	Al
Al	0.006	0.000	0.835	0.627	0.000	0.052	Bal
Al-Mg	5.014	0.000	0.429	0.375	0.249	0.012	Bal
Al-Mg-Zr	5.124	0.304	0.507	0.269	0.238	0.012	Bal

III. Results and Discussion

A. Hardness

Fig. 1 shows the Brinell hardness values of the commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy. It can be clearly seen that Brinell hardness of the Al-Mg alloy is higher and Zr added Al-Mg-Zr alloy increases some extend than that of commercially pure Al. The reason for the increase in hardness may be because of the presence of relatively hard-phase compounds in the alloys. Pure aluminum is very soft because the aluminum atoms are all of the same size. So it is easy for these atoms slide past each other along slip planes [16]. The addition of magnesium to aluminum increases strength through solid solution strengthening. Formation of $L1_2$ (Al_3Mg) and β (Al_3Mg_2) intermetallics during solidification directly increases the hardness of Al-Mg alloys, especially Al_3Mg_2 precipitates [17], [18]. Due to presence of impurities the alloy consists of primary α-Al, Al_3Fe, Mg_2Si precipitates also responsible for the hardening effects. Zr addition improves the hardness of Al-Mg alloy to some extend because of the grain refining effect. The efficiency of Zr in grain refinement of aluminium is due to Al_3Zr, which heterogeneously nucleates the primary aluminium [19], [20].

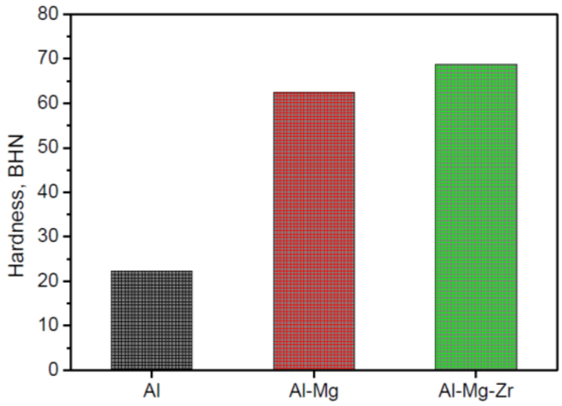

Fig. 1 Hardness of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy

B. Tensile and Impact Properties

True stress-strain curves from tensile tests of the experimental alloys are shown in Fig. 2. As expected, the yield stress and the ultimate tensile strength increase with Mg additions. It is also evident from the curves that additions of Mg reduce the ductility. It is well known that the great mechanical properties of Al-Mg alloys come from Mg solution strengthening [21], [22]. This illustrates that fine-grain strengthening and the existence of a second phase can improve the mechanical properties of the Al-Mg alloy. The second phase Al_3Zr hinders the movement of a dislocation, which increases the stress of the crystal slip and the density of the dislocations, leading to enhanced mechanical properties. When a second phase is finely distributed within the matrix, it will produce a significant reinforcement [23]. Reduction of elongation of Al-Mg alloys is because of the formation of galvanic coupling between the Al matrix and the β phase. The dissolution of continuous grain boundary β phase results in the decrease in the bond strength of grain boundaries, and leads to elements failure. Also the fine precipitates of Al_3Zr act as the early nucleation sites for micro voids. Therefore, fracture resistance of the material decreases. This is replicated in the Zr added alloy by showing lowest percent elongation [24].

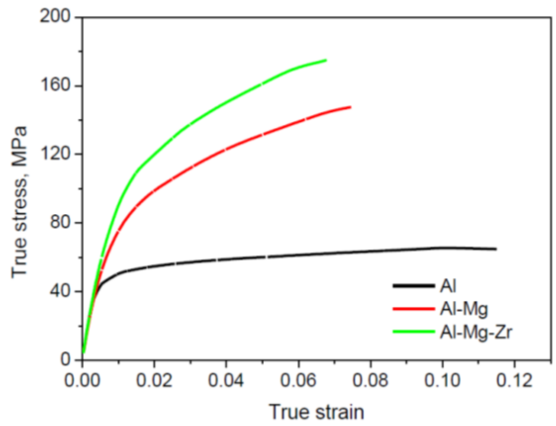

Fig. 2 True stress-strain curves of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy tensile tested at strain rate of $10^{-3}s^{-1}$

Young's modulus of as cast commercially pure Al, Al-Mg alloy and Al-Mg-Zr is shown in Fig. 3. It is clear that the Young's modulus of Al-Mg alloy is higher than that of commercially pure Al. The improvement can be attributed to the presence of high modulus Mg_2Si phases in the microstructure. Young's modulus is an intrinsic property and governs by volume fraction and modulus of phases within the alloy [25]. The addition of Zr reduces the size of the primary Mg_2Si particles of Al-Mg alloy. At the same time its volume fraction almost remains constant which is uniformly distributed into the matrix [26]. As a result minimum variation of modulus is shown for the Zr added alloy.

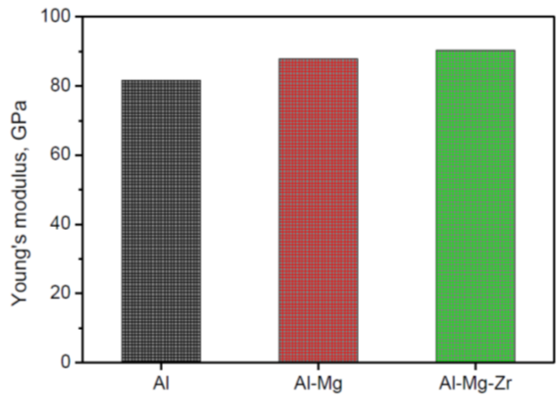

Fig. 3 Young's modulus of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy

Fig. 4 represents the strain-hardening exponent values of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy which are calculated from true stress-strain curves. Increased values of these parameters with Mg concentration are due to formation of finer dendritic structure and more precipitates of Al_3Mg_2 leading to more precipitation hardening and greater extent of solid solution strengthening [27]. Strain hardening exponent also is primarily dependent on the matrix and dislocation-matrix or dislocation precipitates' interaction which led to dislocation multiplication and increase in dislocation density in the matrix. However, Al_3Zr precipitates are formed in the matrix in case of Al-Mg-Zr alloy which marginally increases dislocation precipitation and greater dislocation density. As a result, marginally higher value of "n" is expected [28].

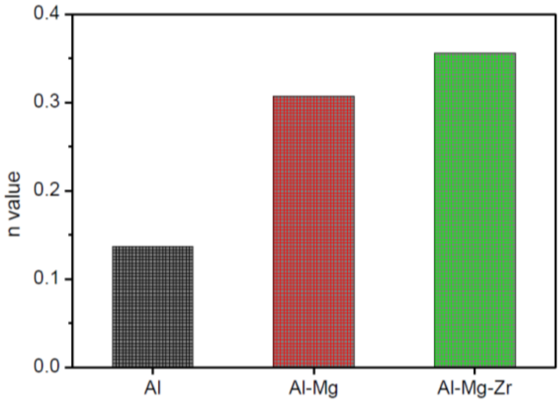

Fig. 4 Strain-Hardening Exponents of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy

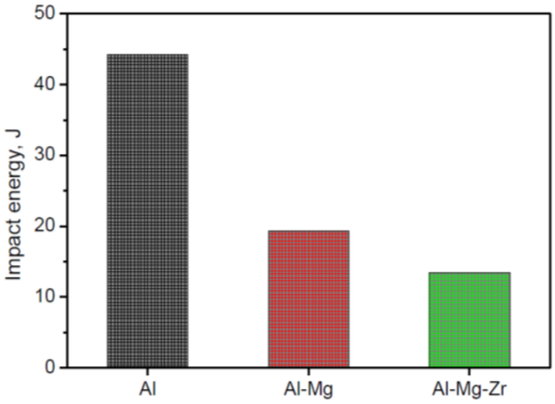

Fig. 5 Impact energy of commercially pure Al, Al-Mg alloy and Al-Mg-Zr alloy

Fig. 5 shows the impact toughness properties of the experimental alloys at cast condition. It is observed that Mg addition decreases the impact energy of commercially pure Al. This observation may be attributed to the precipitation of both Al_3Mg and Al_3Mg_2 phases. The alloying elements diffuse from the solid solution and form the intermetallic compound which concentrates at the grain boundaries during solidification. Presence of these particles on the grain boundaries is obtained to brittle fracture [29]. Trace Zr forms Al_3Zr precipitates as well as refines the grain structure during solidification of the alloy which makes the alloy more brittle [30], [31]. The impact strength shows the similar nature as percentage elongation of the experimental alloys. Impact strength is also a determining factor of the ductility properties of the material. It is inversely related to strength [32].

C. Optical Microscopic Observation

The optical micrographs of commercially pure Al, Al-Mg and Al-Mg-Zr alloy are shown in Fig. 6. The cast microstructure of commercially pure Al (Fig. 6 (a)) exhibits fine columnar structure and coarse equiaxed grains. Due to presence of impurity elements like iron and silicon, this type of microstructure consists of phases of aluminum-iron or aluminum-iron-silicon [33]. It can be seen in Fig. 6 (b) that the Mg added as-cast alloy contains dendrites with black second phase particles within inter-dendritic spaces, which exist with an irregular shape. Dendrite structures are commonly observed during solidification of Al-Mg alloy. In traditional casting procedures, dendrite morphology does not vary much within a wide range of cooling rate [34]. It is visible that the amount of constituents increases with Zr addition and the as-cast microstructure shows a diminution in the amount of second phase particles (Fig. 6 (c)). Zr addition could result in grain refinement in as-cast alloy due to the presence of fine Al_3Zr particles, which act as crystallization nuclei [35].

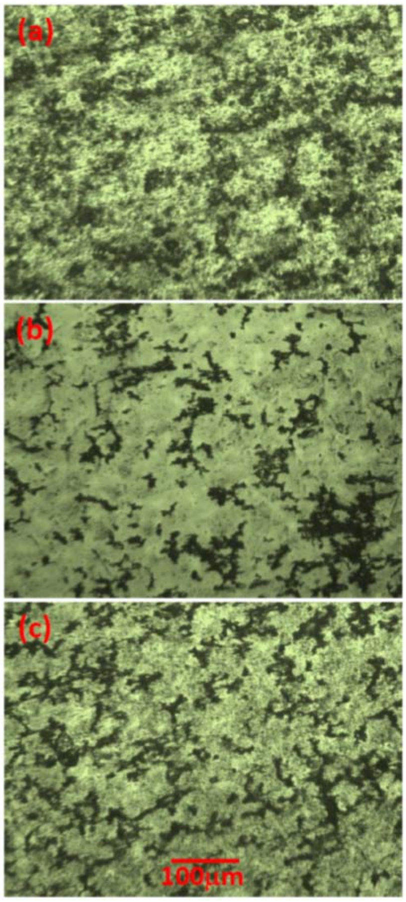

Fig. 6 Optical micrograph of (a) commercially pure Al, (b) Al-Mg alloy and (c) Al-Mg-Zr alloy

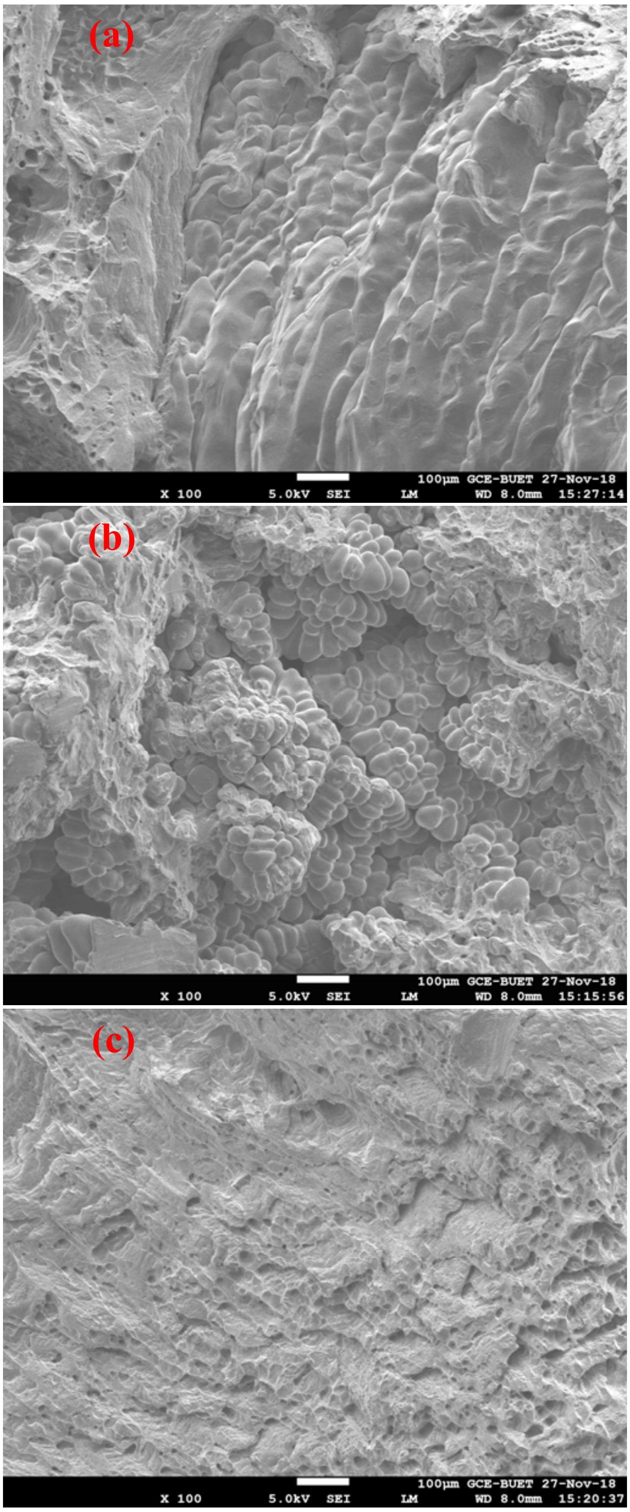

Fig. 7 SEM images of the fracture surface tensile tested at strain rate of $10^{-3}s^{-1}$ (a) commercially pure Al, (b) Al-Mg alloy and (c) Al-Mg-Zr alloy

D. Fracture Surface Observation

After tensile test, the fractured surfaces of commercially pure Al, Al-Mg and Al-Mg-Zr alloy are shown in Fig. 7. The dimple is observed into the fractured surface of pure Al sample, but only cleavage is shown in some regions (Fig. 7 (a)) [36]. As can be seen (Fig. 7 (b)), for Al-Mg alloy fractured surface, coarse secondary phases in grain boundaries cause initiation and fast propagation of cracks. This can explain low elongation values of the specimens. The fractured surface is brittle, and little of dimples are observed at the fractured surface. It is also associated with large voids and macro cracks resulting in interdendritic failure, which corresponds to brittle mode of fracture. The coarse dendritic structure acts as a source of stress concentration and crack initiation [37]. It is seen form fracture surface of Al-Mg-Zr alloy (Fig. 7 (c)) that it is brittle and there are the numbers of dimples at the fractured surface. The number of the dimples increases significantly when adding Zr. Brittle fracture, which presents as flakes under the dimples. Zr refined specimen showed more fine dimples [23].

IV. Conclusion

Magnesium addition increases the mechanical properties with decrease in ductility of commercially pure aluminium because of solution hardening effects. These properties accelerate through the presence of Zirconium as it forms the fine precipitates of Al_3Zr into the alloys. Mg added alloys contain dendrites with black second phase particles. Zr addition refines the grain structure due to formation of Al_3Zr, which heterogeneously nucleates the primary Al. Second phase particles in grain boundaries initiate the fast propagation of cracks causes the brittle fractured surface. Due to grain refining effects Zr bearing alloy shows more fine dimples into the fracture surface.

Acknowledgment

The authors thank Department of Glass and Ceramics Engineering for providing the laboratory facilities.

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