DEVELOPMENT OF HIGH STRENGTH TO WEIGHT RATIO ALUMINIUM – MAGNESIUM ALLOY WITH ENHANCED CORROSION RESISTANCE

Cinto C.J[1], Sreejith P.S[2]

[1]*Workshop Superintend, Thiagarajar Polytechnic College, Alagappanagar, Thrissur, Kerala, 680302*
[2]*Professor, Dean, Faculty of Engineering CUSAT, Kerala, India*

***

Abstract – *Aluminium and aluminium alloys are widely used in industrial and automobile applications in the recent past. Nowadays Al6061 (Al – Mg alloy) is widely used in many applications like marine, towers, pipe line and automobile field etc. It is having good mechanical properties. But there arises pitting corrosion as the main problem when this alloy is used in marine application.*

This project aims to develop an aluminium alloy which has better corrosion resistance and better mechanical properties compared with Al6061. It is done by adding minor elements like manganese, zirconium etc.

Al – Mg alloys are the better choice. We found that when Mg is added to Al in small quantity, it results in forming alloys which leads to higher strength and ductility than the pure Aluminium.

As a part of study the wt. % of Mg in the Al – Mg base alloy is fixed as 4% and the effect of minor alloying elements in the base alloy are also examined. These alloys derive their strength from the solid-solution strengthening due to presence of magnesium. Other minor alloying elements such as manganese 0.2 wt. % and zirconium 0.1 wt. % are added for the control of grain and sub grain structures, which also contribute to strengthening. The weight percentage of magnesium addition is limited below 0.2 wt. % in order to avoid the formation of coarse intermetallics. Zirconium has a low solubility in aluminium and only small additions of Zr are therefore necessary to form dispersions. Comparative study of the new developed alloys with Al6061 is done by Microstructure observations, Edax analysis, Density, Hardness and Corrosion test.

Key Words: **Al6061, Selecting and Fixing Compositions of Alloys, Stir Casting, Testing**

1. INTRODUCTION

The properties of aluminium are very attractive. Light weight, ease of fabrication, corrosion resistance, electrical & thermal conductivity, recycling, surface treatment suitability is some of its properties. But it has some disadvantages such as low elastic modulus and low elevated temperature. Important properties of aluminium are its versatility and high strength to weight ratio. The mechanical properties of aluminium can be increased by alloying process. Normally aluminium alloys are used at a temperature of 400 – 500^{0}C and for long term usage it is limited to 250 – 300^{0}C.

In pure state, aluminium has low strength. So it cannot be used in the application where resistance to deformation and fracture is required. Strength can be improved by adding alloying elements to aluminium [1]. The low density combined with high strength has made aluminium alloys attractive in applications where strength-to-weight ratio is a major design consideration. The strength and durability of aluminium alloys vary widely according to the specific alloying, heat treatments and manufacturing processes [1]. Aluminium is mainly used in alloyed form, which results in increasing its mechanical properties. It is used in pure metal form only when corrosion resistance or workability is more important than strength or hardness. A lack of knowledge of these aspects results in improper designed structures and bad reputation to aluminium. The typical alloying elements are copper, magnesium, manganese, silicon and zinc [1].

The aluminium alloy Al6061 is widely used in large number of engineering applications such as transport, construction, aircrafts and other structural applications where strength and weldability are needed. But when this alloy is used in marine application, pitting corrosion arises as the main problem [21]. The objective of this project is to develop an aluminium alloy which has better corrosion resistance and better mechanical properties by adding some alloying elements and to compare the alloy with Al6061.

2. LITERATURE REVIEW

2.1 ALUMINIUM

Aluminium and aluminium alloy are achieving huge industrial applications due to their outstanding fusion of mechanical, physical and tribological properties over the base alloys. They have high specific strength, high wear and seizure resistance, high stiffness, high temperature strength, controlled thermal expansion coefficient and improved damping capacity. These properties are obtained by the addition of alloying elements, cold working and heat treatment [1].

2.2 ALLOYING ELEMENTS IN ALUMINIUM

Alloying elements are selected according to the required property, effects and suitability. The alloying elements are classified into major and minor elements, microstructure modifiers or impurities; but the impurity elements in some alloys act as major elements in others [1]. The different alloying elements, such as silicon, magnesium and copper are used as the major alloying elements. Nickel, Tin etc are used as the minor alloying elements. Titanium, zirconium, scandium, boron etc are used as the microstructural modifying elements [1].

Alloying of aluminium plays a major role in enhancing the properties such as increased strength, hardness and resistance to wear, creep, fatigue etc. The intensity and range of each alloying elements adding to aluminium is specific and it effects properties of aluminium according to different alloying elements and combinations of them. Although most elements readily alloying with aluminium, comparatively very few have sufficient solid solubility to serve as major alloying additions. Among the commonly used elements only copper, magnesium, silicon and zinc have significant solubility [2]. However, other elements like Zirconium and chromium with solubility below 1% confer important improvements to alloy properties. Some of the important elements alloyed with aluminum are discussed below.

1) Silicon (Si)

It provides better castability (high fluidity, low shrinkage) and improved hot tear resistance in castings. Silicon's high heat of fusion contributes a lot to alloy fluidity. It has very low solubility in Al therefore precipitates as virtually pure Si which is hard and thereby improves the wear resistance. Si reduces thermal expansion coefficient of Al – Si alloys. Machinability is poor with addition of silicon in aluminum [1].

2) Titanium (Ti) and Boron (B)

Titanium and boron are used in aluminium and its alloys as grain refiners. Boron is more effective as grain refiner when it is used in combination with titanium in the ratio 1:5. It was found that with normal Ti contents, (ie in the range of 0.015%) the grain refinement is effective. However, upon larger Ti additions to the levels around 0.15%, the grain structure becomes coarser. It leads to increase corrosion resistance but these alloys showed higher wear rates when comparing with binary alloy [1].

3) Manganese (Mn)

When the manganese content increases over 0.5 wt. % in aluminium alloys, both yield and ultimate tensile strength increase significantly without decreasing ductility. Adding manganese to aluminium alloys increases the tensile strength as well as improves the low – cycle fatigue resistance and corrosion resistance [1].

4) Zinc (Zn)

Zinc is only present in 7xx series aluminium cast alloys. Aluminium – zinc alloys containing other elements offer the highest combination of tensile properties. Stress corrosion cracking is occurring in aluminum alloys containing Mg greater than 3.5%. Addition of 1 – 2 wt.% Zn to theses Al – Mg alloy leads to reduce stress corrosion cracking due to the formation of Al – Mg – Zn Phase [1].

5) Copper (Cu)

Copper improves the strength and hardness in cast alloy [3]. Both cast and wrought Al – Cu (aluminum – copper) alloys respond to solution heat treatment and subsequent ageing. The strength is maximum between 4 and 6 wt. % of Cu [2]. It improves machinability and reduces corrosion resistance [1].

6) Nickel (Ni)

Nickel is commonly used with copper for increasing elevated temperature properties. It also reduces coefficient of thermal expansion [3]. When nickel is added to Al alloys it forms intermetallic compound Al_3Ni which leads to increase hardness, compression and flexion resistance [1].

7) Magnesium (Mg)

Magnesium provides substantial strengthening and improvement of the work hardening characteristics of Al. It can impart good corrosion resistance, weldability and extremely high strength [1]. Si combines with Mg to form the hardening phase Mg_2Si that provides the strengthening. Optimum strength is obtained by employing Mg in the range of 0.40 to 0.70 wt. %, beyond which it leads to reduce the thermo-mechanical properties [3].

8) Strontium (Sr)

Strontium is used to modify the morphology of eutectic silicon in Al – Si alloy. Effective modification can be achieved at very low addition levels, but a range of recovered Sr of 0.008 to 0.04 wt. % is commonly used. Higher addition levels are associated with casting porosity, especially in processes or in thick-section parts in which solidification occurs more slowly. Degassing efficiency may also be adversely affected at higher Sr levels in the melt [3].

9) Iron (Fe)

When iron content is increased, it leads to promote the formation of plate-like β-Al_5FeSi intermetallic compounds, which is a crack initiators and it leads to reduce the mechanical properties. In addition to their negative effect on the mechanical properties of final product, β-

Al_5FeSi intermetallics is treated as deleterious to castability. Great care must be exercised to minimize the iron concentration in order to produce premium quality castings [4].

2.3 ALUMINIUM ALLOY CLASSIFICATION & DESIGNATION

Aluminium alloys are alloys in which aluminium is the predominant metal. They are classified as wrought alloys and cast alloys. The designation of the alloy enables the user to identify the particular alloy and understand the chemical composition. There are separate designations for both these classes.

2.3.1 Wrought aluminium alloy designation system

Wrought aluminium alloy designation consists of four digits sometimes including alphabet prefixes or suffixes. First digit indicates major alloying element of the series. Second digit indicates the variation in that alloy from the original composition [5].

- (0) for original composition
- (1) for the first variation
- (2) for the second variation etc.

Table 2.1 Wrought alloy designations [5]

Designation	Major alloying element
1xxx	Mostly pure aluminium
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and silicon
7xxx	Zinc
8xxx	Other elements

2.3.2 Basic temper designations

Temper designation is always represented with a hyphen followed by a letter and digit. (e.g.: 2024-T6). This indicates the process undergone by the alloy [6].

F – Fabricated. Applied to wrought or cast products made by shaping process.

O – Annealed. Applies to wrought alloys that are annealed to obtain the lower strength

H – Strain hardened. Strength increased by cold working.

W – Solution heat treated. Apply to only alloys that age spontaneously after solution heat treating.

T – Thermally treated to stable tempers other than F, O, and H.

A summary of various microstructure property relationships for aluminum alloys is given in Table 2.2 [6].

Table 2.2 Microstructure – property relationships for aluminum alloys

Property	Desired microstructural features	Function of features
Strength	Fine grain size with a uniform dispersion small, hard particles	Inhibit dislocation motion
Ductility & toughness	Fine structure with clean grain boundaries and no large particle or shearable precipitates.	Encourage plasticity and work hardening, inhabit void formation and growth.
Creep resistance	Thermally stable particles within the matrix and on the grain boundaries.	Inhibit grain boundary sliding and coarse microstructure.
Fatigue crack initiation resistance	Fine grain size with no shearable particles and no surface defects	Prevent strain localization, stress concentrations, and surface slip steps.
Fatigue crack propagation resistance	Large grain size with shearable particles and no anodic phases or hydrogen traps.	Encourage crack closure, branching deflection and slip reversibility.
Pitting	No anodic phases	Prevent preferential dissolution of second phase particles.

2.3.3 Cast alloy designation system

Cast alloy designation system also has four digits. First digit specifies the major alloying constituent. The next two digits identify the particular alloy (e.g. 319, 356 etc.) and the digit after the dot indicates whether it is cast or ingot form [6]. 319.0 is cast whereas 319.1 is an ingot. The cast alloy designation system is shown in Table 2.3.

Table 2.3 Cast alloy designations [6]

Designation	Major alloying element
1xx.x	Pure aluminium
2xx.x	Copper
3xx.x	Silicon added with Cu/Mg
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused series
7xx.x	Zinc
8xx.x	Tin

2.4 ALUMINUM CASTING PROCESSES

Foundry practice is the most economical and easiest way of transforming raw materials into finished products. Casting is a manufacturing process by which a liquid material is usually poured into a mould, which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is known as casting, which is ejected or broken out of the mould. Different types of casting processes are used in foundry. Among these, sand casting, high pressure die casting and gravity die casting are most widely used in foundries because of cost effectiveness and high productivity.

2.4.1 Sand casting

The most versatile method for producing aluminium products is sand casting. The process starts with a pattern that is a replica of the finished casting. In this process pattern is pressed into fine sand mixed with binders and water to form the mold into which the aluminium is poured. The melt is poured into cavity and allowed to solidify. Because of low thermal conductivity of sand, cooling rate is low resulting in a casting of less strength. As compared to die and permanent mold casting, sand casting is slow process but versatility in wide range of alloys, shapes and sizes when large casting is required [3].

2.4.2 Gravity die casting

The hot metal is fed into collapsible mould by its own weight of liquid metal allowed to solidify. The mould or die is then opened either by levers or mechanical and the casting extracted. The operation is rather slower than the pressure die or machine operated die because the freezing time takes longer due to the metal being hotter and the feeders larger. Compared to sand casting, gravity die castings provide higher strength and finer structure because chilling effect of the die and the feedback from the risers.

2.4.3 High pressures die casting

In high pressure die casting the molten metal is forced under a pressure up to 280MPa in to a water cooled dies. The casting is held under pressure until it solidifies, resulting the molten is rapidly fill on the mould cavity by the action of a hydraulic ram [3]. This type of casting is a automatic process for high production rates with good strength, parts with complex shapes and good dimension accuracy.

2.4.4 Squeeze casting

Squeeze casting is a modern casting process used to obtain near net shape castings with higher mechanical properties for the forged components by application of pressure during solidification. Squeeze casting involves the slow, direct application of pressure to a volume of liquid metal before, during and after solidification. The pressure applied during the process increases heat transfer between the casting and the die due to the direct contact, reduces or eliminates porosity in the final casting, ensures complete filling of the die, reduces metal wastage and better mechanical properties are obtained [7].

2.4.5 Stir casting

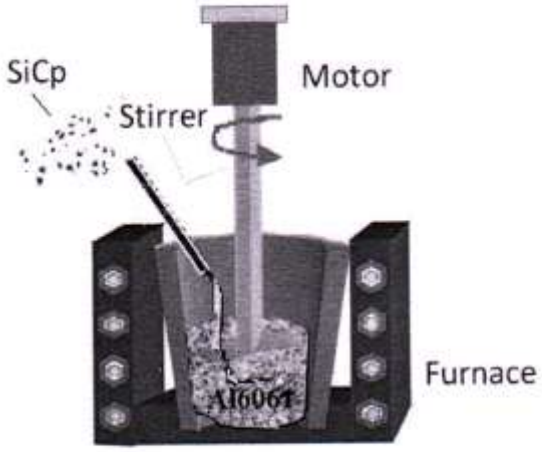

Fig. 2.1 Stir casting

The main advantages of stir casting are simplicity, flexibility and applicability to large scale production. It is also attractive because it allows a conventional metal processing route to be used and minimizes the final cost of production. The composite are added to the rotating crucible. In order to achieve the optimum properties of the metal matrix composite, the distribution of the reinforcement material in the matrix should be uniform and the wettability between the molten matrix and reinforcement particles should be optimized. Fig. 2.1 indicates stir casting arrangement. The vortex method is one of the best approaches used to create a good distribution of the reinforcement material. After the metal is melted, it is stirred vigorously by a mechanical stirrer to form a vortex at the surface of the melt and the reinforcement material is then introduced at the side of the vortex [8].

2.5 CORROSION IN ALUMINUM

Corrosion is a natural process by which the nature attempts to return the metal in to their original, stable state. When new aluminium surface is exposed to air or an oxidizing agent, rapidly it acquires hard, protective, self-healing film of aluminum oxide (about 0.5µ in air).The aluminum oxide forms a protective barrier between the metal and the surrounding medium. Due to corrosion the useful properties of a metal such as malleability, ductility and electrical conductivity are lost. In general, aluminum alloys have good corrosion resistance.

1) Fresh waters(natural, treated, reclaimed)
2) Sea Waters (quay side, open water) [12].

2.5.1 Uniform attack

All areas of the metal corrode at a similar rate. After a long period the exposed metal undergoes oxidation by aggressive ions, and at last the metal fails due to thinning. Uniform attack can be predicted by immersion test (Weight loss over a period of time). Uniform attack can be prevented by following ways.

1) Selection of appropriate materials or coatings, non-metallic or metallic coating example anodizing
2) Use of inhibitors example chromic acid
3) Application of cathode protection

2.5.2 Galvanic corrosion

It is natural reaction between metals in contact in the presence of an electrolyte. When aluminium is placed in contact with a more cathodic metal (Metal other than magnesium, zinc or cadmium) in the presence of an electrolyte, it tends to corrode more rapidly than if it is exposed to this same environment by itself [12]. Fig. 2.2 indicates galvanic corrosion. It is very damaging because it concentrates on the less noble metal at the metal-metal junction, where deep attack occurs. At the junction a large corrosion current can pass because the electrical resistance of the short path through the electrolyte is low.

When aluminium is coupled with copper or brass, corrosive attack upon the aluminium is accelerated by these materials in severe or modest atmospheres and conditions of immersion.

Fig. 2.2 Galvanic corrosion

2.5.3 Pitting corrosion

Pitting is a form of localized corrosion due to local cell action that produces cavities on the surface. These cavities are filled by corrosion products. The pit depth is limited to 0.5mm [12]. Corrosion products can form caps over pit cavities which are known as nodules. The shapes of the pits may vary widely and they are usually roughly saucer shaped, conical, or hemispherical. Pit walls are usually irregular in profile when viewed under a microscope. Fig. 2.3 indicates pitting corrosion. It occurs when a film protected metal is not completely resistant to corrosion, as in the case of aluminium and its alloys. It usually occurs on a metal surface immersed in a solution or moist environment, such as soil. It can occur on a surface exposed to the atmosphere if there are droplets of moisture or condensed moisture film present on the metal surface.

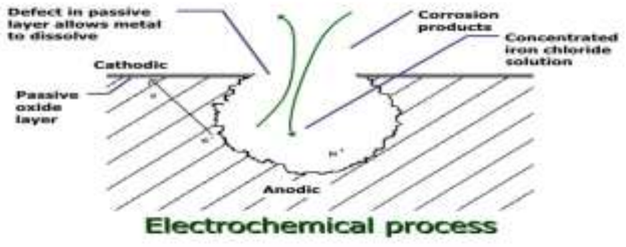

Fig. 2.3 Pitting corrosion

2.5.4 Crevice corrosion

It is an aerobic, localized corrosion in narrow back lower than 1mm.The meniscus forces of water draw and inhibit drying and the necessary exposure to oxygen results an acceleration to corrosion in the form of pit and etch at patches between the two surfaces. Example: water-staining of aluminum sheet and extruded products [12]. Fig. 2.4 indicates crevice corrosion.

In an aluminium crevice, corrosion makes little progress, probably due to the precipitation of aluminium oxide, a corrosion product that restricts the entrance to the recess.

Fig. 2.4 Crevice corrosion

2.5.5 Intergranular corrosion

The Intergranular corrosion is less noticeable than pitting or galvanic corrosion. This form of corrosion consists of localized attack in which a path is corroded preferentially along the grain boundaries of the metal. Fig. 2.5 indicates Intergranular corrosion. This type of corrosion is dependent upon the formation of local cells at the grain boundaries. These local cells are a result to the second phase precipitates.. During the formation of second phase precipitates along the grain boundaries, an adjacent matrix zone is formed that has a different solution potential. The degree of intergranular corrosion depends upon its microstructure, size, and distribution of second phases which is a result of the metallurgical history and thermal treatment. Heat treatments that cause precipitation throughout the grain tends to diminish the intergranular attack. It is significant that in certain aged conditions, Al – Mg – Cu alloys may suffer intergranular corrosion [12].

Fig. 2.5 Intergranular corrosion

2.5.6 Exfoliation corrosion

It is a form of corrosion which propagates simultaneously along the several grain boundaries parallel to the metal surface. The remain metal between corrosion paths then opens up like the leaves of book. This type of corrosion is regarded as serious, as it leads to reduction in thickness and strength [12]. Fig. 2.6 indicates exfoliation corrosion. Generation of corrosion products forces the layers apart and causes the metal to 'swell'. Metal flakes may be pushed up and even peel from the metal surface. Exfoliation corrosion is the most common in the heat treatable Al – Mg and Al – Zn – Mg – Cu alloys. However, if the grain structure is equiaxed, exfoliation corrosion does not usually occur.

Fig. 2.6 Exfoliation corrosion

2.5.7 Filiform corrosion

It is a type of corrosion which affects under the film surfaces. It is a structurally insensitive form of corrosion which is often more detrimental to appearance than strength. In high humidity conditions a two coat system is recommended the first coating is either anodizing or a suitable epoxy coating [12]. Fig. 2.7 shows filiform corrosion.

Fig. 2.7 Filiform corrosion

2.6 ALUMINIUM (Al) – MAGNESIUM (Mg) ALLOY

Al – Mg alloys have been widely used in the aerospace, automotive, ship building and construction industries by virtue of their light weight, fabric ability, physical properties and low cost. However, most Al – Mg alloys appear to have low resistance when submitted to wear [9]. The magnesium is a low density metal (1.73 g/cm^3) when compared with aluminium. For the development of high strength to weight ratio Al alloy, 5xxx series in which Mg is the master alloying element can be used. Increasing magnesium content forms dendritic network structure with a irregular shape and particles. Al – Mg based alloys possess good weldability and good corrosion resistance [13].

Most of the phase diagram of Al – Mg agrees that the equilibrium solid phases are the α (A1) fcc solid solution with a maximum solubility of Mg of 18.9 wt. % at the eutectic temperature of 450 ^{0}c the (Mg) solid solution with a maximum solubility of Al of 11.8 at.% at the eutectic temperature of 437^{0}c [14].

Byeong-Hyeon Lee [15] investigate the effect of Mg on the mechanical behavior of Al Alloys with a sample of Al – 3Mg, Al – 5Mg, Al – 7Mg & Al – 10Mg (Fig. 2.8 & 2.9). It was found that

1) The tensile strength of alloy was increased linearly from 23MPa to 170MPa and 57 MPa to 385 MPa respectively and it increases furthermore.
2) The ductility was decreased slightly with increase in the Mg content up to 3% and then increased gradually and linearly
3) When Mg content is 10% yield strength decreases slightly comparing with deformation

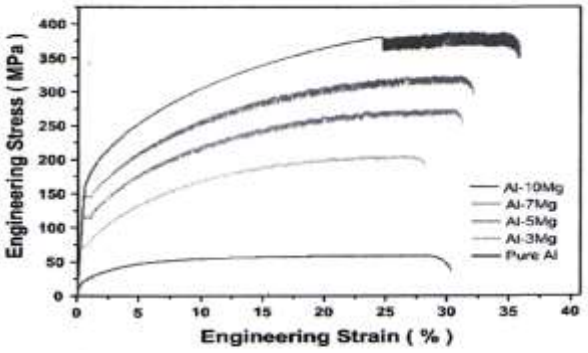

Fig. 2.8 Stress strain curve

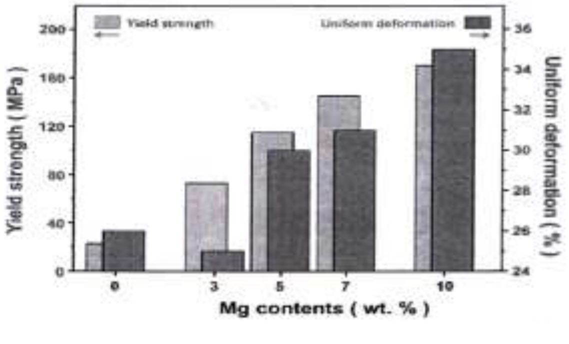

Fig. 2.9 Yield strength and uniform deformation

Rajat Goel, Mahesh investigate the effect of Mg on the mechanical behavior of Al Alloys with a sample of 2.3 wt. %, 5 wt. % & 12.44 wt.% of Mg [13]. It was found that

1) When Mg content was 2.3 wt. % four different types of precipitates were observed. These are coarser irregular shape (15 – 25μm), coarser spherical shape (2 – 5μm), fine spherical shape (500nm – 2.0μm) and rod type (1 – 2μm).
2) When Mg content 5 wt. % which is not continuous in nature and observed two types of precipitates one at the grain boundary and other is distributed throughout the grain boundary.
3) When Mg content 12.44 wt. % observed that plate like structures uniformly distributed and specimen is severely cracked during the cold rolling due to very high Mg content.

2.7 EFFECT OF MANGANESE (Mn) IN Al – Mg ALLOY

Soo Woo Nam and Duck Hee Lee [16] investigated the effect of Mn on the mechanical behavior of Al – Mg Alloys (See Fig. 2.10 & 2.11). It was found that when the manganese content increases over 0.7 wt. % in aluminum alloys, both yield and ultimate tensile strength increase significantly without decreasing ductility. Adding manganese to aluminum alloys enhance the tensile strength. It significantly improves low-cycle fatigue resistance. Corrosion resistance is also improved by the addition of manganese.

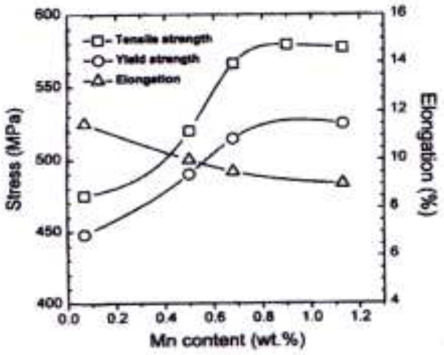

Fig. 2.10 Effect of Mn on tensile properties

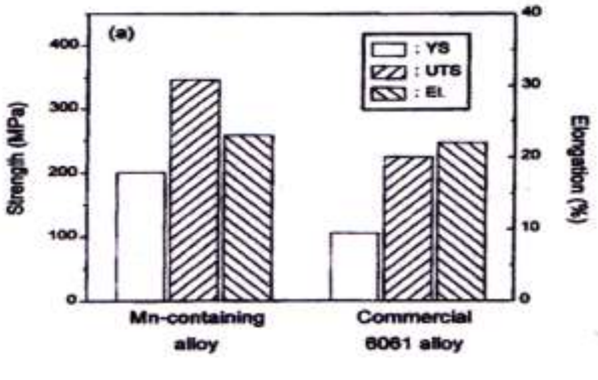

Fig. 2.11 Comparison of tensile properties of Mn containing alloy with commercial 6061

On the microstructure evolution and thermal stability of Al – Mg – Mn alloy have a wide range of applications in fields of aviation, spaceflight and machine building due to their medium strength, good corrosion resistance, easy formability and good welding property. It was reported that the addition of alloying elements can modify the microstructure and thus improve the properties of Al – Mg – Mn alloys. Hence the addition of Mn will help to increase the ductility of the alloy. But Mn is a high density metal (7.21g/cm^3) which will increase the density of the alloy.

2.8 EFFECT OF ZIRCONIUM (Zr) IN Al – Mg ALLOY

A.E Mahmoud investigates the influence of Zr on the grain refinement of Al6063 alloy. The experimental results indicate that the coarse dendrites structures are effectively refined by the addition of Zr. The grain size of Al6063 can be refined from 256 µm to 95 µm by the addition of 0.2 wt. % [10].

Jiang Li Ning proposed that the addition of these minor-alloying elements to Al alloy can offer several benefits, such as excellent grain refinement and the inhibition of recrystallization. It has been found that addition of 0.2 wt. % Zr can refine the grain size of the as-cast alloy due to the formation of primary Al_3Zr, and the mechanical properties can be improved [11].

As a part of study, a comparison of Al – Mg – Mn alloy with and without Zr is done Fig. 2.12. The alloy containing without Zr known as A_1 and with Zr known as A_2. Fine structures with grain sizes of about 1 – 2 µm were obtained, due to the existence of Al_3Zr dispersions.

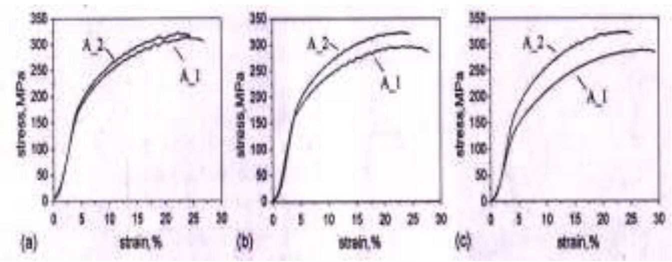

Fig. 2.12 Tensile-stress strain curve of Al - 4.58Mg - 0.56Mn without Zr(A_1) and with (A_2)

The tensile stress – strain curves of water quenched A_1 and A_2 alloys are shown in Fig. 2.13 (a). It was found that the strength of A_2 alloy was slightly higher than that of A_1 alloy. The tensile stress – strain curves of the air-cooled two alloys are shown in Fig. 2.13 (b), and it can be seen that the strength of A_1 alloy is decreased compared to the water quenched one, but the A_2 alloy is kept stable. It is due to the static recovery and static re crystallization of A_1 alloy during the air cooling process and it reduces the strength effectively, while A_2 alloy remained stable due to the presence of Al_3Zr particles. Fig. 2.13 (c) Shows the tensile stress – strain curves obtained for the two alloys after annealing at 460^{0}C for 1 hr. The strength of A_1 alloy is decreased furthermore compared to the air – cooled one, while A_2 alloy is still kept stable. The coarse grained structure of A_1 alloy after secondary recrystallization induces the dramatic reduction of the tensile strength. However, the stable fine grained structure of A_2 alloy due to the Al_3Zr particles leads to stable the mechanical properties [11].

But the density of Zr is 6.49 g.cm^{-3} Hence the addition of Zr to Al results to increase the density of alloy. The addition of 0.145 wt. % Zr on Al – Mg – Si alloy leads to increased tensile strength (220 MPa – 265 MPa) & hardness (72 HB – 83 HB). But the electricity conductivity is decreased from 55.5% IACS – 54% IACS [17]. In order to getting better % conductivity Zr should not contain more than 0.12 wt. % [18].

From the above study it is concluded that the addition of minor Zr can improve the super plastic property of Al – Mg – Mn alloy. The elongation to failure of Al – Mg–Mn alloy with Zr is larger than that of Al – Mg – Mn alloy without Zr at the same temperature and initial strain rate. In addition, Al – Mg – Mn alloy with minor Zr exhibits higher strain rate and super plastic properties.

2.9 FINDINGS FROM THE LITERATURE

Findings from the literature review are:

1. Aluminium alloys are better corrosion and the mechanical properties can be increase by alloying the metal.
2. Al – Mg alloy is non-heat treatable alloy and mostly strengthening is achieved by secondary processing.
3. The higher Mg wt.% will leads to softening the Al – Mg alloy
4. Formation of defects like edge cracking in high Mg content alloys can be reduced by addition of grain refiners such as Zr.
5. Zr addition in Al – Mg alloy has predominant effect on the microstructure compared to other alloying elements. Zr addition helps in recrystallization, grain refinement and improvement in tensile properties.
6. Al_3Zr phase is formed due to the addition of zirconium in aluminium alloys
7. Zirconium has a low solubility in aluminium (0.28% at 660^{o}C), and therefore precipitates out during the initial homogenization heat treatment in the form of met stable Al_3Zr particles.
8. In conventional casting methods, the addition of over 0.28 wt. % of Zr is known to produce relatively large intermetallic compounds, both at grain boundaries and in the matrix, which could act as initiation sites for cracks.
9. The addition of Mn will give a fine precipitation and will lead to increase of strength. The Al_6Mn will give better corrosion resistance.
10. Al6061 is widely using in the marine, aircraft and automobile field etc. It is having good mechanical properties and good corrosion resistance. But in marine conditions, pitting corrosion is the problems faced in this alloys.

3. PROBLEM AND METHODOLOGY

3.1 DETAILS OF PROPOSED PROJECT

3.1.1 Al6061

Al alloy Al6061 is widely used in numerous engineering applications including transport construction and aircrafts where superior mechanical properties such as tensile strength, hardness etc., are essentially required. A typical chemical composition of Al6061 is presented in superior strength makes it a suitable candidate material for marine structural applications.

The first digit of the aluminum alloy designation, “6”, means that the Al alloy contains magnesium and silicon. The relative weight percentages (wt.%) are given by the third and the fourth digits, where “6” means that there is 0.6 wt.% Si and “1” means that there is 1 wt.% Mg, respectively. The second digit “0” means that no other alloying elements were used. The three elements, Al, Mg and Si together constitute a two-phase Al alloy since Mg and Si form the single phase or compound Mg_2Si. The applications and typical uses of Al6061 are trucks, towers, canoes, railroad cars, furniture, pipelines and other structural applications where strength and weldability are needed. The chemical composition limits of Al6061 are 0.40 to 0.8 Si, 0.7 Fe max, 0.15 to 0.40 Cu, 0.15 Mn max, 0.8 to 1.2 Mg, 0.04 to 0.35 Cr, 0.25 Zn max, 0.15 Ti max and balance Al [19]. Properties of Al6061 alloy is given in Table 3.1.

Table 3.1 Al 6061 alloy composition [20]

Al6061(as cast)	Hardness (BHN)	Young’s Modulus(GPa)	% Elongation
	62.8	79.8	8

3.1.2 Limitation of Al6061 (Problem background)

Al6061 is widely using in the aircraft, automobile field etc. It is having good mechanical properties. But in marine application, pitting corrosion is the problem that is faced by using this alloy [21].

3.2 OBJECTIVES OF THE PROJECT

The main objectives of this project work is as follows

1. To develop a new Al alloy which will have better corrosion resistance and mechanical properties compared with Al6061 aluminium alloy.
2. To study about the role of Magnesium in the mechanical properties of aluminium.
3. To study about the effect of minor alloying elements such as Manganese and Zirconium in the Al – Mg base alloy.
4. Comparison of the mechanical properties of the developed alloys with Al6061 alloy after the secondary process.

3.3 ADDITION OF MAGNESIUM (Mg) TO ALUMINIUM (Al)

When Mg is added to Al, it produces a plate like dendritic network structure and when Mg atoms dissolved in Al matrix, act as obstacles to the motion of dislocations. The density of Mg is less than Al and increase of Mg content in Al also helps to increase corrosion resistance, weldability and extremely high strength [1].

The investigation of Byeong–Hyeon Lee [15] found that when Mg is added to Al in 3 wt. % the yield strength is increased when compare with deformation. But when Mg is added to less than 3 wt. %, the yield strength is reduced when compare with deformation. The same effect is also happened when the Mg is added to Al in 10 or more wt. %. The Mg content increased to 3 wt. % or more (less than 10wt. %), yield strength increased gradually and linearly compared with deformation. According to Lee’s investigation the Mg content should contain between 3 wt. % to less than10 wt. %.

The Rajat Goel [13] investigated the addition of Mg to Al at 2.3 wt. %, 5 wt. % & 12.44 wt. %. When Mg is 2.3 wt. % obtains different grain structures like coarser irregular, coarser spherical, fine spherical & rod type. But when the Mg content is increased to 5 wt. %, precipitates are not continuous in nature. When the Mg content is increased to 12.44 wt. %, plate like structure is obtained. But the specimen is severely cracked during cold rolling due to very high Mg content. So it can identify that when the Mg content is increased to 5 wt. % or more, fine grain structure is not produced. According to Goel’s investigation Mg content should contain between 2.3 wt. % to less than 5 wt. %.

The investigation of Furukawa [22] found that when Mg is added to Al – Sc alloy at 3 wt. %, the grain size is reduced to 0.2 μm and results high superplastic ductility. But when it is increased to 5 wt. %, the grain size is increased to 0.3 μm.

The investigation of Shubin Ren [23] found that when Mg is added to Al at lower than 4 wt. %, leads to develop poor thermo – physical properties because of higher porosity in the composites. But when Mg content is increased to beyond 8 wt. %, results higher porosity in the composites due to lower pressure of Mg. From this investigation Shubin Ren found that optimum content of Mg addition to Al is 4 – 8 wt. %.

From the above studies the content of Mg is fixed to 4 wt.% in Al for the newly developing alloy in order to getting fine grain structure & increase corrosion resistance.

3.4 ADDITION OF MANGANESE (Mn) TO Al – Mg ALLOY

When Mn is added to Al, Al_6Mn is produced which is dispersoid and produce an incoherent structural relationship with respect to the matrix and retract the motions of dislocations that increases strength. Addition of manganese to aluminum alloys enhances good corrosion resistance, weldability, high strength the tensile strength and low cycle fatigue resistance [1].

The investigation of Soo Woo Nam and Duck Hee Lee [16] found that when the manganese content increases over 0.5 wt. % in Al alloys, both yield and ultimate tensile strength increases significantly without decreasing ductility. From the graph (Fig. 2.11) Mn content wt.% V_s stress MPa, indicate that when Mn content was increased in between 0.2 wt.% to 0.7 wt.% in Al alloy, both yield and ultimate tensile strength increased. But beyond 0.7 wt. %, both yield strength and ultimate strength remains constant. Lee's investigation indicates that Mn should contain in between 0.2 wt. % – 0.7 wt. %.

The investigation of Zhao Zhihao [24] found that the addition of Mn at 0.2 wt.% to Al – Mg – Si alloy, both ultimate and yield strength are increased from 416.9 MPa to 431.4 MPa and 360.8 MPa to 372 MPa respectively. The grain refinement reaches maximum when Mn is 0.2 wt. %.

The density of Mn (7.4gm/cm^3) is higher than Al (2.7gm/cm^3). So increasing Mn content in Al alloy will lead to increase the density of developing alloy. So considering the above studies, content of Mn is fixed to 0.2 wt. % in Al for the newly developing alloy.

3.5 ADDITION OF ZIRCONIUM (Zr) IN Al – Mg ALLOY

When Zr is added to Al, fine Al_3Zr is produced which are stable against coarsening and redissolution cause a more uniform distribution of dislocations and pin grain boundaries.

The investigation of A.E Mahmoud [10] found that when Zr is added to 0.2 wt. % in Al6063, the coarse dendrites in the microstructure of alloy can be refined from 256 µm to 95 µm.

The investigation of Jiang Li Niang [11] found that when Zr is added at 0.16 wt.% in Al – Mg alloys, fine grain size about 1 – 2 µm is obtained due to the formation of primary Al_3Zr, and increases mechanical properties.

The investigation of Wuhua Yuan [17] found that addition of Zr at 0.145 wt. % in Al – Mg – Si alloy leads to increase tensile strength & hardness. But the electricity conductivity decreases. Another investigation of T.Knych[18] indicates that for getting better % electric conductivity, Zr wt. % should not contain more than 0.12 wt.%.

The investigation of A.Bahrami [25] found that when 0.1 wt. % of Zr is added to Al – Mg_2Si, the average grain size is reduced to 56 µm – 24 µm. It also leads to increase ultimate tensile strength and elongation from 160 MPa to 292 MPa and 3.2% to 9.5%. Another investigation of Zhimin Yin [26] found that when Zr is added to 0.1 wt. % to Al – Mg based alloy, the strength is increased by 150 MPa.

The density of Zr (6.49gm/cm^3) is higher than density of Al (2.7gm/cm^3). So when Increasing Zr wt. % in Al will lead to increase the density of newly developing alloy. So considering above studies the content of Zr is fixed to 0.1 wt. % in Al for the newly developing alloy.

3.6 FIXING COMPOSITION

First step is to fix the compositions for the casting

- Based on methodology it was found that when Mg is added to Al in 4 wt. %, it results to increase strength and ductility than pure Al. So the first casting is set to a composition of Al with 4 wt. % Mg.

- Based on methodology it was found that when the Mn content increases over 0.2 wt. % in Al – Mg alloys, it results to increase corrosion resistance, yield and ultimate tensile strength without decreasing ductility. So the second casting is fixed to Al – Mg with 0.2 wt. % Mn.

- Based on methodology it was found that addition of 0.1 wt. % Zr can refine the grain size of Al – Mg alloy due to the formation of primary Al_3Zr and the mechanical properties can be improved. So the third casting is fixed to Al – Mg with 0.1 wt. % Zr.

- The fourth casting is Al – 4 wt. % Mg – 0.2 wt. % Mn – 0.1 wt. % Zr. (Adding all alloying elements in to Al)

- The fifth casting is re-casting Al6061

ie Al – 0.6wt. % Si – 1wt. % Mg.

3.7 PLAN OF WORK

Casting Processes

The casting is conducted by Al, Mg, Mn, Zr & Si at various percentage. Different types of casting processes can be conducted such as sand casting, high pressure die casting, stir casting and gravity die casting which are most widely used in foundries because of cost effectiveness and high productivity. Due to the availability stir casting is selected in my project.

Sample Preparation

The different types of samples prepared are

1. Al – 4Mg 2. Al – 4Mg – 0.2Mn 3. Al – 4Mg – 0.1Zr

4. Al – 4Mg – 0.2Mn – 0.1Zr 5. Al – 0.6Si – 1Mg (The Al6061 is also recasting for comparing properties with other four samples) In sample preparation a piece of sample is

machined from casting and following operation are performed.

a) Fine grinding

The specimen was hand rubbed against the abrasive emery paper, which is laid over a flat glass plate. The grades of abrasives used are 100, 220, 400, 600 and 1000 grits. The specimen was first ground on 100 grit paper, so that the scratches are produced at right angles to those initially existing on the specimen which was produced during preliminary grinding. Then grinding was continued on 220 grit paper by turning the specimen through 90º and polishing to remove the previous scratch marks. This was repeated with the 400, 600 and 1000 grits.

b) Rough polishing

A very small quantity of diamond powder (particle size 6 micron) carried in a paste is placed on the nylon cloth covered surface of a rotating wheel. Specimen was pressed against the cloth of a rotating wheel with considerable pressure to ensure the uniform polishing.

c) Final polishing

In final polishing, the fine scratches are removed. The polishing compound used is diamond powder of particle size 0.25 micron. The cloth used is velvet. Fine polishing makes surface free from scratches.

EDAX (Energy Dispersive X-ray Analysis) Analysis

EDAX analysis is the preferred method to determine the elements and concentration of metallic samples. This process is widely used in the metal making industries, including primary producers, foundries, die casters and manufacturing.

Microstructure Analysis

Microstructure analysis is a conventional technique used to reveal the orientation, crystal structure, phase and other structural parameters such as grain size etc. present in the alloy samples, which is conducted by scanning electron microscope.

Mechanical Properties

Tensile measurements were carried out by using Universal hardness testing machine, in order to determine the tensile strength. The BHN was measured using ball indenter. The diameter of the impression made on the test piece was subsequently measured by means of a microscope with an accuracy of ±0.01 mm.

Corrosion Test

Electro chemical and immersion tests are the two types of corrosion tests. Here immersion test is conducted for checking the corrosion rate of the alloys. For the study, prepared sample, immersed in 3.5 wt.% of NaCl solution for T hours [27, 28]. After that samples are taken out of the salt water and dip in the Nitric acids to remove the oxides form on the surface. The weight loss is calculated and the corrosion rate can be obtained by the equation.

$$\text{Corrosion rate} = \frac{\text{K x W}}{(\text{A x T x D})} \tag{3.1}$$

Where, K = 87600 mm/yr (constant), W = Weight loss in grams, A = Area in cm^2

T = Time of exposure in hours & D = Density in g/cc

Density Calculation

The density measurement was done using the Archimede's relation Where ρ, W_{air} and W_{water} are the density, weights of the sample measured in air and distilled water respectively

$$\rho = \frac{W_{\text{air}}}{W_{\text{air}} - W_{\text{water}}} \tag{3.2}$$

4.1 ALLOY PREPARATION:

The five different type combinations was prepared they are

1. Al – 4Mg
2. Al – 4Mg – 0.2Mn
3. Al – 4Mg – 0.1Zr
4. Al – 4Mg – 0.2Mn – 0.1Zr
5. Al – 0.6Si – 1Mg.

4.2 CASTING EQUIPMENTS

The following equipment and tools are used for melting and castings

- Induction Furnace for melting (0 – 1200^{0}C)
- Preheater for heating mould, slag removing tool, tongs etc.
- Thermocouple and temperature indicator (0 – 1200^{0}C)
- Tongs, slag removing tool (SRT), ladle etc.
- Crusible
- Electronic weighing balance

Fig. 4.1 Induction furnace & Preheater

4.2.1 Induction furnace

Electrical induction furnace is used for melting the alloying elements are shown in Fig. 4.1. The heat is transferred to the metal through convection and radiation. Furnace temperature ranges from 0 to 1200°C. The temperature of melt alloy was monitored by thermocouple in temperature indicator.

4.2.2 Crucible

Crucible made from graphite and clay is used to prepare the melt. They are preheated using oven for 8 hours up to 800 °C. The temperature is raised in steps of 100°C in each 1 hour.

4.2.3 Casting procedure

The Al ingots & Cast iron moulds which are used for casting are preheated to a temperature of 250^{0}C by preheater for avoiding moisture. The furnace (Induction type) was switched on and the crucible containing Al ingots was placed into furnace. The tongs, slag removing tool and metal mould were kept inside the preheater for preheating to avoid moisture. Then metal moulds are placed on wise. The remaining alloy (other than master alloy) was in powder form.

Fig. 4.2 Stirring

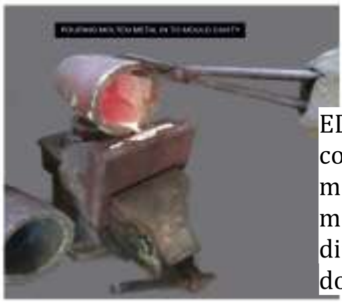

Fig. 4.3 Pouring molten metal in mould cavity

When the temperature of the melt reached around 700^{0}C, then stirring started at 70 – 100 r.p.m is shown in Fig. 4.2. The remaining alloys according to the required wt. % were added. Then crucible containing Al alloy again heated to 5 – 10 min. Then the crucible was taken out and slag was removed by using slag removing tool.

Then within 3 minutes the melts were poured at 700^0 – 710^{0}C into preheated mould and allowed to solidify is shown in Fig. 4.3. After solidification the casting was taken out. The dimension of the plate was 100mm x 100 mm x 10 mm

4.3 SPECIMEN PREPARATION

Tensile, Corrosion, EDAX and Microstructure test samples were prepared by electric discharge machining process. Density and Hardness test specimens were prepared by conventional machining process.

Fig. 4.4 Electric discharge machine

Fig. 4.5 Initial cutting by EDM

EDM (Electrical Discharge Machining) is a non – conventional machining technique mainly used for cutting metals which are not possible to produce with traditional methods. Delicate cavities and intricate contours which are difficult to produce with other conventional machines can be done with EDM. The Fig. 4.4 indicates Electric discharge machine (EDM) used for different specimen preparation. A brass wire of diameter 0.2 mm is used as an electrode or cutting tool. A wire driver section is used for moving the wire accurately at a constant tension. It cuts the work piece with electrical discharge just like a band saw. The casting was fixed on the table, which has a contour movement control unit. Deionized water (Conductivity is Zero) was used as coolant and was supplied with constant specific resistance at 12 l/min to flushing the material between the brass wire and electrode. The power supplied to it was 3ϕ 4440V. A sample with the dimension of 100mm x 10mm x 5mm was removed from the edge of castings for finding porosity which is shown in Fig. 4.5.

4.3.2 Specimen preparation for Tensile Test

The specimen for the tensile test is flat in shape. The size of the samples was prepared as per ASTM E8M04 standard which is shown in Fig. 4.6. After 5mm thickness was removed from the edge of castings, 2.5 mm thickness was removed from middle portion and then 12 mm thickness was removed according to the shape of test specimen which is shown in Fig 4.7. One sample from each castings (two samples of each alloy) was prepared which is shown in Fig. 4.8.

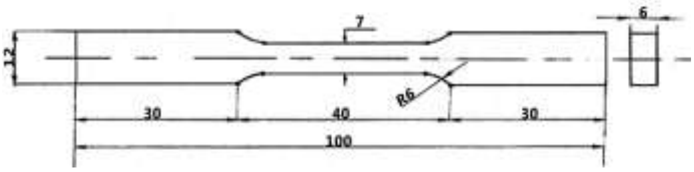

Fig. 4.6 Dimensions of tensile specimen

Fig. 4.7 Procedure of tensile specimen preparation

Fig. 4.8 Specimens for tensile test

4.3.3 Sample preparation for EDAX & Micro structure analysis

After the sample was prepared for tensile test, a square with a size of 10mm x 10mm x 10mm was removed from the edge of each casting by EDM Processes for EDAX and microstructure analysis. One sample from each casting was prepared which is shown in Fig. 4.9.

Fig. 4.9 Samples for EDAX and microstructure analysis

4.3.4 Sample preparation for Corrosion test

After the tensile test, a sample size 6mm x 8.9mm x 4mm was prepared from tensile specimen by EDM process. One sample from each casting (two samples of each alloy) was prepared. All the faces of the samples have to be finely polished to get better corrosion result. The surface finish was obtained by rubbing against the emery paper, which is laid over a flat glass plate. The grades of abrasives used are 80, 100, 160, 200 and 220.

4.3.5 Sample preparation for Density and Hardness test

After the tensile test, a sample size 10mm x 10mm x 29mm was prepared from tensile specimen by conventional machining process (Hacksaw cutting & Filing). One sample from each casting (two samples of each alloy) was prepared. Weight of each samples were noted. In hardness test, the surface of samples should be cleaned by emery paper at a grade size of 80, 100, 160, 200 and 220 for getting accurate size of impression.

4.4 DENSITY TESTING

Fig. 4.10 Density measuring machine

The density, or volumetric mass density of a substance is its mass per unit volume. It can be measured using the Archimedes' principle, which is shown in Fig. 4.10.

$$\rho = \frac{W_{air}}{W_{air} - W_{water}}$$

Where ρ, W_{air} and W_{water} are the density, weight of the samples measured in air and distilled water respectively.

4.5 EDAX & MICROSTRUCTURE ANALYSIS

Fig. 4.11 Scanning electron microscope

The EDAX analysis system works as an integrated feature of scanning electron microscope. In the EDAX analysis the sample is hit with an electron beam inside the scanning electron microscope. The hitting electrons collide with electrons of the specimen atoms. Automatically a higher energy electron from an outer shell will possess a position vacated by an ejected inner shell electron. Due to this some energy of outer shell electron will be released in the form of X-ray. The atoms of every element in the alloy releases energy during in the transferring process. The amount of energy released depends on which shell it is transferring from and which shell it is transferring to. By measuring the energy in the X-ray during the hitting is the identity of the atom of a particular element can be established. Here the micro structure and percentage of each alloying elements of samples can be identified by Scanning electron microscope - (Model JSM6390), which is shown in Fig. 4.11. The size of the specimens for the analysis was 10mm x 10mm x 10mm. Initially the specimen was placed on heating chamber for removing the moisture content. In EDAX analysis, tests were repeated at different locations of the specimen and an average value was generated for the alloying elements present in the material.

4.6 MECHANICAL TESTING

4.6.1 Tensile testing

TMC Universal Testing Machine (Model CUTM-50KN) was used for tensile testing. The tests were conducted in the cast state. The specimens were prepared as per the standard size (ASTM E8M04). The work piece was fixed on the fixtures. During this test, the force applied to the test piece and the amounts of elongation of the test piece were measured simultaneously. The applied force and amount of stretch were measured by the test machine. Two samples of each alloy were tested and noted their average value. The Fig. 4.12 indicates samples after tensile test.

Fig 4.12 Samples after tensile test

4.6.2 Hardness testing

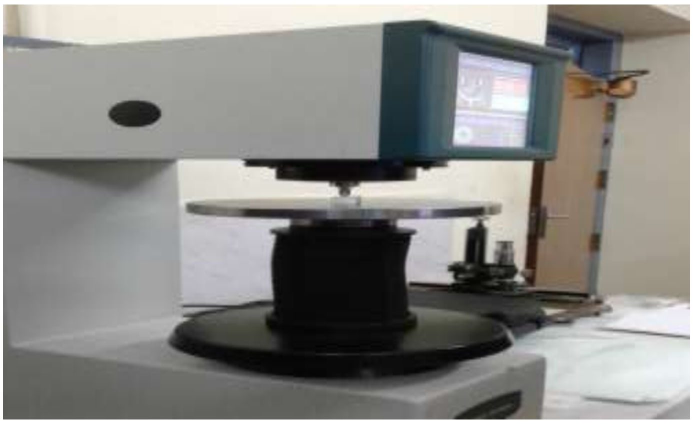

Fig. 4.13 Hardness tester

Hardness measurements were carried out using Indentec universal hardness testing machine which is shown in Fig. 4.13. The BHN (Birnell Hardness Number) was measured using indenter steel ball with a diameter of 2.0 mm and a load of 50 kgf. The surface of the specimen was machined and polished by emery paper at a grade size of 80, 100, 160, 200, 220 etc and an impression was made by using indenter on it. The diameter of the impression made on the test piece was subsequently measured by means of a microscope with an order of accuracy being ±0.01mm. The distance between the centers of indentation from the edge of specimen or edge of another indentation is maintained at least half the diameter of the indentation. Hardness of two samples of each alloys were taken and three hardness values of each samples at different positions were also noted.

4.6.3 Corrosion testing

Fig. 4.14 Corrosion testing

Two different corrosion tests are electro chemical test and immersion corrosion test. Here immersion test is conducted for checking the corrosion rate of the alloys. For this study, some samples with the size of 6mm x 8.9mm x 4mm were immersed in the 3.5% of NaCl (salt water) solution for 9 days which is shown in Fig. 4.14. After the test the samples were taken out of NaCl (salt water) and have to dip in the Nitric acids to remove the oxides formed on the surface. The weight loss was calculated and the corrosion rate can be obtained by the following equation:

$$\text{Corrosion rate} = \frac{K \times W}{(A \times T \times D)}$$

Where,

K = 87600 mm/yr (constant)

W = Weight loss in grams

A = Area in cm^2

T = Time of exposure in hours

D = Density in g/cc

RESULTS AND DISCUSSION

5.1 EDAX ANALYSIS

The main goal of the present work is to develop a new aluminium alloy of better corrosion resistance and good mechanical property comparing with Al6061 alloy. The effect of manganese and zirconium to Al – Mg base alloy also comes under study. The entire casted alloys have the same percentage of Magnesium content. One of the alloys containes Zr without Mn and other one is having Mn without Zr. And the final alloy combinations have both Mn and Zr of same weight percentage. EDAX analysis indicates % of elements contained in each casted alloys by scanning electron microscope.

The Table 5.1 indicates required percentage of elements and actual percentage of elements for Al – 4Mg alloy.

Table 5.1 Elements of Al – 4Mg alloy

Elements	Required percentage	Percentage actually present
Mg	4	3.82
Al	96	96.18

The Table 5.2 indicates required percentage of elements and actual percentage of elements for Al – 4Mg – 0.2Mn alloy.

Table 5.2 Elements of Al – 4Mg – 0.2Mn alloy

Elements	Required percentage	Percentage actually present
Mn	0.2	0.19
Mg	4	3.87
Al	96	95.94

The Table 5.3 indicates required percentage of elements and actual percentage of elements for Al – 4Mg – 0.1Zrn alloy.

Table 5.3 Elements of Al – 4Mg – 0.1Zr alloy

Elements	Required percentage	Percentage actually present
Zr	0.1	0.12
Mg	4	3.96
Al	96	95.9

The Table 5.4 indicates required percentage of elements and actual percentage of elements for Al – 4Mg – 0.2Mn – 0.1Zr alloy.

Table 5.4 Elements of Al – 4Mg – 0.2Mn – 0.1Zr alloy

Elements	Required percentage	Percentage actually present
Zr	0.1	0.11
Mn	0.2	0.21
Mg	4	3.97
Al	96	95.71

The Table 5.5 indicates required percentage of elements and actual percentage of elements for Al6061 alloy.

Table 5.5 Elements of Al6061 alloy

Elements	Required percentage	Percentage actually present
Si	0.6	0.61
Mg	1	0.98
Al	98.4	98.41

From the EDAX study it is found that Mg varies from 3.82 – 3.97 wt.% for newly developed alloy and 0.98 wt.% for Al6061. But the actual requirements were 4 wt.% for newly developed alloy and 1 wt.% for Al6061. In the case of Mn, it varies from 0.19 – 0.21 wt.% for newly developed alloy but the actual requirement was 0.2 wt.% for newly developed alloy. In the case of Zr, it varies from 0.11 – 0.12 wt.% for newly developed alloy but the actual requirement was 0.1 wt.%. Similarly silicon content in Al6061 is 0.61 wt.% but the actual requirement was 0.6 wt.%. The slight variation of particular elements in the alloys may be due to the loss at the time of casting. Similarly all the alloy combinations are in the acceptable limit and the variations present in the alloys may be due to the inclusion from the ingot which can be neglected.

5.2 DENSITY

The density is calculated using the Archimedes' principle:

$$\rho = \frac{W_{air}}{W_{air} - W_{water}}$$

Table 5.6 Density of the alloys

Alloy	Al-4Mg	Al-4Mg-0.2Mn	Al-4Mg-0.1Zr	Al-4Mg-0.2Mn-0.1Zr	Al 6061
Density (g/cc)	2.658	2.667	2.664	2.665	2.71

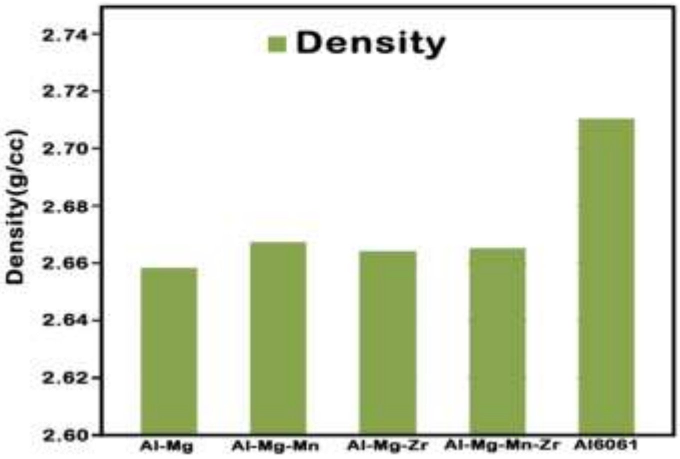

Fig. 5.1 Density comparison

As the project is concerned about the development of high strength to weight ratio alloy, the density is one of the important factor. Density of the casted alloy is shown in Table 5.6 and their variation shown in Fig. 5.1. It is found that the density of the developed alloys is lesser than that of Al6061. The density of Al6061 is 2.71 g/cc. The lesser density alloys with good mechanical properties are having wide application in the engineering field. It is found that the density of Al – 4Mg alloy is lesser (2.658 g/cc) compared to other developed alloys. The presence of higher density elements like Mn (7.21 g/cc) and Zr (6.52 g/cc) in remaining alloys made a slight increase in the density, when compared to the Al – 4Mg alloy.

5.3 HARDNESS

The hardness of the alloys are taken in cast condition using Birnell Hardness Machine under 50 kgf for 20 sec. The result is given below in the Table 5.7.

Table 5.7 Hardness Value of alloys

Alloy	Al-Mg	Al-Mg-Mn	Al-Mg-Zr	Al-Mg-Mn-Zr	Al 6061
Hardness (BHN)	52	55	73	71	62.8

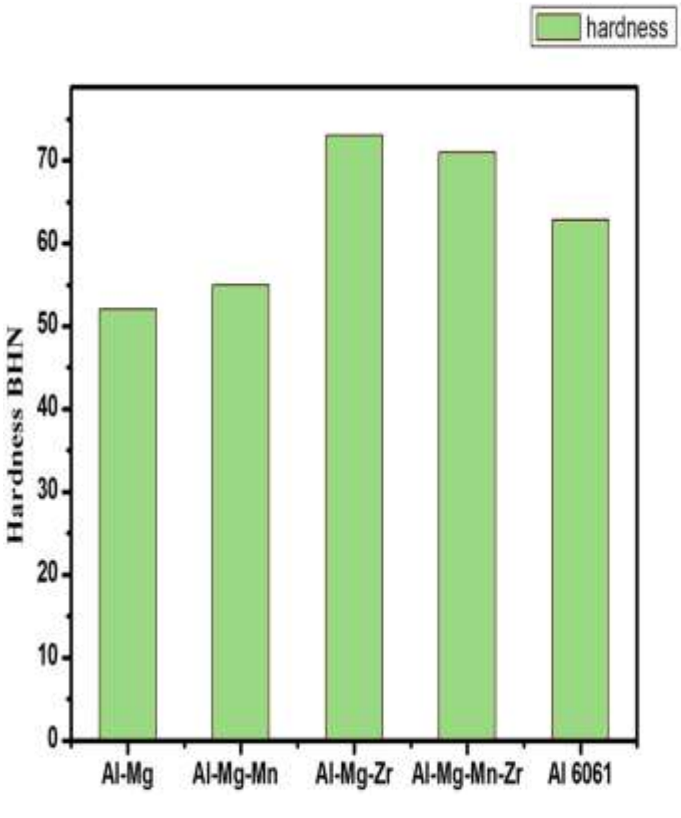

Fig. 5.2 Hardness comparison

The hardness value obtained for Al – Mg – Zr in cast condition is 73 BHN, which is the highest hardness value among the five alloys. It is also found that the 4% addition of Mg to pure Al increases the hardness of the alloy nearly 50 – 54 BHN. The BHN of the pure aluminum was 15. The minor percentage addition of Mn doesn't make much increase in the hardness value of the alloy. But 0.1 wt. % of zirconium addition shows significant increase in the hardness value in Al – Mg – Zr and Al – Mg – Mn – Zr. The addition of Zr refines the grains and thus improves the hardness. The Birnell Hardness Number for Al6061 in cast condition is 62.8. The Fig. 5.2 indicates hardness comparison of different alloys.

5.4 TENSILE TEST

Table 5.8 Tensile strength value of samples

Alloy	Ultimate Tensile strength (MPa)	
Al-4Mg	190.08	184.02
Al-4Mg-0.2Mn	219.17	214.20
Al-4Mg-0.1Zr	195.8	199.77
Al-4Mg-0.2Mn-0.1Zr	231.58	228.5
Al6061	200.14	195.21

Table 5.9 Tensile strength comparison

Alloy	Al-4Mg	Al-4Mg-0.2Mn	Al-4Mg-0.1Zr	Al-4Mg-0.2Mn-0.1Zr	Al6061
UTS (MPa)	187.05	216.68	197.78	230.04	197.67

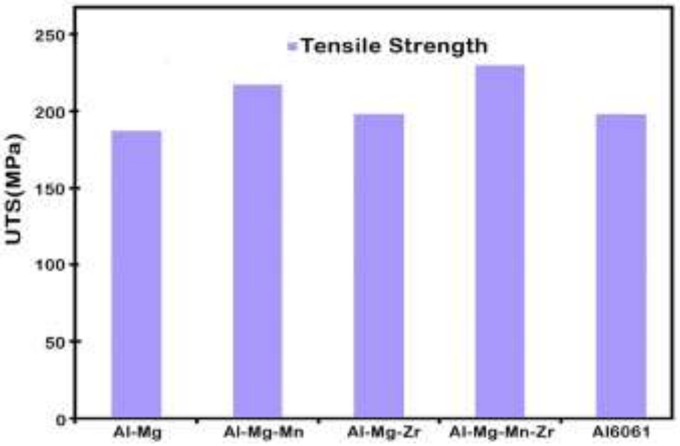

Fig. 5.3 Tensile strength comparison

The tensile test of the developed alloy is conducted in cast condition. The tensile strength of various alloys is shown in Table 5.8 and their average value is reported in Table 5.9. The maximum tensile strength is found as 230.04 MPa for Al – 4Mg –0.2Mn – 0.1Zr and the minimum tensile strength is found as 187.05 MPa for Al – 4Mg. The variation of tensile strength of various alloys is shown in Fig. 5.3.

5.4.1 Elongation

The elongation of the developed alloys is shown in Table 5.10 and their variation is shown in Fig. 5.4. From the study, it is found that the addition of Mn to Al – 4Mg gives better ductility compared to others. The zirconium content gives better hardness property to the alloy but gives adverse effect on ductility. The addition of Mn and Zr to the alloy gives a better percentage of elongation and tensile strength. Here for 0.2 % of Mn causes 32.75% increase in the percentage of elongation compared to the base alloy. Zirconium alone didn't give much variation in the result, but it is found that the 0.1 % of Zr and 0.2%Mn combined to give almost 18.1% of elongation compared to the base alloy. In cast condition the elongation of Al6061 alloy is 8%. It is found that the Al – Mg – Mn and Al – Mg – Mn – Zr are having the comparable elongation property with Al6061 alloy.

Table 5.10 Elongation comparison

Alloy	Elongation (mm)		Average value (mm)
Al-4Mg	21.875	21.30	21.587
Al-4Mg-0.2Mn	28.9	28.4	28.65
Al-4Mg-0.1Zr	21.875	21.1	21.4875
Al-4Mg-0.2Mn-0.1Zr	26.25	24.75	25.5
Al6061	25.5	25	25.25

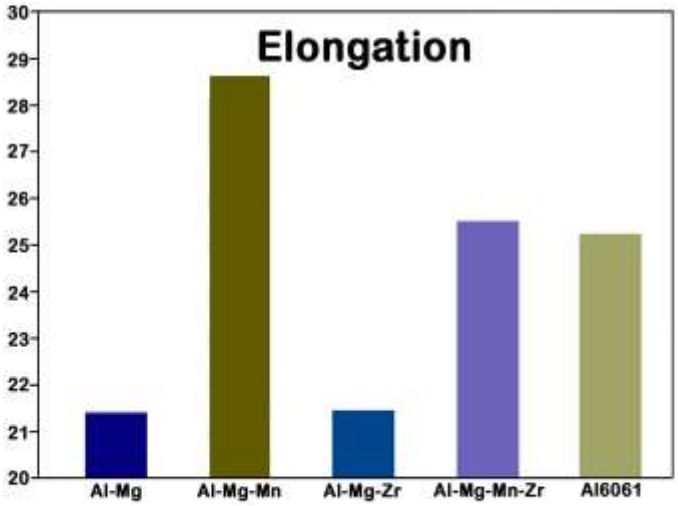

Fig. 5.4 Elongation of cast alloy

5.5 MICROSTRUCTURE

The Fig. 5.5 shows the microstructure of the casted Al – 4Mg alloy. The dissolvability of Mg in Al matrix caused to form Al_3Mg_2, and it acted as obstacles to the motion of dislocations, that leads to develop a solid solution hardening. The solid solution hardening is a result of an interaction between the mobile dislocations of the Mg atoms. When the Al atom is substituted by the Mg atoms resulting in the size misfit, there created a strain field around the atoms. The microstructure view of casted alloy reveals a typical equiaxed dendritic structure formation. Careful inspection of many areas indicates that though grains in alloy is fine, there is change in the configuration of array in equiaxed and elongated grains.

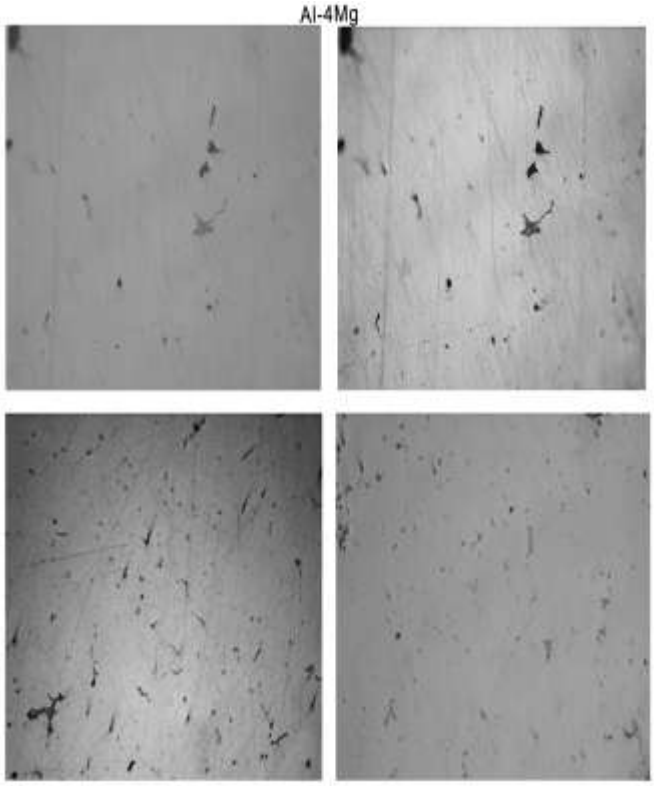

Fig. 5.5 Microstructure of Al – 4Mg

The Fig. 5.6 shows the structure of Al – 4Mg with the addition of 0.2 % of Mn. When Mn is dissolved in Al matrix, Al_6Mn and Al_8Mg_5 are formed. Then grain refinement occurs over the matrix phase due to the formation of Al_6Mn, which is a dispersoid to develop incoherent structural relationship with respect to the matrix. From the microstructural analysis, it is found that the fine particles are uniformly distributed over the matrix. It will act as a solid solution strengthening agent in the alloy.

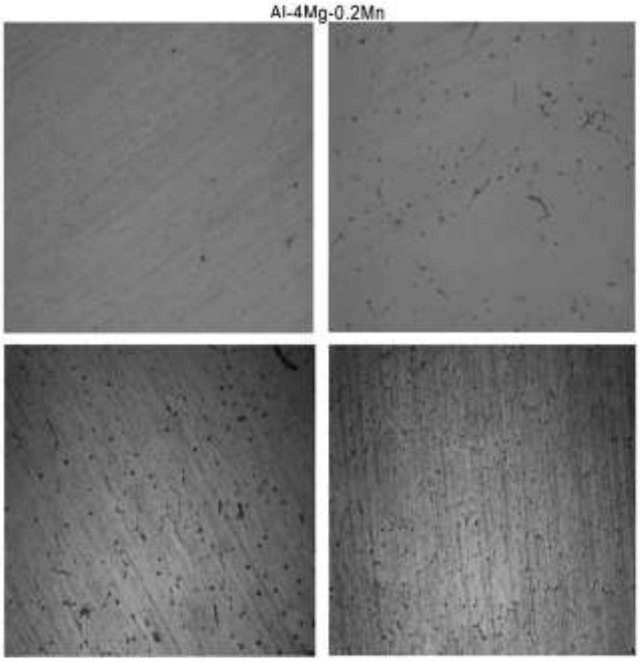

Fig. 5.6 Microstructure of Al – 4Mg – 0.2Mn

In Al – Mg based alloys, Fe is the main impurity and it caused to create Al_3Fe which is in needle – like form as shown in Fig. 5.16. Needle – like morphology of Al_3Fe caused to create brittle features and stress concentration which leads to reduce the mechanical properties of alloy. Fe was also considered a detrimental element in corrosion resistance. Usually Mn is added to Al – Mg-based alloys to compensate the negative effects of the inter metallic Al_3Fe. The addition of Mn to the alloy transforms the Al_3Fe phase to the Al_6 (Fe, Mn) phase, and the needle-like morphology of Al_3Fe will be changed. Here the particles are fine in nature and if the Mn wt. % in the alloy combination goes higher it may cause to form coarsen particles of Al_6Mn which are not recommended.

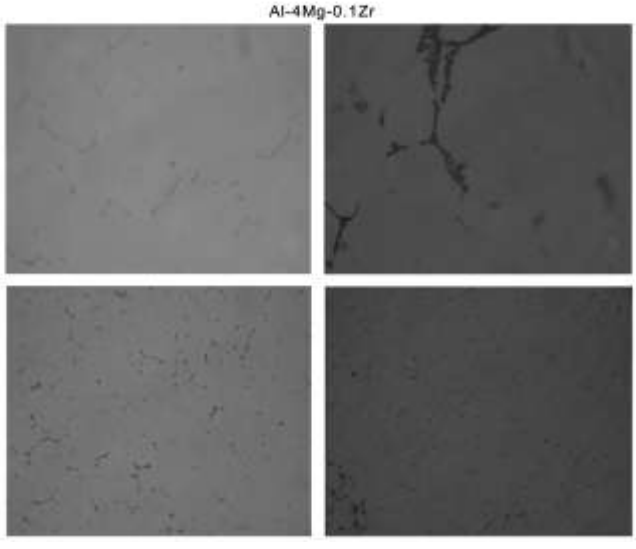

Fig. 5.7 Microstructure of Al – 4Mg – 0.1Zr

Fig. 5.7 shows the microstructure of Al – 4Mg with the addition of 0.1wt% Zr. Zirconium is usually used as a recrystallization inhibitor and grain refiner in commercial aluminum alloys. However, even very small additions of Zr can produce a significant hardening response. When Zr is added to the Al – Mg alloy, Al_3Zr is produced for acting as the nucleus of Al during solidification. During the solidification process, Al_3Zr (intermetallic phase) precipitates directly from the melts. This trialuminide (Al_3Zr) particles are stable. It is found that the addition of Zr causes decrease in the precipitation size and increase in the grain refinement.

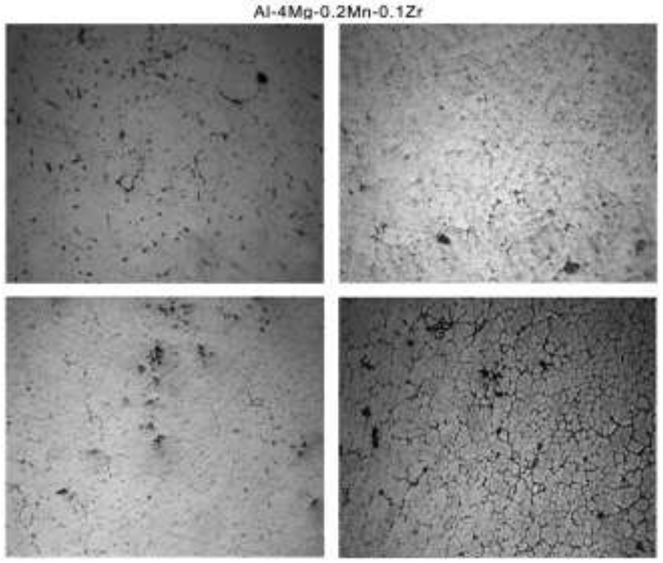

Fig. 5.8 Microstructure of Al – 4Mg – 0.2Mn – 0.1Zr

Fig. 5.8 shows the micro structure of the Al – 4Mg – 0.2Mn – 0.1Zr alloy for studying the combined effect of Mn and Zr in the Al – 4Mg alloy. From the morphology, it can be seen the rod and spherical type intermetallic which may be the Al_6Mn phase and the Al_3Zr phase respectively.

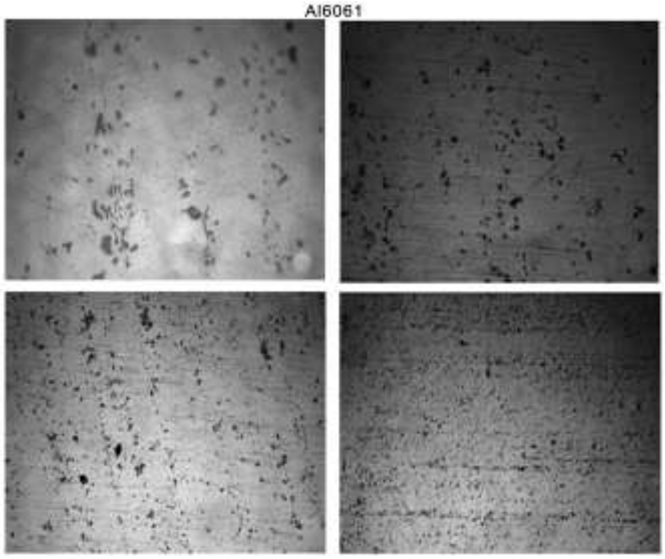

Fig. 5.9 Microstructure of Al6061

The Fig. 5.9 shows the optical microstructure of Al6061. The main components of the alloys are magnesium and silicon which form a precipitate of Mg_2Si. This Mg_2Si distributed randomly on the matrix phase. Excess of silicon enhances effect of precipitation hardening of the alloys, but decreases their ductility because of segregation of silicon at the regions of grain boundaries.

5.6 CORROSION

Immersion type corrosion test is done under 3.5% Nacl solution for nine days. The weight loss and the corrosion rate of alloys are obtained. The Table 5.11 indicates average weight loss.

The corrosion rate of the each alloy is calculated by the equation

$$\text{Corrosion rate} = \frac{K \times W}{(A \times T \times D)}$$

Where, K = 87600 mm/yr (constant), W = Weight loss in grams, A = Area in cm^2 , T = Time of exposure in hours, D = Density in g/cc

Here all the alloy samples are in uniform size and the time required for the test is 216 hours.

Table 5.11 Corrosion weight loss

Alloy	Samples	Weight loss (gm)	Average weight loss (gm)
Al-4Mg	1	0.008	0.0095
	2	0.011	
Al-4Mg-0.2Mn	1	0.003	0.003
	2	0.003	
Al-4Mg-0.1Zr	1	0.007	0.007
	2	0.007	
Al-4Mg-0.2Mn-0.1Zr	1	0.006	0.0055
	2	0.005	
Al-6061	1	0.010	0.00972
	2	0.0093	

Table 5.12 Corrosion rate of each alloy

Alloy	K value (constant)	Weight loss in grams(W)	Time(T)	Density (g/cc)	Corrosion Rate(mm/yr)
Al-4Mg	87600	0.0095	216	2.658	0.644
Al-4Mg-0.2Mn	87600	0.003	216	2.667	0.2027
Al-4Mg-0.1Zr	87600	0.007	216	2.664	0.4736
Al-4Mg-0.2Mn0.1Zr	87600	0.0055	216	2.665	0.3719
Al-6061	87600	0.00972	216	2.71	0.646

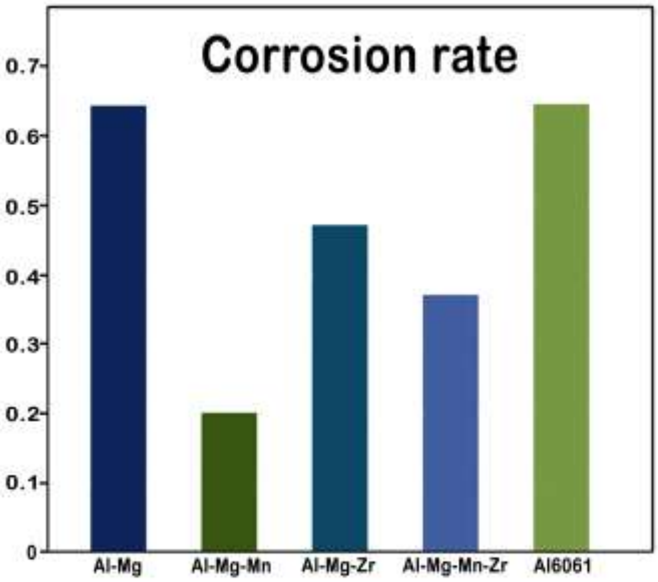

Fig. 5.20 Corrosion rate comparison

The Table 5.11 is the average weight loss calculation of developed alloys and the Table 5.12 is the average corrosion rate of developed alloys. Comparison of the corrosion rate of alloys is shown in Fig. 5.20. The corrosion rate of Al 6061 alloy is higher than all the other developed alloys. It is found that the Al – 4Mg alloy has a corrosion rate of 0.644 mm/yr and when 0.1 wt. % Zr is added to the Al – 4Mg alloy the corrosion resistance is increased. This may be due to better grain refinement by the Zirconium. The lowest corrosion rate is obtained for the Al – Mg – Mn alloy. As found in the literature, the addition of Mn to the Al – Mg alloy increased the corrosion resistance. It is found that addition of 0.1 wt. % Mn decreases the corrosion rate around 68% compared to the Al – 4Mg alloy. This may be due to the grain boundary strengthening of the Al – 4Mg alloy by manganese. When the Zirconium and Manganese is added to Al – 4Mg alloy, it is found that such alloys are providing good corrosion resistance compared to Al – 4Mg. The corrosion rate of Al – 4Mg – 0.2Mn–0.1Zr is 0.3719 mm/yr which is lesser compared to Al – Mg and Al – Mg – Zr alloys.

5.7 ECONOMIC ASPECTS

The Table 5.13 indicates price list of each alloying elements per kilogram & the Table 5.14 indicates material cost for each alloy per kilogram.

Table 5.13 Price list of each elements.

Sl No.	Items	Price per kg
1	Aluminium (Solid)	₹250
2	Aluminium (Powder)	₹1200
3	Silicon	₹2100
4	Magnesium	₹2100
5	Manganese	₹2100
6	Zirconium	₹8400

Table 5.14 Material cost for each alloy

Sl No.	Items	Price per kg
1	Al-4Mg	₹324.0
2	Al-4Mg-0.2Mn	₹327.7
3	Al-4Mg-0.1Zr	₹332.15
4	Al-4Mg-0.2Mn-0.1Zr	₹335.85
5	Al6061	₹279.6

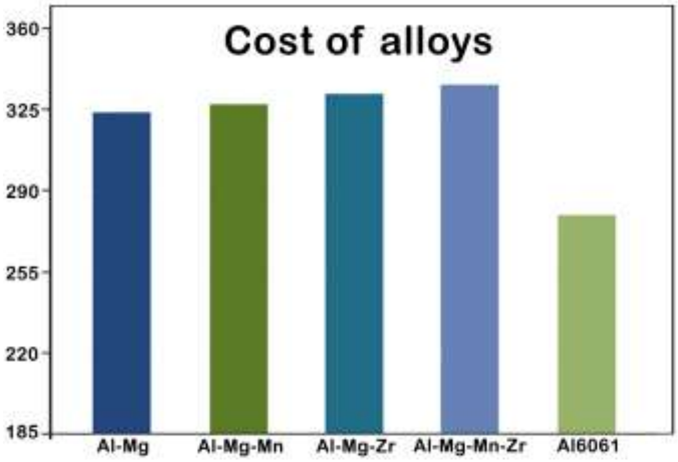

Fig. 5.21 Cost of alloys

From the price list, (Table 5.13) it indicates that the Zr has the highest price (₹8400/kg) and the lowest price is for Al (₹250/kg for solid state and ₹1200/kg for powder form). From the table 5.14, it indicates that the cost of base alloy Al – 4Mg is ₹324 which is in second position among the five alloys. The alloy Al – 4Mg – 0.2Mn – 0.1Zr is reported with the highest material cost (₹335.85) because it includes more number of elements. There is a 3.65% increase in cost from the base alloy. The alloy Al6061 is reported with lowest material cost (₹279.6) ie around 20.12% decrease when it compared with Al–4Mg – 0.2Mn – 0.1Zr.The pictorial representation of cost variation is shown in Fig. 5.21.

CONCLUSIONS

In recent years the major aim of the ship building, aircraft and automobile manufacturers are to produce high strength, low weight materials in the body manufacturing. Several materials like plastics and composites are replacing the metal body to reduce the weight. One of the best alloys that can be used in this part is Al alloys. These alloys have light in weight; the strength of the Al can be increased by the addition of Mg to it. Mg is completely soluble in the Al and its density is lesser than Al which will further help to reduce the weight. But it will reduce the ductility of the metal, which will not prefer for making of sheet metals.

1. The microstructure result reveals the formation of Al_3Mg_2 phase in Al – Mg alloys. This increases the mechanical property of pure Al.
2. The density result shows all the developed alloys having less density when comparing with Al6061 and the Al – Mg alloy having the lowest density among the developed alloys.
3. The tensile strength of Al – 4Mg alloy is 187.05 MPa which is very low when compare with other developed alloy.
4. The corrosion rate of Al – 4Mg alloy is 0.644 mm/yr which is high compared with other developed alloy
5. The microstructure results of zirconium added alloys show the formation of Al_3Zr which is responsible for the reduction in grain size in the alloy.
6. Reduction in grain size is significant when 0.1% Zirconium added to the alloys.
7. Considerable variation in the ultimate tensile strength is evident for the base alloys and modified alloys. The maximum tensile test is reported as 230.04MPa for Al – 4Mg – 0.2Mn – 0.1Zr
8. Increase in the ultimate tensile strength from 197.78 MPa to 230.04 MPa is due to the precipitate of Al_3Zr_4 and Al_6Mn.
9. The hardness result indicates that addition of 0.1% Zr gives better hardness in alloy Al – 4Mg – 0.1Zr and Al – 4Mg – 0.2Mn – 0.1Zr due to the better grain refinement
10. The addition of 0.2 wt % of Mn gives better corrosion resistance to the Al alloy due to the formation of Al_6Mn. The corrosion rate of Al – Mg – Mn is 0.2027 mm/yr which is the lowest corrosion rate.
11. The tensile property of the Al – Mg – Mn is better when compared with Al-Mg base alloy
12. Noticeable improvement in elongation is observed at Al – 4Mg alloy with the addition of Mn
13. The elongation in Al – 4Mg – 0.1Zr is very less due to the addition of 0.1% Zr which produces high hardness.
14. The Al6061 is having poor corrosion resistance in marine field and its corrosion rate is 0.646 mm/ year
15. The properties of Al – 0.2Mg – 0.1Mn – Zr are better compared with the Al 6061. They are given below in Table 6.1

Table 6.1 Mechanical properties of Al – 4Mg – 0.2Mn – 0.1Zr and Al6061

Alloy	Al-0.2Mg-0.1Mn-Zr	Al 6061
Density(g/cc)	2.665	2.71
Hardness BHN (as cast)	71	62.8
Corrosion rate (mm/yr)	0.3719	0.646
UTS (MPa)	231.1	197.6
Elongation(mm)	25.5	25.25
Material Cost per kilogram	₹335.85	₹279.6

16. The Al – 0.2Mg – 0.1Mn – Zr alloy is having better mechanical property as well as corrosion resistance compared with Al-6061 alloy.
17. The Al – 0.2Mg – 0.1Mn – Zr alloy is having better mechanical property as well as corrosion resistance compared with Al-6061 alloy.

6.1 Future Scope

The developed alloys have better strength to weight ratio compared with the Al 6061 alloy. But in the engineering applications, the machinability and the weldability of the alloy have to be study. The effect of alloying elements with variable alloying percentage and secondary process shall be studied.

REFERENCES

1) R.S. Rana, Rajesh Purohit, and S Das, “Review on the influence of alloying elements on the micro structural and mechanical properties of aluminium alloy”, International Journal of Scientific and Research Publications, 2012, Volume 2, Issue 6.

2) P. Rambabu, N. Eswara Prasad, V.V. Kutumbarao and R.J.H Wanhill, “Aluminium alloys for aerospace application”, Aerospace Materials and Material Technologies, Indian Institute of Metal Series, 2017.

3) J Guilburt Kaufman and Elwin L Rooy, “Aluminum Alloy Castings, Properties, Process and Applications”, ASM International, 2004.

4) Puncreobutr C, Lee P.D, Kareh K.M, Connolley T, Fife J.L and Phillion, A.B, “Influence of Fe-rich intermetallics on solidification defects in Al – Si – Cu alloys”, Acta Materialia, 2014, Volume 68, pp. 42 – 51.

5) Guilburt Kaufman J, “Introduction to Aluminium alloys and Temper”, ASM International, 2000.

6) Starke Jr. EA and Staley JT, “Application of modern aluminum alloys to aircraft”, Progress in Aerospace Sciences, 1996, Volume 32, pp. 131 – 72.

7) Aweda.J.O and M.B Adeyemi, “Determination of temperature distribution in squeeze cast aluminium using the semi-empirical equations method”, Journal of Materials Processing Technology, 2009, Volume 209, pp. 5751 – 5759.

8) K.Umanath, S.T.Selvamani and K.Natarajan, “Influence of silicon carbide particulate reinforcement on the fracture toughness of Al6061 alloy composite produced by Stir Casting Method”, IEEE, 2010.

9) Panagopoulos C.N. and Georgiou E.P, ”Cold rolling and lubricated wear of 5083 aluminium alloy”, Materials and Design, 2010, Volume 31, pp. 1050 – 1055.

10) A.E. Mahmoud, M. G. Mahfouz and H. G. Gad – Elrab, “Influence of Zr on the grain refinement of Al 6063 alloy”, Journal of Engineering Research and Applications, 2014, Volume 4, Issue 7, pp. 188 – 194.

11) Jiang Li Ning and Da Ming Jiang, “Influence of Zr addition on the microstructure evolution and thermal stability of Al – Mg – Mn alloy processed by ECAP at elevated temperature”, Materials Science and Engineering, 2007, Volumes – 453, pp. 552 – 557.

12) AFSA, “Pocket guide for corrosion resistance of Aluminium”, 2011, Aluminium federation of south africa.

13) Rajathgoel and Maheshupadyay, "Effect of magnesium in strain hardening of Al – Mg – Mn based alloys”, International Conference for Advanced Manufacturing and Material Engineering, 2014, Volume 5, pp. 1241 – 1247

14) Chartrand. P and Pelton A. D, "Critical evaluation and optimization of the thermodynamic properties and phase diagrams of the Al – Mg, Al–Sr, Mg –Sr, and Al – Mg – Sr systems", Journal of phase Equilibria, 1994, Volume 15, Issue 6, pp. 591 – 605.

15) Byeong-Hyeon Lee, Sung-HoonKim, Jun-HyoungPark, Hyung-WookKim and Jae-Chul Lee, “Role of Mg in simultaneously improving the strength and ductility of Al – Mg alloys”, Materials Science & Engineering, 2016, Volume 657, pp. 115 – 122.

16) Soo Woo Nam and Duck Hee Lee, “The effect of Mn on the mechanical behavior of Al alloys”, Metals and Materials, 2000, Volume 6, Issue 1, pp. 13 – 16.

17) Wuhua Yuan and Zhenyu Ling, “Effect of Zr addition on properties of Al – Mg – Si aluminum alloy used for all aluminum conductor”, Materials and Design, 2011, Volume 32, pp. 4195 – 4200.

18) T.Knych, M.Piwowarska – Uliasz and P.Uliasz,“Aluminum alloys with Zr additions, in the range from 0.05 to 0.32%, Intended for application in the overhead electrical power engineering”, Archives of Metallurgy and Materials, 2014, Volume 59, Issue 1, pp. 339 – 343.

19) The Aluminum Association, “International alloy designations and chemical composition limits for wrought Aluminium and wrought Aluminium alloys”, 2015.

20) Christy T.V, Murugan N. and Kumar S, “A comparative study on the microstructures and mechanical properties of Al 6061 Alloy and the MMC Al 6061/TiB2/12P”, Journal of Minerals & Materials Characterization & Engineering, 2010, Volume 9, Issue 1, pp. 57 – 65.

21) Kalenda Mutombo, “Intermetallic particles – induced pitting corrosion in 6061 – T651 aluminium alloy”, Materials Science Forum, 2011, Volume 690, pp. 389 – 392.

22) M.Furukawa, A.Utsunomiya, K.Matsubara, Z.Horita and T.G.Langdon, “Influence of Mg on grain refinement and ductility in a ductile Al – Sc alloy”, Acta Materialia, 2001, Volume 49, Issue 18, pp. 3829 – 3838.

23) Shubin Ren, Xinbo He, Xuanhui Qu, Islam S.Humail, and Yan Li, “Effect of Mg and Si in the aluminum on the thermo – mechanical properties of pressure less infiltrated SiCp/Al composites”, Composite Science and Technology, 2007, Volume 67, pp. 2103 – 2113.

24) Zhao Zhihao, Meng Yi and Cui Jianzhong, “Effect of Mn on microstructures and mechanical properties of Al – Mg – Si – Cu – Cr – V alloy”, Laboratory of Electromagnetic Processing of Materials, 2012, pp. 349 – 355.

25) A Bahrami, A.Razaghian, M.Emamy and R.Khorshidi, “The effect of Zr on the microstructure properties of hot extruded Al –M_{g2}Si composite”, Materials and Design, 2012 Volume 36, pp. 323 – 330.

26) Zhimin Yin, Qinglin Pan, Yonghong Zhang and Feng Jiang, “Effect of minor Sc and Zr on the microstructure and mechanical properties of Al – Mg based alloys”, Materials Science & Engineering, 2000, Volume 280, Issue 1, pp. 151 – 155.

27) Dasappa Ramesh, Ragera Parameshwarappa Swamy, Tumkur Krishnamurthy Chandrashekar, “Corrosion behaviour of Al6061 – Frit particulate metal matrix composites in sodium chloride solution”, Journal of Minerals and Materials Chracterization and Engineering, 2013,Volume 1, Issue 1, pp. 15 – 19.

28) A Pardo, M.C Merino, A E Coy, R Arrabal, F Viejo, E Matykina, “Corrosion behavior of magnesium/aluminium alloys in 3.5wt.% Nacl”, Corrosion Science, 2008, Volume 50, Issue 3, pp. 823 – 834.