# Effect of Quenching Media on Corrosion Resistance of Al-Si-Mg Alloy

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**ABSTRACT**

This study aims to preparing of Al-Si-Mg alloy and study the effect of quenching media (polymer solution and water) on the properties of prepared alloy such as corrosion resistance in 3.5% NaCl , surface roughness and microstructure. Also study the effect of addition alloying elements (Boron and Titanium) on above properties of prepared alloy. The results showed that improvement in corrosion resistance and surface softness of prepared alloys when addition of boron and titanium to the prepared alloy and when quenched in polymer solution. Optical microscopic results showed that the microstructure of prepared alloys when quenched in polymer solution consists of shape, size and uniform distributing for grains in comparison with the same alloys when quenched in water.

**Keywords: Al-Si-Mg alloy, Alloying Elements, Quenching, Corrosion, Ageing**

# تأثير وسط الإخماد على مقاومة التآكل لسبيكة Al-Si-Mg

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**الخلاصة**

إن الهدف من هذه الدراسة هو تحضير السبيكة Al-Si-Mg ودراسة تأثير وسط الإخماد (محلول البوليمر والماء) على مقاومة التاكل في محلول 3.5% NaCl وخشونة السطح والبنية المجهرية للسبيكة المحضرة، وكذلك دراسة تاثير عناصر السبك (البورون والتيتانيوم) على الخصائص اعلاه للسبيكة المحضرة. أظهرت النتائج تحسن في مقاومة التآكل ونعومة السطح للسبائك المحضرة عند اضافة البورون والتيتانيوم الى السبيكة المحضرة وعند الإخماد في محلول البوليمر. نتائج المجهر الضوئي بينت أن البنية المجهرية للسبائك المحضرة عند الإخماد في محلول البوليمر يكون فيها حجم وشكل الحبيبات منتظم التوزيع مقارنة بنفس السبائك عند الإخماد بالماء.

## INTRODUCTION

For over fifty years, aluminum ranks at second to iron and steel in the metal market. The demand of aluminum grows rapidly because it is attributed to unique combination of properties which makes it become one of the most versatile of engineering and construction materials [1]. Aluminum alloys have many desirable properties such as high fluidity, light weight, low melting points, high thermal conductivity and good surface finish these properties making aluminum alloys for using widely in casting.

Aluminum alloys with silicon as a major alloying element constitute a class of material, which provides the most significant part of all shaped castings manufactured especially in the aerospace and automotive industries [2]. In recent decades, aluminum alloys used in the automobile industry as car body panels to reduce weight and thus improve fuel economy and emissions [3].

Addition of alloying elements such as magnesium and silicon to aluminum improve mechanical properties of aluminum and increase the aluminum response to heat treatment due to formation of $Mg_2Si$ intermetallic compound, which improves the casting, corrosion resistance property as well as the strength of the alloy [4]. Al−Si−Mg alloys are widely used as medium-strength heat-treatable alloys for structural applications due to their excellent formability, weldability and good corrosion resistance. In Al −Si−Mg alloys, Mg and Si are added either in a balanced amount to form binary Al−$Mg_2Si$ alloys or with excess amount of Si to form the Al−$Mg_2Si$ quasi-binary composition, to enhance the kinetics of the precipitation process without changing the nature of precipitates [5].

The heat treatment is one of the important methods for improving the mechanical properties of Al-Si-Mg alloys this heat treatment consists of solution heat treatment , quenching, and then either natural or artificial ageing [6]. Quenching is one of the crucial heat treatment processes for manufacture of the products with desired mechanical properties [7].

The quenching is the process of rapid cooling of materials to room temperature to preserve the solute in solution. The cooling rate needs to be fast enough to prevent solid – state diffusion and precipitation of the phase. The rapid quenching creates a saturated solution and allows for increased hardness and improved mechanical properties of the material [8]. Quenching may be performed by means such as total immersion in an aqueous polymer solution, liquefied gas, cold water, hot water, or boiling water, or by air blast or fog [9]. Also quenching is performed in oil [10]. Cold water used to be the dominant quenchant for heat treating aluminum alloys. However, in many cases, cold water quench produces unacceptable distortion due to high thermal gradients induced upon cooling [11].

Aqueous solutions of polyalkylene glycol (PAG) are used to improve the cooling characteristics of the quenching medium and to reduce the machining requirements after the heat treatment. PAG concentrations vary from (4 to 30)%, depending on the type of product being processed. For the heat treatment of aluminum alloys, such polymeric solutions have been widely applied during more than 30 years [12]. Intensive studies of corrosion resistance of aluminum materials are focusing on the methods and materials that can help in improving corrosion resistance of such materials, where the effect of alloying elements on the corrosion resistance of aluminum showed that magnesium tends to enhance corrosion resistance of aluminum [13]. The aim of the present study was to studying the effect of quenching media (water and 35% PAG) and alloying elements boron (B) and titanium (Ti) on corrosion resistance and surface roughness of prepared Al-Si-Mg alloy.

## EXPERIMENTAL WORK

Aluminum wires were cut into small pieces and melting in an electric furnace at temperature 750℃ after putting in alumina crucibles, then the alloying elements were added in the required weight percentages where remain for (5-10) minutes after each element addition. During the addition of alloying elements, there must be continuous mixing by using a graphite stirring rode to ensure a best mixing and dissolution of alloying elements and to avoid segregation defects. All alloying element are packing with Al-foils to avoidance of oxidization. Finally, the molten alloy is poured in the steel mould and after solidification, the steel mould is opened to obtain the ingot rods. The above steps were repeated for the various aluminum alloys which used in this work. The chemical composition of prepared alloys as shown in Table (1). Alloy specimens were prepared and subjected to three different heat treatment conditions .The first treatment was subjected the specimens to homogenization treatment at temperature (430℃) for three hours ,the second treatment was subjected the specimens to solid solution treatment at 525℃, then quenching rapidly in two different quenchant media (water and 35% PAG polymer type polyethylene glycol), and the finally treatment was subjected the specimens to artificial ageing at temperature 175℃ at different times.

**Table (1) The chemical composition of prepared alloys.**

| Code of alloy | Si Wt% | Mg Wt% | B Wt% | Ti Wt% | Al Wt% |
|---|---|---|---|---|---|
| A | 0.9 | 0.5 | -- | -- | Bal. |
| B | 0.9 | 0.5 | 0.15 | -- | Bal. |
| C | 0.9 | 0.5 | -- | 1.0 | Bal. |
| D | 0.9 | 0.5 | 0.15 | 1.0 | Bal. |

## TESTS and MEASUREMENTS

### Corrosion Test

Electrochemical method was used to found the corrosion current and potential by using Tafel tester type ( PARSTAT 2273, made in USA) with electrochemical cell. This tester consists of electrochemical cell and its electrodes ,the cell made from glass and contains three electrodes are reference electrode (saturated calomel electrode), auxiliary electrode (platinum electrode), and working electrode contains the specimens. The polarization curves anodic and cathodic are automatically plot since the electrochemical cell connected to electronic processor supplied with program. This test was carried out in the (Ministry of Sciences and technology/ Research Office of Materials).

### Surface Roughness Test

Surface roughness degree of the specimens was measured after grinding and polishing of the specimens by using surface roughness tester type (TR-100).This tester contains a sensor records the roughness magnitude of the specimen surface. This test was carried out in the (Laboratory of Corrosion / College of Materials Engineering /Babylon University).

### X-Ray Diffraction Test

This test was performed through scanning the specimen continuously within Bragg angle (2θ) range (30º-70º) using Cu target (λ=0.154 nm) at voltage of 40 *kV* and 30 *mA* of current with continuous scan mode by general electric diffraction type(XRD-6000). X-ray diffraction test was carried out in the (Ministry of Sciences and Technology/ Research Office of Materials).

Grain size was measured by using Scherrer equation which is given by the following equation [14].

$$G = \frac{0.89\,\lambda}{W_f \cos\theta} \quad \text{..................(1)}$$

where G is the grain size.

λ is the wave length.

$W_f$ is the full width at half maximum (FWHM) in radian units.

θ is the diffraction angle.

### Optical Microscopic Testing

Microstructure of alloys were appeared after homogenization and ageing treatment with magnification (400X) by using ( SIMRAN optical microscope made in USA).Before doing this test, the specimen surface was etched to Keller's reagen solution which consists of 95% $H_2O$, 2.5% $HNO_3$, 1.5% HCl and 1%HF**.**This test was carried out in the (Laboratory of Metallurgical /College of Materials Engineering /Babylon University).

## RESULTS and DISCUSSION

### The Corrosion Results by Electrochemical Method

This method was carried out to determine the corrosion current density , corrosion potential and corrosion rate in saline solution ( 3.5% NaCl) for all samples which were quenching in water and 35% PAG and aged at 175℃.

Table (2) shows the values of the corrosion current, corrosion potential and corrosion rate for all alloys (A,B,C, and D) and these values were obtained by Tafel extrapolation technique. Figures from(1 to 8) show Tafel curves for all samples when quenching in water and 35% PAG and aged at 175℃.

**Table (2) Value of the corrosion current, corrosion potential and corrosion rate of alloys.**

| Code of alloy | $I_{Corr.}$(µA/cm²) | | $E_{Corr.}$(mV) | | Corrosion Rate (×10⁻² mmpy) | |
|---|---|---|---|---|---|---|
| | Water quench | PAG quench | Water quench | PAG quench | Water quench | PAG quench |
| A | 6.635 | 1.685 | -1217.48 | -854.07 | 7.26 | 1.84 |
| B | 1.828 | 1.016 | -954.53 | -906.10 | 2.00 | 1.11 |
| C | 3.807 | 1.083 | -829.53 | -866.93 | 4.30 | 1.18 |
| D | 0.884 | 0.654 | -980.15 | -818.42 | 0.96 | 0.71 |

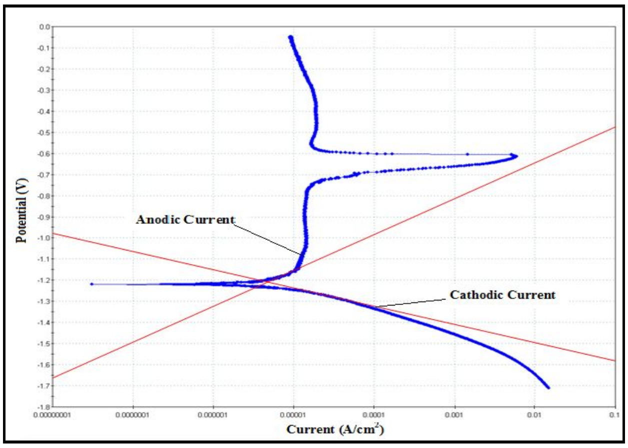


**Fig. (1) Tafel curve for (A alloy) that quenched in water.**

From Table (2) and Figure (1) it can be seen that (A alloy)that quenched in water has low resistance to corrosion where the fine precipitates of magnesium silicide ($Mg_2Si$) would form and dispersed throughout the matrix during the artificial ageing process,these fine precipitates are slightly more anodic than the aluminum matrix. Thus, corrosion potential of the remainder matrix would increase due to dilution of matrix from these elements.

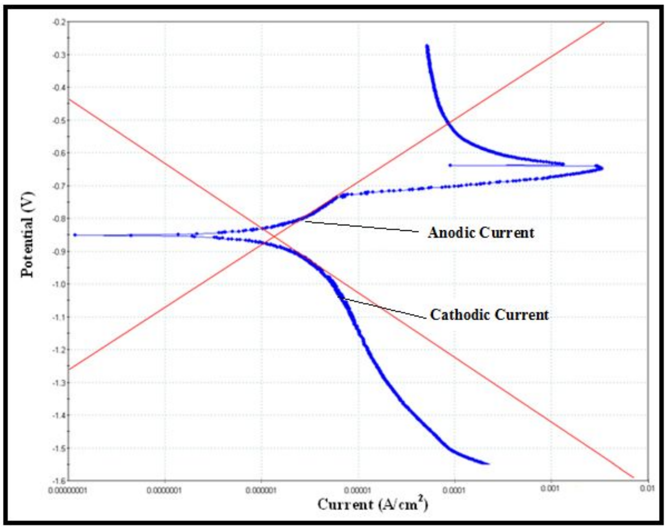


**Fig. (2) Tafel curve for (A alloy)that quenched in 35%PAG.**

From Table (2) and Figure (2) it concluded that the corrosion current and corrosion rate of (A alloy)that quenched in 35% PAG was decreased by 74% in comparison with the (A alloy)that quenching in water ,this means that (A alloy) quenching in 35% PAG has higher corrosion resistance in 3.5% NaCl solution than the same alloy when was quenching in water since the PAG polymer is the best to reduces residual stresses, distortion and cracking in comparison with water.

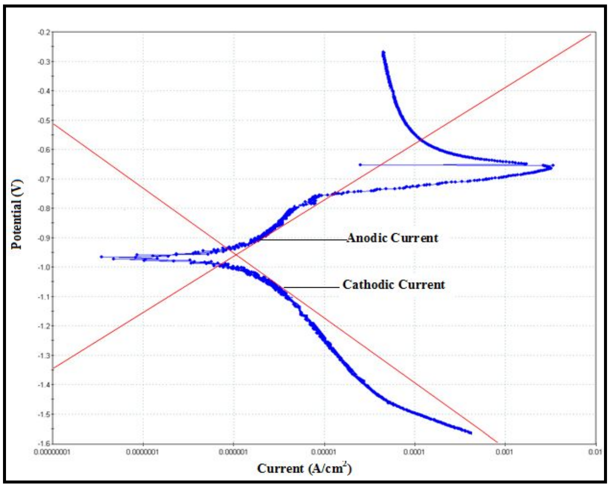


**Fig. (3) Tafel curve for (B alloy) that quenched in water.**

From Table (2) and Figure (3) it is concluded that the corrosion current and corrosion rate of (B alloy) that quenched in water was decreased by 72% in comparison with the (A alloy) that quenching in water,this means that (B alloy)(quenched in water) has higher corrosion resistance in 3.5% NaCl solution than the (A alloy) because the addition of element boron to the (B alloy) and this element done to produce small grain size.

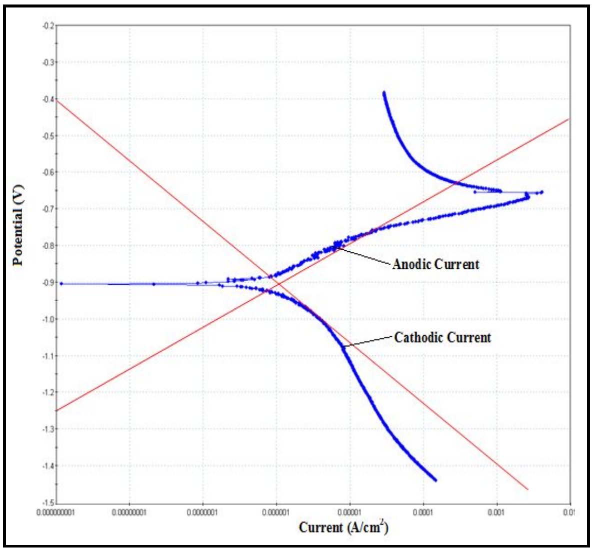


**Fig. (4) Tafel curve for (B alloy) that quenched in 35%PAG.**

From Table (2) and Figure (4) it is concluded that the corrosion current and corrosion rate of (B alloy)that quenched in 35%PAG was decreased by (84%,39%) in comparison with the (A alloy)that quenching in water and 35% PAG respectively this means that (B alloy)(quenching in 35%PAG) has higher corrosion resistance in 3.5% NaCl solution than the (A alloy)when was quenching in 35%PAG because the addition of element boron to the (B alloy) and this element done to produce small grain size, also (B alloy)was quenched in 35% PAG polymer where this polymer is excellent to reduces cracking and distortion .

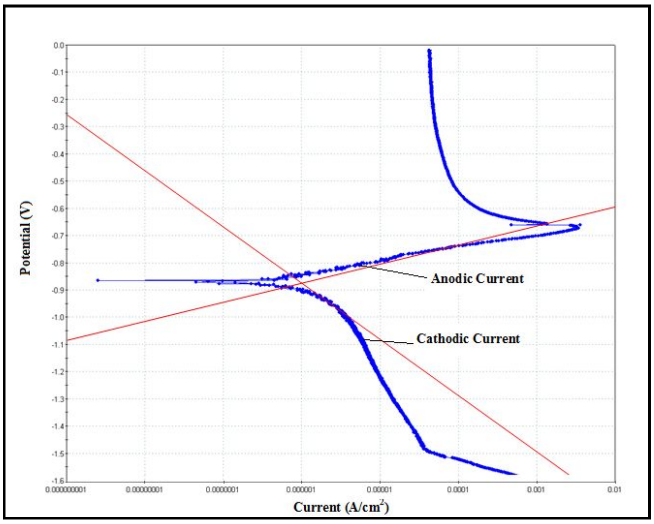


**Fig. (5) Tafel curve for (C alloy) that quenched in water.**

From Table (2) and Figure (5) it is concluded that the corrosion current and corrosion rate of (C alloy) that quenched in water was decreased by 42% in comparison with the (A alloy) that quenching in water, this means that (C alloy) (quenched in water) has higher corrosion resistance in 3.5% NaCl solution than the (A alloy) because the addition of element titanium to the (C alloy) and this element done to softening the size of grains.

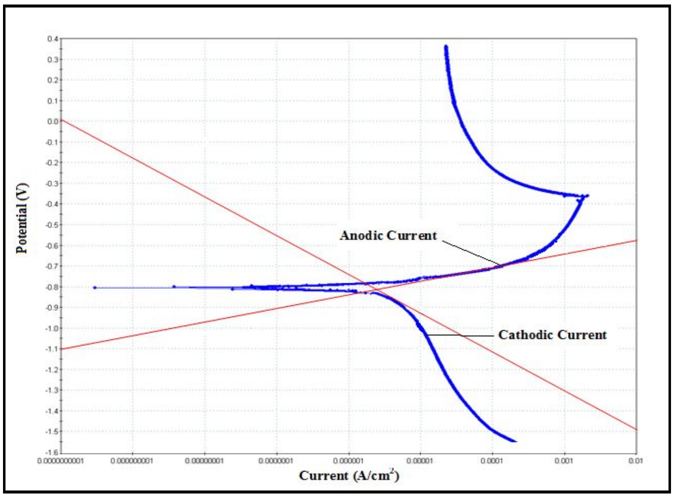


**Fig. (6) Tafel curve for (C alloy) that quenched in 35%PAG.**

From Table (2) and Figure (6) it is concluded that the corrosion current and corrosion rate of (C alloy) that quenched in 35%PAG was decreased by (83%,35%) in comparison with the (A alloy)that quenching in water and 35%PAG respectively, because the addition of element titanium to the (C alloy) and this element done to softening the grains, also (C alloy) was quenched in 35% PAG polymer where this polymer is excellent to reduces cracking and distortion .It is clear that (C alloy) has corrosion resistance few lower than (B alloy), since the (B alloy) contains the element boron, therefore it is concluded that boron is the best than titanium in reducing corrosion current.

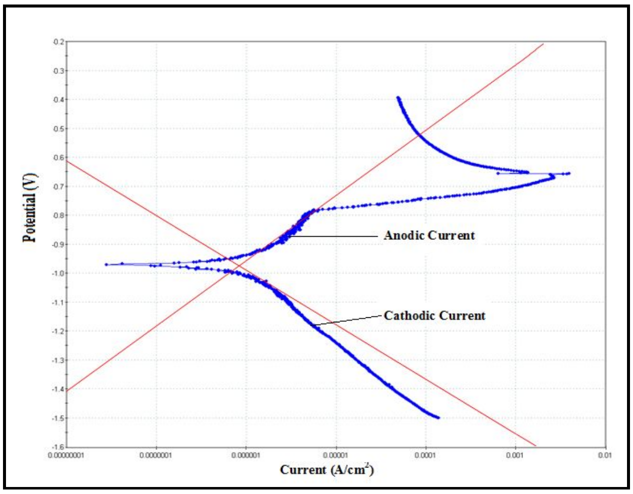


**Fig. (7) Tafel curve for (D alloy) that quenched in water.**

From Table (2) and Figure (7) it is concluded that the corrosion current and corrosion rate of (D alloy) that quenched in water was decreased by 86% in comparison with the (A alloy)that quenching in water, this means that (D alloy) (quenched in water) has higher corrosion resistance in 3.5% NaCl solution than the (A alloy) because the addition of elements (boron and titanium) to the (D alloy) and these elements produced an intermetallic phases caused small grain size.

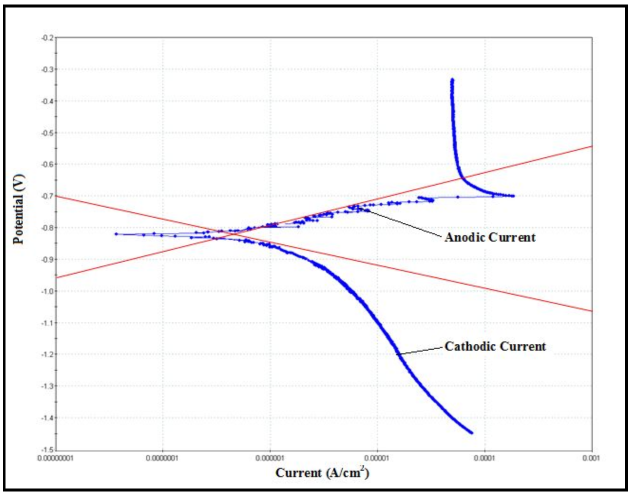


**Fig. (8) Tafel curve for (D alloy) that quenched in 35%PAG.**

From Table (2) and Figure (8) it is concluded that the corrosion current and corrosion rate of (D alloy) that quenched in 35%PAG was decreased by (90%,61%) in comparison with the (A alloy)that quenching in water and 35%PAG respectively, because the addition of alloying elements boron and titanium to the (D alloy). It is clear that the (D alloy) (quenched in 35%PAG) has the highest corrosion resistance among the other alloys that used in this study and also all alloys that quenching in 35% PAG appears higher corrosion resistance than the same alloys when quenching in water because the PAG polymer quenched is the best in reduces residual stresses, distortion and cracking than water quenched.

**Surface Roughness Results**

This test was carried out to determined the degree of surface roughness where the softened surfaces prevent producing the cracks and reduce the corrosion. Table (3) explains the surface roughness testing results for all samples that quenching in (water and 35%PAG) and aged at 175℃.

**Table (3) Surface roughness testing results.**

| Code of alloy | Gage Length ($\mu_m$) | |
| --- | --- | --- |
| | Water quench | Polymer quench |
| A | 0.810 | 0.763 |
| B | 0.429 | 0.387 |
| C | 0.466 | 0.409 |
| D | 0.414 | 0.328 |

From Table (3) it can be seen that (B alloy) has surface roughness less than (C alloy), D alloy is the best in softened surface among the other alloys. All alloys when quenching in 35% PAG have finer surface in comparison with the same alloys when quenching in water since the PAG reduces the distortion and cracking. It is concluded that the addition of alloying elements boron and titanium were decreased the surface roughness and it is clear that the element boron is better than titanium in grain refining, also the addition of boron and titanium together gives the best results in grain refining.

**X-Ray Diffraction Analysis**

In this test , the spacing between planes, full width at half maximum (FWHF) and Miller indices (hkl) were determined.Type of the crystal structure was determined by using computer programmer "International Center for Diffraction Data (ICDD 1997)", and it is found C alloy consists of Cubic, Orthohombic, and Tetragonal structure. D alloy consists of Cubic, Hexagonal, Orthorhombic, and Tetragonal structure. Also, it is appeared that (D alloy) has smaller grain size than C alloy since its contains the elements boron and titanium together which their done grain refine. X-ray diffraction patterns of (C and D)alloys, as shown in Figures (9) and (10) ,also the structural properties of (C and D) alloys as shown in Tables (4) and (5).

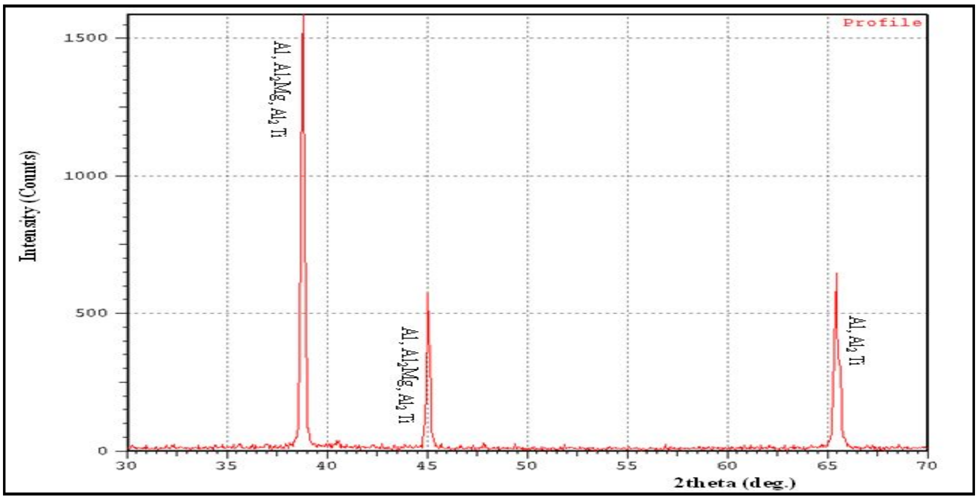


**Fig. (9) XRD Pattern of (C alloy) at the as-aged state.**

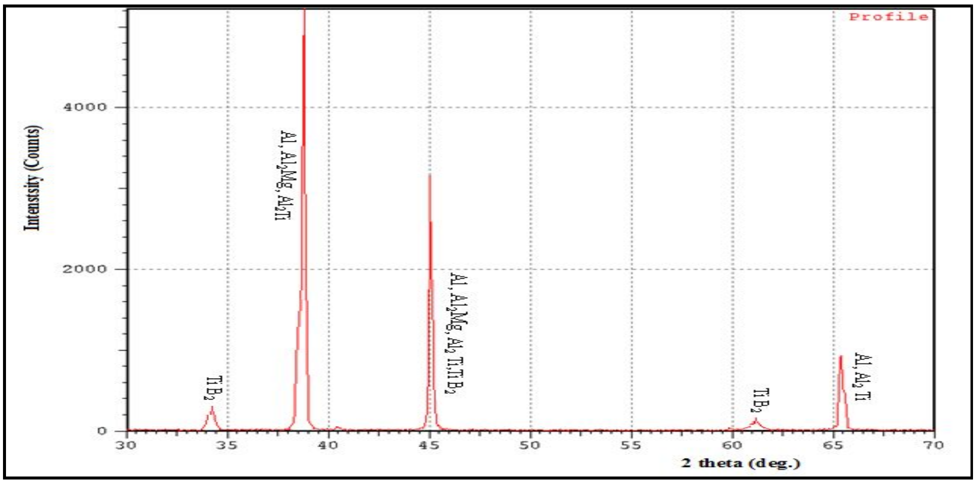


**Fig. (10) XRD Pattern of (D alloy) at the as-aged state.**

**Table (4) Structural properties of (C alloy).**

| C alloy | | | | | | Grain size average =49nm |
|---|---|---|---|---|---|---|
| Theta (deg) | FWHM (rad) | d(Å) | Phase | Crystal Structure | Miller Indices | Grain Size(nm) |
| 19.40 | 0.0032 | 2.318 | Al | Cubic | (111) | 45 |
| | | | $Al_2Mg$ | Tetragonal | (116) | |
| | | | $Al_2Ti$ | Orthorhombic | (311) | |
| 22.53 | 0.0028 | 2.010 | Al | Cubic | (200) | 53 |
| | | | $Al_2Mg$ | Tetragonal | (024) | |
| | | | $Al_2Ti$ | Orthorhombic | (020) | |
| 32.72 | 0.0034 | 1.422 | Al | Cubic | (220) | 48 |
| | | | $Al_2Ti$ | Orthorhombic | (602) | |

## Table (5) Structural properties of (D alloy).

| D alloy | | | | | | Grain size average =41nm |
|---|---|---|---|---|---|---|
| Theta (deg) | FWHM (rad) | d(Å) | Phase | Crystal Structure | Miller Indices | Grain Size(nm) |
| 17.13 | 0.0039 | 2.613 | $TiB_2$ | Hexagonal | (100) | 37 |
| 19.40 | 0.0036 | 2.323 | Al | Cubic | (111) | 40 |
| | | | $Al_2Mg$ | Tetragonal | (116) | |
| | | | $Al_2Ti$ | Orthorhombic | (311) | |
| 22.53 | 0.0033 | 2.010 | Al | Cubic | (200) | 45 |
| | | | $Al_2Mg$ | Tetragonal | (024) | |
| | | | $Al_2Ti$ | Orthorhombic | (020) | |
| | | | $TiB_2$ | Hexagonal | (101) | |
| 30.60 | 0.0042 | 1.512 | $TiB_2$ | Hexagonal | (110) | 38 |
| 32.72 | 0.0037 | 1.425 | Al | Cubic | (220) | 44 |
| | | | $Al_2Ti$ | Orthorhombic | (602) | |

**Optical Microscopic Results**

The microstructure of alloys as homogenization that are used in this study is shown in Figure (11) and it is noted that most of the grains in this condition which appear much equiaxed structure and observed precipitates present on the grain boundaries to alloys.

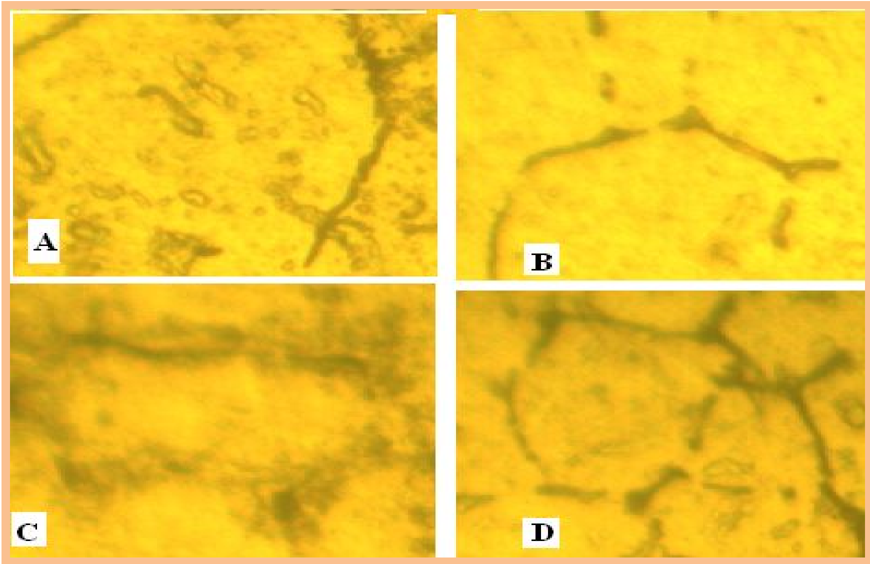


**Fig. (11) Microstructure of (A, B,C and D) alloys as homogenization treatment, 400X.**

Figures (12) and (13) show microstructure of alloys when quenching in two different media ( water and 35% PAG) with ageing temperature at 175°C and from these figure noted that the precipitates were distributed in structure , the grains sizes homogenizing and did not find any cracks in alloys that quenched in polymer compared with alloy that quenched in water. Generally when comparing the figures, it is obtained that the microstructure of alloy when quenched in 35% PAG consists of shape, size and uniform distributing for grains in comparison with the same alloy when quenched in water.

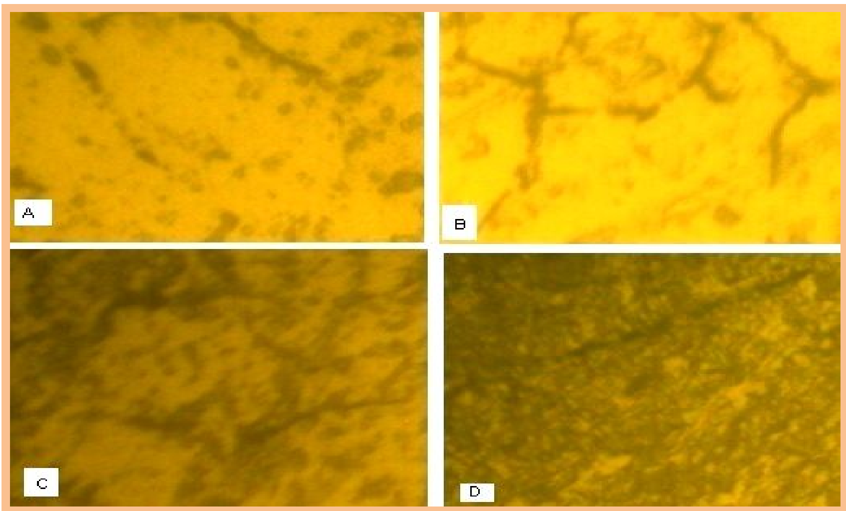


**Fig.(12) Microstructure of (A, B,C and D) alloys as solution heat treatment (quenched in water and aged at 175°C), 400X.**

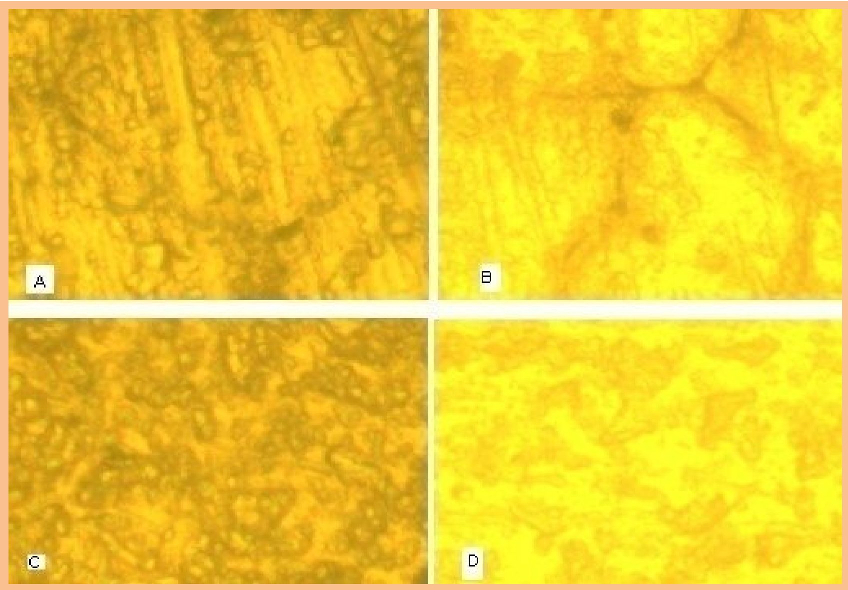

**Fig.(13) Microstructure of (A, B,C and D) alloys as solution heat treatment (quenched in 35%PAG and aged at 175℃), 400X.**

## CONCLUSIONS

The conclusions of this work can be summarized as follows:

1- The addition of 0.15% B to the base alloy is better than the addition of 1% Ti, in improving the corrosion resistance and smoothing surface and these properties are more improvement when the addition of (B and Ti) together.
2- Corrosion resistance and smoothing surface of prepared alloys improvement when quenched in 35% PAG in comparison when quenched in water.
3- X-ray results appeared that reducing in grain size is increasing when the addition of (B and Ti) together to the base alloy.
4- Alloys when quenched in 35% PAG have microstructure consists of shape, size and uniform distributing for grains in comparison with the same alloys when quenched in water.

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