Study of The Structure and Corrosion Behavior of Al-15%Mo Alloy

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Abstract. The influence of the addition of molybdenum on the structure and corrosion behaviour of aluminium was studied using optical microscopy, scanning electron microscope (SEM), potentiodynamic polarization and electrochemical impedance spectroscopy. The results show that the addition of 15%-wt molybdenum causes the precipitation of the Al12Mo intermetallic phase which appears in plate form on the αAl matrix. The results of the electrochemical tests show that the addition of molybdenum displaces the corrosion potential of aluminium towards positive values from -699 mV/ECS to -633 mV/ECS and increases the charge transfer resistance from to 4752 Ω.cm² to 6608 Ω.cm².

1. Introduction

Aluminium alloys plays an important role in the industry, they occupy the second place in the manufacturing of parts after ferrous alloys. These alloys are largely used in several sectors, particularly in the aeronautics industry, where the materials are frequently subjected to high temperatures. The improvement of the mechanical properties of these alloys has been of great importance for all sectors of industry [1]. It requires the hardening of these alloys by precipitates which have a high melting point [2]. Generally, transition metals have a low diffusivity in aluminium which results in the precipitation of a number of refractory intermetallic phases in the α-aluminium matrix [3]. The main alloying elements added to aluminium are copper, manganese, magnesium, silicon, zinc and lithium. These elements can be added alone or combined. They causes a structural hardening by solid solution effect if they are not fully integrated into the precipitates [4]. As molybdenum has a very high melting temperature, a low coefficient of thermal expansion, a high level of thermal conductivity and a low diffusion coefficient, it becomes an exceptional material for the production of stable alloys that respond to the most delicate requirements [5-7].
Several studies have been carried out on the phases formed in the Al-Mo binary system [8, 9]. Brewer and Lamoreaux [10] have proved that the Al-Mo binary diagram contains two solid solution phases αMo, αAl and ten intermetallic phases. The formation of these phases depends on the molybdenum content, cooling rate and heat treatment temperature. The objective of our research work is to study the influence of molybdenum addition on the structure and electrochemical behavior of the Al-15%Mo alloy produced in a high-frequency induction furnace.

2. Experimental
The material used in this study is a powder mixture pellet (Al-15%wt.Mo) cold compacted under a force of 10 tons and melted in a high frequency electromagnetic induction furnace. The microstructural study was carried out by optical and scanning electron microscopy on samples mechanically polished by various abrasive papers (600, 800, 1000, 2000, 2400 and 4000) and chemically attacked by the KILLER reagent (2.5% HNO₃, 1.5% HCl, 1% HF and 95% H₂O). Potentiodynamic polarization and electrochemical impedance measurements were carried out on pure aluminium and Al-Mo alloy using a Metrohm Autolab potentiostat-galvanostat. The electrochemical experiments were performed after one hour of immersion at 298K in a conventional three-electrode electrochemical cell: working electrode, platinum counter electrode, and saturated calomel reference electrode. The potentiodynamic polarization curves (Tafel) are plotted over a potential range from -1200 to +800 mV at a scanning rate of 1 mV/s. The electrochemical impedance curves are plotted over a frequency range of 100 kHz to 10mHz with a signal amplitude of 10 mV. The medium used is 3.5% NaCl.

3. Results
3.1. Observation by optical microscopy
Figure 1 illustrates the metallographic structure of the Al-Mo alloy. The alloy exhibits a microstructure composed of two structural components:
- An aluminium matrix; solid solution of molybdenum in aluminium α.
- A stable intermetallic compound.

![Figure 1. Micrographs of the Al-15%Mo alloy at different magnifications.](image)

3.2. SEM and EDS analysis
The SEM microstructures of the Al-Mo alloy are shown in Figure 2. SEM micrographs clearly reveal the shape of the precipitates. The structure of the intermetallic phase appears as fibers and plates.
Figure 2. SEM microstructures of the Al-15\% Mo alloy.

The punctual EDS analysis of the different phases (Figure 3) shows the presence of 81\% aluminium and 1\% molybdenum in the alpha aluminium phase. For precipitates, we note the presence of aluminium and molybdenum in proportions that coincide with the composition Al\(_{12}\)Mo\(_{11}\). This phase has a cubic structure of space group Im-3, with a crystalline parameter \(a=7.577\).

Figure 3. EDS analysis of the different phases of the Al-15\% Mo alloy.
3.3. Electrochemical behavior of the Al-15%Mo alloy in 3.5% NaCl

3.3.1. Potentiodynamic polarization

Figure 4 indicates the potentiodynamic polarization curves of the two materials aluminum and Al-15%Mo alloy in the 0.5% NaCl solution. The (Table 2) gathers the electrochemical parameters deduced from the polarization curves plotted. With the addition of molybdenum, we see that the corrosion potential tends towards positive values, it moves from -699 mV/ECS to -633 mV/ECS, we noticed that the corrosion current density value increases slightly from (0.31 µA cm\(^{-2}\) for Al) to (0.36 µA cm\(^{-2}\) for Al-15%Mo).

In anode branches, a large passivation plate in the anodic region medium is observed for both materials. This passivation is the result of the formation of a protective layer based on oxides [12-14].

![Figure 4. Potentiodynamic polarization curves of the two materials in NaCl at 3.5%.](image)

**Table 1.** Electrochemical parameters deduced from the polarization curves of the two materials in 3.5% NaCl.

| Material       | \(E_{corr}\) (mV/ECS) | \(I_{corr}\) (µA cm\(^{-2}\)) | \(\beta_c\) (mV dec\(^{-1}\)) | \(\beta_a\) (mV dec\(^{-1}\)) |
|----------------|------------------------|-------------------------------|-------------------------------|-------------------------------|
| Al             | -699                   | 0.31                          | 150.9                         | 148.6                         |
| Al-15%Mo       | -633                   | 0.36                          | 390.3                         | 122                           |

3.3.2. Electrochemical impedance measurement

Figure 5 illustrates the Nyquist diagrams of the two materials aluminium and Al-15%Mo alloy in the 3.5% NaCl solution. The electrochemical impedance diagram of aluminium is characterized by two capacitive loops. The first loop is attributed to charge transfer at high frequencies, and the second loop is due to the dissolution of the film formed on the surface of the aluminium. The impedance diagram of the Al-15%Mo alloy consists of a single capacitive loop attributed to charge transfer reaction [15-17].

The values of the different parameters, resulting from the parametric adjustment by the equivalent circuits (figure 6), are grouped in Table 2. This circuit consists essentially of a resistance and a constant phase element (CPE). From these results, we can see that the addition of molybdenum increases the charge transfer resistance and reduces decreased the constant phase element.
5

Figure 5. Impedance diagrams in Nyquist representation of the two materials in 3.5% NaCl.

(a) Rs CPE1 R1 (b)

Figure 6. Equivalent electrical circuits used for the analysis of impedances: (a) Al, (b) Al-15% Mo.

Table 2. Electrochemical parameters derived from impedance diagrams of both materials in 3.5% NaCl.

|        | R_s (Ω cm²) | R_1 (Ω cm²) | CPE1 (µF cm⁻²) | n_1 | R_2 (Ω cm²) | CPE2 (µF cm⁻²) | n_1 |
|--------|-------------|-------------|----------------|-----|-------------|----------------|-----|
| Al     | 24.7        | 3831        | 24.1           | 0.778 | 59.31       | 0.11 9e3        | 0.2271 |
| Al-15% Mo | 39.52   | 6608        | 13.9           | 0.838 |            |                |     |

4. Conclusion

The aim of our research work is to study the influence of molybdenum addition on the structure, mechanical properties and electrochemical behavior of the Al-Mo alloy produced in a high-frequency induction furnace. The influence of molybdenum on the structure and corrosion behaviour of the Al-15%Mo alloy was studied using optical microscopy, SEM, EDS and electrochemical techniques. The following conclusions can be highlighted:

- The addition of 15% molybdenum causes the precipitation of Al12Mo intermetallic phases as plate and fiber form.
- In the presence of molybdenum, the corrosion potential shifts to positive values from -699 to -633 (mV/ECS).
- The impedance diagram of the Al-15%Mo alloy shows the presence of a single capacitive loop attributed to the charge transfer phenomenon. The addition of molybdenum increases the charge transfer resistance from 4752 Ω.cm² to 6608 Ω.cm².
References

[1] Sukiman N L, Zhou X, Birbilis N, Hughes A E, Mol J M C, Zhou X, Garcia S J and Thompson G E 2012 *Aluminium Alloys-New Trends in Fabrication and Applications* 47-97

[2] Gharbi A, Bouhamla K, Ghelloudj O, Ramoul C E, Berdjane D, Chettouh S and Remili S 2021 *Defect Diffus. Forum, Trans Tech Publications Ltd.* **406** 419-429

[3] Debili M Y, Sassane N and Boukhris N 2017 *Anti-Corros. Method. M.* **64(4)** 443-451

[4] Monagheddu M, Delogu F, Schifini L, Frattini R and Enzo S 1999 *Nanostruct. Mater.* **11(8)** 1253-1261

[5] Qiu Y Y, Almeida A and Vilar R 1997 *J. Mater. Sci. Lett.* **16(24)** 1986-1990

[6] Forsyth, J. B., & Gran, G. 1962 *Acta Crystallogr.* **15(2)** 100-104

[7] Almeida A, Carvalho F, Carvalho P A and Vilar R 2006 *Surf. Coat. Technol.* **200(16-17)** 4782-4790

[8] Clare J W H 1961 *J. Inst. Met.* **89(7)** 232-234

[9] Brewer L, Lamoreaux R H, Ferro R and Marazza R 1980 *Bulletin of Alloy Phase Diagrams* **1(2)** 71-75

[10] Vigdorovich V N, Glazov V M and Glagoleva N N 1960 *Izv. Vyss. Uchebn. Zaved., Tsvet. Met* **3(2)** 143-146

[11] Okamoto H 2010 *J. Phase. Equilib. Diff.* **31(5)** 492-493

[12] Bouhamla K, Gharbi A, Ghelloudj O, Hadji A, Maouche H, Remili S and Chettouh S 2021 *Defect Diffus. Forum, Trans Tech Publications Ltd.* **406** 334-347

[13] Ghelloudj O, Gharbi A, Zelmati D, Bouhamla K, Ramoul C E and Berdjane D 2021 *Defect Diffus. Forum, Trans Tech Publications Ltd.* **406** 448-456

[14] Bahi R, Nouveau C, Beliardouh N E, Ramoul C E, Meddah S and Ghelloudj O 2020 *Surf. Coat. Tech.* **385** 125412

[15] Gharbi A, Himour A, Abderrahmane S and Abderrahim K 2018 *Orient. J. Chem.* **34(1)** 314-325

[16] Gharbi A, Maouche H and Ghelloudj O 2017 *Acta Phys. Pol. A* **131(3)** 346-348

[17] Bahi R, Nouveau C, Beliardouh N E, Ramoul C E, Meddah S and Ghelloudj O 2020 *Surf. Coat. Tech.* **385** 125412