



Impact of a hydrogenated environment on the mechanical properties of an aluminum alloy Al-Mg-Si.1

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Abstract

Background/Aim: This study aims to investigate the impact of a hydrogen-rich environment on the mechanical properties of an Al-Mg-Si aluminum alloy from the 6xxx series. Such alloys can exhibit hydrogen embrittlement (HE), especially in aqueous environments. The extent of this embrittlement depends on various microstructural parameters and any heat treatments that the alloy has undergone. **Methods:** Experimental work was conducted on cylindrical test specimens that underwent a homogenisation cycle involving rapid cooling by super-saturation in water (SSW), followed by natural cooling to ambient temperature. This was followed by artificial ageing (AA) tempering after cooling in open air. The samples were pre-charged using the cathodic charging method for different periods ranging from two to eight hours in a simulated environment of 0.05 M sulfuric acid (H₂SO₄) at a current density of 70 mA/cm². **Results:** The results, presented in the form of experimental curves recorded after a mechanical tensile fracture test, consist of breaking the loaded test pieces at ambient temperature. The mechanical characteristics were analysed by hardness tests before and after loading. Scanning electron microscopy reveals the presence of ODA inclusions, which are non-metallic impurities that act as preferred sites for crack initiation. This confirms the mechanism of hydrogen embrittlement, resulting in a decrease in elongation at break. **Conclusion:** There was a noticeable decline in mechanical performance, especially in yield strength and elongation at fracture, during hydrogen charging. The alloy's sensitivity to hydrogen was confirmed by the fact that the level of absorbed hydrogen rose with charging time. An embrittlement index (EI%) was used to measure the hydrogen-induced loss of ductility, reaching 30%.

1. Introduction

Aluminum alloys are extensively utilised in the automotive, aerospace, and structural domains due to their exceptional strength-to-weight ratio, corrosion resistance, and superior formability [1]. However, it has a notable weakness in terms of mechanical strength. As a result, unalloyed aluminum is mainly used in applications where mechanical properties are of secondary importance compared to its other qualities [2]. Mainly for reasons of mechanical strength, aluminum alloys are produced by the controlled addition of alloying elements, such as copper, silicon, magnesium, manganese, titanium, chromium, zinc, and cobalt, which improve their mechanical properties. Among the most common alloys, those belonging to the Al-Cu and Al-Mg-Si families

are the most widely used. Due to their lightweight, improved mechanical properties, excellent castability, and good corrosion resistance, these alloys are primarily used in engineering and automotive applications. These alloys constitute the largest group of cast aluminum alloys and account for 85% to 90% of all aluminum castings [3]. Aluminum alloys in the (Al-Mg-Si)/ 6xxx series are materials that contain two essential alloying elements: magnesium and silicon, which form silicide. They are widely used in the aerospace industry for their high mechanical properties. Their applications are subject to high stresses, which are favoured by their mechanical strength of 350 MPa. Currently, the 6xxx series is widely used in the automotive industry because it possesses

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excellent deformation, mechanical energy, and formability properties, as well as resistance to corrosion, particularly environmental corrosion [1, 3].

Problems associated with the change and degradation of mechanical properties due to the penetration of hydrogen in cation form (H^+) into the crystal lattice of the alloy studied have been explored by [4, 5]. Several studies have been conducted to elucidate the mechanism of hydrogen embrittlement [6-8]. According to the different protocols and industrial conditions adopted [9-13], depending on the process application and cathodic loading regimes in hours [14-16, 18-19-20].

The study using SEM on hydrogen-charged alloys revealed non-metallic inclusions (NMIs), such as cavities and pores, which promote the initiation of cracks. These cracks primarily form at the edges of the cylindrical section after tensile tests [21-23].

Previous research has revealed that this issue is related to a loss of plasticity and a decrease in elongation, highlighting the impact of inclusions on the mechanical strength of materials in the presence of hydrogen [11, 12, 20, 22].

Al-Mg-Si aluminum alloys are susceptible to hydrogen embrittlement, a phenomenon influenced by the alloy's chemical composition and heat treatments [1], making it crucial to consider these parameters when assessing the strength and durability of these alloys in aqueous environments. However, the correlation between treatment regimes and (HE) behavior remains insufficiently explored, especially for raw commercial grades such as AlMgSi.1F/30 (equivalent to 6082).

The main objective of this study is to assess how heat treatments affect the mechanical behavior and hydrogen embrittlement sensitivity of an Al-Mg-Si alloy (grade AlMgSi.1F/30). Cylindrical specimens were subjected to solution treatment at 550 °C, followed by natural or artificial ageing [19, 22]. Hydrogen charging was carried out using a 0.05M (H_2SO_4) solution in an electrochemical cell [22, 23].

The effects of hydrogen embrittlement were evaluated through microhardness measurements, tensile testing, and SEM observations of fracture surfaces [22]. Particular attention was paid to the formation of microvoids and inclusions that initiate cracking [11, 12, 20, 22]. The goal is to assess how heat-induced structural changes affect hydrogen embrittlement and mechanical performance.

2. Materials and Methods

2.1. Materials

The material used in this study is AlMgSi.1F/30/AFNOR A-S7G, which was selected in the form of a raw cylindrical bar with a diameter of 20 mm, delivered in a cold-rolled state.

The research specifically examines the chemical composition of this material, presented in (% by weight) and given in Table 1.

Table 1. Analysis Chemical composition of AlMgSi.1F/30 - 6082 alloy (% by weight).

Chemical element	Chemical composition, mass. (%), Aluminum alloy AlMgSi.1
Fe%	0.50
Mg%	0.50 - 1.20
Si%	0.7 - 1.30
Mn%	0.44 - 1.00
Cu%	0.10
Zn%	0.20
Ti%	0.10
Al%	98.50

2.2. Mechanical properties in as-delivery condition

A mechanical tensile pre-test was performed at a slow displacement speed of $2.6 \times 10^{-6} S^{-1}$ on an unloaded test specimen shown in (Figure 1 (a), (b)). This test was designed to examine the initial mechanical properties of the test piece in its delivery state, without prior heat treatment. The results and significant data from this analysis are detailed in Table 2.

Table 2. Initial mechanical properties (as-received) of the AlMgSi.1F/30/6082 grade.

Mechanical properties (As-received)	Aluminum alloy AlMgSi.1F/30
Stress strength, σ_m , (MPa)	362±2.61
Yield strength, σ_e , (MPa)	258±7.57
Failure strength, σ_r , (MPa)	278±6.25
Reduction percentage, Z, (%)	38%
Elongation Percentage, A, (%)	13%
Hardness, HV ₍₃₀₎ , (N/mm ²)	107
Young modulus, E, (MPa)	69.5
Poisson modulus, ν	0.3

2.3. Manufacture of test specimen

The test samples were made in cylindrical form, in accordance with standard: DIN – 50125, [17]. Manufacturing was carried out using a semi-automatic lathe manufactured by OERLINKO. This method ensured the correct shaping and precise geometry of the final dimensions of the samples, with a diameter of 16 mm and a useful length of 96 ± 0.01 mm (Figure 1).

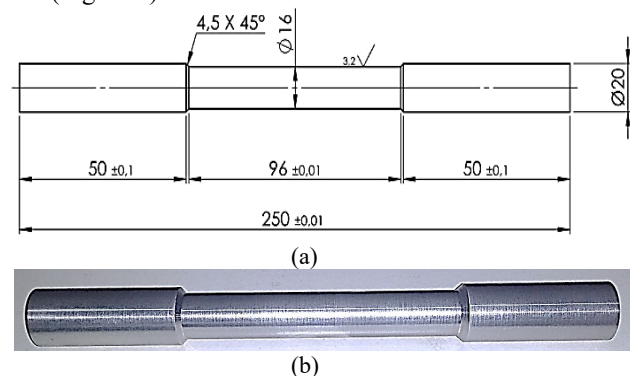


Figure 1. (a): Shape and geometry of the test specimen used in accordance with DIN – 50125. [17], (b): Photo of the aluminum test specimen, polished finish.

2.4. Heat treatment

Using an electric muffle furnace with refractory lining, brand: HERAEUS M170. The AlMgSi1.F/30 alloy test pieces were subjected to homogenising heat treatment at 550°C for 7 hours, followed by rapid cooling by super-saturation water. This process was followed by natural ageing T6 at 150°C for 10 hours, with cooling to room temperature.

In addition, an artificial ageing treatment (T7) was carried out at 240°C for 24 hours, after slow cooling in open air (Figure 2). These treatments aim to optimise the mechanical properties of the alloy, as indicated in the work of [1].

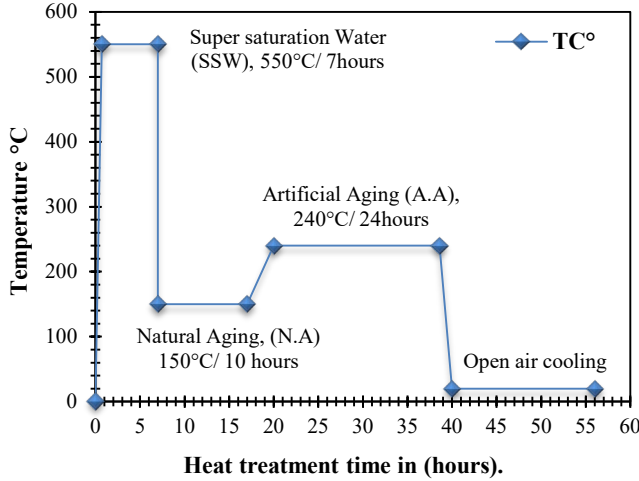


Figure 2. Heat treatment cycle applied [1].

2.5. Electrolytic charging condition

An experimental cell was set up for electrolytic hydrogen charging, using an aqueous solution of sulphuric acid at a concentration of 0.05M. The cathodic polarisation conditions were defined with a current density of 70 mA/cm², similar to the work [22]. The charging times varied between 2 and 8 hours, allowing the effects of these different times on the electrolysis process to be observed. The work of [6-8, 18] was cited to support this study.

2.6. Mechanical tensile test

After the hydrogenation process, a reference instrumented tensile testing machine Frank karl GMBH, is used to perform mechanical fracture testing by traction, which is validated by a previous study [22, 23]. These tests are conducted at an ambient temperature of 20±2 °C. In addition, a constant load (F) of 400 kN is applied, with a slow strain rate ($\dot{\epsilon}$) set at 2.6x10⁻⁶S⁻¹. These experimental conditions are essential to ensure the accuracy and reliability of the results, see (Table 3). Mechanical resistances are calculated using three fundamental equations (1), (2) and (3) cited below:

$$\sigma_m = \frac{(F_m)}{S}; (\text{MPa}). \quad (1)$$

$$\sigma_r = \frac{(F_r)}{S}; (\text{MPa}). \quad (2)$$

$$\sigma_r = \frac{(F_r)}{S}; (\text{MPa}). \quad (3)$$

Where:

F: The load or force applied to the tensile test specimen in (kN).

S: The cross-sectional area of the fractured test specimen in (mm²), and $S = \frac{\pi d^2}{4}$

The evaluation of ductility and plasticity is based on the application of two specific equations, designated (4) and (5). These equations are used to calculate two essential parameters: elongation area (A%) and reduction area in gauge length (Z%) of the test specimens before and after hydrogenation.

$$A(\%) = \frac{(L_0 - L_1)}{L_0} \times 100(\%) \quad (4)$$

$$Z(\%) = \frac{(S_0 - S_1)}{S_0} \times 100(\%) \quad (5)$$

Where:

L₁: The final length of the test piece after breaking and L₀: its initial length as delivered.

S₁: The final cross-sectional area after breaking and S₀: the initial cross-sectional area of the test piece before breaking.

2.7. Vickers hardness test

The mechanical characterisation technique described is based on HV₍₃₀₎ hardness tests, which involve subjecting a test piece to localised plastic deformation. This deformation is achieved using a Vickers diamond indenter, whose pyramidal shape has an angle of 136°. The tests are carried out on samples in their raw state, after homogenisation treatment and after hydrogenation. The hardness tests are performed using a Frank Karl GMBH machine, model 4532 (Figure 3).



Figure 3. Frank Karl HV hardness tester.

The (HV) hardness rating, expressed in (N/mm²), is calculated from the diagonals of the indentation left by the indenter. Equation (6) used for this calculation takes into account the average of the two diagonal diameters of the indentation, denoted d₁ and d₂, as well as the applied load, P, expressed in (N). This method provides accurate data on the hardness of the tested matrix.

$$HV = 4.8544 \left(\frac{P}{D^2} \right); (N/mm^2) \quad (6)$$

Where:

P: The load applied to the localised surface in (N);

D: Average diameter of the indentation calculated based on the two diagonal diameters d1 and d2 in (mm),

3. Results and discussion

3.1. Mechanical properties (σ_m , σ_e , σ_r); and Plasticity (A, Z)

Analysis of the mechanical property results presented in Table 3 and Table 4, as well as the experimental curves illustrated in Figures 7 and 8, has led to several significant observations. Firstly, the curves show clear trends that provide a better understanding of the phenomenon under study. Furthermore, the variations observed in the experimental data highlight the importance of the parameters controlled during the mechanical tensile fracture tests before and after the hydrogenation method.

Table 3. Mechanical characteristics obtained after tensile testing (Tensile, Yield and Failure strength).

Specimens	Hydrogen time in (hours)	Tensile Strength (TS), σ_m MPa	Yield Strength (YS), σ_e MPa	Failure Strength (Fr), MPa
As-received	Uncharged	362±2	258±7	278±6
Specimen.1	2 hours	196±5	122±4	109±4
Specimen.2	4 hours	196±0	119±4	111±9
Specimen.3	6 hours	196±1	118±3	112±4
Specimen.4	8 hours	195±0	116±4	111±9

Table 4. Mechanical characteristics obtained after tensile testing (Elongation area, Reduction area and Hardness).

Specimens	Hydrogen time in hours	Elongation in area, Z, (%)	Reduction in area, A, (%)	Hardness HV ₍₃₀₎ , (N/mm ²)
As-received	Un-charged	13.50	38	107
Specimen.1	2 hours	12.10	41	41.20
Specimen.2	4 hours	11.20	41	39.54
Specimen.3	6 hours	10.30	40	38.84
Specimen.4	8 hours	9.50	41	36.45

Figure 4 shows a slight decrease in mechanical strengths, namely σ_m , σ_e and σ_r , expressed in MPa, as a function of hydrogen loading time. This observation suggests an inverse relationship between loading time and the mechanical strength of the alloy. At the same time, significant improvements were noted in terms of necking, while elongation decreased slightly as a function of hydrogen loading time, as shown in (Subfigure 5). These results highlight the importance of loading conditions, such as loading time, applied current density and simulated medium concentration, on the

mechanical properties of the material studied when subjected to hydrogen.

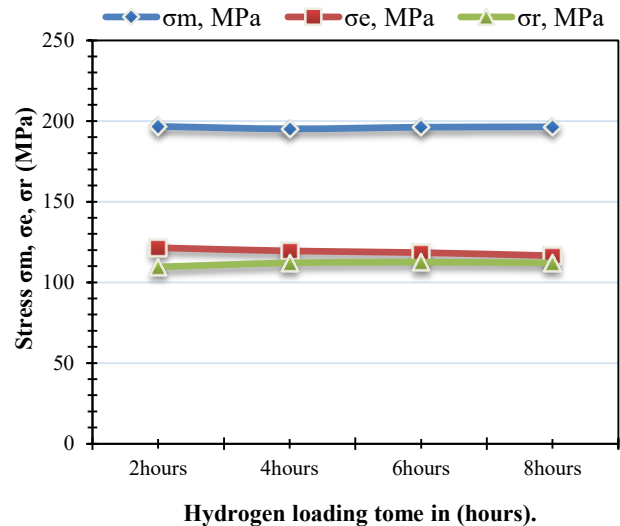


Figure 4. The influence of hydrogen loading time on the variation in stress (MPa).

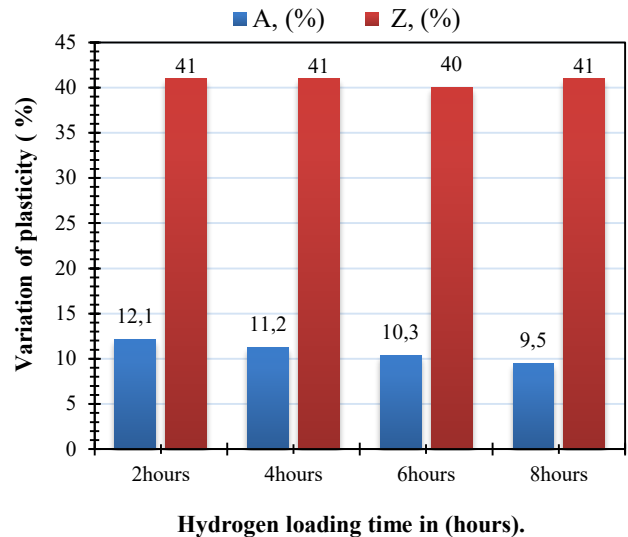


Figure 5. The influence of hydrogen loading time on the variation in plasticity (%).

3.2. Yield strength (σ_e)

Figure 6 shows the elastic limit in (MPa) as a function of the hydrogen loading time in hours, which has a negative effect by lowering this limit from 258 MPa to 122 MPa up to 8 hours, reaching a level of 116 MPa, where the elastic limit passes through a minimum value due to its high solubility in the liquid state and under the effect of the conditions of the medium used and the pre-loading time, thus affecting the value of the polarisation density. hydrogen tends to form pores during solidification (Subfigure 16 (a)), resulting in a reduction in the mechanical properties of the alloy matrix [16].

As a result, this type of AlMgSi.1 alloy material is brittle under environmental conditions, leading to internal cracking induced by the influence of these mechanical properties due to hydrogen adsorption over time.

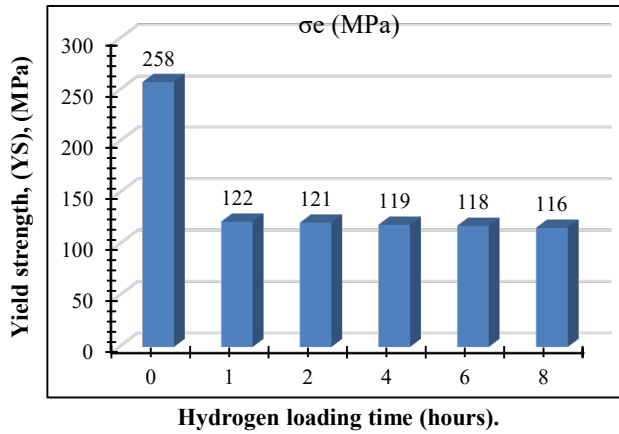


Figure 6. The influence of hydrogen loading time on the yield strength.

3.3. Tensile curves (stress-strain)

Table 3 and Table 4 shows the results of the mechanical characteristics based on the experimental tensile curves recorded on the testing machine.

Figure 7 shows the evolution of tensile elongation (stress-strain) of ALMgSi.1 alloy test samples before and after electrochemical preloading as a function of different loading times up to 8 hours, then broken at a slow displacement speed ($2.6 \times 10^{-6} \text{ s}^{-1}$). In order to present a significant embrittlement by the hydrogen molecule (H_2), the tensile curves also undergo a change in the cases shown, with slight decreases in the maximum stress (σ_m) and elastic limit (σ_e), but a slight improvement in the tensile strength (σ_r). A noticeable reduction in plasticity, reflected in a decrease in deformation ($\epsilon\%$) from 13.50% to 9.50%, [14, 19, 20].

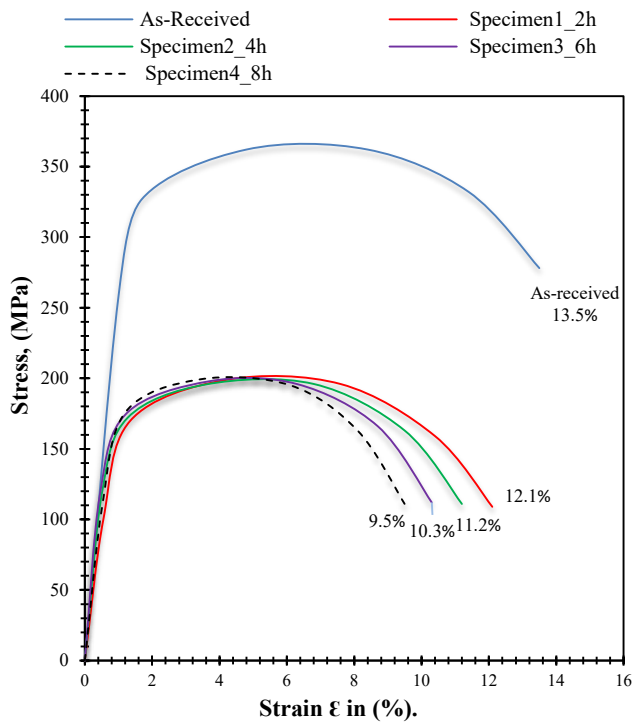


Figure 7. Evolution of the tensile elongation of ALMgSi.1 alloy test samples before and after electrochemical preloading, varying with different loading times.

3.4. Hardness Vickers (HV)

After analysing the results of the $\text{HV}_{(30)}$ microhardness test, the numerical data were recorded in a table. A histogram was created to visualise the variations in microhardness depending on the heat treatments applied and the cooling medium, (Subfigure 8). This graphical representation allowed several significant conclusions to be drawn. It was observed that heat treatments have a significant influence on the microhardness of the samples. The variations in hardness are directly related to the cooling conditions, highlighting the importance of these parameters in the treatment process. The results also indicate that certain heat treatments are more effective than others in improving microhardness, which could have practical implications for the choice of treatment methods in industrial applications.

Table 5. $\text{HV}_{(30)}$ microhardness values after different types of cooling.

Heat treatments applied	Hardness Vickers $\text{HV}_{(30)}$, (N/mm^2)
As-Delivred condition	107
Super-Saturation Water, (SSW)	68.90
Super-Saturation Oil, (SSO)	70.20
Natural Aging, (AN)	54.96
Artificial Aging, (AA)	43.36

Analysis of the histogram reveals that the reference sample has the highest microhardness value, reaching 107 N/mm^2 . The samples that underwent homogenisation treatment, followed by quenching in water or oil, show significantly high microhardness values, ranging from 68.90 to 70.20 N/mm^2 , (Subfigure 8). In contrast, samples treated by natural and artificial ageing, after cooling at ambient air temperature, show the lowest values, ranging between 43.36 and 54.96 N/mm^2 . These results highlight the impact of the different treatments on the microhardness of the samples, see (Table 5).

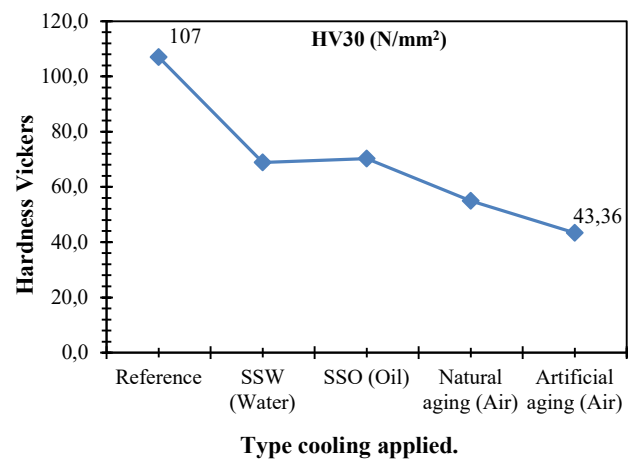


Figure 8. Histogram of microhardness changes depending on the type of cooling medium.

Table 6 shows the $\text{HV}_{(30)}$ microhardness values after hydrogenation, depending on the different loading times in hours. These data are visualised by a histogram of variations, as shown in (Subfigure 10). The following observations can

be made: the variations in microhardness as a function of loading time show significant trends, particularly between 2 and 8 hours, highlighting the impact of loading times on the microhardness of the test samples.

Table 6. $HV_{(30)}$ microhardness values after hydrogenation.

H-charged times in (Hours)	Hardness Vickers $HV_{(30)}$, (N/mm ²)
As-received (H-Uncharged)	107
H-charged - 2 hours	41.20
H-charged - 4 hours	39.54
H-charged - 6 hours	38.84
H-charged - 8 hours	36.45

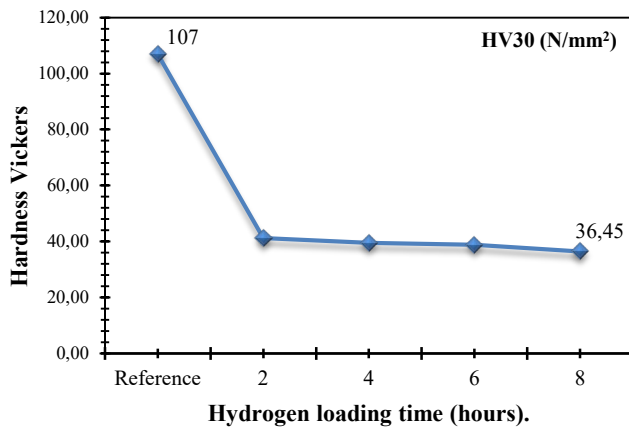


Figure 9. Histogram of microhardness changes as a function of hydrogen loading time in hours.

The hydrogenation of the samples led to a significant decrease in hardness, from a reference value of 107 N/mm² to 41.20 N/mm² (Subfigure 9). This reduction was observed up to a loading time of 8 hours, when the hardness reached a minimum of 36.45 N/mm². The loading conditions, in particular the concentration of the simulated medium and the high applied current density of 70 mA/cm², were identified as crucial factors influencing this change. The results highlight the importance of these parameters in the hydrogenation process and their impact on the mechanical properties of the test samples.

3.5. Microstructure developments

After mechanical polishing, the test specimens were subjected to chemical etching for 20 to 30 seconds with Keller's reagent. This reagent is composed of 1 ml of hydrofluoric acid (HF), 1.5 ml of hydrochloric acid (HCl), 2.5 ml of nitric acid (HNO₃) and 95 ml of distilled water (H₂O). The aim of this procedure was to demonstrate the different changes in microstructures. The observations were made using an Euromax - Holland optical microscope, allowing for a detailed analysis of the microstructural changes. The results are illustrated in (Subfigures 10.a, 10.b, 10.c, 10.d and 10.e).

Subfigure 10. (a) represents particles of different shapes and sizes that are randomly dispersed during the alloy fabrication. During the increase in homogenization temperature to 550°C, the microstructure shows the homogeneity and

uniform distribution of these particles, which can be iron intermetallic precipitates (IMF), as observed in (Subfigure 10. b). During the natural aging treatment at 150°C, the microstructure shows a remarkable number of intermetallic phase (IMF) particles that combine with precipitates (β) inside and at the grain boundaries, (Subfigure 10. c).

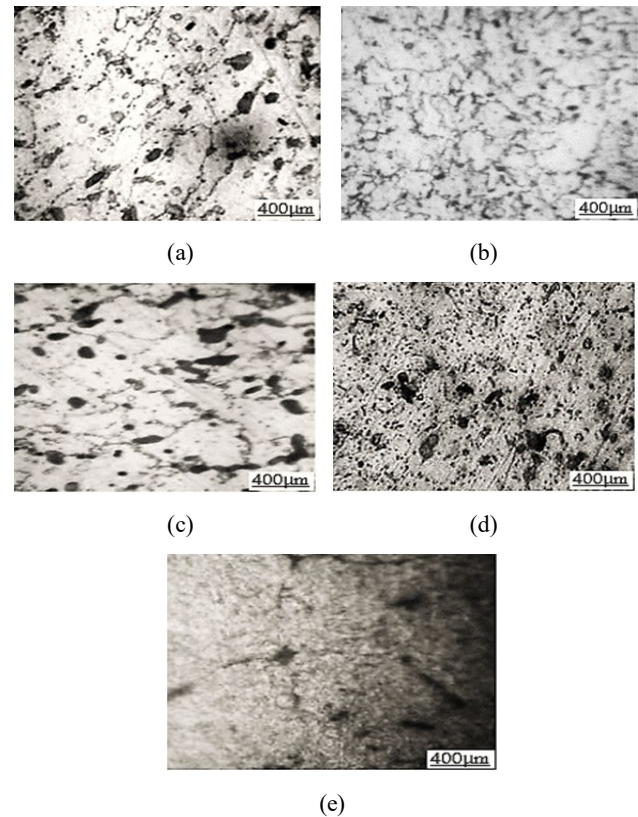


Figure 10. Changes in the microstructures of the AlMgSi.1 alloy (x400) - (a): Microstructure of AlMgSi.1; (b): Microstructure of AlMgSi.1; After homogenization at 550°C/7 hours (cooling: water quenched); (c): Microstructure of AlMgSi.1; After homogenization at 550°C/7 hours then natural aging 150°C/10 hours (cooling: at room temperature); (d): Microstructures of AlMgSi.1; After artificial aging at 240°C/24 hours (cooling: in the open air); (e): Microstructure of AlMgSi.1, After homogenization at 550°C/7 hours (cooling: oil quenched).

The microstructure obtained after an artificial treatment at 240°C results in a new microstructure due to a change and formation of a new equilibrium phase (β) in the form of small plates with a face-centered cubic (F.C.C) structure, (Subfigure 10. d).

Finally, after the application of the homogenization treatment at 550°C followed by rapid cooling in oil, the microstructure shows a notable increase in precipitates, with clear spherical shapes and dark precipitates, indicating the presence of Al₂Cu phases as well as other phases containing iron and silicon, (Subfigure.10. e).

3.6. Faces analysis – (before and after hydrogen-pre-loading)

The study analyzes the effects of mechanical stress on specimens subjected to plastic deformations during a tensile fracture mechanical test. Three types of specimens were compared: a raw specimen without heat treatment, as-re-

ceived (Subfigure 11), and two hydrogen pre-charged specimens for 6 hours and 8 hours respectively shown in (Sufigures 12 (a), (b), (c), (d)). The observations of the cracks on both faces of the samples revealed significant differences depending on the treatment conditions and the durations of hydrogen charging. The results of the mechanical tests allowed the identification of distinct zones and fracture planes on the useful part of the specimens. These results corroborate the previous work of [13, 21], which highlight the embrittlement caused by hydrogen.

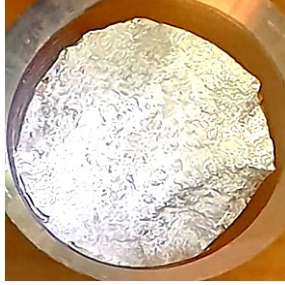


Figure.11. Faces in raw state without thermal treatment (As-received).

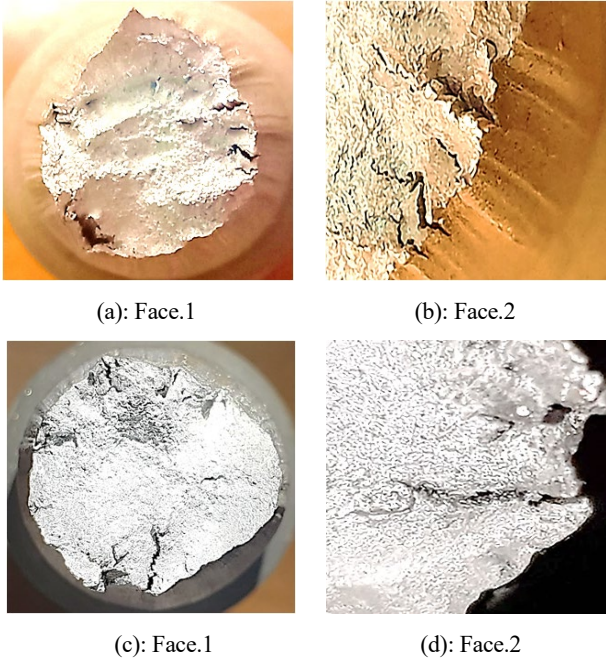


Figure 12. Evolutions of the different crack faces of the two ALMgSi.1 alloy test specimens after hydrogenation and slow tensile fracture testing $\dot{\epsilon} = (2.6 \times 10^{-6} S^{-1})$, (a) and (b): Propagation of a crack for a face charged with hydrogen for 6 hours; (c) and (d): Propagation of a crack for a pre-charged face during 8 hours.

The studies mentioned in accordance with [15], reveal that SSC cracks begin to form after approximately a hundred hours of loading. It is also observed that the crack initiation time increases with the duration of immersion and hydrogen preloading, see zone (4). To validate the hydrogen diffusion and embrittlement mechanism (HDM), three zones have been identified in (Subfigure 13). The crack initiations are found in the brittle zones (1) and (2) and are observed represented by an inclination of the angle of 90° drawn with respect to the applied tensile load. On the other hand, a ductile zone inclined at 45° is deduced in zone (3), in relation to the fracture stress exerted [13, 21].

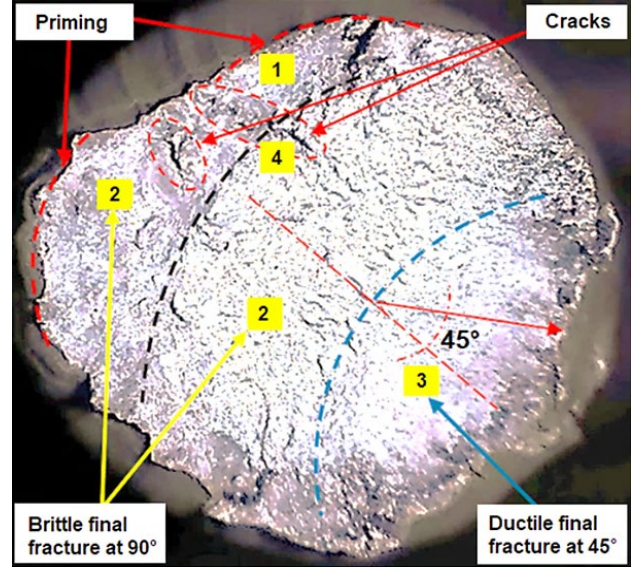


Figure 13. Example of the faces of the test tube with hydrogenated surface in an aqueous medium of $0.05M H_2SO_4$, for a duration of 8 hours after the tensile test of the AL-Mg-Si.1 alloy; zone (1), (2): Initiation of a brittle fracture inclined at 90° to the tensile load applied; zone (3): Initiation of a ductile fracture inclined at 45° to the applied stress; zone (4): Presence and propagation of micro-cracks in the matrix

3.7. Embrittlement Index EI, (%)

The sensitization of this type of alloy to hydrogen embrittlement (HE) was validated by analyzing the loss of plasticity, measured by the percentage ratio of elongations before and after hydrogenation. This analysis is illustrated in Table 3. To quantify this weakening, the embrittlement index (EI) was calculated, as indicated in the works of [9, 19]. Equation (7) allows for the determination of this index, which shows increasing values (HE%) = 30,76%, as shown in (Subfigure 14). These results highlight the importance of hydrogenation on the mechanical properties of the studied alloy.

$$EI(\%) = \frac{A_0 (\text{As-received}) - A (\text{H-charged})}{A_0 (\text{As-received})} \times 100\% \quad (7)$$

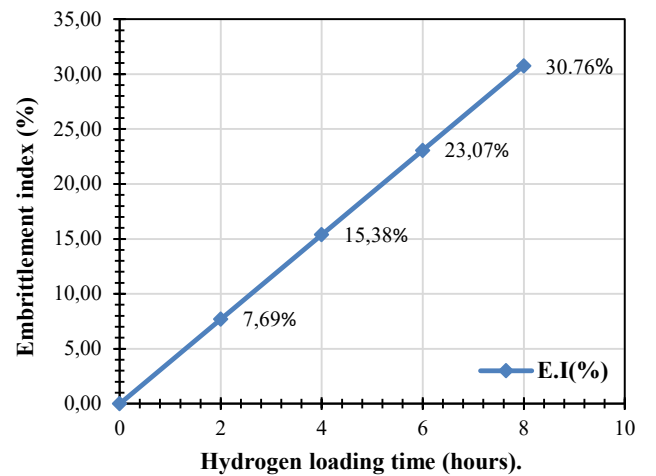


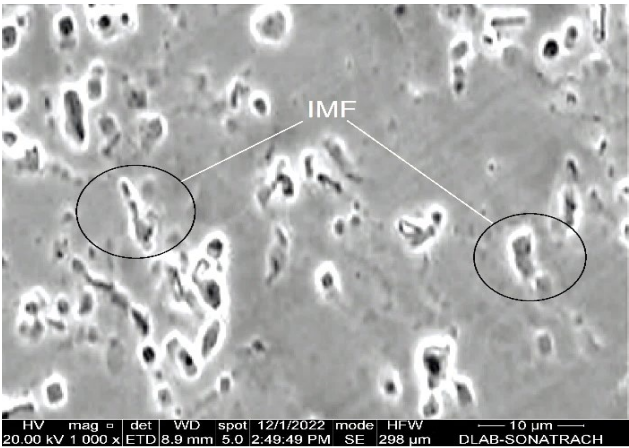
Figure 14. The embrittlement index EI (%) as a function of hydrogen loading time in hours [6, 19].

3.8. SEM analysis observations EDAX

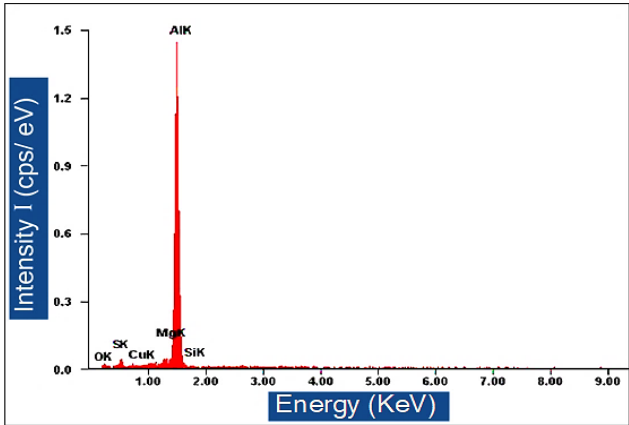
Microstructural observations of the alloy were conducted using the electronic SEM analysis technique, specifically with the Quanta FEG 650 model. This analysis was conducted at an acceleration voltage of 20.00 kV and with a spot size of 5.0 nm.

The results obtained were complemented by the use of EDAX, allowing the examination of the alloy's microstructures in hydrogen-charged and non-hydrogen-charged states. Figures (15) and (16) illustrate these two states, providing valuable information on the microstructural characteristics of the studied alloy.

The analyses conducted in a non-hydrogen-charged context reveal the presence of several iron intermetallic precipitates (IMF), which are characterized by their heterogeneity.



(a)



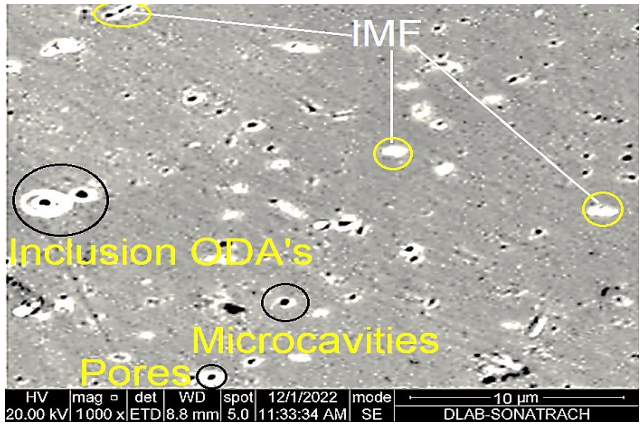
(b)

Figure 15. (a), (b): Microstructure of the ALMgSi.1 alloy, not hydrogen-loaded, observed by (SEM) EDAX (x10μm) Al-Mg-Si.

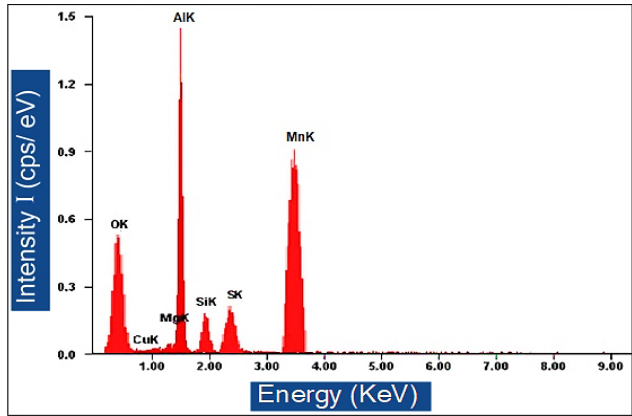
Table 7. Data results before hydrogenated.

Intelligents quantitative results H-Uncharged		
Element	Wt (%)	At (%)
AlK	97.3	98.5
MgK	1.5	1.64
SiK	0.78	0.71
FeK	1.09	0.52
CuK	0.36	0.14

A typical spectrum was observed, highlighting characteristic peaks of the identified elements. The elements quantified in the structure include aluminum (Al), magnesium (Mg), silicon (Si), iron (Fe), and copper (Cu). These results highlight the importance of these elements in the composition of intermetallic precipitates and their potential role in the properties of the analyzed materials (Subfigure 15) and (Table 7). The analysis of the hydrogen-charged specimen (Subfigure 16), after a homogenization treatment, reveals several key points. First of all, a significant reduction in the amount of iron intermetallic precipitates (IMF) was observed. Furthermore, the presence of MgSi particles is noted, which are homogeneous in the structure of the specimen.



(a)



(b)

Figure 16. Observations by (SEM) and ADXA of the ALMgSi.1 alloy charged with hydrogen for 8 hours, (a): Microstructure by SEM on pores in the shape of cavities A (x10μm), (b): presence of inclusions and particles: aluminum oxide (Al-O-S); silicon oxide (Si-O) and Mn-S forming MnS particles.

Table 8. Data results after hydrogenated

Intelligents quantitative results H-charged		
Element	Wt (%)	At (%)
AlK	95.62	93.76
MgK	1.29	1.43
SiK	2.23	2.36
CuK	0.38	0.17
OK	32.78	29.46
SK	2.46	3.8
MnK	42.1	39.27

These results suggest an improvement in the distribution of particles, which could have positive implications for the mechanical properties of the analyzed material. Solidification in an aggressive hydrogenating environment, specifically in the presence of sulfuric acid (H_2SO_4), leads to the formation of pores in the form of micro-cavities [14, 19]. This formation is influenced by the applied electrolytic loading conditions. Moreover, the pores density varies depending on the loading durations, indicating a direct relationship between the exposure time and the resulting porous structure. These observations highlight the importance of loading parameters in controlling the properties of materials in a corrosive environment.

The analyses conducted by EDXA show that the inclusions in the hydrogen-charged matrix have a spherical shape. These inclusions optical dark area (ODA's) [11, 12], are clearly indicated by arrows at point (A), (Subfigure 18. (a)). Moreover, a typical spectrum accompanies these observations, highlighting the characteristic peaks of the identified elements as well as their mass contents, expressed as a percentage (%) (Subfigure 16. (b)).

These results highlight the importance of spherical inclusions in the study of hydrogen-charged matrices and provide valuable data on the elemental composition. The results of the study on (table 8) reveal a high concentration of manganese aluminum oxide (AL-O-Mn) and sulfur (S) with contents of 2.46% by weight and 3.80%, leading to the formation of manganese sulfide (MnS) [20] particles approximately 1.5mm in length.

The analyses show significant manganese content, with 42.10% by weight and 39.27% by atoms. Moreover, oxygen shows contents of 32.78% by weight and 29.46% by atoms, and aluminum with contents of 95.62% by weight and 93.76% by atoms. These data highlight the importance of the studied elements in the composition of the formed particles, promoting the propagation and penetration of the hydrogen molecule within the internal structure. This phenomenon is related to hydrogen embrittlement (HE), highlighting the importance of these elements in the studied process.

4. Conclusion

In this study, a 6xxx series Al-Mg-Si aluminum alloy was subjected to various heat treatments and electrochemical hydrogen charging conditions to examine its microstructural evolution, mechanical behaviour, and sensitivity to hydrogen embrittlement. The following conclusions are drawn from the experimental results, which were acquired via electrochemical analysis, hardness measurements, and tensile testing:

Both intrinsic material properties, such as chemical composition, microstructure, surface roughness, and thermal history, as well as extrinsic factors, such as electrolyte concentration, (pH), temperature, current density, and charging time, affect the alloy's embrittlement in acidic environments.

Following hydrogen charging, there was a noticeable decline in mechanical performance, especially in yield strength and elongation at fracture. The alloy's sensitivity to hydrogen was confirmed by the fact that the absorbed hydrogen level rose with charging time. A fragilization index (EI%) was used to measure the hydrogen-induced loss of ductility, and it reached 30%.

Heat treatments were essential in changing the alloy's hardness. The samples with the highest (HV) values were those quenched in either water or oil. Nevertheless, a decrease in hardness was observed upon exposure to hydrogen in a 0.05M (H_2SO_4) medium, indicating hydrogen uptake and the alloy's reduced resistance to deformation.

Overall, the findings highlight how crucial it is to regulate environmental factors and material processes in order to lessen hydrogen embrittlement.

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Uticaj vodonirane sredine na mehanička svojstva aluminijumskog legura Al-Mg-Si.1

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Apstrakt

Uvod/Cilj: Cilj ove studije je da ispita uticaj okruženja bogatog vodonikom na mehanička svojstva aluminijumskog legura Al-Mg-Si iz 6xxx serije. Takvi leguri mogu da pokažu krhkost izazvanu vodonikom (HE), posebno u vodenim okruženjima. Step en ove krhkosti zavisi od različitih mikrostrukturnih parametara i od svih toplotnih tretmana kojima je legura podvrgnuta.

Metode: Eksperimentalni rad je sproveden na cilindričnim ispitnim uzorcima koji su prošli ciklus homogenizacije koji je obuhvatao brzo hlađenje preko zasićenja u vodi (SSW), nakon čega je usledilo prirodno hlađenje do sobne temperature. Nakon hlađenja na otvorenom vazduhu usledilo je veštačko starenje (AA). Uzorci su prethodno napunjeni metodom katodne punjenja u različitim vremenskim periodima, od dva do osam sati, u simuliranom okruženju 0,05 M sumporne kiseline (H₂SO₄) pri gustini struje od 70 mA/cm². **Rezultati:** Rezultati, predstavljeni u obliku eksperimentalnih krivih zabeleženih nakon mehaničkog ispitivanja zatezanjem do pucanja, sastoje se od pucanja opterećenih ispitnih komada na sobnoj temperaturi. Mehanička svojstva su analizirana merenjem tvrdoće pre i posle opterećenja. Skenirajuća elektronska mikroskopija otkriva prisustvo ODA inkluzija, koje su nemetalne nečistoće i deluju kao preferirana mesta za nastanak pukotina. Ovo potvrđuje mehanizam krhkosti izazvane vodonikom, što dovodi do smanjenja produžaja pri prekidu. **Zaključak:** Tokom punjenja vodonikom došlo je do primetnog pada mehaničkih svojstava, naročito čvrstoće pri pucanju i izduženja pri lomljenju. Senzitivnost legure na vodonik potvrđena je činjenicom da je nivo apsorbovanog vodonika rastao sa vremenom punjenja. Za merenje gubitka duktilnosti izazvanog vodonikom korišćen je indeks krhkosti (EI%), koji je dostigao 30%.

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