



Effect of Tungsten Alloying and T7 Heat Treatment on the Corrosion Behavior of AlSi5Cu2Mg Alloy: Electrochemical and Long-term Immersion Study

M. Matejka ^{a,*} , M. Sýkorová ^a , D. Bolibruchová ^a , Ľ. Halimovič ^{b,c} 

^a University of Zilina, Faculty of Mechanical Engineering,
Department of Technological Engineering, Slovak Republic

^b University of Zilina, Faculty of Electrical Engineering and Information Technology,
Department of Physics, Slovak Republic

^c University of Zilina, Research Centre, Slovak Republic

* Corresponding author: E-mail address: marek.matejka@fstroj.uniza.sk

Received 04.06.2026; accepted in revised form 18.08.2026; available online 23.09.2026

Abstract

This article presents a systematic study of the effect of tungsten additions as a modifying alloying element and of the subsequent T7 heat treatment on the corrosion stability associated with the microstructural characteristics of the hypoeutectic aluminum alloy AlSi5Cu2Mg. The corrosion resistance of aluminum alloys generally depends primarily on electrochemical potential differences between the solid solution matrix and the present intermetallic phases, whereby targeted microstructural modification can thermodynamically and kinetically stabilize the surface against local galvanic degradation. The aim of this work was to elucidate the combined action of microstructural and electrochemical mechanisms in the experimental alloy. The experimental alloy with graded tungsten additions (0.05, 0.10, and 0.15 wt. % W) was prepared by gravity casting into a metal mold. Corrosion resistance was evaluated through long-term immersion exposure tests in a 3.5% NaCl solution for 20, 40, 60, and 80 days and electrochemical potentiodynamic polarization tests. In the cast state, the addition of tungsten reduces galvanic microcells and shifts the corrosion potential toward more noble values, which was optimally demonstrated at a concentration of 0.15 wt. % W, where the corrosion rate decreased to 0.0192 mm/year. The T7 treatment enabled effective redistribution of copper and magnesium, thereby eliminating the heterogeneous phases (θ -Al₂Cu and β -Mg₂Si) that cause intergranular degradation. The variant with 0.15 wt. % W after T7 heat treatment, which recorded the lowest corrosion current density (0.69 μ A/cm²) and a minimum corrosion rate of 0.0095 mm/year due to the dominant suppression of the corrosion mechanism kinetics and matrix stabilization.

Keywords: Al-Si-Cu-Mg alloy, Tungsten, Alloying, Heat treatment.

1. Introduction

Al-Si-Cu-Mg-based alloys are widely recognized as the industry standard for high-stress automotive applications, owing to their optimal combination of mechanical properties and casting characteristics. The presence of copper and magnesium in the



© The Author(s) 2026. Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

aluminum-silicon matrix ensures the material's heat-treatability, which is crucial for components such as pistons and engine blocks, where dimensional stability and high material durability are required [1,2].

The final performance properties of Al-Si-Cu-Mg alloys are determined by the solidification kinetics and the resulting phase composition of their microstructure. However, the presence of coarse α -Al dendrites, plate-like (unmodified) eutectic silicon, and especially iron-based intermetallic phases (β -Al₃FeSi phases) does not merely pose a risk to mechanical properties in the form of stress concentrators. In addition to a decrease in strength properties, these structural components play a key role in the corrosion attack of the matrix, where they act as cathodic sites accelerating, for example, pitting corrosion [3].

From a thermodynamic perspective, corrosion is a spontaneous process in which metal seeks to transition from an energetically unstable (metastable) state to a more stable form of oxides or other compounds. In the case of aluminum alloys, this process occurs primarily through an electrochemical mechanism, in which microscopic anodic and cathodic regions form on the material's surface in the presence of an electrolyte. At the anodes, oxidation and gradual dissolution of the metal occur according to the equation (1):



while hydrogen or oxygen is being reduced at the cathodes [4,5]. Although aluminum is a non-precious metal with a significantly negative electrode potential, its high durability is due to its ability to naturally passivate. Under the influence of oxygen or water, a compact and chemically stable layer of aluminum oxide (Al₂O₃) spontaneously forms on its surface; this layer, several nanometers thick, effectively prevents further oxidation and ion transfer [6]. However, the corrosion stability of aluminum alloys is limited in practice by their chemical composition and microstructural heterogeneity. Alloying elements significantly influence the stability of the passive layer and the formation of intermetallic phases, which form galvanic couples with the aluminum matrix. The presence of copper leads to the formation of phases such as θ -Al₂Cu, which are cathodic in nature and stimulate intense anodic dissolution of aluminum in their immediate vicinity, resulting in pitting corrosion [7]. Iron-based phases that form cathodic particles such as Al₃Fe or β -Al₃FeSi have a similarly adverse effect. Conversely, elements such as magnesium can form anodic phases (β -Mg₂Si) that dissolve preferentially, thereby partially suppressing the activity of other cathodes. To achieve optimal corrosion resistance, it is therefore essential to ensure a fine-grained and homogeneous microstructure in which element segregation at grain boundaries and the presence of coarse intermetallic inclusions are minimized [7,8].

The corrosion behavior of Al-Si-Cu-Mg alloys is governed not only by their chemical composition, but also by their thermal history, since heat treatment controls the size and distribution of the intermetallic phases acting as local galvanic couples. Solution treatment dissolves the coarse θ -Al₂Cu and β -Mg₂Si particles and homogenizes the copper and magnesium distribution in the α -Al solid solution, thereby reducing the potential gradient between the matrix and the second-phase particles [10]. The ageing regime, however, has an ambivalent effect. In the under-aged condition, the

segregation of copper at the grain boundaries promotes intergranular corrosion, whereas with an increasing degree of ageing, the grain-boundary precipitates and the associated precipitation-free zones reduce this potential difference, increase the polarization resistance and shift the degradation mode toward localized pitting [10]. Similarly, an optimized over-ageing regime in Al-Si-Mg-based alloys produced a uniform dispersion of nanoscale precipitates without grain-boundary segregation and the highest corrosion resistance, while excessive ageing temperatures deteriorated the corrosion response [11]. This trade-off is the primary reason for selecting the over-aged T7 regime in the present study.

The effect of tungsten on the corrosion of aluminum has so far been examined almost exclusively in non-equilibrium systems. Owing to the very low solid solubility of W in Al, single-phase Al-W alloys can only be prepared by routes such as sputter deposition, in which the addition of approximately 9 at. % W shifted the pitting potential by as much as 2600 mV and the breakdown potential above 2000 mV, with a reduction of the corrosion rate at the open-circuit potential by more than two orders of magnitude [12,13]. This behavior is attributed to the incorporation of oxidized tungsten species into the passive film, and an analogous ennoblement has been reported for other transition metals of limited solubility in Al, such as Mo, Cr and Ti [14,15]. The precipitation of a W-rich second phase was found to be detrimental relative to the supersaturated single-phase state [12]. In conventionally cast alloys, where W forms fine Al₁₂W particles acting as heterogeneous nucleation sites [3], the corrosion response is therefore governed by a competition between the cathodic character of these particles and the beneficial effect of grain refinement — a competition not yet resolved for Al-Si-Cu-Mg alloys.

Although the influence of conventional grain refiners in Al-Si-Cu-Mg alloys is well-documented, and the effects of heat treatment and of refractory-metal additions have been addressed separately, their combined action has not yet been systematically investigated in a conventionally cast Al-Si-Cu-Mg alloy. The synergy of W alloying and the T7 state may lead to optimal phase redistribution, which is key to suppressing pitting corrosion initiation sites. In contrast to previous works, limited predominantly to non-equilibrium Al-W systems and short-term electrochemical measurements, the corrosion response is assessed here by a dual methodology combining potentiodynamic polarization with long-term immersion exposure of up to 80 days and metallographic analysis of the degraded surface layers. The main objective of this article is therefore to clarify the effect of different tungsten concentrations on the corrosion stability of the investigated alloy, thereby creating the conditions for its broader industrial use in more aggressive operating conditions.

2. Experimental methodology

2.1 Preparation and casting of samples

In the course of the experimental work, the hypoeutectic aluminum alloy AlSi5Cu2Mg was used as the base experimental material. In industrial practice, this material is used primarily in the production of castings subjected to high mechanical stress. Long

pure alloy without alloying additives served as a reference material for comparison with the tungsten-alloyed variants.

The melting process was conducted in an electric resistance furnace (type T15) using a graphite crucible with a protective coating. The melting temperature was kept constant at $750 \pm 5^\circ\text{C}$ for an 8 kg total charge weight. To ensure a precise and homogeneous distribution of tungsten in the matrix, a pre-melted AlW5 master alloy (containing 5 wt. % W) was utilized. This master alloy was prepared separately in an induction furnace and then added in liquid state into the base AlSi5Cu2Mg melt. The amount of AlW5 master alloy was calculated to obtain nominal tungsten concentrations of 0.05, 0.10, and 0.15 wt. % W in the final experimental alloys. These material variants were designated according to their nominal contents as 0.05 W, 0.10 W, and 0.15 W.

Ten experimental castings were prepared for the reference alloy (containing no W addition) and for each of the alloyed variants. The castings were produced by gravity casting into a metal mold, which had been preheated to $150 \pm 5^\circ\text{C}$ prior to casting. From every batch, one half of the castings was subsequently subjected to heat treatment in the T7 mode, whereas the remaining half was retained in the as-cast condition for comparison. During the T7 cycle, the samples were first held at $500 \pm 5^\circ\text{C}$ for 6.5 hours in order to dissolve the coarse intermetallic phases ($\theta\text{-Al}_2\text{Cu}$ and $\beta\text{-Mg}_2\text{Si}$) within the $\alpha\text{-Al}$ matrix, and then rapidly quenched into water maintained at $85 \pm 5^\circ\text{C}$. Artificial over-ageing followed at $250 \pm 5^\circ\text{C}$ over 4 hours, after which the samples were allowed to cool freely in still air.

2.2 Analysis of chemical composition

The chemical composition of all prepared alloy variants was analyzed using a VANTA X-ray spectrometer. The measured values of the chemical composition of the material variants are summarized in Table 1.

Table 1
Chemical composition of the AlSi5Cu2Mg alloy variants [wt. %]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	W
Ref.	6.45	0.23	2.54	0.015	0.15	0.004	-
0.05 W	6.48	0.22	2.38	0.014	0.16	0.007	0.020
0.10 W	6.31	0.22	2.36	0.013	0.22	0.006	0.044
0.15 W	6.41	0.23	2.37	0.012	0.18	0.006	0.075

Table 1 shows that the tungsten contents obtained by measurement (0.020, 0.044, and 0.075 wt. % W) fall below the nominal targets of 0.05, 0.10, and 0.15 wt. % W, on which the AlW5 master alloy dosage was based. Although the labels 0.05 W, 0.10 W, and 0.15 W correspond to these nominal targets, the true W concentration incorporated into the matrix corresponds to the value reported in Table 1. Several mechanisms may account for the gap between the intended and the measured W content. Owing to its high density, tungsten tends to cluster together and accumulate at the bottom of the crucible or mold. Furthermore, during melting a reaction between W and Al may occur, giving rise to Al_2W intermetallic particles that can remain trapped in the melting

apparatus. Additional losses may result from the restricted solubility of W in the molten Al-Si-Cu-Mg alloy at the working temperature. In the discussion of the results that follows, the measured W concentrations reported in Table 1 will be adopted as the reference values.

2.3 Methodology for evaluating corrosion resistance

The corrosion stability of the AlSi5Cu2Mg alloy with varying tungsten content was evaluated using two complementary tests: long-term immersion exposure tests and electrochemical potentiodynamic tests.

As part of a comprehensive assessment of corrosion stability, an immersion exposure test was conducted in a 3.5% water solution of NaCl, into which samples of the alloy with varying tungsten content were placed. The immersion test was performed in accordance with the general procedures described in ASTM G31, adapted to the cylindrical specimen geometry used in this study. The corrosion attack process was monitored at time intervals of 20, 40, 60, and 80 days at a stable ambient temperature of $20 \pm 2^\circ\text{C}$. The experiment was conducted on cylindrical specimens with dimensions of $\varnothing 15 \text{ mm} \times 30 \text{ mm}$, whose preparation prior to exposure included sanding (P100 sandpaper), degreasing in ethanol, and subsequent drying. The key parameter for determining the corrosion kinetics was the mass loss Δm , which was determined by the difference in mass before and after exposure. Weighing was performed on analytical balances with an accuracy of $\pm 0.1 \text{ mg}$. After removal from the corrosive medium, the samples were rinsed in distilled water, immersed in ethanol, and chemically cleaned to remove the adherent corrosion products using the procedure recommended for aluminum and its alloys, in accordance with the same standard, followed by drying in warm air and final weighing on the analytical balance. Based on the obtained data, the corrosion rate in $[\text{mm}/\text{year}]$ was calculated using equation (2):

$$v = \Delta m \cdot 8760 \cdot \sigma^{-1} \cdot S^{-1} \cdot t^{-1} \quad (2)$$

where Δm represents the mass loss [g], σ the material density $[\text{g}/\text{mm}^3]$, S the initial geometric surface area of the sample exposed to the environment $[\text{mm}^2]$, and t the exposure time in hours.

Electrochemical measurements were performed in a sealed corrosion cell connected to a BioLogic VSP300 laboratory potentiostat, which was configured in a three-electrode setup. In this configuration, the material surface served as the working electrode, while a platinum mesh acted as the reference electrode (Fig. 1). A saturated calomel electrode was used as the reference electrode, with its potential shifted by +0.2446 V relative to the standard hydrogen electrode.

The experiments were conducted in a 3.5% NaCl solution at a controlled ambient temperature of $20 \pm 2^\circ\text{C}$. Test specimens measuring $50 \times 30 \times 10 \text{ mm}$ were mechanically prepared in advance by grinding with P600-grit sandpaper and subsequently chemically cleaned with ethanol. For this type of electrochemical test, samples with extreme tungsten concentrations were specifically selected, namely variants with the lowest (0.05 wt. % W) and highest (0.15 wt. % W) content of this element, which were compared with a

reference material. Polarization began after a 30-minute stabilization of the open-circuit potential (OCP) in the range from -150 mV to +1000 mV relative to this value. At a constant scanning rate of $1 \text{ mV} \cdot \text{s}^{-1}$, the recorded data were subsequently processed in EC Lab software, with five repeated measurements performed for each tested variant to ensure the reproducibility of the results. The corrosion rate i_{corr} was calculated automatically by the EC-Lab software from the corrosion current density i_{corr} using Faraday's law.

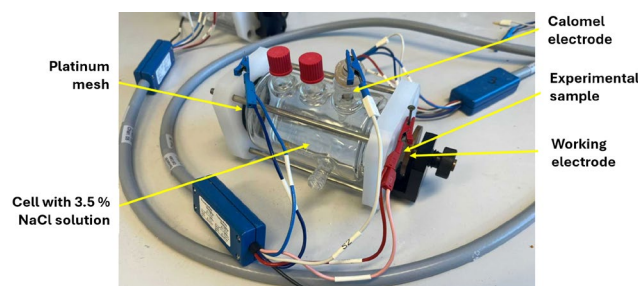


Fig. 1. Three-electrode circuit and corrosion cell

3. Results

3.1 Exposure test

The initial phase of evaluating the corrosion resistance of the AISi5Cu2Mg alloy involved determining the change in weight of the samples after their exposure to a 3.5% NaCl solution. The monitored time intervals were set at 20, 40, 60, and 80 days, which corresponds to 480, 960, 1440, and 1920 hours of exposure to the corrosive medium. The measured values of mass loss as a function of tungsten concentration and alloy state are graphically shown in Fig. 2, while Fig. 4 documents the calculated corrosion rate derived from the relevant relationship (2).

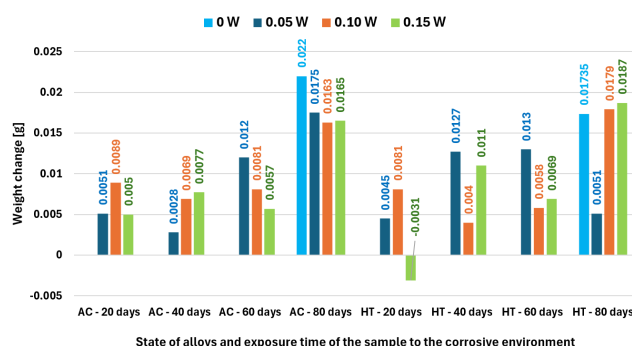


Fig. 2. Weight change of experimental alloys with graded W addition and change in alloy state

Analysis of the measured data showed that the most significant material degradation occurred in the reference alloy without tungsten additive in the as-cast state. After the maximum exposure period (80 days), the weight loss for this variant reached 0.022 g. This increase in weight loss can be attributed to the absence of

stabilizing elements in the microstructure, which under normal circumstances would prevent the penetration of aggressive chloride ions to the surface of the metal matrix. In contrast to these results, the low-tungsten alloy (0.05 wt. % W) in the as-cast state exhibited a minimal recorded loss of 0.0028 g after 40 days of exposure.

A specific phenomenon was the weight gain observed in the alloy containing 0.15 wt. % W following heat treatment in the T7 mode during the initial 20-day phase. The mass change here reached a negative value of $\Delta m = -0.0031 \text{ g}$, which represents a change compared to normal metal dissolution. This weight gain is most likely the result of the intensive formation of corrosion products and a passivation layer on the sample surface (Fig. 3). This behavior suggests that the combination of a higher tungsten concentration and subsequent heat treatment significantly accelerates the kinetics of protective layer formation, which in the initial stages exceeds the mass of the etched material.

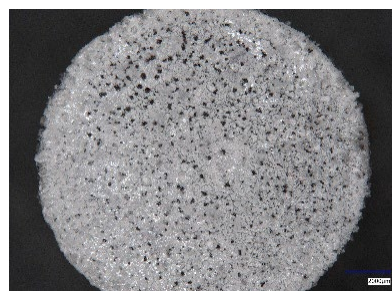


Fig. 3. Image of a sample containing 0.15 wt% W after removal from a 3.5% NaCl solution following 20 days of exposure

An evaluation of the corrosion rate confirmed (Fig. 4) that the critical point in the process occurred when the alloy containing 0.10 wt. % W was exposed in its as-cast state for 20 days, at which point the corrosion rate rose to 0.038 mm/year. This local increase could have been caused by an initial electrochemical imbalance in the intergranular regions. In contrast, the variant with 0.05 wt. % W exhibited the most stable long-term response after heat treatment, with the corrosion rate dropping to a minimum of 0.005 mm/year after 80 days. This result confirms the beneficial effect of microstructure homogenization through heat treatment in the T7 mode on increasing resistance to long-term corrosion attack.

The negative corrosion rate (-0.007 mm/year) observed in the 0.15 wt. % W + T7 sample after 20 days directly corresponds to the observed tendency toward rapid surface passivation. However, it is important to note that although this variant exhibited favorable parameters initially, as the exposure time was extended, this positive effect was gradually negated, and the stability of alloys with lower tungsten concentrations came to the fore.

Based on the evaluation of the exposure tests, samples representing key stages of material degradation were specifically selected for detailed microstructural analysis. The selection included the reference alloy after 80 days of exposure (maximum weight loss), a sample with 0.10 wt. % W in the as-cast state (maximum corrosion rate after 20 days), and a variant containing 0.15 wt. % W after T7 heat treatment, which exhibited weight gain at the beginning of the process.

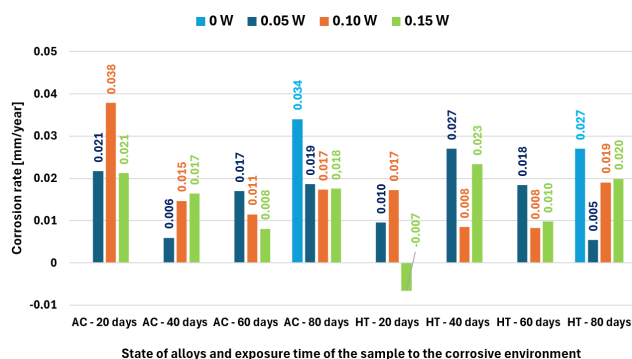


Fig. 4. Corrosion rate of experimental alloys with varying tungsten content and changes in alloy state

Analysis of the reference sample in the as-cast state confirmed the dominant occurrence of pitting corrosion, localized primarily at grain boundaries in eutectic regions (Fig. 5a). This mechanism was initiated by the presence of coarse intermetallic phases of the θ -Al₂Cu and β -Al₃FeSi types, which act as strong cathodes in the aluminum matrix. Due to the difference in electrochemical potentials, selective dissolution of the α -Al solid solution occurred, with corrosion penetration extending deep into the matrix, which correlates with the measured maximum weight loss.

In the case of the T7 heat-treated sample (Fig. 5b), localized corrosion attack was observed, likely in areas with lower passive layer integrity. Although in this case, the corrosion exhibited more pronounced penetration into the material depth associated with degradation of the α -phase. The compact rounded morphology of the eutectic Si particles obtained after T7 was preserved during the corrosion attack, confirming a higher resistance to the applied corrosive environment.

For the alloy containing 0.10 wt. % W in the as-cast state, after 20 days of exposure, intense initiation of corrosion centers along the surface was observed on the alloy (Fig. 6a). Detailed cross-section images confirmed that corrosion penetrated into the material depth selectively through the eutectic regions (Fig. 6b). The initial phase of degradation manifested as dissolution of the α -phase matrix, while the eutectic particles remained intact for the time being, leading to the highest corrosion rate being reached during this time interval.

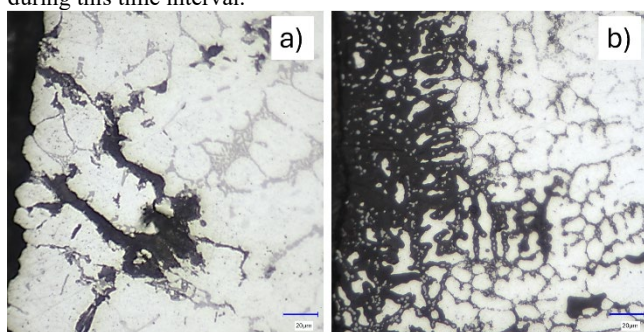


Fig. 5. Microstructure of the surface layer of the reference alloy after an 80-day exposure test: a) as-cast state; b) T7

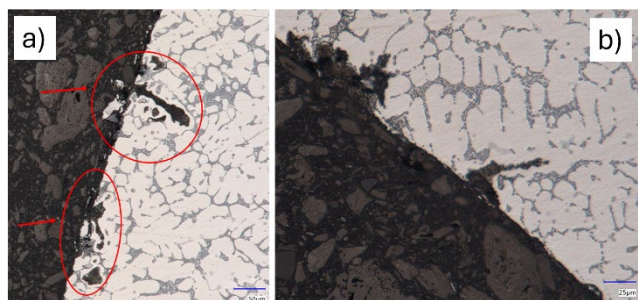


Fig. 6. a) Microstructure of the surface layer of 0.10 W alloy in the as-cast state after a 20-day exposure test; b) Detail

The effect of heat treatment on the 0.15% W alloy after the same exposure time of 20 days is shown in Fig. 7a. In this state, a more uniform distribution of initial pitting corrosion centers was observed. A detailed image (Fig. 7b) shows only a shallow penetration depth in the pitting corrosion.

A significant change occurred after extending the exposure to 80 days for the alloy containing 0.15 wt. % W following T7 heat treatment (Fig. 7c). At this stage, pitting corrosion took on a more aggressive character, which can be explained by the mechanism of its formation, where the corrosive environment (3.5% NaCl solution) did not act uniformly on the surface but concentrated on areas with lower corrosion resistance, such as grain boundaries or eutectic regions. Analysis of a cross-section of the sample showed that the corrosion pit appeared as a rugged space within the material that extended deep below the original surface line. A detailed image (Fig. 7d) documents this progressive corrosion front, where massive selective particle separation and breakdown of the dendritic structure occurred, leading to an increase in the corrosion rate to 0.020 mm/year.

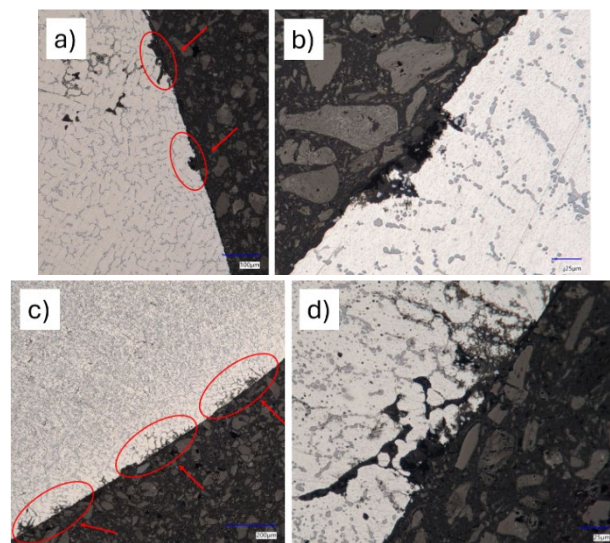


Fig. 7. Microstructure of the surface layer a) 0.15 W alloy after T7 heat treatment following a 20-day immersion test; b) 0.15 W alloy after T7 heat treatment following a 20-day immersion test – detail; c) 0.15 W alloy after T7 heat treatment following an 80-day immersion test; d) 0.15 W alloy after T7 treatment following an 80-day immersion test – detail

3.2 Potentiodynamic polarization test

As part of the electrochemical characterization, key corrosion parameters were determined from the measured polarization curves using Tafel analysis. The monitored characteristics were the corrosion potential E_{corr} , the corrosion current density i_{corr} , the slope coefficients of the anodic and cathodic curves β_a and β_c , and the resulting corrosion rate r_{corr} . A graphical comparison of the potentiodynamic polarization curves of reference alloy in the as-cast state and after T7 heat treatment is shown in Fig. 8. The numerical values of the corrosion parameters for the reference alloy AlSi5Cu2Mg are summarized in Table 2, where the data represents the arithmetic mean calculated from five independent measurements.

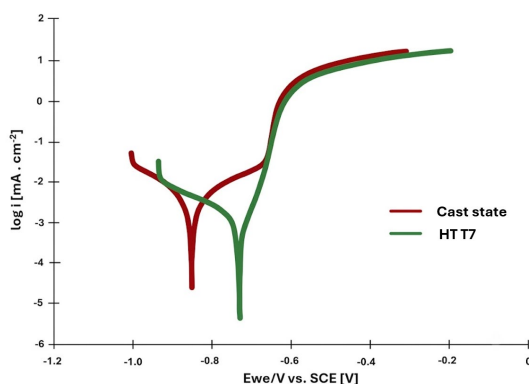


Fig. 8. Potentiodynamic polarization curve of reference alloy

The application of heat treatment in the T7 mode led to a significant improvement in the monitored electrochemical parameters compared to the as-cast state. The corrosion potential E_{corr} increased by 11 %, indicating an increase in the thermodynamic stability of the surface and a suppression of its natural reactivity in a corrosive environment. At the same time, a significant 78 % decrease in the corrosion current density i_{corr} was recorded. This decrease directly documented a reduction in the intensity of charge transfer at the metal-electrolyte interface, which manifested itself in a reduction of the corrosion rate r_{corr} from the original value of 0.058 mm/year to 0.013 mm/year. This improvement can be interpreted on the basis of the redistribution of copper and magnesium during heat treatment. In the as-cast state, copper concentrates in the intermetallic phase θ -Al₂Cu (−640 mV) along the grain boundaries. The resulting potential difference relative to the depleted zones (−750 mV) creates micro-galvanic cells. Exceeding the solubility limit of Mg leads to the formation of the β -Mg₂Si anodic phase (−1200 mV), which disrupts the passivation layer and causes local degradation relative to the matrix (−750 mV) [5, 9]. In the as-cast state, these phases form a network, which initiates intergranular corrosion progressing into the depth of the material. The observed 78 % reduction of the corrosion current density after T7 heat treatment is consistent with the dissolution of these grain-boundary phases discussed in more detail in Section 3.3.

In the subsequent phase of the potentiodynamic corrosion tests, the experimental alloys with the lowest and highest tungsten content were analyzed. The results of the PD tests on experimental

alloys with graded tungsten additions in the as-cast state and after T7 heat treatment are shown in Fig. 9, and the corresponding electrochemical characteristic data are listed in Table 2. The values in the table, as with the reference alloy, represent the average of five measurements on each sample.

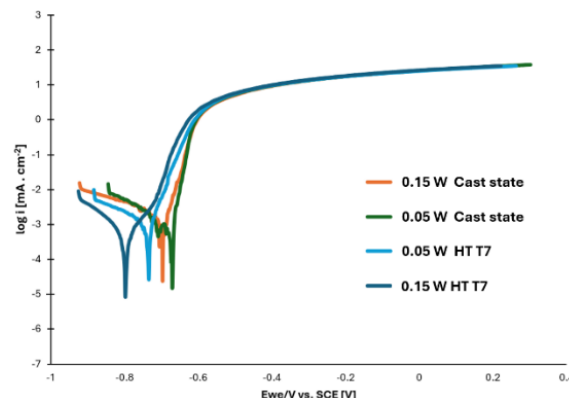


Fig. 9. Potentiodynamic polarization curves of experimental alloys as a dependence on the W content and the alloy state

The AlSi5Cu2Mg alloy with added tungsten (0.05 wt. % W and 0.15 wt. % W) in the as-cast state demonstrated improved electrochemical properties compared to the reference alloy. In the as-cast state, both alloyed alloys exhibited a more noble corrosion potential, with the most significant effect observed at a content of 0.15 wt. % W, which reached a value of −701 mV.

At the same time, the corrosion rate decreased to 0.0192 mm/year, representing more than a double reduction compared to the reference alloy in the as-cast state (0.058 mm/year). After T7 heat treatment, the differences between the individual variants became even more pronounced. The alloy containing 0.05 wt. % W, despite the shift in corrosion parameters, exhibited a poorer kinetic response ($i_{\text{corr}} = 1.17 \mu\text{A}/\text{cm}^2$; $r_{\text{corr}} = 0.0162 \text{ mm/year}$) compared to the reference alloy after T7. Conversely, the alloy with 0.15 wt. % W achieved the highest corrosion resistance among all tested samples after T7 heat treatment, and despite a less noble corrosion potential (−798.2 mV), it exhibited the lowest corrosion current density ($0.69 \mu\text{A}/\text{cm}^2$) and a minimum corrosion rate of 0.0095 mm/year.

The polarization data are fully consistent with the microstructural picture presented in Section 3.3. A low tungsten content (0.05 wt. % W + T7) still leaves a residual electrochemical heterogeneity that limits the improvement of the kinetic parameters ($i_{\text{corr}} = 1.17 \mu\text{A}/\text{cm}^2$; $r_{\text{corr}} = 0.0162 \text{ mm/year}$), whereas the 0.15 wt. % W + T7 combination produces a dominant suppression of the corrosion mechanism kinetics, as evidenced by the lowest corrosion current density ($0.69 \mu\text{A}/\text{cm}^2$) and the minimum degradation rate (0.0095 mm/year) recorded in Table 2.

3.3 Microstructural analysis

The results of the corrosion tests can be rationalized on the basis of the microstructural evolution induced by tungsten alloying and by the subsequent T7 heat treatment. In the as-cast reference alloy, the coarse α -Al dendritic network (Fig. 10a) was

accompanied by an incompletely rounded eutectic Si (Fig. 10a red frame) and by long needle-like β -Al₃FeSi and blocky θ -Al₂Cu phases located along the grain boundaries and in the interdendritic regions.

The addition of tungsten progressively refined this structure. The DAS index decreased from 33.45 μm in the reference alloy to

32.61 μm at 0.05 wt. % W (a marginal reduction), and further to 27.52 μm at 0.10 wt. % W and 24.32 μm at 0.15 wt. % W (a marked refinement of the dendritic network, Fig. 10b–d), reflecting the segregation of W ahead of the growing solid-liquid interface and the associated constitutional undercooling.

Table 2.

Electrochemical behavior of an experimental alloy after a dynamic polarization test in a 3.5 % NaCl solution with added tungsten in the as-cast (AC) state and after T7 heat treatment

Alloy	E_{corr} [mV] vs. SCE	I_{corr} [$\mu\text{A}/\text{cm}^2$]	β_a [mV/dek]	β_c [mV/dek]	r_{corr} [mm/year]
Ref. AC	-835	3.51	131	142	0.058
Ref. -T7	-746	0.76	36	171	0.013
0.05 W-AC	-724	1.27	55	159	0.0177
0.15 W-AC	-701	1.39	34	202	0.0192
0.05 W-T7	-734	1.17	42	204	0.0162
0.15 W-T7	-798.2	0.69	70	135	0.0095

In parallel, the eutectic Si was refined into smaller, more compact grains and, at 0.10 and 0.15 wt. % W, into dense clusters of fine rounded particles (Fig. 10b–d red frame), while the needle-like β -Al₃FeSi was progressively shortened and largely replaced by compact, partially spheroidized Fe-rich particles.

The T7 heat treatment left the α -Al dendritic morphology essentially unchanged (Fig. 11) but significantly modified the eutectic Si (Fig. 11 red frame). Solution treatment spheroidized the eutectic Si particles through interfacial-energy minimization; because the initial Si morphology was already refined by tungsten, the shorter diffusion distances in the W-alloyed variants yielded a more complete and uniform globular morphology than in the reference alloy.

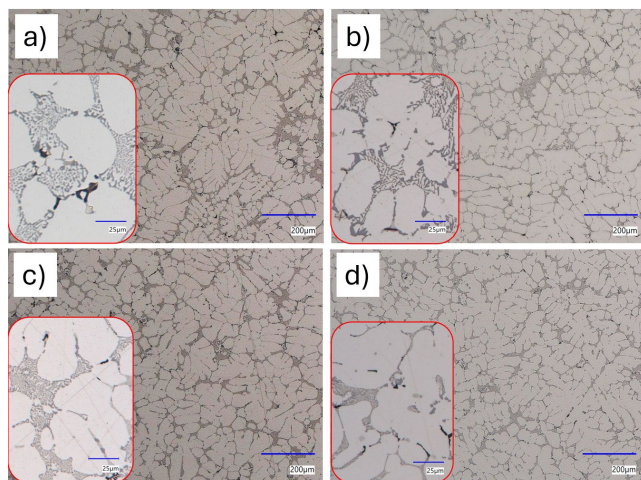


Fig. 10. Dendritic network and morphology of the eutectic Si of the experimental AlSi5Cu2Mg alloy, as-cast state: a) reference alloy; b) 0.05 W; c) 0.10 W; d) 0.15 W.

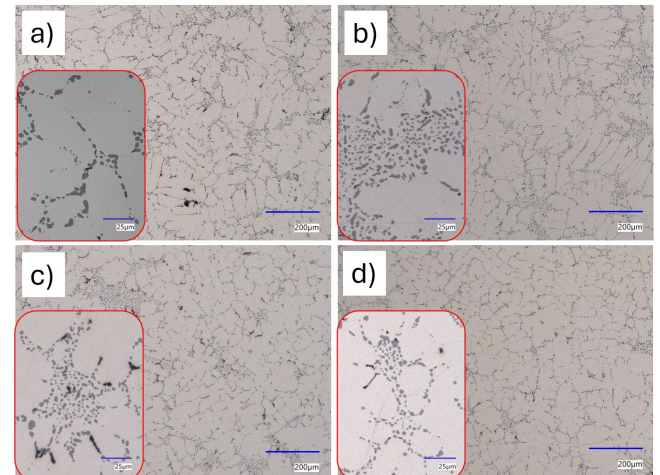


Fig. 11. Dendritic network and morphology of the eutectic Si of the experimental AlSi5Cu2Mg alloy after T7 heat treatment: a) reference alloy; b) 0.05 W; c) 0.10 W; d) 0.15 W.

The optimum corrosion performance of the 0.15 wt. % W + T7 variant is therefore the cumulative outcome of these effects. From the as-cast stage this variant inherits the highest degree of dendritic refinement (lowest DAS index), the finest eutectic Si, the strongest suppression of needle-like β -Al₃FeSi and the highest degree of W incorporation into the supersaturated α -Al matrix, which together increase the density of grain boundaries available for a compact passive film, reduce the number of geometrically favorable pit-initiation sites and ennoble the intrinsic electrochemical response of the matrix. The T7 treatment additionally dissolves the coarse θ -Al₂Cu and β -Mg₂Si networks that otherwise act as continuous paths for intergranular corrosion, replacing them by finely dispersed precipitates that no longer form extensive galvanic surfaces. Both the anodic dissolution of the matrix and the intergranular corrosion mechanism are thus simultaneously suppressed, which is reflected in the lowest corrosion current density and the lowest corrosion rate

recorded in this study. This is accompanied by a gradual transition from the predominantly localized (pitting) attack characteristic of the reference alloy toward a more uniform corrosion mode, in agreement with the elimination of the coarse intergranular phases and with the observed reduction of the overall corrosion rate.

4. Conclusions

This study systematically analyzed the individual and synergistic effects of tungsten addition and T7 heat treatment on the corrosion behavior and electrochemical characteristics of the AlSi5Cu2Mg alloy. The results confirmed that tungsten acted as an effective matrix stabilizing element. In the as-cast state, the addition of 0.15 wt. % W refined the dendritic structure, suppressed the segregation of alloying elements at grain boundaries, and reduced the size of galvanic microcells, which shifted the corrosion potential toward more noble values and reduced the corrosion rate to 0.0192 mm/year.

The application of T7 heat treatment significantly changed the corrosion characteristics by redistributing copper and magnesium into the solid solution lattice, thereby eliminating the θ -Al₂Cu and β -Mg₂Si anodic phases that cause intergranular degradation. The synergy of adding 0.15 wt. % W and the T7 treatment ensured the precipitation of fine stabilizing particles without the formation of extensive galvanic surfaces. Despite a slight negative shift in the corrosion potential after heat treatment, the kinetic component of corrosion was dominantly suppressed. This condition exhibited the highest resistance with a minimum corrosion current density of 0.69 μ A/cm² and the lowest corrosion rate of 0.0095 mm/year.

Metallographic analysis of the surface layers showed that while localized pitting corrosion initiated by the θ -Al₂Cu phase and Fe phases occurs in the reference alloy, the addition of tungsten with the T7 treatment promotes a more uniform distribution of corrosion centers. In the initial stages of exposure, temporary surface passivation occurs through the formation of stable corrosion products; however, long-term 80-day exposure leads to the breakdown of this barrier and a transition to more aggressive pitting corrosion that selectively dissolves the α -Al solid solution. The study thus confirms the application of tungsten for enhancing the corrosion resistance and electrochemical stability of Al-Si-Cu-Mg alloys.

Acknowledgements

The article was created as part of the KEGA grant agency project: 003ŽU-4/2024. The authors thank for its support.

References

- [1] Mohamed, A.M.A., Samuel, E., Zedan, Y., Samuel, A.M., Doty, W.H. & Samuel, F.H. (2022). Intermetallics formation during solidification of Al-Si-Cu-Mg cast alloys. *Materials*. 15(4), 1335, 1-24. DOI: 10.3390/ma15041335.
- [2] Pezda, J. (2025). Effect of heat treatment on the microstructure and mechanical properties of aluminum cylinder heads. *Archives of Foundry Engineering*. 25(4), 190-197. DOI: 10.24425/afe.2025.157617.
- [3] Matejka, M., Sýkorová, M. & Bolibruchová, D. (2026). Microstructural modification of AlSi5Cu2Mg alloy by tungsten addition and heat treatment. *Archives of Foundry Engineering*. 26(1), 105-111. DOI: 10.24425/afe.2026.157975.
- [4] Hadzima, B. & Liptáková, T. (2008). *Fundamentals of Electrochemical Corrosion of Metals*. Žilina: EDIS-Publishing Institution of the University of Žilina.
- [5] Vargel, C. (2020). *Corrosion of Aluminium*. (2nd ed.). Kidlington: Elsevier. 813 p. ISBN 978-0-08-099925-8.
- [6] Dziková, J., Hadzima, B., Liptáková, T. & Kajánek, D. (2021). *Corrosion of Metallic Materials*. Žilina: EDIS-Publishing Institution of the University of Žilina.
- [7] Zhou, W., Xue, F. & Li, M. (2025). Corrosion behavior of Al-Mg alloys with different alloying element contents in 3.5% NaCl solution. *Metals*. 15(3), 327, 1-17. DOI: 10.3390/met15030327.
- [8] Raabe, D., Ponge, D., Uggowitzer, P. J., Roscher, M., Paolantonio, M., Liu, C., Antrekowitsch, H., Kozeschnik, E., Seidmann, D., Gault, B., De Geuser, F., Deschamps, A., Hutchinson, C., Liu, c., Li, Z., Prangnell, P., Robson, J., Shanthraj, P., Vakili, S., Sinclair, C., Bourgeois, L. & Pogatscher, S. (2022). Making sustainable aluminum by recycling scrap: The science of “dirty” alloys. *Progress in Materials Science*. 128, 100947, 1-150. DOI: 10.1016/j.pmatsci.2022.100947.
- [9] Vargel, C. (2004). *Corrosion of Aluminium*. Kidlington: Elsevier. 700 p. ISBN 978-00-804-4495-6.
- [10] Tian, Q., Yang, Q.-M., Lin, Y.-C., Wang, J.-Q. & Zhu, X.-H. (2021). Effects of aging treatment on corrosion behavior of a tensile deformed Al-Cu-Mn-Fe-Zr alloy in 3.5% NaCl solution. *Materials*. 14(17), 5062, 1-13. DOI: 10.3390/ma14175062.
- [11] He, J., Liu, J., Cui, X., Lu, C., Wang, Z., Gao, S., Shi, W. & Tie, D. (2026). Effect of Heat Treatment on Microstructure and Corrosion Resistance of Al-Si-Mg-Zr-Cu-Sc Alloy. *Materials*. 19(7), 1422, 1-20. DOI: 10.3390/ma19071422.
- [12] Shaw, B.A., Davis, G.D., Fritz, T.L. & Olver, K. (1991). The influence of tungsten alloying additions on the passivity of aluminum. *Journal of The Electrochemical Society*. 138(11), 3288-3295. DOI: 10.1149/1.2085404.
- [13] Metikoš-Huković, M., Radić, N., Grubač, Z. & Tonejc, A. (2002). The corrosion behavior of sputter-deposited aluminum-tungsten alloys. *Electrochimica Acta*. 47(15), 2387-2397. DOI: 10.1016/S0013-4686(02)00040-3.
- [14] Davis, G.D., Shaw, B.A., Rees, B.J. & Ferry, M. (1993). Mechanisms of passivity of nonequilibrium Al-W alloys. *Journal of The Electrochemical Society*. 140(4), 951-959. DOI: 10.1149/1.2056234.
- [15] Esquivel, J. & Gupta, R.K. (2017). Corrosion behavior and hardness of Al-M (M: Mo, Si, Ti, Cr) alloys. *Acta Metallurgica Sinica (English Letters)*. 30, 333-341. <https://doi.org/10.1007/s40195-017-0550-2>.