SELECTIVE CORROSION OF Al₂Cu INTERMETALLIC PHASE IN ORTHOPHOSPHORIC ACID AQUEOUS SOLUTIONS

Al₂Cu phase has been obtained by melting pure metals in the electric arc furnace. It has been found that the intermetallic phase undergoes selective corrosion in the H₃PO₄ aqueous solutions. Aluminium is dissolved, the surface becomes porous and enriched with copper. The corrosion rate equals to 371 ± 17 g·m⁻²·day⁻¹ ( aerated solution) and 284 ± 9 g·m⁻²·day⁻¹ (deaerated solution). The surface of Al₂Cu phase after selective corrosion was characterised by using electrochemical impedance spectroscopy. It was found that the surface area of the specimens increases with temperature due to higher corrosion rate and is between 2137 and 3896 cm².

Keywords: intermetallic phase; selective corrosion; orthophosphoric acid; electrochemical impedance spectroscopy

1. Introduction

Microstructure of wrought aluminium alloys is complex and composed of several intermetallic phases. One of the most important is Al₂Cu. According to the Al-Cu phase diagram, it is formed in the peritectic reaction, at 873 K [1]. Al₂Cu phase is hard and ensures good strength of precipitation hardened Al-Cu-Mg-Mn alloys, as well as Al-Cu alloy-based metal matrix composites [2].

Al₂Cu phase is more noble when compared to Al-based solid solution, regardless of the pH of the environment [3-5]. The particles of this phase constitute the local cathodes in the galvanic cells, where the reduction of O₂ or H₃O⁺ occurs. The overpotential of both cathodic processes on Al₂Cu is lower when compared to Al. Therefore, fine precipitates of Al₂Cu phase, within the matrix of Cu-rich aluminium alloys, deteriorate their corrosion resistance significantly [3]. The corrosion behaviour of Al₂Cu phase itself was mainly evaluated in the chloride media. It was shown that the intermetallic phase remains passive in 0.1 M NaCl aqueous solution in the wide range of pH (2.5-12) [4]. Similar results were obtained in the borate buffer. However, when the exposition time was sufficiently long, its surface became enriched with copper [3]. The selective corrosion of Al₂Cu is much more severe in 10 wt. % NaOH [6] and 2 M H₂SO₄ [7]. On the other hand, this process can be utilised for synthesis of nanoporous materials [6].

In this work, the corrosion of Al₂Cu intermetallic phase in orthophosphoric acid aqueous solution has been studied for the first time. It is important from practical point of view, since H₃PO₄ is used e.g. for etching of aluminium alloys as the pre-treatment step for anodisation. Detailed knowledge of the corrosion behaviour of the intermetallic phases in acidic solutions is useful for better understanding of the behaviour of aluminium alloys during etching and application of the appropriate corrosion inhibitors.

2. Experimental

The Al₂Cu electrodes with three different content of copper were obtained by the electric arc melting process of Al and Cu (99.999 wt. % purity). It was carried out in water-cooled copper crucibles, by using a tungsten electrode, in the atmosphere of Ar (p = 60 kPa). Then they were annealed (T = 823 K, t = 24 h), cut by using the electrical discharge machine to 10 mm diameter specimens and mounted in the epoxy resin.

The characterisation of the electrodes included determination of their chemical (ARL ADVANT XP Sequentialional X-ray Fluorescence Spectrometer, Thermo Scientific) and phase (ARL X’Tra X-ray diffractometer, Cu Kα radiation source) composition as well as microstructure (Leica DM 3000 light microscope, HITACHI S-3400N Scanning Electron Microscope). Prior microscopic examination, specimens were etched in diluted hydrofluoric acid (0.5 cm³ HF (48 wt.%) and 99.5 cm³ H₂O). The chemical composition of the solutions after the corrosion process

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was determined by using the inductively-coupled plasma optical emission spectroscopy ICP-OES (Ultima 2 Horiba Jobin Yvon).

Prior the electrochemical examination, the Al$_2$Cu electrodes (0.79 cm$^2$) were abraded by a sandpaper (grit 320 and 500), washed with water, isopropyl alcohol and dried with compressed air. The electrochemical research were conducted in the standard, three electrode setup (graphite counter electrode, Ag/AgCl 3 M KCl reference electrode), by using Bio-Logic SP-300 potentiostat, in 100 cm$^3$ of 0.5 M H$_3$PO$_4$ aqueous solution, at 295, 300 and 307 K.

The corrosion potential of Al$_2$Cu phase was determined after 20 h of exposition in the solution. The impedance spectra were then recorded in the frequency range between 200 kHz and 10 mHz and approximated with the equivalent circuit (vide infra) by using the Zview software (Scribner Associates). The experiments were repeated 3 times. Data points in the graphs represent the average of 3 values. Their uncertainties $u$ were then calculated (Eq. (1)):

$$u = t \frac{SD}{\sqrt{3}}$$

where SD is the standard deviation of the averaged value, $t = 2.92$ (90% confidence level). The potentiodynamic polarisation curves were determined at the scanning rate of 5 mV·min$^{-1}$ for aerated and deaerated solution in the vicinity ($\pm$ 25 mV) of the corrosion potential. The anodic polarisation curves, in turn, were recorded at the scanning rate of 0.5 mV·s$^{-1}$.

![Fig. 1. The microstructure of the specimens as a function of their chemical composition, after casting a), c), e) and subsequent annealing at 823 K for 24 hours b), d), f), arrows indicate the remaining of the eutectic mixture in the microstructure](image-url)
3. Results and discussion

3.1. The microstructure and phase composition of the Al₂Cu phase

The content of copper in the three Al-Cu alloys obtained in the arc melting process was the following: 49.5, 51.2 and 51.9 wt. %. It should be noted here that the maximal range of stability of Al₂Cu phase is between 51.9 and 53.4 wt. % of Cu. Microscopic characterisation of the as-cast alloys (without annealing) revealed that their microstructure is composed of the eutectic mixture of Al₂Cu and Al(Cu) solid solution crystals, together with the hypereutectic crystals of the Al₂Cu phase (Fig. 1a, c, e). Since the cooling rate was very high and the crystallisation occurred under non-equilibrium conditions, the specimens were annealed for 24 hours, in order to achieve the equilibrium microstructure. The heat treatment applied reduced the relative volume of the eutectic mixture in the microstructure (Fig. 1b, d, f). Virtually single-phase alloy was obtained for the highest concentration of copper (Fig. 1f). Therefore, this alloy was applied in the subsequent corrosion experiments.

The phase composition of the obtained materials was also confirmed by using the X-ray diffraction method (Fig. 2). All the diffraction lines obtained were ascribed to the Al₂Cu phase (ICDD 04-001-0923 card). The diffraction lines characteristic for aluminium (2θ equal to 38.47°; 44.74°; 65.13° and 77.22°) were not found. It was also observed that the intensities of diffraction lines differ between the specimens. It is due to the big grain size of the prepared alloys.

3.2. The mechanism of corrosion of Al₂Cu phase

The corrosion rate of Al₂Cu phase in 0.5 M H₃PO₄ aqueous solution was calculated on the basis of the concentration of aluminium and copper in the solution, after 20.4 hours of immersion (Table 1). The following results were obtained: 284 ± 9 g·m⁻²·day⁻¹ for deaerated and 371 ± 17 g·m⁻²·day⁻¹ for aerated solution. When the solution is deaerated, almost only Al atoms are leached. Oxygen dissolved in the solution act as an additional depolariser and increases the corrosion rate. In addition, more copper is dissolved when compared to the former case. It can be concluded that the corrosion rate of Al₂Cu phase is very high when compared to aluminium 1050 or 2024 alloy immersed in the same solution (c.a. 15 g·m⁻²·day⁻¹ [10,11]).

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration in the solution</th>
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<tbody>
<tr>
<td></td>
<td>purged with Ar</td>
</tr>
<tr>
<td>Aluminium</td>
<td>193.00 ± 5.84 mg·dm⁻³</td>
</tr>
<tr>
<td>Copper</td>
<td>57.3 ± 8.2 μg·dm⁻³</td>
</tr>
</tbody>
</table>

The examination of the surface of Al₂Cu specimen with SEM confirmed that Al₂Cu phase underwent selective corrosion (Fig. 3a and b, Table 2). The surface became porous and significantly enriched with copper due to dissolution of aluminium. Parts of this porous structure can be mechanically detached from the surface and dissolve in the solution containing oxygen. It is probably responsible for the increased concentration of Cu in the aerated solution when compared to the deaerated one (Table 1).

<table>
<thead>
<tr>
<th>Area in Fig. 3a</th>
<th>Chemical composition, at. %</th>
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<tbody>
<tr>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
</tr>
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<td>5</td>
<td>48</td>
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Fig. 2. X-ray diffraction patterns of the alloys obtained, black diamonds indicate the diffraction lines ascribed to the Al₂Cu phase
Subsequently, the electrochemical methods were applied for better understanding of the corrosion mechanism. Prior polarisation experiments, the open circuit potential vs. immersion time was recorded (Fig. 4). It can be observed that the surface of Al₃Cu phase quickly becomes enriched with copper. It is related with the increase of the electrode potential. The averaged values of corrosion potential (after 20.4 hours) for aerated and deaerated 0.5 M H₃PO₄ solutions are of –14 ± 102 mV vs. SHE and 11 ± 23 mV vs. SHE respectively. The equilibrium potential of the hydrogen electrode is –65 mV vs. SHE (pH = 1.1).

Since the corrosion potential is more positive than the equilibrium potential for hydrogen evolution, the corrosion with hydrogen depolarisation occurs only for a few hours after immersion of the specimens in the solution. Further corrosion is possible due to cathodic reduction of dissolved oxygen or copper ions on the surface of Al₃Cu phase. These processes were investigated by using the linear polarisation method (Fig. 5a). The polarisation curves were recorded in the aerated and deaerated...
ated solution, in the vicinity of the corrosion potential. They were subsequently approximated by using the Eq. (2), as it was proposed by Mansfeld [12]:

\[
i = \frac{1}{2.303R_p} \frac{\beta_a \beta_c}{\beta_a + \beta_c} \left[ \exp \left( \frac{2.303\eta}{\beta_a} \right) - \exp \left( \frac{-2.303\eta}{\beta_c} \right) \right]
\]

(2)

where \(R_p\) is the polarisation resistance, \(\eta\) – overpotential, \(\beta_a\) and \(\beta_c\) – Tafel constants for the anodic and cathodic process respectively. The results obtained are presented in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in equilibrium with air</th>
<th>Value purged with Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_p)</td>
<td>33.1 ± 0.3 Ω</td>
<td>30.6 ± 0.3 Ω</td>
</tr>
<tr>
<td>(\beta_a)</td>
<td>69 ± 4 mV</td>
<td>105 ± 17 mV</td>
</tr>
<tr>
<td>(\beta_c)</td>
<td>74 ± 4 mV</td>
<td>180 ± 48 mV</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.999</td>
<td>0.999</td>
</tr>
</tbody>
</table>

The cathodic process in both cases is reduction of oxygen, dissolved in the electrolyte. The value of Tafel constant (74 ± 4 mV) obtained for the solution in equilibrium with air suggests that the limiting step is the charge transfer through the solid/liquid interface. The theoretical value of \(\beta_c\) for this process is equal to 100 mV [12]. However, Cu\(^{2+}\) ions are also present in the solution and can be reduced on the surface. Thus, obtained value of \(\beta_c\) accounts for both processes. When the solution was deaerated, the Tafel constant reached much higher value, which indicates that the cathodic process is under diffusion control. The diffusing species are presumably O\(_2\) molecules (due to incomplete deaeration of the solution) and maybe also Cu\(^{2+}\) ions, but copper concentration in the solution is very low. It can also be observed that at the sufficient cathodic polarisation (−25 mV), the process of reduction of H\(_3\)O\(^+\) originates (cathodic current in Fig. 5a starts to increase).

The anodic polarisation curves, obtained for Al\(_2\)Cu phase immersed in 0.5 M H\(_3\)PO\(_4\) aqueous solution, are presented in Fig. 5b. Their shape suggests active dissolution of the specimens. At the potential above ca. 0.4 V vs. SHE, copper is dissolved and subsequently deposited onto the surface of the counter electrodes. In the case of deaerated solution, the current increase around this potential value is clearly visible. It should be noted here that the current density was not calculated, since the real surface area of the electrodes remains unknown. However, it is much bigger when compared to the geometric one (vide infra).

Passivity of Al\(_2\)Cu phase in acidic solution (0.1 M NaCl, pH = 2.5) has already been reported, however, relatively low value of the corrosion potential (ca. −350 mV vs. SHE) was obtained [4]. The discrepancy between the cited results and presented in this work is probably related with the different copper content on the surface due to different aggressiveness of the solutions and probably different immersion time. What is more, when the electrode potential was around 0 V vs. SHE, as it is reported in this work, intermetallic phase underwent corrosion in the transpassive region of the polarisation curve [4]. It supports the observation that Al\(_2\)Cu corrodes in the studied solution in the active state.

### 3.3. EIS characterisation of Al\(_2\)Cu phase after the corrosion process

Selective corrosion of the Al\(_2\)Cu phase causes its significant porosity. The impedance of the porous electrode was modelled by using the so called “two CPE model”, where CPE stands for constant phase element, composed of two R-CPE loops connected in series. The first, high frequency one is related to the porosity of the electrode, the other one to the charge transfer process [13]. In this work, the capacitor, representing the double layer capacitance \(C_d\) was used instead of the low frequency CPE, without deterioration of the fit quality. The approximation of the impedance spectra obtained for different temperature of the solution, by using the “two CPE model” are presented in Fig. 6a. The temperature dependency of \(R_1\) and \(R_2\) is given in Fig. 6b.

![Fig. 6. The impedance spectra of the Al\(_2\)Cu electrode in 0.5 M, deaerated, H\(_3\)PO\(_4\) as the function of the solution temperature, continuous lines represent their approximation with the equivalent circuit given a), the values of the resistance from the equivalent circuit as the function of the solution temperature b) (Image)](image-url)
It can be concluded that the resistance $R_2$ decreases with the increasing temperature, contrary to $R_1$. Since these results were obtained for deaerated solution, the resistance $R_2$ was ascribed to the faradaic impedance. It takes into account the charge transfer resistance related with the corrosion process caused by small amount of oxygen and traces of copper in the solution as well as the mass transfer impedance which is related with their diffusion to the surface of the electrode. The double layer capacitance is high due to large surface area of the electrode (high porosity), caused by the selective corrosion process. Moreover, it increases with the increasing temperature due to the higher corrosion rate of the electrode (Fig. 7). The surface area of the electrodes was calculated using the values of $C_{dl}$ obtained, assuming the ideal capacitance of the metallic surface equal to $20 \, \mu F \cdot cm^{-2}$ [13] and neglecting the influence of temperature and pH. The following values were obtained: $2137 \pm 352 \, cm^2$, $3933 \pm 1070 \, cm^2$ and $3896 \pm 1342 \, cm^2$ for 295, 300 and 307 K respectively.

The dependency of the corrosion rate of Al$_2$Cu phase on the concentration of orthophosphoric acid was also estimated. The impedance spectra obtained for deaerated solutions are presented in Fig. 8. They were approximated by using the same equivalent circuit. It is possible to see that the faradaic impedance does not depend on the concentration of H$_3$PO$_4$ (Fig. 9a). The capacitance of the double layer also does not change significantly (Fig. 9b). Thus, it can be concluded that the rate of corrosion of Al$_2$Cu phase virtually does not depend on the concentration of orthophosphoric acid.

### 4. Summary

Al$_2$Cu phase undergoes selective corrosion in 0.5 M H$_3$PO$_4$ aqueous solution. The corrosion rate is much higher when compared to aluminium 1050 and 2024 alloy. Oxygen dissolved in the electrolyte behaves as the additional depolariser and increases the corrosion rate of intermetallic phase as well as the concentration of copper in the solution.

The Al$_2$Cu electrodes after the corrosion process were investigated by using the electrochemical impedance spectroscopy. The impedance spectra were approximated with the so-called “two-CPE model”. The faradaic impedance and double
layer capacitance were determined. It was shown that the former decreases whereas the latter increases with the increasing temperature of the solution. The surface area of the Al$_2$Cu phase after corrosion process was determined as between 2.7 and 4.9 thousand times higher than the geometric value. The increase of the concentration of orthophosphoric acid in the range between 0.25 and 1 M neither increase the surface area of the electrode after corrosion process, nor the faradaic impedance.

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**REFERENCES**