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EFFECT OF THERMOMECHANICAL TREATMENT ON THE INTERGRANULAR CORROSION OF Al-Mg-Si-Type ALLOY BARS

VPLIV TERMOMEHANSKE PREDELAVE NA INTERKRISTALNO KOROZIJO PALIC IZ ZLITIN Al-Mg-Si

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Al-Mg-Si-type alloys (6xxx-series alloys) exhibit good mechanical properties, formability, weldability and good corrosion resistance in a variety of environments. They often find use in the automotive industry and other applications. Some alloys, however, particularly those with higher copper levels, show increased susceptibility to intergranular corrosion. Intergranular corrosion (IGC) is typically related to the formation of microgalvanic cells between cathodic, more-noble phases and depleted (precipitate-free) zones along the grain boundaries. It is encountered mainly in Al-Mg-Si alloys containing Cu, where it is thought to be related to the formation Q-phase precipitates ($Al_4Mg_8Si_7Cu_2$) along the grain boundaries. The present paper describes the effects of mechanical working (pressing, drawing and straightening) and artificial ageing on intergranular corrosion in a bar of the 6064 alloy. The resistance to intergranular corrosion was mapped using corrosion tests according to EN ISO 11846, method B. The corrosion tests showed that with continuing ageing and over-ageing, deep IGC changes into pitting corrosion with a smaller depth of attack. However, the corrosion resistance of the bars is impaired by post-quench mechanical working (drawing and straightening).

Keywords: Al-Mg-Si-Cu alloy, 6064 alloy, extruded bars, thermomechanical treatment, intergranular corrosion, pitting corrosion

Zlitine vrste Al-Mg-Si (6xxx-vrsta zlitin) kažejo dobre mehanske lastnosti: preoblikovalnost, varivost in dobro korozijsko odpornost v različnih okoljih. Pogosto se uporabljajo v avtomobilski industriji in tudi v druge namene. Vendar pa nekatere zlitine, posebno tiste z višjo vsebnostjo bakra, kažejo povečano občutljivost na interkristalno korozijo. Interkristalna korozija (IGC) je značilno povezana z nastankom mikrogalvanskih celic med katodno, bolj plemenito fazo in osiromašenim (brez izločkov) področjem, vzdolž meja kristalnih zrn. To se pojavlja predvsem v AlMgSi zlitinah, ki vsebujejo Cu in kjer se predpostavlja, da je to povezano z nastankom izločkov Q-faze ($Al_4Mg_8Si_7Cu_2$), vzdolž meja med zrni. Članek opisuje vpliv mehanskega preoblikovanja (stiskanje, vlečenje, ravnanje) in vpliv umetnega staranja na interkristalno korozijo palic iz zlitine 6064. Odpornost na interkristalno korozijo je bila preslikana s pomočjo korozijskih preizkusov, skladno s standardom EN ISO 11846, metoda B. Korozijski preizkusi so pokazali da se z nadaljevanjem staranja in prestaranjem globoke interkristalne korozije, spremenijo v jamičasto korozijo, z manjšo globino napada. Vseeno pa je korozijska odpornost palic poslabšana z mehansko predelavo (vlečenje in ravnanje) po gašenju.

Ključne besede: zlitina Al-Mg-Si-Cu, zlitina 6064, iztiskane palice, termomehanska predelava, interkristalna korozija, jamičasta korozija

1 INTRODUCTION

Al-Mg-Si-type alloys (6xxx-series alloys) exhibit good mechanical properties, formability, weldability and good corrosion resistance in a variety environments. They frequently find use in automotive, aviation and other applications.[1,2] Some of these materials are alloyed with copper to improve their strength. In these alloys, particularly higher-copper alloys, increased susceptibility to intergranular corrosion (IGC) can be observed, most notably in the unaged condition and less often in the T6 temper condition. The effects of Cu as well as the opportunities for enhancing the resistance to intergranular corrosion have received considerable attention in a number of studies.[3–11] Intergranular corrosion (IGC) is typically related to the formation of microgalvanic cells between the cathodic more-noble phases and the depleted (precipitate-free) zones along the grain boundaries. It is encountered mainly in AlMgSi alloys that contain Cu, where it is thought to be linked to the formation of cathodic Q-phase ($Al_4Mg_8Si_7Cu_2$) along the grain boundaries. The occurrence of phases along the grain boundaries was observed using scanning-transmission electron microscopy (STEM).

The impact of Cu additions and heat treatment on IGC was described in several papers.[3–6] The alloys contained 0.5-0.6 % Mg, 0.6-0.8 % Si, 0.2 % Fe, 0.2 % Mn and Cu at 0.02 through 0.7 % of mass fractions. The occurrence of IGC was monitored in 2.5 mm × 78 mm extruded flat bars. The effects of the cooling rate from the extrusion temperature were studied[3], as were the effects of artificial ageing.[4,5] Corrosion tests were carried out according to EN ISO 11846, method B. Corrosion was only monitored on the surface of the extruded parts. EN ISO 11846 specifies that the corrosion is monitored on the long side of the specimen. In an alloy with a Cu level of 0.02 %, no IGC was found. In an alloy with

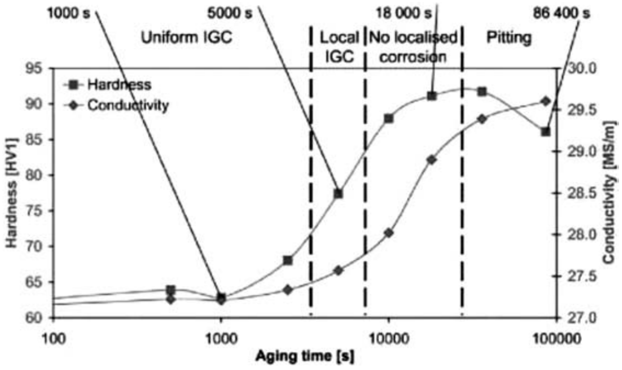

Figure 1: The dominant corrosion types in a material aged at 185 °C, according to[5]

Slika 1: Prevladujoče oblike korozije v materialu, staranem na 185 °C po viru[5]

0.2 % Cu, IGC occurred depending on the artificial ageing time, and changed into pitting corrosion. These findings suggest that between the occurrence of IGC and pitting corrosion, there is a region in which no IGC occurs (**Figure 1**).

Hence, over-ageing (by increasing either temperature or time) permits a transition from a region with IGC to a region with suppressed IGC.

The AA6056 material for the aviation industry is used in overaged condition. It is supplied in the T78 state with an enhanced resistance to IGC. According to[6,7], the T78 temper is achieved by two-stage ageing: 175 °C/6 h + 210 °C/5 h.

Two-stage ageing was explored by the authors of the study.[11] The alloy had a nominal composition of 1.0 % Mg, 1.2 % Si, 0.3 % Cu, 0.6 % Mn, 0.12 % Cr, 0.12 % Fe and a balance of Al. An ageing schedule specified as 180 °C/2 h + 160 °C/120 h led to better results than 175 °C/6 h + 210 °C/5 h. However, this work was carried out using specimens of rolled sheet with a 2-mm thickness, where the corrosion attack was monitored on the sheet surface and not on its cross-section.

Thermomechanical treatment generally has a great influence on the corrosion in other types of aluminium alloys.[12] In this research the effect of the thermomechanical treatment (extrusion, drawing and ageing) on the intergranular corrosion in bars from EN AW-6064A (AlMg1SiBi) machineable alloy was studied. AlMgSi-type machinable alloys are used in the automotive industry. Their improved machinability is imparted by alloying with Pb (6012 alloy) or with Bi+Pb (6262 and 6064 alloys). These alloys have higher alloy levels and contain more phases than the alloys studied in [3–11]. These phases include Bi and Pb cathodic particles.

2 EXPERIMENTAL PART

The chemical composition of the EN AW-6064A bars is shown in **Table 1**. The bars of 17 mm diameter were made by an industrial hot-extrusion process using a multiple-hole die. The process temperature was 540–546 °C. Right after extrusion, the bars were water-wave cooled (T1 condition). The quenched bars were then drawn to the final diameter of 15 mm at 22 % reduction and straightened in a Schumag straightening machine (T2 temper). The final operation was artificial ageing to T8. Bars in conditions corresponding to each process step were gathered for testing. The samples are listed in **Table 2**.

The bars that did not undergo ageing (HA1, HB2 and HF) were used in artificial ageing trials: single-stage and two-stage ageing to the under-aged, peak-aged and over-aged condition. The artificial ageing schedules are presented in **Table 3**.

Table 1: Chemical composition of the alloy 6064A, in mass fractions (*w*/%)

Tabela 1: Kemijska sestava zlitine 6064A, v masnih deležih (*w*/%)

Sample	Si	Fe	Cu	Mn	Mg	Cr	Pb	Bi
H	0.60	0.23	0.27	0.04	1.03	0.05	0.28	0.49

Table 2: Samples description

Tabela 2: Opis vzorcev

Sample	Diameter	Temper	Description of thermomechanical processing
HA1	17 mm	T1	Extruding, quenching
HB2	15 mm	T2	Extruding, quenching, drawing
HF	15 mm	T2	Extruding, quenching, drawing, straightening
HC	15 mm	T8	Extruding, quenching, drawing, straightening, ageing

Table 3: Heat treatment HT (artificial ageing) for samples HA1, HB2, HF

Tabela 3: Toplotna obdelava (umetno staranje) vzorcev HA1, HB2, HF

HT	One-stage	HT-A	Two-stage A	HT-B	Two-stage B
1	160 °C/4 h	1A	160 °C/4 h+ 220 °C/4 h	1B	160 °C/4 h+ 205 °C/4 h
2	160 °C/8 h	2A	160 °C/8 h+ 220 °C/4 h	2B	160 °C/8 h + 205 °C/4 h
3	180 °C/4 h	3A	180 °C/4 h+ 220 °C/4 h	3B	180 °C/4 h+ 205 °C/4 h
4	180 °C/8 h				

The progress of ageing was monitored by a HV5 hardness measurement using a DURASCAN 50 hardness tester. Tests of resistance to intergranular corrosion were conducted in accordance the EN ISO 11846 standard, method B.[13] For these tests, specimens of 2 cm in length were made from the bars. Their cut surfaces were ground with P-1200 grinding papers. The original surface of the bar was not altered. Before testing, the specimens were degreased in acetone. In accordance with the standard requirements, they were etched with 5 % NaOH solution at 55 °C for 2 min. After a water rinse, they were placed in concentrated nitric acid for cleaning. The test itself involved submerging in a test solution for 24 h at room temperature. The solution was 30 g NaCl/L solution + 10 mL concentrated hydrochloric acid.

Following the test, the specimens were rinsed with water. Metallographic sections were prepared on longitudinal cross-sections through the specimens. The corrosion attacks on the bar surface as well as on the transverse cut surface were examined. The maximum corrosion depth was determined and documented using light microscopy. The surfaces of the specimens after corrosion testing were examined in a JEOL JSM 6380 scanning electron microscope.

3 RESULTS

3.1 Initial microstructures

The microstructure of T8-temper HC bars upon drawing, straightening and ageing is shown in **Figure 2a**. A micrograph of the phases is in **Figure 2b**. The microstructure is fully recrystallized. The grains in the surface layer are relatively fine, with a size of 70 µm. In the centre, the grains are coarser, of the order of several hundred µm. Different grain sizes in the surface and in the interior are a typical occurrence in extruded bars from Al alloys. Typically, the surface layer contains coarse grains and the interior remains unrecrystallized.[1,2]

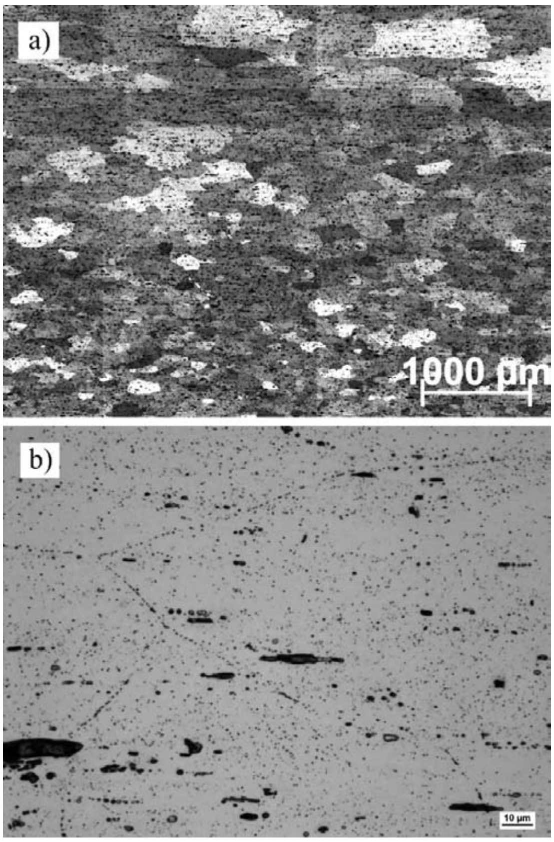

Figure 2: Micrographs of grains and phases in HC samples upon drawing and ageing: a) electrolytically etched with Barker's reagent, polarised light, b) etched with Dix-Keller's reagent

Slika 2: Posnetka zrn in faz v HC vzorcu, po vlečenju in staranju: a) elektrolitsko jedkano z Baker jedkalom, polarizirana svetloba, b) jedkano z Dix-Keller jedkalom

The phases in the microstructure are banded and aligned in the extrusion/drawing direction. Large elongated particles consist of Bi or Bi+Pb. The small ones are alpha-$Al_{15}(Fe,Mn,Cu,Cr)_3Si_2$ particles. Other small particles are Mg_2Si particles. The Bi, Pb and alpha-$Al_{15}(Fe,Mn,Cu,Cr)_3Si_2$ particles are more noble, cathodic. The Mg_2Si particles are anodic. With cathodic particles, the matrix of the aluminium solid solution is etched away preferentially when placed in a corrosion environment. With anodic particles, it is the particles that are attacked. The microstructure may also contain cathodic Q-phase particles ($Al_4Mg_8Si_7Cu_2$). **Figure 2b** also shows minute particles along grain boundaries. EDS analysis revealed that they contain higher amounts of copper, which suggests that they are Q-phase particles.

3.2 Corrosion tests

Specimens to be tested according to EN ISO 11846, method B, are to be alkaline pre-etched with 5-10 % NaOH solution. With this etch, the Al matrix and anodic phases are attacked. The etched surface of a specimen is shown in **Figure 3**. The large pits are the result of the Al matrix being etched away from around the Bi, Pb and alpha-$Al_{15}(Fe,Mn,Cu,Cr)_3Si_2$ cathodic phases. The small pits are the locations of Mg_2Si anodic particles that were

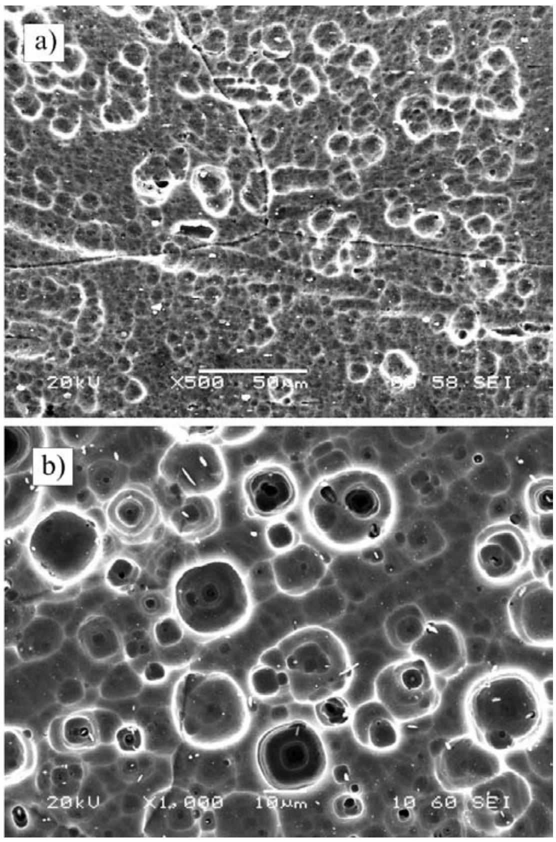

Figure 3: SEM micrographs of the surface of HC sample upon etching with NaOH: a) sample surface, b) transverse cut surface

Slika 3: SEM-posnetka površine vzorca HC, po jedkanju z NaOH: a) površina vzorca, b) prečni prerez vzorca etched away. The grain boundaries were slightly attacked.

In order to evaluate the corrosion, the specimens were cut longitudinally after the test. On the cross-section, the type and depth of the corrosion on the bar's surface and on its transverse cut surface were examined.

3.2.1 Corrosion tests of materials in initial condition

The initial condition evaluation was carried out on HF samples supplied in the T2 (non-aged) condition and on the HC samples supplied in the T8 (peak-aged) condition. The HC bars were drawn and aged during the 24 h following quenching. The surface corrosion is shown in **Figure 4**. Its evaluation is detailed in **Table 4**.

Table 4: Evaluation of corrosion and hardness of initial samples in T2 and T8 condition

Tabela 4: Ocena korozije in trdota začetnih vzorcev po T2 in T8 obdelavi

Sample	Temper	HV5	Place	Corrosion depth (μm)	Corrosion type
HF	T2	108	Surface	420.5	IGC + pitting
			Transverse cut	493.2	IGC + pitting
HC	T8	124.3	Surface	217.8	Pitting, transgranular
			Transverse cut	607.7	Pitting

The surface of the non-aged HF sample shows extensive intergranular corrosion (IGC) with a depth of more than 420 μm. In the artificially-aged HC sample (T8 peak-aged temper), the corrosion changed into the pitting type, which spreads perpendicularly to the surface to a depth of more than 200 μm. The corrosion type corresponds to transgranular corrosion. On the cross-section through the HF specimen, IGC with a depth of approximatelz 500 μm was found as well. The corrosion on the transverse cut surface of the HC sample is very extensive too. It is, however, pitting-type corrosion, which reached a depth of up to 600 μm. It follows the bands of coarse cathodic Bi, Pb and alpha-$Al_{15}(Fe,Mn,Cu,Cr)_3Si_2$ particles (**Figure 4d**). **Table 4** lists HV5 hardness values. The HF sample in the T2 state exhibits 108 HV5. Age-hardening to T8 increased the hardness to 124 HV5.

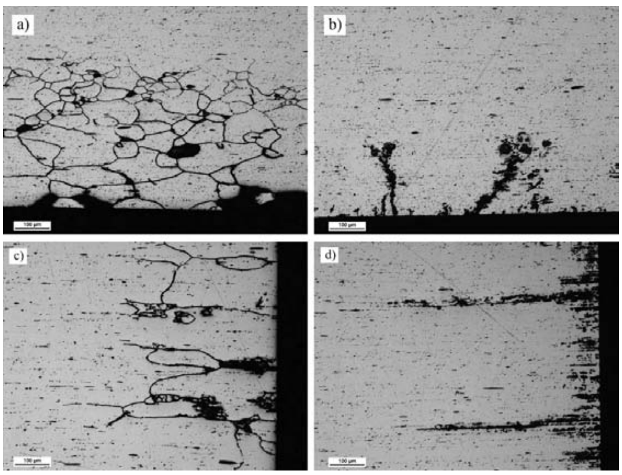

Figure 4: Corrosion attack in as-received bars: a) HF surface – temper T2, non-aged, b) HC surface – temper T8, peak-aged, c) HF transverse cut surface, d) HC transverse cut surface

Slika 4: Korozija na dobavljenih palicah: a) HF površina - žarjenje T2, nestarano, b) HC površina – žarjenje T8, starano, c) HF prečni presek, d) HC prečni presek

3.2.2 Corrosion tests after experimental heat treatment (artificial ageing)

Using these tests, the impact of various artificial ageing schedules (under-ageing, over-ageing) on the corrosion in bars in various conditions was monitored:

- Sample HA1 – after extruding and quenching;

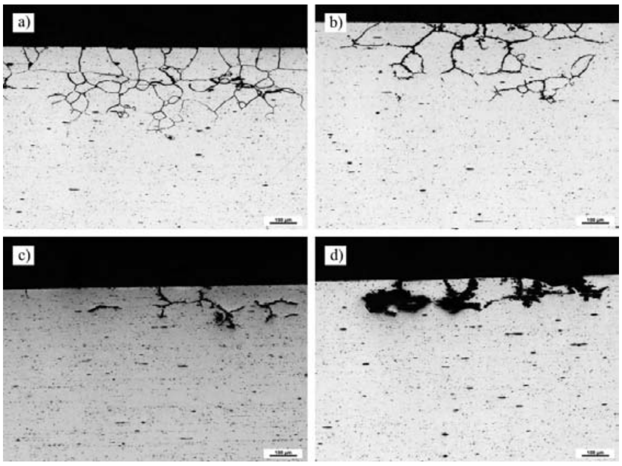

Figure 5: Corrosion on the HA1 bar surface upon ageing: a) 160 °C/8 h under-aged, b) 180 °C/8 h, c) 160 °C/4 h + 205 °C/4 h, d) 160 °C/4 h + 220 °C/4 h overaged

Slika 5: Korozija na površini HA1 palice, po staranju: a) 160 °C/8 h, podstarano, b) 180 °C/8 h, c) 160 °C/4 h – 205 °C/4 h, d) 160 °C/4 h + 220 °C/4 h, prestarano

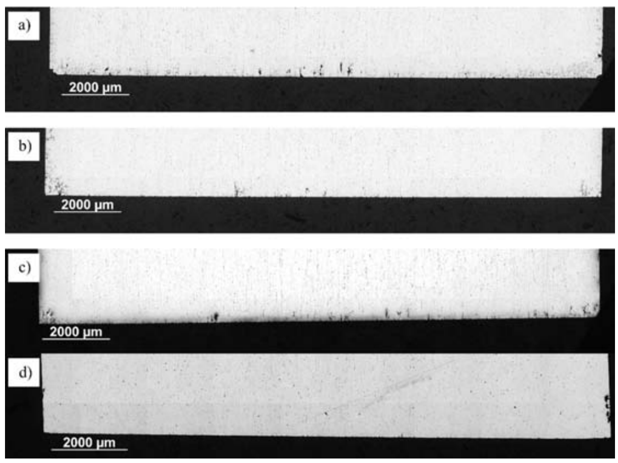

Figure 6: Corrosion on the HA1 transverse cut surface upon ageing: a) 160 °C/8 h under-aged, b) 180 °C/8 h, c) 160 °C/4 h + 205 °C/4 h, d) 160 °C/4 h + 220 °C/4 h overaged

Slika 6: Korozija na prečnem prerezu HA1 po staranju: a) 160 °C/8 h podstarano, b) 180 °C/8 h, c) 160 °C/4 h + 205 °C/4 h, d) 160 °C/4 h + 220 °C/4 h prestarano

- Sample HB2 – after extruding, quenching and drawing;
- Sample HF – after extruding, quenching, drawing and straightening
- Corrosion tests of specimens of HA1 extruded bars

The surface corrosion of selected specimens in variously aged conditions is illustrated in **Figure 5**. The corrosion of the transverse cut surface is shown in **Figure 6**. **Table 5** contains the results of the corrosion evaluation and the HV5 hardness levels, which indicate the progress of ageing. In specimens in the under-aged condition, the most extensive surface corrosion was found, involving continuous IGC with a maximum depth of more than 300 µm. In the peak-aged condition, the depth of attack decreased and IGC ceased to be continuous. In the over-aged condition, only sporadic pitting corrosion can be observed with a depth of about 120 µm.

Table 5: Evaluation of corrosion and hardness of samples HA1
Tabela 5: Ocena korozije in trdota vzorcev HA1

Sample HV5	US	Place	Corrosion depth (µm)	Corrosion type
HA1-2 92.5	160 °C/ 8h	Surface	309.3	IGC + pitting sporadic
	Under-ageing	Transverse cut	421.1	IGC near-edge + pitting
HA1-4 113.7	180 °C/ 8 h	Surface	296.4	IGC 50 %
	peak ageing	Transverse cut	460.8	IGC near-edge + pitting
HA1-1B 114.7	160 °C/4 h + 205 °C/4 h	Surface	158.9	IGC + pitting sporadic
	peak ageing	Transverse cut	381.5	IGC + pitting
HA1-1A 109.3	160 °C/4 h + 220 °C/4 h	Surface	120.4	Pitting sporadic
	Over-ageing	Transverse cut	93.4	Pitting sporadic

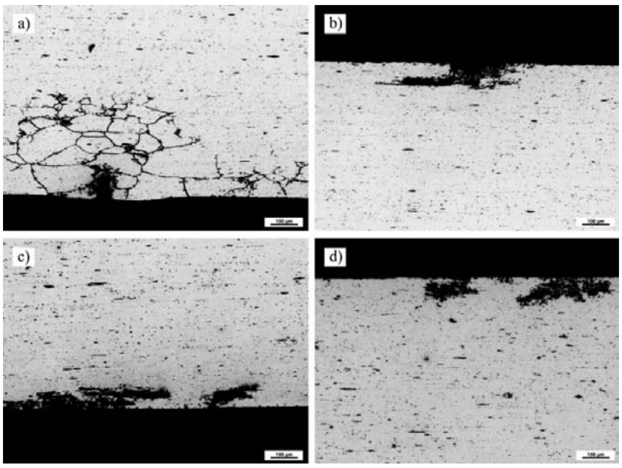

Figure 7: Corrosion on the HB2 transverse cut surface upon ageing: a) 180 °C/4 h under-aged, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h overaged

Slika 7: Korozija na prečnem prerezu HB2 po staranju: a) 180 °C/4 h podstarano, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h prestarano

The same type of corrosion was found on the transverse cut surface. However, the corrosion depth was larger there: more than 400 µm. The only exception was the over-aged sample where the depth was less than 100 µm.

3.2.3 Corrosion tests of specimens of HB2 drawn bars

The surface corrosion of selected specimens in variously aged conditions is illustrated in **Figure 7**. The corrosion of the transverse cut surface is shown in **Figure 8**. Results of the evaluation of corrosion are given in **Table 6**.

Table 6: Evaluation of corrosion and hardness of samples HB2
Tabela 6: Ocena korozije in trdota vzorcev HB2

Sample HV5	US	Place	Corrosion depth (µm)	Corrosion type
HB2-3 120	180 °C/4 h	Surface	382.5	IGC 60 % + pitting sporadic
	Under-ageing	Transverse cut	528.4	IGC, near-edge
HB2-4 120.7	180 °C/8 h	Surface	123.6	Pitting, sporadic
	peak ageing	Transverse cut	755.6	Pitting, near-edge
HB2-3B 123.3	180 °C/4 h + 205 °C/4 h	Surface	81.8	Pitting
	peak ageing	Transverse cut	742.6	Pitting
HB2-3A 106.7	180 °C/4 h + 220 °C/4 h	Surface	88.3	Pitting
	Over-ageing	Transverse cut	678.1	Pitting, near-edge

In HB2 drawn bars, IGC was found only in the under-aged condition (**Figure 7a**). This intergranular

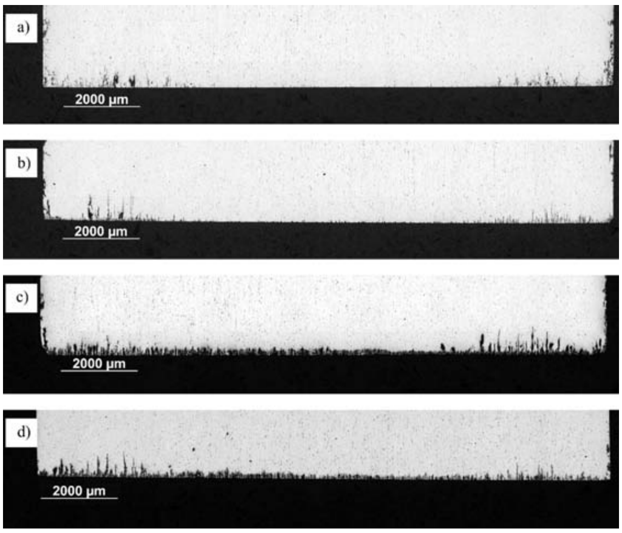

Figure 8: Corrosion on the HB2 transverse cut surface upon ageing: a) 180 °C/4 h under-aged, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h overaged

Slika 8: Korozija na prečnem prerezu HB2 po staranju: a) 180 °C/4 h podstarano, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h prestarano

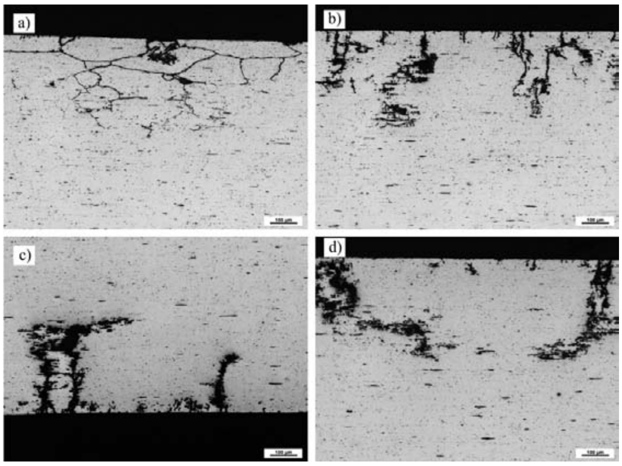

Figure 9: Corrosion on the HF bar surface upon ageing: a) 180 °C/4 h under-aged, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h overaged

Slika 9: Korozija na površini HF palice, po staranju: a) 180 °C/4 h podstarano, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h prestarano

corrosion is not continuous. On the surface of the bar, the corrosion depth is approx. 400 µm. On the transverse cut surface, IGC is more frequent in the fine-grained surface layer. The depth of attack exceeds 500 µm (**Figure 8**). In the peak-aged and overaged conditions, the bar's surface only exhibits pitting corrosion with a depth of about 100 µm. Besides that, corrosion spreads parallel to and beneath the surface, along the bands of coarse cathodic phases. The authors in[10] describe this type of corrosion as ELA (Exfoliation-Like Attack). On the transverse cut surface, corrosion is of the pitting type as well. It is much deeper and, again, more frequent in the near-surface areas.

Figure 10: Corrosion on the HF transverse cut surface upon ageing: a) 180 °C/4 h under-aged, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h overaged

Slika 10: Korozija na prečnem prerezu HF, po staranju: a) 180 °C/4 h podstarano, b) 180 °C/8 h, c) 180 °C/4 h + 205 °C/4 h, d) 180 °C/4 h + 220 °C/4 h prestarano

3.2.4 Corrosion tests of specimens of HF drawn and straightened bars

Surface corrosion of selected specimens in variously aged conditions is illustrated in **Figure 9**. The corrosion of the transverse cut surface is shown in **Figure 10**. Results of the evaluation of corrosion are given in **Table 7**.

Table 7: Evaluation of corrosion and hardness of samples HF
Tabela 7: Ocena korozije in trdota vzorcev HF

Sample HV5	US	Place	Corrosion depth (µm)	Corrosion type
HF-3 123	180 °C/4 h	Surface	364.9	IGC
	Under-ageing	Transverse cut	545.9	IGC, near-edge
HF-4 123.3	180 °C/8h	Surface	307.1	Pitting
	peak ageing	Transverse cut	93.6	Pitting, sporadic
HF-3B 115.4	180 °C/4 h + 205 °C/4 h	Surface	348.9	Pitting, transgranula r
	Over-ageing	Transverse cut	471.2	Pitting
HF-3A 110.3	180 °C/4 h + 220 °C/4 h	Surface	366.1	Pitting, transgranula r
	Over-ageing	Transverse cut	122.3	Pitting, sporadic

In specimens in underaged condition, there is deep IGC on the bar's surface, as well as on the transverse cut surface. In the peak-aged and over-aged conditions, the bar surface only exhibits pitting corrosion that spreads perpendicularly to the surface to a depth of more than 300 µm. It is transgranular corrosion, as it penetrates the grains. On the transverse cut surfaces, the least extensive corrosion was found in the peak-aged condition (**Figure 10b**). In the slightly-overaged condition, the corrosion is extensive and deep (**Figure 10c**). In increasingly overaged specimens, the number and depth of corrosion attack locations decrease (**Figure 10d**).

4 DISCUSSION

The main mechanism of IGC is reported to be the formation of micro-galvanic cells between cathodic more-noble phases and the depleted (precipitate-free) zones along the grain boundaries. In this case, the key cathodic phase is the Q-phase ($Al_4Mg_8Si_7Cu_2$), which precipitates along the grain boundaries. As a result, the grain-boundary areas become depleted of Cu and other elements. In addition, a thin Cu film forms along the grain boundaries and plays the key role in IGC growth and propagation.[3–6] The entire precipitation process is thermally activated and depends on the diffusion of alloying elements. Its rate is described by an Arrhenius equation. With increasing ageing temperature and time, the Q-phase precipitates coarsen and the volume fraction of the Cu film along the grain boundaries decreases. Consequently, the susceptibility to IGC is reduced and the material typically exhibits only pitting corrosion.

The EN AW-6064 alloy contains a number of other primary cathodic phases (Bi, Pb, alpha-$Al_{15}(Fe,Mn,Cu,Cr)_3Si_2$). Their arrangement in bands with short distances between the phases helps the pitting corrosion to propagate to larger depths, most notably beneath the transverse cut surface (**Figure 4d**). In some cases there were great differences between the corrosion attack on the bar's surface and on the transverse cut surface.

In the extruded bars (HA1), it was found that with increasing over-ageing the large-depth IGC changes into shallower pitting corrosion, which is in agreement with the findings presented in [3–6]. In the overaged condition, the corrosion penetrations on the transverse cut surface were smaller. Sporadic pitting corrosion with a depth of about 100 μm was found.

In the drawn bars (HB2), the transition from IGC to shallower pitting corrosion was observed as well. Unlike the specimens from bars that had not been drawn, all the specimens in this group showed very deep corrosion (more than 500 μm) on their transverse cut surfaces (**Figure 8**).

In the drawn and straightened bars (HF), another type of corrosion was observed. In the under-aged bars, IGC was found on both the bar surface and the transverse cut surface. With ongoing ageing, IGC changes into pitting corrosion, which – on the bar surface – propagates perpendicularly to the surface and by transgranular mechanism to a larger depth than the pitting corrosion in the drawn bars (**Figures 9b** to **9d**). This corrosion type corresponds to transgranular stress corrosion cracking (SCC).[14] The difference can be attributed to the variation between the internal stresses induced by drawing and straightening. Drawing typically induces tensile stress. Straightening, however, involves alternating bending loads and tensile and compressive stresses, which lead to non-uniform residual stress that promotes corrosion propagation, perpendicularly to the surface and to a larger depth. The transverse cut surface, unlike HB2 specimens, shows – in some cases – shallow sporadic pitting corrosion (**Figures 10b** and **10d**).

5 CONCLUSION

Extruded and drawn bars from the EN AW-6064A alloy were used for exploring the impact of thermomechanical treatment on intergranular corrosion (IGC). The effects of forming (drawing and straightening) and artificial ageing were mapped, along with the type of corrosion and corrosion depth on the bar surface and its transverse cross-section. The corrosion tests were carried out in accordance with EN ISO 11486 – method B.

The results of the corrosion tests show that the thermomechanical treatment affects both the type and depth of corrosion.

The bar surface exhibited three types of corrosion:

- IGC in under-aged specimens: typically extensive corrosion with a depth of more than 300 μm.
- Pitting corrosion in more aged and over-aged extruded/drawn bars, where the corrosion depth was approximately 100 μm.
- Transgranular pitting corrosion in more aged and over-aged bars that had undergone final straightening. Here, the corrosion depth was larger and exceeded 300 μm.

With more intensive ageing and over-ageing (temperature, time), IGC changed into pitting corrosion in extruded/drawn bars. There was an adverse impact of the post-drawing straightening operation on the resistance to surface corrosion in the bars, evidenced by deep transgranular pitting corrosion.

In most cases the transverse cross-sections exhibited very deep pitting corrosion with depths up to 800 μm, which followed the bands of coarse cathodic phases. Exceptions were found in severely over-aged bars (extruded or extruded and straightened), which showed sporadic pitting corrosion with depths of approximately 100 μm.

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