UDK 669.715:621.785:620.193
Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 39(4)101(2005)

THE INFLUENCE OF THE EXTRUSION PROCESS AND HEAT TREATMENT ON THE PROPERTIES OF SOME AA6XXX EXTRUDED PROFILES

VPLIV PROCESOV EKSTRUZIJE IN TOPLOTNE OBDELAVE NA LASTNOSTI NEKATERIH EKSTRUDIRANIH PROFILOV AA6xxx

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Prejem rokopisa – received: 2004-12-06; sprejem za objavo – accepted for publication: 2005-06-20

The effects of chemical compositions, the extrusion process and the heat-treatment variables on the properties of extruded profiles were investigated in three AA6xxx aluminium alloys. The tensile and corrosion properties of three heat-treatable AA6xxx aluminium alloys (AlMgSi1, AlMgSi0.7 and AlMgSi0.7Zr) in the T5 tempered condition were investigated. The influence of minor additions of Mn and Zr to an AlMgSi0.7 base alloy on the mechanical properties and corrosion behaviour in natural water was also investigated. The behaviour of the extruded profiles was compared to aluminium of commercial purity in terms of the corrosion properties in natural water.

Key word: extrusion, AA6xxx Al alloys, corrosion behaviour, effect of Zr and Mn additions

Vpliv toplotne obdelave in procesov ekstruzije ter toplotne obdelave na lastnosti ekstrudiranih profilov je bil raziskan za tri aluminijeve zlitine AA6xxx za toplotno obdelavo (AlMgSi1, AlMgSi0.7 in AlMgSi0.7Zr) v stanju T5. Določen je bil vpliv majhnih dodatkov Mn in Zr v osnovni zlitini AlMgSi0.7 na mehanske lastnosti in korozijo v naravni vodi. Korozijske lastnosti v naravni vodi ekstrudiranih profilov smo primerjali z aluminijem komercialne čistosti.

Ključne besede: ekstruzija, Al-zlitine 6xxx, korozijske lastnosti, vpliv dodatkov Mn in Zr

1 INTRODUCTION

Structural medium-strength aluminium alloys based on the Al-Mg-Si system have been popular for a wide range of applications for a long time. These alloys are widely used for decorative, architectural and structural applications[1, 2]. The development of Al-Mg-Si alloys for light structures has led to an increasing market for extrusions of intricate shape, medium strength and good toughness[3-6]. These alloys are required to meet specified tensile properties and to have good corrosion resistance, safe toughness levels and good fatigue strength, welding characteristics and formability. Also, it is desirable that the alloys have high extrudability and low quench sensitivity. The AA6xxx series alloys exhibit generally excellent corrosion resistance in rural, industrial and marine atmospheres and have an excellent stress-corrosion cracking resistance.

In the present work we investigated three age-hardening Al-Mg-Si alloys (AlMgSi1, AlMgSi0.7 and AlMgSi0.7Zr) in terms of their mechanical properties and corrosion behaviour in natural water. The effect of Zr and Mn additions on the mechanical and corrosion properties of an AlMgSi0.7 base alloy is also reported.

2 EXPERIMENTAL PROCEDURE

The chemical compositions of three tested alloys are listed in **Table 1**. The first is the typical 6082 alloy and other two are AlMgSi0.7 containing a small excess of silicon. The chemical composition of the AlMgSi0.7Zr alloy was designed to provide a higher strength in the as-T5-tempered condition (quenching in an air flow and artificial aging). Hence, the effects of small additions of zirconium and manganese on the mechanical properties and the corrosion behavior in fresh water were investigated.

Table 1: Chemical composition of the investigated alloys, *w*/%
Tabela 1: Kemična sestava raziskanih zlitin, *w*/%

	Mg	Si	Mn	Zr
AlMgSi1	1.0	0.9	0.50	
AlMgSi0.7	0.63	0.71	0.07	
AlMgSi0.7(Zr)	0.54	0.68	0.12	0.10

The alloys were semi-continuously cast into billets of 200 mm diameter and homogenized for 12 h at 570 °C. The billets of length 620 mm were extruded into rectangular rods and rectangular tubes, **Table 2**.

The billets were soaked before extrusion in a continuous pusher-type furnace, extruded at different temperatures in a hydraulic press with a direct metal flow, quenched directly on the press with blown air, cooled to room temperature (cooling installation with ventilators), stretched and artificially aged.

The temperature of the press container was 420 °C, while the billet temperature, T_{billet}, varied between 400

Table 2: Extrusion ratios, die and profile types
Tabela 2: Pogoji ekstruzije ter vrste matrice in profila

Alloy	Profil	Die	Extrusion ratio
AlMgSi1	Rectangular tube	Single-hole bridge die	64.0
	Rectangular rod	Normal die (two holes)	78.5
AlMgSi0.7 AlMgSi0.7Zr	Rectangular tube	Single-hole bridge die	74.0
	Rectangular rod	Normal die (four holes)	52.0

°C and 520 °C. During the experiment, the following parameters were measured:
- direct extrusion pressure (P_{max} and P_{min}),
- billet temperature, T_{billet},
- extruded profile temperature (against the die),
- extrusion speed (profile exit speed),
- surface quality of the extruded profiles.

After the extrusion and stretching, the profiles were aged at 160 °C and 170 °C for up to 11 h, **Table 3**.

Table 3: Parameters of artificial aging for the investigated Al-Mg-Si alloys
Tabela 3: Parametri za umetno staranje Al-Mg-Si zlitin

Alloy	AlMgSi1	AlMgSi0.7	AlMgSi0.7Zr
Conditions of artificial aging	170 °C/9^{h} 160 °C/11^{h}	170 °C/6^{h} 170 °C/9^{h}	170 °C/4,5^{h} 170 °C/6^{h} 170 °C/9^{h}

The mechanical properties and the corrosion of the profiles were determined with a standard methodology. The corrosion characteristics were determined with accelerated methods: monitoring of the corrosion potential, E_{corr}, for 3600 s, the determination of the polarization resistance values, R_{pol}, of the corrosion current, i_{corr}, of the potential, $E_{(i=0)}$, and of the corrosion rate. The investigation of the corrosion was performed with a PAR-332 system (potentiostat-galvanostat mod 273, MK-047 cell, software PAR SOFTCORR 352 II). "Instron" equipment was used to determine the tensile properties.

3 RESULTS AND DISCUSSION

3.1 Extrusion process parameters

Temperature is one of the most important parameters in extrusion. The temperature changes during the extrusion depend on the billet temperature, the heat transfer from the billet to the container, and the heat developed by deformation and friction. **Figure 1** shows the dependence of the extrusion pressures (characteristic maximum and minimum values) on the billet temperature for the AlMgSi1 and AlMgSi0.7(Zr) alloys. The extrusion pressure decreases with increasing billet temperature and the decrease of P_{min} values is smaller to that of the P_{max} changes. The extrusion load includes the

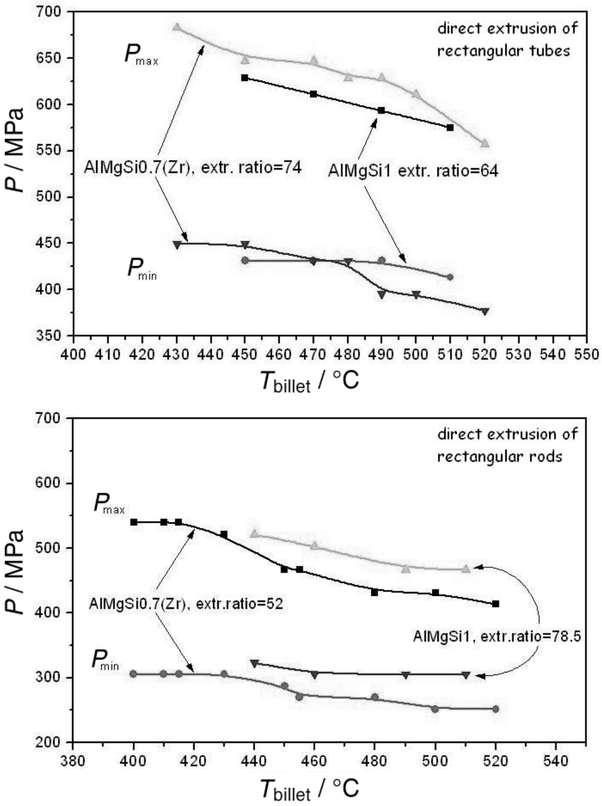

Figure 1: Dependence of the maximum pressure at the start of the extrusion (P_{max}) and the minimum pressure at the end of the extrusion (P_{min}) on the billet temperature and extrusion ratio. Extrusion of (a) rectangular tubes and (b) rectangular rods
Slika 1: Odvisnost največjega pritiska pri začetku ekstruzije (P_{max}) in minimalnega pritiska na koncu ekstruzije (P_{min}) na temperaturo gredice in razmerje ekstruzije. Ekstruzija (a) pravokotne cevi in (b) pravokotni profili

flow stress, the internal shearing losses that arise during the deformation, and losses due to the friction between the container, the die and the billet. The load arising from the friction between the container and the billet decreases linearly with decreasing billet length and, therefore, explains the typical shape of the extrusion-load displacement diagram for direct extrusion. It is characterized by a maximum at the start of the extrusion followed by a gradual load decrease to a minimum and then a steep increase at the end of the extrusion. The flow stress, as a significant part of the extrusion load, is reduced if the temperature is increased and the easier deformation produces more intensive changes of P_{max}.

The influence of the billet temperature and the extrusion ratio on the temperature of the extruded profiles (near the die exit) is shown in **Figure 2**. The profile temperature is very important for the final profile properties. The hot working is carried out at a high temperature with the aim to reduce the yield stress to a value that enables high strains to be attained economically. However, if the exit temperature, which is related to the initial billet temperature and the extrusion

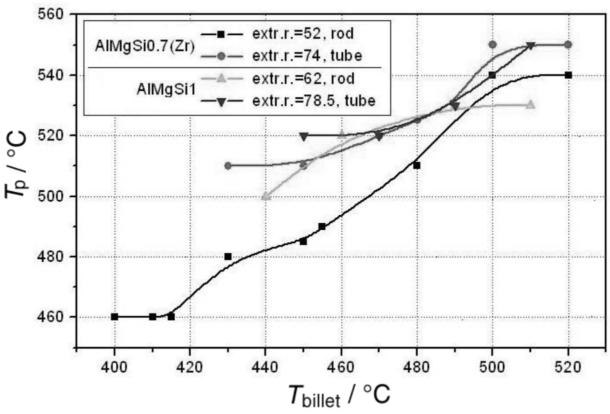

Figure 2: Temperature of profiles T_p vs. billet temperature
Slika 2: Temperatura profila T_p v odvisnosti od temperature gredice

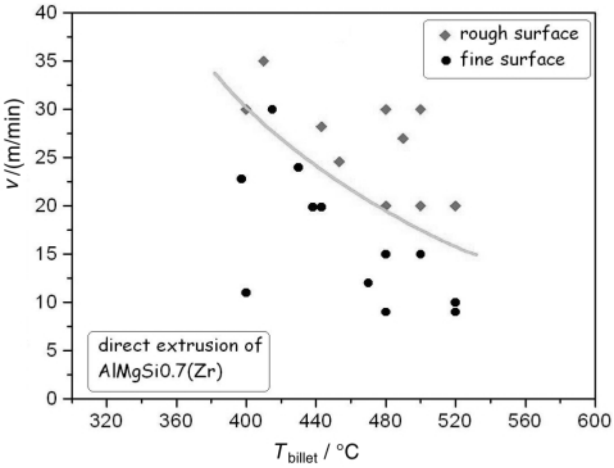

Figure 4: Maximum speed v of the profile billet temperature; direct extrusion of AlMgSi0.7(Zr) profiles
Slika 4: T_p Največja hitrost v profila proti temperaturi gredice; direktna ekstruzija AlMgSi0.7(Zr) profilov

speed, is too close to the solidus temperature, unacceptable surface tears and roughness are obtained.

The temperature difference between the end and the beginning of the profile decreases with increasing the T_{billet}. The difference is about 15 °C for the T_{billet} > 490 °C and approaches the extrusion process to isothermal conditions, **Figure 3**.

The achieved average exit speeds of the extruded AlMgSi1 profiles were about 7 m/min in the case of the rectangular tube and 16 m/min for the rectangular flat rods. These speeds correspond to approximately 30 % of the maximum available press speed. With a further increase in the profile speed, unacceptably rough profile surfaces are obtained.

With the extrusion of the AlMgSi0.7 alloy, a fine, smooth profile surface was obtained with a speed of 20–25 m/min. For a further increase of the exit profile speed a good quality of profile surface can be achieved by decreasing the billet temperature below 440 °C.

In the plot of maximum speed of profile versus the billet temperature in **Figure 4**, the "alloy limiting curve" is shown, above which the alloy AlMgSi0.7(Zr) starts to tear and form a rough surface. The area under the curve represents a combination of possible extrusion working parameters that ensure a good profile surface.

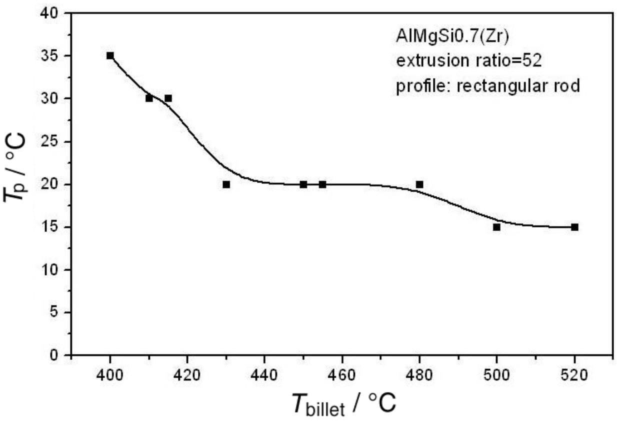

Figure 3: Influence of T_{billet} on the temperature difference between the end and the beginning of the AlMgSi0.7(Zr) profile T_p
Slika 3: Vpliv T_{billet} na razliko v temperaturi med začetkom in koncem AlMgSi0.7(Zr) profila T_p

One of the aims of this investigation was to achieve the maximum exit speeds for the profiles. During the testing, the limiting pressure value of the extrusion press (near 780 MPa) was not achieved. Accordingly, the limiting parameter in our experiment was the appropriate temperature range (left and/or down from the "alloy limiting curve") required to prevent the formation of surface defects like blackouts and surface cracks.

3.2 Mechanical properties of the profiles

The changes in the mechanical properties of the extruded profiles in the T5 tempered condition were determined in terms of their dependence on the billet temperature and several artificial aging treatments according to **Table 3**. In **Table 4** the tensile properties of the aged profiles, previously extruded at T_{billet} = 520 °C and quenched in blown air are shown.

The different quenching and aging effects are due to the differences in the content of the alloying elements. The AlMgSi0.7(Zr) profiles, aged effectively for 6 h at 170 °C, exhibited the best properties in terms of tensile strength and yield stress.

In **Figure 5** the influence of billet temperature on the mechanical properties of the tested alloys aged under selected treatments that give a higher strength is shown.

At higher extrusion temperatures better quenching effects and a greater strength of the profiles were obtained. The AlMgSi0.7(Zr) alloy is the most sensitive to the changes of billet temperature, since the achieved values of tensile strength increase from 240 MPa and 310 MPa within the selected range of T_{billet}. The other two alloys are less sensitive to quenching temperature

Table 4: Tensile properties of aged profiles, extruded at T_{billet} = 520 °C and quenched in blown air
Tabela 4: Raztržne lastnosti profilov ekstrudiranih pri T_{billet} = 520 °C in ohlajenih v toku zraka

Alloy	AlMgSi1		AlMgSi0.7		AlMgSi0.7(Zr)		
Ageing conditions	170 °C for 9^{h}	160 °C for 11^{h}	170 °C for 9^{h}	170 °C for 6^{h}	170 °C for 4.5^{h}	170 °C for 6^{h}	170 °C for 9^{h}
R_{m}/MPa	266	257	272	275	249	311	247
$R_{\mathrm{p0,2}}$/MPa	249	250	251	233	215	282	219
A/%	11	11	7	12	9	7	8

and show similar levels of yield stress. The AlMgSi1 alloy shows the lowest strength after T5 tempering due to small quenching effects connected with the relatively slow cooling rates for air quenching compared with water quenching, which is recommended for the combination of the main alloying elements. This also explains the highest level of total elongation for the AlMgSi1 profiles. The aging time substantially affects the yield stress and the elongation (**Table 4**). It is possible in this way to obtain different levels of ductility for the same level of tensile strength and to obtain a better condition for further profile machining or processing.

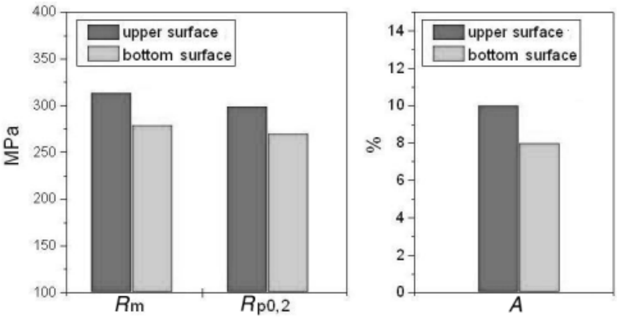

Figure 6: Influence of profile surface position, in relation to the air stream, on the mechanical properties of extruded AlMgSi0.7(Zr) profiles
Slika 6: Vpliv mesta na površini profila glede na tok zraka na mehanske lastnosti ekstrudiranih profilov AlMgSi0.7(Zr)

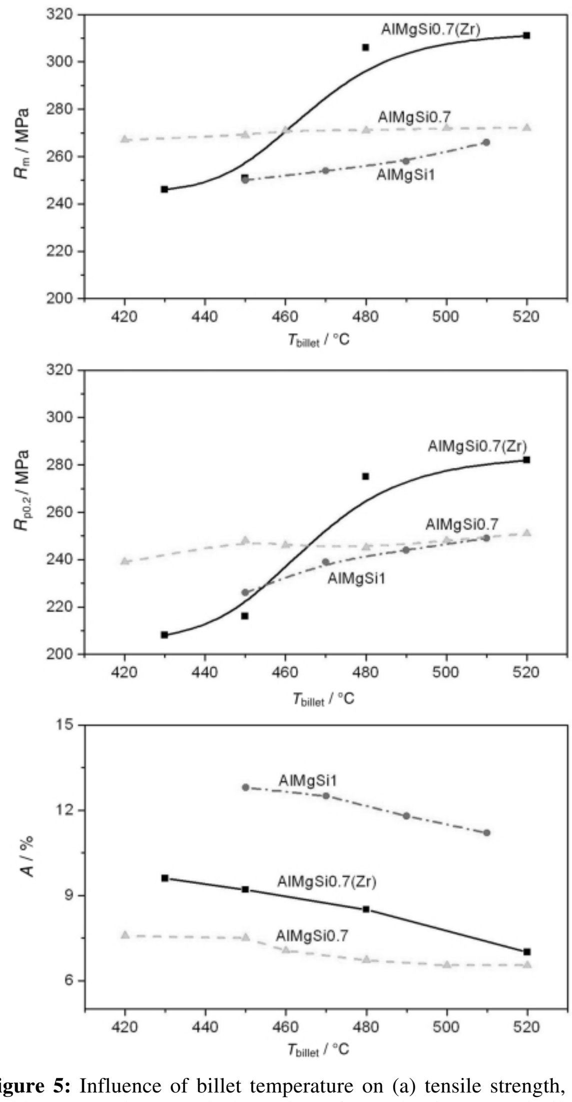

Figure 5: Influence of billet temperature on (a) tensile strength, (b) yield stress and (c) total elongation of tested T5 tempered alloys. Aging treatments: 170 °C for 6 h – AlMgSi0.7(Zr); 170 °C for 9 h – AlMgSi0.7 and AlMgSi1
Slika 5: Vpliv temperature gredice na (a) raztržno trdnost, (b) mejo plastičnosti in (c) skupni raztezek T5 toplotno obdelanih zlitin. Pogoji staranja: 170 °C 6 h – AlMgSi0.7(Zr); 170 °C 9 h – AlMgSi0.7 in AlMgSi1

Figure 6 illustrates the influence of profile surface position, in relation to the air stream, on the mechanical properties of the extruded profiles (upper and bottom sides of the rectangular tubes). On the upper surface of the profile, directly exposed to the air flow by air quenching, the alloy has a 4 % higher strength and almost 20 % better ductility than on the bottom side of the same profile.

3.3 Corrosion properties of the profiles

The corrosion behavior of the profiles in fresh natural water was investigated after T5 tempering, and the changes in corrosion potential, E_{corr}, are presented in **Figure 7**. The corrosion potential increases rapidly during the first 250 s and shows a significant rate of passivation. After 1500 s the corrosion potentials of all three Al-Mg-Si alloys increase almost linearly; however, the trend of rising of the $E_{\mathrm{corr}} = f(\tau)$ curves is low. Alloys containing higher levels of alloying elements, AlMgSi0.7(Zr) and AlMgSi1, show a 9 % lower corrosion potential than the alloy AlMgSi0.7. It is interesting that the level of E_{corr} of the tested Al-Mg-Si alloys is almost 15% higher than that for the Al99.7 sample.

Figure 8 shows the changes of potential as a function of the current for linear polarization and for poten-

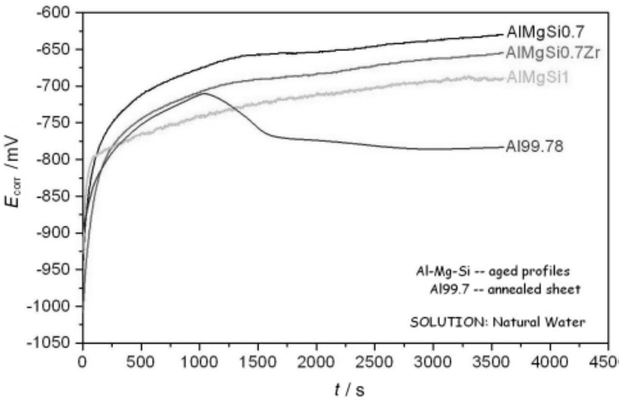

Figure 7: Corrosion potential of tested Al-Mg-Si alloys in fresh, natural water as a function of time

Slika 7: Časovna odvisnost korozijskega potenciala raziskanih Al-Mg-Si zlitin v sveži naravni vodi

tiodynamic conditions. The results obtained by the linear polarization testing show that the AlMgSi0.7(Zr) alloy has the lowest level of potential, which is about 18 % lower than that for the alloy AlMgSi0.7.

Curves of $E = f$ (current density) for the potentiodynamic conditions of corrosion testing are situated at

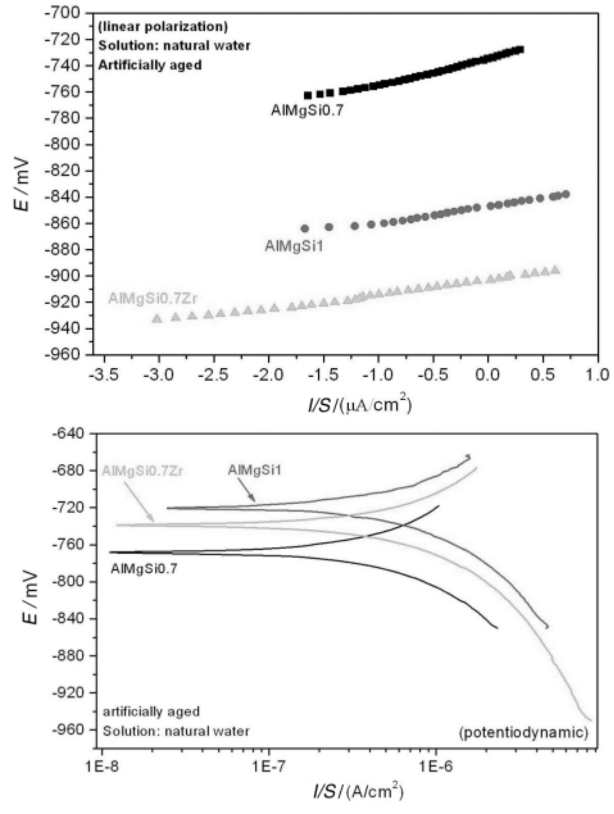

Figure 8: The influence of the current on the potential of investigated Al-Mg-Si alloys in T5 temper (a) method of linear polarization and (b) potentiodynamic method

Slika 8: Vpliv toka na potencial raziskanih Al-Mg-Si zlitin po T5 toplotni obdelavi; (a) metoda linearne polarizacije in (b) potenciodinamična metoda

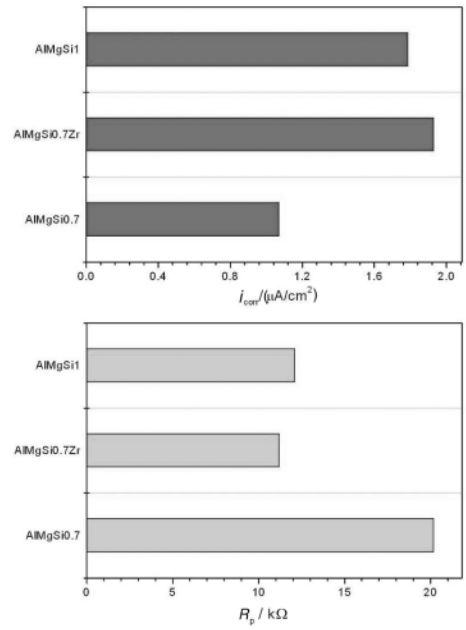

Figure 9: Corrosion current i_{corr}, and polarization resistance R_{pol} of tested alloys

Slika 9: Korozijski tok i_{corr} in polarizacijska upornost R_{pol} za raziskane zlitine

less negative values of potential when compared to the case of linear polarization. The lowest level of potential, as a function of the current, was found for the base AlMgSi0.7 alloy; however, the difference of the parameter between the tested alloys is small, only about 4 %.

The measured values of corrosion current, i_{corr}, and the polarization resistance, $R_{pol,}$ are shown in **Figure 9**. The alloy AlMgSi0.7 shows the lowest i_{corr} and the highest R_{pol}. The other two alloys show slightly higher values for i_{corr} and lower for R_{pol}, which represents a good combination of corrosion characteristics.

Table 5: Corrosion rate of investigated extruded profiles in T5 temper

Tabela 5: Hitrost korozije raziskanih ekstrudiranih profilov po T5 toplotni obdelavi

	AlMgSi1	AlMgSi0.7	AlMgSi0.7Zr
Corrosion rate per year /(g m^{-2})	1.96	1.18	2.12
i_{corr} /(μA/cm^2)	1.79	1.074	1.933
R_{pol} /kΩ	12.13	20.22	11.24

Table 5 presents the corrosion rate as mass loss per year. The corrosion rates of the tested alloys correspond to the changes of corrosion current: the lowest mass loss is found for the base alloy AlMgSi0.7. The small addition of Zr and Mn causes an increase in mass loss per year; however, the loss level of 2 g/m^2 year is more than acceptable compared to other structural materials.

The alloy AlMgSi0.7(Zr) shows the same corrosion properties as the AlMgSi1 alloy, particularly the corrosion rate, polarization resistance and corrosion current, and significantly better tensile strength and yield stress, while retaining a good ductility. The AlMgSi0.7(Zr) alloy contains less magnesium, silicon and manganese as the main alloying elements and is suitable for the more economical air-flow quenching.

The base alloy AlMgSi0.7, with the smallest content of alloying elements, shows the same strength and ductility as the AlMgSi1 alloy and almost two times lower values of mass loss per year and polarization resistance. The small addition of zirconium and manganese to the base AlMgSi0.7 alloy ensures significantly higher tensile strength and yield stress by acceptably decreasing the corrosion properties. The alloys AlMgSi0.7 and AlMgSi0.7(Zr) offer a wide range of combinations of good mechanical and corrosion properties suitable for a wide range of profile applications.

4 CONCLUSION

The influence of small additions of Zr (0.1 %) and Mn (0.12 %) to an AlMgSi0.7 base alloy containing a small excess of Si on the tensile and corrosion properties was investigated and compared to the properties of AlMgSi1 extruded profiles after T5 tempering. The addition of zirconium and manganese significantly increases the strength, reaching 310 MPa of tensile strength, while the alloy AlMgSi1 achieved a lower strength in the same processing conditions (air quenching). The corrosion behavior in fresh, natural water of all the tested Al-Mg-Si alloys is very satisfactory, though the increase of alloying elements content caused a small deterioration. The AlMgSi0.7(Zr) alloy has the most favorable combination of tensile and corrosion properties and is capable of using the more economical air-flow quenching. The small addition of zirconium and manganese to the base AlMgSi0.7 alloy ensures significantly higher tensile strength and yield stress, which is, however, connected to an acceptable decrease of the corrosion properties. The alloys AlMgSi0.7 and AlMgSi0.7(Zr) offer a wide range of combinations of good mechanical and corrosion properties, suitable for a wide range of profile applications.

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