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THE DUCTILITY AND CORROSION PROPERTIES OF SOME AA5XXX AUTO BODY SHEETS

DUKTILNOST IN KOROZIJSKE LASTNOSTI NEKATERIH PLOČEVIN AA5XXX ZA AVTOMOBILSKE KAROSERIJE

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An investigation of the ductility and corrosion properties of some AlMg4.5 alloys as well as their dependence on some parameters of the thermomechanical processing is presented. The effect of the cold rolling on work hardening and earing behavior of some AA5xxx alloy sheets was analyzed. The sheet-forming ability increases with the increase in the content of alloying elements. The effect of softening during the paint-bake process is influenced by e.g. the alloy composition and can be reduced by adding a small amount of other alloying elements (Cu). The corrosion characteristics of the investigated AA5xxx sheets are comparable to (or better) than the Al99.78 T0 sheet properties. The most favorable combination of ductility, softening behavior and corrosion properties is shown by the 5182 alloy with the addition of Mn, Zn and Cu.

Key words: auto-body, AlMg4.5 alloy, hardening, softening, corrosion

Opisana je raziskava duktilnosti in korozijskih lastnosti zlitin AlMg4,5 in njihovih odvisnosti od parametrov termomehanske obdelave. Analiziran je vpliv deformacijske utrditve na ušesenje nekaterih pločevin AA5xxx. Oblikovalnost pločevine raste z vsebnostjo legirnih elementov. Učinek mehčanja med žganjem barve je odvisen od sestave zlitine in ga je mogoče zmanjšati z dodatkom majhne količine drugih legirnih elementov (Cu). Korozijske značilnosti pri raziskani zlitini AA5xxx so primerljive (ali boljše) kot pri pločevini TO Al 99,78. Najboljšo kombinacijo duktilnosti, mehčanja in korozijskih lastnosti ima zlitina 5182 z dodatkom Mn, Zn in Cu.

Ključne besede: avtomobilska karoserija, zlitina AlMg4,5, utrditev, mehčanje, korozija

1 INTRODUCTION

The need to reduce the weight of vehicles, improve their fuel economy and reduce their exhaust emissions has led to the increased use of lightweight materials such as aluminum alloys. Aluminum alloys have found applications in the more classical design of high-volume vehicles, competing with zinc-coated steels, particularly for the car body. In recent years, research has focused on materials that would result in improved mechanical capabilities and reduced manufacturing costs[1-6]. AA5xxx aluminum alloys are widely considered for such applications in the automotive industry, they tend to be used for interior structural applications because of their high formability, suitability for adhesive bonding, weldability and good corrosion resistance[7,10]. This paper discusses the effect of cold rolling on work hardening and earing behavior of some AA5xxx alloy sheets. The mechanical behavior of these alloys was investigated using tensile and different sheet-formability tests in annealed, hardened and recovered tempers. The effects of the heat treatment during the simulation of the auto-body paint-baking process are described. The corrosion characteristics of the tested AA5xxx sheets in annealed and recovered tempers are also presented.

2 EXPERIMENTAL PROCEDURES

The sheets of 1.25-mm thickness were produced in the three chemical compositions, listed in **Table1**. The investigated sheets were produced in the laboratory of the University of Montenegro, MTM Department. Cast plates (h×b×l=10×100×200 mm) were homogenized at 470-510 °C (depending on chemical composition) for four hours and cold rolled (with intermediate annealing) to their final thickness, see **Figure 1**. The mechanical testing involved hardness tests, tensile tests to determine the S value[11], cup drawing tests ($\beta = 2$), biaxial tool-stretching and hydraulic bulging. Scanning electron microscopy was used to investigate the fracture surfaces. The corrosion characteristics were determined using accelerated methods: monitoring of the corrosion potential E_{corr} for 3600 seconds; determining the values of the polarization resistance R_p, corrosion current i_{corr}, and potential $E_{(I=0)}$. The corrosion investigations were performed using the PAR-332 system (potenciostat-galvanostat model 273; MK-047 cell, SCE), natural water and the solution of NaCl (0.51 mol). At the same time the corrosion characteristics of Al99.78 annealed sheets were monitored in order to compare them with the Al-Mg alloys.

Table 1: Chemical compositions of the investigated alloys
Tabela 1: Kemična sestava raziskanih zlitin

Type of alloy	Chemical composition, % (wt)					
	Mg	Zn	Cu	Mn	Fe	Si
AlMg4.5Mn	4.23	0.02	0.015	0.42	0.26	0.13
AlMg4.5MnZnCu	4.03	0.34	0.16	0.43	0.24	0.22
AlMg4.5Zn1.5MnCu	4.00	1.31	0.18	0.21	0.22	0.21

3 RESULTS AND DISCUSSION

The thermomechanical process for the laboratory production of Al-Mg sheets of 1.25-mm thickness is presented in **Figure 1**. The mechanical properties of the sheets in their final annealed state vs. alloying-elements' content are shown in **Figure 2**.

The hardness, tensile properties and formability index S increase with increasing amount of alloying elements. The 1.25-mm thick sheets of thickness were tested under biaxial stretching conditions with hemispherical and cylindrical tools. The hydraulic bulging test was also performed. The micro-appearance of the fracture surfaces after biaxial stretching is presented in **Figure 3**. The photographs of the fracture surfaces of sheets after hydraulic and hemispherical punch stretching as well as the values of IE_{27} and H_{bulge} illustrate the ductile properties of the sheets in the annealed temper. The place of the fracture, indicated in the sketch, is near the top of the bulge. The surface of the fracture occurred in an area between the wall and the bottom of the cup is also presented. This is the area of poor ductility near the plain-strain state, and the micrographs show characteristic surfaces of shear fracture.

The changes in the corrosion potential E_{corr} of the annealed and recovered (20% of cold rolling and annealing at 180 °C for 1h) Al-Mg alloy sheets in natural water are presented in **Figures 4 and 5**, respectively.

All three of the Al-Mg alloys show more positive values of E_{corr} than the Al99.78 T0 sheet. The tested materials exhibit peaks on the E_{corr}-time curves. After rising to the peak values the E_{corr} decreases and after 2000 seconds it stabilizes to an almost constant level.

The effect of the chemical composition on the final value of E_{corr} after 3600 seconds is presented in **Figure 6**. The recovered sheets show more negative values of corrosion potential than the annealed ones, but they are still higher than those of the Al99.78 T0 sheet. The increasing content of alloying elements causes the E_{corr} to decrease, particularly in the recovered temper.

The results of monitoring the E_{corr} of the Al-Mg sheets in 0,51 mol NaCl solution are presented in **Figure 7**. The final values of E_{corr} also decrease with increasing amounts of alloying elements, and there are small differences between the annealed and the recovered

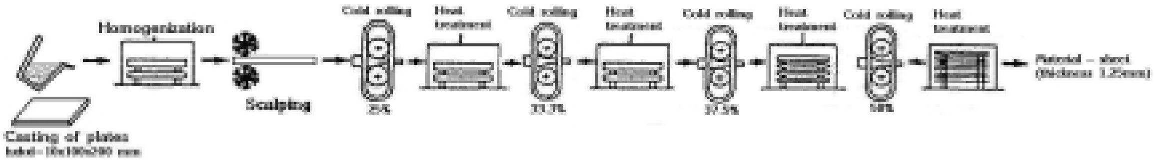


Figure 1: The technological scheme of laboratory production of Al-Mg sheets of 1.25 mm thickness
Slika 1: Tehnološka shema laboratorijske izdelave pločevine z debelino 1,25 mm

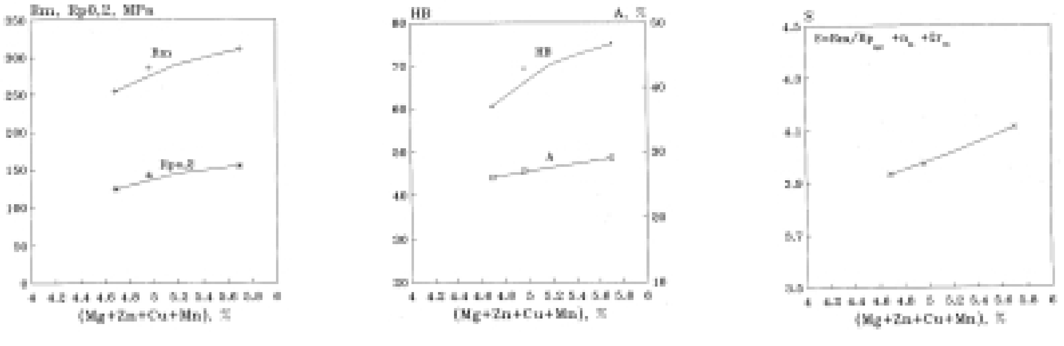


Figure 2: The influence of alloying elements' content on (a) tensile strength and yield stress, (b) hardness and elongation, (c) formability index S of final annealed Al-Mg sheets of 1.25 mm thickness

Slika 2: Vpliv vsebnosti legirnih elementov na (a) raztržno trdnost in mejo plastičnosti, (b) trdoto in raztezek, (c) indeks oblikovalnosti S za končno žarjene Al-Mg pločevine z debelino 1,25 mm

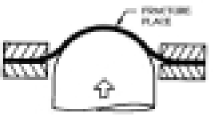
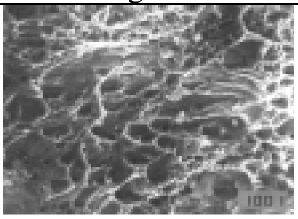
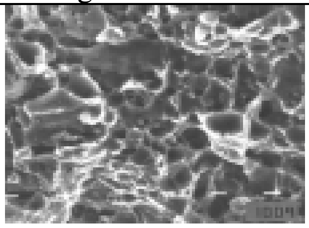
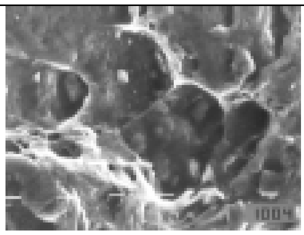
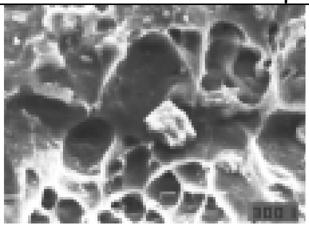
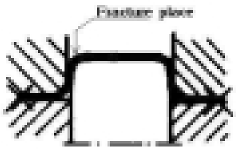
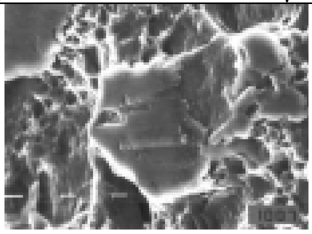
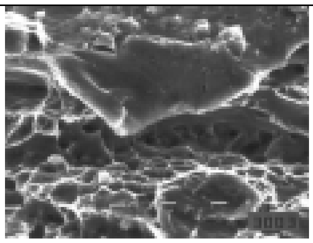
Stretching method	AlMg4.5Mn	AlMg4.5Zn1.5MnCu
 Hemispherical punch	 IE_{27}=9 mm wm=20µm	 IE_{27}=9.8 mm wm=10 µm
 Hydraulic pressure	 H_{bulge}=29 mm wm=10 µm	 H_{bulge}=33 mm wm=10 µm
 Cylindrical punch (deep drawing)	 ε_1=0.20; ε_2=0.009 wm=10 µm	 ε_1=0.23; ε_2=0.009 wm=10 µm

Figure 3: The micro-appearance of the fracture surfaces after biaxial stretching with hemispherical and cylindrical punches and under hydraulic pressure. IE_{27} max. stretching depth, H_{bulge} - max. "bulge" height, ε_1 - major strain, ε_2 - minor strain in the plane of the sheet. WM - white mark (line) on the photo

Slika 3: Mikroskopska oblika prelomne površine po biaksialnem raztezanju s polkroglastim in valjastim trakom in hidravličnim pritiskom. IE_{27} največja globina deformacije, H_{bulge} - največja višina izločanja, ε_1 - največja deformacija, ε_2 - najmanjša deformacija v ravnini pločevine. WM - beli znaki (črte) na posnetku

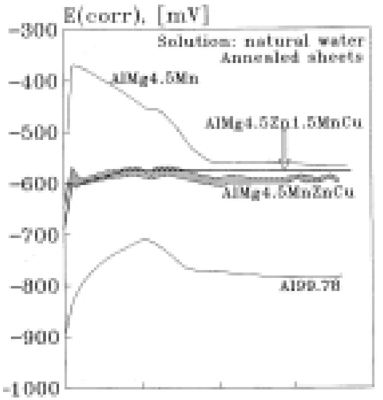


Figure 4: Corrosion potential as a function of of time and type of Al-Mg annealed sheets in natural water

Slika 4: Korozijski potencial v odvisnosti od časa za različne žarjene pločevine Al-Mg v naravni vodi

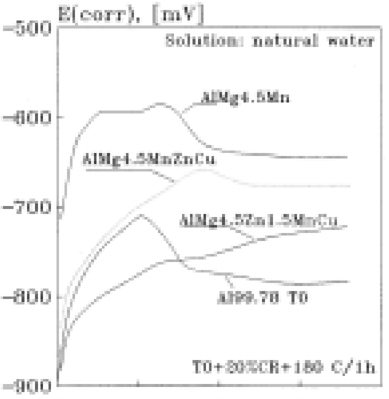


Figure 5: Corrosion potential as a function of time and type of Al-Mg recovered sheets in natural water

Slika 5: Korozijski potencial v odvisnosti od časa za različne popravljene pločevine v naravni vodi

Table 2: Values of R_p, i_{corr}, and $E_{(I=0)}$ of annealed and recovered Al-Mg sheets in natural water and a solution of 0.51 mol NaCl.
Tabela 2: Velikost R_p, $i_{kor.}$ in $E_{(I=0)}$ za žarjene in popravljene pločevine Al-Mg v naravni vodi in 0,51 mol raztopini NaCl

Type of alloy	Temper	Natural water			Solution of 0.51mol NaCl		
		R_p, kΩ	i_{corr},μA/cm^2	$E_{(I=0)}$mV	R_p, kΩ	i_{corr}, μA/cm^2	$E_{(I=0)}$, mV
AlMg4.5Mn	Annealed	119,00	0,18	-555	4,53	4,8	-736
AlMg4.5MnZnCu		56,56	0,38	-665	5,26	4,32	-737
AlMg4.5Zn1.5MnCu		92,93	0,23	-681	6,00	4,12	-770
AlMg4.5Mn	Recovered	69,46	0,31	-662	7,23	3,0	-724
AlMg4.5MnZnCu		73,83	0,29	-751	5,15	4,22	-738
AlMg4.5Zn1.5MnCu		25,1	0,86	-817	4,70	4,61	-769
Al99.78	*Annealed*	***106,32***	***0,20***	***-771***	***13,00***	***2,86***	***-800***

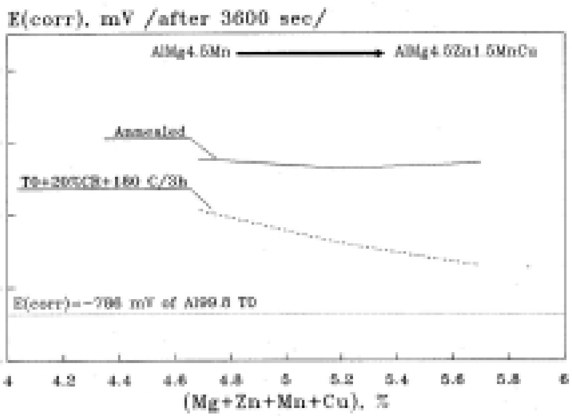


Figure 6: The effect of chemical composition on the final value of E_{corr} (after 3600 seconds) of the annealed and recovered Al-Mg sheets in natural water. The value of final E_{corr} of the Al99.78 T0 sheet is indicated by the dotted line

Slika 6: Vpliv kemijske sestave na končno vrednost E_{corr} (po 3600 sekundah) za žarjeno in popravljeno pločevino v naravni vodi. Končna vrednost E_{corr} za pločevino Al 99,78 TO je označena s prekinjeno črto.

Al-Mg sheets. The levels of E_{corr} are comparable with the range of the corrosion potential of Al99.78 T0 sheet in 0.51 mol NaCl solution.

The values of R_p, i_{corr}, and $E_{(I=0)}$ for the tested annealed and recovered Al-Mg sheets in natural water and a solution of 0.51 mol NaCl are presented in **table 2**. The values of R_p and $E_{(I=0)}$ decrease with an increasing of

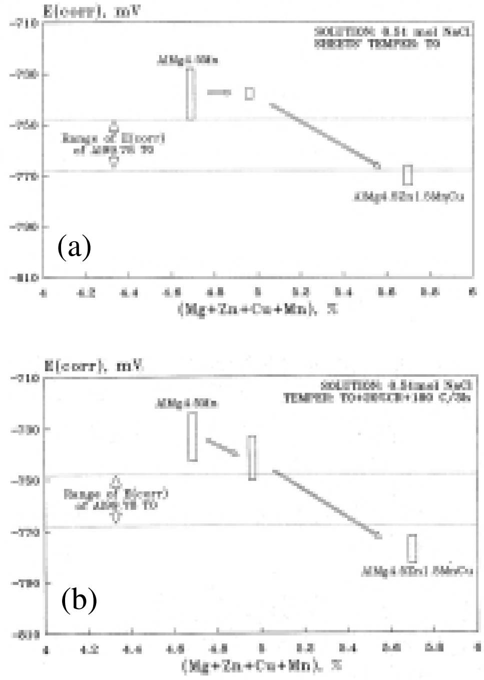


Figure 7: The effect of chemical composition on the final value of E_{corr} (after 3600 seconds) of the (a) annealed and (b) recovered Al-Mg sheets in 0.51mol NaCl solution. The range of final E_{corr} of the Al99.78 T0 sheet is indicated by the dotted lines

Slika 7: Vpliv kemijske sestave na končno velikost E_{corr} (po 3600 sekundah) za (a) žarjeno in (b) popravljeno pločevino Al-Mg v 0,51 mol raztopini NaCl. Končna velikost za E_{corr} za pločevino Al 99,78 TO označuje prekinjena črta.

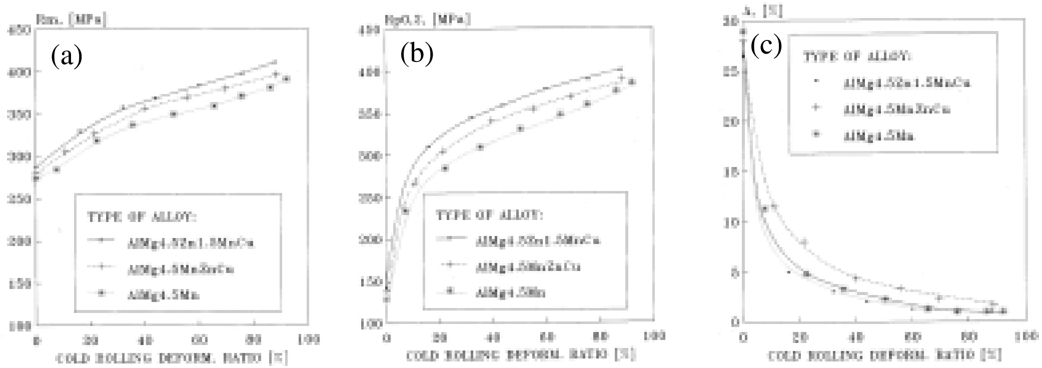


Figure 8: The influence of cold rolling reduction on (a) tensile strength, (b) yield strength, (c) elongation
Slika 8: Vpliv deformacije pri hladnem valjanju na (a) raztržno trdnost, (b) mejo plastičnosti, (c) raztezek

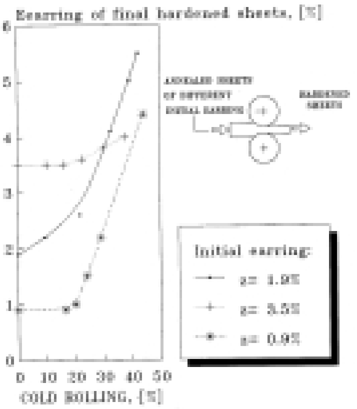


Figure 9: The influence of the cold rolling on the earing of the hardened Al-Mg sheets
Slika 9: Vpliv hladnega valjanja na ušesenje utrjene pločevine Al-Mg

alloying elements' content. The values of $E_{(I=0)}$ for the tested Al-Mg alloys are more positive than those of the Al99.78 T0 sheet. The value of i_{corr} increases with increasing amounts of alloying elements and they are close to the appropriate Al99.78 T0 values.

The influence of the cold rolling reduction on the mechanical properties of the investigated alloys is shown in **Figure 8**. Changes to the mechanical properties during the cold rolling represent the usual behavior of metal sheets: an intensive work hardening with an increase in strength and a decrease in the elongation after the first 20% of reduction. The initial differences in the properties, as result of alloying, remain in the whole cold-rolling reduction range.

The influence of cold rolling on the earing of the hardened sheets is presented in **Figure 9**. Annealed sheets of different initial earing were rolled to give a 40% reduction and then tested using the Swift deep-drawing test. The earring significantly increases as a rolling reduction of more than 20% is applied. The influence of the cold rolling between the two heat treatments on the earing of the annealed sheets is presented in **Figure 10**. Annealed sheets of different initial earring were cold rolled up to 75% reduction and subsequently annealed. The cold rolling and subsequent annealing of the sheets with high initial ears causes the ears to be reduced. In the case of a sheet with a low initial earring, a cold rolling that results in a more than 40% reduction increases the ears.

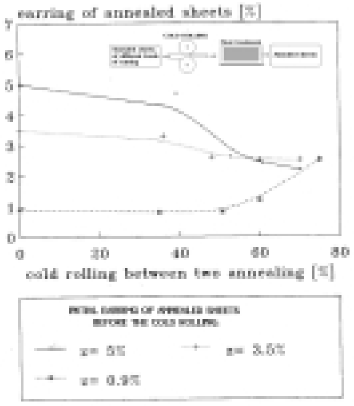


Figure 10: The influence of the cold rolling between the two heat treatments on the earing of annealed Al-Mg sheets
Slika 10: Vpliv hladnega valjanja med dvema toplotnima obdelavama na ušesenje žarjene pločevine Al-Mg

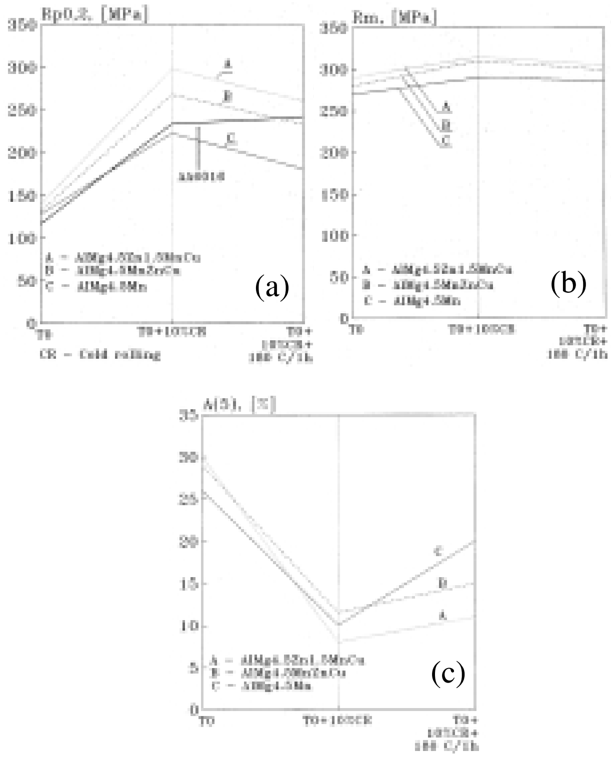


Figure 11: The influence of the paint-bake simulation treatment (annealing at 180 °C/1^h after 10% of prestrain) on (a) yield stress, (b) tensile strength and (c) elongation of Al-Mg prestrained sheets. Note: The curve of AA6016 is taken from ref. /7/
Slika 11: Vpliv žarjenja za simulacijo žganja barve (žarjenje pri 180 °C 1 uro po 10-odstotni deformaciji) na (a) mejo plastičnosti, (b) raztržno trdnost in (c) raztezek deformirane pločevine. Opozorilo. Krivulja za AA6016 je iz ref. /7/.

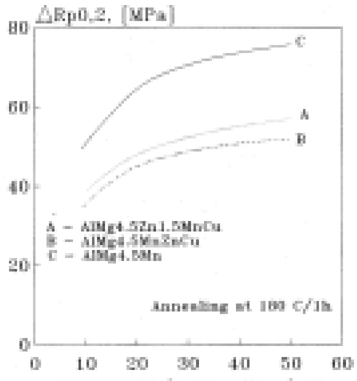


Figure 12: The effect of prestrain on the degree of softening of Al-Mg sheets
Slika 12: Vpliv deformacije na stopnjo mehčanja pločevine Al-Mg

The influence of the paint-bake simulation treatment (annealing at 180 °C for 1^h) on the tensile properties of the 10% prestrained sheets is presented in **Figure 11**. The yield strength of the prestrained sheets decreases during the annealing as a result of the high diffusivity of the Mg atoms, which allows an easy dislocation rearrangement. Also, the high level of stored energy from the extensive work hardening provides a large driving force for the thermal recovery and the softening[8]. The addition of Zn and Cu reduces the softening effects in comparison with the basic AlMg4.5Mn alloy. The tested alloy AlMg4.5Zn1.5MnCu, compared to the age-hardenable AA6016 [7] alloy, shows a slightly higher value of $R_{p0,2}$ in the final condition, **Figure 11a**.

The effect of prestrain on the degree of softening defined by the decrease in flow stress after a paint-bake simulation is presented in **Figure 12**. The slope of the curves is similar to the work-hardening curves of the cold rolling. The addition of Zn and Cu significantly decreases the effects of softening during the paint-bake treatment.

4 CONCLUSION

The ductility of the tested Al-Mg sheets increases with increasing alloying elements' content in the investigated ranges. The corrosion characteristics of the tested AA5xxx sheets in the annealed and the recovered tempers are comparable, or better than, the Al99.78 T0 sheet's corrosion properties. This is the typical behavior for metal sheets during cold rolling, and a low level of anisotropy can be successfully controlled by appropriate thermomechanical processing parameters. The effect of softening during the paint-bake process is influenced by alloy composition and can be reduced by addition of small amounts of other alloying elements (Cu). The most favorable combination of ductility, softening behavior and corrosion properties is shown by the 5182 alloy with the addition of Mn, Zn and Cu.

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