COMPARATION OF CORROSION AND MECHANICAL PROPERTIES OF COMMERCIAL AND RECYCLED 6060 AND 6082 ALUMINIUM ALLOYS

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Although the same quality of various metals from the recycling process is considered for granted, obtaining aluminum of high purity and aluminum alloys with identical properties as from production from pure raw materials is a very challenging process, especially if the sources for recycling are numerous materials that contain different impurities. In this study, recycled alloys were produced by melting of aluminum scrap with the addition of the required components. This paper aims to compare two commercial Al alloys with their analogs from the recycling process. Both of the alloys belong to the aluminum series 6000, with designations 6060 and 6082. The results of comparing corrosion and physical characteristics are presented in this study. Physical characterization was performed by measuring the alloys' hardness and electrical conductivity. The electrochemical investigation used several corrosion methods, OCP (open circuit potential), measuring polarization curves in apparent Tafel region with extrapolation of results, and LRP (linear polarization resistance). The corrosion environment was acidulated 0.5M Na_2SO_4 with pH=2.5. The received results have confirmed insignificant differences between the properties of the commercial and alloys produced by the recycling. Recycled alloys have achieved almost identical mechanical properties and even slightly better corrosion characteristics, which was the consequence of the lower concentration of impurities in recycled alloys or higher concentration of microalloying components.

Keywords: recycling, aluminium alloys, corrosion, Tafel extrapolation, linear polarization resistance

Introduction

Aluminum (lat. aluminum), one of the most commonly used metals today with about 8% in the earth's crust, is the most abundant of all metals, and after oxygen (46.7%) and silicon (27.7%), it is the most abundant chemical element [1-3]. Due to its good characteristics (low density, good plasticity, satisfactory mechanical strength, high thermal and electrical conductivity) and wide range of uses, aluminum is the most used metal in the world after steel [4]. Aluminum alloys are also often used in deep sea work where light components and good mechanical properties are required [5]. Aluminum and its alloys are used in almost all branches of industry. Aluminum, unlike other metals, can be recycled many times without significant changes in important characteristics. Primary aluminum production remains a vital part of the US aluminum supply chain, more than 80% of US production today is in the production of recycled (or secondary) aluminum [5]. New aluminum products can be made 100% from recycled aluminum with energy savings of up to 95% compared to obtaining aluminum from bauxite [1-6].Secondary aluminum-based raw materials, given that they do not contain traces of corrosion or lead, do not have a harmful effect on the environment and do not require special measures for storage in warehouses or protective measures for collectors [7].

The 6000 series alloys are versatile, heat treatable, highly formable, weldable, and have moderately high strength along with excellent corrosion resistance. Alloys in this series contain silicon and magnesium in order to form magnesium silicide in the alloy [8]. In addition to these two main alloying elements, manganese and other elements are most often found in alloys, depending on the type of alloy. The 6000 series of alloys belongs to the group of aluminum alloys that are subject to thermomechanical treatment and are therefore used today mostly in the automotive and construction industries [3].

The 6000 series alloys contain silicon and magnesium in approximately the proportions required to form the magnesium silicide (Mg_2Si) phase [9-10].

Aluminum is resistant to corrosion due to the formation of an extremely stable oxide film on its surface, which makes aluminum alloys protected and useful for application in various corrosive environments [11-13]. However, the presence of aggressive ions and the presence of particles of the second phase in the matrix can lead to local corrosion. These alloys may be susceptible to intergranular corrosion (IGC), which is assumed to be caused by Si concentrations greater than the Mg_2Si ratio [11]. Aging precipitates and grain boundaries are considered the most desirable initiating sites for corrosion processes in Al-Mg-Si alloys [10-12].

The aim of this research was the comparative characterization of corrosion and physical properties of alloys 6060 and 6082 of commercial quality and alloys obtained by recycling. The process of obtaining alloys by recycling included: separating aluminum from other metals, melting and casting ingots into graphite molds.

Materials and methods

The melting process was carried out in a Heraeus K 1150/2 furnace (voltage 380 V, power 5 kW). During the melting process, the composition was corrected in order to obtain alloys of standard composition. Homogenized annealing, in order to eliminate internal stresses, was performed in an electric resistance furnace with a chamber. The plastic processing was carried out by the rolling process at a total degree of deformation of 70%.

Chemical characterization of the samples was done using the XRF method (Roentgen Thermo Scientific Niton KSL3t-900: Niton, Palomar, Model: Niton KSL3t-900 Series). Tensile strength and elongation tests were performed on a universal tensile, compression and bending testing machine of the "Mohr + Federhaf + Losenhansen" type - Mannheim. The hardness was measured on the "VEB Leipzig" hardness tester, using the Vickers method.

The electrochemical characterization of the alloys was performed using the following methods: open circuit potential (OCP), linear polarization resistance (LPR), and Tafel extrapolation in an electrochemical cell with three electrodes (working, reference, and counter).Measurements were performed on potentiostat/galvanostat Interface 1000 (Gamry Instruments Inc.) and Gamry Framework software. For analysis of the results and determination of the results and determine corrosion parameters, the Gamry Echem Analyst software package was used. The area of each working electrode was 0.50 cm^2. A platinum sheet with a surface of 1 cm^2 was used as a counter electrode. The potential of the working electrodes was measured relative to a saturated calomel reference electrode (SCE).

The tests were performed in a solution of sodium sulfate (Na_2SO_4), concentration 0.50 mol/dm^3 + 1 ml concentrated H_2SO_4 in the aim to obtain pH~2.50 (measured value pH=2.52). Before each measurement, after SiC grinding (series of papers up to 1 200), the sample was polished using 0.5μm diamond paste. The experiments were performed at a temperature of 25±1 °C, by the use of thermostated cell. Open circuit potential (OCP) was measured over 60 minutes. LPRhas been measured at potentials ±20 mV with respect to OCP, at a potential change rate of 0.167 mV/s. Tafel polarization curves were measured at potentials of ±200 mV with respect to OCP at a potential change rate of 1 mV/s.The results of measuring OCP and LPR are given mainly in tabular form as the results of the analysis using the above-mentioned software, with the default settings.

Results and discussion

Chemical compositions of recycled and standard AlSi1MgMn (6082) and AlMnSi0.5 (6060) alloys are shown in Table 1. In Table 2 mechanical properties of these alloys are presented.

Table 1 Chemical compositions of recycled and standard AlSi1MgMn (6082) and AlMnSi0.5 (6060)

Elements,	AlSi1MgMn (6082)		AlMnSi0.5 (6060)	
[%]	With recycled Al	EN AW-6082	With recycled Al	EN AW-6060
Zn	0.115	max. 0.20	0.010	
Cu	0.042	max. 0.10	0.012	max. 0.1
Fe	0.354	max. 0.50	0.174	0.1-0.3
Mn	0.453	0.40-1.00	0.006	max. 0.1
Mg	0.696	0.6-1.20	0.594	0.35-0.6
Cr	0.012	max. 0.25	<0.003	max. 0.05
Ni	0.012		0.028	
Al	97.32	min. 95.25	98.60	97.85-99.05
Si	0.807	0.7-1.3	0.490	0.3-0.6
Ti	0.010	max. 0.10	0.005	max. 0.1
V	<0.003		0.014	
Pb	0.019		<0.003	
Co	0.099		<0.003	
Sn	<0.003		<0.003	
Zr	<0.003		<0.003	
Other	Zn: 0.01 Ni: 0.028 V:0.014 Total: 0.052	Each: 0.05 Total: 0.15	Zn: 0.01 Ni: 0.028 V:0.014 Total: 0.049	Each: 0.05 Total: 0.15
Σ	100.00	100.00	100.00	100.00

From Table 1, it can be concluded that the chemical composition of alloys 6060 and 6082 obtained by recycling is in accordance with EN AW-6082 and EN AW-6082 standards, respectively. Content of aluminium in alloy 6082 is almost 2% higher than the minimum, and in alloy 6060, it is almost 1%.

Table 2 Mechanical properties of recycled and commercial AlSi1MgMn (6082) and AlMnSi0.5 (6060)

	Tensile strength Rm, $[N/mm^2]$	0.2% proof strength $Rp_{0.2}$, $[N/mm^2]$	Min. elongation at Fracture A, [%]	Brinell hardness, [HB]
AlSi1MgMn (6082) (with recycled Al)	293	242	11	65
AlSiMgMn (6082) (commercial)	290	250	12	62
EN AW-6082	270-310	200-260	12	58-70
AlMnSi0.5 (6060) (with recycled Al)	170	145	7	65
AlMnSi0.5 (6060) (commercial)	180	140	8	68
EN AW-6060	170-190	140-150	8	70

The results of testing the mechanical properties of commercial aluminum alloys and alloys obtained by using recycled aluminum indicate that remelting does not significantly affect the change in the mechanical characteristics of the tested alloys. The measurement results for OCP, Tafel slopes and coefficient B used to determine the corrosion current from the LPR measurement results, for alloys 6060 and 6082, are given in Table 3.

Table 3 Tafel slopes, coefficients of the Stern-Geary equation (B) and OCP in 0.5M Na_2SO_4+ 1 ml conc. H_2SO_4, pH = 2.5 at 25 °C for recycled and commercial AlSi1MgMn (6082) and AlMnSi0.5 (6060) alloys

Alloys	β_a, [mV/dec]	β_k, [mV/dec]	B, [mV]	OCP, vs. SCE, [mV]
AlSi1MgMn (6082) (with recycled Al)	102.4	−150.0	60.86	−552.4
AlSiMgMn (6082) EN AW-6082	117.2	−116.4	58.40	−565.6
AlMnSi0.5 (6060) (with recycled Al)	68.2	−126.8	44.35	−569.8
AlMnSi0.5 (6060) EN AW-6060	75.9	−128.0	47.65	−583.0

From Table 3, it can be observed a very high similarity of the Tafel slopes for the same alloy, regardless of whether it was obtained by recycling or not. The consequence is the great similarity of the parameter B (in mV) between the recycled and commercial alloy in both cases. In alloy 6060, coefficient B has a value in the region of 45 to 50 mV, which is relatively close to pure aluminum [6], and therefore logical because the alloy contains 98-99% Al. Alloy 6082 has a slightly lower Al content ranging between 95 and 98%, which is also close to pure aluminum, and the higher coefficient B (about 60 mV) is due to alloying elements.These values for B are marginally lower than about 80 mV for the pure Al in 0.5M H_2SO_4 [14,15]. The differences in open circuit potential between the recycled and commercial alloys are small and are close for all tested alloys.

Figure 1 shows polarization curves in the Tafel region for two recycled and two commercial 6000 series alloys.

In figure 1 a high uniformity for all alloys can be seen. The corrosion potentials of recycled and commercial alloy 6060 are very close, while for alloy 6082 the difference is slightly larger and amounts to almost 30 mV. In absolute terms, it is still a small difference, although it appears significant in the picture.

The closeness of the corrosion current values, which are about 3 $\mu A/cm^2$, can be observed for all tested alloys. The precise data are given in Table 4. An extremely high similarity is also observed in the shape of the curve; thus, the recycled 6082 and 6060 commercial alloys have almost identical shapes. The anodic portions of the polarization curves are similar for all alloys, except to some extent for 6082 commercial. In the cathodic part, there is a slight deviation with the 6060 recycled alloy, which caused a slightly higher absolute value of the cathodic Tafel slope (the largest of all four alloys). However, all of this is close enough to be attributed to the closeness of the entire series, which also corresponds to their relatively similar chemical composition (alloying elements; metals except Si).

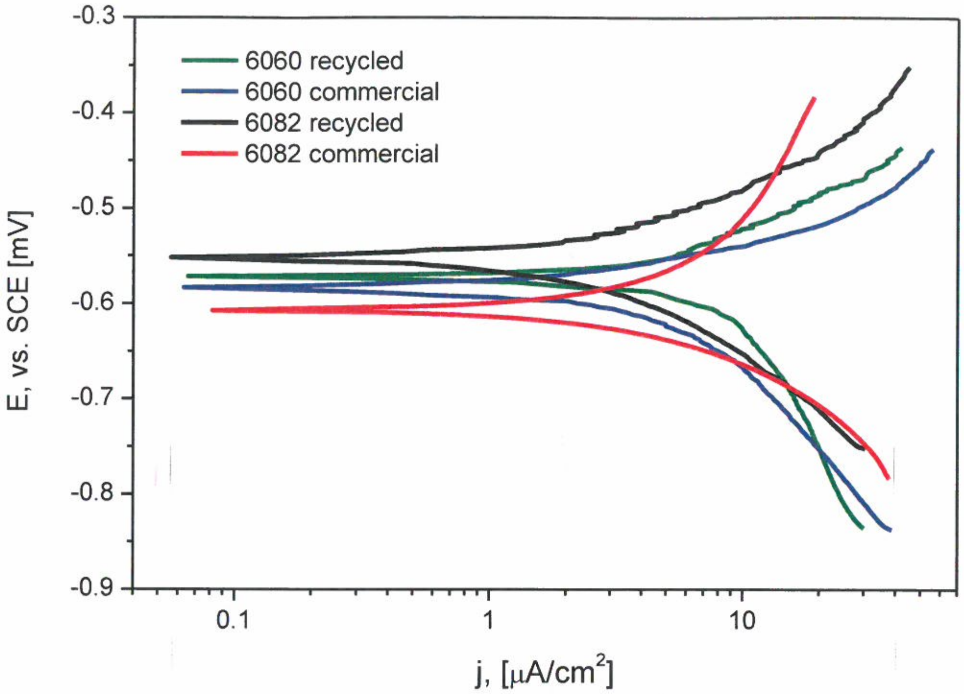

Figure 1 Polarization curves in Tafel region in 0.5 mol/dm^3 Na_2SO_4 + 1 ml conc. H_2SO_4 at pH=2.50solution for recycled and commercial AlSi1MgMn (6082) and AlMnSi0.5 (6060) alloys

Table 4 Corrosion parameters of recycled and commercial AlSi1MgMn (6082) and AlMnSi0.5 (6060) alloys in 0.5 mol/dm^3 Na_2SO_4 + 1 ml conc. H_2SO_4 at pH=2.50

Alloys	Linear polarization			Tafel	
	R_p, [kΩ·cm^2]	$I_{corr.}$, [μA·cm^{-2}]	$E_{corr.}$,vs. SCE [mV]	$I_{corr.}$, [μA·cm^{-2}]	$E_{corr.}$, [mV]
AlSi1MgMn (6082) (with recycled Al)	8.655	**3.053**	−554.3	**3.168**	−553.0
AlSiMgMn (6082) EN AW-6082	8.059	**3.146**	−594.6	**3.260**	−592.7
AlMnSi0.5 (6060) (with recycled Al)	6.846	**2.813**	−570.7	**2.658**	−571.6
AlMnSi0.5 (6060) EN AW-6060	6.462	**3.202**	−584.9	**3.037**	−583.4

From Table 4, it can be seen that the results are very similar for all four alloys. With alloy 6060, higher values of corrosion current density are obtained by the LPR method, and with 6082, the reverse is true, but with very small differences. The analysis leads to the conclusion that both alloys of the 6000 series are more corrosion resistant than the metal itself, with 20-30% lower are lower values for j_{corr} compared to pure Al [7]. You can also see the very high uniformity of the results, which is reflected in the very small difference between the methods used (about 5%, for all 8 values always below 10% difference). Recycled alloys have better results than both commercial alloys. With alloy 6082 the difference is small (about 3%), while with alloy 6060 it is slightly over 10%. In absolute values, these are small differences, and in a practical sense, they can be ignored for both alloys (assuming that they have identical corrosion characteristics for the tested corrosion environment).

If alloys 6060 and 6082 are compared, it can be seen that the former showed somewhat better results, which was not expected, because it contains less silicon than the latter. Due to the fact that Tafel gives lower values for 6060 and vice versa for 6082, the comparison is best done by calculating the average values of the two methods, after which we get: j_{corr} = 2.735 μA/cm^2 6060 recycled; j_{corr} = 3.12 μA/cm^2 6060 commercial; j_{corr} = 3.11 μA/cm^2 6082 recycled, and j_{corr} = 3.203 μA/cm^2 6082 commercial. In recycled alloys, the difference is 13.7% (lower value for alloy 6060) and only 2.7% for commercial alloys (again lower value for 6060). In absolute terms, this is not a significant difference, and both alloys can be considered approximately equally resistant in the examined environment. The corrosion rate is between 30 and 35 μm /year, which is relatively low. Consequently, these Al alloys can be used as construction materials in a tested environment.

Conclusion

The following conclusions can be drawn:

1) The results of testing the mechanical properties of commercial aluminum alloys and alloys obtained by using recycled aluminum indicate that remelting does not significantly affect the change in the mechanical characteristics of the tested alloys.

2) There are no significant differences in corrosion characteristics between recycled and commercial alloys. Somewhat better results were obtained for recycled alloys, probably due to higher Si content.

3) Both alloys showed that they are relatively stable in Na_2SO_4 acid solution, which was chosen as a very aggressive environment. Corrosion rates of the order of tens of mm per year were determined, which is acceptable for their technical application in the tested solution.

4) It was shown that the applied recycling process produces alloys that are not only comparable but marginally better than commercial ones in terms of corrosion resistance.

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