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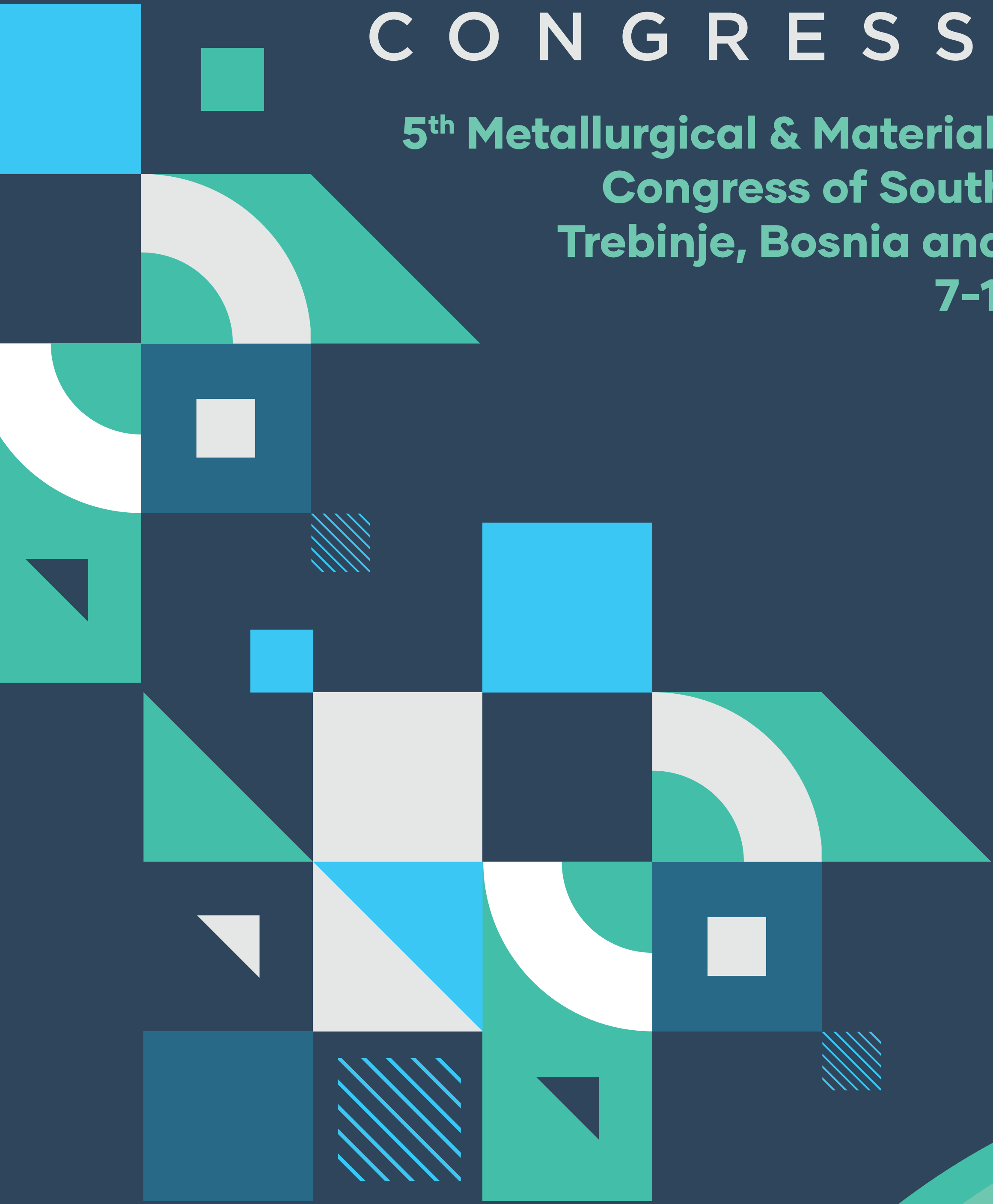
CONGRESS 2023

5th Metallurgical & Materials Engineering Congress of South-East Europe
Trebinje, Bosnia and Herzegovina
7-10th June 2023



CONGRESS PROCEEDINGS

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INFLUENCE OF COLD ROLLING AND ANNEALING ON THE MECHANICAL AND CORROSION PROPERTIES OF AN AA5182 Al-Mg ALLOY

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In this study we investigated the effect of cold rolling reductions and different annealing conditions, on the mechanical properties and corrosion resistance of an AA5182 type Al-Mg alloy. Material was industrially produced and supplied as hot rolled 12 mm thick plates. Further lab-processing included cold rolling with 40-85% reduction in thickness, and 2h of annealing in the range of temperatures from 300-350°C. Annealed specimens were used for room temperature tensile testing while corrosion testing was performed on the annealed and sensitized specimens. Intergranular corrosion (IGC) susceptibility was determined by nitric acid mass loss test (NAMLT) for the selected states.

The results showed that corrosion resistance, tensile strength and yield point elongation were mostly affected by a degree of cold deformation. It was found that increasing in cold rolling reduction from 40-85% before annealing causes an improved strength level due to grain size refinement. However, yield point elongation became more pronounced and a tendency towards Lüdering as undesirable surface appearance was increased. NAMLT testing showed that the material was corrosion resistant in as-annealed condition while it became susceptible to intergranular corrosion after sensitization treatment. IGC susceptibility of sensitized specimens increases with cold rolling reduction and a grain size refinement.

Keywords: Al-Mg alloy, degree of deformation, strength, yield point elongation, intergranular corrosion

Introduction

Wrought Al-Mg alloys are important and promising material for application in transportation industry primarily due to favorable strength to weight ratio. Their use in the field of transportation reduces the weight of vehicle constructions, which lowers fuel consumption and reduces carbon dioxide emissions. In addition to these benefits, one of the key criteria for using Al-Mg alloys as light structural materials is their ability to provide high strength, corrosion resistance, and acceptable surface quality without suffering from Lüders and PLC bands appearance, which occurs due to serrated flow or yield point phenomena [1,2]. Al-Mg alloys have to meet the following specifications in order to be used in the automotive industry: yield strength in the range of 110-160 MPa; ultimate tensile strength above 255 MPa; total elongation more than >24 % [3,4]. Such a good tensile properties can be achieved by a variation of chemical composition and optimization of thermomechanical processing parameters including a degree of deformation and annealing conditions. One of the important requirements for Al-Mg alloys in transport industry is to provide resistance against intergranular corrosion (IGC). It is well known that alloys containing > 3% Mg, such as AA5182 alloy, may become susceptible to intergranular corrosion (IGC) when they are exposed to temperatures between 50 and 200°C for a long time [5]. Under this low temperature heat treatment, Al_3Mg_2 (β-phase) precipitates along grain boundaries, and the process is known as "sensitization" [5-8]. The presence of highly anodic β-phase at the grain boundaries is responsible for IGC susceptibility of Al-Mg alloys [5-8]. The fraction of the grain boundary area that can be populated by the β-phase during sensitization strongly depends on the microstructure: grain size, and also on the type and orientation of the grain boundaries [6]. The microstructure development of Al-Mg products may vary significantly with different thermo-mechanical processing conditions, producing recovered, partially or fully recrystallized structure.

For this reason, it is of great importance to study and understand the effect of processing parameters on the IGC susceptibility of Al-Mg alloys [6].

In the present study, we applied different cold rolling and annealing conditions in order to investigate their effect on the microstructure, mechanical properties and IGC corrosion resistance of an Al-Mg AA5182 type alloy. The aim was to achieve the properties required by the transportation industry.

Materials and methods

The material used in this study was industrially produced as a standard AA5182 type Al-Mg alloy with the chemical composition given in Table 1. Hot rolled 12 mm thick plates supplied by Impol-Seval Aluminium Rolling Mill, Sevojno, Serbia, were further lab-processed by cold rolling with different reductions in thickness, and annealing in the range of temperatures 300-350°C for 2h.

Table 1 Chemical composition of the AA5182 type alloy, wt.%

Alloy	Mg	Mn	Si	Fe	Ti	Cu	Zn	Cr	Rest
Study	4.04	0.37	0.073	0.186	0.0019	0.011	0.0223	0.011	0.008
Standard	4.0-5.0	0.2-0.5	≤0.2	≤0.35	≤0.1	≤0.15	≤0.25	≤0.1	≤0.15

Tensile testing was performed at room temperature on a Shimadzu AGX-Plus 250 kN machine, according to the requirements of EN ISO 6892-1 standard. All the specimens were tested in transverse direction, 90° in relation to the rolling direction (RD). An applied cross-head speed was v=1 mm/min, giving an initial strain rate of 3.3×10^{-4}/s. The width of tensile specimens was 12.5 mm while the thickness was: 7.2 mm (r=40%), 4.8 mm (r=60%) and 1.8 mm (r=85%), for different cold rolling reductions. An extensometer with gage length of l_0=50 mm was used for the testing.

The susceptibility to intergranular corrosion (IGC) was evaluated by a mass loss after exposure to nitric acid (NAMLT). Sample preparation was conducted according to ASTM G 67 standard [9]. The test was performed on the specimens with the length of 50 mm and 6 mm in width. The length of the specimens was parallel to the rolling direction. Two groups of the specimens were prepared for NAML testing: (1) specimens cold rolled with 40, 60 and 85% reductions and annealed at 320°C/2h, and (2) specimens additionally sensitized at 130°C for 17h. Sensitization treatment of cold rolled and annealed specimens was performed to induce precipitation of β-phase (Al_3Mg_2) particles and achieve sensitized condition. For each cold rolling reduction (40, 60, and 85 %), at least three specimens were tested for each state: annealed and sensitized. According to ASTM G 67 [9], IGC resistant state is achieved if mass loss per unit area is between 1-15 mg/cm^2, while large mass loss of the order of 25-75 mg/cm^2 corresponded to IGC susceptible state.

For metallographic observations selected specimens were prepared by grinding, polishing and etching in Barker's reagent. Microstructure characteristics after cold rolling (40-85%) and annealing at 350°C/2h, were revealed by optical microscope under polarized light. The grain size was determined by the intercept method according to ASTM E 112 [10].

Results and discussion

The influence of the degree of cold deformation and annealing on the tensile properties of investigated AA5182 alloy is shown in Figure 1. The results showed that yield strength (YS) was in the range of 120-155 MPa (Fig. 1a), UTS was between 265-280 MPa (Fig. 1b), while the values of total elongation for all tested samples were greater than 24% (Fig. 1c). Therefore, the requirements for automotive applications were fulfilled as the mechanical properties of AA5182 alloy in the soft annealed state O/H111 [3] were met.

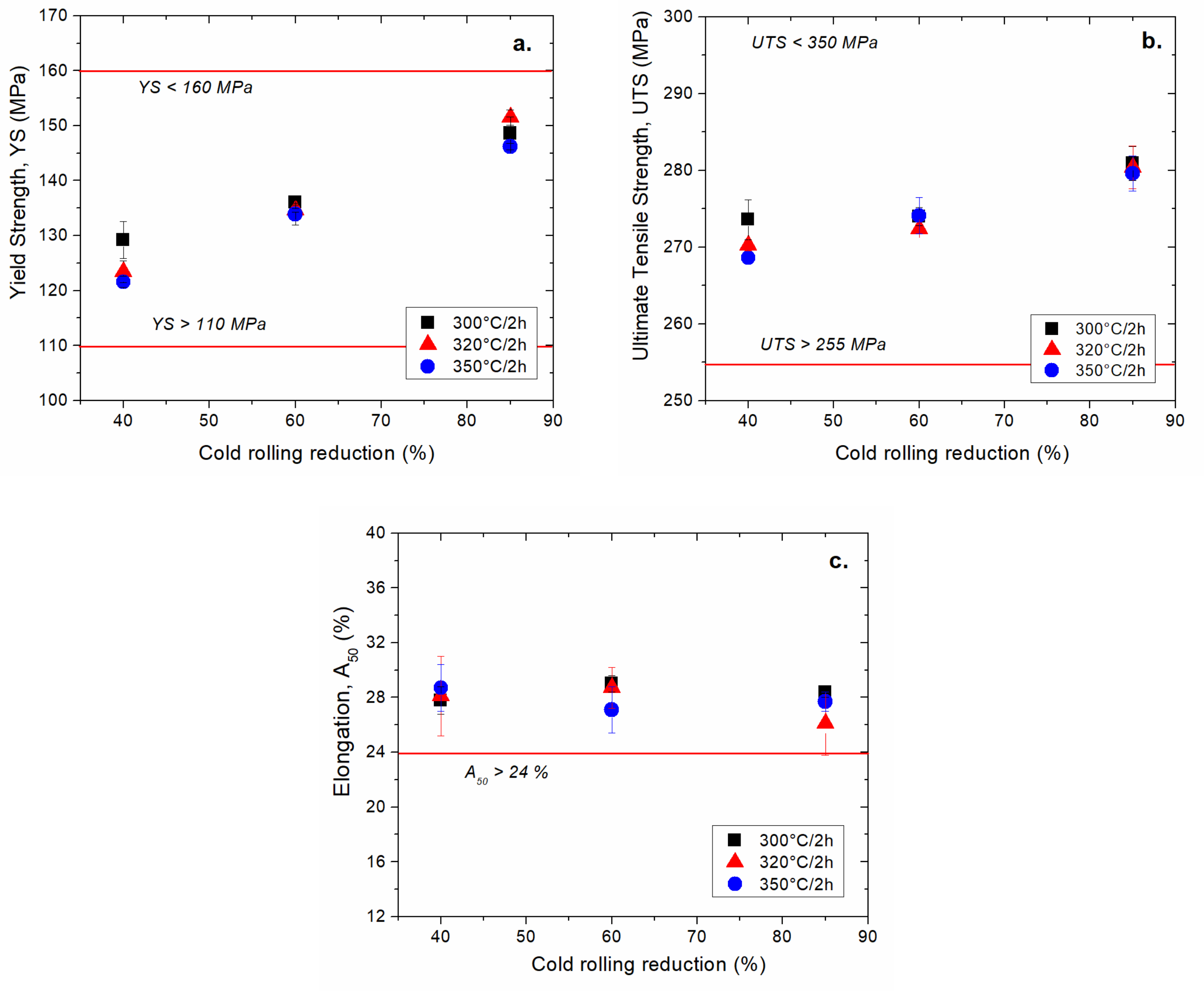

Figure 1 Variation of tensile properties (a) yield strength (YS), (b) ultimate tensile strength (UTS) and c) elongation (A_{50}) with cold rolling deformation.

The results in Fig.1 showed that tensile properties were more affected by a variation in cold rolling reduction than by different annealing conditions. With an increase in the degree of deformation from 40% to 85%, the yield strength was increased for about 25-30 MPa (Fig. 1a). This is due to grain size strengthening mechanism and a decrease of the grain size within recrystallized structure developed after annealing at 300-350°C, as illustrated in Fig. 2.

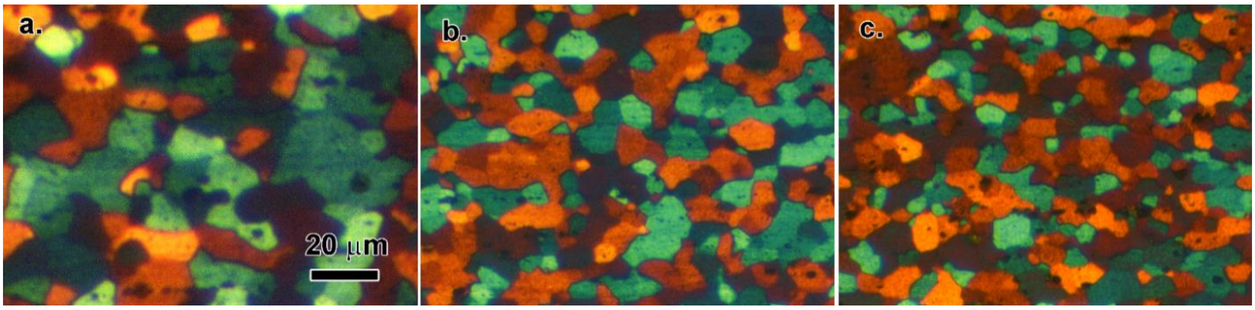

Figure 2 OM micrographs of AA5182 samples cold rolled with (a) 40%, (b) 60%, and (c) 85% reduction and annealed at 350°C/2h; the average grain size was around (a) 16-17 µm, (b) 11-12 µm, and (c) 9 µm

Figure 2 shows typical fully recrystallized structure revealed in cold rolled samples annealed at 350°C/2h. Fine grained recrystallized microstructure with an average grain size was around 9-11 µm corresponded to 60% and 85% cold rolled samples (Fig. 2b-c).

In the 40% cold rolled sample coarse grain structure was developed, with an average grain size of 16-17 µm (Fig. 2a). Figures 1 and 2 showed that there is a clear correlation between the tensile strength level and a size of recrystallized grains. It is evident that the increase in cold rolling reduction facilitated the grain refinement (Fig. 2) and therefore induce a grain size strengthening effect (Fig. 1a). It is likely that only in the sample 40% deformed and annealed at 300°C/2h, the recrystallization process is not completed, as the strength is slightly higher than in case of annealing at 320°C and 350°C (Fig. 1a-b). Tensile properties were not affected by a variation of annealing temperature in the range from 300 to 350°C, as shown in Figure 1.

During tensile testing of an AA5182 alloy a pronounced yield point elongation at the beginning of the deformation, and serrated flow during the deformation appear on the deformation curve. It was observed that with increasing of the cold rolling reduction, Lüders elongation became longer as shown in Table 2 and Figure 3. Total Lüders elongation is related to grain size (elongation is greater with decreasing grain size) as previously reported [1,4]. The increase of the Lüders elongation with decreasing grain size can also be explained from the point of view of dislocation glide.

Table 2 Values of Lüders elongation for AA5182 alloy in the annealed state

Cold rolling reduction (%)	Lüders elongation, e_L(%)		
	300°C/2h	320°C/2h	350°C/2h
40	0.44 ± 0.05	0.81 ± 0.03	0.88 ± 0.11
60	1.10 ± 0.20	1.16 ± 0.13	1.09 ± 0.09
85	1.79 ± 0.09	1.72 ± 0.02	1.70 ± 0.05

The results show that the yield point elongation was increased from ~ 0.4% to 1.8% with increasing of cold deformation from 40% to 85%. This dependence can be related to the influence of the size of the recrystallized grains on the appearance of the pronounced yield point. Namely, as the grain size decreases (Fig.2), the Lüders elongation increases (Tab.2, Fig.3). Figure 2 indicates that in samples deformed 85%, the structure is fine-grained. Increasing of the annealing temperature from 300°C to 350°C did not affect values of Lüders elongation. However, for 40% deformed samples annealed at 300°C/2h, Lüders elongation has the lowest value.

Figure 3 illustrates the influence of cold rolling reductions and the annealing temperature on the value of Lüders elongation for the tested AA5182 alloy.

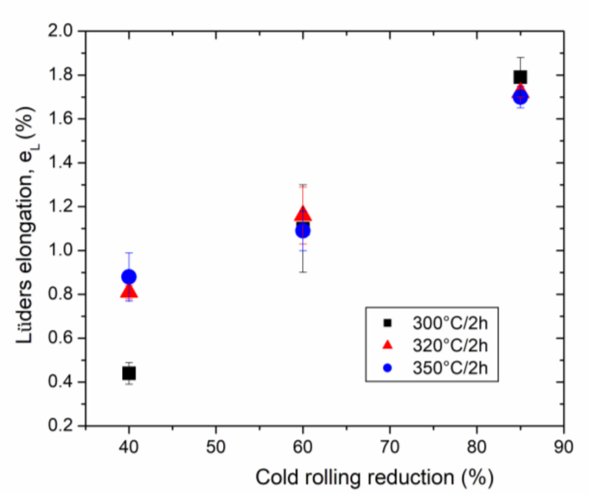

Figure 3 The influence of cold deformation and annealing temperature on the Lüders elongation.

This can be related to the microstructure, which is not completely recrystallized after 2 hours of annealing at 300°C, which is indicated by the higher value of the yield strength than after annealing at 320°C and 350° C (Fig. 1a). In ref. [4] it was shown that samples with a low degree of cold deformation (20%) didn't show yield point elongation. In order to avoid the appearance of a pronounced yield point and the occurrence of Lüders elongation, the samples should be pre-deformed before the tensile test.

Results of the corrosion testing are summarized in Figure 4. Susceptibility to intergranular corrosion was evaluated through the calculation of the mass loss per unit area (Δm/A) for annealed and sensitized specimens. Results shown in Fig. 4 indicated high IGC resistance of the annealed state, as the mass loss was very low 1-2 mg/cm^2. IGC resistance of annealed specimens was unaffected by prior cold rolling reduction. On the other hand, an increase in cold deformation from 40 to 85% increased the susceptibility to IGC of sensitized samples. Cold rolled and annealed specimens became susceptible to IGC after sensitization treatment at 130°C/17h. The mass loss was increased between 15.8 and 35.6 mg/cm^2 with the raise of cold rolling reductions from 40% to 85%.

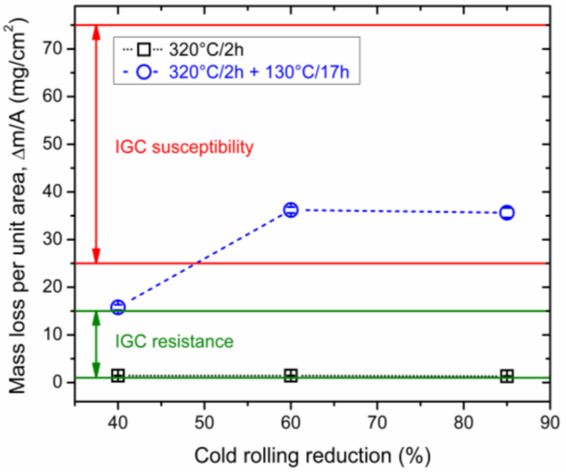

Figure 4 Variation in mass loss per unit area with cold rolling reduction for annealed (320°C/2h) and sensitized (320°C/2h + 130°C/17h) specimens

Sensitized specimens cold rolled with 40% reduction, with mass loss of 15.6 mg/cm^2, were on the borderline of acceptable IGC resistivity. However, the mass loss became higher for 60 and 85% deformed specimens, around 35.6 mg/cm^2, indicating high level of IGC susceptibility for both states. This can be correlated to the microstructure developed during annealing at 320°C and the grain size, as well as with precipitation of highly anodic β-phase (Al_3Mg_2) during sensitization. Mg in the form of β-phase is preferentially dissolved by the nitric acid compared to the state when it is dissolved in Al matrix, i.e. in the form of Mg solid solution (α-Al) [6-9]. According to Al-Mg phase diagram, β-phase in Al-4Mg alloys, such as AA5182, is unstable and dissolves in Al matrix at temperatures higher than ~210°C [11,12]. Therefore, Mg atoms are in solid solution (α-Al) after annealing at 320°C/2h. For this reason, annealed samples exhibited IGC resistance not affected by prior cold rolling reduction. This is in accordance with the results of previous studies related to the temperature stability of β-phase and IGC resistance of samples annealed at temperatures higher than 200°C [12,13]. Previous studies have shown that coarse-grained structure can (i) prolong the diffusivity of dissolved Mg atoms from the grain interior to the grain exterior to form the β-phase and (ii) reduce the grain boundary area that can be populated by the β-phase [6-8,14]. For these reasons, the distribution and morphology of intergranular β-phase at the grain boundaries is likely to be more favorable and IGC resistance was better in case of sensitized samples 40% cold rolled (coarse grained) compared to the sensitized specimens of the tested AA5182 alloy with fine grained structure (60% and 85% cold rolled).

Those fine grained specimens (60% and 85% cold rolled) with large mass loss of around 35.6 mg/cm^2 exhibited high IGC susceptibility indicating that intergranular β-phase is mostly precipitated along the grain boundaries.

Conclusion

The corrosion resistance, tensile strength, and yield point elongation of investigated AA5182 alloy were mostly affected by the degree of cold deformation. The increase in cold rolling reduction from 40 to 85% promoted a grain refining effect and an improvement in the strength level of annealed specimens, while it did not affect the total elongation. The yield point elongation and tendency towards Lüdering became more pronounced with the increase in the cold rolling reduction and grain size refinement. Regardless the applied cold rolling reduction, annealed specimens exhibited high resistance against IGC. On the other hand, sensitized samples with fine grain size (cold rolled with 60% and 85% reduction) were susceptible to IGC. Coarse grain structure developed after 40% cold rolling and annealing provided IGC resistance after sensitization.

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