



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

INFLUENCE OF SURFACE ROUGHNESS ON THE HYDROGEN EMBRITTEMENT BEHAVIOR OF AA6351 ALUMINUM ALLOY

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Abstract. *In the present work, an experimental investigation concerning the influence of surface roughness on the susceptibility to hydrogen embrittlement of AA 6351 aluminum alloy was performed. Different levels of surface roughness were induced in the material by performing turning operations with varying cutting parameters in order to produce cylindrical tensile test specimens. Hydrogen permeation was achieved by cathodic charging in a 0.5M H₂SO₄ solution containing 0.25 mg/l NaAsO₂ with a current density of 100 mA/cm². Then, the tensile strength of samples before and after charging was compared and the susceptibility to hydrogen embrittlement was evaluated as a function of the relative change in the maximum elongation observed in the tensile tests. The results obtained showed that by increasing surface roughness, the susceptibility to hydrogen embrittlement was also increased.*

Keywords: *Aluminum alloy, hydrogen embrittlement, tensile strength, cathodic charging, electrochemical behavior*

1. INTRODUCTION

Aluminum alloys are largely employed in many industries as structural materials because of their low cost, elevated strength-weight ratio, good corrosion resistance in neutral pH environments, among others. In the manufacturing of mechanical components in general, machining operations such as facing, drilling and turning are among the most common production processes applied currently in the industry. In these processes, the material surface is plastically deformed, which may cause local microstructure modifications and produce changes in surface mechanical properties (strain-hardening, with increases in dislocation density).

Hydrogen embrittlement is a phenomenon that can significantly affect mechanical properties, reducing tensile strength, ductility and toughness in various metallic alloys. The hydrogen embrittlement process starts with the absorption of hydrogen, which takes place in the following general steps: (i) adsorption of H₂ gas molecules or H⁺ ions on the metal surface; (ii) dissociation of gas molecules (or conversion of H⁺ ions to H atoms) producing atomic hydrogen at the surface; (iii) absorption of the atomic hydrogen in the materials crystal structure (Louthan, 2008; McCafferty, 2010). In the case of aluminum alloys, hydrogen absorption has been observed in connection with surface corrosion reactions, such as: H₂O + e⁻ → OH⁻ + H (Kamoutsi *et al.*, 2006).

The presence of crystal defects such as dislocations (Zhou *et al.*, 2016) or vacancies (Lu and Kaxiras, 2005) increase the equilibrium hydrogen concentration in the material. Higher concentrations of hydrogen reduce plasticity by restricting dislocation motion (Xie *et al.*, 2016). Since dislocation densities are higher in the vicinities of internal defects *e.g.* cracks and crack-tips, damage propagation is accelerated.

In the present work, an experimental investigation on the influence of machining parameters on surface roughness and hydrogen embrittlement of a structural aluminum alloy grade is presented. Material selection was determined by the widespread use of aluminum alloys and it is expected that this study may contribute to the understanding of the relation between manufacturing/environment conditions and their influence on the mechanical integrity of engineering components.

2. EXPERIMENTAL PROCEDURE

The materials used in the current investigation were aluminum alloy AA6351 (nominal composition 0.7-1.3%Si, 0.4-0.8%Mg, 0.4-0.8%Mn) received initially in the cold-rolled condition (hardness 82±1HV average of 24 measurements) in the form of 5/8" circular bars. The materials were then subject to turning operations with rotations of

1000, 1500, 2000 and 2500 rpm and forward speed in order to produce standard tensile test specimens (following ASTM E8/E8M) with 6 mm diameter and 40 mm gauge length.

Half of the tensile test specimens were then immersed in a 0.5M H₂SO₄ solution, containing naturally dissolved O₂ and 0.25 mg/l NaAsO₂ for hydrogen permeation (Klimovicz and Latanision, 1978). Prior to hydrogen permeation, the electrochemical behavior of the AA6351 Al-alloy was investigated by employing an IVIUM Vertex potentiostat/galvanostat connected to a 600 ml horizontal cell for flat specimens. A three-electrode setup was employed, with a Ag/AgCl reference electrode, Pt-wire counter electrode and working electrode (a polished sample). In order to promote hydrogen absorption, the AA6351 samples were submitted to cathodic charging at a current density of 100 mA/cm² by adjusting the voltage between the test material and graphite electrodes, as illustrated in Figure 1 for 2 hours.



Figure 1. Hydrogen permeation set-up: (a) cathodic charging cell, (b) evolution of H₂ bubbles on the tensile test specimen surface and (c) connections to the electrochemical cell.

After hydrogen charging, samples were immediately submitted to tensile testing in a EMIC10000 device with controlled strain rate and the results were compared with non-charged specimens with the same surface condition. Fracture evaluation was carried out by Scanning Electron Microscopy (SEM) while microstructure and microhardness evaluations of charged and uncharged specimens were performed by Optical Microscopy (OM) and by employing a Vickers microhardness tester with 10 gf load.

3. RESULTS AND DISCUSSION

The electrochemical behavior of the AA6351 Al-alloy in 0.5M H₂SO₄ is illustrated in Figure 2, in which the main cathodic and anodic reactions are indicated. The evolution of bubbles on the aluminum alloy surface shown in Figure 1(b) indicated that the cathodic reaction occurred by H₂ evolution $H^+ + H_{ads} + e^- \rightarrow H_2$, which is preceded by the creation of adsorbed hydrogen by $H^+ \rightarrow H_{ads}$ (McCafferty, 2010).

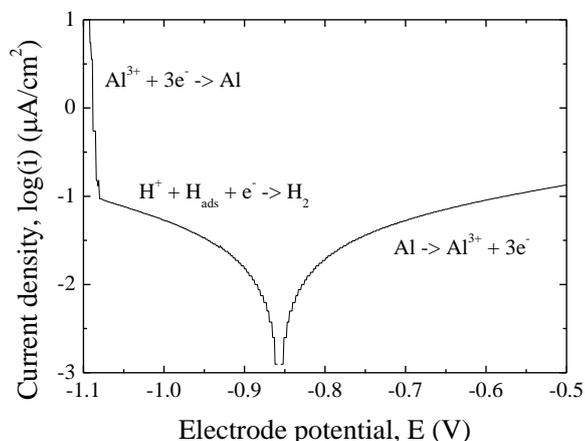


Figure 1. Tafel plot obtained for the AA6351 Al-alloy in H₂SO₄ containing naturally dissolved O₂.

The roughness of the machined tensile specimens was evaluated after the turning operations. Average surface roughness values (R_a) of 3.04, 2.68, 2.95 and 2.38 μm respectively for rotations of 1000, 1500, 2000 and 2500 rpm. The results of the tensile test, performed before and after hydrogen permeation, are illustrated in Figure 3 (a) (results obtained for the 2.38 μm surface finish). In Figure 3(b), the percentage of hydrogen embrittlement (determined from the relative change in maximum elongation by comparing the charged and non-charged samples) is presented as a function of the average surface roughness.

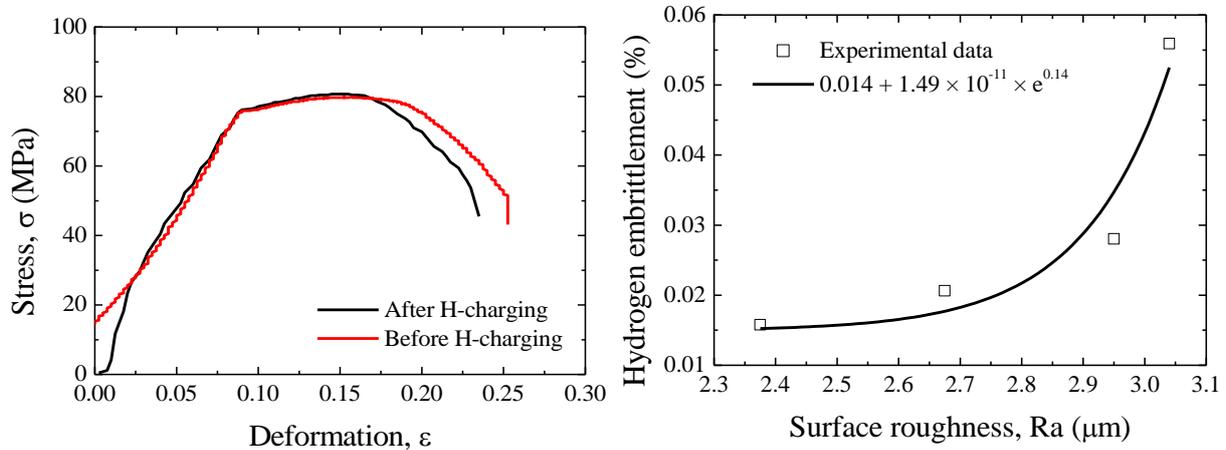


Figure 3. (a) Results of the tensile tests performed on the sample with 2.38 μm surface finish before and after hydrogen charging and (b) Summary of the effects of hydrogen charging as a function of surface roughness.

It is possible to notice that the chosen set of cutting parameters did not lead to significant differences regarding surface roughness among the tested samples. In general, all sample surfaces can be considered to present good quality finish. A possible reflection of this is the relatively low changes in ductility observed after hydrogen charging with value ranging from close to 1.6% (for the 2.38 μm surface roughness) to 5.7% (for the sample with 3.04 μm surface roughness). Despite this, it is possible to see that a trend could be identified in Figure 3(b), suggesting a non-linear but positive correlation between surface roughness and hydrogen embrittlement susceptibility.

In order to explore further aspects of the tensile test, the strain-hardening rate ($d\sigma/d\varepsilon$) is plotted as a function of the deformation (ε) in Figure 4, for the 2.38 μm surface roughness sample. According to Ji *et al.* (Ji *et al.*, 2014) the evolution of the strain-hardening rate (SHR) reveals the occurrence of distinct mechanisms during plastic deformation. After the yield point (Stage A), a sharp drop in SHR is noticed for both materials which is indicative of dynamic recovery of dislocations. After this, in Stage B, the SHR becomes almost constant indicating no alterations in the primary plastic deformation mechanism. At approximately 0.17 strain levels the SHR presents a slight decrease (Stage C) for both materials. Thus, by analyzing the results presented in Figure 4, which are representative of the remaining tested samples, it is possible to notice that the hydrogen charging process, apart from the reduction in ductility, did not lead to further alterations regarding the plastic deformation behavior of the AA6351 aluminum alloy. This is expected since the strain-hardening behavior, as evaluated in tensile tests, can be considered a bulk characteristic whereas hydrogen permeation is mainly a surface phenomenon.

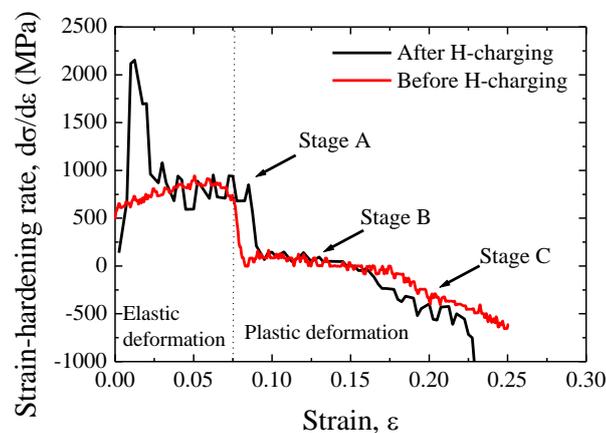


Figure 4. Evolution of the Strain-Hardening Rate (SHR) before and after hydrogen charging for the 2.38 μm surface roughness sample.

The reasons for the behavior observed in Figure 3, in which a positive correlation between surface roughness and hydrogen embrittlement was identified are possibly related to the fact the rougher surfaces can be expected to have experienced larger levels of plastic deformation during the cutting process. Thus, in these cases, defect density is increased which favors trapping of hydrogen atoms and increases the amount of absorbed hydrogen (Carreño *et al.*, 2003).

4. CONCLUSIONS

In the present work, the influence of cutting parameters on surface roughness and susceptibility to hydrogen embrittlement of AA6351 aluminum alloys was analyzed. The results showed that by elevating surface roughness, even by small amounts, the susceptibility to hydrogen embrittlement (analyzed in terms of the relative loss in maximum elongation) is also increased. The analysis performed revealed further that, apart from the loss in ductility, the machining process in the applied conditions did not lead to significant alterations in materials tensile behavior.

5. ACKNOWLEDGEMENTS

The authors acknowledge financial support from FAPEMIG, CAPES and CNPq.

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