Effects of annealing temperature on the mechanical properties and sensitization of 5083-H116 aluminum alloy

Ren-Yu Chen¹, Hsiao-Yeh Chu², Cheng-Chyuan Lai³ and Chih-Ting Wu⁴

Abstract
This study elucidates how annealing temperature affects the mechanical properties and sensitization of 5083-H116 aluminum alloys. Nitric Acid Mass Loss Test was conducted to investigate the sensitization behavior of the annealed specimens. The results indicated that the mechanical properties were more sensitive to the annealing temperature than to the annealing time. The mechanical properties of the alloys became rapidly worse upon annealing between 250 and 350 °C. 5083-H116 aluminum alloy became sensitized and susceptible to intergranular corrosion at an annealing temperature of 175 °C for 48 h. The distribution and shapes of β-phase particles markedly affected the sensitization. Exposing at the temperatures of 230–250 °C for 10–30 min could effectively improve the sensitization of the 5083-H116 alloys.

Keywords
5083-H116, sensitization, β-phase, intergranular corrosion, Nitric Acid Mass Loss Test

Date received: 2 February 2013; accepted: 4 October 2013

Introduction
5xxx Al-Mg alloys, such as 5083, are medium-strength, non-heat treatable wrought aluminum alloys. They have been widely used in marine structures owing to their light weight, weldability, and favorable corrosion resistance. These Al-Mg alloys, which exhibit a range of useful material properties, are highly desired for being used in fast sea transportation for commercial and military applications. Since the 1950s, U.S. Navy has preferred to use magnesium-strengthened 5xxx alloys, which are also favored for use in new high performance vessels.¹² It is well known that the strength of Al-Mg alloys increases with increasing Mg content, but raising temperature during the annealing process lowers the strength of Al-Mg alloys.³ In addition, although increasing Mg content can enhance strength, it may be accompanied by a decrease in corrosion resistance.⁴

5xxx Al-Mg alloys that contain more than 3 wt.% Mg are supersaturated at room temperature. The excess Mg solute atoms tend to precipitate out as β-phase (Mg2Al3) particles, distributed along the grain boundaries during prolonged aging at room temperature, or after shorter periods of exposure at slightly elevated temperatures (65–200 °C).⁵⁻⁷

As displayed in Figure 1,⁸ marine alloys such as 5086 (3.5–4.5 Mg), 5083 (4.0–4.9 Mg), and 5456 (4.7–5.5 Mg) become sensitized, and thus susceptible to corrosion, upon exposure to temperatures in the range that is indicated by the hashed area (in the α + β phase field). Since the β-phase is electrochemically more active than the Al-matrix, plates destabilize over time and are susceptible to exfoliation, intergranular corrosion (IGC), and stress corrosion cracking (SCC) in stress and corrosive environments.²⁹ Such phenomena are normally referred to as “sensitization,”¹⁰ especially in the heat-affected zone (HAZ) of a weld or in deck and superstructure.

¹School of Defense Science, Chung Cheng Institute of Technology, National Defense University, Taoyuan, Taiwan
²Department of Mechanical Engineering, Kun Shan University, Tainan, Taiwan
³Department of Mechatronic, Energy and Aerospace Engineering, Chung Cheng Institute of Technology, National Defense University, Taoyuan, Taiwan
⁴Army Academy R.O.C., Taoyuan, Taiwan

Corresponding author:
Hsiao-Yeh Chu, Department of Mechanical Engineering, Kun Shan University, Tainan 71003, Taiwan.
Email: hsiaoyeh@mail.ksu.edu.tw
applications involving severe solar radiation. This is an insidious problem of 5xxx Al-Mg alloys that is caused by the gradual formation and growth of the β-phase at grain boundaries. It has long been well known that the mechanical properties, including the corrosion behavior, of most engineering materials can be modified effectively by altering their microstructures using various heat treatments. Several studies have attempted to sensitize 5xxx series aluminum alloys by IGC and SCC, in which the critical sensitizing temperature of these alloys were approximately 175 °C.11–16 However, these studies have focused on local temperature sensitization (100–200 °C) and most did not achieve a significant improvement. According to the phase field boundaries around the Al-rich corner of the Al-Mg binary phase diagram (see Figure 1), β-phase precipitation can be eliminated by annealing the alloys at elevated temperatures exceeding the solubility limit of Mg in aluminum, for instance, the optimal stabilization temperature of the 5083-H116 alloys was around 240 °C. According to the diagram, the equilibrium state of the alloy is single-phase α. The continuity of the second-phase β precipitant networks is expected to be gradually eliminated by the diffusion of Mg atoms into the α-matrix, changing the sensitized microstructure and its properties. However, the annealing temperature and time must be controlled in the recovery stage to prevent softening of the plate.

In present work, the effects of annealing on the mechanical and sensitization properties of a 5083-H116 aluminum alloy are examined, and a stabilizing heat treatment is applied to restore corrosion resistance of these highly sensitized specimens. The ultimate purpose of this research is to improve the sensitization properties of 5xxx Al-Mg alloys, thereby extending their service life.

**Experimental procedures**

A commercial 5083-H116 aluminum alloy plate with 6 mm in thickness was utilized in the present study. The detailed chemical composition of this alloy is Al-4.51 Mg-0.54 Mn-0.07 Cr-0.29 Fe-0.11 Si-0.05 Cu-0.01 Ti-0.12 Zn-0.07 Zr (wt.%). Annealing was set at the temperatures of 100, 150, 200, 250, 300, 350, 400, 450, 500, and 550 °C. Each specimen was held for 30 min during annealing before quenching in room temperature water. Tensile tests using a 25-mm gauge length and a 6-mm gauge diameter were performed according to the ASTM B557 with an initial strain rate of 0.003 s⁻¹. A Vickers test for microhardness with a load of 150 g for 15 s was adopted to measure the hardness of the experimental specimens.

Nitric Acid Mass Loss Test (NAMLT) was conducted to investigate the sensitization behavior of the annealed specimens. The time of NAMLT was 30 min, 12 h, 24 h, and 48 h, in compliance with the ASTM G67 procedure. Additionally, the sensitization reversing properties with different sensitive structures were investigated, in which the sensitized specimens were denoted as S1 (recovery plate annealed at 175 °C for 48 h) and S2 (recrystallization plate annealed at 450 °C for 30 min and then sensitized at 175 °C for 48 h). According to those results,
holding sensitized specimens (S1 and S2) at a heat treatment temperature of 240 °C for 10, 30, 60, and 120 min restored their corrosion resistances, as demonstrated by their compliance with the NAMLT requirements set by ASTM B928 (<15 mg/cm²).10

The microstructure was examined by optical metallography. Specimens for metallographic characterization were prepared by electrochemical polishing and etched using Barker’s solution. To determine the extent and distribution of the β-phase precipitates, sensitized specimens were prepared by mechanical polishing and etching with a 5% hydrofluoric acid solution.

Results and discussion

Mechanical properties

The mechanical properties of the annealed 5083-H116 alloy are closely related to the characteristics of deformed microstructures. Figure 2 shows that annealing below 200 °C slightly reduces the ultimate tensile strength (UTS) and yield strength (YS) and increases the uniform elongation. Between 200 and 250 °C, the uniform elongation increases markedly from 18% to 19%, reflecting the microstructural changes at 200 °C, which is attributed to a slight
change in the dimension of dislocation substructures and the rearrangement of dislocations. The tensile properties change substantially between 250 and 350°C, a rapid drop in UTS and YS occurs because of recrystallization. A steady value of UTS and YS can be obtained between 350 and 550°C, mainly because the formation of a recrystallized structure.

Figure 3 presents the results of the hardness test of the annealed samples. The results of the hardness test exhibit the same trend as those of the tensile test in Figure 2. Hardness declines as the temperature and time increase. These curves demonstrate that annealing between 100 and 250°C slightly reduces hardness throughout the recovery process. Significant changes in hardness caused by recrystallization occur between 250 and 350°C and are determined by the annealing temperature and time. Accordingly, the basic softening process is limited to the temperature range of 250–350°C. The similar hardness values that are obtained upon annealing between 350 and 550°C indicate that the coarsening of recrystallized grains only weakly influences hardness. Therefore, the hardness of the annealed samples is clearly dominated by the fraction of recrystallized...
grains rather than the rate of coarsening thereof recrystallized grains. Consequently, the effective range of temperatures for stabilization is between 200 and 250°C.

Figure 4 plots the effect of annealing temperature on the microstructural evolution during 30 min of isochronal annealing at temperatures of 25–550°C. There is no observable change in the microstructure with elongated fibrous grains parallel to the direction of rolling when the annealing temperature below 200°C (Figure 4(a)). This result is expected since boundary mobility is very low at these temperatures. For the same reason, alloys retain their fibrous microstructure morphology following annealing at the slightly higher temperature of 250°C. However, at that temperature, some fibrous grains are thickened laterally to a greater extent than those annealed at 200°C (Figure 4(b)). Notably, the results of the tensile and microhardness tests of the samples annealed at 100–550°C (Figures 2 and 3) reveal that their mechanical properties begin to change around 250°C. This phenomenon is consistent with the microstructure in Figure 4(b), which verifies the occurrence of the recovery at this temperature.19

Annealing at a temperature of over 350°C yields recrystallized coarse structures (Figure 4(c)). The high uniform elongation of materials annealed at 350–550°C is evidently attributable to an increase in the amount of recrystallized and/or coarsened grains.

**Corrosion resistance in HNO₃**

Figure 5 summarizes the results of the NAMLT test conducted on the 5083-H116 alloy following annealing treatments for 48 h. The weight loss of samples annealed at temperatures ranging 100–200°C are on average greater than that of the other samples, revealing that the sensitizing range of 5083-H116 alloys is between 100 and 200°C, around a maximum at 175°C. However, samples annealed above 200°C
yield the greatest resistance to IGC owing to dissolution of the \( \beta \)-phase in a solid solution.

Metallographic examination of the annealed samples reveals that outside the sensitizing range, the microstructure remains unchanged and consists of uniformly dispersed \( \beta \)-phase precipitates (Figure 6(a)). However, samples for either the recovered structure (S1 sample: annealed at 175 °C for 48 h) or recrystallized structure (S2 sample: annealed at 450 °C for 30 min and then sensitized at 175 °C for 48 h) indicate that \( \beta \)-phase tends to precipitate along the grain boundaries under the sensitizing range (Figure 6(b) and 6(c)).

Figure 7. NAMLT test results of the sensitized samples as a function of exposure time at 240 °C.

Figure 8. Microstructure with the sensitized plates following brief exposure at 240 °C: (a) S1 specimens heat-treated for 10 min, showing semi-continuous network of grain boundary; (b) S2 specimens heat-treated for 10 min, showing semi-continuous network of grain boundary; and (c) S1 and S2 specimens heat-treated for 30 min, showing discontinuous network of grain boundary.
Figure 6(d) to 6(f) present the metallographs of samples in Figure 6(a) to 6(c), respectively, following their immersion in HNO₃ for 24 h. Figure 6(d) shows that the edge of the sample was smooth without any evidence of IGC. However, according to Figure 6(e) and 6(f), both the edges subjected to intergranular attacks along the network of the grain boundaries at which precipitation occurred and the shapes of edges formed by corrosion were determined by their grain configurations. Based on the above results, IGC depends not only on the presence of β-phase particles but also strongly on their morphologies and distribution in the microstructure.

**Reversing sensitization properties**

After annealing at 240°C for over 30 min, both recovered (S1: recovery plate annealed at 175°C for 48 h) and recrystallized (S2: recrystallization plate annealed at 450°C for 30 min and then sensitized at 175°C for 48 h) specimens are restored almost to the full corrosion resistance of the fresh plates, as indicated by the NAMLT results (Figure 7).

Optical metallography verifies that stabilization treatment produces a discontinuous or semi-continuous network of precipitates at grain boundaries, as expected from the NAMLT results. Figure 6(b) and (c) presents the evidently continuous networks that are formed by the β precipitation in the plates. Following brief exposure (10–30 min) at 240°C, the β-phase particle precipitated along the grain boundaries with either the recovery or the recrystallization structure merge with a solution (Figure 8(a) and 8(b)). The sensitized specimens finally reverted back to a state with a low NAMLT test value approaching those of fresh plates upon exposure for more than 30 min (Figure 8(c)).

**Conclusions**

This study elucidates how annealing temperature affects the mechanical properties and sensitization of 5083-H116 aluminum alloys. The following conclusions are drawn from the above analysis.

1. The mechanical properties of 5083-H116 alloys that are annealed at temperatures below 250°C only have a slight change, but mechanical properties become rapidly worse upon annealing between 250 and 350°C.
2. The mechanical properties of 5083-H116 alloy are more sensitive to the annealing temperature than to the annealing time.
3. Being annealed in the sensitization range at an annealing temperature of 175°C for 48 h, the alloy becomes sensitized and susceptible to IGC. The distribution and shapes of β-phase particles markedly affect the sensitization.
4. Exposing at the temperatures of 230–250°C for 10–30 min can effectively improve the sensitization of the 5083-H116 alloys.

**Acknowledgement**

This work was supported by the National Science Council of the Republic of China under the grants of NSC101-2221-E-168-015.

**Funding**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**References**


