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# Locally Reversing Sensitization in 5xxx Aluminum Plate

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**Aluminum-magnesium alloys are ideal for ship construction; however, these alloys can become sensitized and susceptible to intergranular corrosion when exposed to moderately elevated temperatures. A stabilization treatment has been developed to reverse sensitization and restore corrosion resistance such that in-service plate can be refurbished rather than replaced. This treatment involves a short exposure to a specific elevated temperature range and can be implemented with portable units onboard a ship.**

**Keywords** aluminum, corrosion testing, heat treating

## 1. Introduction

Aluminum-magnesium, or 5xxx series alloys have a combination of good strength, weldability, and corrosion resistance that makes them ideal for ship construction. However, aluminum alloys with greater than about 3% Mg (including 5456 and 5083) can be sensitized and become susceptible to intergranular corrosion when exposed to elevated temperatures and are not considered suitable for service above 65 °C. Sensitization, in this case, is defined as a microstructure wherein Mg precipitates on grain boundaries as $Al_3Mg_2$, also known as β phase in a semi-continuous fashion. The β phase is anodic to the grain interiors and thus plates with a sensitized microstructure are susceptible to intergranular corrosion, exfoliation, and stress-corrosion cracking when exposed to stress and corrosive media.

This problem gained new attention in 2002 after more than 200 commercial vessels built with 5083-H321 were found to be susceptible to intergranular corrosion (Ref 1). Many of these vessels required new hulls and superstructures, which led to the adoption of a new ASTM standard B928 (Ref 2). This standard required additional certification of aluminum alloy plates for marine use including the use of the nitric acid mass loss test (NAMLT) (Ref 3) to better demonstrate corrosion resistance. Nitric acid dissolves β phase thus, causing grains surrounded by a relatively continuous network of β to fall out resulting in significant mass loss from the test sample. Unfortunately, Al-Mg alloy plate samples can pass the B928 requirements and yet, over time, the plate still develops a sensitized microstructure in service, especially in the heat affected zone of a weld (Ref 4). That is, at temperatures within the suitable service envelope for these alloys (e.g., below 65 °C) β phase can still precipitate on grain boundaries over long time periods.

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During fabrication of 5xxx plate, rolling is often followed by a stabilization heat treatment. While stabilization often refers to a process developed in order to prevent age-softening, there is another stabilization treatment by which magnesium is precipitated in grain interiors or discontinuously on grain boundaries to reduce the likelihood of future sensitization (Ref 5). However, this practice is difficult to apply, as the proper heat-treatment temperature range is narrow and varies with rolling practice (Ref 6). If the plate is treated at a temperature that is too low, β will precipitate on grain boundaries and sensitization will be accelerated. If the stabilization temperature is too high, the Mg will go back into solution in the aluminum matrix but the strain hardening Al-Mg alloys rely on for strength will be annealed out and a significant loss in strength will result. In addition, Mg in solution is not stable and may re-precipitate to the grain boundaries over time under the right conditions.

A schematic of the stabilization temperature range for Al-Mg alloys is shown in Fig. 1. As shown, marine alloys such as 5083 (4.5 Mg) and 5456 (5.1 Mg) can become sensitized and thus corrosion susceptible, on exposure to the temperature range depicted by the shaded area. Additional factors are also important in defining the various regions for a given plate. These factors include the exposure time at a given temperature, the extent of recrystallization, and the amount of cold work applied during fabrication. Figure 1 also shows that these alloys can be annealed at temperatures above the β phase solid solubility limit. In between these two regions is the stabilization range wherein β phase can be re-distributed such that it is not continuous along grain boundaries while avoiding softening the plate.

Recently, the U.S. Navy has experienced intergranular cracking in some 5456 plate used in combatant ship superstructures (Ref 8). This investigation was undertaken to determine if a heat treatment, analogous to a mill stabilization treatment, could be used to reverse sensitization and restore corrosion resistance to existing Al-Mg structures. The goal was to simulate classical stabilization treatment performed during plate production leading to non-semi-continuous grain boundary β. The treatment attempted herein was to de-sensitize plate that had realized a simulated service life causing an increased susceptible to intergranular corrosion. In effect, a de-sensitization or an in-service stabilization practice would then be used as a basis for the development of a process to apply an in situ heat treatment on ship superstructures as an alternative to the costly repair method of cutting out sensitized plate and welding in patches of fresh plate or replacing entire structures altogether.

## 2. Technical Approach

A laboratory approach was used to determine the feasibility of reversing sensitization on 0.25 in.-thick 5456 plate. The plate was evaluated via tensile testing, NAMLT testing, and metallographic examination in the as-received (H116), sensitized and treated conditions. Holding specimens at 150 °C for 24 h was found to effectively sensitize them as indicated by failing NAMLT requirements as per ASTM B928 (<25 mg/cm$^2$). In order to show that the sensitization is reversible, a treatment in which the NAMLT results are brought below 15 mg/cm$^2$ (an ASTM B928 passing result) was sought. As-received 5456-H116 plate was subjected to a sensitization treatment (24 h at 150 °C) and then exposed to temperatures from 200 to 340 °C to determine a suitable stabilization treatment. Tensile testing was used to show the extent of softening (i.e., potential annealing) and determine if too high a treatment temperature was used. In addition, optical metallography was used to confirm the presence or absence of a sensitized microstructure. The photos presented below represent the L-ST orientation at the t/2 location of the plate. Metallographic specimens were etched with a 40% aqueous phosphoric acid solution. A sensitized microstructure was indicated by a semi-continuous or continuous network of grain boundary precipitates.

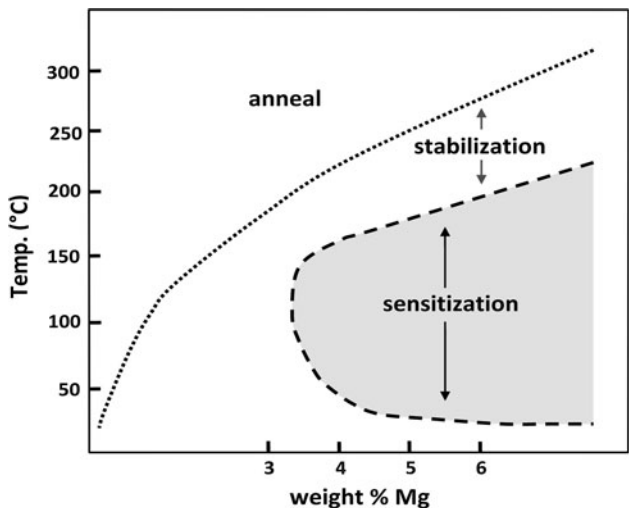


**Fig. 1** Schematic of effect of temperature on Al-Mg alloys (adapted from Ref 6 and 7)

## 3. Results and Discussion

Treatment times of 24 h were initially investigated as a proof of concept and then subsequent exposure times were decreased to facilitate future implementation. The NAMLT and yield strength test results from 10 and 30 min treatments are shown in Fig. 2.

These curves show that a sensitization treatment and a stabilization treatment below about 300 °C does not significantly affect strength. The exact conditions for an effective anneal have yet to be determined as the high-temperature treatment given was for 340 °C for 24 h, but it is clear that annealing does not occur below approximately 300 °C.

The sensitization treatment applied has shown to effectively give NAMLT results above 25 mg/cm$^2$ and stabilization treatments that reduce NAMLT to below 15 mg/cm$^2$ need to be performed at temperatures greater than approximately 230 °C. While an effective stabilization temperature may be

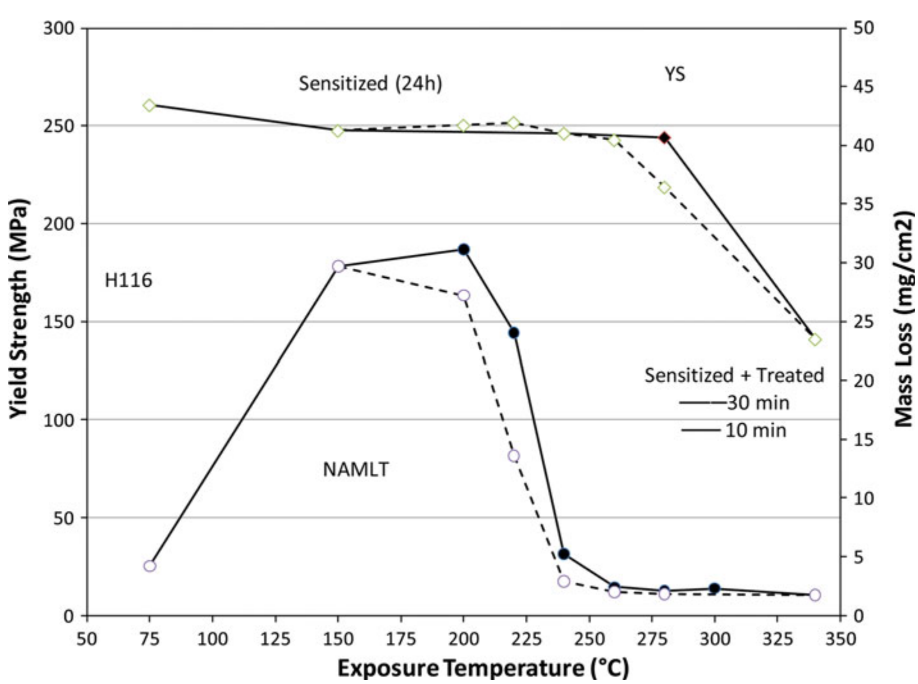


**Fig. 2** Yield strength and NAMLT results vs. exposure temperature in 5456

slightly lower for longer exposure times (e.g., 30 vs. 10 min) a reasonable temperature range appears to be from 240 to 280 °C; the plate will remain sensitized below this range while the yield strength significantly declines above this range.

As shown in Figs. 3 and 4, optical metallography confirms that the sensitization treatment did result in a semi-continuous network of grain boundary β, as expected from the NAMLT results.

After a 340 °C treatment, the sensitized specimens revert back to a low NAMLT test value but the resultant low strength indicates that annealing occurred. Optical metallography confirmed that after 24 h at 340 °C the grain boundary β has gone back into solution (Fig. 5). However, as expected from the NAMLT results, a treatment of 10 min at 240 °C also effectively dissolves the grain boundary β (Fig. 6), although without the softening due to significant annealing.

When implementing a stabilization treatment to existing structures in the field, the process must be robust as it is likely that plate from multiple mills with varying thermomechanical histories were used during construction. Several additional factors must be considered including the effects of the heat transferred to ancillary structures connected to the targeted plate as well as the condition of the plates adjacent to the target area. Sensitization of corrosion resistant plate outside of the target area must be avoided.

Since a ship superstructure cannot be removed and furnace treated as a unit, the stabilization treatment must be performed via a portable heat unit. To demonstrate one possible method of stabilization, a flexible ceramic pad heater was used to treat a vertical as-received 5456-H116 panel. Figure 7 demonstrates an operator using the portable heating unit. Since the panel is larger than the heat source used, the heat source has to be moved around the panel to treat the entire surface. This process causes the plate adjacent to the heat source to experience some intermediate level of heating. To determine if the stabilized plate would become re-sensitized, additional tests were performed.

In addition, Fig. 8 shows that once plate is treated to reverse sensitization and is stabilized, nuisance heating adjacent to the target area of a portable heating unit does not cause any significant change in NAMLT value and thus will not result in re-sensitization.

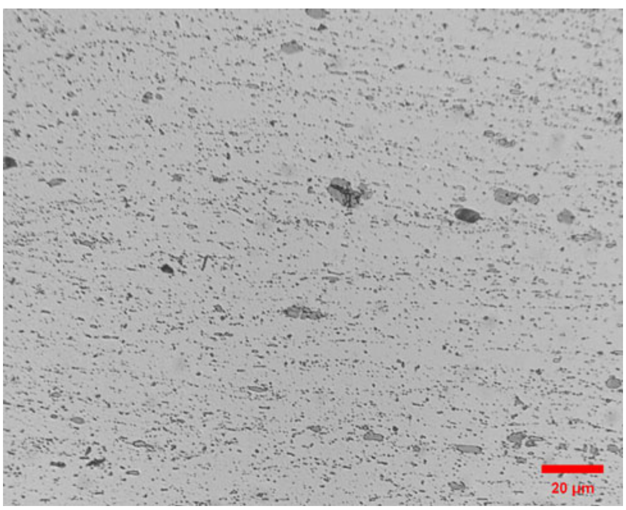


**Fig. 3** 5456-H116 as received

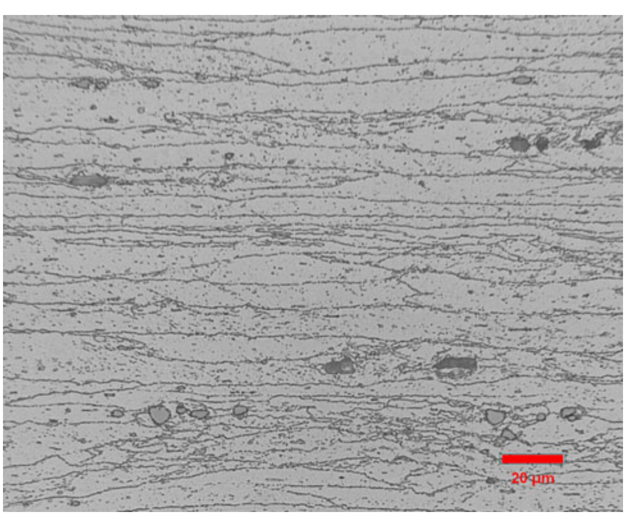


**Fig. 4** 5456 sensitized 24 h at 150 °C

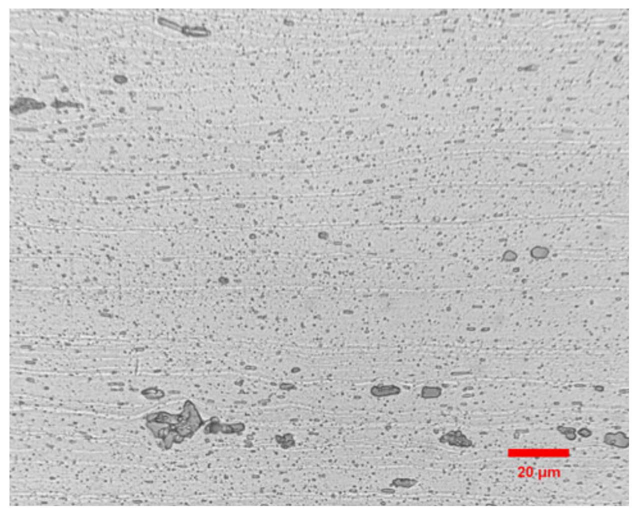


**Fig. 5** Sensitized 5456 after 1 h at 340 °C

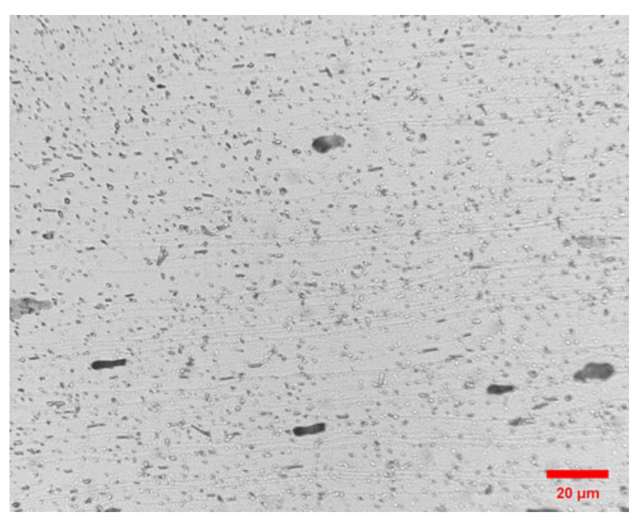


**Fig. 6** Sensitized 5456 after 10 min at 240 °C

Figure 8 shows the sensitization cycle of an as-received 5456-H116 plate that is intentionally sensitized, treated to become stabilized (for 10 min at 280 °C) and then exposed again to an elevated temperature to determine if the plate would re-sensitize. Temperatures adjacent to this treatment area (i.e., the treatment heat affected zone) may approach the treatment temperature for a few minutes but as shown, specimens held for 1 h at 200 °C and at 240 °C do not revert back to a sensitized state but instead are stable. However, an aggressive 24 h treatment at 150 °C (e.g., the same cycle as the initial sensitization treatment) results in the plate being sensitized as it did for the as-received plate. A shorter exposure time of 6 h increases the corrosion susceptibility somewhat although the plate remains below the ASTM B928 limit of 15 mg/cm$^2$. In general, it appears that the treatment given has restored the sensitized plate to near its original condition; this does not make the plate impervious to sensitization, but re-sets the starting point so that its service life is effectively extended. In addition, Fig. 8 shows that once plate is treated to reverse sensitization and is stabilized, nuisance heating adjacent to the target area of a portable heating unit does not cause any significant change in NAMLT value and thus will not result in re-sensitization.

**Fig. 7** Manual stabilization treatment of aluminum panel

## 4. Conclusion

A new thermal process was developed that reverses the sensitization in highly corrosion susceptible 5xxx aluminum alloys and effectively stabilizes the plate to a non-sensitized condition. The process consists of exposing the sensitized plate to temperatures in the range of 240-280 °C for times as short as 10 min. While effective at reversing the sensitized condition of the plates, this process does not adversely affect mechanical properties.

The ability to effectively reverse sensitization of 5xxx aluminum alloys can lead to processes that enable affected structures to be reconditioned rather than scrapped. Sensitization has been observed in plate material at lower operating temperatures than previously thought sufficient to induce sensitization and in plate that had been previously certified to ASTM B928. Thus, it is important to monitor the progress of sensitization on structures (perhaps via new degree of sensitization or DoS probes under development), especially welded ones, before the onset of intergranular corrosion and cracking. Previously, sensitized plate was typically allowed to continue in service until cracking occurred, and then it was removed and a new plate was patched in by welding. An alternative method that reverses sensitization and prevents cracking exists with the application of a simple thermal process. This alternative method enables an extension of service life with lower maintenance costs. The short-treatment time allows for shipboard implementation by means of portable heating units. This process is also amenable to automation including robotic

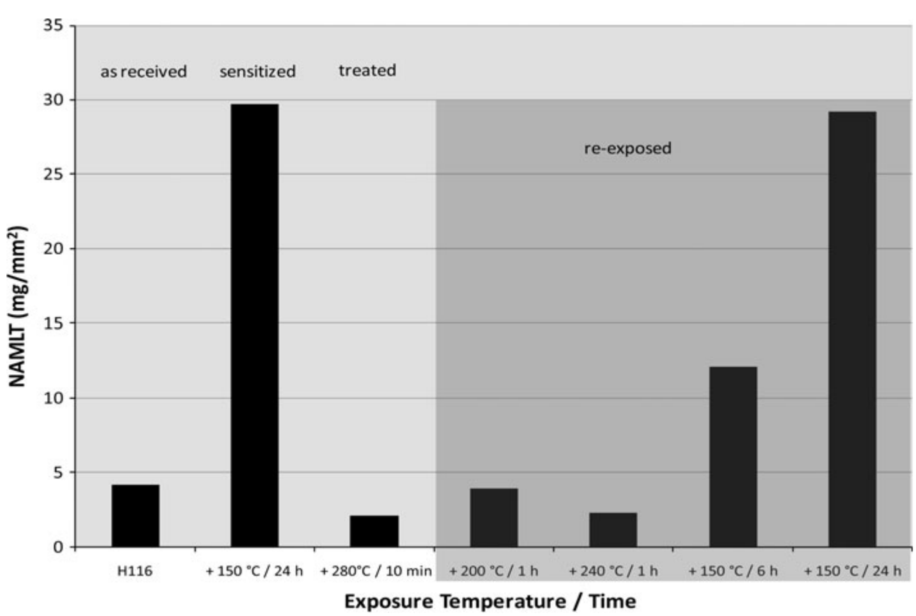


**Fig. 8** NAMLT results of 5456-H116 plate after progressive elevated temperature exposures

manipulation of heater units. Additional development is required to see if the parameters of the treatment cycle are suitable for a wide range of 5xxx alloys produced at different mills under different conditions and to optimize the engineering of the heater units for portable, on-board effectiveness.


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