Development of a Stress Corrosion Test Specimen for Determining the Stress Corrosion Resistance of Aluminum 5XXX Marine Alloys

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ABSTRACT

ASTM Task Group B07.03/G01.09 needed a stress corrosion test specimen for relating nitric acid mass losses (ASTM G67) cited in ASTM B928 to stress corrosion resistance in marine environments.

ASTM B928 was established in 2004, following an inspection survey in 2002 of several boats exhibiting stress corrosion cracking in hull and deck plates of 5083-H321. (1) The intent of B928 is to prevent use of alloys and tempers that are not resistant to intergranular corrosion, exfoliation and stress corrosion. Resistant tempers cited in B928 are –H116 and –H321.

This paper describes how a preform- stressed specimen configuration was found to serve this purpose.

Results of Point Loma, CA. atmospheric test of preformed samples of sensitized 5083-H321 in both sheet and plate thicknesses are provided.

This led to the ASTM Task Group's current use of a modified perform specimen configuration (U-Bend) for more extensive SC tests of the 5XXX alloys with varying mass loss values.[1]

[1] It should be noted that the –H321 temper was not suitable for marine applications until 2004. Since 1972, the –H116 was the only strain hardened temper recommended in North America for use in marine applications. See ASTM Specification B209, 2001

INTRODUCTION

In 2000-2001, cracking of 5083-H321 plated structures was detected on several patrol and catamaran ferry boats built in the Pacific Northwest. A field survey and metallographic studies concluded that the cracking was the result of stress corrosion cracking (SCC). The presence of selective, continuous grain boundary precipitation of the Mg_2Al_3 phase, which results in intergranular, exfoliation and stress corrosion cracking, was the result of improper metallurgical processing. [1] ***This same problem had been observed 30 years earlier and was well documented.*** [2]

A new ASTM Standard, B928, was established in 2004 for marine aluminum alloy. Its purpose is to prevent re-occurrence of these failures. B928 requires producers to certify that their marine alloy products in the –H321 as well as the –H116 temper [(2)] [2] ***met the resistance to intergranular corrosion (IGC) , exfoliation and stress corrosion cracking (SCC) as determined by testing by ASTM G66 (ASSET),) ASTM G67 Nitric Acid Mass Loss Test (NAMLT) and metallographic examination. See B928, paragraphs 9.2, 9.3 and 9.4.*** [3]

In 2005, a Task Group was established jointly under ASTM B07.03 and G01.09 with the purpose of correlating G67 NAMLT mass loss results with performance in natural marine environments. (Some thought the pass/fail mass loss criterion of < 15 mg/cm^2 was too severe.)

For two years, this Task Group struggled to prepare a test matrix involving selection of suitable sample configurations, exposure conditions and alloy types that would assess the correlation of NAMLT mass loss values to resistance to IGC, Exfoliation and SCC in natural marine environments.

In 2007, preliminary testing of residual stressed weldments, made from scrap 5083 plate left over from 2001 was begun. No cracking has been detected after several weeks testing in the laboratory and in marine atmosphere. Since SC failures were noted in service on welded structures, some consider this may have been the result of a relative low susceptibility of the test plates and to an inadequate level of residual tensional stress in the test weldments.

Also in 2007, earlier recommendations to consider the preform stress corrosion sample, as shown in Figure 5 of ASTM 30, were accepted and tests were begun at a Point Loma CA. Pieces of SC susceptible 5083-H321 plate that had been exposed to seawater spray conditions were provided from scrap for the first phase of the study.

In 2009, following the successful completion of preliminary test of preform SC samples in sheet thickness, machined from the salvaged 5083-H321 plate, the second phase of testing was begun using full plate thickness preform specimens from two different 5083 plate sources. This was considered necessary to alleviate concerns of some Task Group members that plate thickness preforms would not SCC.

This report describes the testing and results obtained from Point Loma exposure.

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[2] The –H116 temper was developed in 1969, following discovery of exfoliation and intergranular pitting in5456-H321hull plates on Army and Navy patrol boats. The –H321 temper was no longer acceptable for marine applications in North America.

EXPERIMENTAL PROCEDURE

Phase 1 –Sheet Thickness Preform Sample Testing

In August of 2007, two plates of 0.190 inch (4.8 mm) 5083-H321 were provided by Kvichak Marine, from scrap left after re-sheeting several boats that had exhibited SCC during a few months service in 2000-2001. These two plates came from a doublet plate that served as a temporary repair on the Jet Cat Express catamaran for about 5 months of ferry service between Long Beach and Catalina Island, CA. in late 2001. The plates have been in storage at the Seattle shipyard since that time. [4]

The front side, which had been exposed to the sea water spray for 5 months, exhibited superficial "pitting" attack which subsequent metallographic study showed to be IGC. The back side, not exposed to sea water spray, shows a mottled white-gray-black water stain surface and no pitting.

Small full thickness pieces were cut from the plate for metallographic examination and standard NAMLT test coupons. To provide thin sheet gage, long transverse (LT) to the rolling direction preform samples, one of the plates was machined down from the full thickness of 0.190 inches (4.8 mm) to a final thickness of 0.062 inches (0.157 mm). The machining was done from the front, seawater exposed surface so that the finished sheet gage samples could be stressed with either the backside, water stained surface or the machined sub-surface in tension. A total of 23 flat sheet preform samples were machined from one of the plates.

The flat sheet samples were preformed over an 8T radius to a permanent set of 90 degrees. The legs were trimmed to 3.5 inches (1.34 cm). The stressing tool was used to place the preforms into Micarta [(3)][3] ***fixtures having a 2.5 inch (0.98 cm) span.***

Concerned that the water stained surface may provide protection against SC crack initiation, additional LT preform samples were stressed with the machined sub-surface in tension.

In addition, a few sheet samples were sensitized [(4)] ***by heating for 1 week at 250F (120 C) before preforming. This treatment had been used years ago at Kaiser Aluminum for creating the greatest sensitivity to IGC and SCC. (Others producers used 1 week at 212F (100C).***

Arrangements were made to expose most of the preformed samples at the City of San Diego, CA waste water treatment plant at Point Loma CA.

There was a set of 4 preforms exposed 8/31/07 with the water-stained surface in tension. An additional two samples with the machined sub-surface in tension were exposed on 9/5/07 and two "sensitized 1 week @ 250F" preforms were exposed on 10/5/07 with the machined sub-surface in tension.

Figure 1 shows how the samples are exposed on the back side of a sign, facing the ocean, about 100 feet above the sea.

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[3] Micarta is a trademark of the Norplex-Micarta laminated composite of linen, canvas, paper, fiberglass, and other fabrics in a thermosetting plastic

.4. Sensitize, Sensitization – to induce susceptibility to exfoliation, intergranular corrosion and stress corrosion cracking through thermal treatments which result in the formation of selective, continuous Mg_2Al_3 precipitation along the grain boundaries in aluminum alloys containing more than 3 % magnesium.

Three preforms with the machined sub-surface in tension were sent to Alcoa Technical Center for testing in ASTM G44, 3.5% NaCl Alternate Immersion (AI). Another set of three performs with machined sub-surface in tension were sent to Alcan and exposed at their Brest France marine atmospheric site.

NAMLT tests of the full thickness plate, as received and after sensitizing by heating 1 week @ 250 F, were conducted at the Naval Surface Warfare Center and by the author.

Phase 2 Testing of Full Thickness Preform Plate Samples

Two lots of 5083 plate were tested. All samples were machined to 12 inches (4.7 cm) in length, 0.8 inches (2 cm) wide with 3/8 inch (0.95 cm) dia. holes on 11 inch (4.5 cm) center.

Remnants of the salvage 5083-H321 plate from Kvichak Marine were not adequate to provide a full set of triplicate preforms. Moreover, samples could only be machined and preformed in the longitudinal direction (Long), rather than the long transverse (LT) direction, which is more SC susceptible. Only two preforms were exposed. One was as received, mass loss 45 mg/cm^2 and the other was heated for one week @ 250 F (120 C) before preforming, mass loss of 77 mg/cm^2.

The second lot was provided by Alcoa Technical Research Center in plate form. It was described as 5083-H323, heated for 6 hours at 347 F (175 C). NAMLT mass loss was reported to be 50.4 mg/cm^2. [5, 6] *Three LT preform samples were machined from this plate.*

A bending tool was made for preforming and stressing of the 0.190 inch (4.8 mm) plates. The samples were preformed over a 1.5 inch (8.6 mm) bend radius to a permanent set of 90 degrees. Then the 90 degree preform was further bent over a 0.25 inch (0.64 mm) radius to a span width of 4.5 inches (1.77 cm). A threaded galvanized steel bolt with lock washer and nut were tightened to hold the span width to 4.5 inches. Protective neoprene based coating was used to protect the galvanized steel bolt, nut and lock washer from corrosion in the marine atmosphere.

XRD residual stress measurements showed that the maximum tensional stress occurs at the apex and is of the order of 35-40,000 psi. Residual stress was reduced to 15, 000 psi after heating a preform-stressed plate sample for one week @ 250 F. [7.] *(This treatment simulates the effect of long time exposure of fabricated parts in service to ambient temperatures that exceed 160 F (80 C), as may occur in tropical regions.)*

Atmospheric testing at the Point Loma test site began on June 12, 2009.

RESULTS PHASE 1

Figure 2 shows that the stress corrosion cracks occur at or near the apex of the preform where the highest residual tensional stress exists.

Results of NAMLT, atmospheric and laboratory testing have been reported in periodic minutes of the Task Group 2007 and 2008 meetings. [8]

NAMLT testing showed that the mass loss for the 5083-H321 doublet plate increased from 45-50 mg/cm^2 to 77-80 mg/cm^2 with the additional sensitizing by heating at 250F for one week. [9]

Table 1 contains results of preform tests during the first year exposure at Point Loma. Stress corrosion cracking occurred with all four of the water stained- surface in tension preform samples over a period of 7 to 48 weeks. The two preform samples with the machined sub-surface in tension have not failed during the 1st year exposure. All of these samples have a NAMLT mass loss of 45 mg/cm^2. The two "sensitized 1 week @ 250F" preform samples with the machined sub-surface in tension SC cracked after only 2 and 8 weeks, (NAMLT 77-80 mg/cm^2).

Table 1

Point Loma Exposure of 5083-H321Preform Stress Corrosion Samples
(Exposed from 8/31/07, 9/5/07 and 10/5/07)

Condition Tested	*Time to Cracking*
As rec'd, stained surface in tension, exposed 8/31/07 *NAMLT 45 mg/cm^2*	*4/4 after 7, 8, 24 and 48 weeks*
Heat 1 wk @ 250F, machined sub-surface in tension, exposed 10/5/07 *NAMLT 77-80 mg/cm^2*	*2/2 after 2 and 8 weeks*
As rec'd, machined sub-surface in tension, exposed 9/5/07 *NAMLT 45 mg/cm^2*	*0/2 after 52 weeks (1 year)* *Test terminated after 18 months*

Metallographic studies by C. Henon and B. Davo revealed SCC and IGC on the tension surface and IGC on the underside, compression surface of a Point Loma preform sample. [10]

There were no failures of LT preforms with the machined sub-surface in tension, having a mass loss of 45 mg/cm^2 , at either Brest France atmosphere or in 3.5 % NaCl AI, ASTM G44.

Metallographic examination was made in Spokane on the as received plate and plate heated for one week @ 250F before preforming. Figures 3 show the microstructure of the doublet plate, as received. There is selective, continuous precipitation of the Mg_2Al_3 phase along the recrystallized grain boundaries, typical of an IGC susceptible material. Figure 4 reveals how the continuity of grain boundary precipitation of the Mg_2Al_3 phase increased with heating at 250F for a week.

RESULTS PHASE 2

The three 5083 LT preform plate samples exhibited stress corrosion cracking within 2 to 3 weeks at Point Loma. (Mass loss 50.4 mg/cm^2) Two of the SC cracked preforms are shown in Figure 5.

The longitudinally stressed, sensitized preform plate sample from the doublet plate cracked between 14 and 21 days. (Mass loss 77 mg/cm^2)

The longitudinally stressed preform plate sample from the doublet plate remains intact after 60 weeks exposure at Point Loma.

CONCLUSIONS

The Point Loma CA marine atmospheric testing clearly shows that the preform sample configuration is able to replicate the SC cracking found in service on boat hulls made with SC susceptible metal.

The preform specimen is a relatively simple and economical means of evaluating the relative SC resistance of aluminum marine alloys. It provides the means of achieving the objective of the Task Group in determining the relative significance of various NAMLT mass losses to SC cracking in natural marine environments.

The difference in stress corrosion resistance between longitudinal and long transverse stressed preform samples is significant. This difference was well known some 50 years ago when the marine grade aluminum alloys were first developed.

Residual tensional stresses, introduced during manufacture of boat components, are relieved significantly as the result of long term exposure at high ambient temperature. This may reduce the incidence of SCC in susceptible materials if the remaining residual stress is below the threshold stress. However, it will not prevent exfoliation corrosion or intergranular pitting corrosion.

STATUS

With only one plate preform still intact, the Point Loma exposure was terminated after 18 months exposure.

Experimental testing of the preform sample and the similar U-Bend configuration, in full plate thickness, was currently underway in 2009 at Alcoa Research Center and their Point Judith RI atmospheric test site. SCC was observed in both the laboratory and atmospheric exposures, confirming the Point Loma results .[11]

After a review of the comparative data for the two configurations, the U-Bend sample was selected by the Task Group in 2010 for a limited study of U-Bends specimens in atmospheric, tide range, splash zone and full immersion.[12]

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Dan Stiles and Catherine Wong, Naval Surface Warfare Center, NAMLT testing.
Jacob Padrul, Alcan, ASTM B07.03 Task Group Chairman

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FIGURE 1

The preform samples are mounted vertically on the back of a sign, about 100 feet above the ocean at Point Loma CA. Prevailing winds blow the sea salt spray up to the test site.

FIGURE 2

Stress corrosion cracked sensitized preform sheet sample with machined sub-surface in tension. Cracked in 2 weeks, Point Loma, CA.

FIGURE 3

Microstructure of 5083-H321 doublet plate, as received. Etched, 550X

Note the continuous outlining of the recrystallized grains boundaries as of the result of the precipitation of Mg_2Al_3.

FIGURE 4

Microstructure of 5083-H321doublet plate after heating for 1 week at 250 C. Etched, 450 X.

Compared to Figure3, note how the intensity of grain boundary and grain matrix precipitation has increased as the result of the heating at 250 F.

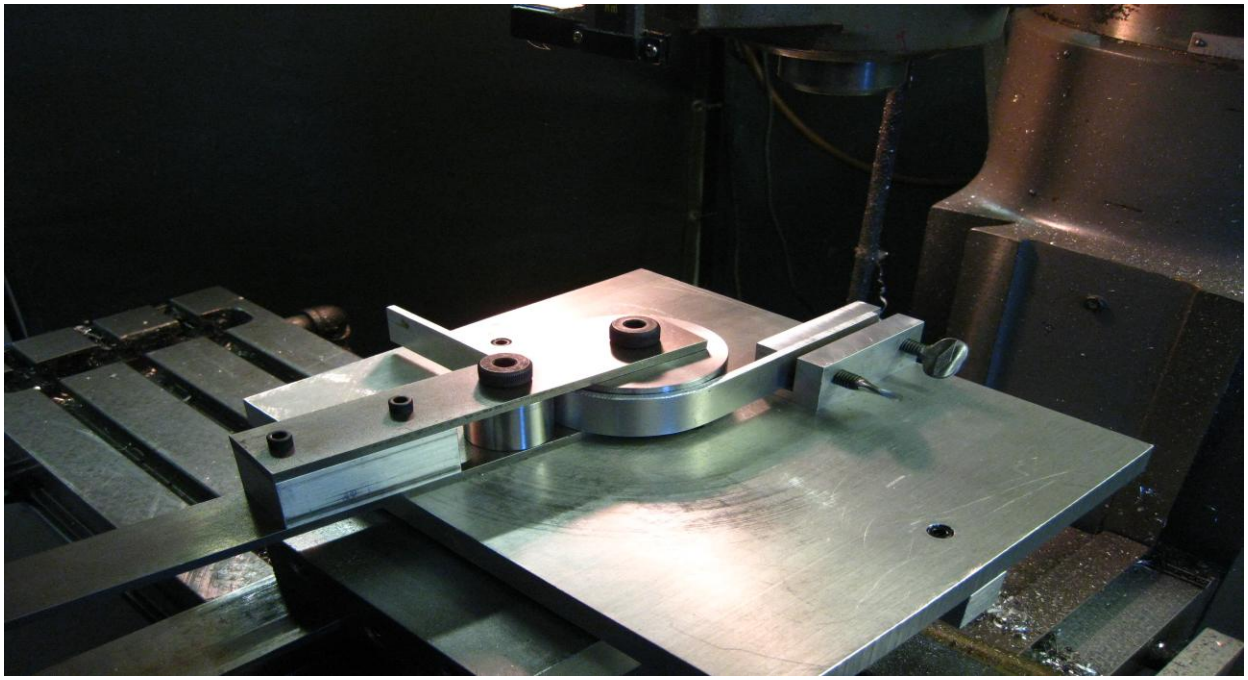

FIGURE 5

Bending Tool for Plate Thicknesses 5XXX Marine Alloys

Sample is bent over a 1.5 inch radius to a permanent set of 90 degrees.

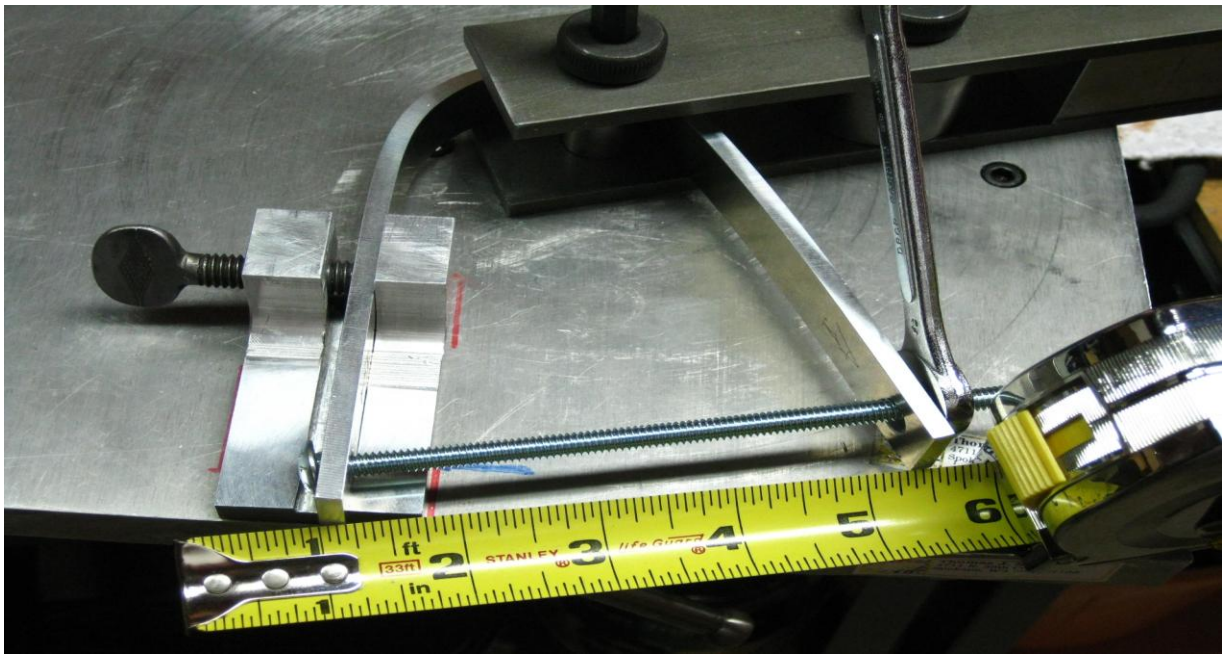

FIGURE 6

Preformed sample is bent over a 0.25 inch radius to a span with of 4.5 inches and held at that span length by means of a galvanized steel bolt, lock washer and nut. For laboratory and natural environment testing, these components are coated with a neoprene based protective coating.

FIGURE 7

Two of the plate gage preforms exhibit SCC after a few weeks at the Point Loma marine atmospheric site.