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Stress-Corrosion Cracking Susceptibility of Various Product Forms of Aluminum Alloy 2519

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Aluminum alloy 2519 is the main structural alloy for the Advanced Amphibious Assault Vehicle (AAAV). A potential drawback to the use of 2519, particularly for an amphibious vehicle, is its susceptibility to corrosion. General corrosion, which is largely in the form of pitting, may reduce the effective life of the system, while stress-corrosion cracking (SCC) of any high strength aluminum alloy can lead to catastrophic failure. Therefore, an evaluation of the SCC susceptibility of various 2519 product forms was performed. Plate, extrusions, ring roll forgings, and weldments all exhibited excellent SCC resistance as measured by a series of standard ASTM tests. Multi-axis hand forgings were the only product forms that exhibited SCC susceptibility, and this susceptibility was remedied via the use of a specifically designed heat treatment. While all product forms passed the prescribed SCC tests, each exhibited a significant reduction in strength after simultaneous exposure to both stress and the saline corrosion environment. Such behavior was not apparent when the exposure was limited to the corrosion media alone. That is, while resistant to SCC, the load-bearing capacities of all products tested are somewhat degraded during concurrent exposure to stress and corrosive media by a mechanism that includes pitting. This article will discuss the effort that was conducted by the National Center for Excellence in Metalworking Technology (NCEMT) to evaluate the SCC susceptibility of 2519 in various product forms and tempers.

Keywords Advanced Amphibious Assault Vehicle (AAAV), aluminum alloy 2519, stress corrosion

1. Introduction

The Advanced Amphibious Assault Vehicle (AAAV) is an armored personnel carrier with a maximum allowable vehicle weight of approximately 34 000 kg (76 000 lb.). The AAAV will be launched from a ship stationed over the horizon relative to shore. After deployment, the vehicle will travel in littoral waters; upon reaching shore, it switches to ground transport mode.

The prime contractor, General Dynamics Land Systems (GDLS, Sterling Heights, MI), baselined Al-Cu-Mg alloy 2519[1-3] as the main structural alloy for armor plate, forgings, and several extrusions. The aluminum alloy 2519 is a logical candidate for armored personnel carriers due to its relatively low density and good combinations of strength and ballistic penetration resistance, even though the high copper alloys are generally more susceptible to corrosion[4,5] compared with the more widely used 5083 Al-Mg alloy. Corrosion resistance is particularly important for the AAAV, an amphibious vehicle. General corrosion, which for aluminum alloys is largely in the form of pitting, may increase the operational and support costs of the system, while stress corrosion cracking (SCC) can lead to catastrophic failure. Therefore, an evaluation of the SCC susceptibility of 2519 in the product forms and tempers that may be used on the AAAV was performed. These include 2519-T87 plate, T8 T-section extrusions, T6 forgings, T8 turret rings, and friction stir (FS) and gas-metal arc (GMA) weldments.[6,7]

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2. Technical Approach

2.1 Test Procedures: Plate, Extrusion, Forgings

Round tensile-type specimens were machined from plate, extrusions, and forgings in accordance with ASTM G49.[8] In this testing, self-stressed rigs were used to provide a constantly applied displacement to the specimens equivalent to a load that is 75% of the tensile yield strength. The rigs are then subjected to an alternate immersion cycle as per ASTM G44[9] (50 min dry/10 min wet per hour) in a 3.5% NaCl aqueous solution and monitored. Typically, catastrophic failure results shortly after the initiation of a stress-corrosion crack, making this an effective screening test.

The test matrix included various product forms including 50.8 mm (2 in.) thick 2519-T87 plate, two 2519-T8 T-section extrusion profiles, a 2519-T6 open-die multi-axis forging, a 2519-T6 bearing support, and a 2519-T8 roll-ring forged turret ring component. The SCC specimens were machined in the short-transverse (ST) orientation for the plate and forgings, the long-transverse (LT) orientation for the extrusions, and the axial orientation for the turret ring. ST specimens were exposed for 10 days, while LT specimens were exposed for 40 days in accordance with ASTM G64. Figure 1 shows the orientations of the specimens for the various 2519 product forms.

The 2519-T87 plate and bearing support forging were commercially produced, while the extrusions and turret ring were custom fabricated for the AAAV. The open die forgings were produced using an equivalent commercial forging practice for 2519.[10] Direct chill cast, homogenized ingots, 6 in. diameter

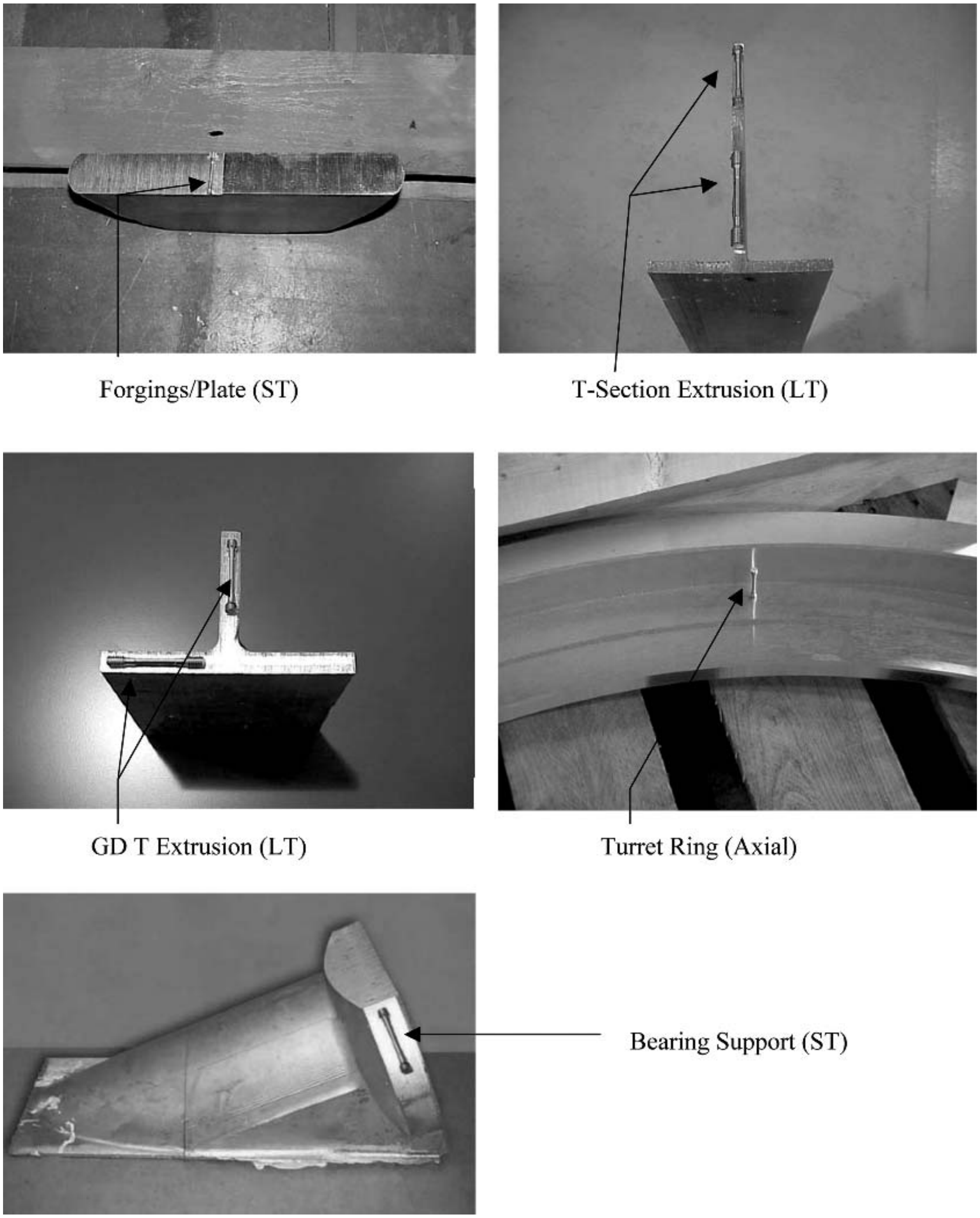

Fig. 1 2519 Product forms (specimens = 50.8 mm [2 in.] length, forging specimen = 38.1 mm [1.5 in.])

by 130 in. long, were sectioned into 12 in. lengths for the open die (i.e., "hand") forging. These billets were then open-die upset forged along three orthogonal axes: A-B-C-A in a process that was selected to break down the cast structure as in commercial forging.

2.2 Test Procedures: Weldments

The AAAV hull is subject to a variety of ballistic threats, making the ductility of the welds of prime importance. GMA welded 2519 butt joints exhibit characteristically low ductility when compared with 5083. As a consequence, GMA butt welds have been eliminated from the AAAV design resulting in increased manufacturing complexity and cost. FSW, a relatively new solid-state joining technology,[11] is being evaluated as an alternative to conventional arc welding, particularly as a means to achieve satisfactory plate-to-plate butt welds.

FSW has numerous advantages over conventional fusion welding, including: superior strength and ductility, significant

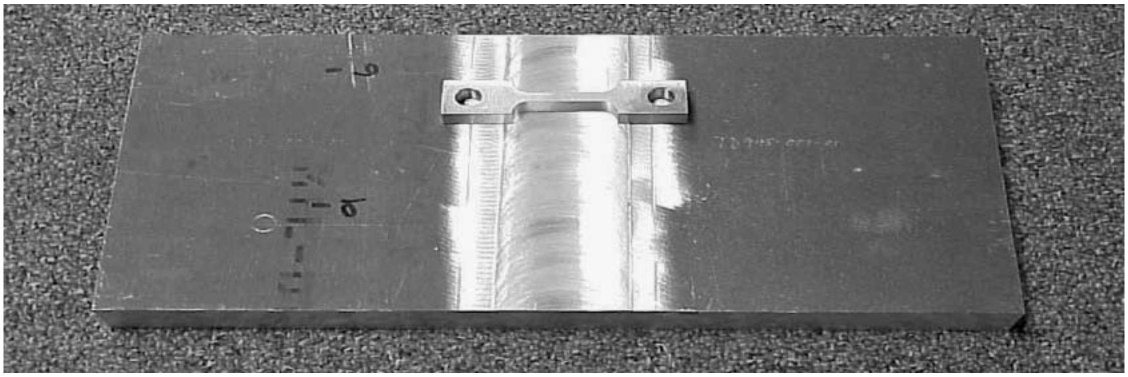

Fig. 2 FS weldment SCC specimen (specimen = 89 mm [3.5 in.] length)

reduction in residual stresses, elimination of filler wire, superior corrosion resistance, greatly simplified weld preparation procedures, and reduced environmental health and safety concerns.

Friction stir and GMA weldments were tested in accordance with ASTM G58[12] in which a rectangular, pin-loaded tensile specimen was subjected to alternate immersion in a 3.5% NaCl solution while under a constant load. Figure 2 shows the orientation of the specimen with relation to the weldment and the base plate. The specimen is shown lying on top of an FS weldment, which includes the shoulder of the weld; however, the specimen was actually taken from the mid-thickness of the plate. The specimen gauge length therefore includes weld nugget and heat affected zone, as it does for the GMA weldments.

The testing rigs were specially fabricated and use a weight and pulley system to apply a constant, or dead load. The load chosen for these tests was equivalent to 75% of the specimen's tensile yield strength. Prior to loading the specimen, the rigs were calibrated using a load cell in place of the specimen. To ensure no galvanic effects, all metal surfaces that may contact the NaCl aqueous solution were encapsulated (as recommended in ASTM G44) with a stop-off lacquer (Miccro SuperXP 2000 LR, Tolber Div., Hope, AR) so that the only metal exposed to the solution was the gauge length of the specimen. The test rig was outfitted with an automatic switch that recorded the time of any failure. The standard LT specimen test duration of 40 days was used.[13]

After testing, specimens were removed from the test rigs and the surviving specimens were pulled in tension to determine their residual yield strength. This type of test can be used to determine the effects of exposure plus stress on tensile properties. Metallography of the specimens was also performed.

3. Test Results

3.1 Plate, Extrusion, Forgings

Specimens of 2519 were loaded to the conditions described in Table 1. Approximately 15-20 specimens from each product form were prepared. Two of these were used for pre-exposure tensile tests, two were exposed with no applied stress, and the remaining specimens were exposed at 75% of the measured yield strength.

Table 1 SCC Test Conditions for 2519

Material	Orientation	Test Duration, Days	Mean YS, MPa	Applied Stress, MPa	Equivalent Microstrain, mm/mm $\times 10^{-6}$
Plate	ST	10	442	332	4535
T-Extrusion A	LT	40	367	275	3764
T-Extrusion B	LT	40	331	248	3396
Hand Forging	ST	10	332	249	3403
Hand Forging (a)	ST	10	303	227	3103
Bearing Support	ST	10	287	207	2830
Turret Ring	Axial	10	345	259	3547

(a) Alternative T6 heat treatment.

No fractures occurred during testing for the plate, extrusion, bearing support, and turret ring specimens. Specimens of the 2519 short-transverse hand forgings failed within the exposure period as detailed in Table 2, although 2519 hand forgings that were heat treated by an alternative T6 cycle passed the test. The rationale behind this alternative heat treatment is provided below.

One possible conclusion regarding the failure of the forged specimens is that the solute in the alloy did not completely go into solution during solution heat treatment resulting in the presence of Cu-containing constituent particles that contributed to SCC susceptibility.

Alloy 2519 at Cu levels above about 5.3%, like its predecessor 2219, contains solute content that is sufficiently high such that not all solute can go into solid solution during solution heat treatment (SHT), if time and temperatures for SHT are not sufficient. The excess solute above the solubility limit can contribute to strength by increasing precipitation kinetics and is also effective in increasing weldability via a reduction in hot tearing.[7,10] Consequently, alloys 2519 and 2219 are solution heat treated very close to the solidus temperature. While the plate and extrusions were effectively solutionized, the thicker cross-section of the forgings (~76 mm) as compared with the plate (~50 mm) may have caused the center region of

Table 2 Duration of 2519 Short Transverse SCC Tests—Hand Forgings

Material	YS, MPa	Applied Stress, MPa	Time to Failure, Days (a)
2519-T6	332	249	4, 4, 5, 5, 5, 5, NF, NF, NF
2519 Alternate T6	303	227	NF, NF, NF

(a) NF—no failure.

the forgings to have been substantially below the solidus temperature during solution heat treatment. This would result in a higher volume fraction of constituent particles to remain in the microstructure than would be obtained by more effective solutionizing.

Based on these considerations, an alternative SHT cycle was run for the 2519 hand forgings. While the original SHT cycle consisted of holding the forgings at 532 °C for 1 h, the alternate cycle consisted of a ramp from room temperature to 315 °C, hold for 3 h, ramp to 532 °C, and hold for 8 h, and water quench. After SHT, the forgings were aged to the T6 condition, specimens machined in the ST orientation, and 10 day SCC constant displacement tests were run. The results of these tests indicate that the forgings did respond favorably to the alternate heat treatment, and SCC resistance can indeed be acceptable for T6 forgings. In addition, a commercially forged and heat-treated 2519-T6 bearing support showed SCC resistance, thus providing additional confidence in forgings that are properly heat treated to a T6 temper.

To separate the effects of stress and environment, the surviving SCC specimens and the unstressed specimens that were exposed to the saline environment and alternate immersion cycle were pulled to obtain their residual strength after exposure. The results, as shown in Table 3, give an indication of the extent of the reduction in cross-sectional area of the specimens and stress concentration effects, due to intergranular or pitting corrosion. Such effects are manifested by a reduction in strength. The reduction in strength is greater when specimens are exposed under load. That is, a greater reduction in cross-section and/or a more damaging morphology of the pitting for the specimens exposed to both stress and saline environment resulted in lower post-test strength values. This phenomenon occurred for 2519 in all product forms. Quite noticeable, however, is the very large difference between post-test properties for stressed and unstressed specimens for the hand T6 forgings and commercially forged T6 bearing support. In fact, the post-test results for the stressed specimens machined from these components were so low as to question whether the stress-assisted corrosion resulted in relaxation of the specimen during testing, thus enabling the specimens to survive the test duration.

Selected post-test tensile specimens were sectioned, mounted, and polished for metallographic investigation. Figure 3 and 4 compare a 2519 plate specimen that was unstressed and a specimen that was stressed to 75% YS. Clearly, the pitting in the unstressed specimen (Fig. 3) is general in nature, with two pits visible in the center of the micrograph advancing into the specimen. The stressed specimen (Fig. 4) displays pits that are longer and sometimes directional along grain boundaries as in the center of the micrograph. Although no 2519-T87 plate specimens failed the SCC test, the directional pitting in the plate is stress-assisted.

Any contribution of stress to pitting is less clear for the 2519-T8 extrusions in the LT orientation (Table 3). For both T-extrusions, the post-exposure yield strength was actually higher when stressed than when unstressed, suggesting that pitting was not stress assisted. However, the post-exposure ultimate tensile strength was lower for stressed specimens than it was for unstressed specimens, as was the case for 2519-T87 plate. It is possible that pitting is also stress assisted in the extrusions, but the LT orientation exposes fewer S-L oriented grain boundaries, which are more susceptible to both pitting and geometric stress concentration resulting from the longer pitting path along the extrusion (L) direction. This might not have a discernable effect on post-exposure yield strength, but would be discernible by a reduction in ultimate tensile strength as deformation proceeds in the plastic regimen.

3.2 Test Results: Weldments

Both GMA and FSW specimens of 2519 were tested in the dead-load rigs at loads equivalent to 75% of the measured yield strength. Test conditions are given in Table 4.

All 2519 weldment specimens passed the 40-day test duration. No stress corrosion was noted, although the general corrosion was extensive.

4. Discussion

The 2519 plate, extrusions, forgings, and turret ring specimens exhibited good SCC resistance. Initially, the hand forgings tested exhibited SCC susceptibility, although the use of an alternative T6 heat treatment procedure resulted in good SCC resistance. This can be due to a number of factors. First, the grain structure of the forgings was significantly different from that of the plate and extrusions. While plate and extrusions have a very textured, lamellar grain structure, the A-B-C-A forging process likely produced a more equiaxed grain structure. In fact, it is not certain whether the hand forging schedule adequately broke down the cast structure of the billets. Second, the T8 heat treatments used for plate and extrusions required a cold stretch after quench. Since this uniform cold stretching cannot be performed for forgings, the peak-aged T6 temper does not have the benefit of the dislocations to stimulate the nucleation of the very fine strengthening precipitates, which increase strength and reduce the scale of composition gradients. Nevertheless, the modified heat treatment, which essentially kept the forging at the solution treatment temperature longer, was able to provide both good strength and SCC resistance.

Reference 14 is an investigation of the SCC results utilizing optical and electron microscopy. The primary author, Roy Crooks, recommended the modified heat treatment cycle for the hand forgings as a method of ensuring adequate solutionizing of the alloy. That is, the thickness of the hand forgings may have inhibited an adequate T6 solution heat treatment by not allowing sufficient strengthening elements to go into solution. If so, then less copper would be available for precipitation

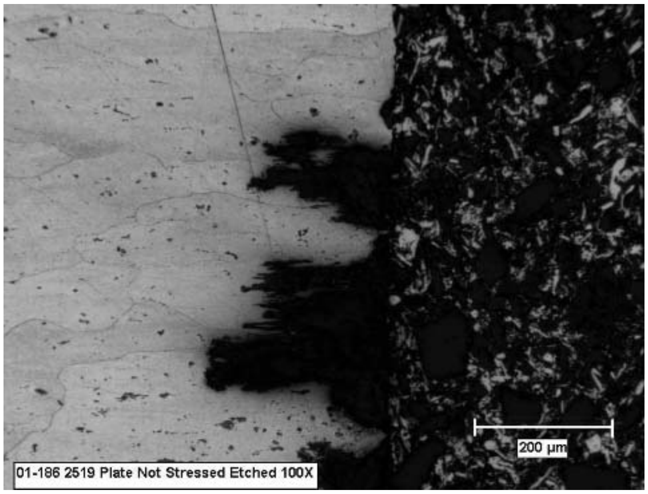

Fig. 3 Post-test cross-section of 2519-T87 plate (not stressed during exposure)

Fig. 4 Post-test cross-section of 2519-T87 plate (stressed at 75% YS during exposure, stress applied normal to cross-section)

Table 3 Post-SCC Test Mean Tensile Properties for 2519

Material	Orientation	Pre-Test YS, MPa	Pre-Test UTS, MPa	Exposure, Days	Applied Stress, MPa	Post-Test YS, MPa	Post-Test UTS, MPa
T87	ST	442	469	10	332	355	361
Plate					Unstressed	378	397
T8	LT	367	445	40	248	328	365
T-Extrusion A					Unstressed	306	392
T8	LT	331	426	40	275	290	49.6
T-Extrusion B					Unstressed	276	365
T6 Hand	ST	332	418	10	249	failed (b)	failed
Forging					Unstressed	314	416
T6 Hand	ST	303	410	10	227	n/a (c)	n/a
Forging (a)					Unstressed	288	369
T6 Bearing	ST	287	391	10	207	n/a	15
Support					Unstressed	229	276
T8	Axial	345	439	10	259	290	332
Turret Ring					Unstressed	294	337

(a) Alternative T6 heat treatment.
(b) Failed indicates that the specimens failed the standard 10-day test duration.
(c) n/a indicates that the specimens passed the SCC test; however, they corroded to the extent that they did not exhibit a measurable YS and UTS in the post-test tensile test.

hardening, leaving more of these elements as primary particles, resulting in a compromise in the SCC resistance of the alloy. The modified heat treatment proved successful in decreasing SCC susceptibility—likely by providing more strengthening precipitates, and fewer primary particles. Perhaps most important, an actual AAAV 2519-T6 forging, the bearing support, was shown to be SCC resistant.

Although the 2519 plate, extrusion, forging, and turret ring specimens passed the SCC test, further testing for these product forms may also be warranted. Stress-assisted pitting is apparent in these specimens with the degradation occurring along the major axes of grain boundaries. These directional pits may also have caused a relaxation of the stress, as small cracks can, as described in ASTM G49. This relaxation could have enabled the specimens to survive the test duration. Post-test yield strength values were either close to the original applied stress, or very low, implying that applied stress relaxed during SCC testing.

Both GMA and FS weldments of 2519 plate exhibit good SCC resistance (Table 5).

5. Conclusions

Alloy 2519-T87 plate, T8 extrusions, T8 ring-roll forgings, and T6 forgings displayed no SCC susceptibility in the standard 3.5% NaCl aqueous solution under conditions of alternate immersion specified in ASTM standard G64. SCC failures were observed for laboratory-scale open die hand forgings of 2519 in a T6 temper. The SCC failures were likely caused by incomplete solution heat treatment and a forging sequence that did not adequately break up the cast structure. An alternative

Table 4 Weldment SCC Test Conditions

Material	Measured LT YS, MPa	Applied Stress, MPa	Applied Load, kg	Exposure Days
GMA	163	122	602	40
FSW	183	138	679	40

Table 5 Measured Composition of 2519, wt.%, Balance Al

	Cu	Mg	Mn	Ti	V	Zr
Spec. (a)	5.3-6.4	0.05-0.4	0.05-0.4	0.02-0.4	0.05-0.15	0.1-0.25
Plate	5.61	0.30	0.21	0.05	0.10	0.80
Extrusion	5.42	0.31	0.26	0.04	0.08	0.08
Forging	5.29	0.32	0.25	0.05	0.08	0.08

(a) MIL-A-46192-B.

T6 heat treatment, in which the solution heat treatment step was modified, was successfully used to provide SCC resistance.

Alloy 2519-T87 plate displayed stress assisted pitting, despite passing the standard SCC tests. This mechanism of environmental attack has not previously been reported for 2519-T87. This attack may reduce the load-bearing strength of the 2519 structural member. Further investigation is warranted to evaluate this effect, although corrosion protective coatings have been investigated to mitigate this effect in alloy 2519. In addition, a very large difference between post-test properties for stressed and unstressed specimens were noted for both the 2519-T6 hand forgings and 2519-T6 commercially forged bearing support. That is, while these product forms passed the SCC requirement, both exhibited a significant reduction in strength after exposure to both stress and a saline environment. Thus, further evaluation of 2519-T6 forgings is warranted.

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