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STRESS CORROSION CRACKING OF AN ALUMINUM-LITHIUM ALLOY

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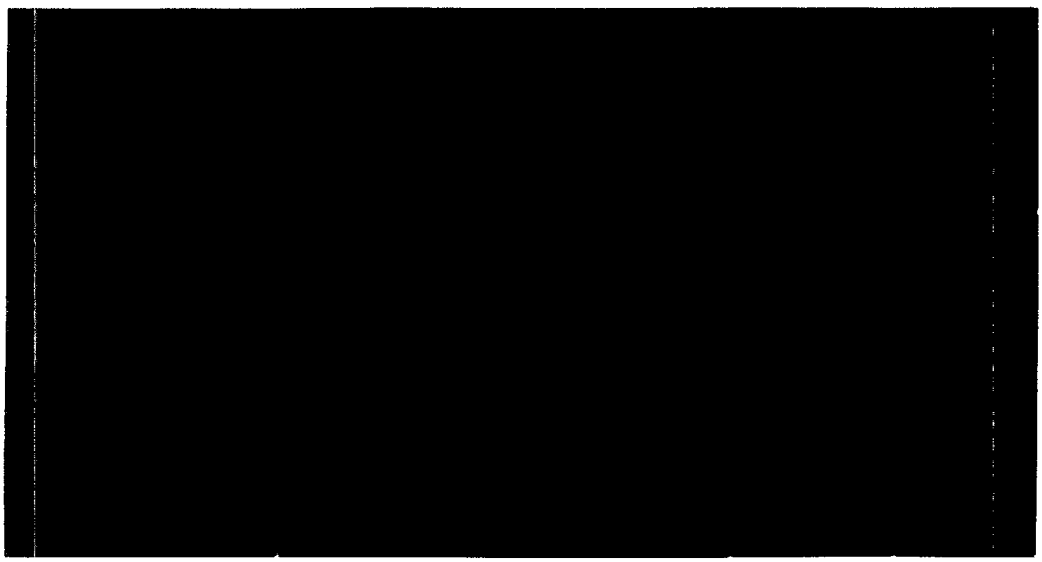

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STRESS CORROSION CRACKING OF AN ALUMINUM-LITHIUM ALLOY

by

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Canada

ABSTRACT

The breaking load method was used to evaluate the susceptibility of the aluminum-lithium alloy, AA 8090-T8771, to stress corrosion cracking when exposed to alternate immersion in sea water. The performance of this alloy was compared with that of a conventional aluminum alloy, AA 7075-T651. The original test method showed that both alloys were susceptible to stress corrosion cracking, with threshold stresses close to zero. The method also indicated that both alloys were weakened by a degradation mechanism that occurred in the absence of an externally-applied stress. Microscopic examination showed that the weakening was caused by intergranular cracking.

The extreme value distribution was found to provide a reasonably good fit to the data, but its use did give rise to several problems previously noted in an interlaboratory test program. The procedure involving Box-Cox transformations did alleviate these problems and served to confirm the conclusions reached using the original method, even though the statistical calculations may not have been strictly valid. Analysis of variance of the transformed data showed that there was no significant difference in the overall behaviour of AA 8090-T8771 and AA 7075-T651 when exposed to alternate immersion in sea water at several different stress levels for several different lengths of exposure. Analysis of variance also suggested that the initiation of intergranular and stress corrosion cracking occurred in a shorter period of time for 8090 than for 7075, but propagation of stress corrosion cracks then occurred more rapidly in 7075 once cracking had been initiated.

1. INTRODUCTION

Aircraft designers, manufacturers and operators are continually seeking new materials for aircraft structures that have higher strength-to-weight ratios in order to achieve significant weight reductions. A lighter airframe can result in lower fuel consumption, longer range, higher acceleration and/or heavier payloads. This search has led to heightened interest in the development and use of aluminum-lithium (Al-Li) alloys. These alloys offer the promise of lower density, higher elastic modulus, higher strength and improved thermal stability when compared to conventional aluminum alloys[1,2].

Historically, improvements in mechanical properties with new alloys have often resulted in increases in susceptibility to corrosion that were not adequately studied prior to the specification of these alloys in aircraft structures. For example, aircraft designers were quick to specify the T6 temper of Aluminum Alloy (AA) 7075 because of its high modulus and strength. It was subsequently discovered to be highly susceptible to stress corrosion cracking (SCC) and exfoliation in marine environments, thereby resulting in substantial costs for aircraft operators[3]. A new procedure for determining the susceptibility of aluminum alloys to SCC that does not depend on traditional time to failure methods has been developed by Alcoa Laboratories for the National Aeronautics and Space Administration. This procedure, known as the breaking load method[4], appeared to have the ability to separate the effects of SCC from the damage caused by pitting and general corrosion. However, a recent interlaboratory test program aimed at assessing the reproducibility of the breaking load method revealed several shortcomings in the statistical procedure that was used[5]. An alternate approach, based on Box-Cox transformations[6], was proposed and tested.

The Canadian Department of National Defence had been planning to acquire a new helicopter to replace its existing Sea King and Labrador fleets. The manufacturer of this helicopter favoured the extensive use of Al-Li sheet, extrusions and die forgings. In order to acquire some first hand experience with the resistance of these alloys to SCC and as part of larger experimental program to assess both the original breaking load method and the proposed modification incorporating the Box-Cox transformation, the Defence Research Establishment Pacific (DREP) has used these techniques to determine the SCC behaviour of plate made from AA 8090-T8771 that was subjected to alternate immersion in sea water. The behaviour of this alloy was compared with that of AA 7075-T651, which was tested under identical conditions. The susceptibility of the latter alloy to SCC has been extensively studied by traditional methods, to the point that it appears as an example in the American Society for Testing and

Materials (ASTM) Standard G47-79[7] for conducting SCC tests and was used in the interlaboratory test program[5].

2. BACKGROUND ON THE BREAKING LOAD METHOD

The raw data for the breaking load method is obtained by measuring the "apparent tensile strength" of smooth tension specimens that have been stressed to pre-determined levels in a "constant strain" fixture and then exposed to the corrosive environment for set periods of time. The apparent tensile strength of each specimen is calculated using its original cross-sectional area without consideration for any thinning of the specimen due to general corrosion or stress corrosion cracking. This data provides an indication of the change in load carrying capability of the specimens as a function of exposure time and externally-applied stress. Reductions in the apparent tensile strength for stressed specimens beyond those found for unstressed specimens are assumed to be due to stress corrosion cracking.

Statistical analysis of the breaking load data is based on the assumption that the specimen breaks at its weakest point. If a specimen develops SCC, it may contain a wide spectrum of crack sizes but fracture will always occur at the largest crack. As a result, the distribution of all crack sizes within a group of specimens is not as important as the distribution of the largest cracks. The extreme value distribution pioneered by Gumbel[8] applies to the largest cracks, assuming that the distribution of all crack sizes is exponential. These assumptions were supported by the work of Aziz[9], who characterized pitting depth with an exponential distribution and showed that the maximum pit depth followed the related extreme value distribution. Since SCC is also related to the microstructure, the breaking load data for specimens suffering from SCC should follow an extreme value distribution as well. However, since fracture stress is related to the largest flaw size in an inverse manner, the appropriate distribution for a fracture stress would be an extreme value distribution of smallest values[4]. This distribution is bell-shaped but skewed to the left, so a group of replicate tests is likely to produce a wider range of fracture stresses below the most probable value than above.

The probability for survival, with survival defined as no failure at the stress of interest during the period of exposure, is expressed by the following equation, attributed to Gompertz[10]:

$$P = \exp(-e^{Z}) \qquad (1)$$

where P is the probability of survival and Z is the reduced variate, which has the form:

$$Z = (S-\hat{\mu})/\hat{\sigma} \quad (2)$$

where S is the exposure stress and $\hat{\mu}$ and $\hat{\sigma}$ are estimates of the distribution location and scale parameters, respectively. These parameters, which are comparable to the mean and standard deviation of the normal distribution, are determined using the probability plotting method[11]. The breaking strengths of the replicate specimens in a test group are ranked in descending order and plotted against the expected value of each ranked observation. Specimens which broke during the last day of exposure are included in the calculations with a breaking strength equal to the applied exposure stress. Specimens which broke prior to the final day are assumed to belong to the distribution, and hence affect the expected values, but are not available for plotting.

The expected value of the i^{th} observation is estimated by the R^{th} fractile of the distribution, where:

$$R_i = (i-½)/N \quad (3)$$

and N is the sample size. For the extreme value distribution of smallest values, the expected value of the i^{th} observation is:

$$E_i = -\ln[-\ln(R_i)] \quad (4)$$

If the data from a test group follows an extreme value distribution, a plot of E_i versus the ranked breaking strengths will yield a straight line. The slope, m, and intercept, b, of this line are determined by linear regression and provide estimates of $\hat{\mu}$ and $\hat{\sigma}$ for a large sample size, denoted by $\hat{\mu}_\infty$ and $\hat{\sigma}_\infty$, from the following equations:

$$\hat{\mu}_\infty = -\frac{b}{m} \quad (5)$$

$$\hat{\sigma}_\infty = -\frac{1}{m} \quad (6)$$

Before their use in Equation 2, these parameters must be adjusted to account for the small sample size employed in our experiments according to the following equations:

$$\hat{\sigma} = \hat{\sigma}_\infty(\sigma_\infty/\sigma_n) \quad (7)$$

$$\hat{\mu} = \hat{\mu}_{\infty} - \hat{\sigma}_{\infty} y_{\infty} + \hat{\sigma} \bar{y}_n \tag{8}$$

where n is the number of the N specimens which survived to be tensile tested, $\sigma_{\infty} = \pi/\sqrt{6}$, $y_{\infty} = 0.577$, and σ_n and $\bar{y}_n$ are found in a table extrapolated from the work of Gumbel[12] by Sprowls and co-workers[13].

One of the advantages reported for the breaking load method is the ability to estimate the survival probability, P (Equation 1), with reasonable confidence as the actual probability of survival for a resistant material approaches 1.0. Such a material normally displays very few failures in traditional time-to-failure methods. As a result, a prohibitively large number of specimens would be required to determine a value of P with reasonable confidence.

A more meaningful use of the breaking load data can be obtained by calculating the tensile stress at which 99% of the specimens could be expected to survive a specified exposure stress for a specified length of time. This 99% survival stress(S_{99}) is determined using the following equation:

$$\begin{aligned} S_{99} &= \hat{\mu} + \hat{\sigma} \cdot \ln[\ln(0.99)^{-1}] \\ &= \hat{\mu} - 4.60 \cdot \hat{\sigma} \end{aligned} \tag{9}$$

and not only permits a direct comparison of stressed and unstressed specimen performances, but also provides a numerical value for comparing materials. Furthermore, the 99% survival stress can be used with fracture mechanics theory to estimate the equivalent flaw size that would not be exceeded in 99% of the SCC specimens that survived. A plot of this flaw size as a function of time could provide information about crack growth rates.

The 99% survival stress obtained for a given material at a specified exposure stress and length of exposure does not generally correspond to a threshold stress below which SCC would not be expected to occur within the specified exposure time. However, a series of S_{99} values can be used to obtain a statistically-defined threshold stress, S_{th}, such as the stress for which there is a 95% confidence of a probability of survival greater than 99%. This threshold stress is determined by plotting S_{99} against the exposure stress for each exposure time and calculating the intersection of each best fit line, obtained by linear regression analysis, with the line defined by S_{99} equalling the exposure stress. The mean, m, and standard deviation, s, of these intersection points are calculated and then used to determine the lower confidence limit, LCL, from the following equation:

$$LCL = S_{th} = m - \frac{t_{n-1} \cdot s}{\sqrt{n}} \tag{10}$$

where n is the number of different exposure times (intersection points) and the value of t_{n-1} is obtained from a table of the cumulative t distribution[14] for a one-tailed t-test with 95% confidence. The value of S_{th} provides a single number which can be used to rate the behaviour of different alloys in the same environment.

3. BOX-COX TRANSFORMATIONS

A major problem with the original breaking load method that was identified by the interlaboratory test program is the extreme sensitivity of the value of the 99% survival stress to differences in the standard deviation of different test groups. Colvin and Emptage[5] showed an example of data from an identical test group (five specimens of AA 7075-T651 exposed to alternating immersion in 3.5% sodium chloride for 6 days at 138 MPa) from two different laboratories. From the number of specimens which failed prior to tensile testing, it was clear that one group had suffered more damage than the other. However, the calculated value of S_{99} was lower for the group with more survivors, simply because there was a greater variation between individual breaking strengths within that group. Furthermore, eliminating the worst performing specimens(those that broke prior to tensile testing) from the calculations of $\hat{\mu}$ and $\hat{\sigma}$ biased the test results, leading to higher values of S_{99} for groups in which some specimens failed than would occur if those specimens had barely survived to be tested. Use of the extreme value distribution could also give rise to negative values for S_{99}, and hence for S_{th}, which are physically impossible. The obvious first approach of setting negative values of S_{99} to zero was shown to result in misleading conclusions. Finally, the statistical procedure could only be applied to the individual stress/time test groups. As a result, the method could not be used to obtain an overall estimate of the variance which would account for inconsistencies not related to resistance to SCC, such as machining finish and location within the exposure apparatus.

The Box-Cox transformation was proposed to address the problems encountered with the extreme value distribution. Successful implementation of the transformation is predicated on the assumption that the variance increases in some manner with decreasing residual strength. This assumption seems reasonable for specimens which are experiencing stress corrosion cracking. Prior to the initiation of SCC, there should only be a small variation in the breaking strengths of individual specimens. However, as cracks grow, and the breaking strength decreases, there should be an ever increasing variation in crack lengths resulting from even slight differences in crack growth rates between specimens.

The first step in the procedure involves a preliminary transformation of the original breaking strength values, X, by the following equation:

$$X_{tr} = \frac{100 \cdot X}{X_0} \qquad (11)$$

where X_0 is the average breaking load for no exposure for the given alloy or temper. The value of X_{tr} provides the percent retention of the original breaking strength and therefore standardizes the results for alloys with different uncorroded strength levels.

The average, m, and the standard deviation, s, are calculated for each individual stress/time test group with more than one specimen which survived to be tensile tested. The slope, α, of the best fit straight line is determined from the plot of ln(s) versus ln(m) for each different alloy. This plot describes the nature of the relationship assumed to exist between the breaking strength and the variance. If the plot is not linear, the Box-Cox procedure cannot be applied to the system under investigation. If a meaningful value of α can be determined, the Box-Cox transformation is a power transformation which has the form:

$$Y = (100/100^{\lambda}) \cdot (X_{tr}^{\lambda} - 1) \qquad (12)$$

where the power of transformation, λ, is equal to $1 - \alpha$. The constant, $100/(100)^{\lambda}$, gives rise to transformed values of Y in the range from 0 to 100, which is the same range as the values of X_{tr}.

As shown in Figure 1, the Box-Cox transformation essentially stretches the residual strength axis for large strength values and compresses the axis for small values. As a result, the transformation provides a means of discriminating between alloys with high levels of resistance to SCC. Such alloys would be difficult to separate using traditional pass/fail criteria. Another important effect of the transformation is also illustrated in Figure 1. The variances of the individual stress/time test groups, which increase with decreasing mean breaking strength, are all approximately equal after transformation. Furthermore, the transformed data follows a normal distribution in many cases. As a result, standard statistical techniques, such as t-tests and ordinary analysis of variance[15] (ANOVA), can be used. Since the variance is equivalent throughout the Box-Cox transformed metric, least significant differences and lower confidence limits are easily calculated.

Once the value of λ has been determined, statistically plausible values of Y are generated for the specimens which fail prior to tensile

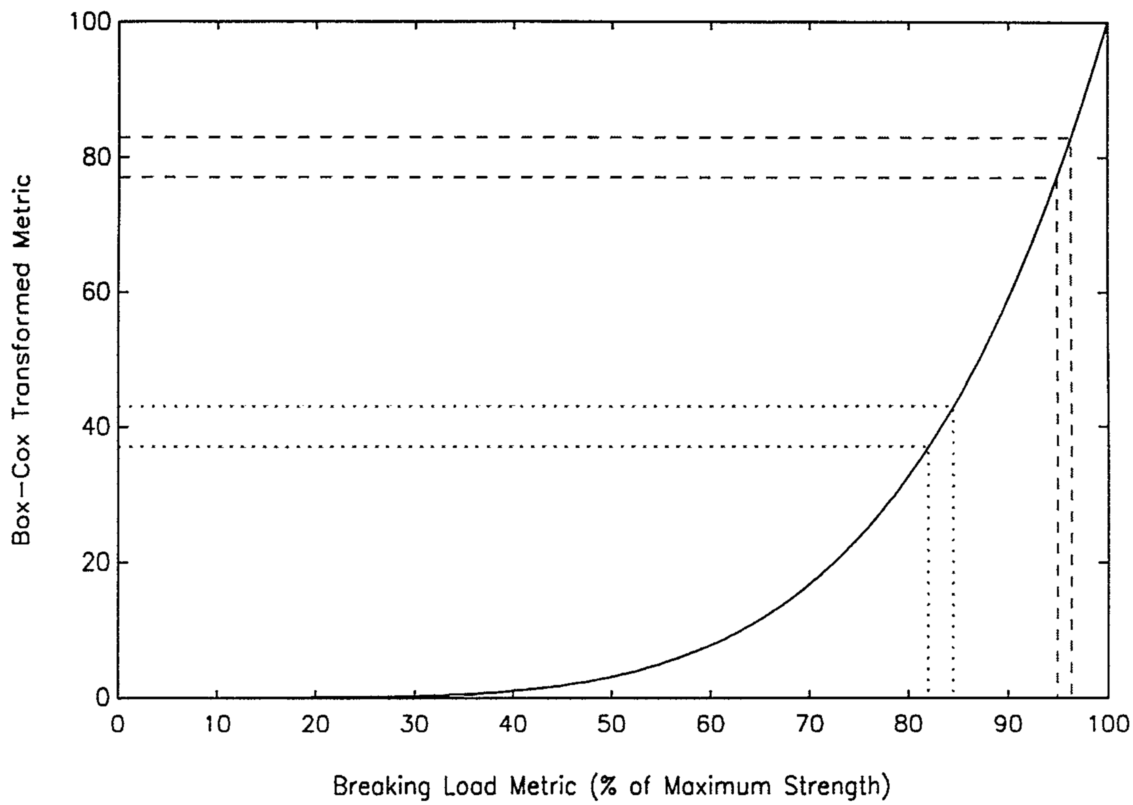

Figure 1. Box-Cox transformation curve for the example of λ=5. The dashed lines illustrate the transformation of the variance for one hypothetical test group while the dotted lines illustrate that for another test group with lower breaking strength and larger variance.

testing. A specimen which fails on the day it is scheduled to be tensile tested is assigned a value of Y equal to the transform of the exposure stress, Y_{exp}. A specimen which fails prior to the final day is assigned a value of Y obtained by generating a random number over the interval $(0, Y_{exp})$. This procedure is simple, conservative and allows the use of the analysis of variance technique.

A simple way of analyzing a set of transformed data would involve the determination of the mean and standard deviation of each cell (stress/time test group) in the data table. Since each cell has the same number of "observations", the pooled estimate of the standard deviation, s_p, is:

$$s_p = \sqrt{\frac{(s_1^2 + s_2^2 + \ldots + s_r^2)(N - r)}{r(N - r - c)}} \tag{13}$$

where N is the total number of observations (specimens), r is the number of data cells and c is the number of specimens that failed prematurely. The smallest difference in the means of the two cells that is statistically significant, the least significant difference of LSD, is given by:

$$LSD = t_\nu s_p \sqrt{\frac{2}{n}} \tag{14}$$

where n is the number of observations per cell, the degrees of freedom, ν, are given by:

$$\nu = N - r - c \tag{15}$$

and t_ν is obtained from a table of the cumulative t distribution[14] for a two-tailed t-test with 95% confidence. The value of LSD can be used to compare two cells to determine whether or not the data in them comes from two populations with different means.

In order to compare cells from two different alloys, the estimated variances from the two data sets must first be pooled. For data sets 1 and 2, with variance estimates, s_1^2 and s_2^2, and degrees of freedom, ν_1 and ν_2, respectively, the pooled standard deviation is given by:

$$s_p = \sqrt{\frac{\nu_1 s_1^2 + \nu_2 s_2^2}{\nu_1 + \nu_2}} \tag{16}$$

A lower confidence limit for the mean value of any data cell can be calculated from the expression:

$$LCL = m_{BC} - \frac{t_\nu s_p}{\sqrt{n}} \tag{17}$$

where m_{BC} is the average Box-Cox transformed value and t_ν is obtained from a table of the cumulative t distribution[14] for a one-tailed t-test. The LCL values can then be transformed back to either the X_{tr} or the original X metrics.

4. EXPERIMENTAL PROCEDURE

Round tension specimens with a diameter of 3.18 mm, a gauge length of 25.4 mm and an overall length of 50.8 mm were machined from a 76.2 mm thick plate of AA 7075-T651 in the short transverse orientation in accordance with ASTM Standard G49-76[16]. The AA 8090-T8771 material was only available in a plate with a thickness of 37.5 mm. As a result, the length of each of the threaded ends of these specimens was reduced by 6.4 mm in order to maintain a gauge length of 25.4 mm. The chemical analysis of the two alloys is shown in Table 1.

Tensile stresses of 0, 69, 138 or 241 MPa were applied to the specimens using a commercially-available, wedge-type, constant-strain frame as shown in Figure 2. Longer stressing frame nuts were specially machined to accommodate the shorter Al-Li specimens. The frames were assembled finger-tight and then placed in a commercially-available, synchronous loading device that was developed by Alcoa Research Laboratories[17]. Operation of the device caused the inward movement of the wedge-shaped side pieces of the stressing frame, producing an uniaxial tensile stress in the specimen. This stress was related directly by Hooke's law and Young's modulus to the strain of the specimen, which was measured with an MTS model 623.13B-20 extensometer that had a 12.7 mm gauge length. Friction between the various components of a stressing frame maintained a constant strain after removal of the frame from the loading device.

Sets of five replicate specimens of each of the four stress levels for each alloy were exposed to alternate immersion in sea water in accordance with the procedure described in ASTM Standard G44-75[18] for 2, 4, 7 or 14 days. A total of eighty specimens were exposed for each alloy. The specimens were continuously immersed in the sea water for 10 min of each hour and then allowed to dry for the remaining 50 min. This cycle was achieved by placing a pump on a timer. While the pump was operating, it maintained sufficient flow to ensure that all the specimens in a tank were immersed in sea water. When the timer shut the pump off, the tank was quickly emptied through a gravity drain. The sea water, which had a

TABLE 1. Chemical Composition of Breaking Load Specimens (weight percent)

	Li	Cu	Mg	Zr	Fe	Zn	Mn	Si	Cr	Ti	Al
8090	2.69	1.23	0.66	0.12	0.05	-	-	-	-	-	rem
7075	-	1.39	2.45	-	0.15	5.92	0.06	0.09	0.2	0.03	rem

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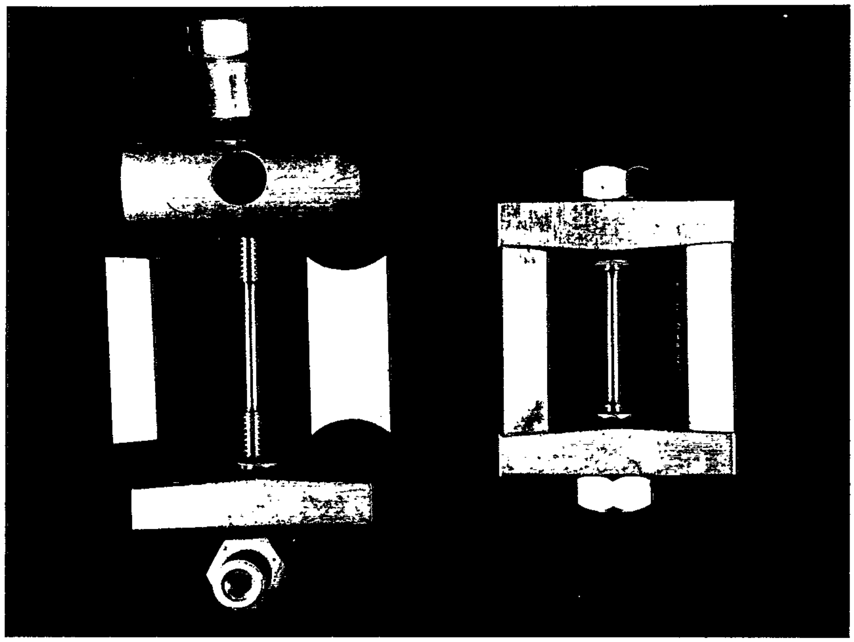

Figure 2. Exploded view of the components of the stressing frame, including the specimen, and the final stressed assembly.

temperature of 13°C throughout the experiment, was obtained directly from the Strait of Juan de Fuca and used on a once-through basis.

Each surviving specimen was removed from the stressing frame after its scheduled length of exposure, rinsed in deionized water, dried and tension tested in accordance with ASTM Standard E8-89[19]. The apparent tensile strength was then calculated on the basis of the original cross-sectional area. Finally, five specimens of each alloy, which were not stressed or exposed to sea water, were broken in the tensile testing machine to determine the initial breaking strength.

5. RESULTS AND DISCUSSION

The residual breaking strengths of the AA 8090-T8771 and 7075-T651 specimens exposed to alternate immersion in sea water are shown in Tables 2 and 3, respectively. In these tables, a specimen that failed prior to tensile testing is marked by an "f" followed by the number of the day during which it failed or a "?" if that day was not determined. The large number of specimens that failed under the highest external load prior to tensile testing, in contrast to the unstressed specimens which did not fail, indicated that both alloys are susceptible to stress

TABLE 2. Residual Breaking Strengths (MPa) of AA 8090-T8771 Specimens Exposed to Alternate Immersion in Sea Water

Stress	0 MPa	69 MPa	138 MPa	241 MPa
Time (days)				
0	527 514 514 514 508			
2	516 502 481 450 445	484 433 352 313 305	486 465 428 361 220	463 371 370 312 290
4	461 452 414 410 354	440 302 267 240 213	460 453 381 304 199	453 416 f4 f4 f4
7	499 411 410 364 322	271 247 220 198 178	407 274 248 206 136	483 482 278 f? f?
14	336 308 305 303 237	213 206 159 137 f?	177 f14 f? f? f?	369 294 f? f? f?

corrosion cracking in sea water. Without statistical analysis, these tables also suggested that the 8090 specimens were more resistant to SCC than 7075. A total of 13 Al-Li specimens failed, with 1 failure at the lowest non-zero stress level (69 MPa). These numbers are substantially less than those observed for the 7075 alloy, which suffered a total of 25 failures, with 6 failures at 69 MPa.

The calculated value of the 99% survival stress for each test group for each alloy is shown in Table 4, along with the correlation coefficient, r, of the best fit line determined for the plot of E_i (Equation 4) versus the ranked breaking strengths. Specimens which were known to have failed during the last day of exposure were assigned a breaking strength equal to the externally-applied stress for these calculations. A sample calculation of S_{99} appears in Appendix 1. A value of r=-1 should occur if the data within each cell followed the extreme value distribution exactly. Visual inspection of the r values reveals

TABLE 3. Residual Breaking Strengths (MPa) of AA 7075-T651 Specimens Exposed to Alternate Immersion in Sea Water

Stress	0 MPa	69 MPa	138 MPa	241 MPa
Time (days)				
0	512 505 503 503 500			
2	527 525 520 504 489	487 464 447 444 427	474 467 462 432 386	483 386 380 359 340
4	506 501 500 494 482	408 318 305 183 84	431 271 131 122 88	300 f4 f4 f4 230
7	497 476 463 458 451	85 f7 f7 48 f?	316 132 106 f? f?	f? f? f? f? f?
14	349 328 327 308 276	f14 f14 65 14 f?	f14 35 f? f? f?	f? f? f? f? f?

that this distribution did provide a reasonable description of the behaviour of the specimens within a test group. However, the sample size was too small to completely rule out other distributions.

The effects of the exposure time and the externally-applied stress on the values of S_{99} are shown graphically in Figure 3 for AA 8090-T8771 and Figure 4 for AA 7075-T651. The general tendency toward decreasing values of S_{99} with increasing applied stress observed in these figures indicates that both alloys are susceptible to SCC in sea water. Deviations from this trend can be attributed to problems associated with the original breaking load method or to the small sample size. For example, the increase in S_{99} between the 138 MPa and 241 MPa stress levels for the 4 day exposure for the 7075 alloy resulted from the decision to use the value of the exposure stress as the breaking load for the three specimens in the 241 MPa cell that failed on the final day just prior to tensile testing. As noted in the introduction to Box-Cox transformations,

TABLE 4. Calculated Values of 99% Survival Stress, S_{99}, and Correlation Coefficient, r, for Each Test Group for AA 8090-T8771 and AA 7075-T651

	Stress	0 MPa	69 MPa	138 MPa	241 MPa
Time					
		AA 8090-T8771			
0 days	S_{99} r	469 -0.860			
2 days	S_{99} r	292 -0.950	-113 -0.912	-233 -0.980	-54 -0.926
4 days	S_{99} r	174 -0.979	-289 -0.872	-275 -0.984	-427 -0.816
7 days	S_{99} r	5 -0.951	6 -0.978	-348 -0.947	-1700 -0.843
14 days	S_{99} r	77 -0.937	-192 -0.960	-536 -1	-989 -1
		AA 7075-T651			
0 days	S_{99} r	476 -0.898			
2 days	S_{99} r	418 -0.974	318 -0.953	229 -0.967	21 -0.854
4 days	S_{99} r	444 -0.986	-472 -0.987	-729 -0.867	38 -0.750
7 days	S_{99} r	358 -0.918	-91 -0.955	-1660 -0.935	- -
14 days	S_{99} r	160 -0.989	-268 -0.820	-1730 -1	- -

one of the problems with the original breaking load method was the extreme sensitivity of the value of S_{99} to differences in the standard deviation of different test groups. This problem was highlighted by the values of S_{99} of 5 MPa and 77 MPa for the 7 and 14 day exposures, respectively, for the 0 MPa stress level for 8090. The individual breaking loads within the 7 day test group gave rise to a higher arithmetic mean (410 MPa versus 298 MPa) but the higher standard deviation (66 MPa versus 37 MPa) resulted in the lower value of S_{99} for the shorter exposure time.

Even with these problems, the original breaking load method allowed several conclusions to be reached about the behaviour of these alloys in sea water. In addition to showing that both alloys suffered from SCC, the

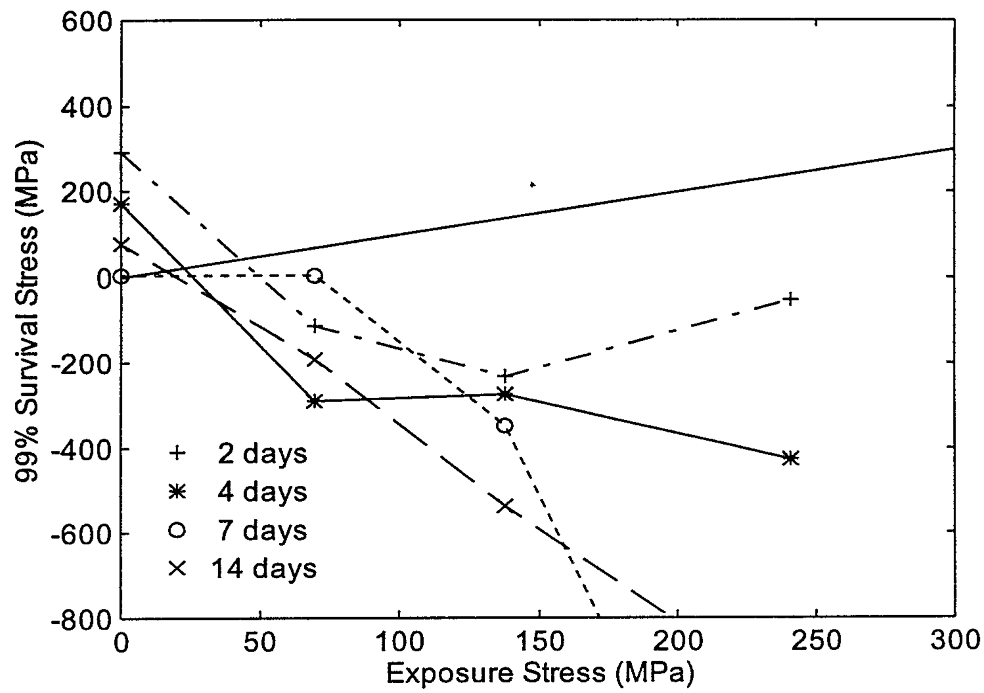

Figure 3. Plot of 99% survival stress versus externally-applied exposure stress for AA 8090-T8771.

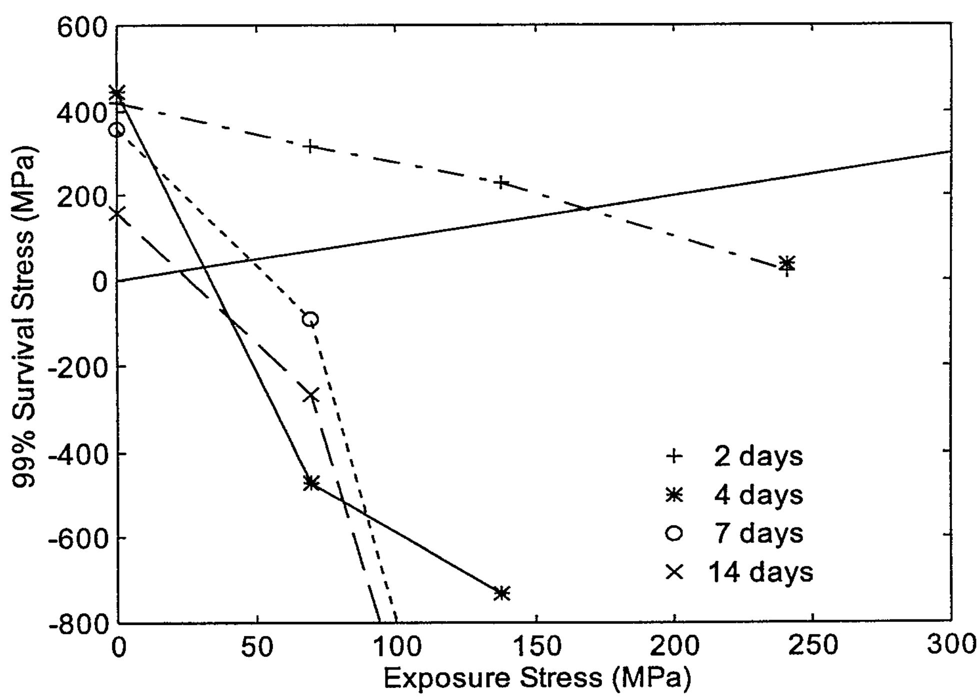

Figure 4. Plot of 99% survival stress versus externally-applied exposure stress for AA 7075-T651.

method indicated the presence of a degradation mechanism that was independent of an externally-applied stress. Both alloys experienced a substantial drop in the value of S_{99} by the 14^{th} day of the 0 MPa exposure. Microscopic examination of the 14 day, 0 MPa specimens after tensile testing showed that intergranular cracking had occurred in both alloys in the absence of an external stress (Figure 5 and Figure 6). The breaking load method also suggested that the effects of intergranular cracking appeared after a shorter exposure time for 8090 than for 7075.

Negative values of S_{99} are, of course, physically impossible but were retained to provide more discrimination between the effects of different stress levels and a more conservative estimate of the threshold stress than would be obtained by setting negative values to zero. Using this approach, the threshold stress for AA 8090-T8771 exposed to sea water was found to be 8.0 MPa, while S_{th} for AA 7075-T651 was found to be -14 MPa. Details of these calculations appear in Appendix 2. The value of S_{th} for 7075 was well within the range reported by the interlaboratory test program[5], which varied from -119.5 MPa to 59.4 MPa. The threshold stresses of both alloys are close to zero and indicate that both alloys are susceptible to SCC.

Figure 5. Intergranular cracking of AA 8090-T8771 exposed to alternate immersion in sea water for 14 days. Etched with Keller's reagent. 128x.

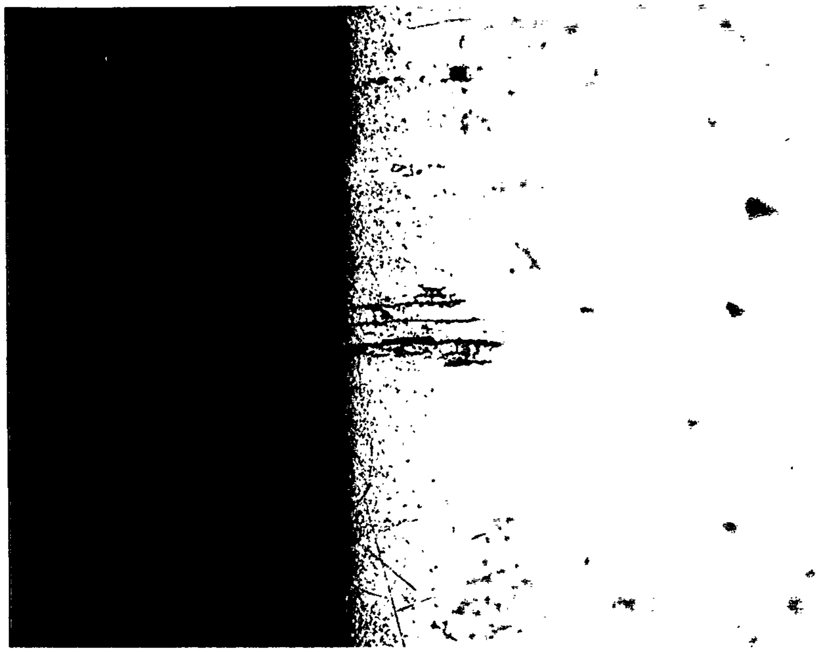

Figure 6. Intergranular cracking of AA 7075-T651 exposed to alternate immersion in sea water for 14 days. Etched with Keller's reagent. 250x.

As noted in the introduction to the Box-Cox transformation, successful implementation of the transformation is based on the assumption that the natural logarithm of the standard deviation of each individual stress/time group increases linearly with decreasing natural logarithm of the mean breaking strength. The correlation coefficients shown in Table 5 indicate a rather poor fit to the data for both alloys. Nevertheless, the slopes did result in power parameters that served to stretch the residual strength axis for large strength values and compress the axis for small

TABLE 5. Slope of ln (Standard Deviation) versus ln (Mean of Normalized Breaking Strengths), Correlation Coefficient and Power Parameter for Each Alloy

Alloy	Slope (α)	Correlation Coefficient (r)	Power Parameter (λ)
AA 8090-T8771	-0.556	-0.217	1.56
AA 7075-T651	-0.450	-0.359	1.45

values. However, the transformed data may not follow a normal distribution or have variances for the individual stress/time groups that are approximately equal. As a result, calculations of the least significant difference and the analysis of variance may not be strictly valid.

The mean of the Box-Cox transformed data for each stress/time group is plotted in Figure 7 for AA 8090-T8771 and Figure 8 for AA 7075-T651 as a function of the externally-applied stress. Each graph also shows the value of the least significant difference, LSD, at the 95% confidence level for that alloy (Equation 14). These values were found to be 26.6 for 8090 and 18.9 for 7075.

The Box-Cox transformation served to confirm several of the conclusions that were reached using the original breaking load method and removed some of the anomalous behaviour that resulted from the original statistical procedure. A statistically-significant reduction in the mean of the transformed data was observed for both alloys as a result of the application of an external stress, indicating that both alloys did suffer from stress corrosion cracking. The effects of an external stress were masked somewhat for the 8090 alloy by the significant reduction in breaking strength which occurred by the 7^{th} day in the absence of an external stress. As noted previously, this reduction was due to intergranular cracking. The transformation also showed that the intergranular cracking grew worse by the 14^{th} day, thereby removing the anomaly observed with the original method in which the 7 days specimens appeared to suffer more damage than the 14 day specimens at the 0 MPa stress level. Significant intergranular cracking also occurred on the 7075 specimens, but not until some time between the 7^{th} and 14^{th} days of exposure. The trend toward higher means observed for both alloys between the 138 MPa and 241 MPa stress levels during the 7 and 14 day exposures was not statistically significant and was purely a result of the choice of values assigned to the large number of failed specimens in these test groups.

An analysis of variance table involving all three variables (stress level, exposure time and alloy) for the transformed data appears in Table 6. In this table, the four means appearing under the four different applied stress levels were calculated using all specimens that were tested under each load, independent of the length of exposure and alloy type. Similarly, the four means appearing under the four different exposure times involved all specimens for each exposure time, independent of the applied load and the alloy type. Finally the two means appearing under the two different alloy designations involved all specimens for each alloy, independent of the stress level and length of exposure. The error

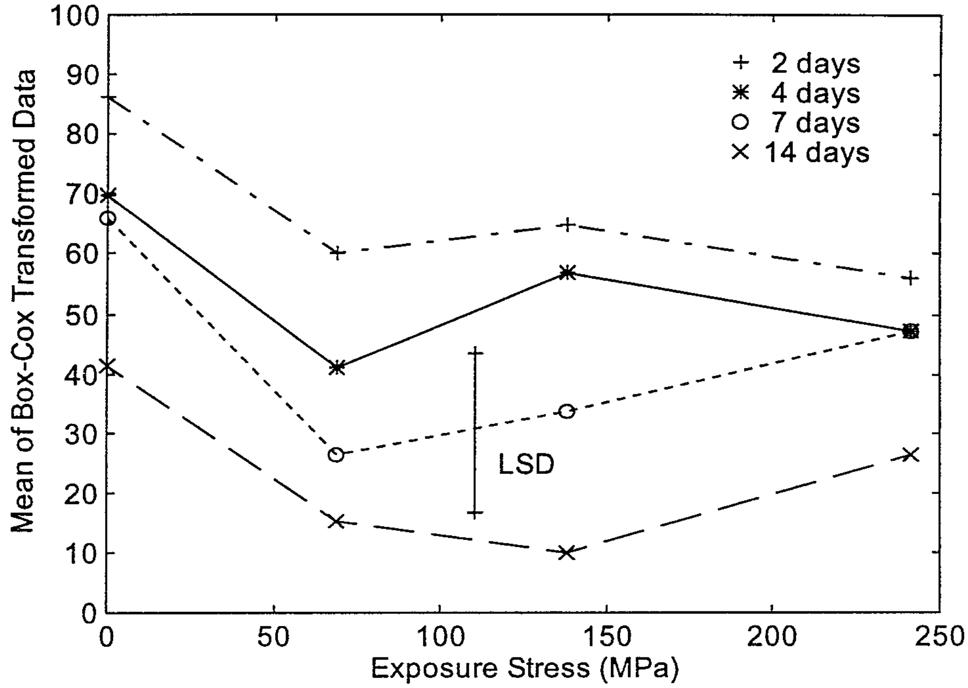

Figure 7. Plot of the mean of the Box-Cox transformed data for each test group of AA 8090-T8771 versus exposure stress.

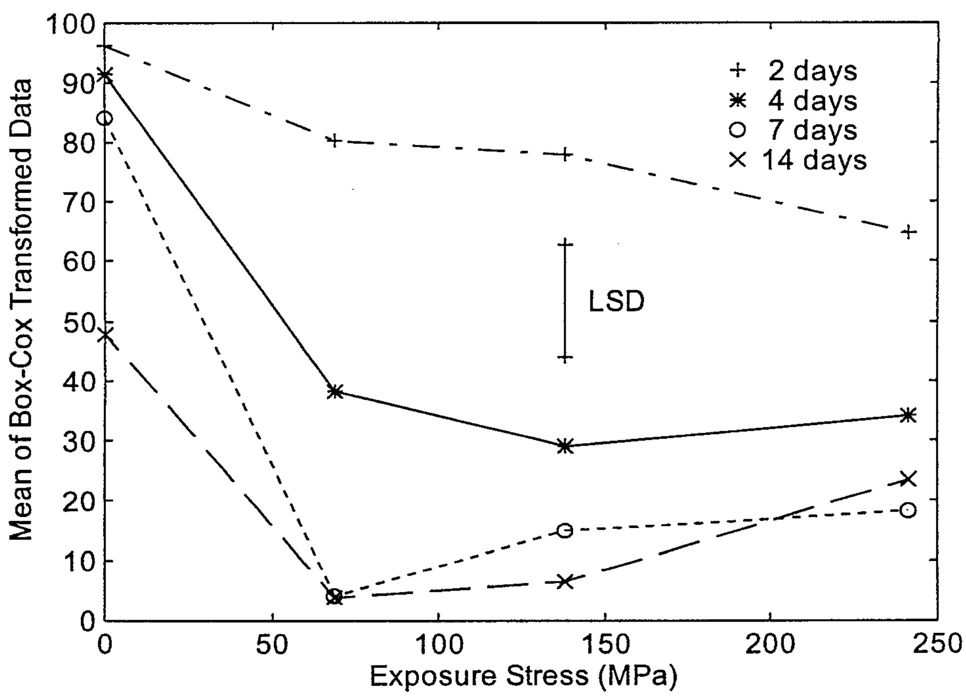

Figure 8. Plot of the mean of the Box-Cox transformed data for each test group of AA 7075-T651 versus exposure stress.

Table 6. Analysis of Variance Table for the Box-Cox Transformed Residual Breaking Strengths for AA 8090-T8771 and AA 7075-T651

Stress	0 MPa	69 MPa	138 MPa	241 MPa	Grand Mean
Mean	72.9 (2.6)	33.7 (2.6)	36.7 (2.6)	39.7 (2.6)	45.7
Time	2 days	4 days	7 days	14 days	Error
Mean	73.3 (2.6)	51.0 (2.6)	36.8 (2.6)	21.8 (2.6)	7.2
Alloy	8090	7075			
Mean	46.8 (1.8)	44.6 (1.8)			
Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	$F_{0.99}$
Mean	1	334000	334000		
Stress	3	40100	13400	51.0	3.95
Time	3	57600	19200	73.3	3.95
Alloy	1	183	183	0.7	6.85
Stress-Time Interaction	9	6440	716	2.7	2.56
Stress-Alloy Interaction	3	3700	1230	4.7	3.95
Time-Alloy Interaction	3	3580	1190	4.6	3.95
Three Factor Interaction	9	3600	400	1.5	2.56
Error	128	33500	262		
Total	160	483000			

shown under the grand (overall) mean represents the standard error for each stress/time group for each alloy. This table shows that there was no significant difference in the overall behaviour of AA 8090-T8771 and AA 7075-T651 when exposed to alternate immersion in sea water at several different stress levels for several different lengths of exposure. Both alloys suffered a significant reduction in breaking strength in the presence of an externally-applied stress. However, removing the 0 MPa stress level from the ANOVA table showed that there was no significant difference between the effects of the three non-zero stress levels. Thus, an external load of 69 MPa was sufficient to induce stress corrosion cracking in both alloys, but the addition of still higher loads did not affect the extent of damage. Table 6 also shows that the breaking strength decreased with each increasing length of exposure. There was a significant interaction between the effects of the applied stress and the length of exposure. This result is not surprising as the effects of stress would not be expected to be independent of the exposure time. Finally, there were significant interactions between the alloy tested and the exposure time and between the alloy and the applied stress. These interactions suggest that there are some differences in the manner in which the stress level and length of exposure affect each of these alloys.

A comparison of the two-factor ANOVA tables for AA 8090-T8771 (Table 7(a)) and for AA 7075-T651 (Table 7(b)) suggests that 8090 experienced significantly more damage in the absence of an externally-applied stress than 7075. This conclusion is supported by a two factor ANOVA table involving both alloys for the different lengths of exposure at the 0 MPa stress level (Appendix 3). As noted previously, the damage at the 0 MPa stress level was due primarily to intergranular cracking for both alloys. The 8090 alloy also suffered more damage during the two day exposure than 7075. Since there was no difference in the overall behaviour of the two alloys, these results suggest that the initiation of intergranular and stress corrosion cracking occurred more slowly on 7075 but SCC then proceeded more rapidly once it had been initiated.

6. CONCLUSIONS

The original breaking load method showed that AA 8090-T8771 and AA 7075-T651 were both susceptible to stress corrosion cracking when exposed to alternate immersion in sea water, with threshold stresses close to zero. The value of the threshold stress for 7075 was well within the range reported by an interlaboratory program designed to test the reproducibility of the method and to evaluate alternate statistical procedures. The method also indicated that both alloys were weakened by a degradation mechanism that was independent of an externally-applied stress. Microscopic examination showed that the weakening was caused by intergranular cracking. The breaking load method suggested that the effects of intergranular cracking appeared after a shorter exposure time for 8090 than for 7075.

The extreme value distribution was found to provide a reasonably good fit to the data, but its use did give rise to several problems previously noted in the interlaboratory test program. The procedure involving Box-Cox transformations did alleviate these problems and served to confirm the conclusions reached using the original method, even though the statistical calculations may not have been strictly valid.

TABLE 7(a). Analysis of Variance Table for the Box-Cox Transformed Residual Breaking Strengths of AA 8090-T8771.

Stress	0 MPa	69 MPa	138 MPa	241 MPa	Grand Mean
Mean	65.8 (4.3)	35.8 (4.3)	41.3 (4.3)	44.3 (4.3)	46.8
Time	2 days	4 days	7 days	14 days	Error
Mean	66.8 (4.3)	53.8 (4.3)	43.3 (4.3)	23.2 (4.3)	8.7
Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	$F_{0.99}$
Mean	1	175000	175000		
Stress	3	10400	3470	9.2	4.13
Time	3	20400	6790	18.0	4.13
Interaction	9	2040	227	0.6	2.72
Error	64	24100	377		
Total	80	232000			

TABLE 7(b). Analysis of Variance Table for the Box-Cox Transformed Residual Breaking Strengths of AA 7075-T651.

Stress	0 MPa	69 MPa	138 MPa	241 MPa	Grand Mean
Mean	80.0 (2.7)	31.6 (2.7)	32.0 (2.7)	35.1 (2.7)	44.6
Time	2 days	4 days	7 days	14 days	Error
Mean	79.8 (2.7)	48.1 (2.7)	30.3 (2.7)	20.4 (2.7)	5.4
Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	$F_{0.99}$
Mean	1	159000	159000		
Stress	3	33400	11100	75.9	4.13
Time	3	40800	13600	92.7	4.13
Interaction	9	8000	889	6.1	2.72
Error	64	9390	147		
Total	80	251000			

Analysis of variance of the transformed data showed that there was no significant difference in the overall behaviour of AA 8090-T8771 and AA 7075-T651 when exposed to alternate immersion in sea water at several different stress levels for several different lengths of exposure. Both alloys suffered significant reductions in breaking strength from stress corrosion cracking and from intergranular cracking. ANOVA also suggested that the initiation of intergranular and stress corrosion cracking occurred in a shorter period of time for 8090 than for 7075, but propagation of stress corrosion cracks then occurred more rapidly in 7075 once cracking had been initiated.

These experiments have shown that one aluminum-lithium alloy, AA 8090, in the T8771 temper is susceptible to two of the corrosion mechanisms that have caused problems with AA 7075. Successful use of this aluminum-lithium alloy in aircraft components will require the same corrosion prevention techniques, such as painting and sealing, that are applied to components made from 7075 alloys.

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APPENDIX 1. Sample Calculation of 99% Survival Stress

The ranked breaking strengths for the five specimens of AA 8090-T8771 exposed to alternate immersion in sea water for 7 days at 69 MPa are shown in the following table, along with the expected value of each ranked observation, E_i.

Observation i	$R_i = (i-½)/5$	$E_i = -\ln[-\ln(R_i)]$	Breaking Strength (MPa)
1	0.1	-0.834	271
2	0.3	-0.186	247
3	0.5	0.367	220
4	0.7	1.031	198
5	0.9	2.250	178

A plot of E_i versus the ranked breaking strengths yields a best-fit line with slope, m, equal to -0.215, intercept, b, equal to 7.46, and correlation coefficient, r, equal to -0.978. The value of r near -1 indicates that the extreme value distribution provides a good fit to the data.

Initial estimates of the distribution location and scale parameters, $\hat{\mu}$ and $\hat{\sigma}$, are found to be:

$$\hat{\mu}_{\infty} = -\frac{b}{m} = 34.8 \tag{1}$$

$$\hat{\sigma}_{\infty} = -\frac{1}{m} = 4.66 \tag{2}$$

These parameters are adjusted to account for the small sample size using the following equations:

$$\hat{\sigma} = \hat{\sigma}_{\infty}(\sigma_{\infty}/\sigma_n) = 4.66((\pi/\sqrt{6})/0.7932) = 7.53 \tag{3}$$

$$\begin{aligned}\hat{\mu} &= \hat{\mu}_{\infty} - \hat{\sigma}_{\infty} y_{\infty} + \hat{\sigma}\,\overline{y}_n \\ &= 34.8 - 4.66(0.577) + 7.53(0.4564) \\ &= 35.5\end{aligned} \tag{4}$$

The value of the 99% survival stress, S_{99}, is then calculated:

$$\begin{aligned}S_{99} &= \hat{\mu} - 4.60 \cdot \hat{\sigma} \\ &= 35.5 - 4.60(7.53) \\ &= 6.0\end{aligned} \tag{5}$$

APPENDIX 2. Determination of the Threshold Stress, S_{th}.

The first step in determining the statistically-defined threshold stress involves calculation of the slope, B, and intercept, A, of the best-fit line obtained from a plot of the 99% survival stress, S_{99}, versus the exposure stress, S_{exp}, for each length of exposure. The point of intersection of this line with the line defined by $S_{99} = S_{exp}$ is given by:

$$S'_{th} = -\frac{A}{B-1} \tag{1}$$

The results for AA 8090-T8771 appear in the following table:

Exposure Length	Slope	Intercept	S'_{th} (MPa)
2 days	-1.28	117	51.2
4 days	-2.18	39.6	12.5
7 days	-7.21	300	36.5
14 days	-4.47	90.6	16.6

The mean, m, and standard deviation, s, of the values of S'_{th} are determined and used to calculate S_{th}:

$$\begin{aligned} S_{th} &= m - t_{0.95(3)} \cdot \frac{s}{\sqrt{4}} \\ &= 29.2 - 2.353 \cdot \frac{18.0}{\sqrt{4}} \\ &= 8.0 \text{ MPa} \end{aligned} \tag{2}$$

The results for AA 7075-T651 appear in the following table, which was obtained using all values of S_{99} except that for the 4 day, 241 MPa cell. The value for this cell is an artifact of the method for reporting failed specimens and would severely distort the calculation of S'_{th}:

Exposure Length	Slope	Intercept	S'_{th} (MPa)
2 days	-1.63	430	163
4 days	-8.51	335	35.2
7 days	-14.6	545	34.8
14 days	-13.7	332	22.6

APPENDIX 2. (cont.)

The value of S_{th} was then found to be:

$$S_{th} = 64 - 2.353 \cdot \frac{66}{\sqrt{4}} = -14 \text{ MPa} \quad (3)$$

APPENDIX 3. Analysis of Variance Table for the Box-Cox Transformed Residual Breaking Strengths of AA 8090-T8771 and AA 7075-T651 for Different Lengths of Exposure at the 0 MPa Stress Level.

Time	2 days	4 days	7 days	14 days	Grand Mean
Mean	91.1 (2.8)	80.7 (2.8)	75.1 (2.8)	44.6 (2.8)	72.9
Alloy	8090	7075			Error
Mean	65.8 (2.0)	80.0 (2.0)			3.9
Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F ratio	$F_{0.99}$
Mean	1	212000	212000		
Time	3	12000	400	51.7	4.13
Alloy	1	2000	2000	25.9	7.08
Interaction	3	374	125	1.6	4.13
Error	32	2480	77		
Total	40	229000			

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The breaking load method was used to evaluate the susceptibility of the aluminum-lithium alloy, AA 8090-T8771, to stress corrosion cracking when exposed to alternate immersion in sea water. The performance of this alloy was compared with that of a conventional aluminum alloy, AA 7075-T651. The original test method showed that both alloys were susceptible to stress corrosion cracking, with threshold stresses close to zero. The method also indicated that both alloys were weakened by a degradation mechanism that occurred in the absence of an externally-applied stress. Microscopic examination showed that the weakening was caused by intergranular cracking.

The extreme value distribution was found to provide a reasonably good fit to the data, but its use did give rise to several problems previously noted in an interlaboratory test program. The procedure involving Box-Cox transformations did alleviate these problems and served to confirm the conclusions reached using the original method, even though the statistical calculations may not have been strictly valid. Analysis of variance of the transformed data showed that there was no significant difference in the overall behaviour of AA 8090-T8771 and AA 7075-T651 when exposed to alternate immersion in sea water at several different stress levels for several different lengths of exposure. Analysis of variance also suggested that the initiation of intergranular and stress corrosion cracking occurred in a shorter period of time for 8090 than for 7075, but propagation of stress corrosion cracks then occurred more rapidly in 7075 once cracking had been initiated.

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