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APPLICATION OF TIME-TEMPERATURE-STRESS PARAMETERS TO HIGH TEMPERATURE PERFORMANCE OF ALUMINUM ALLOYS

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Abstract

For many years, it has been recognized that the creep and stress rupture properties of aluminum alloys may be analyzed and extrapolated utilizing time-temperature parametric relationships. The Larson-Miller Parameter (LMP), based loosely on the rate-process theory, has proven one of the most useful. In this paper we will update the theory and application of such parameters to aluminum alloys important in marine and transportation application, not only to creep and stress-rupture data but also to other performance data involving long-time exposure to temperatures above 75 ^{o}C (150 ^{o}F). Representative data and master curves will be provided, and illustration of the application of parametric relationships to tensile properties and corrosion resistance. The authors will describe tests underway to further define the precision and limits of such applications.

Introduction

Because the properties of aluminum alloys are dependent upon both the exposure temperature and also to the length of time of exposure, the prediction of design values for structures designed to last many years is a significant challenge. For relatively short-life structures, the need is addressed simply by planning ahead and carrying out a test plan that replicates the intended service conditions. This is feasible for structures whose design life might be as much as a year or even five years, but it is not very practical for structures for which the life expectancy is 10 years or more.

Since the early 1950s, the analyses of long time, high temperature data for aluminum alloys, ferrous metals and superalloys (1-4), has been addressed through the use of time-temperature parametric equations that permit the consolidation of data obtained over a variety of temperatures and exposure times into a single relationship. Once such relationships are established based upon the available experimental data and optimized, it is possible to extrapolate to service conditions substantially beyond the range of the test data themselves. This must always be done cautiously and with awareness of the extent of the extrapolation, but it provides a better perspective than simply extrapolating individual strength life curves.

Within the scope of this paper, the authors will briefly review the background for and the application of the most widely used time-temperature parameter, the Larson-Miller Parameter (LMP) plus, more importantly, demonstrate that there is value in the application of such parameters to types of data and performance characteristics beyond the creep-rupture data for which they are best known and most widely used.

Illustration of the Need for Time-Temperature Parameters

The need for a method of extrapolating experimental creep-rupture test data to longer times for estimating service life design values may be readily seen by the representative experimental data shown in Figure 1 for 5454-O. Typically the data for each temperature appear as discrete lines of decreasing rupture stress with increasing time at temperature. The longest experimentally determined rupture lives are in the range of 5000-10,000 hours, whereas service lives are typically at least 10 years or approaching 100,000 hours. Utilizing the individual temperature curves alone, the extrapolations would be at least one full order of magnitude of rupture life.

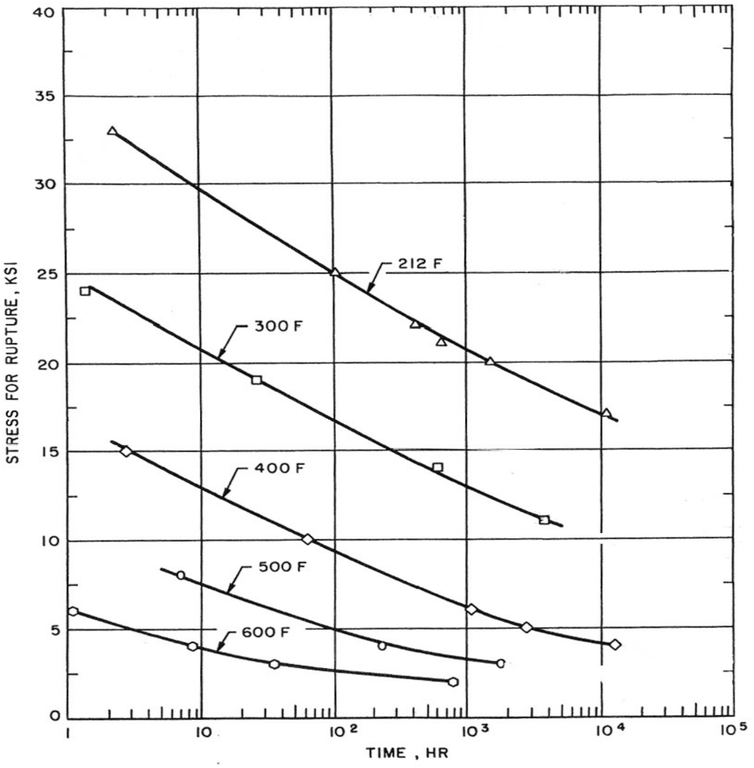


Figure 1 – Creep rupture strengths of aluminum alloy 5454-O

So the advantage of having some type of parametric relationship involving stress, time, and temperature is to provide for the consolidation of the individual curves into a single master relationship that would enable the ready prediction of the cumulative effects of both time and temperature on stress. It is precisely such consolidation that parametric analyses of the type described herein accomplish, and it is the background and broader application of such parameters that are described.

Several time-temperature-stress parameters have been applied with considerable success over the years, especially to stress-rupture data for a variety of metals, and to a lesser extent, to creep rates, and total accumulated creep of various amounts. The three most commonly utilized have been the Larson-Miller Parameter (1), the Manson-Haferd Parameter (2), and the Dorn-Sherby Parameter (3). While not necessarily showing great technical advantage over the other two parameters, the Larson-Miller Parameter (LMP) has become the most widely used, for aluminum alloys at least, primarily because of the ease of its application in iterative analyses to achieve the most useful results. Therefore, in this paper, the authors will focus on the LMP criteria. More detailed information on the application of all three parameters, including direct comparisons of their usefulness, is provided in Reference 5.

Rate Process Theory and the Larson-Miller Parameter

The early development and application of the high temperature parametric relationships, including the Larson-Miller Parameter, to data for aluminum alloys as well as many ferrous alloys was based upon what was known as the "rate process theory." It was first proposed by Eyring in 1936 (6) and was first applied to metals by Kauzmann (7) and Dushman et al (8), expressed as follows:

$$(1) \qquad r = A\ e^{-Q(S)/RT}$$

where: r = the rate for the process in question, A = a constant, Q(S) = the activation energy for the process in question, R = the gas constant, T = absolute temperature

In 1963, Manson (9) illustrated that the LMP and other commonly used parametric relationships derive from the following form of the rate process equation:

$$(2) \qquad P = \frac{(\log t)\,\sigma^{Q} - \log t_A}{(T - T_A)^R}$$

where: P = a parameter combining the effects of time, temperature, and stress σ= stress, ksi, T = absolute temperature, T_A, Log t_A, Q, and R = constants dependent upon the material

Larson and Miller (1) chose to simplify the relationship by pre-selecting values of the four constants as follows:

$Q = 0$; thus $\sigma^Q = 1$
$R = -1.0$
$T_A = -460\ ^0F$ or $0\ ^0R$
$\log t_A$ = the constant C in the LMP

Thus the general equation reduces to:

(3) $P = (\log t + C)\,(T)$ or, for the Larson-Miller Parameter,

$$(4) \qquad LMP = T(C + \log t)$$

This analysis has the advantage that log t_A or C is the only constant that must be defined by analysis of the data in question, and it is in effect equal to the following at isostress values:

$$(5) \qquad C = (LMP/T) - \log t$$

In such a relationship, isostress data (i.e., data for the same stress but derived from different time-temperature exposure) plotted as the reciprocal of T vs. log t should define straight lines, and the lines for the various stress values should intersect at a point where1/T = 0 and log t = the value of the unknown constant C.

Larson and Miller took one step further in their original proposal, suggesting that the value of constant C could be taken as 20 for many metallic materials. Other authors have suggested that the value of the constant varies from alloy to alloy, and also with such factors as cold work, and thermo-mechanical processing, and phase transitions or other structural modifications.

From a practical standpoint, most applications of the LMP are made by first calculating the value of C that provides the best fit in the parametric plotting of the raw data, and values for aluminum alloys, for example, have been shown to range from about 13 to 27.

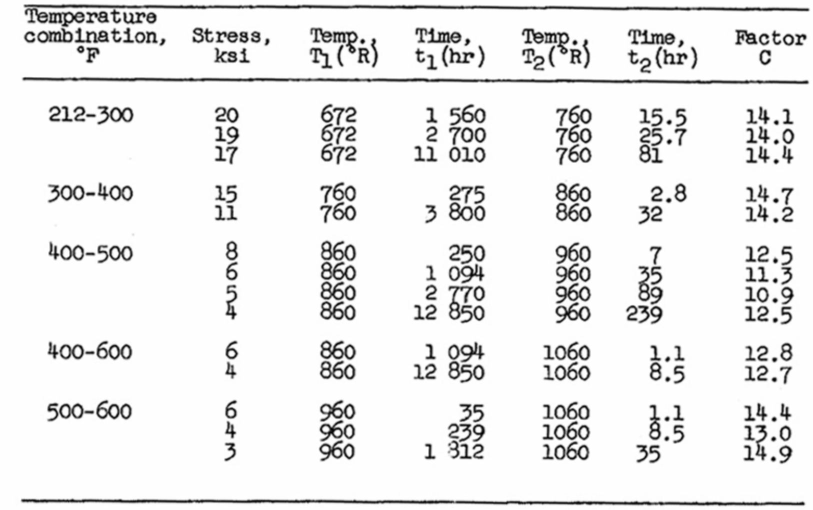
Illustrative Application of LMP to Creep Rupture Data

Several interesting facets of the value and limitations of the parametric relationships may be seen from looking at a representative illustration of the application of LMP to the data for 5454-O presented earlier. Alloy 5454 is the highest strength Al-Mg alloy recommended for applications involving high temperatures; with higher magnesium, some susceptibility to stress corrosion cracking may result from long-time high-temperature exposure.

Figure 1 provides a graphical summary of the empirically-determined creep-rupture strengths for 5454-O over the temperature range from room temperature (75 ^{o}F or 535 ^{o}R) through 600 ^{o}F (1060 ^{o}R) from Reference 4. The data are plotted as rupture strength as a function of rupture time for each test temperature.

In order to apply the LMP to these data, it is first necessary to calculate the appropriate value of the constant C in the LMP. As noted earlier, while Larson and Miller has judge a generally useful value to be 20, experience has shown that for aluminum alloys, the best approach is to calculate the constant providing the best fit for the available experimental data. This is done by utilizing the graphical presentation in Fig. 1 to identify as many values of stress providing rupture lives at two or more temperatures, referred to as “isostresses.”

Table 1 summarizes the isostress calculations to determine the LMP for 5454-O utilizing the data from Fig. 1. Some of the isostress selections involved modest extrapolations of the experimental data, but all appear reasonable based upon the graphical presentation. A range of values of C from 12.7 through 14.9 was observed.



Temperature combination, °F	Stress, ksi	Temp., T_1 (°R)	Time, t_1 (hr)	Temp., T_2 (°R)	Time, t_2 (hr)	Factor C
212-300	20	672	1 560	760	15.5	14.1
	19	672	2 700	760	25.7	14.0
	17	672	11 010	760	81	14.4
300-400	15	760	275	860	2.8	14.7
	11	760	3 800	860	32	14.2
400-500	8	860	250	960	7	12.5
	6	860	1 094	960	35	11.3
	5	860	2 770	960	89	10.9
	4	860	12 850	960	239	12.5
400-600	6	860	1 094	1060	1.1	12.8
	4	860	12 850	1060	8.5	12.7
500-600	6	960	35	1060	1.1	14.4
	4	960	239	1060	8.5	13.0
	3	960	1 312	1060	35	14.9

Table 1 – Isostress calculations to determine Larson-Miller Parameter constant C for 5454-O creep rupture data

The scientists carrying out this work (4) elected to use a mean value of 14.3 for C for 5454-O. This was subjective to the extent that this is in the higher end of the range of calculated values of C but reflects a leaning toward values of C associated with the lower stresses and longer creep lives most likely to be involved in extrapolations to actual service conditions, e.g., creep rupture lives in excess of 100,000 hours.

Fig. 2 illustrates the master LMP relationship generated utilizing the value of 14.3 for the constant C. The quality of the fit is generally relatively good, the principal exceptions being several of the data points obtained at 400 ^{o}F which fall just slightly below the master curve. This is reflective of the fact that a value of C around 12.5 might better have fit the relationship in the range of 400-500 ^{o}F. At any rate the relationship in Fig. 2 appears satisfactory for extrapolations of at least one order of magnitude, perhaps more.

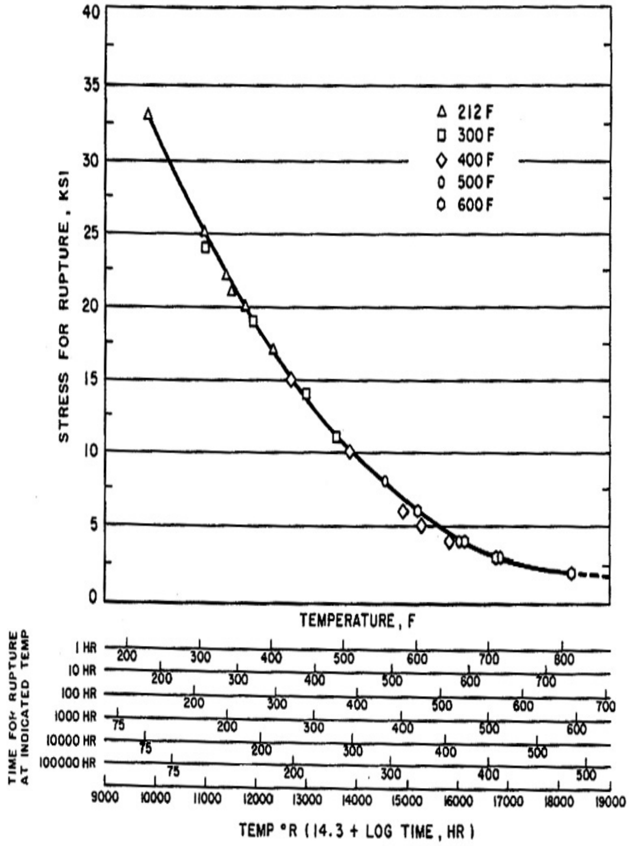


Fig. 2 Master Larson-Miller Parameter (LMP) curve for creep rupture strengths of 5454-O

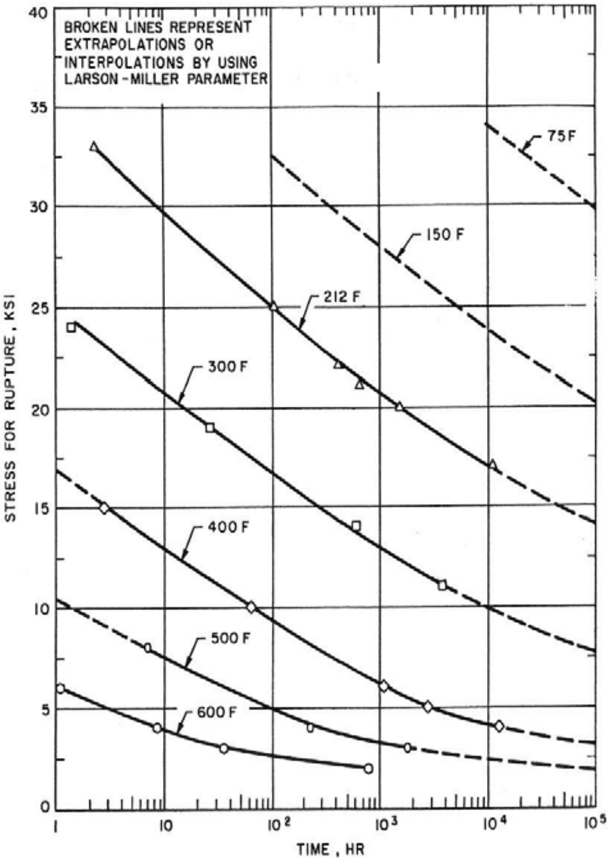


Fig. 3 – Extensions of creep rupture strength curves for 5454-O by extrapolation using the LMP master curve

Fig. 3 illustrates the extrapolations of the creep stress vs. rupture life curves out to 100,000 hours generated utilizing the LMP with a constant of 14.3.

Applications to Other High Temperature Data for Aluminum Alloys

While the application of the Larson-Miller Parameter and time-temperature parameters to creep data, including rupture life and times to develop specific amounts of creep strain (i.e., 0.1%, 0.2%, 1% etc) is fairly wide spread, little use is made of the parameters in analyzing other types of high temperature data for aluminum alloys.

One obvious example of other high temperature data to which the parameters might be applied is tensile properties at temperatures above room temperature. For aluminum alloys, both the temperature and the time of exposure at temperature affect the resultant values, and the effects of time at temperature are cumulative if the exposure is alternating. The LMP may be of value in extrapolating the effects of exposures longer than those covered by the experimental testing.

Using 5456-H321 as the example, Fig. 4 illustrates the effects of time at different temperatures on tensile strength at temperatures from 212 ^{o}F (100 ^{o}C) to 600 ^{o}F (315 ^{o}C). There are clear indications in the plots for some individual temperatures that the LMP may not be of value over the whole range; for example, it appears that at 450, 500 and 600 ^{o}F (230, 260, and 315 ^{o}C, respectively) values are relatively independent of exposure time, so that blending via LMP is unlikely. However there is also some indication that at intermediate temperatures, say 212-400 ^{o}F (100-205 ^{o}C), the LMP approach may be helpful.

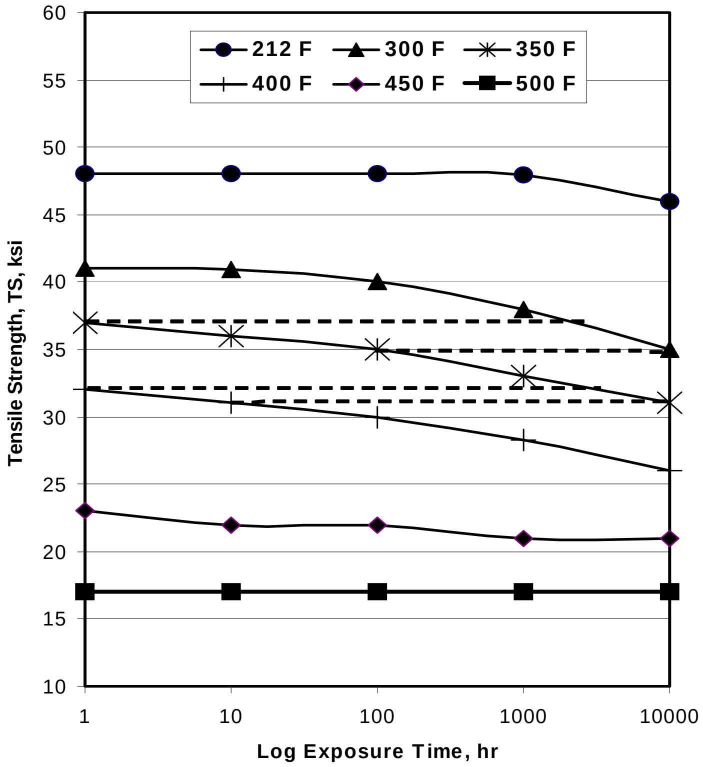


Fig. 4 – Tensile strengths of 5456-H321 at elevated temperatures after various exposure times at the test temperatures

Calculations of the LMP constant C for 5456-H321 tensile strengths leads to quite a wide range of values (~40-65), with an average value of 54. This value leads to the master LMP curve in Fig. 5. The master curve looks remarkably uniform and consistent with most data point, the major exceptions being those for the higher temperatures noted previously. It would appear that for the intermediate temperatures at least, the LMP may be a useful tool for long-exposure extrapolation, but that it must be used with caution, and by careful comparisons with other graphical means of extrapolations.

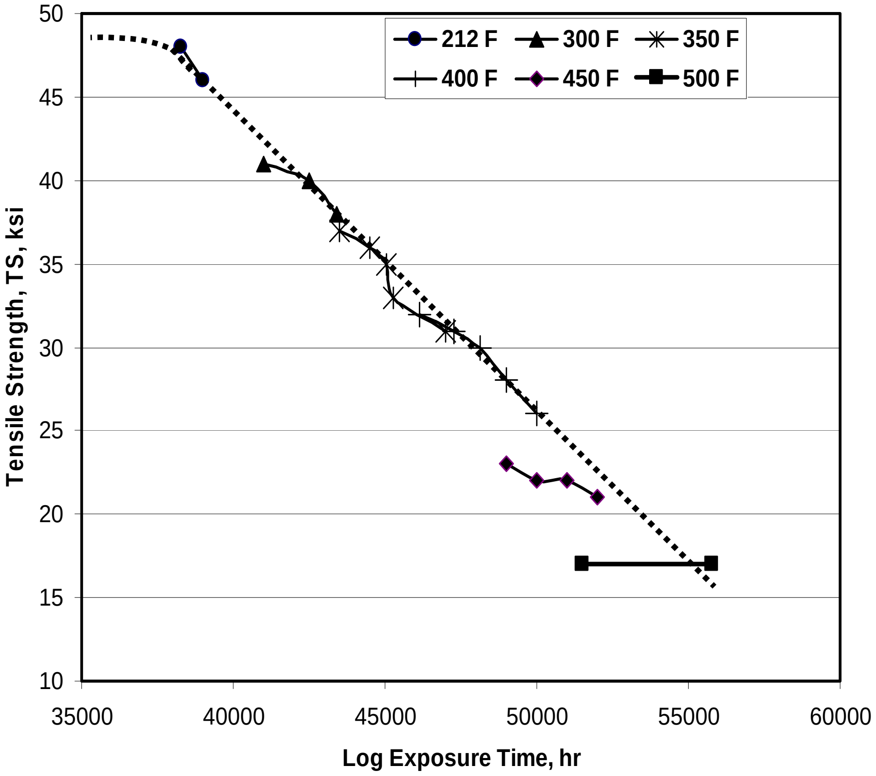


Fig. 5 – Master LMP curve for tensile strength of 5456-H321 at elevated temperatures

Application to Microstructural Changes and Corrosion Performance

While there has been little published on the application of parameters such as LMP to study microstructural changes from high temperature exposure or for corrosion performance following extended high temperature performance, the authors are presently involved in studies involving both characteristics.

The desirability and usefulness of such an approach is illustrated by marine exposure experience by the U.S. Navy and Coast Guard in which ships stationed for years in equatorial environments are subjected to endless hours of on-deck temperatures approaching 150 ^{o}F (65 ^{o}C). In battle zones such as recent years in the Mideast, high temperature exposures are aggravated by temperature rises in the deck components surrounding gun turrets firing at regular intervals. The net result may be the equivalent of 20-30 years of exposure to temperatures averaging 150 ^{o}F (65 ^{o}C).

Because some aluminum-magnesium alloys, like early versions of 5456-H321, have been widely used in ship superstructures for more that 40 years, such exposures have sometimes resulted in a gradual buildup of beta phase precipitates along the grain boundaries in such alloys, in turn making them susceptible to grain boundary corrosion and exfoliation attack after many years of service. (10)

In order to identify or develop new aluminum alloys and tempers that are not subject to such grain boundary buildup and resultant corrosion attack, there is a need to establish some short-term test to predict the performance after many years of exposure. The LMP appears to offer a means to achieve this.

For example, to determine short-term exposures that might predict the microstructural conditions after thirty years of exposure at 150^{o}F (65 ^{o}C):

- Using LMP with a LMP constant of 20, the exposure of about 30 years (say 250,000 hr) at 150 ^{0}F (65 ^{0}C) becomes

$$(6)\quad \text{LMP} = 338(20 + \log 250{,}000) = 338 \times 25.383 = 8580$$

- For an equivalent rapid-response test to be complete in 4 hours, the exposure temperature must be:

$$(7)\quad 8580/(20 + \log 4) = 8580/20.598 = 417\ {}^{0}\text{K or } 291\ {}^{0}\text{F } (144\ {}^{0}\text{C})$$

- For an equivalent rapid-response test to be complete in 4 days (96 hours.), the exposure temperature must be:

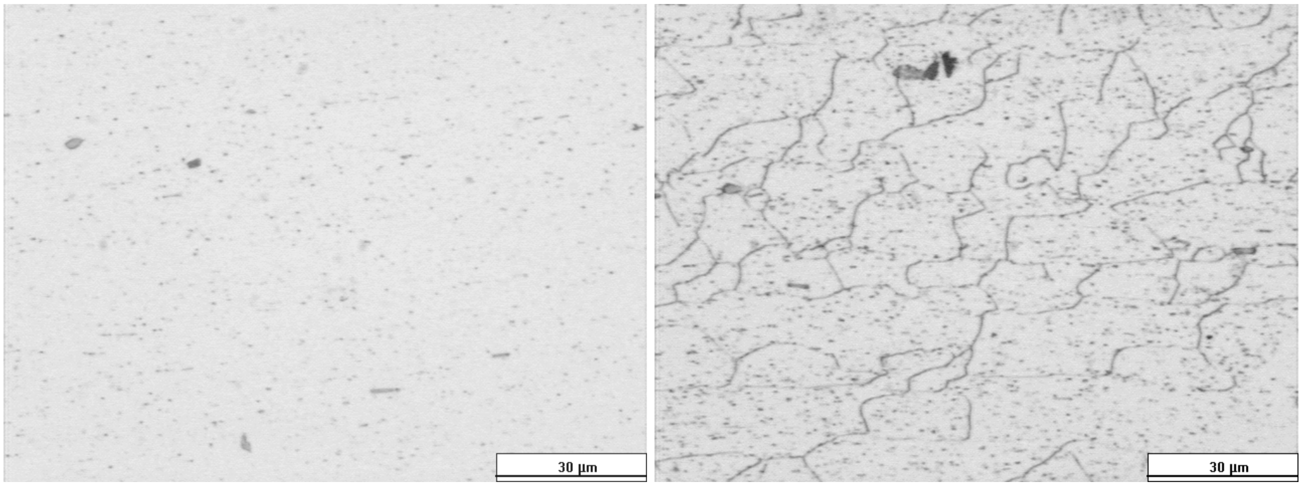
$$(8)\quad 8580/(20 + \log 96) = 8580/21.976 = 390\ {}^{0}\text{K or } 243\ {}^{0}\text{F } (117\ {}^{0}\text{C})$$

These calculations utilizing the LMP suggest that relatively short-time experimental exposures of either 4 hrs at 291 ^{0}F (144 ^{0}C) or 96 hours at 243 ^{0}F (117 ^{0}C) may be useful in predicting the effect of marine service exposures of thirty years at temperatures up to 150 ^{0}F (65 ^{0}C)

Tests are under way to explore this approach with four Al-Mg alloys, including Mg contents ranging from 3-5%. Some alloys with Mg contents in the upper end of this range, notably 5456 in the H321 temper, have exhibited susceptibility to exfoliation and grain boundary corrosion attack as a result of beta phase precipitate buildup along grain boundaries following extended high temperature exposure.

Preliminary results, illustrated by the micrographs in Fig. 6, show that as a result of the 4 and 96 hours exposures at 291 ^{0}F (144 ^{0}C) and 243 ^{0}F (117 ^{0}C), respectively, the microstructures of 5456-H116 exhibit greater precipitation and severe concentration along the grain boundaries where it would likely lead to grain boundary corrosion attack.

Obviously it will take many years to prove conclusively if this approach is accurate and reliable. Nevertheless, in the short term, it offers a means of estimating effects that would otherwise be completely unpredictable.



(a) As fabricated, before LMP exposures (b) After LMP exposures

Figure 6 – Representative microstructures of 5456-H116 before and after LMP exposures projecting thirty years exposure at 150^{o}F (65 ^{o}C)

Conclusions

The usefulness of the use of parametric relationships such as the Larson-Miller Parameter (LMP) for the analysis and extrapolation of high temperature data for aluminum alloys has been described herein, noting the considerable value for creep and stress-rupture strength calculations. An example of the application of LMP to the tensile properties of one alloy (5456-H321) has also been illustrated, indicating its limitations at extreme temperatures (at or above 500 ^{o}F, 260 ^{o}C) but potential value at intermediate temperatures, say 212-400 ^{o}F (~100-205 ^{o}C).

A study currently underway is also described in which the LMP is being utilized to estimate the effects of long-term exposure to high temperatures on the microstructure and corrosion resistance of several alloys. The study includes four Al-Mg alloys with 3%-5% Mg, which with prolonged exposure at 150 ^{0}F (65 ^{0}C) or more, may exhibit grain boundary precipitation and in some cases resultant grain boundary and exfoliation corrosion attack. Short-term exposures have been devised using LMP in order to make a first judgment of the effects of very long time exposures on the corrosion performance of these alloys.

For more detail on the development of time-temperature parameters and their application to aluminum alloys, readers are directed to Reference 5 (to be published in 2007).

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