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MODELING ALUMINUM-LITHIUM ALLOY WELDING CHARACTERISTICS

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INTRODUCTION

The occurrence of microfissures - small cracks at grain boundaries at temperatures near solidus - has been observed in various metals as a result of the welding process. Aluminum-lithium alloy seems to be particularly susceptible. These defects may take several forms: delaminations in the parent next to the weld fusion line, fusion line cracks through the thickness of the plate, and fissures in the weld material itself. These defects are shown in Figure 1.

Each type of defect is associated with strain in a direction perpendicular to the orientation of the cracks. The susceptibility of a metal to microfissuring is a function of a number of variables, including grain size, heat treatment, material composition, and previous welding history. There does not appear to be a reliable method for prediction of the onset of microfissuring.

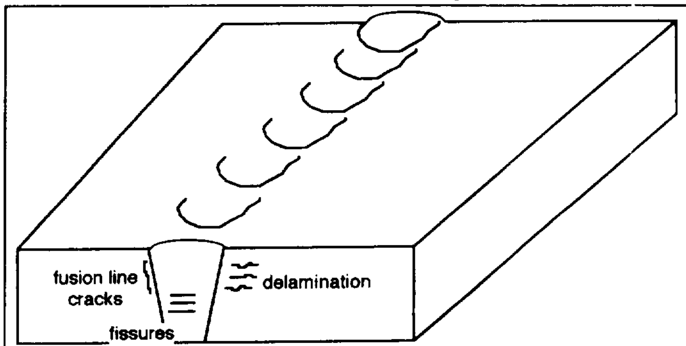


Figure 1. Microfissure Defects after Welding

A theory was developed (Nunes, Ref. 1) in an attempt to explain the onset of microfissures. The theory proposes that microfissuring will occur when three factors are considered: the value of a critical isothermal hot-cracking strain ε_c as a function of temperature; a history of plastic strain in the vicinity of the weld, arising from the temperature field produced by the welding heat input into the plate; and a theory of cumulative damage, analogous to Miner's theory of fatigue prediction. This theory depends on the calculation of a damage measure D defined as

$$D = \sum \frac{\Delta\varepsilon_p}{\varepsilon_c} \tag{1}$$

where $\Delta\varepsilon_p$ is the increase in plastic strain resulting from the heating of the material adjacent to the weld. When D reaches a value of unity, microfissuring is expected to occur. A computer model based on the elements of this theory showed a promising correlation with experimental results.

This purpose of this project was to develop a finite element model of the heat-affected zone in the vicinity of a weld line on a plate in order to determine an accurate plastic strain history. The resulting plastic strain increments calculated by the finite element program were then to be used to calculate the measure of damage D. It was hoped to determine the effects of varying welding parameters, such as beam power, efficiency, and weld speed, and the effect of different material properties on the occurrence of microfissuring. The results were to be compared first to the previous analysis of Inconel 718, and then extended to aluminum 2195.

TEMPERATURE DISTRIBUTION

Plastic strains which are believed to lead to the onset of microfissuring develop due to the action of tensile strains in the weld heat-affected zone during the period when this region cools down, while the environment continues to heat up and expand. The region of temperatures in which this effect occurs is a relatively small band adjacent and parallel to the weld line. In order to accurately model the steep thermal gradients in this region, it was necessary to calculate the temperature distribution to determine the size of this significant area on the plate.

The flow of heat in a plate in the vicinity of a weld has been represented as a moving line source (Rosenthal, Ref. 2) by the equation

$$T\text{-}T_o = -\frac{P_2}{2\pi k d}\, e^{-\frac{v}{2\alpha}x}\, K_0\!\left(\frac{v}{2\alpha}r\right) \tag{2}$$

where $T\text{-}T_0$ = temperature above ambient, P_2 = net welding beam power applied to plate, k = thermal conductivity, α = thermal diffusivity, v = velocity of line source, x= distance from line source along weld line, r = radial distance from line source = $\sqrt{x^2 + y^2}$, K_0 = modified Bessel function of second kind and zero order, and d = thickness of plate

The coordinate system used for the analysis is shown in figure 2. The origin is taken at the center of the plate at the point of the heat source. The weld line is along the x-axis, the y-axis represents the distance perpendicular to the weld line at the top surface of the plate, and the z-axis is directed through the thickness of the plate.

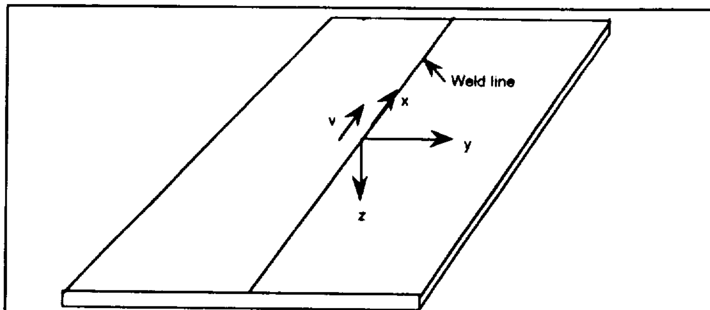


Figure 2. Coordinate System in the Plate

Equation (2) was then evaluated to locate the region of the plate in which rising temperatures cause tensile strains resulting in plastic deformation.

ANALYSIS OF INCONEL 718

Microfissuring of Inconel 718 was analyzed in reference 1. Microfissuring was predicted for a power level of 1.7 kW and a welding speed of 7 inches per minute. The same material and welding parameters were examined in the present analysis for comparison. Properties used in equations (1) were k = 1.61 x 10^{-4} kW/(in-°F), α = 0.2977 in^2/min, v = 7 in./min, and P_2 = 1.41 kW. The net power P_2 was calculated using an overall power transfer efficiency estimated at 83%. A temperature distribution was calculated for this case. The results of this calculation are shown in figure 3, as contour lines of constant temperature. Temperatures are also shown in figure 4 in the form of a time history along the line x = 0, by setting x = vt at times x = 0,

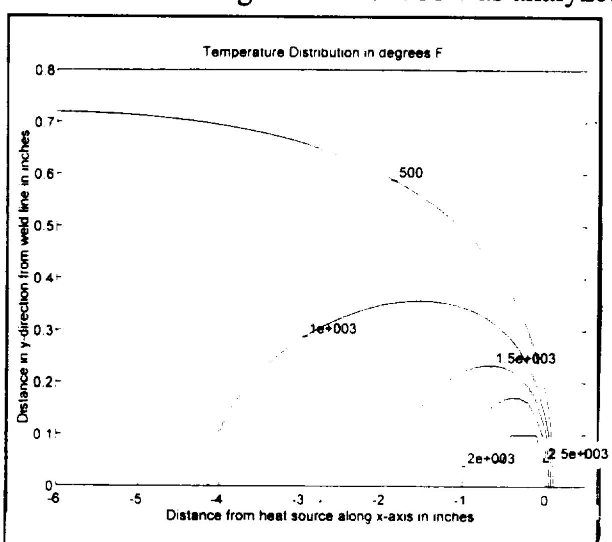
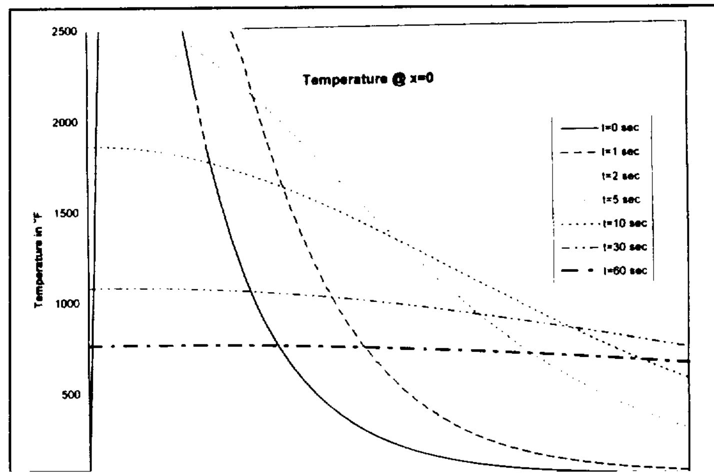


Figure 3. Contour Plot of Temperature

1,2,5,30, and 60 seconds. These illustrations show that the significant temperature ranges occur within a distance of 0.4 inches of the center weld line, and within 4 inches of the heat source along the direction of the weld. This area was then chosen for the construction of the finite element model.

The material properties for Inconel 718 were based on reference 3. A maximum melting temperature of 2500 $^{\circ}$F was used. The modulus of elasticity, coefficient of



delamination microfissures parallel to the plate surface (see figure 1). The maximum plastic strains occurred at the nodes located at 0.083 in below the top surface of the plate. Figure 6 shows the strains at x = 0 for each load step varying along the transverse (y) direction distance from the weld. The magnitudes of the plastic strains range up to 0.014 in./in.

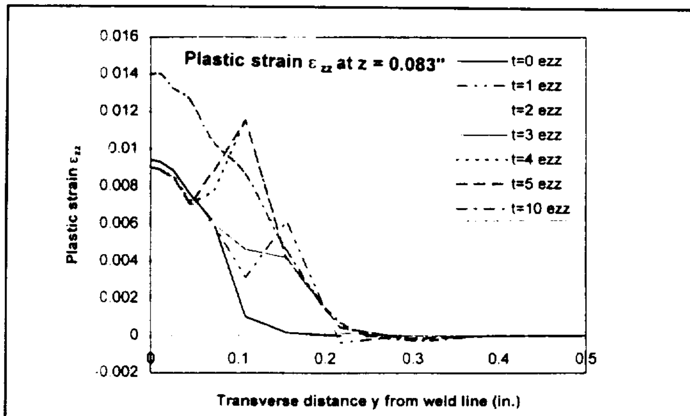


Figure 6. Plastic Strains ε_{pzz} at x = 0.

The computation of the damage D from equation 1 was performed by calculating the increase in plastic strain $\Delta\varepsilon_{pzz}$ associated with each thermal load step. Each of these increments is then divided by the temperature at that node associated with the thermal load. The result of this calculation is the contribution to the total damage D caused at that load step. In order to perform this calculation, a value for the critical hot-cracking strain ε_c was be calculated from the expression in reference 1:

$$\varepsilon_c = 0.002\sqrt{2}e^{\frac{(T-2475)^2}{2058}} \tag{3}$$

where T is the temperature in ^{o}F.

A logarithmic plot of ε_c is shown in figure 7. This figure reveals that for the material selected for analysis, temperatures that vary more than 150 ^{o}F from the melt temperature are associated with extremely large critical strains. Since these critical strains appear in the denominator of the damage term $\frac{\Delta\varepsilon_{pzz}}{\varepsilon_c}$, the plastic strain increments that are associated with such temperatures make a negligibly small contribution to the total damage D.

A sample calculation was performed to estimate the damage D at a distance of y = 0.12 in from the centerline of the weld. This value was selected because it includes the region with significant temperature variation contributing to the total damage. The values used for plastic strain increments $\Delta\varepsilon_{pzz}$ and temperature T were interpolated from the results of the analysis. After the summation in equation (1) was performed, a damage value of D = 1.22 was found. Since this value is greater than one, the occurrence of microfissures is indicated in this case.

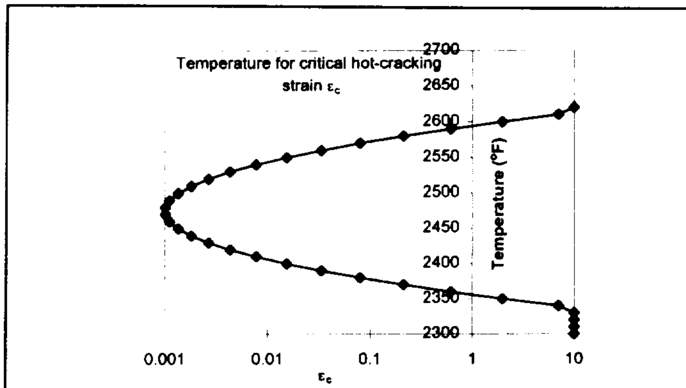


Figure 7. Critical Strain ε_c Near Melt Temperature

CONCLUSIONS

This project succeeded in modeling plastic strain in the vicinity of a weld on a plate. Although a range of welding parameters, namely beam power and speed, were not analyzed, due to time limitations, the procedures used in this report could be applied to produce a more general study of the effect of these quantities on incremental plastic strain and the resulting predicted damage measure. They could also apply to other materials, such as aluminum-lithium alloy 2195.

The solution procedure could be made more efficient and parametric analysis done more easily if a combined thermal and structural finite element analysis were performed. This approach could be taken with the ADINA-T program which has thermal modeling capability.

The finite element approach may not be the best way to verify the damage theory of microfissuring. The great variation in stiffness within the structure, due to the mechanical properties near the melt temperature, are likely to cause convergence problems in achieving a solution. Although these problems were overcome in the present analysis by changing the solution technique, there is no guarantee that this would always be possible.

Another difficulty is the fact that the area of the structure is quite small in which the temperature range both produces an increasing plastic strain, and is also so close to the melt temperature that there is a noticeable contribution to the accumulated damage. The small size of this region requires that the finite element mesh be finely graduated so that the temperature variation from node to node is not too large. This effect may well require that the model for each case that is studied must be remeshed and a separate analysis performed.

The small size of the critical area in which the damage will accumulate might be used to construct an approximate analytical expression, valid in a small range of temperatures and distance, which would allow a simplified solution. The resulting expression could then be analyzed to see the effects of varying the weld parameters. A solution of this type would be a more valuable tool and could be used by designers of welding procedures to predict which techniques would result in welds free of microfissures.

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