ACOUSTIC EMISSION AND FINITE ELEMENT ANALYSIS OF CRACK NUCLEATION AND PROPAGATION IN FATIGUE OF Al 7010 ALLOY

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ABSTRACT

Acoustic emission was used to detect crack initiation and propagation during fatigue of an overaged Al 7010 alloy. We have used elastic-plastic finite element analyses to investigate the effects of particle clustering and the proximity of pores on the stresses and stored elastic energy within particles in a matrix under load. Clustering tends to increase these values while pores tend to decrease them. J integrals have been calculated using crack-tip elements for defects within particles. Calculations have been performed for several combinations of matrix and particle properties. The value of J decreases with the amount of plastic deformation in the matrix.

KEYWORDS:

Fatigue, 7010 Al alloy, Acoustic emission, J integral, Finite element analysis

1. INTRODUCTION

Overaged Al 7010 sheet is used in the aerospace industry for structural components because of its high strength and resistance to fatigue. Recent work [1] has elucidated the sequence of events leading to failure. In both monotonic tension and fatigue, microcracks normal to the loading direction nucleate by the rupture of intermetallic particles. In monotonic tension, the microcracks in a particle cluster first coalesce intragranularly, and final failure occurs by the percolation of cracks between clusters by intra- or inter-granular propagation. In fatigue, the number of nucleated microcracks is generally lower. The microcracks propagate macroscopically in mode I. The number of nucleated microcracks increases when the maximum applied stress is increased. Thus, failure at high stresses can occur by the coalescence of several cracks, whereas failure at low stresses is generally due to the propagation of a single crack to a critical length. Acoustic emission can provide valuable information concerning damage initiation in both monotonic tension and fatigue.

A model is also required to predict the number of cycles necessary to cause particles embedded in the matrix to crack at low stress. The model must be able to take into account the effects of neighbouring pores and particle clusters. Elastic-plastic finite element analysis can be used to study the stress states developed within a particle in a plastically deforming matrix. Particle-pore interactions can also be studied. Based on these results, it is possible to develop a stress or energy-based criterion for particle rupture using for instance the J contour integral which gives a measure of the rate of release of energy when a crack propagates. Finite element analyses can provide J values for cracks (defects) within particles as well as for cracks emanating from particles, from which a law for crack propagation can be derived.

In this paper, we present some results concerning acoustic emission measurements during fatigue of the 7010 alloy. We also present a preliminary numerical study of the stresses and energies in particles in a plastically deforming matrix. We define a criterion using the J integral concept. We calculate J values for defects within particles and investigate the effects of matrix plasticity and modulus on the results. Finally we apply this model to monotonic tension, i.e. for the damage initiation which occurs during the first fatigue cycles.

2. MATERIAL

The processing of the Al 7010 sheet provided by Pechiney, France is descibed in detail elsewhere [1]. The Young's modulus of the overaged material was found to be 72.3 GPa. The tensile properties in the transverse direction for the material in the T7651 condition are shown in Table 1 [1]. Fatigue tests were performed for $\sigma_{max} = 440$ MPa, $R = \sigma_{min}/\sigma_{max} = 0.1$, $\nu = 10$ Hz. The average fatigue life under these conditions was 10000 cycles [1]. The Young's modulus of the intermetallic particles was estimated to be 150 GPa using micro-indentation techniques [1].

Table 1: Tensile properties of Al 7010 sheet, transverse direction, T7651 condition

0.2% yield stress (MPa)	Failure Stress (MPa)	% Area Reduction
438	512	6.7

3. ACOUSTIC EMISSION

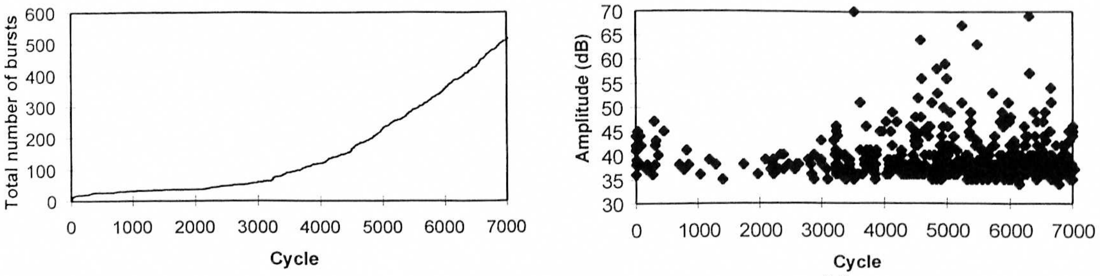
3.1 Experimental Procedure

Acoustic emission refers to the transient elastic waves generated in a material due to micro-displacements. Such micro-displacements can be produced by a phase transformation or by mechanically deforming a material. These waves can be detected by suitable piezo-electric transducers and recorded on a computer. Acoustic emission is thus a very sensitive technique for detecting microscopic events such as crack nucleation and propagation.

In the current set of experiments, hourglass-shaped samples were cycled in fatigue using the conditions described in section 2. One detector was positioned at each end of the specimen, which allowed the location of the origin of any given burst in the gauge section to be determined. A LOCAN 320 computerized acquisition system (Physical Acoustic Corp.) was used to log the data. Using this system, the amplitude, the time, and the load associated with each burst could be measured. The load was also recorded periodically. Teflon disks were used to reduce the noise coming from the hydraulic system of the load frame as described in [2].

The variation in the total number of bursts and in the amplitude of the bursts as a function of the number of cycles during the loading half of each cycle is shown for one test in Figs. 1(a) and (b), respectively. In the early part of the test ($N \leq 100$) there is a rapid increase in the amount of burst emission. This is followed by a region of relative silence which extends up to about 3000 to 4000 cycles, beyond which there is renewed acoustic activity. This sequence was observed for three different specimens under the same test conditions. Fig. 1(b) also shows clearly that there are many more high amplitude (≥ 45 dB) bursts beyond around 3000 cycles. A simple interpretation of these results could be that the high amplitude bursts in the first (≈ 100) cycles are associated with early particle ruptures. The high amplitude bursts beyond 3000 cycles would then correspond to new particle ruptures which result from the concentration of cyclic plastic strain in the matrix adjacent to particles. The corresponding increased amount of low amplitude burst emission would then be associated with the slip processes related to crack propagation, and perhaps crack opening and closing.

These results suggest that acoustic emission can provide valuable information concerning the initiation of fatigue damage which can be used to validate and to help develop new models.



(a) (b)

Figure 1: Variation in (a) the total number of bursts and (b) the amplitude of recorded bursts with cycle number.

4. FINITE ELEMENT ANALYSES

The following study was carried out for monotonic tension. Thus, the results are restricted to the analysis of particle ruptures occurring during the first fatigue cycle.

4.1. Stress and Energies in Heterogeneous Systems

The finite element method provides a means for determining stresses and strains in complex heterogeneous microstructures which allows plastic deformation to be taken into account. The stress fields for (i) an isolated particle, (ii) two particles and (iii) a particle and a pore were determined. Axisymmetric models were used for simplicity and because it greatly reduced the amount of cpu time required. All of the results presented in this section were obtained using the ANSYS finite element package. The behavior of a cyclinder containing a single spherical inclusion under tensile loading was first studied. The geometry and imposed constraints are shown in Fig. 2. The y-axis is the axis of rotation, and the x=0 plane is a mirror plane. Initially, purely elastic behavior was assumed for the particle and the matrix and the stress field was compared with the stress field obtained by analytical techniques based on Eshelby's method (see e.g. [3]). The stresses calculated using the two techniques were identical when the radius of the cylinder was greater than approximately ten times the radius of the particle. A radius ratio of 10 was thus chosen for the model in order to avoid the edge effects observed for smaller radius ratios. The analysis was also performed for a purely elastic particle and a strain hardening matrix. The strain-hardening law used was obtained from the tensile stress-strain curve of the material. The effect of elastic-plastic matrix behavior was to make the stress field in the particle inhomogeneous. The minimum and maximum stresses in the particle were smaller and larger, respectively, than the uniform stress determined under purely elastic conditions.

A second particle, aligned with the first along the loading direction and having the same diameter, was then added to the model. The distance between the particles was varied from $3R_{particle}$ (centre to centre distance) to $-1/2\ R_{particle}$ (effectively a single particle in the shape of an '8'). Beyond $3R_{particle}$, the results were identical to those obtained for an isolated particle. Below spacings of $1.5R_{particle}$, the maximum principal, equivalent (von Mises) and hydrostatic stresses, and the total elastic energy stored in the particle increased significantly. The minimum values were not affected by the presence of a second particle. The regions of stress and energy concentration in the particle are potential rupture sites.

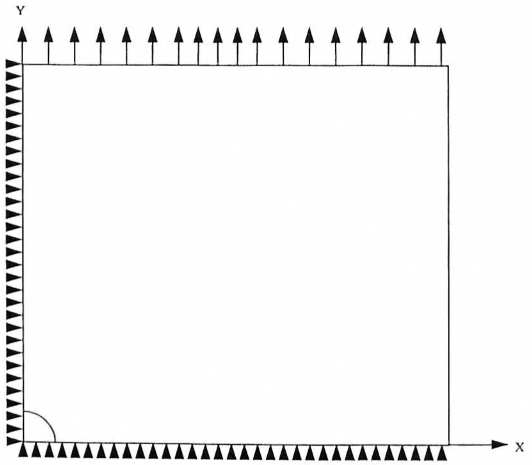


Figure 2: Two-dimensional geometry used in axisymmetric analyses to model an isolated particle in an 'infinite' matrix.

The analysis was then repeated for a pore aligned with the particle along the loading direction and of diameter equal to one half that of the particle. Contrary to the effects of a second particle, the presence of a pore does not affect the maximum values of the various stresses and the energy within the particle, but rather causes a significant reduction in the minimum values. Thus the presence of the pore tends to relieve the stresses within the particle.

4.2. J Integral Calculations

In addition to investigating the effects of additional particles and pores on the stresses and the energy in a particle, we wished to study the effects of a crack within and emanating from a particle. Such problems have traditionally been difficult to examine because of the stress singularity which exists at the crack tip. Most commercial finite element packages now contain singularity elements which can be used to study crack-tip stress fields. In two dimensions, these elements are 8-node quadrilateral elements which have been degenerated into triangles by forcing the three nodes on one side to occupy the same geometrical position (see e.g. [4]). This degenerate side (a point) corresponds to the crack tip. The edge nodes on the sides adjacent to the crack tip are then moved from the middle of the edge to the ¼ position (Fig. 3).

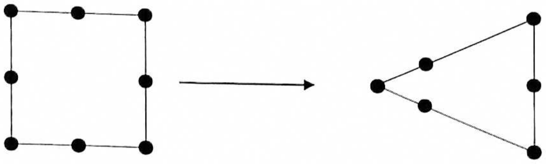


Figure 3: Degeration of 8-node quadrilateral element to yield a crack tip singularity element.

Even with these elements, it is difficult to obtain meaningful and readily interpreted results. However, singularity elements can be used to determine J integrals easily and accurately. All of the numerical results in this section were obtained using the ABAQUS finite element package. The J integral [5] is a contour integral which provides a measure of the rate of liberation of energy due to the propagation of a crack.

$$J = -dU/dA \qquad (1)$$

In Eq. 1, U is the potential energy and A the area of crack formed. The J integral can thus be used as a way to measure the potential energy available in the system to propagate the crack and must be compared to the energy dissipated during the formation of crack surfaces. It is meaningful even in situations where there is significant crack-tip plasticity. In addition, it is independent of the contour chosen as long as it contains the crack tip. The condition for crack propagation is that J must be superior to a critical value which is a material property.

$$J \geq (2\gamma_S + \gamma_P) \qquad (2)$$

In Eq. 2, γ_S is the surface energy and γ_P the plastic energy required to create a unit surface of crack.

The J integrals were calculated for a crack length of $R_{particle}/2$ using a semi-circular mesh contained within the particle (Fig. 4) in the axisymmetric model shown in Fig. 1. J was calculated for the following cases for applied stresses ranging from 100 MPa to 440 MPa (several contours were used for each applied stress) :

1) Purely elastic particle and matrix with same Young's modulus (i.e. homogeneous material, $E = E_{Al} = 72.3$ Gpa)
2) Strain-hardening particle and matrix (homogeneous material)
3) Purely elastic particle and strain-hardening matrix with same Young's modulus ($E_{particle} = E_{matrix} = 72.3$ Gpa)
4) Purely elastic particle and strain-hardening matrix with different Young's moduli ($E_{particle} = 150$ Gpa, $E_{matrix} = 72.3$ Gpa)

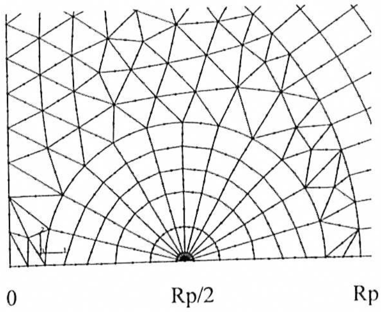


Figure 4: Detail of the mesh with which J integrals were calculated.

These different cases allowed us to study the influence of plasticity and of the elastic and plastic incompatibility between the particle and the matrix on the J integral. For each case the J integral was essentially the same for all of the contours. The results for one of the contours are shown in Table 2 below.

Table2: J integrals for crack length equal to $R_{particle}/2$.

Applied Stress (MPa)	**Case 1**	**Case 2**	**Case 3**	**Case 4**
100	0.3131	0.3126	0.2999	0.2910
200	1.252	1.262	1.252	1.164
300	2.818	2.931	2.818	2.619
400	5.009	6.509	5.326	4.445
440	6.061	12.21	7.841	5.650

Table 2 shows that the J integral increases with the applied stress in all cases. Comparison of cases 1 and 2 shows that J increases in a homogeneous material when the amount of plastic applied stress of 440 MPa (the 0.2% yield stress) is particularly significant. The results for case 3 indicate that the plastic deformation in the matrix adjacent to the purely elastic particle due to stress concentrations causes a slight increase in the J integral compared with case 1. The plastic flow of the matrix results in an inhomogeneous stress distribution within the particle which in turn affects the J integral. In case 4, the purely elastic particle with the higher Young's modulus constrains plastic flow in the matrix adjacent to it and therefore the value of the J integral is reduced compared with case 1. Note that the conclusions drawn here are valid for a pre-existing crack. In actuality, rupture may occur because irregularities in the morphology of particles can act as defects.

The J integral calculations were repeated for a crack of length equal to the radius of the particle. The solution converged for the homogeneous cases 1 and 2, but not for the inhomogeneous cases 3 and 4, as expected. In the latter cases, the J contour had to cross a boundary across which the material properties changed, which the theory is not currently capable of dealing with. The next step in this process is thus to generate a finite element model in which the crack protrudes from the particle sufficiently for it to be possible to define a J contour which is fully contained in the matrix. In fatigue it is possible to formulate crack propagation laws which are functions of ΔJ, analogous to the more common empirical laws based on ΔK, but applicable in situations where there is significant crack tip plasticity. Short crack propagation (cracks no longer than about 3 or 4 grain diameters) represents one situation where the J integral could be a potentially powerful tool. In the present case this would correspond to cracks (defects) within particles and cracks emanating from particles. This early stage of fatigue damage accumulation is often neglected but can represent an important portion of the total fatigue life of a material [6]. Further work is currently being carried out to incorporate these concepts into the present approach and to extend the present analysis to the case of a cyclic loading.

5. CONCLUSIONS

We have shown that acoustic emission can be used to obtain semi-quantitative experimental data on the initiation and propagation of fatigue cracks in an overaged Al 7010 alloy. Elastic-plastic finite element analyses have shown that particle clustering tends to increase the stress and stored energy levels within particles while the presence of a pore tends to decrease these values. J integrals have been calculated for a crack which is completely contained within a particle. The value of J increases with the amount of plastic deformation in the matrix.

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