MODELLING THE EFFECT OF MICRO-PORES ON THE FATIGUE LIFE OF AA7050 ALUMINIUM ALLOY THICK PLATES

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The effect of micropores on the fatigue life of smooth machined samples cut from AA7050 thick plates is investigated and a model is proposed to predict the fatigue life obtained as a function of the initial defect observed by SEM. The model defines an equivalent size of the initial defect as a function of its shape and position relative to the machined surface. Fatigue crack growth rate is used to calculate the fatigue life. This calculated fatigue life is compared to the observed fatigue life. It appears that the calculated fatigue life is a very realictic lower bound of the actual fatigue life. The model can be improved by the adjunction of a initiation phase taking into account the 3D shape of the initial defect and the intermetallic particles situated in its vicinity.

INTRODUCTION

It is common to seperate the fatigue life in two parts : the initiation life and the propagation life. Researchers are still discussing the relative weight of these two phases according to the initial state of the structure in terms of defects and according to the sollicitation. Even more important might be the scale at which the researcher looks at the structure. In this way K. Miller wrote "In polycrystalline metals it can be safely assumed that crack initiation phase does not exist" (1). In any case, when relatively big pores are present, like in cast aluminium products, the propagation stage seems to be at least predominant (see Skallerud et al (2) and Couper et al (3)). On the other hand, very small pores are found in wrought very thick plates, often associated with intermetallic constituent particles. In this case an initiation stage can be considered.

This article focuses on the calculation of the crack propagation life of smooth specimens cut in AA7050 very thick plates of standard quality, thus containing micro-pores (see Elsner et al, Owen et al, Magnusen et al and Heinz et al (4-7)). The proposed model integrates the crack growth rate equation from an initial defect size to a final defect size. The result of the calculation is compared to the observed overall fatigue life. The definition of the initial defect size is the key point of the model. Data are obtained from the examination of fracture surfaces of more than 100 samples by Scanning Electron Microscopy.

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As this simple propagation approach is not completly satisfactory, it appears that the introduction of an initiation stage is necessary. This is particularly true when intermetallic particles are present instead of pores at the initiation locus. The chosen approach to deal with this problem is to compute the initiation life using the stored elastic energy in the particles as proposed by Petton et al (8). A more sophisticated calculation using the Finite Element Method is proposed.

EXPERIMENTAL PROCEDURE

Fatigue specimens were machined in AA7050 T7451 plates, the thickness of which ranged from 100 to 200 mm. The specimens are cut in the long transverse direction (TL), at mid thickness and mid width. The specimen is designed to be sensitive to defects like micro-pores : the volume in which the stress is maximum is relatively big (12.7 mm in diameter and 50 mm length). Fatigue testing was performed as per BMS 7-323 (9) at a stress ratio R=0.1, with the maximum stress ranging from 242 to 320 MPa.

Fractured specimens were observed in Scanning Electron Microscopes (SEM). The dimensions of the defect from which the fatigue crack started was measured as well as its position from the machined surface of the specimen. These data were computed according to a algorithm described below in order to determine the initial equivalent defect size.

Finite Element Method calculations were made by using the ABAQUS code.

DESCRIPTION OF THE CRACK PROPAGATION MODEL

Several models proposed in the literature are relevant to our problem : calculate the fatigue life knowing the geometry of the initial defect and the properties of the base material (Table 1).

The model which we propose derives from the LEFM (Linear Elastic Fracture Mechanics). The reason for this is its simplicity and the fact that satisfactory results were obtained by other researchers on cast aluminium alloys containing pores (2,3). The main difference between the 7050 T7451 and the latter alloys is the yield stress : about 440 MPa for the 7050 against 220 MPa for the cast alloys. The flaw size has the same order of magnitude : average 100 µm ; range : 25 to 250 µm. So the use of EPFM (Elasto Plastic Fracture Mechanics) is even less necessary in the case of AA7050 T7451 than in the case of cast alloys.

Moreover, the stress amplitude is relatively small compared to the cyclic yield stress. The cyclic yield stress of an alloy similar to the AA7050 is about 400 MPa (see Renaud (18)). Miller considers that EPFM must be considered when the stress variation exceeds 2/3 σ_y, that is 270 MPa (19). The stress variation range in our tests is [218 ; 288] MPa. This further justifies the use of LEFM.

The literature review shows that the variation of the stress intensity factor can be approximated by the following formula :

$$\Delta K = 0.7\Delta\sigma\sqrt{\pi a} \quad \text{...(1)}$$

where $\Delta\sigma$ is the stress variation and a is the equivalent initial flaw size. The definition of a is explained in figure 1.

The fatigue crack growth rate (FCGR) da/dN is taken from Schwarmann (20). In this book, the FCGR curve is fitted by Forman's formula with the parameters : C_f=4.11 10^{-6} ; K_f = 55 MPa√m ; m = 2.98 for the 7050 T7451.

In order to take into account the short crack effect, the Paris regime is just extrapolated down to the low ΔK values, instead of using the near threshold data.

TABLE 1 - Some models of the literature relevant to the calculation of the fatigue life in metals containing defects.

	criteria relating to the criticity of a defect (crack will or will not propagate)	propagation life calculations
Linear Elastic Fracture Mechanics (LEFM)	• Couper (3) (Al casting alloys) $\Delta K_{eff} = 0.7\Delta\sigma^{+}\sqrt{\pi a}$ where $\Delta\sigma^{+}$is the positive part of the stress cycle $\Delta K_{eff} \le \Delta K_{threshold}$ => no propagation • Murakami (10, 11) (Steel, Brass, AA2017) $K_{\max} = 0.63\sigma_{\max}\sqrt{\pi\sqrt{defect\_area}}$ Empirical formula for the fatigue limit : $\Delta\sigma_f\sqrt{(defect\_area)^n} = Const.$ • Lukas (12) (Steel) Relationship between the stress concentration factor of the defect, the $\Delta K_{threshold}$ and the fatigue limit	• Couper (3) Simple integration of $\frac{da}{dN} = C\Delta K_{eff}^{m}$ • De Bussac (15) (Ni-based alloys) Integration of $\frac{da}{dN} = C\Delta K_{eff}^{m}$, with K_{op} after Mc Evily. Probability of finding a defect near the surface. • Skallerud (Al casting alloys) (2) $\frac{da}{dN} = f\left(\Delta K_{eff}\right)$ K after Newman & Raju (16) K_{op} after Newman
Elasto-Plastic Fracture Mechanics (EPFM)	• Usami (13) (Steel) Effective defect size which relates to the fatigue life is a function of the plastic zone size at the fatigue limit and the cyclic yield stress. • Mc Evily (14) (Steel and AA6061) $K = \sigma\left(\sqrt{\frac{\pi\rho_e}{4}} + \sqrt{\pi a}\right)$ where ρ_e depends on the defect geometry $\Delta K_{eff} \le \Delta K_{threshold}$ => no propagation Formula for K_{op}.	• Edwards (AA7010 and AA7075) (17) $\frac{da}{dN} = Cr_p^m$ where r_p is the plastic zone size, parameter which really governs the growth of short cracks.

RESULTS AND DISCUSSION

An illustration of the pores found at the initiation of the fatigue failure is shown in figure 2. The size of the pores range from 25 to 250 microns with an average of 100 microns. Most often, the shape of the pore and its position is such that the dimension of the initial flaw size is simply the length of the pore normal to the machined surface.

Figure 3 shows the comparison between the fatigue life calculated by the model and the observed fatigue life. We see that the model gives realistic fatigue lives for a large majority of samples. Both the order of magnitude of the fatigue life and its variation with the initial defect size are roughly predicted without any fitted parameter.

A few samples do last much more than predicted by the model. In this case, the initiation life is probably not negligible. This is why a second step of the program was launched, in order to calculate the number of cycles to initiation. The basis of the model follows Petton's work dealing with the estimation of the stored elastic energy originating from the incompatibility between a particle and a matrix (8). As it is often observed that pores and intermetallic particles are interacting in the fracture process, we produced a model including both a pore and an intermetallic particle. Figure 4 shows how the presence of a pore affects the stress state in the particle. The main conclusion at this stage is that the interaction takes place when the distance between the pore and the particle is less than one diameter of those. The stress in the particle is smaller when a pore is present in its neightbourhood. So, the initiation phase should be delayed. However, once the particle is cracked, the defect size is larger because of the additional crack length due to the pore. The competition between these effects must be clarified.

CONCLUSIONS

- In standard quality very thick plates, the fatigue initiation on smooth specimen takes place at pores situated near the machined surface.

- A model based on the calculation of the propagation life using the Linear Elastic Fracture Mechanics gives realistic results for a large majority of samples. But a few samples have a much longer fatigue life than predicted.

- Often, the pores are associated with intermetallic constituent particles. These intermetallic constituent particles become predominant in high quality plates in which the pores are smaller.

- In order to improve the model, a crack initiation stage must be introduced, rather than modifiying slightly the stress intensity factor calculation. A FEM model is currently developed to tackle this problem, using an energy approach, taking into account the interaction between pores and intermetallic particles.

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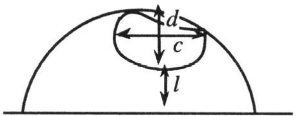

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if $l<d$ then "surface defect"
$p=l+d$
  if $c<p/0.7$ then
$a=\min(p,5c)$
  else $a=\min(c,2.5d)$
$K=0.7\sigma\sqrt{\pi a}$

if $l\geq d$ and $0.2\leq c/d\leq 5$
then $a=\max(c,d)$
$K=0.64\sigma\sqrt{\pi a}$

if $l\geq d$ and $c/d>5$ or $<0.2$
then $a=\max(5c,5d)$
$K=0.64\sigma\sqrt{\pi a}$
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Figure 1. Definition of the equivalent initial defect size

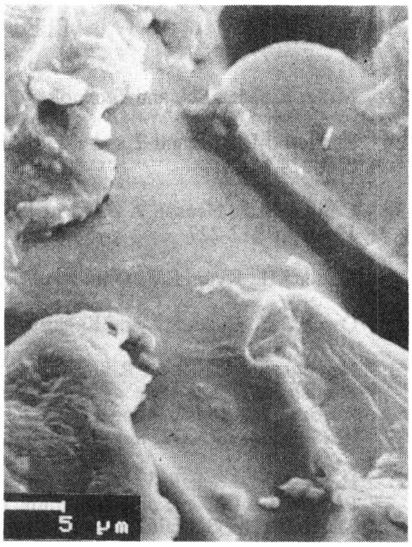

Figure 2. SEM micrograph of a pore at initiation

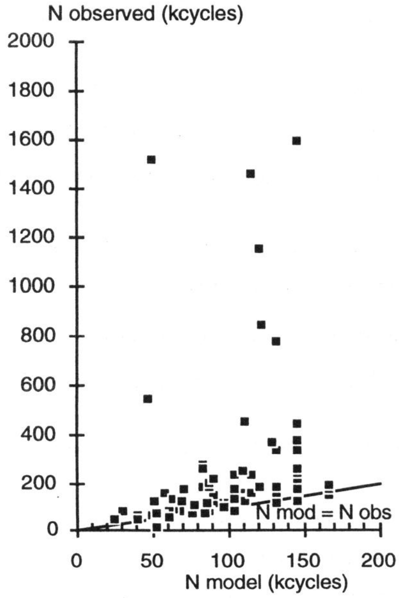

Figure 3.Comparison of the observed and calculated fatigue life.

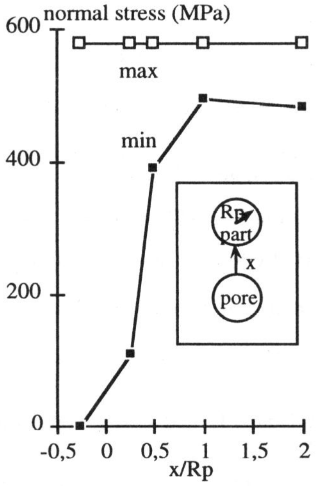

Figure 4. Finite element model showing the interaction between pore and particle (stress in the part.)