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

J.C. Ehrström*, D. Roy**, M. Garghouri *** and R. Fougères ***

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 realistic 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 separate 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
solicitation. 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 completely 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 (Elastic 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 σy, 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:

\[ ΔK = 0.7Δσ\sqrt{πa} \]

(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:
$C_p = 4.11 \times 10^{-6}$; $K_f = 55$ 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 $\Delta K$ 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.

<table>
<thead>
<tr>
<th>Linear Elastic Fracture Mechanics (LEFM)</th>
<th>criteria relating to the criticality of a defect (crack will or will not propagate)</th>
<th>propagation life calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Couper (3) (Al casting alloys)</td>
<td>$\Delta K_{eff} = 0.7 \Delta a^{<em>} \sqrt{a_a}$ where $\Delta a^{</em>}$ is the positive part of the stress cycle $\Delta K_{eff}$ up to $\Delta K_{threshold} =$ no propagation</td>
<td>• Couper (3) Simple integration of $\frac{da}{dN} = C\Delta K_{op}^{m}$</td>
</tr>
<tr>
<td>• Murakami (10, 11) (Steel, Brass, AA2017)</td>
<td>$K_{max} = 0.63 \sigma_{max} \sqrt{\pi a}$ Empirical formula for the fatigue limit $\Delta \sigma / (\text{defect area})^* = \text{Const}$</td>
<td>• De Bussac (15) (Ni-based alloys) Integration of $\frac{da}{dN} = C\Delta K_{op}^{m}$ with $K_{op}$ after McEvily. Probability of finding a defect near the surface.</td>
</tr>
<tr>
<td>• Lukas (12) (Steel)</td>
<td>Relationship between the stress concentration factor of the defect, the $\Delta K_{threshold}$ and the fatigue limit</td>
<td>• Skallen (Al casting alloys) (2) $\frac{da}{dN} = f(\Delta K_{op})$ $K$ after Newman &amp; Raju (16) $K_{op}$ after Newman</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elasto-Plastic Fracture Mechanics (EPM)</th>
<th>criteria relating to the criticality of a defect (crack will or will not propagate)</th>
<th>propagation life calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Usami (13) (Steel)</td>
<td>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.</td>
<td>• Edwards (AA7075 and AA6061) (17) $\frac{da}{dN} = C_r^n$ where $r_p$ is the plastic zone size parameter which really governs the growth of short cracks.</td>
</tr>
<tr>
<td>• McEvily (14) (Steel and AA6061)</td>
<td>$K = \sigma \left( \frac{p \rho_s}{4} + \sqrt{\rho_s} \right)$ where $\rho_s$ depends on the defect geometry $\Delta K_{eff} \leq \Delta K_{threshold} =$ no propagation</td>
<td></td>
</tr>
</tbody>
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Formula for $K_{op}$. |
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 neighbourhood. 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 modifying 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.
REFERENCES

(1) Miller K., Mat. Sci. and Technology, n°9, 1993, pp. 453-462.


(18) Renaud P., Thèse de Docteur de 3ème cycle, Poitiers, 1982


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if \( l < d \) then "surface defect"
\[ p = l + d \]
if \( c > p / 0.7 \) then
\[ a = \min(p, 5c) \]
else \( a = \min(c, 2.5d) \)
\[ K = 0.77 \sigma \sqrt{a} \]

if \( l \geq d \) and \( 0.25c/d < 5 \)
then \( a = \max(c, d) \)
\[ K = 0.64 \sigma \sqrt{a} \]

if \( l \geq d \) and \( c/d > 5 \) or \( < 0.2 \)
then \( a = \max(5c, 5d) \)
\[ K = 0.64 \sigma \sqrt{a} \]

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.)