INFLUENCE OF GEOMETRIC SHAPE OF SPECIMEN IN FATIGUE LIFE CHARACTERIZATION ON WELDED JOINT IN TITANIUM ALLOY

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Abstract: From literature we can find many theories on description of behaviour of different kind of materials. But just a few of them take into account an exact correlation between theoretical and experimental applications. In many instances the behaviour of these materials could be represented in function of some characteristics as density, Young modulus and Poisson ratio. One material with good characteristics of these listed above, that has been subjected to examination in this study, could be represented by titanium alloy and in particular titanium alloy grade 5. This material is suitable for the majority of applications in aeronautical, aerospace and naval industries and biomedical area. To be used in the field mentioned above, often titanium must be incorporated in different structures that can be obtained with welding process assembly. This new component could be more sensitive to crack initiation near the welded area due to the influence of the welding process. In this paper we try to elucidate some problems related to the fatigue life resistance of components simulating the activity during the real life of an assembly. The results have been confirmed by fractography analysis of broken surfaces, with a Scanning Electron Microscopy (SEM) and an optical microscope and have been correlated through numerical analysis.

Key words: FATIGUE LIFE, CRACK INITIATION, WELDED JOINTS

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1. INTRODUCTION

Material inhomogeneities are, in general, defects in the translational invariance of material properties. In a specimen different material regions can be seen, with rapid changes of microstructure and properties, which may be more or less smooth or even abrupt (1). Obviously it is virtually impossible to manufacture particles with perfectly smooth geometries (2).

The presence of micro defects in material due to certain variation of temperature or void merge during the process of fabrication is inevitable. The study of the physical process about the behavior of material can be dedicated to the nucleation phase of crack or void described with the inequality \( a < a_m \) (3), where \( a_m \) is the smallest crack length detectable by current technology, which is about 0.1\( \mu \)m. Heterogeneities in order of few micrometer are present in stainless steel as sulfide inclusions with size of 10 \( \mu \)m (4). In effect damage tolerance analysis which describes fatigue crack growth should be one connection to solve the fatigue nucleation stage.

In a theoretical vision, defects correspond to mathematical singularities in a continuous description that can be easily detected in the elastic field. An important subject of contemporary theoretical and applied mechanics is the fracture. The most relevant notions developed by engineers in that context are those of driving force acting on the tip of a crack and of energy-release rate.

2. OVERVIEW OF THE STATE OF THE ART

Description of fatigue initiation life in different medium, represented by solid mechanics and fluid mechanics fields, is yet open for all research society. Moreover, the technical society until today have provided in literature particular descriptions, lemmas and corollaries in goal to explain that topic. In next few lines, we will point some of the most important issue.

2.1 DEFINITION OF FATIGUE LIFE INITIATION

In literature, fatigue initiation life of solid materials, is assumed to be represented by the phase of crack initiation activity. In this way, for the description of this phase of crack initiation different definitions have been proposed. In absence of standard agreement, it is admitted to define the fatigue life initiation by a threshold crack length. The definition of the micro-crack initiation length is supposed to be quite equal to 0.1 mm for the majority of steels. This dimension is generally easy to detect and corresponds to a defect comparable to the steel grain size average. Fatigue initiation life is a consequence of cyclic slip in slip bands which implies
cyclic plastic deformation as result of moving dislocations. This micro-
plasticity can occur more easily in the grains at the material surface. 
Accordingly the initiation fatigue life is supposed to be completed when 
micro-crack growth is no longer depending on the free surface conditions.

2.2 FATIGUE LIFE WITHOUT INITIATION

Some authors like Murakami (5) considered that each material contains a 
defect as a crack. Where the size is characterized by the root square of the 
‘area’ parameter (‘area’ of the defect projected on the plane perpendicular to 
the direction of the maximum principal stress) and defined that crack 
initiation stage is negligible (Ni ≈ 0). Fatigue life is therefore assumed to be 
controlled by the crack propagation law.

2.3 FATIGUE INITIATION PARAMETER

In any case, fatigue resistance to initiation could be represented by a 
power relationship of the form \( P_i = f(N_t) \) where \( P_i \) is an initiation parameter 
and \( b \) exponent of Basquin’s type. Several approaches have been used to 
define the initiation parameter \( P_i \): effective stress, notch stress intensity 
factor, damage parameter issued from SWT parameter (6), energy parameter.

It is acceptable to use stress range as a parameter to express fatigue 
resistance to initiation. In this case it is necessary to take into account that 
fatigue generally initiates from stress concentration area which induce stress 
gradient at notch tip. Stress distribution at notch tip was assumed to derive 
from Irwin’s elastic stress distribution at crack tip by Creager and Paris (7). 
To avoid stress singularity at notch tip the Irwin stress distribution at notch 
tip is shifted by introduction of a new origin located at distance \( \rho/2 \) to the 
previous one. The stress distribution is governed by the (crack) stress 
intensity factor \( K \) and represented by:

\[
\sigma_{yy} = \frac{K}{\sqrt{\pi r}} \cos \frac{\theta}{2} \left[ 1 + \sin \frac{\theta - 3\theta}{2} \right] + \frac{K \rho}{\sqrt{2\pi r}} \frac{\rho}{2} \theta
\]  

(1)

where \( r \) and \( \theta \) are polar coordinates and \( \rho \) the notch radius

This method assumed that the effective stress is the maximum stress 
located at notch tip which is given by:

\[
\sigma_{max} = \sigma_{yy}(x = \rho/2, \theta = 0) = \frac{2K}{\sqrt{\pi \rho}}
\]  

(2)
Barsom and McNicol (8), Jack and Price (9), Clark (10) and Truchon (11) have used the parameter $\Delta K/\sqrt{\rho}$ to express fatigue resistance on notched specimens.

This fatigue resistance can be expressed by the concept of effective stress range (12) $\Delta \sigma_{ef}$ which represents the average stress over the fatigue process volume often reduced to the average stress over the effective distance $X_{ef}$ due to the assumption that this volume is cylindrical.

$$
\Delta \sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} \Delta \sigma_{yy}(r)dr
$$

Lukas et al. (13) approximated this stress by an equivalent stress in proximity of a notch tip prolongated with fictitious microcracks by the following relationship:

$$
\Delta \sigma_{eq, Lukas} = k \frac{\Delta \sigma_{g}}{\sqrt{1 + 4.5 a_0/\rho}}
$$

$k_t$ is the elastic stress concentration factor $\sigma_g$ the applied gross stress range. The fictitious microcrack length used by Lukas et al (14) is here assumed equal to $a_0$:

$$
a_0 = \frac{1}{\pi} \left( \frac{\Delta K_{th}}{\sigma_D} \right)^2
$$

where $\sigma_D$ is the fatigue limit and $\Delta K_{th}$ the fatigue threshold.

Due to stress concentration, cyclic plasticity occurs generally at notch tip and elasto-plastic stress distribution is generally more complex than the elastic one and it can be obtained by Finite Element computing. By applying effective stress range definition given in formula (3), Capelle and al (15) have presented fatigue resistance to initiation of an X52 pipe steel.

The stress distribution at notch tip at a distance greater than the effective distance can be described by the so-called Notch Stress Intensity Factor (NSIF). Lazzarin et al (16) use the elastic NSIF $K^*$ as parameter for fatigue initiation. Boukharouba et al (17) have compared fatigue initiation criteria with a criterion based on the elasto-plastic notch stress intensity factor $K_{\rho}$ on welded specimens made in low strength steel; The weld toe was considered as a notch with a notch angle of 135°. The NSIF has then unit MPa *m-
where $\alpha$ is the power dependence of the stress distribution ($\alpha = 0.385$).

Smith et al (18) have shown experimentally that the result of equation (6) is constant whatever the stress ratio is:

$$\sqrt{\sigma_{\text{max}} E \varepsilon_a} = C = \text{SWT}$$

where $\sigma_{\text{max}}$ is the maximum stress, $E$ the Young’s modulus and $\varepsilon_a$ the strain amplitude. This result is called the SWT parameter and it is generally used to convert low cycle fatigue resistance at zero stress ratio to low cycle fatigue resistance at any stress ratio. Lazzarin et al (16) have derived a so-called damage parameter $D$ from the SWT parameter and expressed it as a stress (MPa*units); They have presented that for thin plates notched by symmetric lateral U-, V- shaped notches with notch root radii ranging from 0.1 to 10 mm and made in steel. All the results merge in a unique curve independently of the notch radius.

Fatigue crack initiation of engineering components exhibiting significantly small dimensions imperfections “short flaws” is expressed as:

$$\Delta \sigma_{\text{th}} = \frac{\Delta K_0}{F \sqrt{\pi a_c}}$$

(7)

where $F$ is a geometrical factor.

This fatigue initiation stress range for both short and long crack is expressed by Kitagawa and Takahashi diagramme (19) where the crack growth threshold is plotted against the crack size. Using empirical law relationship (5) we can write:

$$\Delta \sigma_{\text{th}} = \frac{\Delta K_0}{F \sqrt{\pi (a_c + a_0)}}$$

(8)

Another formula is presented by Jelaska and Podrug (20) in cumulative HCF/LCF loading:

$$N_i = \frac{N_{\text{gr}} \sigma_{\text{th}}^{n_0}}{\left( \frac{2 \sigma_0 \sigma_a}{\sigma_U + \sigma_a - \sigma_m} \right)^n + \sigma_m^{n_i}}$$

(9)

where $n_i$, $\sigma_{\text{th}}$, $\sigma_U$, $\sigma_m$, $\sigma_0$, $N_{\text{gr}}$, $n_{\text{HCF}}$ are material constant, ultimate strength,
stress amplitude, maximum stress, endurance limit, sufficiently long fatigue life, number of HCF cycles.

3. MATERIALS AND WELDED BUTT JOINTS

In last period materials as titanium and titanium alloy are finding widespread applications due their good characteristics. Consequently they show a good balance of mechanical and chemical properties and hence cover many areas of application in diverse industries. The most widely used titanium alloy is Ti-6Al-4V (α–β alloys). These alloys contain larger amounts of beta stabilizers (4 to 6%) (21). Compared with steel, titanium or titanium alloys have low density and shows a similar fatigue resistance and presents a very attractive strength weight ratio.

The most influential microstructural parameter on the mechanical properties of titanium alloys can be influenced by either α alloys (hexagonal crystal structure) or β alloys (body centered cubic structure) and α–β alloys. Properties of α–β alloys (titanium grade 5) can be controlled through heat treatments (22), (23). Chemical compositions of tested materials are reported in Table 1 and Table 2.

Table 1. Chemical composition of titanium alloy grade 5.

<table>
<thead>
<tr>
<th>Titanium grade 5</th>
<th>C</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>H</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM B265</td>
<td>&lt;0.08</td>
<td>5.5-7.5</td>
<td>3.5-4.5</td>
<td>&lt;0.30</td>
<td>&lt;0.015</td>
<td>&lt;0.03</td>
<td>&lt;0.25</td>
</tr>
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Table 2. Mechanical properties of titanium alloy grade 5.

<table>
<thead>
<tr>
<th>Titanium grade 5</th>
<th>Modulus of elasticity E [MPa]</th>
<th>Ultimate tensile strength R [MPa]</th>
<th>Yield tensile strength R0.2 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM B265</td>
<td>1.138</td>
<td>956.4</td>
<td>760</td>
</tr>
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</table>

The alloy is recommended mainly for design disks, blades, spacer rings, engine body and other aircraft-engine, components operating at temperatures up to 400–450°C (24). In the case where these materials are integrated in structure mentioned above, different procedures for joining are used. One possibility is to use mechanical joining by welding process as butt welded joint. Cited by Casavola et al (22), specimens obtained by process of
welding and more precisely “butt welded joint” show sensitivity to fatigue life initiation at conjunction of weld cord and parent material. Of course, in this region, which corresponds to the heat affected zone (hosting microstructural changes) the stress/strain field is usually amplified with respect to the nominal stress values because of the effects of local geometry of the seam, localized plasticization and secondary bending produced by misalignments.

In the other hand, one great problem is represented by the slags which are formed and deposited, during the welding process, in proximity of the weld cord. Due to the difficult task to eliminate these entities caused by solidification, life of butt welded joint could decrease. For example using metal removal in steels and low alloy steels, can cause un-tempered martensitic to form, which is brittle and causes significant shortening of fatigue life. In this case the welding processes must be improved, redefining welding time and speed (25).

Figure 1 shows the approximate profiles recognized by a tactile device, acquired namely by a Coordinate Measuring Machine (CMM) for the right and reverse sides of the butt welded specimen.

![Figure 1. Butt welded joint specimen: right (upper) (a) and reverse (lower) (b) side seam profile.](image)

4. **RESULTS AND DISCUSSION**

After fatigue tests, on specimens of butt welded joint of titanium alloy, a summary of macrographies about details of microstructure has been
illustrated. Thus such macrography, characterizes areas where initiation of crack occurs. In this way are taken samples all over the material surface, both from the welding area connection and also from the area where the slags irregularities are deposited. With an optical microscope we show the arrangement of grains, in which we can see the distribution of lamellar grains. In figure 2 we can see the distribution of microcracks between grains which occur concerning intergranular life initiation.

![Microcrack initiation in intergranular mode, titanium alloy Ti-6Al-4V (α-β)](image)

On the other hand, in the adjacent area of slag we found some inclusions which can lead to trigger the process of fatigue. Difference in color between material layer under the slag and titanium alloy displayed in figure 3 (a), leads to the idea that, in this area could be occurred a chemical process in different way that also influences the fatigue behavior. At the interface of these layers in figure 3 (b), is evident the distribution of line of fatigue.

![Site of life initiation](image)
Under some influences of temperature variations, correlated with the fatigue damage test effect involved, the critical strain in ductile mode fracture is locally showed. Exceeded this critical strain shear bands and small voids are formed. These voids are known as strain induced porosity (SIP). An example of strain induced porosity in Ti-6Al-4V is shown in figure 4. Once this porosity is created in forging billet, it is not always healed during subsequent forging operations. Consequently, it can be carried over into a finished component as a defect that can act as an early fatigue crack initiation site (25).

In order to correlate the experimental results, we apply the numerical analysis model. Models with Extended Finite Element Method (XFEM) have been realized and the analysis has been executed through Abaqus Software. The numerical model considered had the same shape of butt welded joint acquired by the Coordinate Measuring Machines. For fatigue tests a value of charge loading of 24.5 kN has been imposed. According with the experimental results, the model has incorporated one irregularity. This irregularity is exemplified through one crack of about 0.1 mm in the weld cord area. Shape of specimen is represented in figure 4 a). Although, this crack may produce implications, expecting an increase of stress in the welded cord area, an obvious increase in stress in the slag area, has been registered. These trends of stress distribution are showed in figure 5 b). This complex behaviour can be explained by the appearance of inclusions under the slag area as displayed in figure 6.
CONCLUSION

Experimental determination and numerical analysis of fatigue life initiation are illustrated in this paper. Thus, factors which could influence the behavior of butt welded joint specimen are determined. Some specific parameters which could be mentioned are: distribution of boundary grains on material which show lamellar form and early phase in microcrack intergranular behavior, varieties of some inclusion unexpected in base
material, difference of temperature in the bonding area represented through interface slag and parent material. The same could be cited about factors regarding the growing in size of voids, which involve the strain behavior and initiation life.

On the other hand, by XFEM is presented the distribution of stress along the shape of butt welded joint and the behavior of one irregularity in the body of material alloy, through which we can deduce that, the true life initiation of fatigue, in titanium alloy, is represented by a complex of parameters from shape of material to manufacturing process.

REFERENCES


