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INTERPRETATION OF DUCTILE FRACTURE TOUGHNESS LOADING RATE DEPENDANCE OF TA6V IN TERMS OF A LOCAL APPROACH

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Abstract: Fracture of equiaxed Ti-6Al-4V is studied under two different loading rates namely static loading where $K = 1 \text{ MPaVm/s}$ and dynamic loading where $K = 10^7 \text{ MPaVm/s}$. An important increase in fracture toughness is found from static to dynamic loading. The results are interpreted in terms of a the local approach to fracture based on a local criterion of critical void growth. The increase in fracture toughness is explained from an increase in both the yield strength and the notch ductility from static to dynamic loading.

Résumé: La rupture d'un alliage de Titane TA6V présentant une microstructure équiaxe est étudiée sous deux régimes de sollicitation dénomés chargement statique où $K = 1 \text{ MPaVm/s}$ et chargement dynamique où $K = 10^7 \text{ MPaVm}$. Une élévation importante de la ténacité est mise en évidence avec l'augmentation de la vitesse de sollicitation. Ces résultats sont interprétés à partir de l'approche locale à la mécanique de la rupture à l'aide d'un critère local de croissance critique de cavités. La variation de ténacité provient d'une augmentation conjointe de la limite d'écoulement et de la ductilité sous entaille du matériau avec la vitesse de sollicitation.

INTRODUCTION

The field of dynamic fracture comprises both the study of a stationary crack subjected to very high loading rates and the study of a propagating crack subjected to either static or dynamic loading. This paper focuses on stationary cracks subjected to either static or dynamic loading giving rise to loading rates respectively of 1 MPaVm/s and 10^7 MPaVm/s . Differences in the resistance to crack propagation between static and dynamic loading conditions can arise from a purely mechanical effect of building up of stresses at the crack tip due to wave propagation phenomenon or from inertial effects at the crack tip or from a purely material effect expressed in terms of both deformation and damage kinetics micromechanisms. It is shown that under the loading conditions considered for this study, only the material effects are of significance. Several studies [1, 2] have shown that fracture in equiaxed Ti-6Al-4V occurs in a ductile manner with a micromechanism of cavity nucleation, void growth and coalescence leading to a dimpled fracture surface. Such micromechanisms have been extensively studied for the fracture of steels on the ductile plateau, and fracture of A508 steel has been successfully analysed with the local approach to ductile fracture. Fracture behavior of Ti-6Al-4V is found to be highly dependant on the loading rate, though no change in micromechanism of fracture is observed for this particular equiaxed Ti-6Al-4V. Therefore the concept of a critical void growth criterion R_c/R_0 with a characteristic distance Δa_c is used to express fracture of Ti-6Al-4V under both static and dynamic loading.

MATERIAL AND EXPERIMENTAL PROCEDURES

Material:

The material investigated in this study is an equiaxed Ti-6Al-4V provided in the form of laminated plates of thickness $e = 50$ mm. The thermomechanical treatment received consist of an α/β transformation with heat treatment $730^\circ\text{C} / 2\text{h}$. This material does not contain any form of inclusion but is rather formed of α -phase grains (hcp structure) surrounded by a three-dimensionnal network of β -phase (bcc structure). The deformation incompatibilities between these two phases are known to induce possible twinning and stress concentration at the α/β interface during deformation process [3]. The grain size varies between $15\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$ with the presence of some more elongated grains in the laminate direction (Figure 1).

Figure 1 : Typical microstructure of equiaxed Ti-6Al-4V.($\times 300$)

Experimental procedures:

Mechanical behavior

All the samples used are of axisymmetric shape with the axis along the tranverse direction of the plate. They are taken from the mid-section of the laminated plate.

Compression tests have been performed on small cylinders with diameter $\phi = 10$ mm and height $h = 12$ mm with annular grooves on the opposite faces to avoid buckling during testing. Corresponding constitutive laws have been obtained under static as well as under dynamic loading with the Hopkinson bars apparatus documented elsewhere [4]. Corresponding deformation rates are $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$ under static loading and $\dot{\epsilon} = 10^3 \text{ s}^{-1}$ under dynamic loading. Tensile tests on axisymmetric specimen of diameter $\phi = 7$ mm have also been performed under static loading.

Fracture toughness

Fracture toughness has been determined with axisymmetric tensile specimen of diameter $\phi = 14$ mm, notched and fatigue precracked under rotating bending to a depth $a/R = 0.45$, with a the fatigue crack length and R the radius of the sample (Figure 2). Very good annular fatigue cracks have been obtained. Static tests were performed with two facing extensometers to record the crack mouth opening curves during the test, the load is monitored through the load cell. Load versus crack mouth opening have been derived and J-integral values calculated with the Merkle formula [5] :

$$J = \frac{1}{2\Pi c} \left[-P \delta_{\text{crack}} + 3 \int_0^{\delta_{\text{crack}}} P d\delta_{\text{crack}} \right] \quad (1)$$

where c is the radius of the uncracked ligament prior to testing, P is the recorded load and δ_{crack} the opening due to the presence of the crack

$$\delta_{\text{crack}} = \delta_{\text{experiment}} - \frac{L_0 P}{\Pi R^2 E}$$

where L_0 is the reference length of the extensometer, E the Young modulus. It is assumed that no stable crack growth occurs before final fracture, as confirmed from FEM of the test. The value of J at failure is therefore considered to be a measure of fracture toughness J_{Ic} .

Dynamic tensile test on identical axisymmetric precracked specimen have been conducted on a specially designed apparatus called "Arbalète" [6]. A projectile is accelerated on parallel guides by rubber bands to speeds up to 50 m/s. One end of the sample is screwed on a moving head which is impacted by the projectile, generating a high tensile pulse with a rising duration of 25 μ s. The second head is fixed to a long bar instrumented with a strain gage at 500 mm from the sample. The specimen is instrumented with two strain gages at 20 mm on each side from the crack plane. An optical extensometer ZIMMER (Darmstadt RFA) is used to measure the displacements of two interfaces painted on the sample at 3 mm on each side from the crack plane. Though in a previous study on dynamic fracture of steels [6] the load recorded from the strain gage on the transmitted bar was used to derive load-crack mouth opening curves, it was found here that in the case of Titanium specimen this would lead to overestimate the load carried out by the uncracked ligament. Numerical investigations with the FEM code ABAQUS have shown that a good insight is gained using the displacement of the second interface (with respect to pulse motion) to obtain the stress acting over that section through the theory of uniaxial motion of waves in a cylinder:

$$\sigma = \sqrt{\rho E} \frac{\partial u}{\partial t}$$

Then a load is derived and the Merkle formula (1) is used to establish a J-integral formulation. The value of the J-integral at fracture is taken as the value corresponding to the time when the second interface starts to decelerate.

Ductility as a function of stress triaxiality

In order to determine the influence of stress state on the ductility at failure and to calculate the critical void growth R_c/R_0 tests on axisymmetric notched tensile specimen with different notch radius have been performed under static and dynamic loading (Figure 2). The use of these specimen is now well-established since the early studies of BEREMIN [7]. These specimens allow proportionnal loading within a large volume of material at the center of the specimen under various states of triaxiality. For the use of the concept of a critical void growth at the tip of a crack where the stress triaxiality varies quite significantly, it is necessary to evaluate the dependance of R_c/R_0 with stress triaxiality. Numerical calculations through FEM give the ductility at failure ϵ_R in the minimum section from the knowledge of the overall strain at failure

$$\bar{\epsilon}_F = 2 \ln \left(\frac{\phi_0}{\phi_F} \right)$$

where ϕ_0 is the initial diameter of the minimum section and ϕ_F the diameter of that section at failure. These numerical calculations also determine the stress triaxiality σ_m/σ_{eq} in the minimum section where σ_m is the mean stress and σ_{eq} is the equivalent Von-Mises stress.

Cavity nucleation is assumed to take place in the early stages of plasticity and the strain necessary for cavity nucleation is taken as 0. Void growth is then calculated by integration of the Rice and Tracey expression [8,9]

$$\frac{dR}{R} = 0,283 \exp\left(\frac{3}{2} \frac{\sigma_m}{\sigma_{eq}}\right) d\epsilon_{eq} \quad (2)$$

Notched specimen ductilities are given Table 1. An increase of about 75% is found for the different stress triaxiality conditions. Numerically calculated critical void growth rate are reported Figure 4 for static conditions. A critical value R_c/R_0 of 1.29 can be derived as a mean value.

specimen	AER 2	AER 4	AER 10	AE0	AE0
ϵ_F static	0.144	0.182	0.243	K_J static.	73 MPaVm
ϵ_F dynamic	0.267	0.307	0.423	K_J dynamic.	120 MPaVm

Table 1

Figure 4: Critical R/R_0 (static loading)

Fracture toughness results are reported Table 1 for both static and dynamic conditions. These are K_J values with $K_J^2 = E \cdot J / (1 - \nu^2)$ as a plane strain state of stress prevails within the axisymmetric specimen. The result is an increase of about 65% in fracture toughness for this material with an increase of loading rate from 1 MPaVm/s to 10^7 MPaVm/s.

Fracture surface appearances are very similar with a dimple type fracture surface for the two loading rates considered. (Figure 5) There is no evidence of any difference in the dimple sizes, but as shown by Lautridou [10] final dimples result from the instable flow localization process occurring during void coalescence, and are not directly related to critical void growth rate which is the controlling parameter of fracture.

Figure 5: Fracture surfaces (1) static loading, (2) dynamic loading.

DISCUSSION

Mudry [11] has shown that it is possible to relate J_{Ic} values with metallurgical factors such as inclusion distribution, using as a local rupture criterion the calculated value of void growth at failure R_c/R_0 . The relation can be written in the form

$$J = \alpha \Delta a_c \sigma_y \ln\left(\frac{R_c}{R_0}\right) \quad (3)$$

where $\alpha = 4.5$, σ_y is the yield strength of the material and Δa_c is a characteristic distance. Δa_c can be either derived from microstructural analysis through

$$\Delta a_c = \frac{2}{\sqrt{2}} \sqrt{\frac{1}{N_v}}$$

where N_v is the number of inclusions per unit volume or taken as the size of the square finite element mesh located at the crack tip such as R/R_0 , calculated within this cell at failure is equal to R_c/R_0 obtained from the analysis of notch ductility.

In the case of Titanium Δa_c cannot be obtained from microstructural analysis. Numerical simulations were runned for axisymmetric cracked specimen under static tensile loading with a mesh of square 4-nodes cells at the crack tip to evaluate R/R_0 within the first cell at the crack tip at the time of failure. Very good agreement was found between experimental and simulated load-crack mouth opening curves. Figure 6 describes the value of R/R_0 versus crack mouth opening for different sizes of the mesh cell at the crack tip i.e. different values of Δa_c . A value of R/R_0 of 1.29 is attained at failure in this cell for a cell length $\Delta a_c = 35 \mu m$ (Figure 6).

Figure 6: R/R_0 in the cell at the crack tip as versus crack mouth opening for different mesh sizes.

It can be noted that this value of Δa_c is rather small compared to values obtained in the case of steels, but the materials are quite different. The equiaxed Titanium presents a small grain size which leads to numerous initiation sites for cavity nucleation as those are located at the interface between α and β phases. From these values J_{Ic} can be estimated from (3) to 36 kJ/m^2 which gives a value of K_J equal to $70 \text{ MPa}\sqrt{m}$ for plane strain which is close to the experimental value of $73 \text{ MPa}\sqrt{m}$.

Numerical simulations are much more difficult to run in the case of dynamic loading. As a first approximation the parameters of formula (3) can be evaluated as follow. Δa_c is representative of the distribution of growing initiated cavity sites. Though Titanium is known to allow for more extensive

twinning under the same amount of deformation under dynamic loading then under static loading [3], no evidence was found for any change in type nor in distribution of initiation sites from static to dynamic loading. Therefore Δa_c could be kept equal to the value of 35 μm . The yield strength cannot be readily obtained under dynamic loading, but a 50% increase can be expected from the compression tests conducted. Notch ductility has been shown to increase by about 75% between static and dynamic loading. This gives an increase in the critical void growth rate R_c/R_0 . As

$$\ln(R_c/R_0) = 0,283 \int_0^{\epsilon_p} \exp\left(\frac{3}{2} \frac{\sigma_m}{\sigma_{eq}}\right) d\epsilon_{eq}$$

one can see that $\ln(R_c/R_0)$ is also highly dependant on stress triaxiality for the same amount of equivalent plastic strain prior to failure. Good numerical simulations are necessary to get good estimates of R_c/R_0 , and they rely on precise constitutive laws for tensile loading which are still to be determined. Therefore a rough estimate of $\ln(R_c/R_0)$ under dynamic loading will be taken assuming a 75% increase from the $\ln(R_c/R_0)$ value obtained for static loading, to compare with the increase of notch ductility. This would give a value of 1.56 for R_c/R_0 under dynamic loading. A value of J_{Ic} under dynamic loading can then be estimated from (3) to be equal to 95 kJ/m^2 , and a corresponding value for K_J of 113 $\text{MPa}\sqrt{\text{m}}$. This value compares favorably with the experimental result of 120 $\text{MPa}\sqrt{\text{m}}$.

CONCLUSION

Fracture of equiaxed Ti-6Al-4V under loading rates of 1 $\text{MPa}\sqrt{\text{m}}/\text{s}$ and 10⁷ $\text{MPa}\sqrt{\text{m}}/\text{s}$ can be interpreted in terms of a mechanism of cavity nucleation, void growth and coalescence. No change has been observed in neither the mechanism for cavity nucleation nor the hole growth process leading to failure. The important increase in fracture toughness (65%) with the loading rate can be interpreted from the increase in yield strength and the increase of notch ductility. Fracture would then proceed in the material when a critical void growth rate of 1.29 is attained at the tip of a crack over a distance of 35 μm under static loading and of 1.56 over the same distance in the case of dynamic loading. Further experiments on other specimen geometries should be conducted to validate these results.

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