

FINITE ELEMENT ANALYSIS OF TI-ALLOY FRACTURE BEHAVIOR AND EXPERIMENTAL VALIDATION

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ABSTRACT

Ti-6Al-3Mo-2Cr titanium alloy that finds applications as components of the aircraft engine. Analysis of crack growth in engine compressor disks made of this material has been carried out. It has been observed there is a general trend of increasing stress intensity factor with increasing applied tensile load. It can also be observed that the stress intensity factor increases with increasing crack size and width of the flat specimen. Microfracture analysis of the specimens (tested under $\sigma = 1100$ MPa) has revealed quasi-cleavage fracture with small symptoms of plastic shearing in the early part of cracking.

INTRODUCTION

The engineering science of fracture mechanics is especially useful in design against fracture, particularly when high-strength materials are utilized. The design philosophy inherent to fracture mechanics is that the operating stress must be less than the material's fracture propagation stress. The propagation stress may be much less in "real" engineering structures than in "flaw-free" material as a result of notches or cracks that are present to one degree or another in all structural parts. The knowledge of the microstructural features affecting crack propagation, and the mechanisms by which it occurs, has led to the development of fracture-tough materials and to improvements in materials-processing techniques that increase toughness.

Specific mechanical properties of titanium alloys are the reason of a variety of applications such as military aircraft, atomic energy and ocean components of structures. Simultaneously, the titanium alloys possessive a lot of different structures resulted from manufacturing process, heat treatment and that the fracture properties may also change. Large varieties of microstructural features observed in titanium alloys such as grain sizes, globular or lamellar type of structures, β -phase or $(\alpha+\beta)$

phase morphologies as well as bimodal structures produce different resistance to crack initiation and crack propagation. For this reason the titanium alloys are the objects of wide experimental analyses in the terms of crack growth characteristics and mechanisms of fracture.

In this project work, the attention is paid on the Ti-6Al-3Mo-2Cr titanium alloy that finds applications as components of the aircraft engine. Analysis of crack growth in engine compressor disks made of this material was the subject of the work.

METHODOLGY

The Ti-6.4%Al-2.6%Mo-1.7%Cr-0.5%Fe-0.5%Si (wt%) alloy was subjected to heat treatment consisting of 900°C for one hour, furnace quenching to 650°C , held at 650°C for two hours and then air cooled. Mechanical properties of the material were: ultimate tensile stress $\sigma_U = 968-1100$ MPa, elongation $e_1 = 15-20\%$, reduction of area $r_2 = 36-45\%$. The structure of $(\alpha+\beta)$ type consisted of α -platelets (90%) contained in large prior β -phase. The mean grain size of α -grains was $6-8 \mu\text{m}$. The tensile tests were conducted on plat specimens. The test variables are width of tensile specimen,

crack size and tensile loading. The mechanism of fracture that appeared in the specimens was established from the TEM micrographs of the replicas taken from different zones of the fracture surfaces. The mechanism of fracture was also studied using Finite Element Analysis Software (ANSYS). The results obtained from the FEA were verified with experimental results.

The discretization of tensile test specimens is shown in Figure.2. The element chosen for meshing is PLANE-82. The analysis was assumed under plane strain conditions. 12 – test conditions were modeled in this project work (Table-1). Once the static analysis was completed, POST1, the general post processor was used to calculate fracture parameters viz., stress intensity factor (K_I) and the energy release rate. The POST1 KCALC command (Main Menu > General Postprocessor > Nodal

Calculations > Stress Intensity Factors) calculates the mixed-mode stress intensity factors K_I . This command is limited to linear elastic problems with a homogeneous, isotropic material near the crack region.

Energy release rate is a concept used to determine the amount of work (change of energy) associated with a crack opening or closure. One method to calculate the energy release rate is the virtual crack extension method. In the virtual crack extension method, two analyses are performed, one with crack length a and the other with crack length $a + \Delta a$. If the potential energy U (strain energy) for both cases is stored, the energy release rate can be calculated from

$$G = -\frac{U_{a+\Delta a} - U_a}{B\Delta a}$$

where B is the thickness of the fracture model.

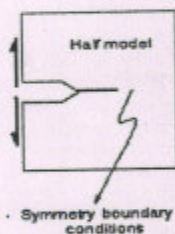


Figure.1 Taking advantage of symmetry



Figure.2 Discretization of 1/4th model of tensile specimen

The crack length is extended by Δa for the second analysis by selecting all nodes in the vicinity of the crack and scaling them in the X direction [NSCALE] (Main Menu> Preprocessor> -Modeling-Operate. Scale) by the factor Δa .

Table-1: Test conditions

Test.No	Width mm	Length mm	Crack size mm	Loading MPa
1	25	100	2.5	900
2	25	100	2.5	1000
3	25	100	2.5	1100
4	50	100	2.5	900
5	50	100	2.5	1000
6	50	100	2.5	1100
7	25	100	5.0	900
8	25	100	5.0	1000
9	25	100	5.0	1100
10	50	100	5.0	900
11	50	100	5.0	1000
12	50	100	5.0	1100

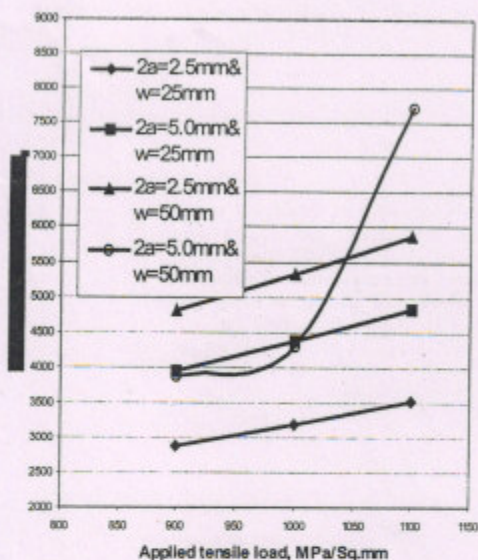


Figure.3 Variation of stress intensity factor with the applied load.

RESULTS AND DISCUSSION

Stress Intensity Factor

Fracture-resistant design has two significant components. The first, which considers the applied stress state and the likelihood of flaws being present in the structure, allows for estimating service stresses in terms of flaw size and the material property, K_1 . The influence of tensile load applied onto the specimen on stress intensity factor is shown in Figure.3. It can be seen a general trend of increasing stress intensity factor with increasing applied tensile load. It can also be observed that the stress intensity factor increases with increasing crack size and width of the flat specimen. Ideally, the curves should go zero stress intensity for zero applied load. In this figure, it can be seen that they do not; they do indicate some value of negative stress intensity, which is interpreted as a residual -stress state that forces the crack surfaces together. It is also revealed that the

specimen having width = 50mm and crack size of 5mm exhibits steep rate of increasing stress intensity factor. The graph curvature is a polynomial of degree three. Under this condition, the crack growth is nonlinear and faster.

STRAIN RELEASE ENERGY

The influence of tensile load on the strain energy is shown in Figure.4. Under all the test conditions, the strain energy increases with increasing applied tensile load. Crack extension can occur when crack-driving force is equal to the energy required for crack growth. The energy required for a crack to grow in a metal is much larger than the surface energy to create the new free surfaces. In metals plastic deformation occurs in front of the crack and during crack extension energy is expended by the formation of a new plastic zone at the tip of the advanced crack. The fracture criterion in the Ti alloy is depicted graphically in the way

shown in Fig.4.14. For a particular stress the energy release rate is proportional to the crack size. As the tensile load and the size of the initial increase, there is a increased crack growth in the Ti alloy. It is observed that the energy release rate is maximum at the crack tip. This indicates that the crack opening is accelerated with increase of tensile load and initial crack size. The crack growth is very high in a tensile specimen having the conditions of width of plate = 50 mm, crack size = 5 mm and tensile load of 1100 MPa (Figure.5).

EXPERIMENTAL ANALYSIS OF FRACTURE MECHANISM

The microstructures of fracture in the Ti alloy are shown in Figure.6. Mechanism of fracture that appeared in the specimens was established from the TEM micrographs of the replicas taken from different zones of the fracture surfaces. In the examined Ti alloy under tension the cracks were observed to be initiated at the interface between α and β phases (Figure 6a) and in α - grains (Figure.6b). The images were taken from the specimens tested under $\sigma = 900$ MPa. In the crack initiation zone evidence of quasi-cleavage fracture with limited plastic striations symptoms was found in the specimen tested under $\sigma = 1000$ MPa, (Figure.6c). Plastic striations were occupied almost whole fracture surface of specimens (Figure.6d). Microfracture analysis of the specimens (tested under $\sigma = 1100$ MPa) has revealed quasi-cleavage fracture with small symptoms of plastic shearing in the early part of cracking (Figure.6e). It was found an interesting phenomenon that below certain depth the cleavage fracture was passed to the plastic striations. The striations were occupied greater part or almost whole fracture surface (Figure.6f).

CONCLUSIONS

In this work the influence of crack size, specimen dimensions and tensile load on the Ti alloy were studied. The results obtained from the finite element analysis were compared with

the experimental results. The following points are concluded from the present work:

Fracture-resistant design has two significant components. The first, which considers the applied stress state and the likelihood of flaws being present in the structure, allows for estimating service stresses in terms of flaw size and the material property, K_I .

There is a general trend of increasing stress intensity factor with increasing applied tensile load. It can also be observed that the stress intensity factor increases with increasing crack size and width of the flat specimen.

It is also revealed that the specimen having width = 50mm and crack size of 5mm exhibits steep rate of increasing stress intensity factor. The graph curvature is a polynomial of degree three.

Under all the test conditions, the strain energy release increases with increasing applied tensile load. Crack extension can occur when crack-driving force is equal to the energy required for crack growth. For a particular stress the energy release rate is proportional to the crack size. As the tensile load and the size of the initial crack increase, there is a increased crack growth in the Ti alloy.

In the examined Ti alloy under tension the cracks were observed to be initiated at the interface between α and β phases and in α - grains for the specimens tested under $\sigma = 900$ MPa and crack sizes of 25 mm and 50 mm respectively.

In the crack initiation zone evidence of quasi-cleavage fracture with limited plastic striations symptoms was found in the specimen tested under $\sigma = 1000$ MPa.

Microfracture analysis of the specimens (tested under $\sigma = 1100$ MPa) has revealed quasi-cleavage fracture with small symptoms of plastic shearing in the early part of cracking.

Figure 4: Variation of strain energy with the applied load

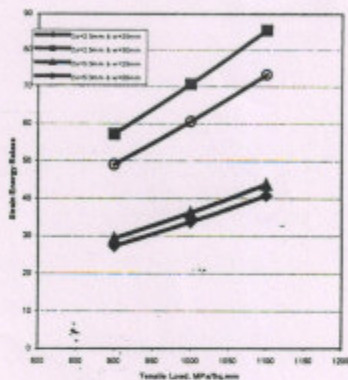


Figure 5: Strain release energy for the test conditions of width = 50mm, crack length = 5.0 mm, load = 1100MPa

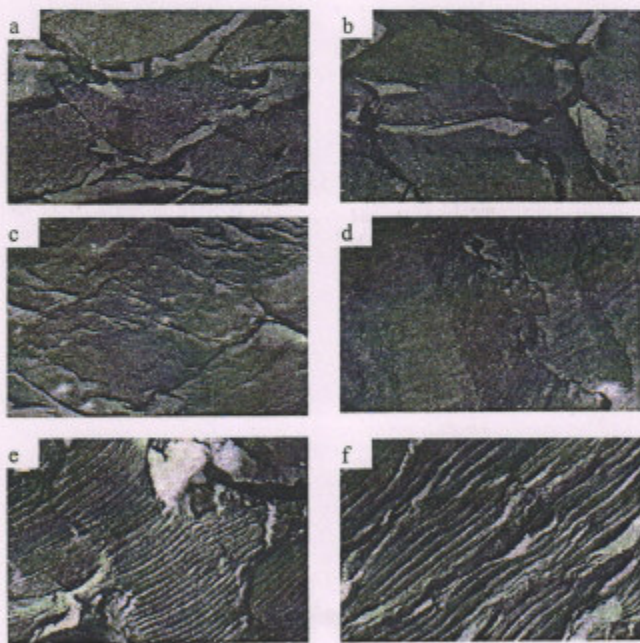


Figure 6: Microstructures of fractured specimens for the test conditions

- (a) Specimen width = 25 mm, crack length = 2.5 mm, load = 900MPa
- (b) Specimen width = 50 mm, crack length = 5.0 mm, load = 900MPa
- (c) Specimen width = 25 mm, crack length = 2.5 mm, load = 1000MPa
- (d) Specimen width = 50 mm, crack length = 5.0 mm, load = 1000MPa
- (e) Specimen width = 25 mm, crack length = 2.5 mm, load = 1100MPa
- (f) Specimen width = 50 mm, crack length = 5.0 mm, load = 1100MPa

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