RATE AND SIZE EFFECTS ON THE FRACTURE TOUGHNESS OF A TITANIUM ALLOY

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Fracture testing results for a titanium alloy at three different loading rates in the intermediate range are presented. Testing was carried out with a specially developed displacement limiter which minimises dwell time after the desired displacement is attained.
Results are discussed in terms of the J-resistance curve focusing on initiation and two representative values of crack extension, as well as the (dJ/da) term.
Toughness is found to increase appreciably with loading rate, but comparison of the intermediate rate results against the data available in the static range indicates that the geometry effects on the R-curves are just as significant.

INTRODUCTION

Previous studies have investigated the elastic plastic fracture behaviour of the titanium alloy 6-2-1-1 [1,2,3]. In a comprehensive study, the effects of geometry of test piece in the fracture toughness of the material were examined under static loading conditions.

The present text discusses the effects of a change in loading rate from static to intermediate rates using compact tension specimens of titanium 6-2-1-1. The designation *intermediate loading rate* implies loading events which are longer than 0.01s and yet too short to be considered static, ranging typically from 0.02s to 2s. Loading events which are shorter than 0.01s are in the dynamic range. Intermediate loading rates are known to affect the fracture properties of a material without introducing appreciable inertial or kinetic effects. The significance of such loading rates relates to the conditions encountered in hydraulic testing of pressure vessels or drop tests of transportation casks and other structures.

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EXPERIMENTAL TECHNIQUE

Tests were performed in a servo-hydraulic machine fitted with an in-house built ramp voltage generator for faster response and a smooth loading path. The loading rates adopted in the tests were 100mm/s, 200mm/s and 400mm/s crosshead speed (which correspond to K rate values of up to 60 000 MPa$\sqrt{m}$/s) as well as the static case.

A multi-specimen technique was adopted for plotting the J-R curves for the various rates, such that each specimen was loaded to a different value of displacement in order to produce the required amount of crack extension. For a typical testing machine, the time required to reverse the direction of the loading once the required displacement has been achieved is about 1s. This results in the load being sustained for a period, the so-called *dwell time*. Non-negligible crack extension can occur due to dwell times which are comparable to the loading events in question. In order to minimise the dwell time, the tests were performed using a specially developed apparatus with a mechanical stop which reduces the load to zero within less than 20ms after the desired displacement is achieved.

The test rig is illustrated in figure 1 and was based upon previous work by Salzbrenner and Crenshaw [4]. The machine actuator is connected to the specimen through two special fixtures — the limiting disk and the coupling — kept together by a shear pin. During loading, the coupling descends and the limiting disk strikes a cylinder which acts as a displacement limiter. The displacement on the sample remains constant thereafter and the load on the shear pin increases as the actuator continues to descend. The shear pin is designed to break soon afterwards, instantly reducing the applied load to zero.

The specimen geometry adopted was the compact tension type with width W=35mm and thickness B=17.5mm. The nominal a_o/W ratio was 0.55. The dimensions are illustrated in figure 2. High strength maraging steel shackles were specially manufactured to minimise the weight of the moving parts of the rig.

A test with a strain gauged specimen was performed to verify the load cell response. Figure 3 shows the position of the strain gauges installed for that purpose.

TEST RESULTS

Signals from the load cell, the clip gauge and and the machine displacement transducer were recorded against time by a 20MHz transient recorder. Testing of the instrumented specimen confirmed the adequacy of the machine load cell response. Comparison between the strain gauge signals and the load cell signal shows good correlation up to the point of fracture of the shear pin. After that, the load cell was not able to respond to the higher frequencies generated as the limiting disk is left hanging on the specimen.

Figure 4 shows the J-R curves for the three values of loading rate studied as well as the static case for both compact tension and three point bend geometry. The corresponding blunting line for titanium is also indicated. The values of the work done in each test were calculated by cross plotting the load signal against the clip gauge displacement signal, fitting polynomials to the curves and integrating the polynomials for the calculation of the area under the curve. The expression used in the J calculations is the one given in ASTM E813:89 whereby

$$J = \eta U/(B*(W-a_o)) \quad (1)$$

and

$$\eta = 2 + 0.522\,(W-a_o)/W \quad (2)$$

where U is the work done.

For the three rates investigated, an increase in toughness with rate was observed. An overall increase in toughness of 0.05MN/m was perceived from 100mm/s to 200mm/s, corresponding to an increase of 35% at initiation and of 10% at 8mm of crack growth, but for the fastest rate (400mm/s), an increase in the value of J of approximately 0.15MN/m was observed throughout the first four millimetres of crack extension, slowly reducing towards 8mm of crack growth. Such discrepancy corresponds to a 100% increase in the initiation toughness when the loading rate increases from 100mm/s to 400mm/s

Figure 5 shows toughness values at initiation, Δa=4mm and Δa=7mm plotted against elastic stress intensity factor rate, K'. Strictly speaking, for the geometry in question, the K dominance can only be valid near initiation. Toughness values at 4 and 7mm of crack extension are included for comparison. Figure 6 shows the same toughness values plotted against loading rate. The validity of the K dominance when crack propagation takes place other than under static conditions is disputable and has been the subject of recent investigations [5]. For that reason, the plot of rate effects against loading rate was included.

CONCLUSION

The test method adopted worked satisfactorily giving minimised dwell times. The main difficulty encountered was the design of the shear pins and, in some of the cases, the pins used broke before attainment of the total displacement aimed at.

The time lag between the load cell signal and the clip gauge signal was responsible for difficulties in cross plotting the two signals. This made the analysis very time consuming but did not compromise the results. Problems with cross plotting have been acknowledged in the past and recommendations on data treatment can be found in the British Standard BS 6729 and elsewhere [6].

For the range of testing data presented, no changes in fracture mechanism were perceived by SEM analysis. Fracture was ductile in the micromode and, although multiple cracking has been associated with an increase in toughness with rate for some materials [7], no such phenomena were observed in the present tests.

Contrary to the usual assumption that titanium alloys are not rate sensitive, it was shown that even a modest increase in strain rate has produced significant increase in fracture toughness.

Strain rate effects are by no means negligible and must be accounted for. However previous work by the same authors indicates that the effects of geometry and size are just as pronounced as those of rate. Preliminary analysis suggests that, in some cases, size effects can associate with rate effects to result in conditions that are more critical that anticipated. The interaction between geometry and rate effects in fracture is not clear and further studies are necessary.

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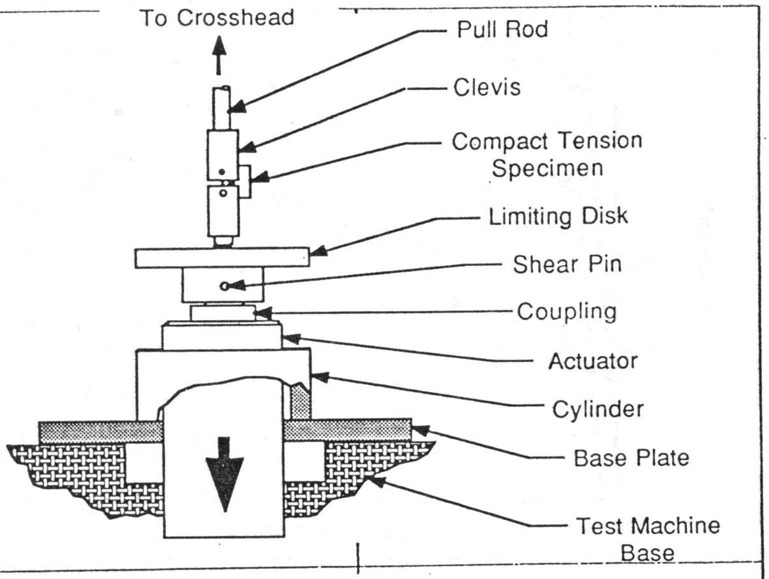

Figure 1 - Mechanical displacement limiter set up

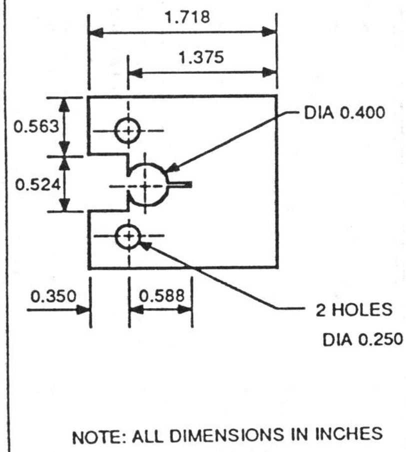

Figure 2 - Specimen dimensions

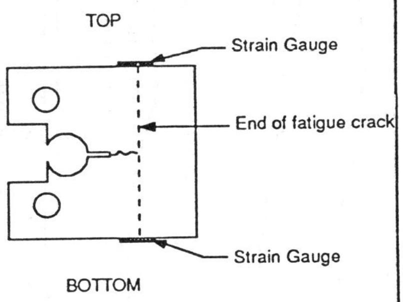

Figure 3 - Strain gauge positions on instrumented specimen

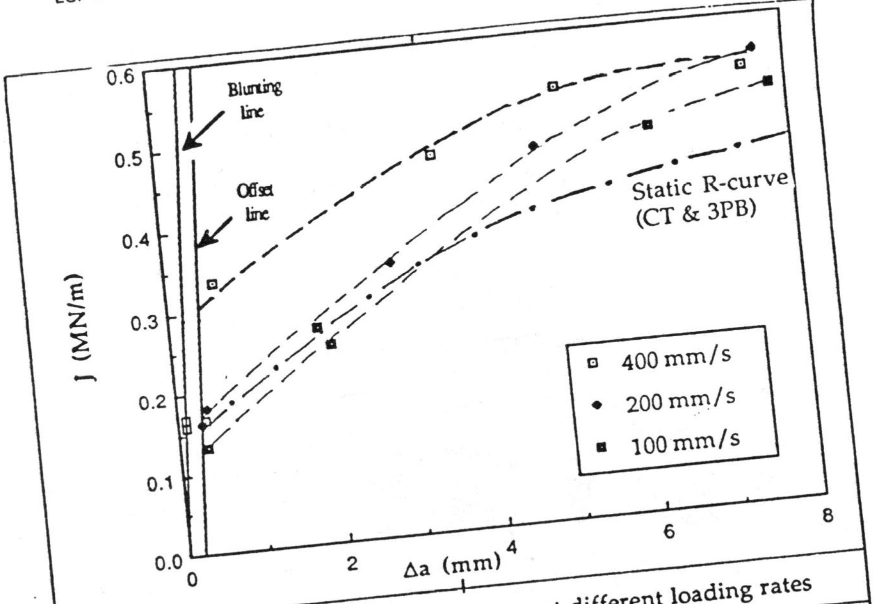

Figure 4 - J resistance curves for titanium at different loading rates

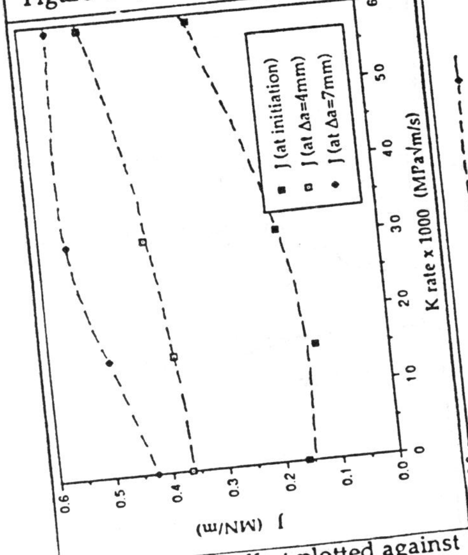

Figure 5 - Rate effect plotted against K rate

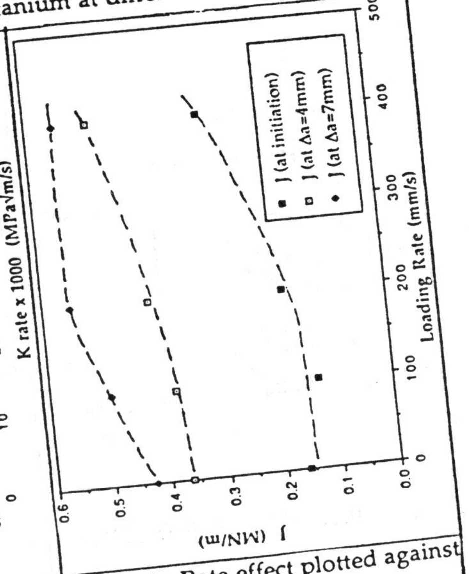

Figure 6 - Rate effect plotted against loading rate