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INFLUENCE OF TRIAXIALITY ON THE FRACTURE BEHAVIOR OF Ti6Al4V TITANIUM ALLOY AT IMPACT LOADING CONDITIONS

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ABSTRACT

This paper shows analysis of the influence of triaxiality on the fracture locus of Ti6Al4V titanium alloy at impact loading conditions. Tensile tests were carried at high strain rates using Kolsky bar technique. Four different geometries of specimens were applied in order to obtain a wide range of stress triaxiality. It was founded that investigated titanium alloy shows fracture mechanism introduced by Bao and Wierzbicki, i.e. at tensile loadings void formation is responsible for failure, whereas at shear loadings rupture is govern by shear bands formation.

Keywords: titanium alloys, failure, fracture, anisotropy, hopopkinson bar.

INTRODUCTION

A new computer aided designing techniques requires new and more sophisticated material models to give prediction results as close as possible to reality. The problem of obtaining a good agreement between experimental and numerical results arises with increase of strain rate since at impact loading conditions viscoelastic properties must be taken into account. Moreover evolution of the fracture mechanism with the increase of strain rate is observed. Analysis based on the experimental and numerical results, carried out by Bao for 2024 aluminium alloy (Bao, 2004), shows that the relation between the equivalent strain to fracture versus the stress triaxiality was quantified and it was shown that there are three distinct branches of this function with possible slope discontinuities in the transition regime. For negative stress triaxialities, fracture is governed by shear mode. For large triaxialities void growth is the dominant failure mode, while at low stress triaxialities between above two regimes, fracture may develop as a combination of shear and void growth modes. Further works over a fracture locus reveals that there is a cut-off value of the stress triaxiality equal to - 1/3, below which fracture never occurs. This feature was derived analytically from the fracture locus in the principal strain space experimentally reported from upsetting tests (Bao, 2005). Similarly, fracture mechanism of austenitic steel was investigated for fracture mechanics specimens (tension, in-plane shear, and out-of-plane shear deformation mode) and undamaged standard test specimens (tension, torsion, and upsetting) in a uniform way. A fracture line was determined for the examined austenitic steel deformed in a stress triaxiality regime between 0 and 2.7. It was funded that the plastic equivalent strain at fracture decreases exponentially with increasing stress triaxiality ratio at fracture (Trattnig, 2008).

The combined effects of strain rate and stress triaxiality on the material's behavior were studied using notched axisymmetric specimens of the structural steel Weldox 460 E. High strain rate tests were carried out using a Split Hopkinson Tension Bar. The strength of the material was found to increase with increasing strain rate, while for the ductility no significant effect of strain rate could be ascertained from the notched specimen tests. The ductility of the material was found to depend considerably on the stress triaxiality (Hopperstad, 2003).

This paper is devoted to analysis of the fracture behavior of Ti6Al4V titanium alloy at both, low at high strain rates deformation. Therefore it is extension of studies introduced by Giglio concerning quasi-static fracture locus of Ti6Al4V titanium alloy (Giglio, 2012). Moreover, anisotropic properties of hot rolled titanium alloy sheet were considered. Numerical analysis of tensile tests introduced in the previous work (Moćko (2), 2015) shows that the strain, temperature and stress triaxiality distribution is non-homogenous in specimen cross-section perpendicular to the loading direction. The value of the strain, temperature and stress triaxiality also depends on the strain rate.

EXPERIMENTAL METHODOLOGY

The tensile tests were carried out using the servo-hydraulic testing machine manufactured by Instron company and pre-tension Hopkinson bar (Staab, 1991; Kolsky, 1949) at quasi-static and dynamic range of strain rates. The testing stand in Motor Transport Institute laboratory (Libura, 2014), shown in Fig. 1, is equipped with the bars of 20 mm in diameter made of 7075-T6 aluminium alloy. The incident bar of 3600 mm in length is divided into a pre-tension section with a length of 1600 mm and a free end. The clamp which confines the bar during initial loading with the use of a hydraulic actuator is placed between the pre-tension and free section of the incident bar. The transmission bar length is equal to 1800 mm. The history of elastic wave in the bars is determined using tensometers, than amplified at the broad-band bridge (Moćko, 2013) and finally recorded by a digital oscilloscope.

The test was recorded using Phantom V1210 fast camera at a resolution of 384x128 and frame rate equal to 150000 at dynamic range of loading. In order to obtain clear view without blurring of measurement grid required in DIC analysis the shutter time was set to 2μs. Very short time of frame acquisition requires very strong lighting, therefore two COOLH illuminators emitting very focused light beam were applied. At the quasi-static deformation rates ARAMIS 4M video system with resolution equal to 2400 x 1728 pixels was used. The videos recorded during experiments were subsequently analyzed by DIC method implemented in the ARAMIS software to determine 2D field of displacement.

Material was delivered in a form of hot rolled Ti6Al4V titanium alloy sheet of 3 mm thickness. The specimens were cut along three orientations with respect to the rolling direction, that is, RD - along, 45D - 45 degree and TD - transverse to rolling direction. Notched specimens with gauge length equal to 2 mm (R1), 5 mm (R5) and 10 mm (type A) were applied to enable various stress triaxiality coefficients during tensile test. Additionally a shear (SHEAR) specimens were designed and fabricated to obtain shear loading conditions. The same geometry was applied for both quasi-static and dynamic testing. Specimens shown in Fig. 2 and Fig. 3 were cut using electro-discharge machining (EDM).

Stress triaxiality during tensile tests was calculated using FEM simulation. Analysis were carried out using ABAQUS Standard software under quasi-static loading conditions. Digital models of specimens consists of 24554, 13070, 30555 and 10866 mesh elements respectively for type A, R1, R5 and shear samples. For geometry of type A, R1 and R5 C3D8R elements were applied, whereas for shear geometry C3D10M elements were used. Values presented in Fig. 4 are an average value calculated from mesh elements located near fracture surface.

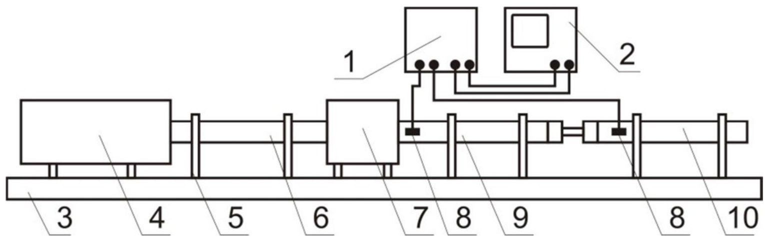

Fig. 1 - Scheme of split tensile Hopkinson bar (Moćko (1), 2015): 1—wideband amplifier, 2—digital oscilloscope, 3—base, 4—pressure tank, 5—support, 6—pre-tension section of incident bar, 7—hydraulic clamp, 8—strain gauges, 9—free section of incident bar, 10—transmitter bar.

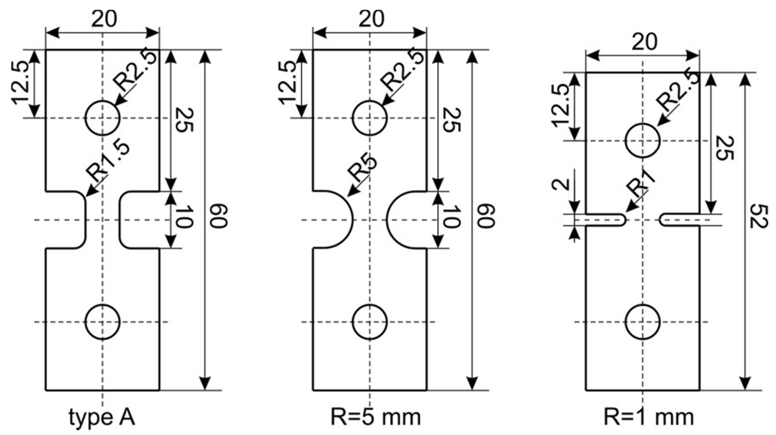

Fig. 2 - Geometry and dimensions (in mm) of pre-notched specimens of type A, R5 and R1.

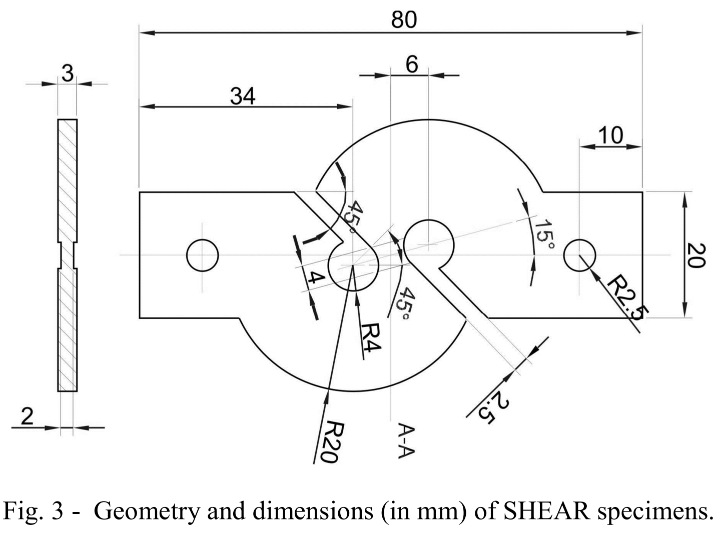

Fig. 3 - Geometry and dimensions (in mm) of SHEAR specimens.

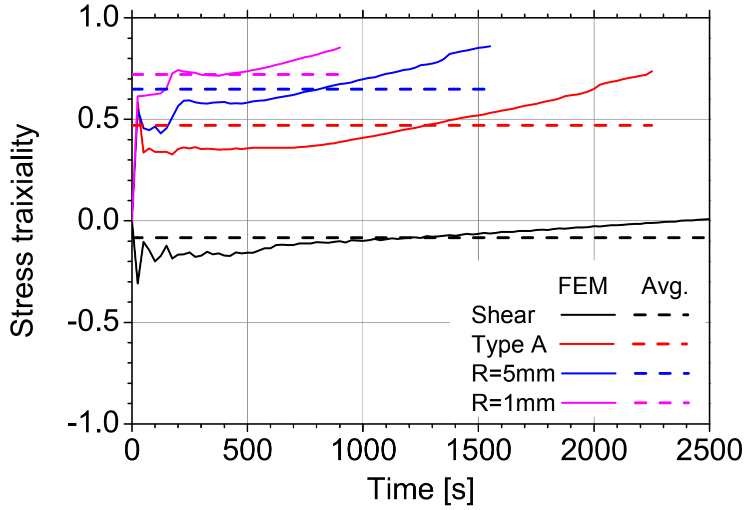

Fig. 4 - Loading path at quasi-static and dynamic loading conditions for specimens with gauge length equal to (a) 10 mm, (b) 5 mm, (c) 2mm and (d) shear specimen

RESULTS AND CONCLUSIONS

The course of stress triaxiality determined using FEM software is shown in Fig. 4. It may be observed that during plastic deformation a value of stress triaxiality slightly increases due to necking phenomenon. An average value of a stress triaxiality for each specimen geometry was selected for further analysis.

As it may be observed in Fig. 5 tensile behavior of Ti6Al4V titanium alloy strongly depends on the loading orientation. The lowest fracture displacement was founded for TD, whereas at RD and 45D the values of fracture displacement were significantly higher. Moreover, evolution of the tensile force is also affected by angle of applied force with respect to the rolling direction.

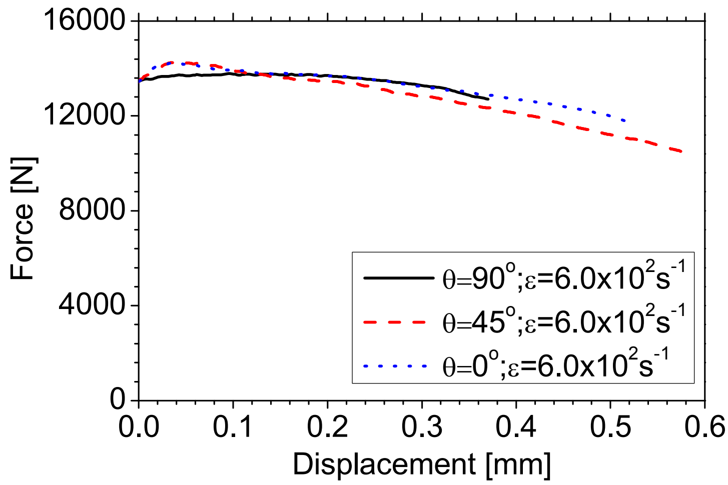

Fig. 5 - Curves representing tensile force determined under dynamic loading conditions at various loading orientations

Figure 6 presents influence of the loading direction and specimen geometry on the fracture pattern. It may be observed that for the specimen marked as R1, corresponding to triaxiality equal to 0.7, fracture pattern obtained for TD and 45D are comparable, whereas pattern for RD is slightly different. In the case of R5 geometry (triaxiality equal to 0.6) fracture surface is oblique for the specimen loaded at RD direction, perpendicular for the specimen loaded at DT and split into two oblique surfaces for 45D.

The most clear to observe differences in fracture pattern may be found in SHEAR specimens. At RD fracture begins with cracks transversal to the applied forces, subsequently longitudinal dominant fracture appears. At TD fracture in a form of a plane surface occurs at angle oblique to the applied force. Finally, at 45D fracture is also a plane surface, however its angle is parallel to the loading force.

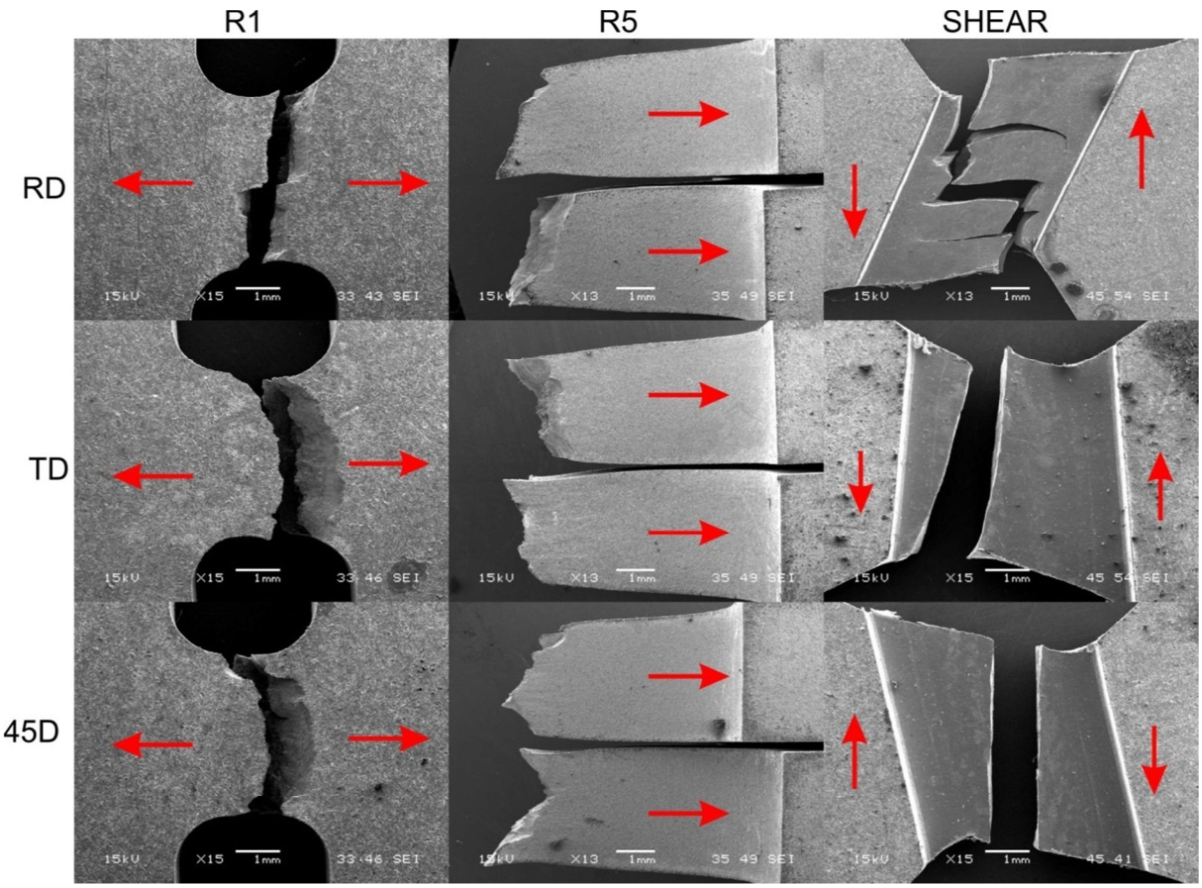

Fig. 6 - View of the specimen fracture region obtained at various geometries and loading directions

Results of DIC analysis are introduced in Fig. 7. For the specimen of geometry marked as R1 there is no clearly observed differences in strain distribution. For the specimen marked as R5 strain pattern depends on the loading direction. In the case of RD strain shows maximum located in the specimen axis, perpendicular to the applied force. In the case of TD the strain is distributed in a form of wide area of equal strain. Finally, for 45D maximum of strain is oblique to the applied force is observed. Strain distribution obtained using DIC technique for SHEAR type specimens were hard to analyse. The software was unable to catch displacement of narrow area of plastic deformation.

Fracture strain estimated using digital image correlation method at various stress triaxialities and strain rates is shown in Fig. 8. It may be observed that similarly to Bao and Wierzbicki model Ti6Al4V titanium alloy loaded at direction RD and 45D shows clear to observe maximum at strass triaxiality equal to 0.5. At stress triaxialities higher than 0.5 void formation mechanism is responsible for the fracture, whereas at stress triaxialities lower than 0.5 failure of the material is govern by shear band formation or mixed mechanism.

In the case of loading force transverse (TD) to the rolling direction local maximum observed at 0.5 for other orientations is significantly diminished. The other observed phenomenon is decreasing of fracture strain with the increase of strain rate. It may be found that RD and 45D orientations are more sensitive to strain rate effect than TD orientation.

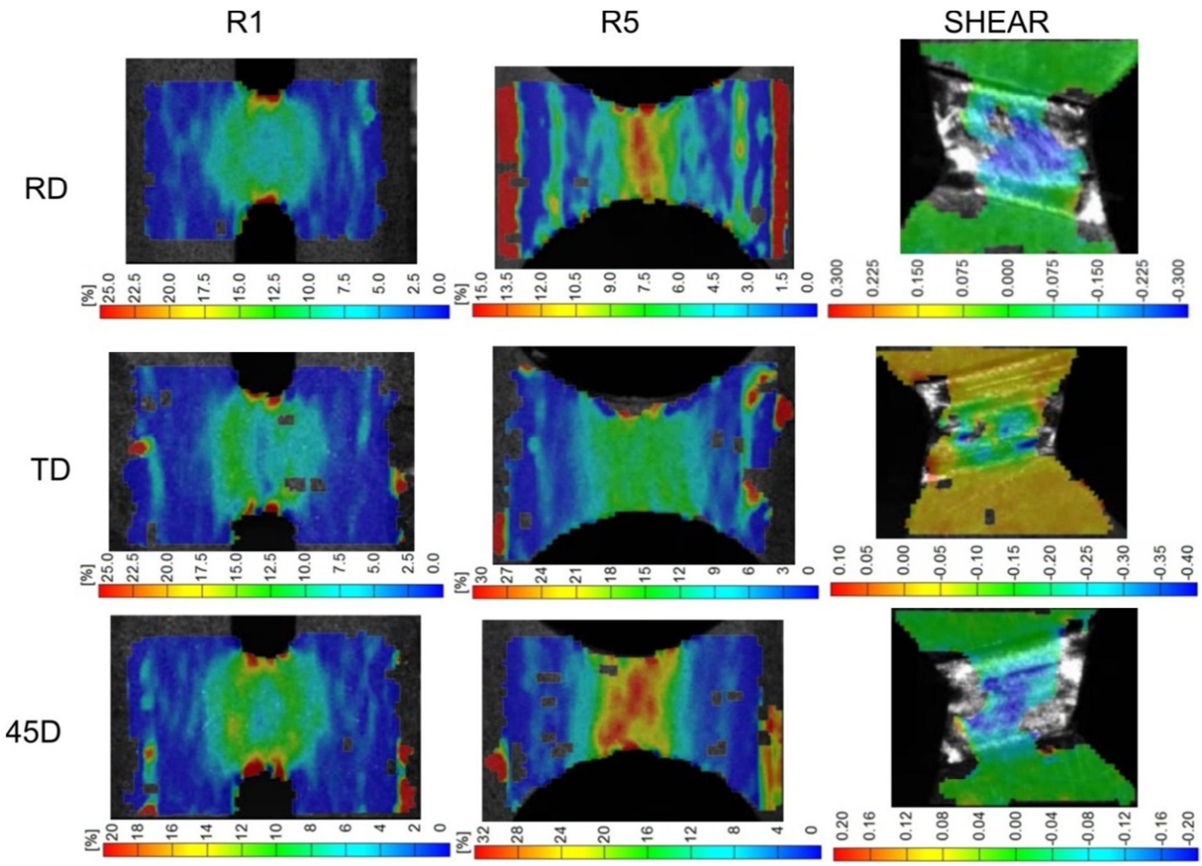

Fig. 7 - The fracture locus of Ti6Al4V determined at (a) quasi-static and (b) dynamic loading conditions at various loading orientations

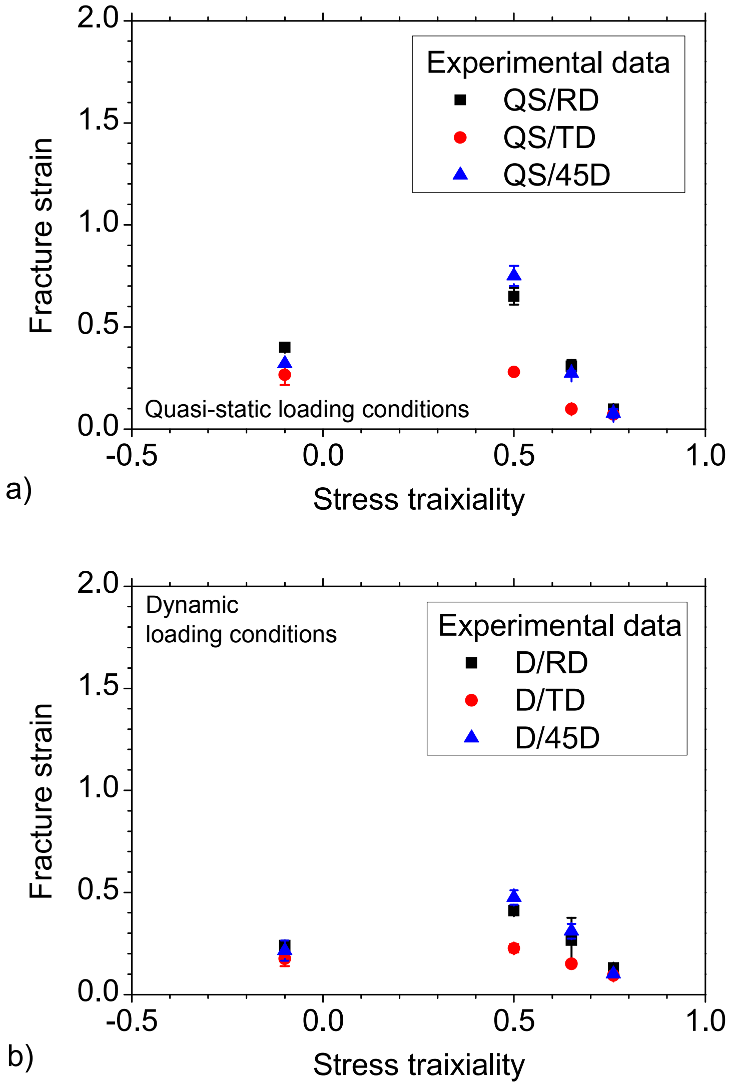

Fig. 8 - The fracture locus of Ti6Al4V determined at (a) quasi-static and (b) dynamic loading conditions at various loading orientations

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