Pure Shear Deformation and Failure of Ti6Al4V Alloy under Quasi-static, Medium and High Strain Rate Torsional Loading

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Abstract. The pure shear flow and failure of Ti6Al4V alloy, conceived for aircraft design applications, are characterized at quasi-static (10^{-3} /s), medium (10^{1} /s) and high strain rates (10^{3} /s), by using a screw driven Zwick machine, a hydraulic Instron machine and a split Hopkinson torsion bar. The shear strain is directly measured from Digital Image Correlation (DIC). This study provides the strain rate dependence of Ti6Al4V alloy and the relation of pure shear failure at quasi-static and high strain rates. The pure shear constitutive relationship at quasi-static is obtained at the location of failure initiation, using a bespoke four camera system. The Ti6Al4V alloy shows limited pure shear plastic deformation at high strain rates, indicating the limited overall temperature rise until final collapse of the torsion specimen. The failure is associated with intensive shear localization at high strain rates, which would be different from that at medium strain rate and is different from that at quasi-isothermal condition.

Introduction

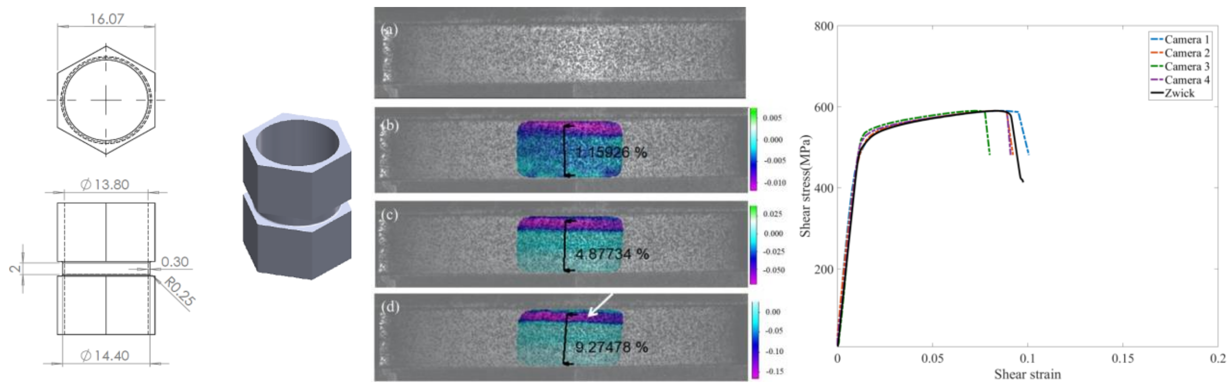
With the combination of light weight, high strength, outstanding resistance to corrosion, the titanium alloys have been widely used in aircraft structural components which would be subjected to impact loading. It is necessary to understand the mechanical response of titanium alloys across a wide range of strain rates.

Experimental Techniques

Torsion tests reveal the fundamental plastic flow of material. Thin wall torsion specimens (Fig.1A) were machined from a supplied Grade 5 Ti6Al4V rod. The quasi-static torsion test was performed by using a Zwick-Roell Z250 machine synchronized with four IDS UEye USB 3.0 Cameras. The shear strain of the torsion specimen was measured from the gauge section using commercial DIC software (Lavision DaVis). The deformation was monitored by four cameras with the angular separation between each camera being approximately 90°. The torsion tests at medium and high strain rates were conducted by using a hydraulic Instron 8854 machine and the split Hopkinson torsion bar synchronized with high speed Photron and Kirana cameras, respectively.

Results

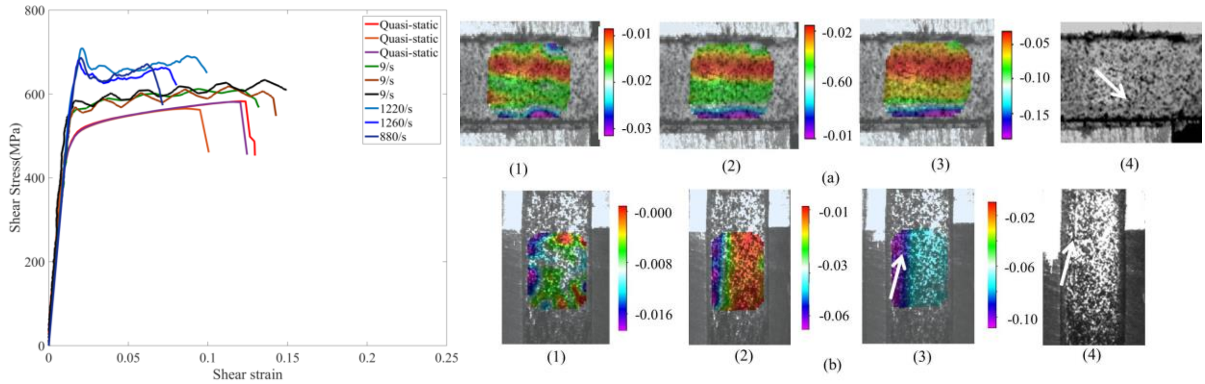
Fig. 1B-(a) shows the image from Camera 1 at the start of the quasi-static test. With the twist from Figs. 1B-(b-d), the shear strain increases with the distortion of the speckle pattern. The shear strain in percentage (the slope of the shear gauge line at the centre of gauge section) is given. The failure initiation is highlighted by an arrow in Fig. 1(B)-d. Except for a region close to the end of the gauge section, most of the gauge section is twisted uniformly. This enables the measurement of shear strain of gauge section. Fig. 1C shows the pure shear stress-strain relationships measured from four cameras. The initial elastic and plastic responses of Ti6Al4V alloy are satisfactorily consistent at four different locations up to the load drop point. The plastic flow from the camera/DIC agrees with that measured from the Zwick machine.



(A) (B) (C)

Fig.1 (A) Geometry and dimension of the Ti6Al4V alloy torsion specimen (Unit: mm) (B) Quasi-static deformation process observed from camera 1. The shear strain contour at each position from DIC analysis is shown. (C) Comparison of the shear stress-strain relationships measured from four cameras and the Zwick machine. Reprinted from Ref. [1].

Fig. 2A presents the dynamic shear stress-strain relationships of Ti6Al4V alloy obtained from the fracture side facing the high speed camera, together with the counterparts at quasi-static and medium strain rate. The flow and failure of Ti6Al4V alloy show significant strain rate sensitivity. Specifically, the yield stress of Ti6Al4V alloy increases from 470 MPa under quasi-static condition, 510 MPa at medium strain rate of 9 /s and 620 MPa at high strain rates of 880-1260 /s. The average failure strain of Ti6Al4V alloy decreases from 0.11 to 0.07 from quasi-static to high strain rates, with a slight increase to 0.15 at medium strain rate. Such a limited plastic deformation at high strain rate indicates the negligible thermal softening effect (arising from self-heating) in the flow and failure of Ti6Al4V alloy [1]. Fig. 2B shows the typical deformation process of Ti6Al4V alloy at different stages at medium strain rate and high strain rate. Corresponding to the sudden load drop, the image at stage 3 in Fig. 2B-b shows the formation of intensive localized deformation marked by a white arrow. The cracks at stage 4 are also highlighted.



(A) (B)

Fig. 2 (A) Comparison of the shear stress-strain relationships of Ti6Al4V alloy from quasi-static to high strain rates. (B) Deformation process at (a) medium strain rate and (b) high strain rate. Reprinted from Ref. [1].

Optical microscopy (OM) is used to characterize the fractured microstructures of Ti6Al4V alloy under torsional loading. Figs. 3 (a-b) show that the microstructures undergo shear deformation at quasi-static and medium strain rate. Fig. 3c shows adiabatic shear bands (ASB) in the fractured Ti6Al4V specimen twisted at high strain rate. The ASB locates at the region where the macro strain localization is observed in the high speed images in Fig. 2B-b. The microstructures adjacent to ASB are heavily elongated along the shear direction, illustrating the highly localized shear characteristic of dynamic failure mechanism [2].

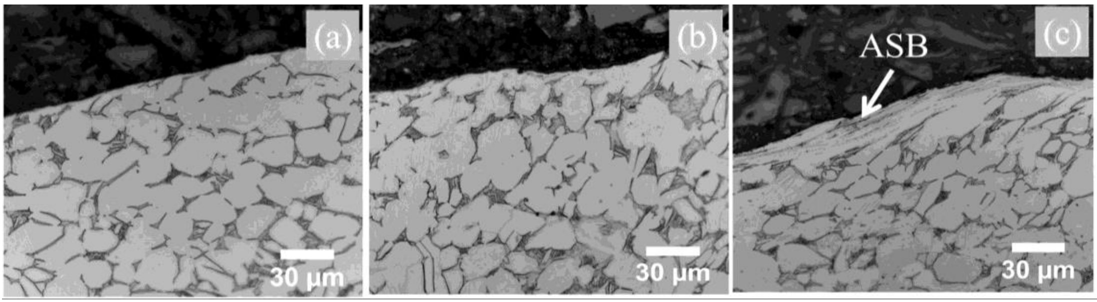


Fig.3 OM images of the microstructures of Ti6Al4V alloy at (a) quasi-static 0.005 /s, (b) medium strain rate of 9 /s and (c) high strain rate of 1260 /s. Reprinted from Ref. [1].

Conclusion

This work studies the pure shear constitutive responses of Ti6Al4V alloy by using the bespoke torsion techniques. The flow stress and failure strain are strain rate dependent. The torsion test of Ti6Al4V alloy at medium strain rate is carried out to connect the relationships of pure shear flow and failure between quasi-static and high strain rates. The ASB occurs in Ti6Al4V alloy with limited plastic deformation at high strain rates. This is different from the material failure at quasi-isothermal condition, and would be also different from that at medium strain rate.

References

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[2] B. Dodd, Y. Bai, Adiabatic Shear Localization: Frontiers and Advances. Elsevier (2012).