Dynamic Necking of a Near $\alpha$ Titanium alloy at High Strain Rates: Experiments and Modelling

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**Abstract.** The tensile behaviour of near $\alpha$ Ti3Al2.5V alloy, conceived for applications in aerospace and automotive engineering, is characterized from quasi-static to high strain rates. The material presents noticeable strain rate sensitivity. The dynamic true strain rate in the necking cross-section reaches values up to one order of magnitude higher than the nominal strain rate. It is also observed that beyond necking the true stress-strain curves present limited rate dependence in the dynamic loading regime. The experimental results at various strain rates and temperatures are used to determine the material parameters of a suitable constitutive model for finite element simulations of the dynamic tensile tests. The model predicts the experimentally macroscopic force-time response, true stress-strain response and effective strain rate evolution with good agreement.

1. **Introduction**

The dynamic tensile behaviour of metals has been popularly characterized by means of the Split Hopkinson Tension Bar apparatus (SHTB) since Harding et al.[1]. However, the interpretation of this experiment is subjected to non-uniform deformations and dynamic necking localization. In the aerospace industry, titanium alloys are used for the manufacturing of structural components such as turbine fan blades and engine containment and are usually designed to be subjected to dynamic loading. In this work, dynamic tensile experiments, complemented by high speed photography and digital image correction, are conducted to measure the engineering and true stress-strain response, as well as the effective strain rate evolution beyond dynamic necking of a near $\alpha$ Ti3Al2.5V alloy, in order to provide useful data for the effective design of structural components for aerospace applications.

2. **Experimental Techniques**

The Grade 9 Ti3Al2.5V alloy consists of primary $\alpha$ grains and small amount of dispersed $\beta$ phase. Tensile specimens with the gauge length to diameter ratio 8mm/3mm and 3mm/3mm were used to obtain a wide range of strain rates. The quasi-static tensile experiments were conducted using a screw-driven Zwick mechanical test machine equipped with high definition camera and telecentric lenses for the acquisition of high-resolution undistorted images. The strain measurements in the specimen gauge section were obtained via analysis of the recorded images using the commercial software Davis. High rate tensile experiments were carried out using a bespoke developed split Hopkinson tension bar designed by Gerlach et al. [2]. Several high rate tensile rate tests at 100 °C and 200 °C were also performed by using the induction heater to evaluate temperature effect on the mechanical behaviour. All experiments were recorded using the ultra-high speed Specialised Imaging Kirana camera.
3. Experimental Results

True stress and true strain data were calculated as follows: 
\[ \varepsilon_{\text{true}} = 2 \cdot \ln \left( \frac{r}{r_0} \right) \quad \text{and} \quad \sigma_{\text{true}} = \frac{F}{\pi r^2}, \]
where \( r \) and \( r_0 \) are the current and the initial radius of the minimum cross section of the specimen, respectively. \( F \) is the instantaneous force acting on the specimen. The true stress–true strain response is determined via image analysis. Fig. 1a shows a comparison of the engineering stress-strain curves obtained at strain rates between 1200 s\(^{-1}\) and 2700 s\(^{-1}\). The short gage length specimens show engineering failure strains about 34% higher than those obtained on 8 mm long gauge length specimens, indicating that after the onset of necking, the engineering strain expresses a length-averaged property, rather than a real property of the material itself. However, the true stress-true strain curves are independent of the specimen geometry. The true stress-strain curves obtained at 2400–2700 s\(^{-1}\) are only slightly higher than those measured at 1200/s. The high rate true stress-strain curves present limited strain rate effect beyond necking. The true failure strain obtained at high strain rates is in the region of 0.48, which is different from the geometry dependent engineering failure strain.

![Figure 1](image1.png)

**(a) Dynamic Engineering stress-strain (b) Dynamic True stress-strain**

**Figure 1.** Comparisons of the high rate tensile stress-strain curves of Ti3Al2.5V titanium alloy

![Figure 2](image2.png)

**Figure 2.** Typical evolution of the true strain rate during high rate tensile experiments conducted at room temperature.

Figure 2 examines the evolution of true strain rate during tensile deformation and shows that the true strain rate increases continuously until failure, up to approximately 10000 s\(^{-1}\), which is one order
of magnitude higher than the nominal strain rate. The short gage specimen exhibits smaller true strain rate at a given true strain under same nominal strain rate loading condition. It is evident that the nominal strain rate underestimates significantly the effective strain rate experienced by the material after strain localisation.

4. Numerical Simulation

The experimental results at various strain rates and temperatures were used to determine the material constants of a suitable constitutive model which was implemented in ABAQUS [3] by means of a VUMAT subroutine for the finite element simulations, in order to assess the accuracy of the model in predicting the dynamic tensile response. Fig.3 compares the experimental and numerical true stress-strain curves and true strain rate histories. The true stress-strain curves from the numerical simulation are in good agreement with the experimental data. The numerical true axial stress and true axial strain values are the averages computed from the elements located at the current cross-section of the neck. The true strain rate is influenced by strain localization and necking occurring during dynamic tensile deformation and reaches values up to one order of magnitude higher than the applied nominal strain rate. Numerical and experimental true strain rate histories are also in excellent agreement.

![Comparison between experimental and numerical true stress-strain data and true strain rate histories](image)

(a) 1200 s\(^{-1}\)  (b) 2400 s\(^{-1}\)

Figure 3. Comparison between experimental and numerical true stress-strain data and true strain rate histories

5. Conclusions

The dynamic tensile engineering strain expresses a length-averaged property instead of a property of the material itself. The analysis of the necking area allows the determination of the effective strain rate due to the strain localization, while the nominal strain rate in the specimens is much lower. The high rate true stress-strain curves present limited strain rate effect beyond necking. The constitutive model predicts the true strain rate evolution and true stress-strain characteristics with good agreement with respect to the experimental data, indicating the suitability of the model for the prediction of the dynamic tensile response of the investigated Ti3Al2.5V alloy.

Full version of this extended abstract will appear in Defence Technology in 2020.

References

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