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Quasi-Static and Dynamic Loading Responses of Ti-6Al-4V Titanium Alloy: Experiments and Constitutive Modeling

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Abstract

The results from a systematic study of the response of a Ti-6Al-4V alloy under quasi-static and dynamic loading at different strain rates and temperatures are presented. It has been shown that the work-hardening rate decreased as the strain rate and the strain increased. The correlations and predictions using modified KHL (Khan-Huang-Liang) viscoplastic constitutive model are compared with those from JC (Johnson-Cook) model and experimental observations. Overall, KHL model correlations and predictions compared much more favorably than the corresponding JC model predictions and correlations.

Key Words : Constitutive Behavior, Elastic-Viscoplastic Material, Finite Dynamic Strain, Ti-6Al-4V Titanium Alloy, Split Hopkinson Bar, Thermal Softening, High Strain-Rate Response

1. Introduction

Titanium alloys have been studied by several and other investigators because of their use in aero-engine, gas turbines and other applications due to their high strength, low density and ability to withstand high temperatures. Examples are Macdougall and Harding(1), Chichili et al. (2), and Cheng and Nemat-Nasser(3). The development of relatively economical Ti-6Al-4V alloy, with high resulting oxygen content, has sparked interest in its possible use in lightweight tanks (Montgomery and Wells(4); the conventional, more expensive Ti-6Al-4V alloy has been used primarily in aerospace components. The potential applications in armor, including ceramic tiles encapsulated in titanium alloys, have motivated several studies (Follansbee and Gray(5); Nemat-Nasser et al. (6); Majorell et al.(7).

The constitutive models used for high strain rate applications can be classified in two categories; the purely phenomenological ones, e.g. Johnson-Cook (J-C)(8) and Khan-Huang-Liang (KHL) models (Khan and Huang(9), Khan and Liang(10), and so called, "physically based models" e.g. the ones by Zerrilli and Armstrong(11), Mecking and Kocks(12). The latter group discusses the mechanisms of plastic deformation, mainly dislocations while completely · ignoring twinning. However, the material constants are determined by not measuring any deformation mechanism related quantities, but by arbitrarily choosing constants to "fit" the uniaxial stress-strain curves at different strain rates and temperatures, just like the purely phenomenological models.

The main objectives of this work is to obtain responses of Ti-6Al-4V and observe the suitability of existing constitutive relations such as KHL and JC models for incorporation in computer codes for penetration simulation. This was achieved through

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uniaxial compression experiments over a wide range of strain rates and temperatures.

2. Approach

2.1 Experiments

Dynamic and quasi-static responses at various strain rates and temperatures were determined for Ti-6Al-4V alloy. The quasi-static compressive experiments were carried out on an MTS axial/torsional material test system. The high strain-rate experiments were performed using the split Hopkinson pressure bar (SHPB) technique. In quasi-static experiments, strain gages were used to measure the deformation of specimens.

2.2 Modeling

The material constants for both, the modified KHL (Khan-Huang-Liang) and JC (Johnson-Cook) models were determined. Using these material constants, correlations were obtained and compared to experimental results. The modified Khan-Huang-Liang (KHL) model is as follows.

$$\sigma = [A + B(1 - \frac{\ln \dot{\varepsilon}}{\ln D_0^p})^{n_1} (\varepsilon^p)^{n_0}](\frac{\dot{\varepsilon}}{\dot{\varepsilon}^*})^C (\frac{T_m - T}{T_m - T_r})^m \quad (1)$$

where σ is the stress and ε^p is the plastic strain. T_m, T, and T_r are melting, current, and reference temperatures in Kelvin, respectively. $D_0^p = 10^6$ s^{-1} and $\dot{\varepsilon}^* = 1$ s^{-1}. $\dot{\varepsilon}$ is the current strain rate. A, B, n_1, n_0, C and m are material constants. For Ti-6Al-4V alloys, the adopted melting temperature was 1933 K, (Nemat-Nasser *et al.*(6). A major feature of this model, unlike the Johnson-Cook (JC) model, is that in this case decreasing work-hardening with increasing strain rate can be accommodated through the material constant n_1. The Johnson-Cook (JC) model is given by the following equation.

$$\sigma = [A + B(\varepsilon^p)^{n_0}](1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}^*})\left(1 - (\frac{T - T_r}{T_m - T_r})^m\right) \quad (2)$$

To determine the material constants for the model, the least squares and a constrained optimization procedure were used to minimize the error between correlated and actual data, using MAPLE. The experimental data at low strain rates were first used to get a set of material constants using the least squares method. Then, higher strain-rate data measured under adiabatic condition were correlated with the assumption that 90 % plastic work was dissipated to heat. Finally, using these material constants for both models, predictions were made and compared to a strain-rate-jump experiment (10^{-5} to 1 to 10^{-5} to 2800 s^{-1}).

3. Results and Discussions

For each uniaxial experiment, true stress- true strain plots were developed using the initial length and diameter of each respective specimen. Material constants for KHL models, are: A = 1049 MPa, B = 831.8 MPa, n_1 = 0.5643, n_0 = 0.5244, C = 0.02354, and m = 1.0934. For JC model, A = 980.0 MPa, B = 860.2 MPa, n_0 = 0.4262, C = 0.01537, and m = 0.9077.

Fig. 1 shows quasi-static and dynamic experimental results (at a temperature of 296 K) for different strain rates with correlations using KHL model. The dynamic correlation is for adiabatic case. The material response at the various strain rates indicates that the material is strain rate dependent. As that the material is strain rate dependent, the yield stress and work hardening constants change as the strain rate is increased. In addition, quasi-static measurements for various temperatures with correlations using KHL and JC models were carried out under different temperatures at a strain rate of 10^{-4} s^{-1}. It was observed that the material behavior is obviously dependent on temperature.

A strain-rate-jump experiment was performed at 296 K with strain rate from 10^{-5} s^{-1}, to 1 s^{-1}, and to 10^{-5} s^{-1} and then, to 2800 s^{-1}. Then the measured response was compared with predicted ones by KHL and JC models (Fig. 3). The predictions were made assuming that 10^{-5} s^{-1} and 1 s^{-1} spans are under isothermal conditions and 2800 s^{-1} experiment is under adiabatic condition. Especially at a strain rate of 2800 s^{-1}, KHL model prediction shows relatively good agreement with the measured response, while JC model overpredicts the experimental results at all strain rates.

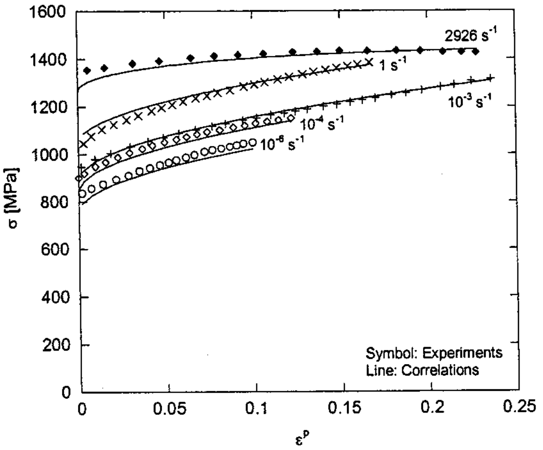

Fig. 1. Quasi-static and dynamic experimental results (at a temperature of 296 K) for different strain rates with correlations using KHL model; the dynamic correlation is for adiabatic case.

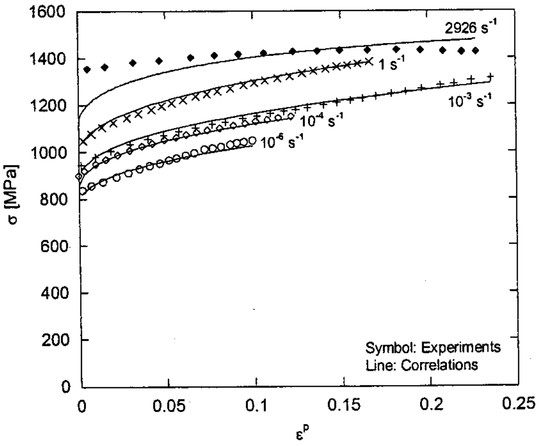

Fig. 2. Quasi-static and dynamic experimental results (at a temperature of 296 K) for different strain rates with correlations using JC model; the dynamic correlation is for adiabatic case

At a strain rate of 1 s^{-1}, the predicted stress is higher than the measured response. This is due to the fact that the deformation at this strain rate is not isothermal. This was already observed in the incremental strain experiment at a strain rate of 1 s^{-1} as described earlier. In the second 10^{-5} s^{-1}, the experimental results are affected by the temperature rise from the preceding deformation regime; the measured response differs slightly from the predictions of both models.

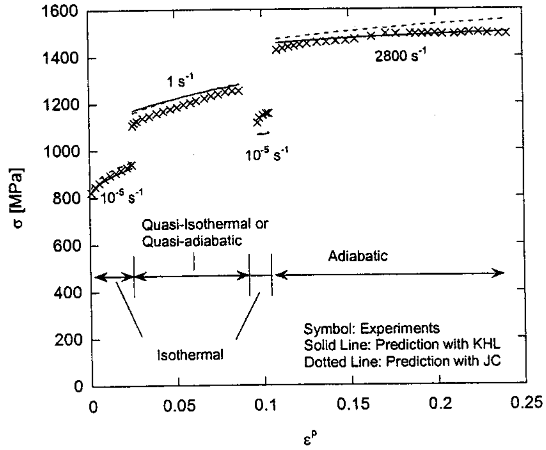

Fig. 3. A comparison of strain-rate-jump experiment results with predictions using KHL and JC models. The test was performed at 296 K with strain rate from 10^{-5} s^{-1} to 1 s^{-1} and to 10^{-5} s^{-1}, and then, to 2800 s^{-1}. The predictions were made assuming that 10^{-5} s^{-1} and 1 s^{-1} regions are under isothermal conditions, and 2800 s^{-1} region is under adiabatic condition. Material constants for JC model used here was determined with optimization.

4. Conclusions

A comprehensive set of experimental results on quasi-static and dynamic responses of Ti-6Al-4V titanium alloy from monotonous and strain-rate-jump compression experiments was carried out. Experimental values from uniaxial loading experiments were used to develop material constants for the KHL and JC constitutive models for Ti-6Al-4V titanium alloy. It was found that Ti-6Al-4V is both a strain rate and temperature dependant material. With high strain rates, thermal softening behavior was also observed.

The KHL model was found to correlate better than JC model over entire range of strain rates including dynamic deformation regime. This is more evident when the thermal softening is taking place with high strain rates and the work hardening rate is decreased as the strain rate and the strain increase. The temperature term of the modified KHL viscoplastic constitutive model could accommodate the case at temperature (200 K) lower than the reference temperature (296 K), while JC model failed in this case.

Material constants of the KHL and JC models, determined previously were used for material behavior predictions with the strain-rate-jump experiment to examine the validity of the model. Again, KHL model provided much better agreement with the measured response than the JC model.

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