Tensile behavior of SiCp/Al composites subjected to quasi-static and high strain-rate loading

YANG WANG, YUANXIN ZHOU, YUANMING XIA
Department of Mechanics and Mechanical Engineering (5th), Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, CAS, Hefei, Anhui 230026, People's Republic of China

Particle-reinforced metal matrix composites (MMCs) have attracted interest for years due to their low density and high strength. In particulate MMCs, ceramic particles are incorporated in metallic alloys to improve their mechanical properties [1]. In a wide range of engineering applications, MMCs may be subjected to extreme loading conditions such as high strain rates. Therefore, it is of great importance to study the strain rate effect on the mechanical behavior of MMCs for using in practice and develop specific constitutive model to characterize their deformation behavior for finite-element computational analysis.

The split Hopkinson bar is a very popular and useful experimental setup for measuring the dynamic behavior of materials at high strain rates. Normally, the constitutive responses in high strain-rate tests are essentially considered to be related to the adiabatic deformation process involving the adiabatic temperature rise due to the heat generated by irreversible plastic work. Such adiabatic temperature rise may affect the deformation behavior, which leads to the thermal-softening phenomenon. Consequently, there exists the coupling of strain-rate strengthening effect, strain-hardening effect and thermal-softening effect during the course of high rate loading. Nemat-Nasser *et al*. [2] performed an interrupted tests in the Hopkinson pressure bar to obtain the isothermal compression stress-strain curves at high strain rates. Such experimental technique makes it possible to decouple the thermal softening effect on the plastic deformation of materials from the strain-rate strengthening and strain hardening effects. Xia *et al*. [3] extended the method developed by Nemat-Nasser *et al*. and performed the recovery tensile impact tests in a bar-bar tensile impact apparatus to obtain the isothermal tension stress-strain curves at high strain rates.

The present paper focuses on the phenomenological constitutive description of SiCp/Al composite in quasi-static and dynamic tension tests. The investigated material was a powder metallurgy aluminum alloy (3.8–4.9% Cu, 1.2–1.8% Mg, 0.3–0.9% Mn and 92.4–94.7 A1) reinforced with 10 vol% of SiC particles. The average particle size was 10 μm. The composite was fabricated by direct extrusion. Uniaxial tension tests were carried out on dumbbell-shaped flat specimens at four strain rates: a quasi-static rate of 0.002 s^{-1} using a Shimadzu-5000 testing machine and high rates of 150, 500 and 1000 s^{-1} using the bar-bar tensile impact apparatus [4]. The tensile impact loading-unloading-reloading stress-strain results at high strain rate of 150 s^{-1} are shown in Fig. 1. Curve 1 is the isothermal stress-strain curve at quasi-static strain rate of 0.002 s^{-1}. Curve 2 is the adiabatic stress-strain curve at 150 s^{-1}. The dashed lines are a series of multi-loading-unloading stress-strain curves at rate 150 s^{-1} using the identical specimen. Curve 3 represents the isothermal of the points initial yielding the elastic proportional limit, upon each loading. The remarkable difference between the adiabatic and the isothermal results at the same high strain rate is solely due to thermal softening. Fig. 2 shows the experimental isothermal stress-strain curve at 0.002 s^{-1} and adiabatic stress-strain curves at 150, 500 and 1000 s^{-1} for SiCp/A1. The initial yield stress with respect to strain rate is shown in Fig. 3. The average values of Young's modulus and initial yield stress at different strain rates are listed in Table I. Experimental data indicate that SiCp/A1 composite is a rate sensitive material. Its initial yield stress increases with increasing strain rate, especially, when the strain rate exceeds about 100 s^{-1}. However, the experimental isothermal results at 0.002 and 150 s^{-1} shown in Fig. 1 illustrate that the strain-rate sensitivity of strain-hardening behavior for SiCp/A1 composite is not as significant as that of initial yield stress.

In order to describe the experimental response observed in SiCp/A1 composite, a phenomenologically-based constitutive model is proposed in the following form:

$$\sigma = \sigma_0\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\mathrm{p}_1}\right] + B\varepsilon^{\mathrm{n}}\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\mathrm{p}_2}\right]e^{-\lambda\Delta\mathrm{T}} \tag{1}$$

where the flow stress is expressed as a function of the plastic strain ε, strain rate $\dot{\varepsilon}$ and adiabatic temperature rise $\Delta T \cdot \sigma_0$ is the material constant associated with initial yielding and B and n are the strain-hardening coefficients. C, p_1 and p_2 are the strain-rate sensitivity coefficients. λ is the temperature coefficient to characterize the thermal softening effect due to the adiabatic temperature rise during the high rate deformation. ΔT is the adiabatic transient temperature rise within the specimen under high strain-rate loading, which is given as

$$\Delta T = \int_0^{\varepsilon} \frac{\gamma}{\rho C_{\mathrm{v}}}\sigma\,\mathrm{d}\varepsilon \tag{2}$$

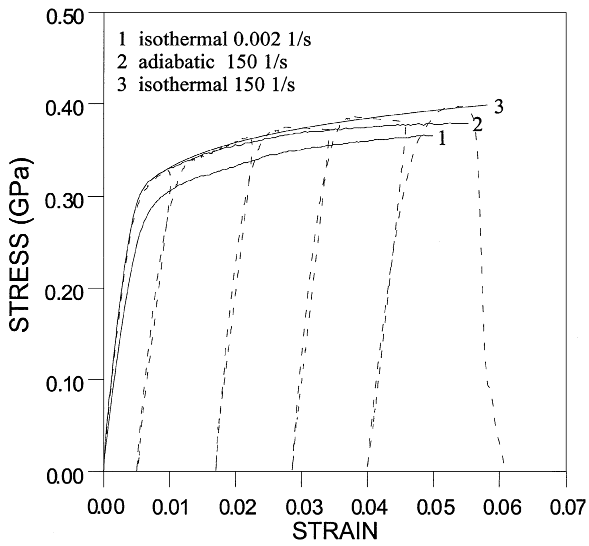

Figure 1 Typical adiabatic and isothermal stress-strain relations at strain rate 150 s^{-1}.

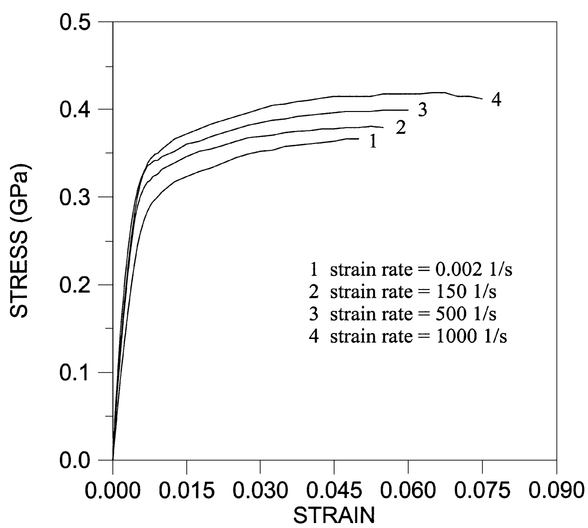

Figure 2 Stress-strain relations at different strain rates.

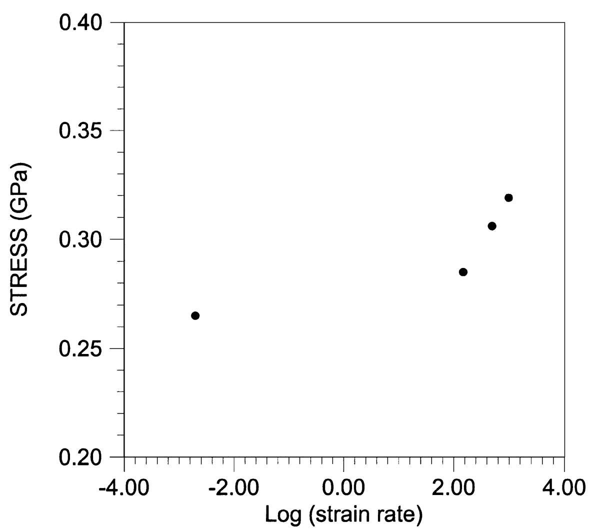

Figure 3 Initial yield stress at different strain rates.

where γ is the fraction of the irreversible plastic work which is converted into heat, ρ is the mass density and C_v is the heat capacity.

The present model is a combination and modification of the models proposed by Johnson and Cook [5] and Cowper and Symonds [6], and that of Meyers *et al.* [7]. The power law strain-hardening rule adopted in Equation 1, $\sigma_0 + B\varepsilon^n$, is used in the Johnson-Cook model to describe the plastic deformation of metals at high strain rates. In order to describe the mechanical behavior of SiCp/A1 composite over a wide range of strain rate from 0.002 s^{-1} to 1500 s^{-1}, the Cowper-Symonds model which scales the yield stress with the factor $1 + (\dot{\varepsilon}/C)^p$ is modified in the present paper by including two strain-rate sensitivity exponents, p_1 and p_2, to account for the strain rate effects on the initial yield stress and the strain-hardening behavior, respectively. Compared with the original Johnson-Cook and Cowper-Symonds models, the present modified model also introduces thermal softening coefficient as in the model of Meyers *et al.*, λ, to characterize the effect of adiabatic temperature rise on the plastic deformation of SiCp/A1 composites at high strain rates.

TABLE I Mechanical properties of SiCp/A1 at different strain rates

Strain rate (s^{-1})	Young's modulus E (GPa)	Initial yield stress $\sigma_{0.2}$ (GPa)
0.002	88.01	0.265
150	89.42	0.285
500	89.78	0.306
1000	89.81	0.319

The material constants in the present model may be determined experimentally using isothermal and adiabatic data at different strain rates.

1. The initial yield point defined in the present paper corresponds to 0.002 plastic strain. Such plastic strain is relatively small and the temperature rise due to the irreversible plastic work at this point is negligible, so the initial yield stress may be approximately expressed as follows:

$$\sigma_{0.2} \approx \sigma_0\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{p_1}\right] \tag{3}$$

where three material constants σ_0, C and p_1 are involved, which can be evaluated by comparing the experimental data for initial yield stress at different strain rates.

2. The isothermal stress-strain curves obtained at quasi-static rate and high strain rates are chosen to evaluate the constants B, n and p_2 by using the following relation reduced from Equation 1.

$$\sigma_{\text{isothermal}} = \sigma_0\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{p_1}\right] + B\varepsilon^n\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{p_2}\right] \tag{4}$$

where $\sigma_{\text{isothermal}}$ is the stress under isothermal condition.

3. The material constant λ is given by

$$\lambda = \frac{1}{\Delta T}\left\{\ln\left[B\varepsilon^n\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{p_2}\right]\right] - \ln\left[\sigma_{\text{adiabatic}} - \sigma_0\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{p_1}\right]\right]\right\} \tag{5}$$

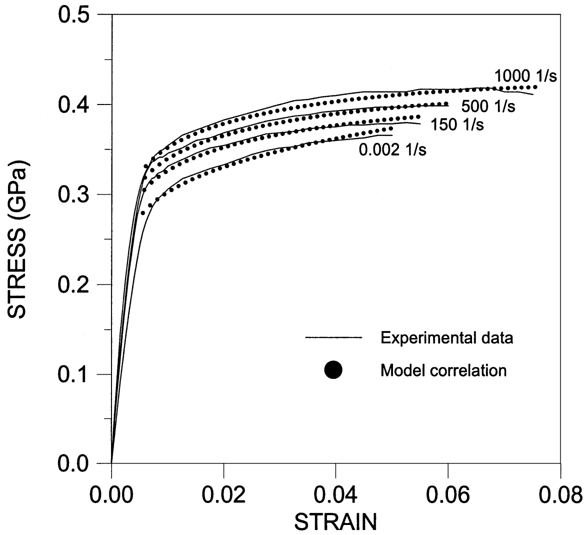

Figure 4 Comparison of model correlations with experimental data at different strain rates.

where $\sigma_{adiabatic}$ is the stress under adiabatic condition. λ can be evaluated using the adiabatic experimental results at high strain rates.

To obtain a more accurate set of values for these material constants, the least square method is used to interpolate the experimental isothermal and adiabatic stress-strain results at different strain rates. The seven material constants in the present constitutive model for SiCp/A1 composite are: $\sigma_0 = 0.215$ GPa, $B = 0.410$ GPa, $n = 0.31$, $C = 60000$, $p_1 = 0.35$, $p_2 = 2.0$ and $\lambda = 0.02/\,^{\circ}$C, respectively. The density of SiCp/A1 composite, ρ, is 2750 Kg/m^3 and the heat capacity, C_v, is 964 J/Kg °C. The conversion factor of work into heat, γ, is taken to be 0.9 at high strain rates based on the theoretically and experimentally motivated assumption. The experimental isothermal curve at 0.002 s^{-1} and adiabatic curves at 150, 500, 1000 s^{-1} and the correlations of the present model are shown in Fig. 4. It can be noticed that the proposed constitutive model gives a good correlation with the experimental response of SiCp/A1 composite over a wide range of strain rates.

References

1. T. CLYNE and P. WITHERS, "An Introduction to Metal Matrix Composites" (Cambridge University Press, Cambridge, 1993).
2. S. NEMAT-NASSER, L. YEOU-FONG and J. B. ISAACS, *Mechan. Mater.* **17** (1994) 114.
3. Y. M. XIA and Y. X. ZHOU, *ACTA Mechanica Sinica (English Series)* **12**(3) (1996) 243.
4. Y. X. ZHOU and Y. M. XIA, *Comp. Sci. and Techn.* **60** (2000) 403.
5. G. R. JOHNSON and W. H. COOK, A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures, in Proceedings of the Seventh International Symposium on Ballistics, The Hague, The Netherlands (1983) p. 541.
6. LS-DYNA3D User's Manual (Nonlinear Dynamic Analysis of Structures in Three Dimensions), Livermore Software Technology Corporation, August 1, 1995.
7. M. A. MEYERS, Y. J. CHEN, F. D. S. MARQUIS and D. S. KIM, *Mater. Trans.* A **26A** (1995) 2493.

Received 26 September
and accepted 24 November 2003