HIGH STRAIN-RATE TEST OF SINTER-FORGED Cu–Cr WITH SPLIT HOPKINSON PRESSURE BAR

Hoon Huh, Ji Ho Lim

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Science Town, Taejon, 305-701, Korea, *hhuh@kaist.ac.kr,

ABSTRACT–Electrodes of vacuum interrupters are manufactured of sinter-forged Cu-Cr that have good electrical and mechanical characteristics. The dynamic characteristics of the sinter-forged Cu–Cr material need to be identified in order to investigate the impact behavior of the electrodes that depends on the strain-rate at the closing stroke. In this paper, a split Hopkinson pressure bar apparatus was used to acquire the dynamic material properties of the sinter-forged Cu–Cr. Experimental results are interpolated to construct the original and modified Johnson–Cook model and the Cowper–Symonds model as the constitutive relation for numerical simulation of the impact behavior of electrodes.

INTRODUCTION: A vacuum circuit breaker (VCB) is a device to distribute the arc uniformly when interruption is required to shut off the electric circuit from the fault or accident. A VCB has a vacuum interrupter (VI) as a core component. VI is a sealed unit in which a pair of contacts (electrodes) is mounted in a vacuum valve. Since the contact material determines efficiency of the vacuum interrupter, the material requires high current interrupting, low electric resistance and high impact resistance. The sinter-forged Cu–Cr is one of the good candidates for the contact material.

The split Hopkinson pressure bar (SHPB) [Kolsky 1963] is a very popular experimental technique for identification of the dynamic material characteristics at the high strain-rate. Lindholm and Yeakley (1989) detailed the procedure in using the split Hopkinson pressure bar in order to obtain complete stress–strain curves for a number of materials, with either tensile or compressive strain rates of the order of 1000/s. Johnson and Cook (1983) suggested a constitutive model determined by five material constants in the constitutive relation for materials subjected to large strains, high strain rates and high temperatures. Zerilli and Armstrong (1987) suggested improved description of the Johnson–Cook model based on the dislocation mechanics. Khan and Huang (1992) proposed a new constitutive model that can predict the experimental results in a very large strain rate range including the high work-hardening region. Kang et al. (1999) acquired high strain-rate tensile properties of sheet metals with a new tension split Hopkinson bar apparatus and proposed a modified Johnson–Cook model for sheet metals.

In this paper, high strain-rate tests have been carried out with a split Hopkinson pressure bar for sinter-forged Cu–Cr and oxygen-free Cu. The experiment provides stress–strain curves for various strain-rates ranged from 1000/s to 10000/s. The experimental results from the both quasi-static and dynamic test are used to construct the constitutive relation with the original and the modified Johnson–Cook model as well as the Cowper–Symonds model for numerical simulation of the impact behavior of electrodes.

EXPERIMENTS: The electrode is manufactured by sintering the powder with 25%wt of Cr and 75%wt of Cu. The quasi-static tests were performed for the strain rates of 0.003/s and 1/s with the Instron 4206 and the Instron 8032 respectively. The dynamic response of the material was obtained from the split Hopkinson pressure bar test using disc-type specimens. The strain rates were acquired in the range from 1000/s to 10000/s. The experimental results demonstrate that the yield stress is greatly influenced by the strain rate and this tendency is more remarkable for sinter-forged Cu–Cr than oxygen-free Cu as shown in Fig. 1.

CONSTITUTIVE RELATIONS: The Johnson–Cook model is represented by Eqn. (1).

$$\bar{\sigma} = \left(A + B\bar{\varepsilon}^{n}\right)\left(1 + C\ln\dot{\bar{\varepsilon}}\right)\left(1 - T^{*m}\right) \tag{1}$$

where T^{*} is the homologous temperature represented by Eqn. (2).

$$T^{*} = \frac{T - T_{room}}{T_{melt} - T_{room}} \tag{2}$$

where T is the temperature of the specimen, and T_{melt} is the melting temperature of the specimen. For better description of the material behavior, the experimental data are interpolated using the quadratic term for the strain rate [Kang et el. 1999] as

$$\bar{\sigma} = \left(A + B\bar{\varepsilon}^{n}\right)\left(1 + C_1\ln\dot{\bar{\varepsilon}} + C_2\left(\ln\dot{\bar{\varepsilon}}\right)^2\right)\left(1 - T^{*m}\right) \tag{3}$$

Since the sinter-forged Cu–Cr shows abrupt increase in the yield strength when the strain-rate is larger than 10^3/s, the initial yield stress has to be interpolated using the cubic or higher term for the strain rate in a modified Johnson–Cook model. This difficulty can be overcome by adopting the Cowper–Symonds model that interpolates the yield stress using the exponential term for the strain rate. This paper proposes a modified Cowper–Symonds model that considers the thermal softening term as in the Johnson–Cook model, which is neglected in the original Cowper–Symonds model.

$$\bar{\sigma} = \left(A + B\bar{\varepsilon}^{n}\right)\left(1 + \left(\frac{\dot{\bar{\varepsilon}}}{D}\right)^{\frac{1}{p}}\right)\left(1 - T^{*m}\right) \tag{4}$$

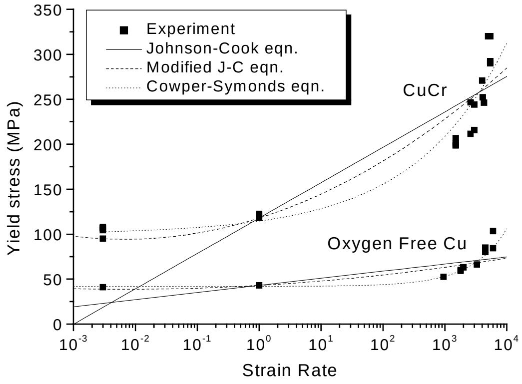
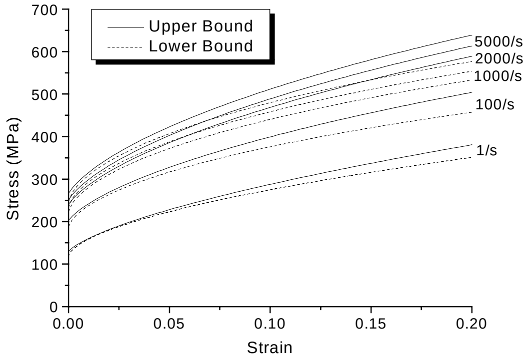
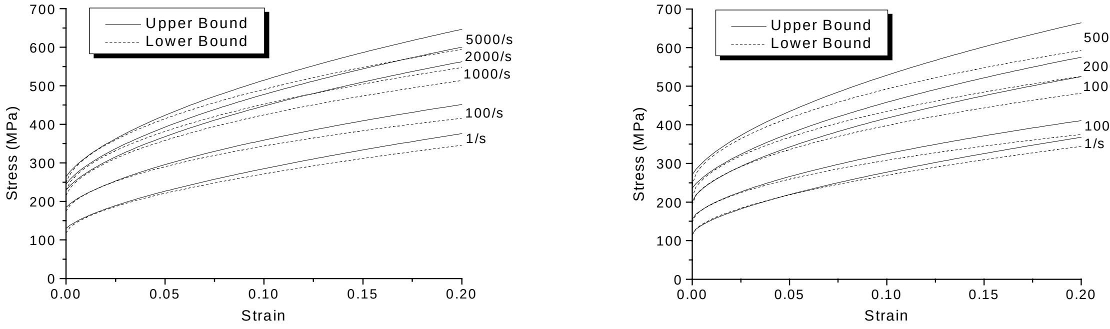


Fig. 1 Yield stress with respect to the strain-rate and the interpolated curves.



(a)



(b) (c)

Fig. 2 The stress–strain curves for sinter-forged Cu–Cr with the upper and lower bounds: (a) Johnson–Cook; (b) modified Johnson–Cook; (c) modified Cowper–Symonds.

The interpolated stress–strain curves for several models are depicted in Fig. 2. The material properties of sinter-forged Cu–Cr showed some variation for each specimen due to the inconsistency of the manufacturing process. In order to take this variation into account, the constants in the original and modified Johnson–Cook model are determined with the lower and upper bounds. The constitutive relations presented were obtained in the adiabatic condition, which would properly describe the dynamic behavior of the material at high strain rates although there still exists discrepancy between the curves and the material behavior when the condition lies between the adiabatic and isothermal ones.

CONCLUSION: Experiments were carried out with a split Hopkinson pressure bar for identification of the dynamic characteristics of sinter-forged Cu–Cr. The experimental results including the quasi-static test results were interpolated with the original and modified Johnson–Cook models in order to provide the constitutive relations for the wide range of the strain rates. The result shows the strain-rate effect on the dynamic characteristic of sinter-forged Cu–Cr is remarkable for the yield strength over the strain rate of 1000/s compared to oxygen-free Cu and the experimental data has to be interpolated by a modified Johnson–Cook model or a modified Cowper–Symonds model.

REFERENCES:

H. Kolsky, 1963, “Stress Waves in Solids”, Dover publications, New York, 41-98.

U. S. Lindholm and L. M. Yeakley, 1989, “High Strain-rate testing: tension and compression”, Exp. Mech., **8**, 1-9.

G. R. Johnson and W. H. Cook, 1983, “A Constitutive model and data for metals subjected to large strains, high strain rates and high temperatures”, Proc. the 7th Int. Symposium on Ballistics, Hague, The Netherlands, 541-547.

F. J. Zerilli and R. W. Armstrong, 1987, “Description of Tantalum deformation behavior by dislocation mechanics based constitutive relations”, J. Appl. Phys., **61**, 1816-1825.

A. S. Khan and S. Huang, 1992, “Experimental and theoretical study of mechanical behavior of aluminum in the strain rate range 10^{-5}–10^{4}”, Int. J. Plasticity, **8**, 397-424.

W. J. Kang, S. S. Cho, H. Huh and D. T. Chung, 1999, “Modified Johnson–Cook model for vehicle body crashworthiness simulation”, Int. J. Vehicle Design, **21**, 424-435.