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New Dynamic Constitutive Model for OFHC Copper Film

Jin Sung Kim, Hoon Huh

***Abstract*—**The material properties of OFHC copper film was investigated with the High-Speed Material Micro Testing Machine (HSMMTM) at the high strain rates. The rate-dependent stress-strain curves from the experiment and the Johnson−Cook curve fitting showed large discrepancies as the plastic strain increases since the constitutive model implies no rate-dependent strain hardening effect. A new constitutive model was proposed in consideration of rate-dependent strain hardening effect. The strain rate hardening term in the new constitutive model consists of the strain rate sensitivity coefficients of the yield strength and strain hardening.

***Keywords*—**Rate dependent material properties, Dynamic constitutive model, OFHC copper film, Strain rate.

I. Introduction

THE rate-dependent material properties of engineering materials are widely utilized for industrial applications. During the past decade, the rate-dependent behavior of metal sheets was investigated by many researchers [1], [2] for automobile applications while the thin films of foregoing remain almost unstudied. Dynamic material properties of the thin films have gained great interests in the area of MEMS (Micro Electro Mechanical System) [3], micro-forming [4] and etc. Material properties of the OFHC (Oxygen Free High Thermal Conductivity) copper film at the strain rates ranging from 0.001/s to 1000/s were recently evaluated using High-Speed Material Micro Testing Machine [5]. Johnson−Cook constitutive model [6], which is widely utilized, assumed that the strain rate hardening is proportional to the logarithm of strain rate. More recently, the modified Johnson−Cook constitutive model was suggested with the strain rate sensitivity term as higher interpolation function of the logarithm of strain rate [2]. In current study, the rate-dependency of strain rate hardening on strain hardening is newly considered to the existing model.

II. Experimental Result

Experimental stress-strain curves of an OFHC copper film with a thickness of 0.1mm are shown in Fig. 1 [5]. The result shows that the flow stress and the strain hardening monotonically increase as the strain rate increases. The Johnson−Cook constitutive model [6] in a form of (1) uses the slope of the normalized yield strength versus the logarithm of strain rate. The yield strength is assumed to proportionally increase as the logarithm of strain rate increases with a proportional coefficient of strain rate sensitivity named as C. The thermal softening term is neglected in this calculation because the temperature change due to the plastic work is negligible when only tension is concerned in engineering sense.

$$\sigma = (A + B\varepsilon^n)[1 + C\ln(\dot{\varepsilon}^*)](1 - T^{*m}) \quad (1)$$

where,

$\dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$: normalized strain rate

$\dot{\varepsilon}_0$: nominal strain rate, s^{-1}

C : strain rate sensitivity coefficient of yield strength

$T^* = \dfrac{T - T_{room}}{T_{melt} - T_{room}}$: homologous temperature

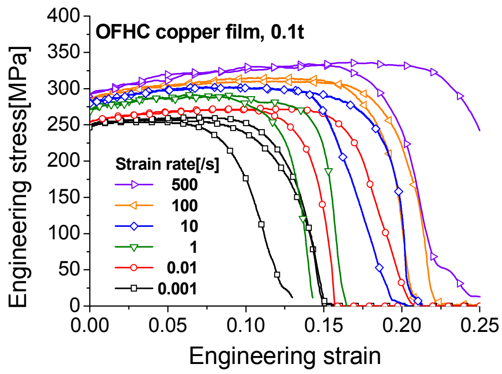

Fig. 1 Engineering stress-strain curves for OFHC copper film

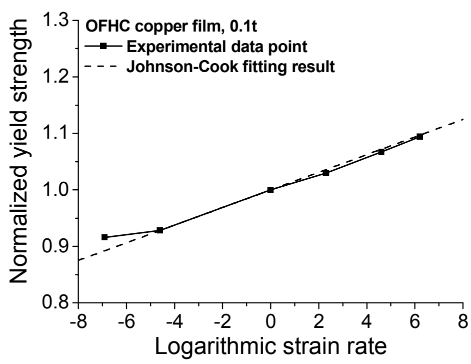

Fig. 2 Normalized yield strength vs. logarithmic strain rate curve

Jin Sung Kim is a senior researcher in New Transportation Systems Research Center ofKorea Railroad Research Institute, Uiwang-si, Republic of Korea (phone: +82-31-460-5266; fax: +82-31-460-5022; e-mail: kjs@krri.re.kr).

Hoon Huh is a professor in the School of Mechanical, Aerospace, and Systems Engineering, Korea Advanced Institute of Science and Technology (e-mail: hhuh@kaist.ac.kr).

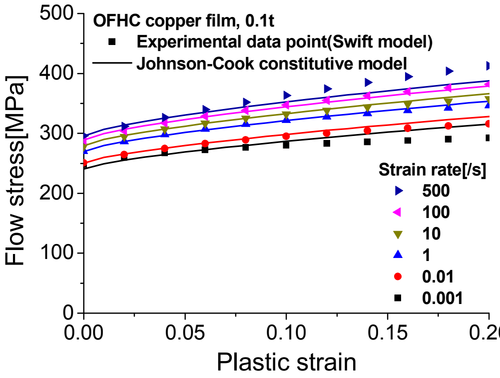

Fig. 3 Johnson−Cook curve fitting result vs. experimental result

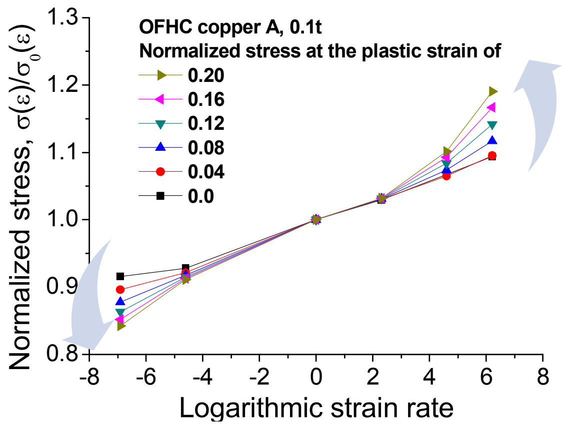

Fig. 4 Variation of normalized stress vs. logarithmic strain rate curves w.r.t. the plastic strain

Fig. 2 denotes the normalized yield strength versus logarithmic strain rate. The normalized yield strength is in proportion to the logarithmic strain rate. The coefficient C, strain rate sensitivity coefficient of yield strength, is the slope of the curve. As a result, Fig. 3 shows that curve fitting results from the Johnson−Cook constitutive model and experiments have large discrepancies as the plastic strain increases. The discrepancies are originated from the variation of strain rate sensitivity coefficient, C, as the plastic strain changes. The strain rate sensitivity coefficient is not constant but varies as the plastic strain increases as shown in Fig. 4.

III. New Dynamic Constitutive Model

A new dynamic constitutive model for OFHC copper film was suggested as shown in (2). The strain rate sensitivity coefficient, C, is assumed as a linear function of the plastic strain. Consequently, the C_1 is the strain rate sensitivity coefficient of yield strength, which is the same as that of Johnson−Cook constitutive model, and the C_2 becomes the strain rate sensitivity coefficient due to strain hardening.

$$\begin{aligned}\sigma(\varepsilon,\dot{\varepsilon}) &= \sigma_0(\varepsilon)\left(1+C(\varepsilon)\ln\left(\dot{\varepsilon}^*\right)\right)\\ &= \sigma_0(\varepsilon)\left(1+\left(C_1+C_2\varepsilon\right)\ln\left(\dot{\varepsilon}^*\right)\right)\\ &= \sigma_0(\varepsilon)\left(1+C_1\ln\left(\dot{\varepsilon}^*\right)+C_2\varepsilon\ln\left(\dot{\varepsilon}^*\right)\right)\end{aligned} \quad (2)$$

where,

$\sigma_0(\varepsilon)$: stress-strain relation at the strain rate of 1 s^{-1}

$\dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$: normalized strain rate

$\dot{\varepsilon}_0$: nominal strain rate, s^{-1}

C_1 : strain rate sensitivity coefficient of yield strength

C_2 : strain rate sensitivity coefficient of strain hardening

A linear fitting curve of C is plotted in Fig. 5. The coefficient C_1 becomes equal to C at the yield point where the plastic strain is zero and the coefficient C_2 is the slope of the curve for C. Fig. 6 demonstrates that rate-dependent stress-strain curves obtained by a new dynamic constitutive equation nicely approximates experimental stress-strain curves.

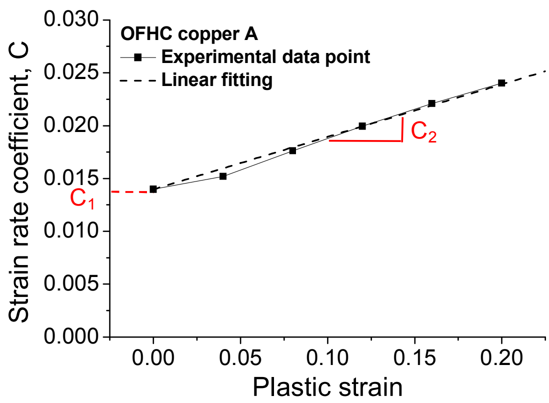

Fig. 5 Linear fitting of the strain rate coefficient, C, w.r.t. the plastic strain

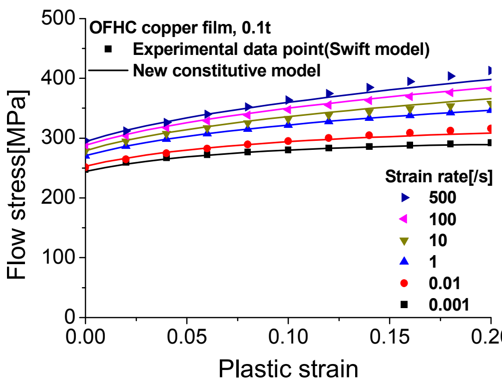

Fig. 6 New dynamic constitutive model vs. experimental result

IV. Conclusion

New dynamic constitutive model of an OFHC copper film has been suggested with a linear approximation of change of strain rate sensitivity coefficient as a function of a plastic strain. The new model shows good approximation with experimental result while the Johnson−Cook constitutive model shows large discrepancy as the plastic strain increases. New dynamic constitutive model implies rate-dependent strain hardening term and can give functional expandability to materials that have change of strain hardening as the strain rate increase.

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