Validation of the Hardening Behaviors for Metallic Materials at High Strain Rate and Temperature by Using the Taylor Impact Test

MingJun Piao[1,a], Hoon Huh[1,b*], Ikjin Lee[1,c], Hyungwon Kim[2], Leeju Park[2]

[1]School of Mechanical, Aerospace and Systems Engineering, KAIST

291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

[2]R&D institute 4-2, Agency for Defense Development,

488 Bugyuseong Daero, Yuseong-gu, Daejeon 305-152, Republic of Korea

[a]mj.piao.kaist.ac.kr, [b]hhuh@kaist.ac.kr, [c]ikjin.lee@kaist.ac.kr

Keywords: Deformation heating; Thermal softening; Taylor impact test

Abstract

This paper is concerned with the validation of the dynamic hardening behaviors of metallic materials by comparing numerical and experimental results of the Taylor impact tests. Several uniaxial tensile tests are performed at different strain rates and temperatures by using three kinds of materials: 4130 steel (BCC); OFHC copper (FCC); and Ti6Al4V alloy (HCP). Uniaxial material tests are performed at a wide range of strain rates from 10^{-3} s^{-1} to 10^{3} s^{-1}. Moreover, tensile tests are performed at temperature of 25 ℃ and 200 ℃ at strain rates of 10^{-3} s^{-1}, 10^{-1} s^{-1}, and 10^{2} s^{-1}, respectively. A modified Johnson–Cook type thermal softening model is utilized for the accurate application of the thermal softening effect at different strain rates. The hardening behaviors of the three materials are characterized by comparing the seven sequentially deformed shapes of the projectile from numerical and experimental results of Taylor impact tests.

Introduction

Hardening characteristics of metals under static loading conditions are remarkably different from those under dynamic loading conditions. Accurate understanding of the hardening behaviors at a wide range of strain rates is important for numerical simulations in the defense industrial application such as explosions, ballistic impacts, and armor crashworthiness.

Dynamic hardening models have been developed by many researchers to describe stress–strain relation at different strain rates and temperature. Some of the well-known dynamic hardening models are the Johnson–Cook model [1], the modified Johnson–Cook model [2], the Khan–Huang model [3], the modified Khan–Huang model [4], the Zerilli–Armstrong model [5], the Preston–Tonks–Wallace (PTW) model [6]. Lim et al. [7] suggested the Lim–Huh model to accurately describe the dynamic hardening behavior of 22 different auto-body steel sheets. Moreover, Piao et al. [8] modified the Lim–Huh model by adding a rate dependent Johnson–Cook type thermal softening term to identify the thermal softening behavior at ultra-high strain rates.

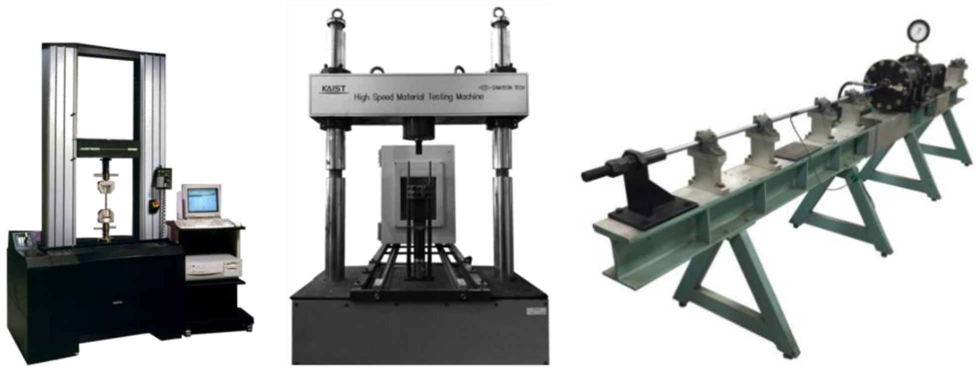
In this paper, the hardening behaviors of the three materials: 4130 steel (BCC); OFHC copper (FCC); and Ti6Al4V alloy (HCP), are evaluated by comparing the seven sequentially deformed shapes of the projectile from numerical simulation results with the experimental results of Taylor impact tests. Several uniaxial tensile tests are performed at a wide range of strain rates from 10^{-3} s^{-1} to 10^{3} s^{-1} by using an Instron 5583, a High Speed Material Testing Machine (HSMTM), and a Tension Split Hopkinson Pressure Bar (TSHB). The thermal softening occurs simultaneously with strain hardening when a material undergoes plastic deformation. In order to investigate the hardening behavior at different strain rates, tensile tests are performed at temperature of 25 ℃ and

200 ℃ at strain rates of 10^{-3} s^{-1}, 10^{-1} s^{-1}, and 10^{2} s^{-1}, respectively. The experimental results from form low to high strain rates are fitted with the modified Lim–Huh model and the hardening behaviors at the ultra-high strain rates are optimized by using the systematic procedure which is suggested by Piao et al. [8].

Experiments

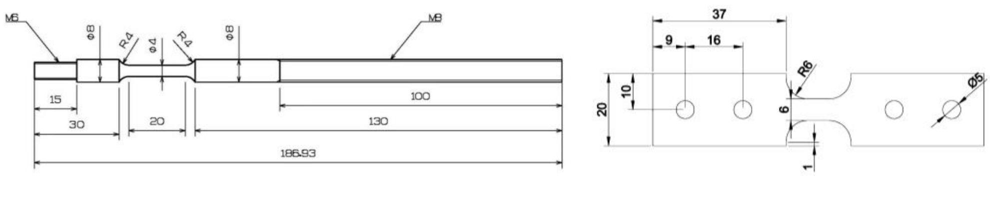
Tensile tests at a wide range of strain rates. Static and dynamic tensile tests have been performed with the three kinds of materials: 4130 steel (BCC); OFHC copper (FCC); and Ti6Al4V alloy (HCP). The Instron 5583 machine is used for the quasi-static tensile tests; a HSMTM (high speed material testing machine) is utilized to obtain hardening behaviors at intermediate strain rates [9]; and a TSHB (tension split Hopkinson pressure bar) has been used for the tests at high strain rates [10]. The three experimental apparatus are shown in Fig. 1. The specimen dimensions for the experiments are shown in Fig. 2. The experimental results of the engineering stress–strain curves are shown in Fig. 3 from strain rates of 0.001 s^{-1} to 2000 s^{-1}. The experimental results from low to high strain rates illustrate that the strain rate effect is indispensable for an understating of material hardening behaviors.

Tensile tests at different temperature. In order to investigate the thermal softening behavior at different strain rates, uniaxial tensile tests are performed at temperatures of 25 ℃ and 200 ℃ and at strain rates of 10^{-3} s^{-1}, 10^{-1} s^{-1}, and 10^{2} s^{-1}, respectively. Two thermocouples are attached at the gauge section to measure the exact temperature of the specimen. The experimental results of the engineering stress–strain curves are shown in Fig. 4.



(a) (b) (c)

Figure 1 (a) Static tensile testing machine, INSTRON 5583;
(b) High speed material testing machine, HSMTM; and
(c) Tension split Hopkinson pressure bar, SHPB.



(a) (b)

Figure 2 Dimension of specimens for: (a) uniaxial tensile tests; and (b) tension SHPB tests.

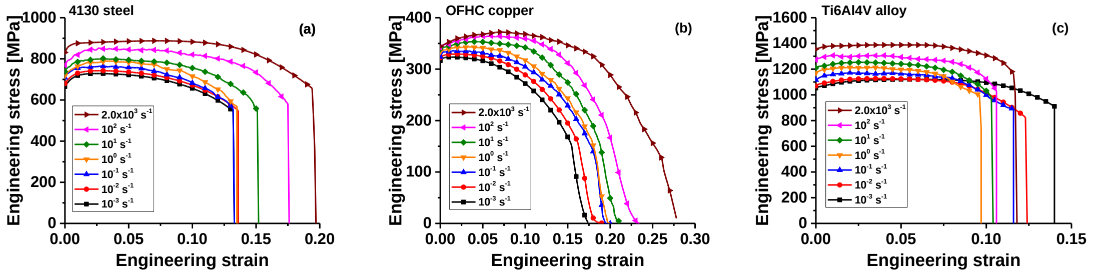


Figure 3 Engineering stress–strain curves at strain rates ranging from 10^{-3} to $2{\times}10^{3}$ s^{-1}:
(a) 4130 steel; (b) OFHC copper; (c) Ti6Al4V alloy

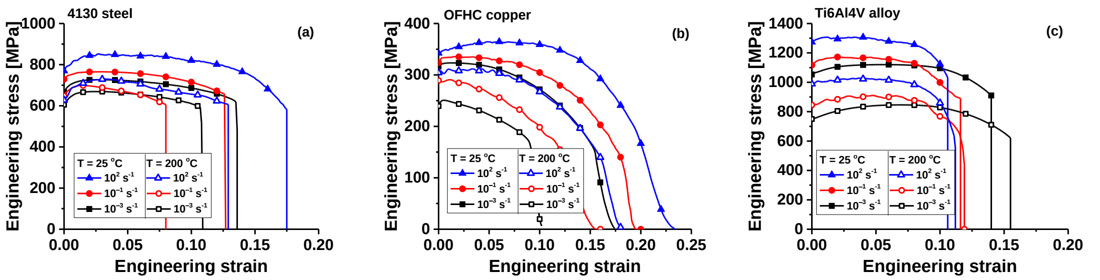


Figure 4 Engineering stress–strain curves
at the temperature of: 25 ℃ and 200 ℃; at the strain rate of: 10^{-3} s^{-1}; 10^{-1} s^{-1}; and 10^{2} s^{-1}:
(b) 4130 steel; (b) OFHC copper; (c) Ti6Al4V alloy

Figure 5 Single stage gas gun developed

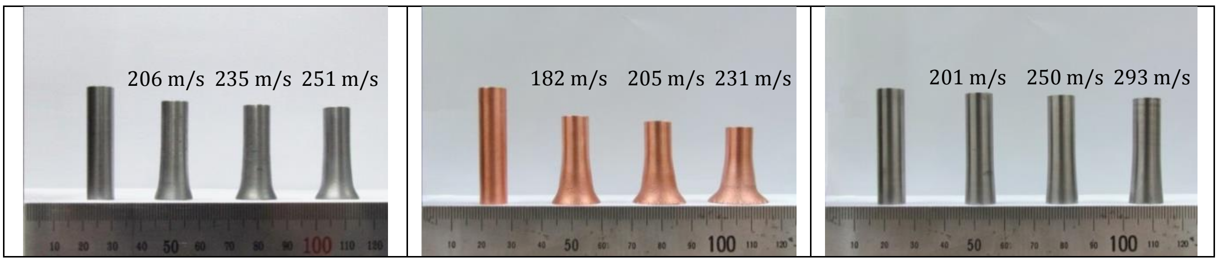


Figure 6 Undeformed and final deformed shape of
4130 steel, OFHC copper, and Ti6Al4V alloy at different impact velocities

Taylor impact tests. The Taylor impact test is a general impact procedure that impacts a cylindrical projectile on a rigid anvil at a high velocity. A single stage gas gun, Fig. 5, has been utilized to perform the Taylor impact tests at different impact velocities. The inner diameter and the length of the gun barrel are 40 mm and 3,000 mm, respectively. Total of nine experiments are performed with three different impact velocities for the three materials. The deformation procedures are recorded by a high speed camera, FASTCAM SA4, with a frame rate of 180,000 fps. The Taylor impact tests are performed with a cylindrical projectile specimen with the diameter of 10 mm and the length of 40 mm. The original specimen and the final deformed shapes are shown in Fig. 6.

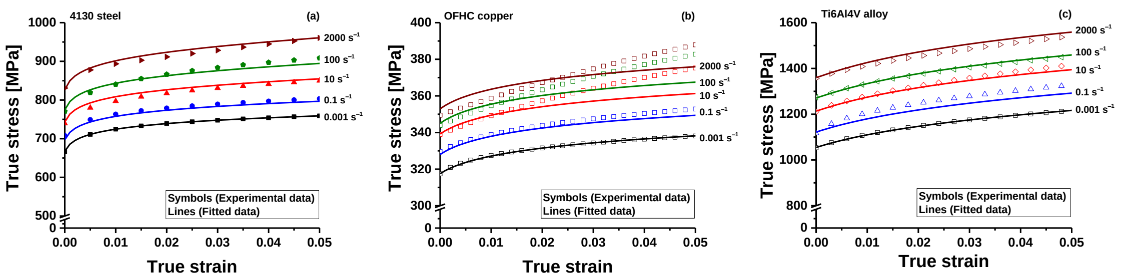


Figure 7 Experimental and fitted data for (a) 4130 steel; (b) OFHC copper (c) Ti6Al4V alloy

Temperature and rate dependent hardening model

Lim–Huh model with modified thermal softening function. Lim et al. [7] suggested the Lim–Huh model to accurately describe the dynamic hardening behavior of 22 different auto-body steel sheets. Moreover, Piao et al. [8] modified the Lim–Huh model by adding a rate dependent Johnson–Cook type thermal softening term to identify the thermal softening behavior at ultra-high strain rates as:

$$\sigma(\varepsilon,\dot{\varepsilon},T)=\left[K(\varepsilon+\varepsilon_0)^n\right]\left[\frac{1+q(\varepsilon)\dot{\varepsilon}^p}{1+q(\varepsilon)\dot{\varepsilon}_r^{\ p}}\right]\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^{m_1-m_2\cdot\ln(\dot{\varepsilon}/\dot{\varepsilon}_r)}\right] \text{ where } q(\varepsilon)=\frac{q_1}{(\varepsilon+q_2)^{q_3}} \quad (1)$$

where ε_r, T, T_m, and T_r represent the reference strain rates, specimen temperature, the melting temperature, and the room temperature, respectively. The nine coefficients are shown in Table 1. The true stress–true strain curves are shown in Fig. 8 with the fitted result by using the modified Lim–Huh model.

Characterization of the flow stress

The characterization process is follow by the Piao et al.[8] work. Seven sequentially deformed shapes are considered in the inverse optimization process. The Lim–Huh type yield stress model is chosen as:

$$\sigma_y(\dot{\varepsilon})=\sigma_{y_0}\frac{1+q\dot{\varepsilon}^p}{1+q\dot{\varepsilon}_r^{\ p}} \quad (2)$$

where q and p is the material parameter, σ_{y0} is the yield stress at the maximum strain rate from experiment. The optimization is performed by finding q and p to minimize the sequentially deformed diameter and length from numerical and experimental results, respectively. The sequentially deformed shapes are shown in Fig. 8 with the parameter in Table 2. The characterized hardening curves and yield stresses are shown in Fig. 9 and Fi. 10, respectively.

Table 1 The material coefficients of the Lim–Huh with the thermal softening term

K [MPa]	ε_0	n	q_1	q_2	q_3	p	m_1	m_2
				4130 Steel				
---	---	---	---	---	---	---	---	---
				OFHC copper				
---	---	---	---	---	---	---	---	---
				Ti6Al4V alloy				
---	---	---	---	---	---	---	---	---

Table 2 The variables of the Lim–Huh type yield stress model before and after optimization

Material	Before optimization		After optimization	
	q	*p*	*q*	*p*
4130 steel	---	---	---	---
OFHC copper	---	---	---	---
Ti6Al4V alloy	---	---	---	---

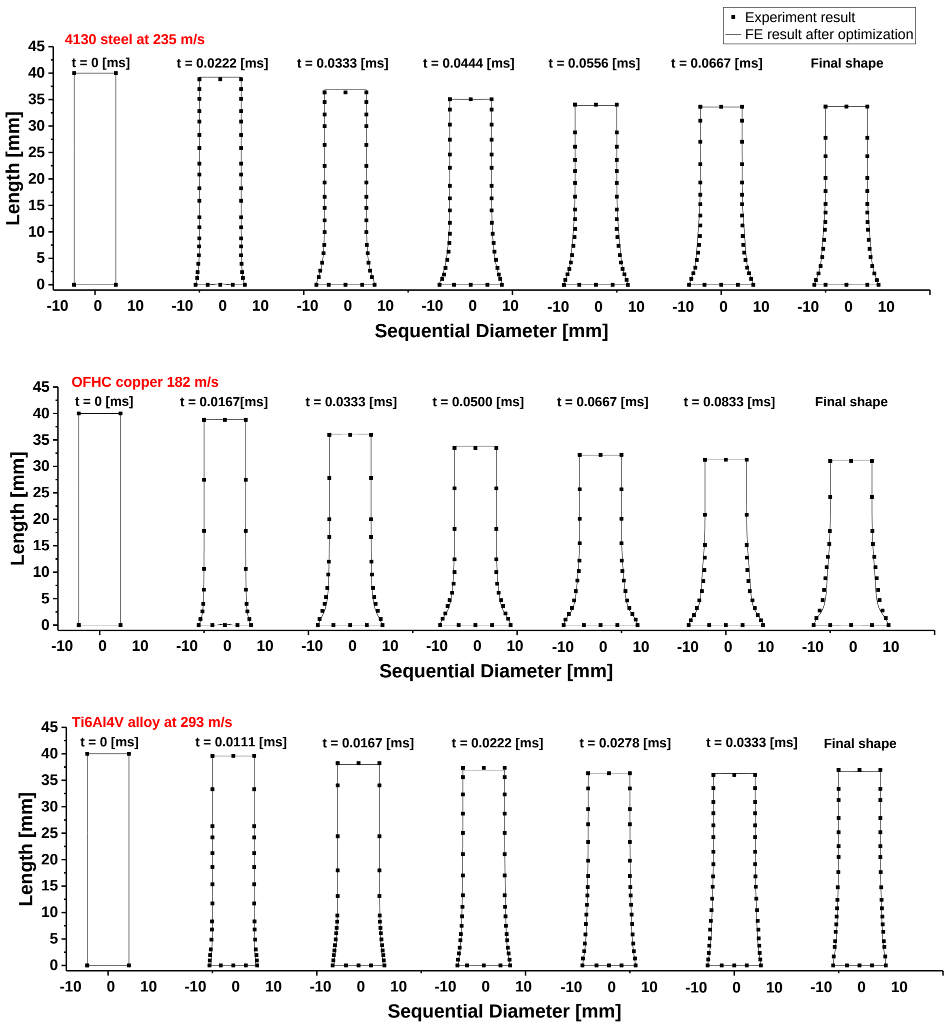


Figure 8 Sequentially deformed shape of 4130 steel, OFHC copper, and Ti6Al4V alloy after optimization

Conclusions

In this paper, hardening behaviors at ultra-high strain rates been carried out by performing several different experiments and inverse optimizations. The characterized stress–strain curves from low to ultra-high strain rates can well estimate the sequentially and final deformed shape of the projectiles from the Taylor impact tests. However, it does not illustrate that the characterized stress–strain relations in this paper are the only one result. An appropriate hardening model, thus, should be selected for the materials, in order to have more reliable results.

The Taylor impact test not only accompany with high strain rate and high temperature but also large strain. As a future work, large strain behavior at ultra-high strain rates will be carried out to estimate the fracture initiation in the Taylor impact tests.

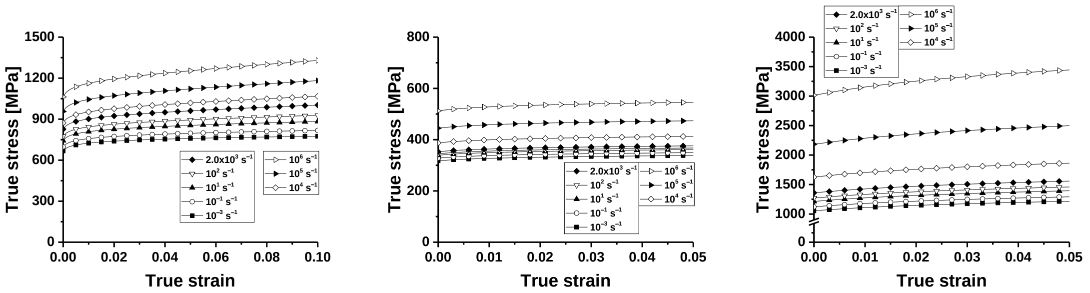


Figure 9 Characterized true stress–strain curves for
(a) 4130 steel; (b) OFHC copper (c) Ti6Al4V alloy

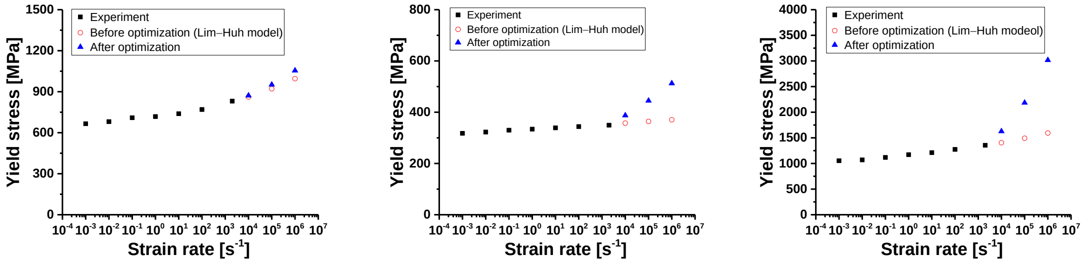


Figure 10 Characterized yield stress for (a) 4130 steel; (b) OFHC copper (c) Ti6Al4V alloy

References

[1] G. R. Johnson and W. H. Cook, "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures," Proceedings of the 7th International Symposium on Ballistics, pp. 541–547, 1983.

[2] W. Kang, S. Cho, H. Huh, and D. T. Chung, "Modified Johnson–Cook model for vehicle body crashworthness simulation," International Journal of Vehicle Design, vol. 4, no. 4, pp. 424–435, 1999.

[3] S. Khan and S. Huang, "Experimental and theoretical study of mechanical behavior of 1100 aluminum in the strain rate range $10^{-5} - 10^{4}$ s^{-1}," International Journal Plasticity, vol. 8, pp. 397–424, 1992.

[4] H. Lee, J. Song, and H. Huh, "Dynamic tensile tests of auto-body steel sheets with the variation of temperature," Solid State Phenomena, vol. 114–117, pp. 259–262, 2006

[5] F. J. Zerilli and R. W. Armstrong, "Dislocation-mechanics-based constitutive relations for material dynamics calculations," Journal of Applied Physics, vol. 61, no. 5, pp. 1816-1825, 1987.

[6] D. L. Preston, D. L. Tonks, and D. C. Wallace, "Model of plastic deformation for extreme loading conditions," Journal of Applied Physics, vol. 93, no. 1, p. 211, 2003

[7] J. Lim, "Study on dynamic tensile tests of auto-body steel sheet at the intermediate strain rate for material constitutive equations," Ph.D. dissertation, KAIST, Daejeon, Korea, 2005.

[8] M. Piao, H. Huh, I. Lee, K. Ahn, H. H. Kim, and L. Park, "Characterization of flow stress at ultra-high strain rates by proper extrapolation with Taylor impact tests," Int. J. Impact Eng., vol. 91, pp. 142–157, 2016.

[9] H. Huh, J. Lim, and S. Park, "High speed tensile test of steel sheets for the stress-strain curve at the intermediate strain rate," International Journal of Automotive Technology, vol. 10, no. 2, pp. 195–204, 2009.

[10] Huh, W.J. Kang, and S.S. Han," A tension split hopkinson bar for investigating the dynamic behavior of sheet metals," Experimental Mechanics, vol. 42, pp. 8–17, 2002.