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Characterization of flow stress at ultra-high strain rates by proper extrapolation with Taylor impact tests

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ABSTRACT

This paper is to provide a novel systematic procedure to obtain the dynamic flow stress of a material at ultra-high strain rates ranging from 10^4 s^{-1} to 10^6 s^{-1} where hardening behaviors are difficult to acquire from conventional experiments. Uniaxial material tests with AISI 4340 steel are performed at a wide range of strain rates from 10^{-3} s^{-1} to 10^3 s^{-1} by using the INSTRON 5583, a high-speed material testing machine (HSMTM), and a tension split Hopkinson pressure bar (SHPB) testing machine. From the uniaxial tests above, stress–strain curves are obtained at the strain rates ranging from 10^{-3} s^{-1} to 10^3 s^{-1}. However, stress–strain curves cannot be obtained at the strain rates higher than 10^4 s^{-1} due to the lack in experimental techniques. In order to characterize hardening behaviors at strain rates ranging from 10^4 s^{-1} to 10^6 s^{-1}, Taylor impact tests are performed when the speed of a projectile is 200 m/s, 253 m/s, and 305 m/s, which entail ultra-high strain rates, high temperature, and large plastic deformation. Flow stresses at the ultra-high strain rates are characterized through an inverse optimization process by comparing the numerical simulation results with the experimental results of the sequentially deformed shapes of a projectile during the Taylor impact test. The thermal softening effect at different strain rates is also considered due to the elevated temperature caused by large plastic deformation. The flow stresses calibrated by the comparison are implemented to numerical simulation resulting in a good coincidence with the Taylor impact tests at different impact velocities. It is noted from the comparison that the yield stress and the comprehensive hardening curves proposed well describe the deformation behavior up to the strain rate of 10^6 s^{-1} beyond the strain rate range for conventional material testing.

1. Introduction

Dynamic plastic deformation at the ultra-high strain rates from 10^4 s^{-1} to 10^6 s^{-1} is important in the defense industrial applications such as explosions, ballistic impacts, and armor crashworthiness tests. The importance of accurate numerical simulations has gained more attention in designing effective structures that can support high dynamic loads. For such numerical simulations, the dynamic hardening model and material hardening behaviors at the ultra-high strain rates become indispensable to investigate for a complete understanding of dynamic plastic deformation.

Hardening characteristics of metals under static loading conditions are remarkably different from those under dynamic loading conditions. Static and dynamic loading effects can be addressed by the strain rates, which can be characterized into: quasi-static; low; intermediate; high; and ultra-high strain rate regions as shown in Fig. 1. Dynamic hardening models have been developed by many researchers to describe stress–strain relation at different strain rates and temperatures. 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], and the Lim–Huh model [7].

Several different types of experiments need to be conducted to obtain material hardening behavior at a wide range of strain rates. A universal testing machine of the INSTRON 5583 can perform tensile tests at the quasi-static state and low strain rates. Huh et al. [8] obtained stress–strain relations at the intermediate strain rates by using a servo-hydraulic type high-speed material testing machine (HSMTM). Kolsky [9] performed split Hopkinson pressure bar (SHPB) tests to identify flow stresses at the high strain rates. Huh et al. [10] also developed a tension split Hopkinson pressure bar testing machine for investigating dynamic behavior of metals at high strain rates using plate type specimens. In addition, the expanding ring test [11] and the drop weight test [12] can be utilized to determine hardening behaviors of materials at the high strain rates with large strain. However, it is difficult to obtain stress–strain curves at the ultra-high strain rates

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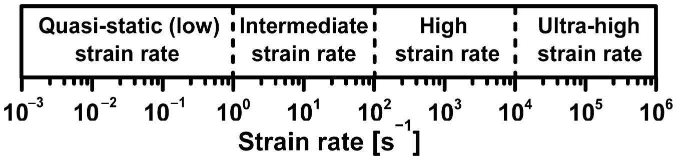

Fig. 1. Characterization of strain rates.

due to the lack in experimental techniques. One method to obtain hardening behaviors at the ultra-high strain rates is to extrapolate stress–strain curves from conventional experimental results by using proper dynamic hardening models. Numerical simulations with the extrapolated stress–strain curves, however, show a large deviation from experimental results of Taylor impact tests.

This paper focuses on the accurate characterization of hardening behaviors at a wide range of strain rates from 10^{-3} s^{-1} to 10^{6} s^{-1}, especially at strain rates ranging from 10^{4} s^{-1} to 10^{6} s^{-1}. Uniaxial material tests are carried out in advance at strain rates ranging from 10^{-3} s^{-1} to 10^{3} s^{-1} by using the INSTRON 5583, the HSMTM, and the SHPB testing machine. In order to precisely characterize hardening behavior at the ultra-high strain rates, temperature elevation during plastic deformation should be considered. The deformation heating effect at different strain rates is evaluated by performing several static and dynamic tensile tests at different temperatures. Furthermore, an inverse optimization method is performed by minimizing the sequentially deformed shapes from the Taylor impact tests and numerical simulation results including the deformation heating effect. Several sequentially deformed shapes of a projectile are considered in the inverse optimization procedures to take into account different strain rate and large strain status during the deformation process. Finally, the comprehensive yield stresses and hardening behaviors are obtained from the low strain rates to the ultra-high strain rates by performing a proper inverse optimization method.

Table 1
Chemical composition of the AISI 4340 steel, in wt %.

Carbon	Manganese	Nickel	Chromium	Silicon	Molybdenum
0.4	0.73	1.69	0.79	0.22	0.21

2. Experiments for obtaining hardening behaviors from low to ultra-high strain rates

In order to accurately evaluate and characterize hardening behaviors at the ultra-high strain rates, it is necessary to primarily perform several Taylor impact tests at different impact velocities. In addition, flow stresses at strain rates ranging from 10^{-3} s^{-1} to 10^{3} s^{-1} are obtained by performing the uniaxial tensile tests and the SHPB tests. The uniaxial tensile tests at different temperatures are also essential to consider the deformation heating effect.

2.1. Material and specimen preparation

AISI 4340 steel has been selected as a test material because it is one of the most popular low carbon alloys and high tensile strength steels. AISI 4340 steel has a BCC crystal lattice structure and is generally utilized in aircraft, automotive, and general engineering industries. The chemical compositions of AISI 4340 steel are shown in Table 1. The AISI 4340 steel is in the form of a hot–rolled bar with 25.4 mm diameter.

The INSTRON 5583 and the HSMTM specimens have the gauge length of 20 mm with the diameter of 4 mm [13]. In order to minimize the inertia effect, the specimens have a long grip region at one end to seize the specimen at the target crosshead speed. At the high strain rates of 10^{3} s^{-1}, the tension SHPB tests are conducted with a plate type specimen. Huh et al. [10] also tested different length of gauge section from 2 mm to 24 mm and concluded that a gauge length between 2 mm and 6 mm was acceptable; therefore, the gauge length of 6 mm is chosen for the plate type specimens. The specific dimensions of tensile test specimens are shown in Fig. 2. The Taylor

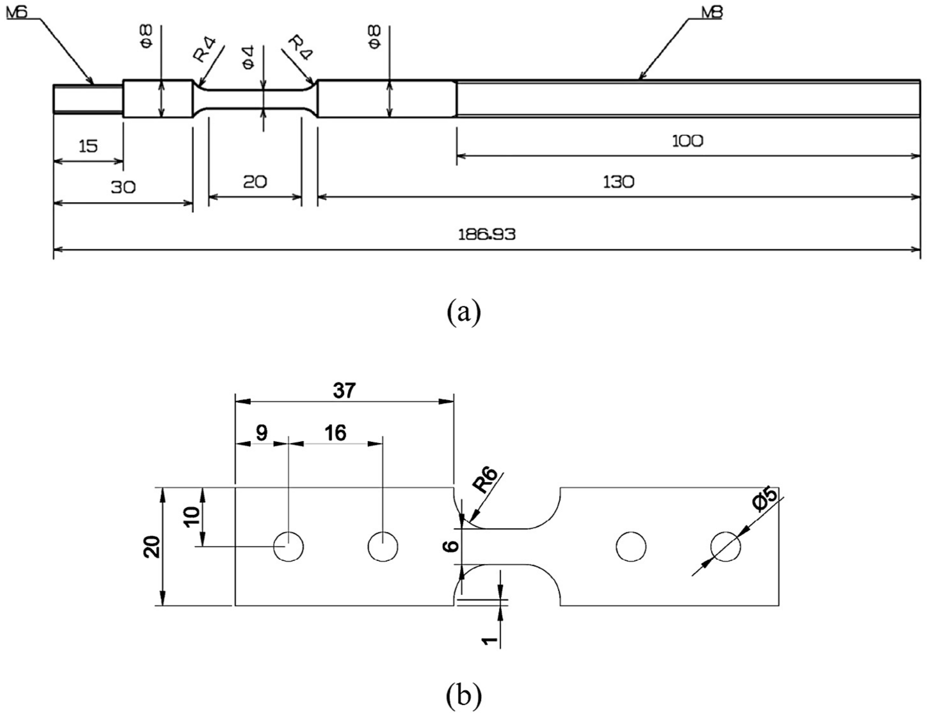

Fig. 2. Dimension of specimens for: (a) uniaxial tensile tests; and (b) tension SHPB tests.