SAND2006-1627C

Determination of Early Flow Stress in Ductile Specimens Using SHPB

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ABSTRACT

In a Hopkinson bar experiment to obtain the high-rate stress-strain response of a ductile specimen, it takes a finite amount of time for the strain rate in the specimen to increase from zero to a desired level. If the strain rate is high, the specimen may yield before the desired rate is attained. In this case, the strain rates at yielding and early plastic flow are lower than the desired value, leading to inaccurate determination of the yield strength and early flow stress. We experimentally examined the validity and accuracy of the flow stresses for ductile materials in a Hopkinson bar experiment. The upper strain-rate limit in determining the yield strength and early flow stress for ductile materials is identified.

INTRODUCTION

Split Hopkinson pressure bar (SHPB) has been extensively used to determine dynamic compressive stress-strain responses of engineering materials including ductile materials at high strain rates. To obtain a family of dynamic stress-strain curves as a function of strain rate with the SHPB, the strain rate in specimen needs to be maintained constant in each experiment, which has been achieved by using pulse shaping technique in a SHPB experiment [1, 2]. However, it takes time for the strain rate in the specimen to increase from zero to the constant level. A rapid increase in strain rates over this initial period of time may generate significant amount of strain in the specimen before it deforms at a constant rate [4]. It is therefore possible that the specimen yields plastically before a constant strain rate is reached due to the small yield strains (~1-2%) in most metallic materials. In this case, interpreting the obtained yield strength and early flow stress as a function of the strain rate eventually achieved at large strains is not acceptable, especially for rate sensitive materials. In hence, it is necessary to examine in detail the conditions under which the dynamic yielding and flow behaviors are obtained.

DYNAMIC EXPERIMENTS WITH A PULSE-SHAPED SHPB

Dynamic compression experiments on a HP9-4-20 (9Ni-4Co-0.20C) steel were conducted with a SHPB modified with double pulse shapers [1, 2]. The pulse shapers employed in this research consist of a partially annealed C11000 copper disk and an M2 steel cylinder. This double pulse shaping design facilitates the high-strength ductile specimen to deform at nearly constant strain rates under dynamically equilibrated stresses [1, 2]. The specimens for dynamic testing were made into cylinders with 6.35 mm in diameter and 3.175 mm long.

By using the double pulse-shaping technique, the profiles of incident pulse were modified to ensure constant strain rate testing conditions under dynamic stress equilibrium [1, 2]. Figure 1 shows the strain-rate and stress histories in the specimens deformed at the strain rates of 1300 and 4900 s^{-1}. An examination of Fig. 1 indicates that it took approximately 40 and 60 μs for the strain rates to increase from zero to the constant strain rates of 1300 and 4900 s^{-1}, respectively. The strain rates cannot be considered constants before 40 μs for 1300 s^{-1} and 60 μs for 4900 s^{-1}, respectively. Figure 1 also indicates that the specimen has been in plastic deformation within the first 60 μs at 4900 s^{-1}; whereas, the specimen compressed at 1300 s^{-1} was still in elastic deformation in the first 40 μs. Therefore, the yield strength and early flow stress measured in the first 60 μs were not obtained at the claimed constant strain rate of 4900 s^{-1}. By contrast, the strain rate has been achieved to a constant value of 1300 s^{-1} before yielding in the experiment at the lower strain rate (1300 s^{-1}) such that the yield strength and early flow stress are determined reliably for this strain-rate testing.

Figure 2 shows the resultant stress-strain curves obtained at the strain rates of 1300 and 4900 s^{-1}. It is noted that only the portions beyond 1.0% strain (corresponding to the time of 40 μs) in the stress-strain curve of 1300 s^{-1} and beyond 7.0% strain (corresponding to the time of 60 μs) in the stress-strain curve of 4900 s^{-1} were obtained at constant strain rates. As a result, a lower early flow stress, as circled in Fig. 2, as compared to the flow stresses at 4900 s^{-1} (as indicated with the red dotted line in Fig. 2), was measured during the experiment due to the low initial strain rates; whereas, no such low early flow stress was observed in the stress-strain curve obtained at the constant plastic strain-rate of 1300 s^{-1}. Therefore, one cannot define the strain rate at yielding to be 4900 s^{-1} because the yielding behavior does not represent the actual response of the material at the strain rate of 4900 s^{-1}. It will be erroneous if the yield strength or flow stress before 7.0% is used as the value obtained at 4900 s^{-1} to study strain-rate effects. Therefore, when the SHPB is used for testing ductile materials at very high strain rates, the validity of yield strength and early flow stress need to be carefully examined. This phenomenon cannot be experimentally avoided. There exists an upper strain-rate limit to obtain reliable yield strength and early plastic flow stress.

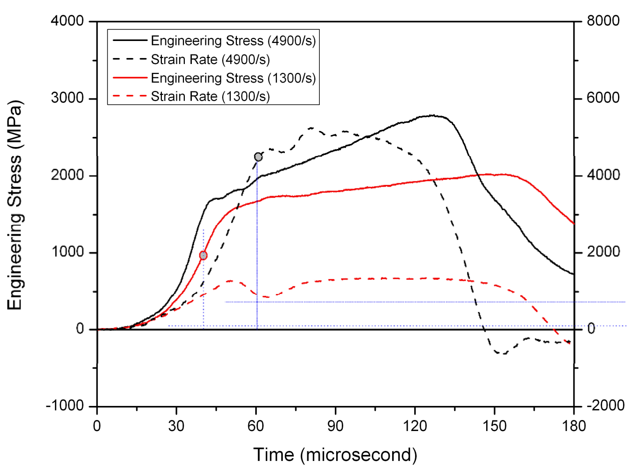

Fig. 1. Strain-rate and stress histories.

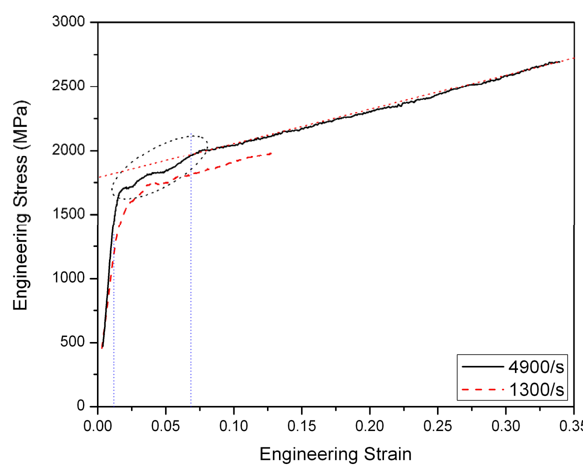

Fig. 2. Engineering stress-strain curves.

Pan et al. [3] studied the upper limit of constant strain rate in a Hopkinson bar experiment on brittle materials. Their conclusion can also be used to estimate the upper limit of constant strain rate when using a Hopkinson bar to determine the yield strength of ductile materials,

$$\dot{\varepsilon}_0 \leq 2\frac{\varepsilon_Y}{\tau} \tag{1}$$

where ε_Y is the yield strain; τ is the rise time from zero to a constant value in strain rate history. In a typical conventional SHPB experiment, the rise time in the incident pulse is approximately 10 μs ($\tau = 10\mu s$), which produces a reflected signal (or strain-rate history) with a rise time longer than 10 μs. In this research, we use $\sigma_{0.2} = 1600MPa$ as the average yield strength. The yield strain (ε_y) for the materials is, $\varepsilon_y = 0.2\% + \sigma_{0.2}/E = 1\%$, on basis of elastic modulus of 200 GPa. According to Eq. (1), the upper strain-rate limit is estimated to be $\dot{\varepsilon}_{0c} = 2\varepsilon_Y/\tau = 2000s^{-1}$. This means that it is not feasible to obtain yield strength at the strain rates above 2000 s^{-1} for this material. Thus, when the SHPB (with or without pulse shaping) is used for characterizing ductile materials at very high strain rates, the validity of yield strength and early flow stress should be carefully examined.

CONCLUSIONS

We conducted dynamic experiments on a high-strength steel alloy at high strain rates with a pulse-shaping split Hopkinson pressure bar, and examined the validity of dynamic yield strength results at various high strain rates. It is experimentally proven that the specimen yields before the strain rate reaches the desired constant value during high-rate experiments. In such experiments, the strain rates corresponding to plastic yielding and early plastic flow are lower than the desired constant value, leading to significant errors in the results for strain-rate sensitive materials. The upper strain-rate limit for obtaining reliable yield strength at high strain rates was also estimated.

ACKNOWLEDGEMENTS

This work was supported by Sandia National Laboratories, Albuquerque, NM and Livermore, CA. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL8500.

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