Numerical Simulation and Experiments for Dynamic Material Properties of Aluminium Alloy in SHPB Experiment using Pulse Shaping Method

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Abstract

For the analysis of high speed forming such as electromagnetic forming and electrohydraulic forming, dynamic material properties are required. The split Hopkinson pressure bar (Kolsky bar) was suggested for measuring dynamic material properties from 100 to 10000 /sec strain rate. In the SHPB experiments, the assumption is needed that specimen between incident bar and transmitted bar reaches the dynamic stress equilibrium. For the derivation of average engineering strain and average engineering stress in SHPB experiments, the stress wave at the front and the back of specimen should match each other.

A pulse shaping method helps to improve the stress equilibrium of specimen. As one of the various pulse shaping methods, a method of attaching a pulse shaper in front of incident bar was carried out.

Numerical simulation and SHPB experiments was performed for verification about pulse shaper effect. The result of experiments and numerical analysis show that the pulse shaper contributes to the dynamic stress equilibrium. The dynamic material properties of Al6061-T6 were obtained, and the simulation was implemented by inputting that properties. As a result of comparing the experiments with new simulation, it was confirmed that the error of specimen length was within 5%.

Keywords

Dynamic material properties, Split Hopkinson pressure bar, Dynamic stress equilibrium, Pulse shaping method

1 Introduction

In the high-tech industries such as automobiles and aerospace, advanced forming process is required for improving productivity of car body and fuselage. High speed forming was introduced because of rapid forming and good formability of the sheet or bulk workpiece for parts in high strain rate condition (M. Seth, 2005). Commonly, mechanical properties of metal alloy show different behaviour between Quasi-static test and dynamic test. For accurate numerical simulation of high speed forming, dynamic material properties are needed. In 1949, Kolsky introduced a method that could be acquired to dynamic mechanical properties based on stress wave propagation theory (H. Kolsky, 1963). The conventional split Hopkinson pressure bar (SHPB) experiment is a method for obtaining dynamic material properties by analysing the elastic wave which is generated by impact between pressure bars.

In the SHPB experiments, the equations regarding the average engineering strain rate and the average engineering stress are derived assuming that the specimen is satisfied with the dynamic stress equilibrium (W. N. Sharpe, Jr., 2008). In the conventional SHPB experiments, dynamic stress equilibrium is difficult to achieve because the dynamic stress wave oscillates large so that the strain rate of specimen is not constant. To solve these problems, the various pulse shaping methods were suggested. The pulse shaping methods helps the specimen to control stress wave shape and characteristic. Among the many pulse shaping methods, attaching soft material like copper in front of the incident bar was used because of convenience.

For verifying effects of the pulse shaper, the numerical simulation using commercial finite element analysis program LS-DYNA explicit was performed. The result of finite element method was that pulse shaper affects the dynamic stress equilibrium of the specimen. In addition, SHPB test were performed to demonstrate stress equilibrium about copper specimen. The result of SHPB test and numerical analysis show that the pulse shaper contributes to the dynamic stress equilibrium.

Based on the improved stress equilibrium of the specimen using a pulse shaper, we conducted SHPB test with pulse shaper for acquiring the flow stress curves about Al6061-T6 materials. We implemented the new numerical simulation by inputting the material properties of aluminum alloy using pulse shaper. As a result of comparing new numerical simulation and SHPB test, we confirmed that the strain of aluminum alloy specimen is similar.

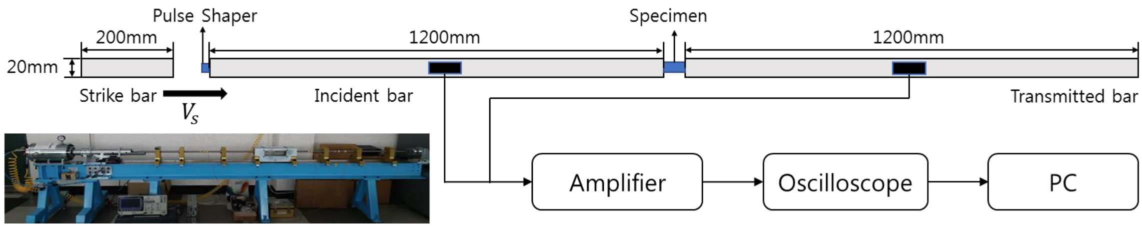


***Figure 1**: Schematic diagram of SHPB experiments and apparatus in PNU*

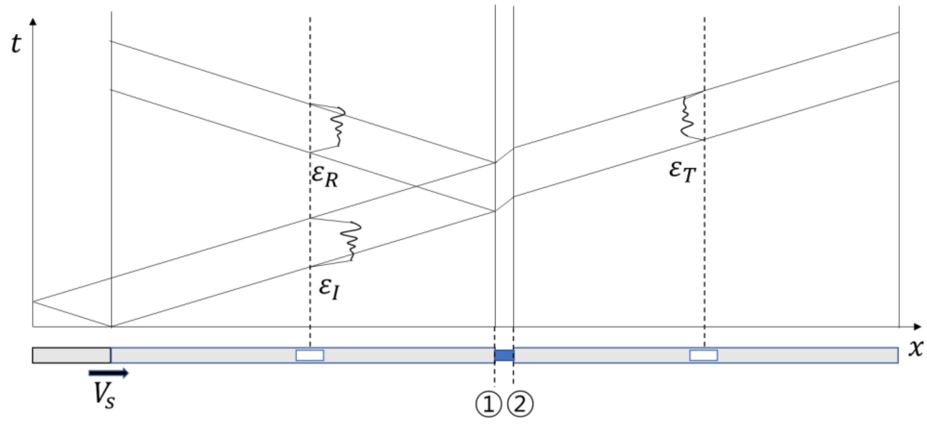


Figure 2*: Location of stress wave along time in SHPB test*

2 SHPB experiments

2.1 SHPB theory

Fig. 1 shows the schematic of SHPB and SHPB apparatus in Pusan national university. The SHPB apparatus in PNU is compressive type, therefore it is composed of the incident bar, the transmitted bar, and strike bar. The guide devices are designed for straightness of pressure bars to satisfy 1-dimension translational motion. In each guide devices, ball bearing is included to minimize friction about 1-D motion.

Using the gas launcher system by applying air pressure, the strike bar is accelerated. When the strike bar reaches a certain velocity, it impacts on the incident bar. Due to the impact between the incident bar and the strike bar, the elastic wave propagates along pressure bars. The stress wave is transferred to the incident bar, specimen, the transmitted bar in sequence, and it deform pressure bars and specimen. The incident bar and transmitted bar are subjected to elastic deformation due to high tensile strength, whereas the specimen has relatively low strength so that it occurs plastic deformation. Because of the difference of impedance between the specimen and the incident bar, some of the stress waves are reflected and some are transmitted. The dynamic material properties of specimen can be obtained by analysing the axial strain due to the stress wave of the reflected wave and the transmitted wave.

The stress equations at the front of specimen (between the incident bar and the specimen, Fig. 2 a) and the back of specimen (between the specimen and the transmitted bar, Fig. 2 b) are shown below respectively.

$$\sigma_1 = E_b \frac{A_b}{A_s}(\varepsilon_I + \varepsilon_R) \tag{1}$$

$$\sigma_2 = E_b \frac{A_b}{A_s}\varepsilon_T \tag{2}$$

In equation (1) and (2), E_b, A_b, A_s are elastic modulus of pressure bars, cross-section area of pressure bars and specimen, respectively. ε_I, ε_R, ε_T are strain by stress wave in incident wave, reflected wave, and transmitted wave. Eq. 1 and 2 are equal when the stress equilibrium is achieved in specimen. If the specimen is satisfied with dynamic stress equilibrium, the sum of the incident wave and the reflected wave is equal to the transmitted wave. The equations of average engineering strain rate of specimen and average engineering stress are derived from the assumption that is stress equilibrium. Therefore, in order to accurately measure the dynamic material properties of the specimen in SHPB experiments, the stress equilibrium inside the specimen should be achieved.

2.2 Pulse shaping methods

Commonly, the shape of stress wave when the strike bar impacts the incident bar is trapezium. As mentioned in the introduction, a pulse shaping method helps control the stress wave profile. Also, a pulse shaping method helps to match the front stress wave and back stress wave of the specimen.

Among the various pulse shaping methods, there is a method of controlling a stress wave by attaching a thin disk made of ductile material such as copper in front of the incident bar. When the strike bar impact on the incident bar with the pulse shaper attached, a pulse shaper is plastically deformed due to the impact, a stress wave is also controlled. A constant strain rate can be obtained through stress wave control.

3 Numerical simulation and experiments of SHPB

3.1 Numerical simulation using LS-DYNA

To confirm the effect of the pulse shaper on the stress wave, the finite element analysis tool, LS-DYNA explicit was used. Fig. 3 shows the model of SHPB experiments with pulse shaper and without pulse shaper, respectively. The specimen is cylindrical, diameter and thickness are 10mm each other. The specifications of pressure bars are shown in Fig. 1. The velocity of strike bar was set 24m/s, which is the velocity when the pressure of 2 bar (0.2 MPa) was inputted into the gas launcher system. Total analysis time was 1msec.

The material properties of pressure bars and Johnson-Cook constitutive model parameters of specimen and pulse shaper are summarized in Table 1.

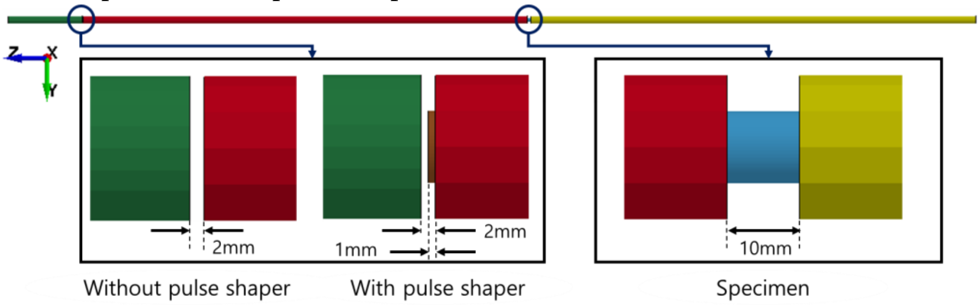


***Figure 3**: The finite element model of SHPB with pulse shaper and without pulse shaper*

Material property	Value	Johnson-Cook parameters	Value
Elastic modulus	196 GPa	A	90 MPa
Yield strength	1.55 GPa	B	292 MPa
Density	7850 kg/m^3	C	0.025
Poisson's ratio	0.3	n	0.31

***Table 1:** Material properties of pressure bars and Johnson-Cook constitutive model parameters of copper (G. R. Johnson, 1985)*

Johnson-Cook constitutive model includes terms for temperature and strain rate hardening. But in this analysis, Because the temperature was not considered, the following equation 3 was used.

$$\sigma = (A + B\varepsilon^n)\left\{1 + C\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)\right\} \tag{3}$$

Where A and B are the work hardening parameters, n is the work hardening exponent constant. And C is the strain rate hardening parameter. The reference strain rate of copper specimen in Table 1 is 1 /sec (G. R. Johnson, 1985). Generally, a static tensile or compressive test rate value (approximately 2 mm/min) is used as a reference strain rate. In this study, however, the reference strain rate value given in the reference was used.

3.2 SHPB experiments

The SHPB experiments were carried out to confirm the effect of stress wave control. The identical experiment conditions as the numerical simulation (the specifications of pressure bar, a pulse shaper, the specimen) were given. Fig. 4 shows schematic experiments with pulse shaper and without pulse shaper. The velocity of the strike bar also was set by inputting 2 bar into the gas launcher system as in the analysis. The strike bar velocity was measured by a photo-gate system using laser sensor. At the centre of each pressure bars, strain gauges were attached for measuring elastic stress wave. The specimen was Al6061-T6 material.

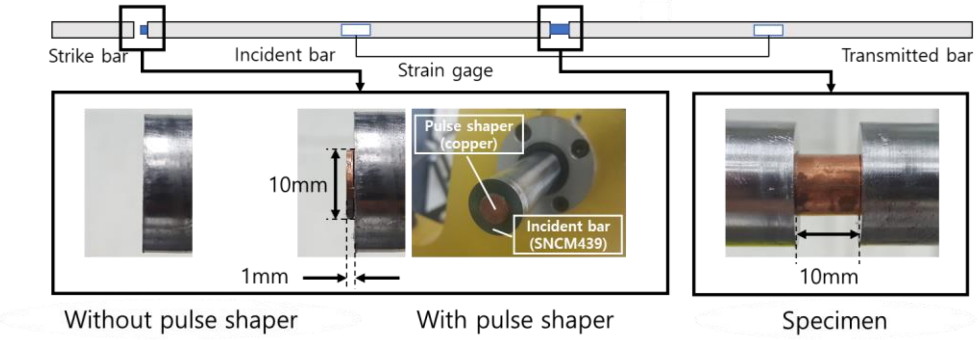


***Figure 4**: The SHPB experiments with pulse shaper and without pulse shaper*

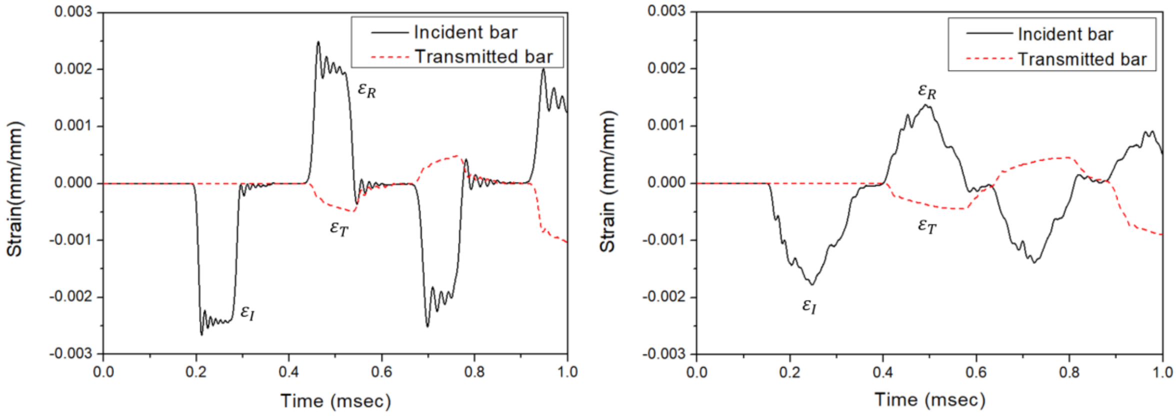


***Figure 5**: Strain data at centre of pressure bars by impact in numerical simulation about copper specimen (Left: without pulse shaper, Right: with pulse shaper)*

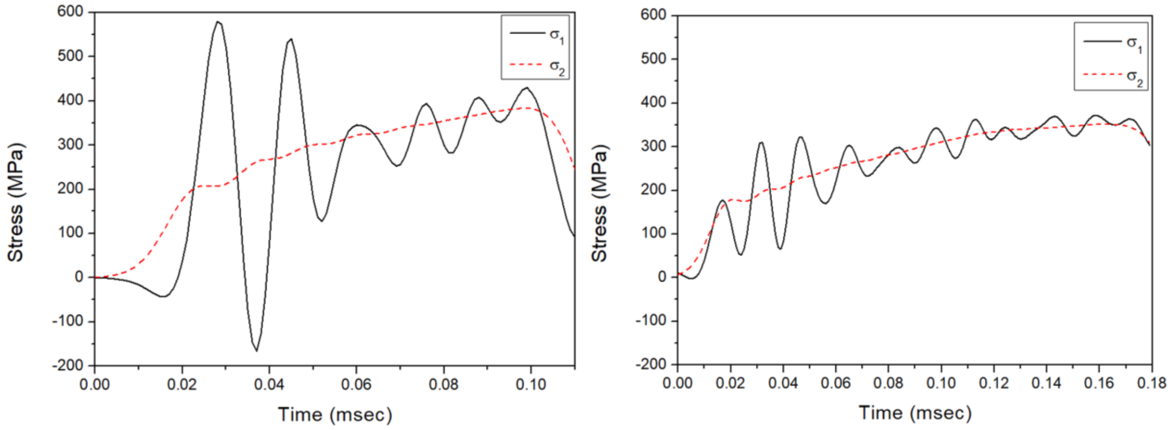


***Figure 6**: Stress wave comparison in numerical simulation about copper specimen (Left: without pulse shaper, Right: with pulse shaper)*

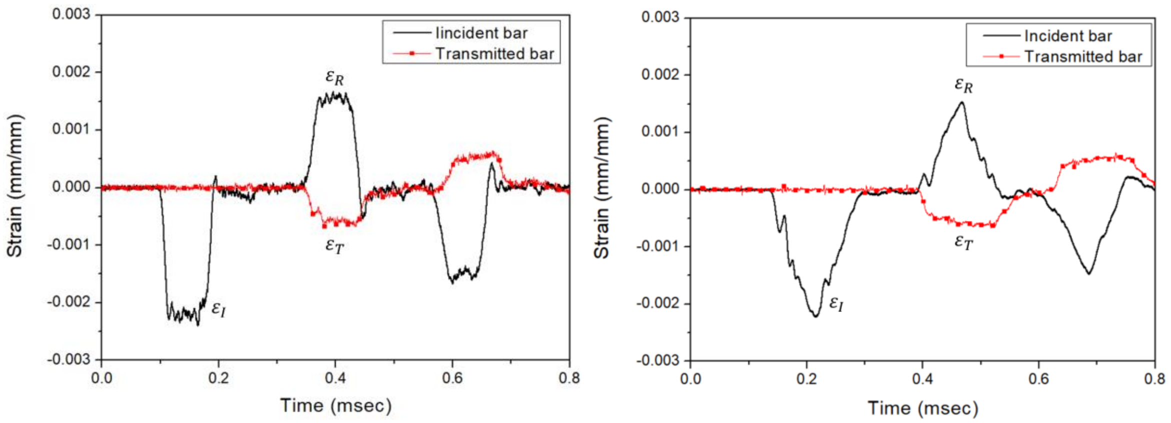
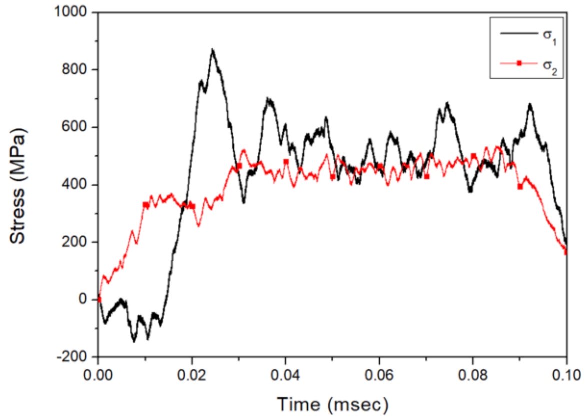


***Figure 7**: Strain data at centre of pressure bars by impact in experiments about Al6061-T6 specimen (Left: without pulse shaper, Right: with pulse shaper)*



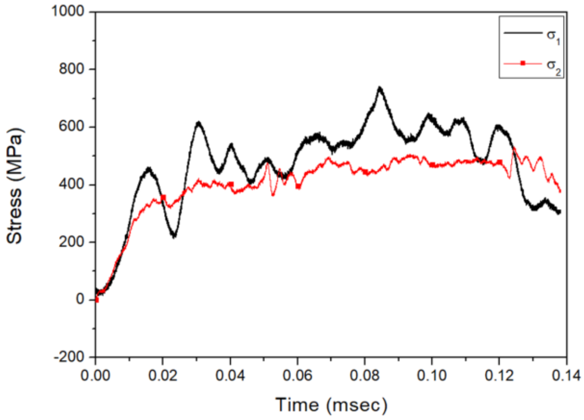


Figure 8*: Stress wave comparison in experiments about Al6061-T6 specimen (Left: without pulse shaper, Right: with pulse shaper)*

3.3 Results of simulation and experiments

First, the elastic strain was confirmed at the centre of the pressure bars to check the incident wave, the transmitted wave, and the reflected wave. Fig. 5 shows the results of the numerical analysis of the elastic strain at the centre in the incident bar and the transmitted bar. When comparing the left and right figure, the shape of the elastic waves was clearly different. The duration time of elastic wave using pulse shaper was longer than when it was not used. Fig. 6 shows the stress wave at the front of specimen and the back of specimen. In case of using pulse shaper, the difference between σ_1 and σ_2 is smaller. Namely, using a pulse shaper helps to match two stress waves. Thus, a pulse shaper contributed to equilibrium of the specimen.

Fig. 7 shows the results of the experiments of the strain in the incident bar and transmitted bar. Similar to the analytical results, the shape of the elastic stress wave changed from trapezoidal to triangular. A pulse shaper controlled the wave shape, duration time, and peak value. Fig. 8 shows the front and back stress waves based on the experimental results. Unlike the analysis results, it can be seen that the difference between the two stress waves with pulse shaper and without pulse shaper is not clear. Therefore, the RMSE(root mean square error) value was used to quantitatively confirm the difference between σ_1 and σ_2. The RMSE values with pulse shaper and without pulse shaper were 109.86 and 194.92, respectively. As the RMSE is smaller, it means that the difference of data is smaller. It was confirmed that when the pulse shaper is used, it becomes close to the stress equilibrium of the specimen.

In order to confirm the accuracy of the numerical simulation, the comparison between the results of SHPB experiments and the numerical simulation of SHPB was carried out. Table 2 summarizes the Johnson-Cook model parameters of Al6061-T6. The Johnson-Cook parameters in Table 2 were derived from experimental results using a pulse shaper. The value of A, B, and n were obtained from quasi-static tensile test, and the strain rate sensitivity factor C, was derived using curve fitting. Table 3 shows the length of specimen and error value about length of specimen between experiments and simulation.

Johnson-Cook parameters	Al6061-T6	Copper
A	258 MPa	90 MPa
B	375.5 MPa	292 MPa
C	0.0195	0.025
n	0.565	0.31

Table 2: *Johnson-Cook constitutive model parameters for comparison of results between experiments and numerical simulation*

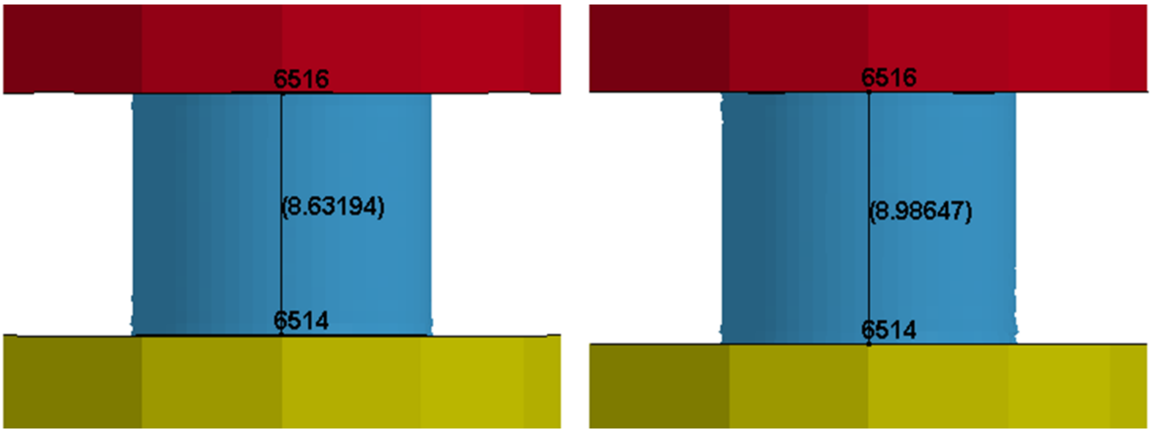


Figure 9*: Length of specimen in numerical simulation (Left: without pulse shaper, Right: with pulse shaper)*

Length of specimen	Without pulse shaper	With pulse shaper
Simulation (mm)	8.63	8.99
Experiments (mm)	8.00	8.65
Error ($\frac{L_{exp} - L_{sim}}{L_{exp}} \times 100$, %)	7.875	3.931

Table 3: *The comparison of specimen length without pulse shaper and with pulse shaper*

Fig. 9 shows the length of specimen with pulse shaper and without pulse shaper. As a result of comparing the specimen length errors obtained from the experiment and analysis, it was confirmed that the error was small when the pulse shaper was used.

4 Conclusion

In this study, the effect of a pulse shaper on the stress equilibrium of the specimen was confirmed. Finite element analysis and experimental results show that the stress on the front and back of the specimen are similar when a pulse shaper was used. As the stress equilibrium was achieved, it was verified that the accuracy of specimen in the numerical analysis was improved.
However, it is still necessary to modify the parameters of Johnson-Cook constitutive equation because of error in the specimen length between the analysis and experiment. In addition, the strain rate of the specimen was not constant, so the material properties at a

specific strain rate could not be measured accurately. In the future study, it is expected that more accurate dynamic properties will be obtained by changing the specification of a pulse shaper or the method for pulse control not only stress equilibrium but also a constant strain rate.

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