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Dynamic deformation of hot temperature degraded POM and PP using a modified SHPB with pulse shaper technique

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Abstract

The conventional split Hopkinson pressure bar (C-SHPB) technique with a special experimental apparatus is used to obtain a dynamic deformation material behavior under a high strain rate loading condition. An experimental modification is introduced to reduce the non-equilibrium on the dynamic material response during a short test period for two polymeric materials. The proposed method uses aluminum pressure bars to achieve a closer impedance match between the pressure bars and the specimen materials such as hot temperature degraded POM (Poly Oxy Methylene) and PP (Poly Propylene) to obtain more distinguishable experimental signals. In addition, a pulse shaper technique is used for increasing the rise time of the incident pulse to ensure the dynamic stress equilibrium and the homogeneous deformation in the specimen under dynamic compression loading condition. The details on the dynamic stress equilibrium and the duration of uniform strain rate during the dynamic deformation of the specimen are experimentally investigated. The effects of degradation at a few different hot temperatures on the maximum compressive stresses are also experimentally studied under varying impulsive loading conditions.

Keywords: C-SHPB (Conventional split hopkinson pressure bar); Dynamic deformation; High strain rate; Pulse shaper; Polymeric materials; Hot temperature degraded; POM (Poly oxy methylene); PP (Poly propylene)

1. Introduction

Some polymeric materials with low strength, low wave propagation velocity and low mechanical impedance are used under the dynamic loading condition in a variety of important applications such as aircraft and automotive components. And the manufacturing processes of some polymeric materials include the high strain rate extrusion and blow moulding. In order to obtain the dynamic material characteristics for such polymeric materials, a thorough understanding on the dynamic mechanical deformation response is needed in detail. However, it is not easy to get accurate dynamic mechanical properties under the high strain rate loading condition.

The conventional split Hopkinson pressure bar (C-SHPB) is the most widely used experimental method for investigating the dynamic deformation behavior of high strength materials in the range of strain rate of 10^2/s~10^4/s [1]. The C-SHPB technique has been continually modified by the author and others to obtain more accurate dynamic properties of a variety of engineering materials such as metals, concrete, ceramic and polymeric and rubbers [2-4]. Especially for the polymers and polymeric composite materials, it has been noted that serious experimental problems occur from the mismatch of mechanical impedance between the specimen and bar materials. These problems include an unacceptable high noise to signal and an impedance mismatch between the soft material specimen and the steel pressure bar. And it is also

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noted that we need to check the dynamic stress equilibrium between the front and rear of the specimen to obtain valid experimental results on soft specimens in the SHPB technique. The specimen also needs to be deformed at a nearly constant strain rate during a dynamic experiment to provide more reliable experimental data [5, 6].

In this paper, the C-SHPB technique has been modified to obtain more accurate dynamic compressive stress-strain data for the hot temperature degraded POM (Poly Oxy Methylene, the static tensile yield stress is 37-120 MPa) and PP (Poly Propylene, the static tensile yield stress is 10-34 MPa) specimens under varying strain rate conditions. A modified SHPB technique uses an aluminum bar set-up and the pulse shaper technique to achieve constant strain rates in the specimen during a modified SHPB experiment.

2. Theory of C-SHPB technique

The C-SHPB technique consists of a striker bar, an incident bar, a transmitted bar, and a specimen placed between the incident and the transmitted bars. The elastic compressive wave arisen in the incident bar by the striker travels through the incident bar, the specimen and the transmitted bar. Some of the incident elastic compressive wave reflects from the bar-specimen interface because of the material impedance mismatch. The transmitted pulse through the specimen travels along the transmitted bar until it hits the end of the bar. A strain gage mounted on the incident bar measures the incident pulse (ε_i) and reflected pulse (ε_r), and a strain gage mounted on the transmitted bar measures the transmitted pulse (ε_t).

Referring to the conventional analysis based on the mechanics of the elastic wave propagation in bars, the stress, strain, and strain rate in the specimen can be obtained as follows.

$$\sigma_{specimen} = E\frac{A}{A_s}\varepsilon_t \tag{1}$$

$$\varepsilon_{specimen} = -2\frac{C_0}{L}\int \varepsilon_r dt \tag{2}$$

$$\dot{\varepsilon}_{specimen} = -2\frac{C_O}{L}\varepsilon_r(t) \tag{3}$$

Where, L is the initial length of the specimen, C_0 is the bar wave propagation velocity, A and A_s are the cross sectional area of the pressure bar and specimen, respectively, and E is the Young's modulus of the bar material. Eqs. (1), (2) and (3) are set based on the assumptions that the specimen undergoes homogeneous deformation.

The correction terms due to both longitudinal and radial inertia in the specimen materials have been analyzed as appeared in Eq. (4) [7].

$$\sigma(t) = \sigma_m(t) + \rho_S\left(\frac{L^2}{6} - \nu_S\frac{D^2}{8}\right)\frac{\delta^2\varepsilon(t)}{\delta t^2} \tag{4}$$

Where, σ_m is the measured stress, ρ_S is the density of the specimen, ν_S is Poisson's ratio of the specimen, L is the specimen length and D is the specimen diameter. Following Eq. (4), we can minimize the correction terms by keeping the strain rate constant or the term inside of the parenthesis zero by making specimen geometry such that

$$\frac{L}{D} = \sqrt{\frac{3\nu_S}{4}} \tag{5}$$

From Eq. (4), the L/D ratio of the specimen should be chosen by Eq. (5) to remove the inertia effect in the specimen. In this paper, we chose a cylindrical specimen with a length of 5 mm and a diameter of 10 mm.

3. A modified SHPB technique

The C-SHPB technique is the most widely used method for investigating the dynamic behavior of varying engineering materials. However, the direct application of this technique for testing low impedance materials has serious problems. Overcoming this problem, an aluminum 7075-T6511 (the yield strength is 503 MPa, the modulus of elasticity is 71.7 GPa and the density is 2.81 g/cm^3) pressure bar set-up to test polymeric specimens has been used in this paper. The ratio of the length to the diameter of the bars was designed to be 100 to ensure one-dimensional stress wave propagation in the bars and specimen. Two bars made of the same material of striker bar have the identical diameter (16 mm) with striker bar. The length of the incident, transmitted, and striker bars was 1,600, 1,500 and 300 mm, respectively.

Generally during the period of dynamic loading in the specimen, the stresses at the interface between the

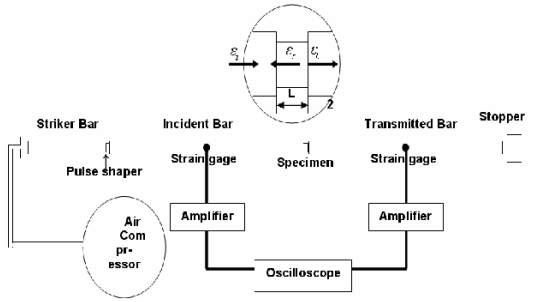


Fig. 1. Schematic of a modified aluminum SHPB apparatus with a pulse shaper for testing polymeric specimens.

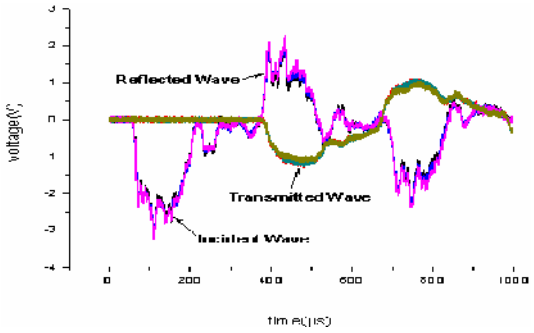
incident bar and the front end of the specimen are different from those at the interface between the transmitted bar and the back end of the specimen. Obtaining valid experimental results on soft specimens in the SHPB experiment, the specimen must deform uniformly under a dynamic stress equilibrium state. Therefore a modification to the C-SHPB experimental equipment with a pulse shaper is used in this paper to obtain a dynamic stress equilibrium state during dynamic deformation of a specimen. Fig. 1 shows a schematic of the modified aluminum SHPB apparatus with a pulse shaper.

It is generally accepted in the C-SHPB experiment that it needs several hundred micro-seconds to reach the stress equilibrium in the specimen. The rise time, t, required for at least three reverberations of the stress pulse within the specimen is estimated for a plastically deformed solid that obeys the Taylor-von Karman theory as follows [5].

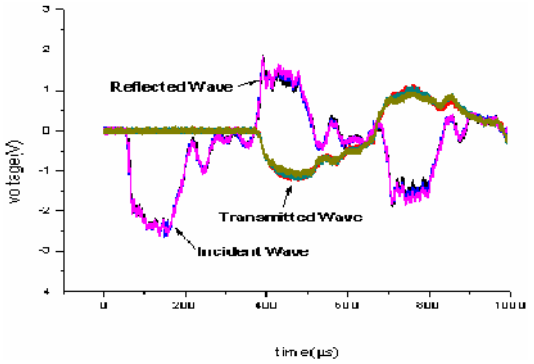
$$t^2 = \frac{\pi^2 \rho_S L^2}{\partial\sigma / \partial\varepsilon} \tag{6}$$

Where, ρ_S is the density of the specimen, L is the specimen length and $\partial\sigma/\partial\varepsilon$ is the work hardening rate of the true stress true strain curve for the material to be tested.

Noting Eq. (6), we can accomplish the equilibrium in a short time by decreasing the specimen length. However, the specimen length may not be decreased without a concomitant decrease in the specimen and bar diameters because of the limit in the range of L/D. The alternative is to increase the specimen rising period, t by adopting an existing pulse shaper technique in which a pulse shaper is attached on the impact side of the incident bar. It helps to achieve an equilibrium stress state in the specimen at the early stage of impact loading [6].



(a) Without pulse shaper (PSX) at 60 kPa



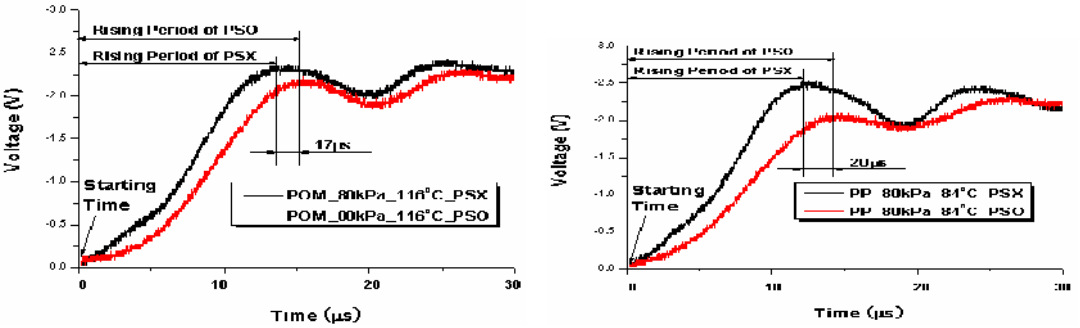
(b) With pulse shaper (PSO) at 60 kPa

Fig. 2. Typical waves in the POM specimen without pulse shaper (PSX) and with pulse shaper (PSO) under 60 kPa impulse pressure, (dimension of pulse shaper; thickness=1.5 mm, dia.=10 mm).

Detailed experimental work is needed to choose the proper material and dimension of the pulse shaper material for a given specimen material. In this experiment, we used a copper (Cu-11000) pulse shaper of a thickness of 1.5 mm and a diameter of 10 mm. This is determined based on our earlier experimental results published in [8, 9].

4. Experimental results and discussions

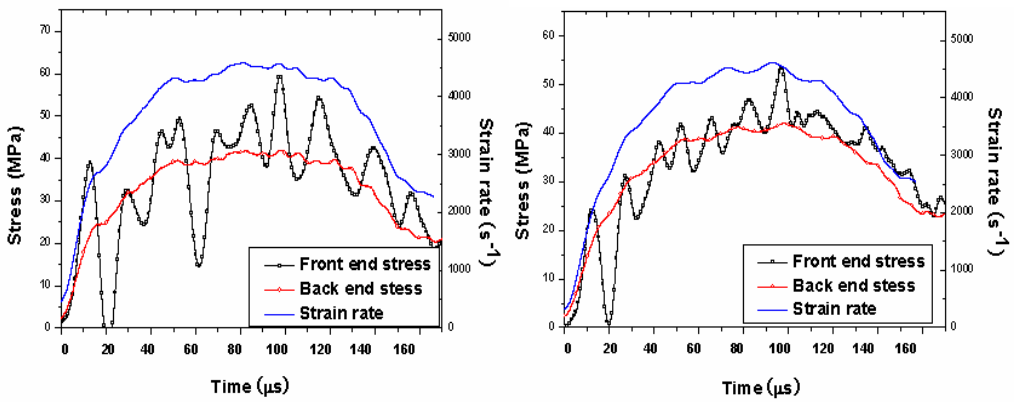
In this study, the aluminum SHPB with a pulse shaper was employed to examine the process of dynamic stress equilibrium for two hot temperature degraded POM and PP specimens during the dynamic deformation period. Fig. 2 shows a typical incident, reflected, and transmitted strain signals from an experiment for POM specimens without a pulse shaper and with a pulse shaper in a modified SHPB experiment under the initial air-gun pressure of 60 kPa impulse loading.



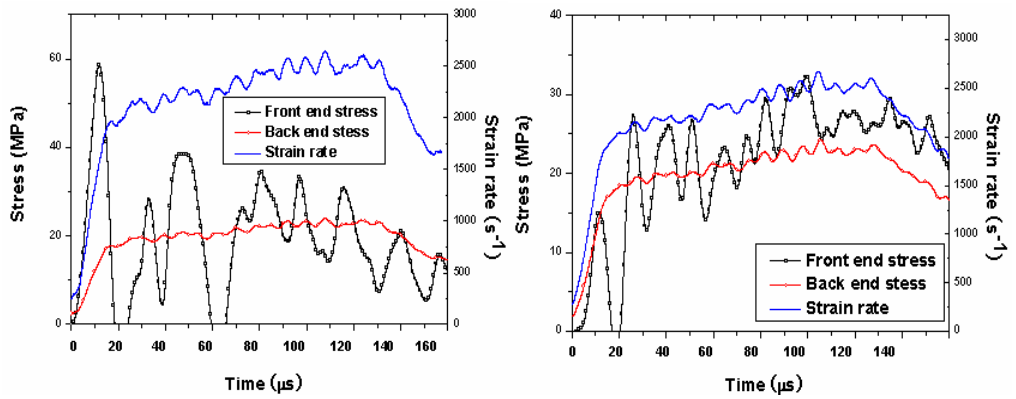
(a) Degradation at 116℃ and experiment with 80 kPa impulse loading (PSX=without pulse shaper, PSO=with pulse shaper))

(b) Degradation at 84℃ and experiment with 80kPa impulse loading (PSX=without pulse shaper, PSO=with pulse shaper)

Fig. 3. Difference in rising periods of the incident waves without pulse shaper and with pulse shaper under 80kPa impulse pressures; (a) POM, degraded at 116℃ for 10 days (b) PP, degraded at 84℃ for 10 days.



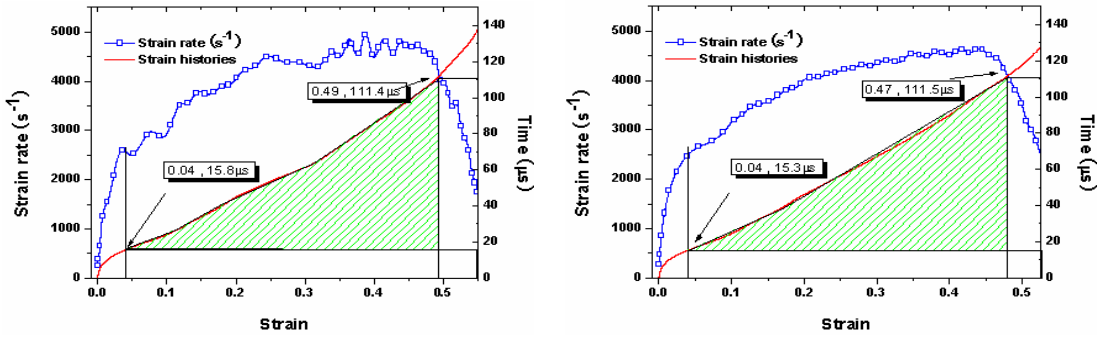
(a) Without pulse shaper and with pulse shaper at 60 kPa, 82.5℃ for 10 days



(b) Without pulse shaper and with pulse shaper at 60 kPa, 60℃ for 10 days

Fig. 4. Comparison of the front end stress to the back end stress; (a) Without pulse shaper and with pulse shaper for POM (60 kPa, 82.5℃ for 10 days) (b) Without pulse shaper and with pulse shaper for PP (60 kPa and 60℃ for 10 days).

It is found from Fig. 2(a) that the shape of the incident pulse shows relatively pronounced fluctuation. And the fluctuation and oscillation at the initial portion of the top duration are modulated significantly due to the pulse shaper as shown in Fig. 2(b). It is recommended that a better dimension and a proper material of a pulse shaper should be determined by taking more experiments to obtain better modulated



(a) Without pulse shaper at 100kPa, 116℃ for 10 days (b) With pulse shaper at 100kPa, 116℃ for 10 days

Fig. 5. A typical strain rate history in POM (a) without pulse shaper (b) with pulse shaper (100kPa and 116℃ for 10 days).

wave signals [10].

Fig. 3 shows typical comparisons of the rising period of the incident wave without a pulse shaper and with a pulse shaper in a modified SHPB experiment for a POM specimen and a PP specimen under two different degraded temperatures and the same dynamic loading pressure.

It is noted in Fig. 3 that the pulse shaper extends the rising period about 17-20 μs for POM and PP under 80 kPa impulse pressure, respectively.

The dynamic stress equilibrium in the specimen during a modified SHPB testing is assessed by comparing the front end stress with the back end (rear) one.

Fig. 4 shows the stress histories on two end faces (front end and back end) and the variation of the strain rate of POM and PP specimens without pulse shaper and with pulse shaper. The variation in strain rate is also included.

The right hand side (without pulse shaper) of Figs. 4(a), (b) shows significant stress fluctuations between the front end stress and back end stress during the total period of deformation comparing the left hand side (with pulse shaper) of Figs 4(a), (b). However, it is noted the difference between the front end stress and back end stress does not significantly involve non-uniform strain rates in these particular cases. However, it is generally accepted that strain rate histories are influenced by a pulse shaper in a modified SHPB experiment as noted in Fig. 5.

The strain rates between points (0.04, 15.8 μs), (0.49, 111.4 μs) and (0.04, 15.3 μs), (0.47, 111.5 μs) for Fig. 5(a) and Fig. 5(b), respectively, are considered as constant in this study. Clearly, the strain rate histories between 0.04 and 0.49 of strain shown in Fig. 5(a) indicate that strain rates without pulse shaper fluctuate more than those with pulse shaper as shown in Fig. 5(b) between 0.04 and 0.47 of strain. It is recommended that more experiments be taken in selection of a proper material and a better dimension of a pulse shaper to have a more uniformly modulated strain rate history during one experiment.

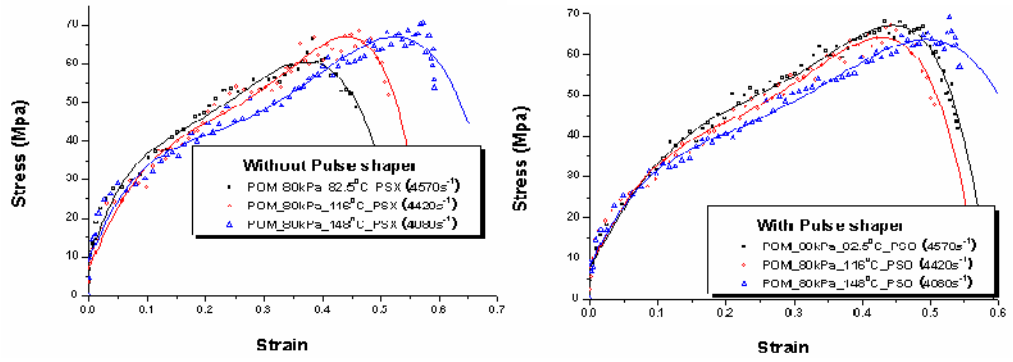
A properly chosen pulse shaper in a modified SHPB method may improve the validity of experimental stress-strain data by keeping the duration of loading period under a constant strain rate longer than one obtained by the C-SHPB experiment. The specimen can be loaded under a dynamic equilibrium stress state about 15-20 μs after the stress wave reaches the front end of the specimen as noted in Fig. 5. In addition, it deforms uniformly under a constant strain rate condition in a modified SHPB technique with a pulse shaper.

The dark region in Fig. 5 indicates a period of time while the strain rate was maintained approximately at a constant value during the SHPB testing. The strain rate becomes an approximate constant at 15 μs through 111 μs as shown in Fig. 5(a), (b).

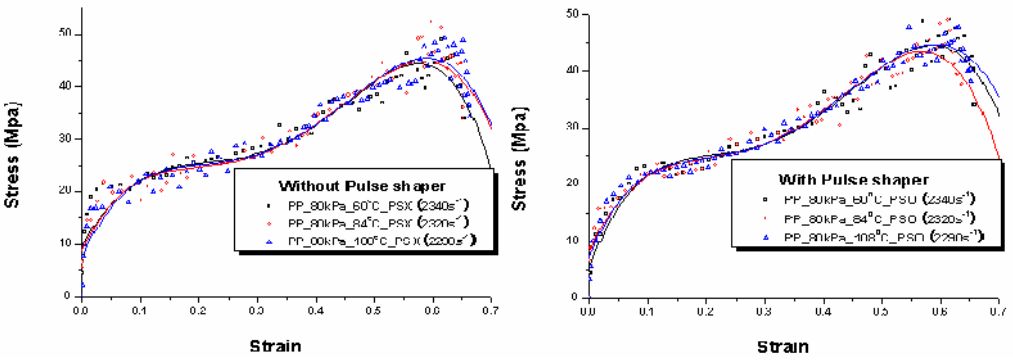
Fig. 6 shows a typical stress strain diagram without pulse shaper and with pulse shaper for hot temperature degraded POM and PP specimens under varying impulse loadings, i.e., varying strain rates of 2.3×10^{3}-4.5×10^{-3}.

It is clearly noted as shown in Fig. 6 that the dynamic stress strain relationship of POM depends highly on varying degraded hot temperature for 10 days. However, PP depends less on the degraded temperatures for 10 days.

Fig. 7 shows the effects of degraded temperature for 10 days on the maximum stress for POM and PP under varying impulse loading conditions. It is noted that the hot temperature degradation for 10days af-

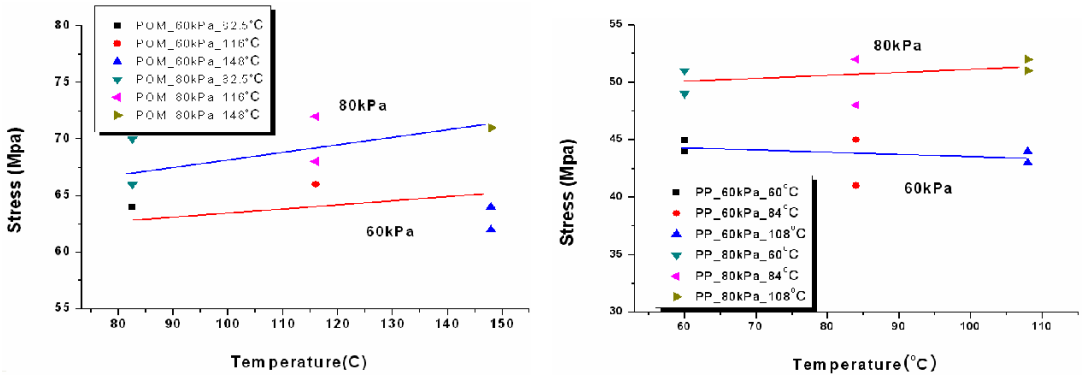


(a) 80 kPa with specimens degraded at 82.5℃, 116℃, and 148℃ for 10 days, respectively



(b) 80 kPa with specimens degraded at 60℃, 84℃, and 108℃ for 10 days, respectively

Fig. 6. Stress-strain diagram without pulse shaper and with pulse shaper (a) POM (80kPa with specimens degraded at 82.3℃, 116℃, and 148℃ for 10 days, respectively, (b) PP (80 kPa with specimens degraded at 60℃, 84℃, and 108℃ for 10 days, respectively). (Solid lines; best fitted).



(a) Relationship between stress and degraded temperature for 10 days under two impulse loadings for POM

(b) Relationship between stress and degraded temperature for 10 days under two impulse loadings for PP

Fig. 7. Maximum compressive stress for hot temperatures degraded under varying impulse loading conditions (a) POM and (b) PP.

fects significantly the maximum compressive stress for POM. With respect to data scatter in Fig. 7, more detailed experimental studies are needed in the near future. However, it is also found that the effects of temperature on the degradation of PP for 10 days may be neglected.

5. Conclusions

In this paper, the dynamic deformation behavior of hot temperature degraded POM (Poly Oxy Methylene) and PP (Poly Propylene) under varying compressive impulse loading conditions is systemically investigated by a modified SHPB using the aluminum striker and pressure bars and a pulse shaper technique. The following experimental results are obtained.

(1) The pulse shaper facilitates the increase of the rising period of the incident pulse to ensure stress equilibrium and homogeneous deformation under a constant strain rate in the low impedance specimens such as POM and PP.

(2) A few more experiments are needed in the selection of a proper pulse shaper in terms of the dimension and material property to obtain valid experimental data under high strain rate in modified SHPB tests.

(3) The dynamic deformation characteristic of POM specimen under dynamic load of strain rate 4×10^{-3} is found to be highly sensitive to the strain rate.

(4) The hot temperature degradation affects significantly with the maximum compressive stress for POM. However, the effects of temperature on the degradation of PP may be neglected.

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References

[1] H. Kolsky, Stress wave in solid, Dover, New York, (1949).

[2] O. S. Lee, S. S. Lee, J. H. Chung and H. S. Kang, Dynamic Deformation Under a Modified Split Hopkinson Pressure Bar Experiment, *KSME International Journal*, 12 (6) (1998) 1143-1149.

[3] O. S. Lee, J. Y. Lee, G. H. Kim and H. S. Hwang, High Strain-rate Deformation of Composite Materials Using a Split Hopkinson Bar Technique, *Key Engineering Materials*, 183-187 (Part 1) (2000) 307-312.

[4] O. S. Lee and G. H. Kim, Thickness Effects on Mechanical Behavior of a Composite Material (1001P) and Polycarbonate in Split Hopkinson Pressure Bar Technique, *Journal of Materials Science Letters*, 19 (2000) 1805-1808.

[5] G. T. Gray, ASM handbook Vol.8 Mechanical Testing and Evaluation, ASM International Material park, U.S.A, (2000).

[6] H. Chen, B. Song, D. J. Frew and M. J. Forrestal, Dynamic Small Strain Measurement of a Metal Specimen with a Split Hopkinson Pressure Bar, *Experimental Mechanics*, 43 (1989) 20-23.

[7] C. Chree, The Equations of an Isotropic Elastic Solid in Polar and Cylindrical Coordinates, Their Solutions and Applications, *Cambridge Phil. Soc. Trans.*, 14 (1889) 250.

[8] O. S. Lee, S. H. Kim and J. W. Lee, Thickness Effect of Pulse Shaper on Dynamic Stress Equilibrium in the NBR Rubber Specimen, *Key Engineering Materials*, 306-308 (Part 2) (2006) 1007-1012.

[9] O. S. Lee, S. H. Kim and Y. H. Han, Thickness Effect of Pulse Shaper on Dynamic Stress Equilibrium and Dynamic Deformation Behavior in the Polycarbonate Using SHPB Technique, *Journal of Experimental Mechanics*, 21 (1) (2006) 51-60.

[10] D. J. Frew, M. J. Forrestal and W. Chen, Pulse Shaping Techniques for Testing Elastic-plastic Materials with a Split Hopkinson Pressure Bar, *Experimental Mechanics*, 45 (2) (2005) 186-195.