Numerical and Experimental Studies of a Conical Striker Application for the Achievement of a True and Nominal Constant Strain Rate in SHPB Tests

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Abstract

The problem of ensuring both nominal and true constant strain rate in the split Hopkinson pressure bar experiment was considered through the application of the conical striker for 316 L steel specimen. The experimentally confirmed results from numerical analyses indicate that the application of a conical striker with the determined apex angle for the given experimental conditions is a good method for achieving a constant value of the strain rate. Moreover, the results of the study showed that the value of the striker apex angle has the greatest influence on the mechanical response of the specimen material. In turn, the impact velocity slightly affects the value of the striker apex angle.

Keywords Split Hopkinson pressure bar · High-strain-rate testing · Constant strain rate · Numerical simulation

Introduction

The basic methodological requirement of a split Hopkinson pressure bar (SHPB) technique is that a specimen needs to deform nearly uniformly at a constant strain rate under dynamically equilibrated stresses, and propagation of elastic waves through the input and output bars is described using a one-dimensional wave theory [1]. Strain acceleration, which is the effect of a non-constant strain rate, can produce additional axial stress and radial stress in a specimen [2–5], which may influence the measurement results [6]. Several methods are available for solving the problem of maintaining the constant strain rate during SHPB tests: a

pulse-shaping technique [7, 8], conical (tapered) striker method [9, 10], and a three-bar technique with a dummy specimen [11].

In the current work, the attention is focused on the incident pulse-forming technique with the use of a conical striker to achieve a constant strain rate. The literature contains a relatively large number of publications on the use of a shaped striker in investigations of brittle materials such as rocks [12–14], concrete [15] and even bones [9, 10]. However, it is difficult to find publications that investigate the use of a shaped striker for testing of metals and their alloys, particularly for materials with a high strain-hardening coefficient. Only Sato and Takeyama published studies on this topic, however, in a narrow range [16, 17].

To achieve the aim of the work, the authors carried out numerical analysis using Ls-Dyna code [18]. The material and geometric parameters of the split Hopkinson pressure bar set-up were the same as those used in the authors' previous experimental measurement system [19]. The numerical considerations were done for the specimens made of 316 L austenitic steel described by the simplified Johnson-Cook model (JC) [18]. Material constants for this material were obtained based on the authors' research (Table 1). In turn, Coulomb's law was used to predict the friction between the interacting surfaces. A friction coefficient was assumed as 0.06 [20], whereas the striker impact velocity V values were within the range of 15–25 m/s. The striker geometry was described in

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Table 1 Material constants of 316 L austenitic steel

ρ [kg/m ³]	8000	A [MPa]	304
E [GPa]	193	B [MPa]	1097
ν [–]	0.27	n [–]	0.492
C [–]	0.014		

Fig. 1. For clarity and simplicity of description, it is assumed that, in the case of the striker impact with the smaller-diameter end, the apex angle is positive, and in the other cases, it is negative (Fig. 1).

Results and Discussion

The influence of conical striker geometry with the given apex angles α on the incident pulse in the SHPB experiments is illustrated in Fig. 2. As the apex angle increases (Fig. 1(a)), the usable portion of the incident pulse, which corresponds to the cylindrical striker curve plateau of the pulse, grows from the smallest value proportional to α . However, the maximum pulse level decreases with the increase of the striker apex angle. In an analogous manner, the influence of the striker apex angle on the incident wave pulse (Fig. 2, blue lines) was investigated for the case in which the striker maximum diameter end impacts the incident bar (Fig. 1(b)).

To obtain a constant strain rate with the use of the conical strikers, numerical analyses, which resulted in obtaining the striker apex angles of the 316 L steel and experimental conditions, were carried out. The results were collected in Fig. 3 which shows a change in both the nominal (solid line) and the true (dashed line) strain rates. For comparative purposes, the curves obtained from the cylindrical striker experiments (black lines) are also included. It was found that to obtain a nominal constant strain rate, the striker apex angle should be $\alpha = 0.8^\circ$, whereas for the true strain rate, the angle is equal to $\alpha = 0.55^\circ$. The abovementioned influence of the striker apex angle on the course of the strain rate curves is also reflected in the profile of the stress-time curves (Fig. 3(b)). Based on Fig. 3(b), the differences between the curves are visible for both the nominal and true constant strain rate. These differences are expressed in a different level of plastic flow stress (black and blue solid lines). This observation is due, as expected, to the sensitivity of steel to the strain rate and to the high value of the

Fig. 2 Influence of apex angle α on the incident pulse shape, red lines—positive apex angles, blue lines—negative apex angles, black line—cylindrical striker, $V = 20$ m/s

strain-hardening coefficient that affects the geometry of the striker, i.e. its mass and impact energy and consequently influences the strain rate of the specimen (Fig. 3(a)).

Since the process of plastic deformation of a sample under the SHPB test conditions is determined by, among others, the dimensions of the specimen, numerical experiments were conducted to determine an influence of the sample geometry and striker impact velocity. The influence of both the diameter and the length of the specimen on the history of the deformation curve was investigated in the case of strikers with apex angles optimized for the following experimental conditions: diameter and length of the sample = 5×5 mm and impact velocity $V = 20$ m/s.

Figure 4(a) shows the influence of the sample diameter on characteristics of the strain rate-time curve. The cases of specimens with diameters of 4, 5 and 6 mm (in which a specimen with a 5-mm diameter is reference specimen for which the striker apex angle is chosen) are considered. Based on Fig. 4(a), it can be concluded that an influence of the sample diameter in the considered range does not significantly affect the strain-rate curve, i.e., plastic deformation of the specimens occurs at a nearly constant strain rate. However, it can be noted that in the case of small-diameter specimens, the strain rate obviously increases slightly with an increase in the specimens deformation but decreases for larger ones. Hence, it can be concluded that a conical striker can be used in studies in which the materials and the diameters of the specimens vary considerably.

Fig. 1 Conical striker geometry; apex angle α is positive in the case of impact with the end of a smaller diameter (a), and negative in the other cases (b)

Fig. 3 Nominal and true strain rate-time (a) and stress-time (b) curves of 316 L steel specimens $V = 20$ m/s

A significantly larger effect of α angle on $\dot{\varepsilon}(t)$ can be observed for specimens of different lengths (Fig. 4(b)). For the tested specimens corresponding to $L/D = 0.5$, 1, and 1.5, the effect of length is relatively large. However, it can be observed, as expected, that the strain rate of the short samples ($L = 2.5$ mm) decreases with an increase in strain, whereas in the case of long samples ($L = 7.5$ mm), the opposite relationship is observed. Useful practical guidelines are also derived from the analysis of the curves shown in Fig. 4(c). These curves show that the conical striker with a given apex angle can be used regardless of the accepted range of the striker impact velocity for nominal strain rates curves.

Additionally, to illustrate the influence of the striker impact velocity on the optimum striker apex angle, Fig. 5 is presented. This figure confirms the earlier observations conducted

based on Fig. 4(c), and at the same time, it reveals a nearly linear dependence of the striker apex angle on the striker impact velocity. Moreover, Fig. 5 clearly shows the dependence of the striker impact velocity on the optimal apex angle for experiments with the true constant strain rate.

A series of dynamic tests was conducted to verify the results of numerical analyses. The experiments were performed using the setup shown in Fig. 6(a). The verification tests were performed using four strikers with different apex angles. The strikers were made of the same steel as the input and output bars.

The number of tests conducted, together with their markings and the experimental conditions, are listed in Table 2. Experimental tests marked with letters A to D were performed under the experimental conditions required to ensure a constant

Fig. 4 Influence of specimen parameters and striker velocity on strain rate-time: diameter (a), length (b), striker velocity (c)

Fig. 5 Influence of conical striker velocity on the optimal striker apex angle for 316 L steel

strain rate, both nominal and true. The experimental strain rate-time curves for these experiments are shown in Fig. 6(b).

The results of experimental investigations on the selected conical strikers are coincident with the results of numerical analyses, which leads to the conclusion that the constant strain rate (both true and nominal) can be obtained using the appropriately selected geometry of the conical striker. It should be noted that,

Table 2 Summary of verification test conditions

Test	V [m/s]	α [°]	Type of strain rate	L_S	D_S
A	15.6	0.78	Nominal	4.95	4.81
B	15.6	0.78	Nominal	5.05	4.81
C	20.2	0.55	True	4.97	4.83
D	20.3	0.55	True	4.99	4.77

in real experimental conditions, the waveforms obtained in the usable range, i.e., the corresponding plateau, deviate from the constant value to a greater degree than in the case of the curves obtained based on numerical analyses (Fig. 6(b)).

The fact that the assumed constancy of the strain rate was not achieved in the experimental conditions results from the discrepancy between the real conditions of the SHPB experiment and the adopted conditions of the numerical experiment. According to the authors, the above discrepancies are mainly a consequence of using the JC constitutive model for the considered materials and the friction model. For example, the slight increase in the true strain rate in the plateau range observed in Fig. 6(b) is probably a result of using the JC model. It should be assumed that this model do not adequately

Fig. 6 (a) Experimental set-up, and (b) nominal and true strain rate-time curves received with his aid (a)

describe the mechanical behaviour of the tested material. In addition, a characteristic change (marked with a dotted ellipse) in the profile of the curves on the plateau section can be observed. The probable cause of this phenomenon is variability of the friction forces occurring on the specimen-bar contact surfaces during the dynamic deformation of the specimen. In the initial stage, the friction forces are relatively small due to a lubricant layer between the contact surfaces. As a result, the initial increase in the strain rate is visible. Due to deformation of the specimen and the applied loading, the lubricant layer decreases until it disappears entirely (time less than 60 μ s). This effect on the strain rate-time curve is expressed by changing the curve trend from increasing to decreasing or approximately constant. This phenomenon was not included in the numerical model because it was assumed that the coefficient of friction does not depend on the conditions of the experiment.

Conclusion

The numerical and experimental analyses presented in this article showed that application of a conical striker is a good method for achieving a constant strain rate, both nominal and true, in SHPB experiments. However, this method requires the use of a numerical model of the SHPB experiment to determine the conical striker apex angle for a given specimen material, its geometry (diameter, length) and the impact velocity of the projectile.

Contrary to the initial predictions, the use of the striker with a specific geometry does not limit its use to the given experimental conditions. For a given material group, preparation of a several conical strikers set (3–4 pieces) is sufficient for adjustment of the experimental conditions to achieve a constant strain rate. The results of this research showed that the mechanical response of the specimen materials has the greatest influence on the value of the striker apex angle, whereas the dimensions of the disk sample storage affect it to a lesser extent, with the exception of short samples, i.e., those with an L/D ratio lower than 1. Similarly, the impact velocity has a small effect on the value of the striker apex angle. In the case of a nominal strain rate, this angle is nearly independent of the striker velocity, whereas for the true strain rate, it depends on this velocity and is nearly a linear function.

Based on the observations from the experimental studies, it can be concluded that guaranteeing a constant strain rate requires the development of a more complex numerical model that considers the physics of the specimen dynamic deformation. In such a case, striker geometry may deviate from the shape of the cone with a complex contour which is more difficult to develop and probably has a limited range of the use compared with conical strikers.

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