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Research Paper

The Direct Impact Method for Studying Dynamic Behavior of Viscoplastic Materials

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Abstract. This work is devoted to the direct impact method for determining the deformation diagrams of viscoplastic materials at high strain rates. As the conventional Split Hopkinson Pressure Bar method, the direct impact method is based on the measuring bar technique. The description of the experimental scheme and the traditional experimental data proceeding method are given. The description and the results of numerical analysis of the direct impact scheme are presented. A modified procedure for processing experimental information is proposed which allows to expand the area of correct calculation of strains in the specimen according to the experimental data obtained by the direct impact method. As an illustration the deformation diagrams of copper S101 and aluminum alloy D16T in the strain rate range from 1000 to 10000 s^{-1} have been obtained using the Split Hopkinson Pressure Bar method and the direct impact method. The use of the direct impact method made it possible to obtain deformation curves at strain rates an order of magnitude higher than the conventional SHPB method. The range of studied plastic deformations is increased by 4 times for the case of copper and 3 times for aluminum alloy.

Keywords: Strain rate, measuring bar, plastic deformation, yield stress, numerical simulation, substantiation, experiment.

1. Introduction

At the current stage of the world development, the main task of industries is to produce competitive and topical products of a new generation in the shortest time possible.

The key and the most science-intensive technology providing the competitiveness of such new-generation products is Computer-Aided Engineering, CAE [1]. It is to be noted that, alongside with the development of methods for analyzing complex engineering problems, it is extremely important to equip CAE systems with initial data, the most important of them being mathematical models describing the behavior of materials used in producing the designed product [2, 3]. It is defining relations that, for the most part, determine the quality of a digital twin in the sense of its identity with the actual object. To construct a reliable digital copy of a product, it is not only necessary to describe in enough detail its special geometrical features, but also to take into account all the meaningful effects characterizing the behavior of the materials the product is made of in its exploitation conditions. Thus, for problems of evaluating strength of dynamically loaded structures, it is critical to account for the strain rate effect on strength and deformation characteristics of materials [4]. Experimental methods for analyzing such an effect can be constructed based on the measuring bar technique. Such methods include, for instance, the well-known Split Hopkinson Pressure Bar (SHPB) method [5-13]. Numerical analysis of the classical SHPN method is presented in [14-17]. The methodological limitations of the above experimental scheme necessitated the development of its alternative versions to widen the range of realized strain rates studied.

Equipping mathematical models of deformation of viscoplastic materials with the necessary parameters and constants requires comprehensive experimental data meeting the requirements of the problem being analyzed. For problems of evaluating strength of dynamically loaded structures, it is important to account for the strain rate effect on the yield surface radius. For the problems of the supercritical behavior of structures, it is important to know the characteristics of the deformation of the material in a wide range of plastic deformations up to the ultimate fracture strain. The construction of deformation curves up to rupture from high strain rate tension experiments is complicated by the strain localization and the formation of a neck. Therefore, simple but reliable methods for obtaining deformation curves at high strain rates and large plastic deformations are of practical interest.

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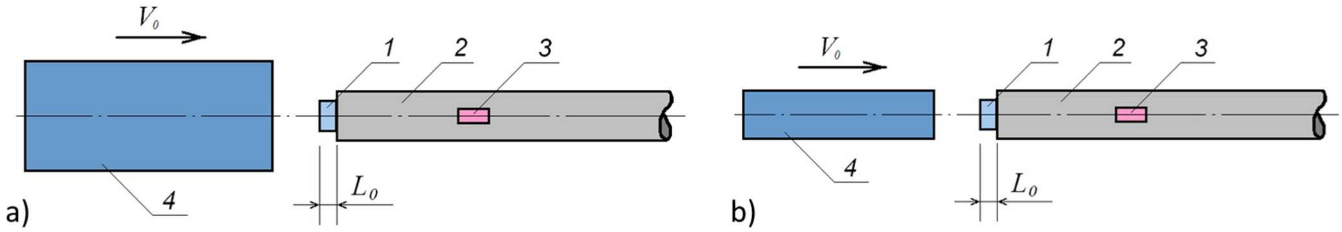

Fig. 1. Layouts of the two versions of the direct impact method: 1 – specimen, 2 – measuring bar, 3 – strain gauges, 4 - impactor

The present paper is devoted to one of such methods - the method of direct impact. The detailed description of experimental scheme and procedure of proceeding of experimental data are given, including effects of friction and inertia effects. Then using the numerical simulation, it is shown that traditional proceeding method can lead to significant errors in specimen's strain determination and it is important to consider wave effects in impactor. The modification is proposed to improve the accuracy of specimen's strain determination. Two examples are given showing how utilization of direct impact method jointly with SHPB method expands the ranges of strain rates and plastic strain values during experimental investigation of mechanical behavior of materials.

2. Direct Impact Method Description

The strain rate range realized in using the Kolsky method is limited because of one of the main assumptions of the methodology – elastic deformation of measuring bars. In this method, a specimen is loaded through an incident measuring bar. A maximal velocity of the impactor providing the formation of an elastic loading pulse in the incident measuring bar is defined by the following provision:

$$V_{\max} = \frac{2 \cdot c \cdot \sigma_T}{E}, \tag{1}$$

where c is rod sound velocity in the material, E is Young's modulus, σ_T is yield strength. The impactor and the measuring bar are assumed to be made of the same material and to have the same diameter.

Thus, the maximal strain rate in an experiment is limited by the value:

$$\dot{\varepsilon}_{\max} = \frac{V_{\max}}{L_0}, \tag{2}$$

where L_0 is specimen length.

In practice, a maximal velocity of an impactor that can be used in tests turns to be substantially lower than Vmax, as large loading amplitudes in the measuring bar lead to interrupting the resistance strain gauge chain located on the surface of the incident bar. As a result, signals are not registered, and a deformation diagram cannot be constructed. The wave amplitude in the support measuring bar is limited by yield strength of the material, so proper choice of the specimen dimensions can substantially decrease the load acting on the support measuring bar and provide reliable registration of signals.

This idea underlies the direct impact method, where a specimen is installed at one end of the measuring bar and directly loaded by the impactor without an intermediate measuring bar. Such a scheme called the 'direct impact method' was introduced in Houser [18] for determining dynamic properties of materials at strain rates of 10^3-10^4 s^{-1}. This method was considerably developed in the papers by Klepaczko [19]. Since then, the direct impact method has been successfully used by researchers to study the behavior of various materials under high strain rates [20-22].

There exist several versions of the direct impact method. The two most popular configurations [19] are depicted in Figure 1. The first of them uses a massive impactor possessing the kinetic energy multiply increasing the work of elastoplastic deformation of the specimen (Figure. 1a). In this case, the velocity of the striker is assumed constant or slowly varying during the entire deformation process of the specimen, whereas the process of loading the specimen has an inertial character. The second configuration uses an impactor of a considerably smaller mass and of the same diameter that the measuring bar (Figure 1b). Here, the loading process has a wave-like character.

In both versions of the direct impact method, a tested specimen (1) of length L_0 is located at one end of a long thin measuring bar (2) with high yield strength, which is struck by an impactor (4) at velocity V_0 from several meters per second to several tens meters per second. In the course of the test, strain gauges (3) register a strain pulse at a certain cross-section of the measuring bar, which makes it possible to determine stress in the specimen. An important parameter used in constructing a deformation curve, based on the data from such an experiment, is impactor velocity that must also be registered in each test. It should be kept in mind that, when the first experimental configuration (Figure 1a) is used for testing high-strength materials, the direct impact method leads to considerable inaccuracies in determining strains of the specimen, as the assumption of a constant velocity of the striker in the process of loading is not satisfied, especially at an initial part of the diagram (up to 5-7%). To overcome this drawback, Y. Klepaczko introduced a technique where the displacement of the 'impactor-specimen' interface is registered with an optical sensor. In the recent years, experimental schemes have been developed that make it possible to register the change of velocity of the impactor in the course of the experiment, which substantially improves the informative characteristics of the method, as well as its accuracy [19].

The velocity of the 'specimen-support bar' contact interface is determined, as in the case of using the split Hopkinson pressure bar (SHPB), based on the pulse of elastic strain in the measuring bar:

$$V_1(t) = c \cdot \varepsilon_T(t), \tag{3}$$

where c is sound velocity in the measuring bar.

In the first configuration of the technique (Figure 1a), the 'impactor-specimen' interface velocity remains constant and equal to the impactor velocity, V_0.

Then the rate of change of the specimen length can be determined using the formula:

$$V_s(t) = V_0 - c \cdot \varepsilon_T(t), \tag{4}$$

If L_0 is initial specimen length, then average strain rate of the specimen is defined as:

$$\varepsilon_n(t) = \frac{1}{L_0}(V_0 t - c_0 \int_0^t \varepsilon_T(\vartheta) d\theta) \tag{5}$$

Average engineering stress in the specimen can be found according to the formula:

$$\sigma(t) = E \cdot \left(\frac{D_b}{D_s}\right)^2 \cdot \varepsilon_T(t) \tag{6}$$

where E is Young's modulus of the measuring bar, D_b and D_s are diameters of the measuring bar and the specimen, respectively.

In the Laboratory for Dynamic Tests of Materials, Research Institute for Mechanics, Nizhny Novgorod Lobachevski State University, the second experimental configuration (Figure 1b) was chosen for determining deformation curves at strain rates over 10^3 s^{-1}. This was determined by the possibility to use the standard Kolsky test configuration, using the same loading equipment. The experimental conditions are chosen so that the specimen was deformed elastoplastically, while the impactor and the measuring bar were deformed elastically.

After the impact, the same wave propagates both in the striker and in the measuring bar. This makes it possible to find average rate of change of the specimen length, based on strain pulse $\varepsilon_T(t)$ registered in the measuring bar, using the following formula [19]:

$$V_s(t) = V_0 - 2 \cdot c \cdot \varepsilon_T(t), \tag{7}$$

where V_s is rate of change of the specimen length.

Thus, average strain rate in the specimen is:

$$\dot{\varepsilon}(t) = \left(\frac{V_s}{L_0}\right) \tag{8}$$

Then, average engineering strain in the specimen will be defined as follows:

$$\varepsilon(t) = \frac{1}{L_0}\left(V_0 \cdot t - 2 \cdot c \cdot \int_0^t \varepsilon_T(\tau) d\tau\right) \tag{9}$$

The formulas (6) and (9) allow to calculate engineering values of stresses and strains. The true (logarithmic) strains and true stresses can be calculated in usual way.

As the direct impact method is designed for studying material characteristics at elevated strain rates (of over 10^3 s^{-1}), it is necessary, when processing test results, to take into account inertial stresses in the specimen. Besides, friction present at the 'impactor-specimen-measuring bar' interfaces also lead to the appearance of radial stress components.

Effects of friction, radial and axial inertia in cylindrical specimens are analyzed in detail in Y. Malinowski and Y. Klepaczko [23]. The authors showed that radial stress σ_r is not constant along the specimen radius and has its maximal value for R=0, i.e., along the axis of the specimen. In [18], it was proposed to evaluate radial stresses using their maximal value, i.e.

$$\sigma_{r\max}(t) = \frac{\rho \cdot R(t)^2}{4 \cdot L(t)(1-\varepsilon_n(t))^2}\left[\frac{3V_x^2}{2L(t)(1-\varepsilon_n(t))} + \frac{dV_x}{dt}\right] \tag{10}$$

where V_x is rate of change of the specimen length, ρ is density of the material of the specimen, R(t) and L(t) are current radius and current specimen length, respectively.

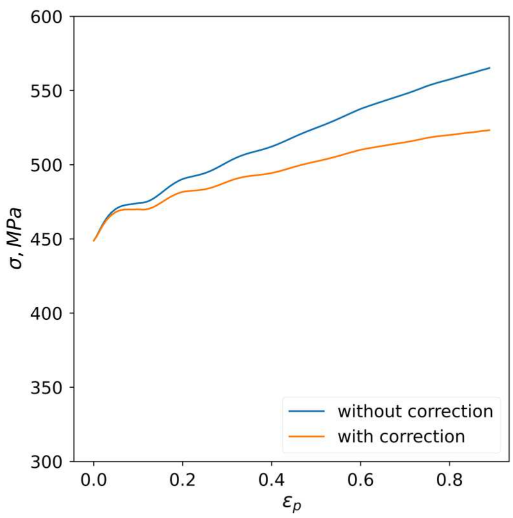

Fig. 2. Deformation curves for copper S101, constructed with and without accounting for radial inertia

There also exist other relations for evaluating σ_r, which yield similar results. For in-stance, in [23], the following expression for evaluating the radial component of stress is given:

$$\sigma_r(t) = \frac{3}{8}\rho\left(R_0 V/L_0\right)^2\left(1-\varepsilon_n(t)\right)^{-3} \tag{11}$$

Figure 2 shows plastic parts of deformation curves of copper S101, obtained using the direct impact method for strain rate of about 10^4 s^{-1}. The vertical axis represents true effective stress. The horizontal axis represents true effective plastic strain of the specimen. The orange curve was obtained with accounting for radial inertia. It can be seen that, in the conditions in question, the correction for inertia introduces a considerable contribution. The difference between effective stresses for the maximum of the achieved strain amounts to about 10 %.

The stress due to axial inertia, according to [16], is defined by the following relation:

$$\sigma_{axial} = \frac{\rho D_S^2}{12}\left(S^2 - \frac{3}{16}\right)\left(\dot{\varepsilon}^2 + \ddot{\varepsilon}\right) + \frac{3\rho D_S^2}{64}\ddot{\varepsilon} \tag{12}$$

where, $S = \frac{L}{D\dot{\varepsilon}}$ and $\ddot{\varepsilon}$ are strain rate (axial) of the specimen and its time derivative.

As is shown in [24], the inertial component of the axial stress up to the rates of ~$5\cdot10^3$ s^{-1} does not exceed ~1 % and can be neglected, whereas for the strain rates of over $5\cdot10^3$ s^{-1} the inertial components of stress must be accounted for according to formula (12).

Friction at the 'impactor-specimen-measuring bar' interfaces results in radial stress σ_{fr} in the specimen, which can be evaluated by the following simple relation:

$$\sigma_{fr}(t) = \frac{\mu\sigma(t)}{3S(t)}, \quad \text{where } S(t) = \frac{L(t)}{D(t)}, \tag{13}$$

where L and D are current length and diameter of the specimen, σ is axial stress in the specimen, μ is friction coefficient.

The reliability of formula (13) using numerical analysis is assessed in [3].

3. Numerical Analysis of the Direct Impact Method

Numerical simulation of the experiment was performed to analyze the processes characteristic of the described method. The homogeneity and one-dimensionality of the stress-strain state of the specimen in the direct impact method in the presence of friction forces were numerically assessed in [25]. In the present paper, numerical experiments were aimed at assessing the accuracy and defining the scope of applicability of the formulas for determining strains and stresses in the specimen, using relations (6)-(9). Figure 3 shows a part of the model. The problem was analyzed in an axisymmetric formulation, using CAE of the Abaqus Student Edition software package. The behavior of the materials of the measuring bar and impactor was described by a linear elastic model with the following parameters: density=7800 kg/m^3, Young's modulus =200 GPa, Poisson coefficient =0.28, bar sound velocity = 5065 m/s. The length of the impactor was 300 mm, the length of the measuring bar was 1.5 m, the diameters of the impactor and measuring bar were 20 mm. The behavior of the specimen material was described by an elastoplastic bilinear model with the following parameters: density 2600 kg/m^3, Young's modulus 70 GPa, Poisson coefficient 0.33, yield strength 260 MPa, hardening modulus 1000 MPa. The height of the specimen was 5mm, the diameter was 10 mm. Initial velocity of the impactor was V_0=30 m/s. In Figure 2, the following notations are used: V_1 is mass velocity of the motion of the right end of the impactor (left end of the specimen), V_2 is mass velocity of the left end of the measuring bar (right end of the specimen).

In the analysis, the axial strain pulse in the measuring bar was determined (in analogy with the full-scale experiment), as well as the forces on the 'specimen-measuring bar' contact, rates of displacement of the 'impactor-specimen' and 'specimen-measuring bar' interaction interfaces, the law of change of the specimen length, strains in the specimen. Figure 4 compares the forces found in the virtual experiment with directly registering the contact force (the end) with those computed based on the pulse in the measuring bar (the measuring bar). It can be seen that the curves nearly coincide. The difference is observed in the slope of the frontal part of the time history: the initial part of the curve determined based on the strain pulse in the measuring bar is less steep. Besides, the force computed based on the strain pulse in the measuring bar shows oscillations. Both effects are due to wave dispersion in an elastic bar of a finite diameter. This effect is described in detail in [26, 27] with the related analysis.

Figure 5 compares the velocities at the ends of the specimen, as determined by direct registration in the process of computation (numerical modeling), and as found using formula (3), based on the pulse registered in the measuring bar (theoretical analysis). On the left, the histories for the left end of the specimen (contact with the impactor) are compared, on the right, the histories for the right end (contact with the bar) are compared. It is evident that the law of motion of the right end is reconstructed accurately enough over the entire the loading time of the specimen. At the same time, formula (3) gives a relatively accurate evaluation of the velocity of the 'impactor-specimen' contact only on the time interval corresponding to two wave travels along the impactor (the black vertical line in the Figure). After that, the motion of the impactor end is affected by the wave reflected from its free end.

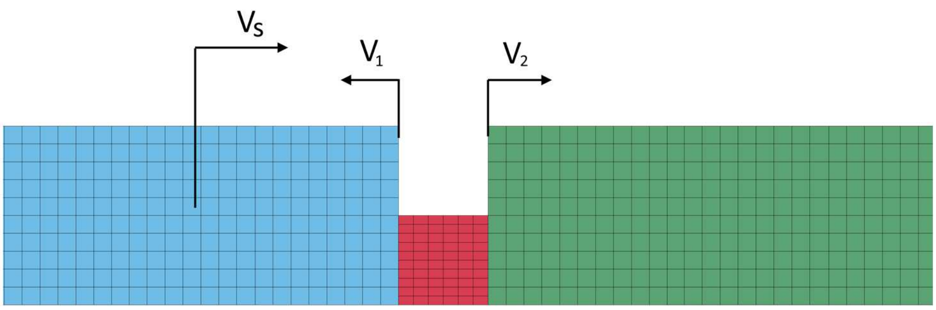

Fig. 3. A part of the model

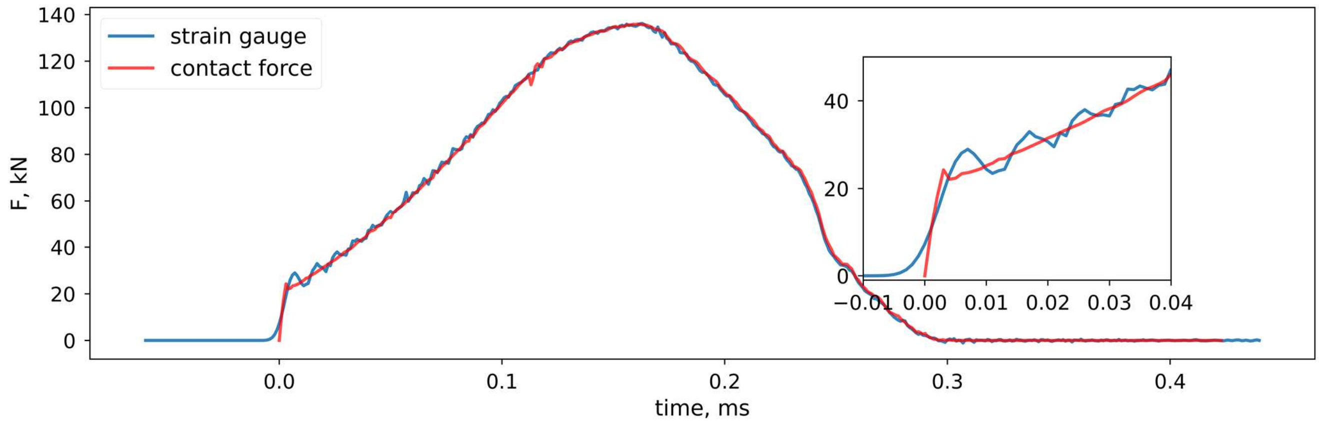

Fig. 4. Comparison of the forces

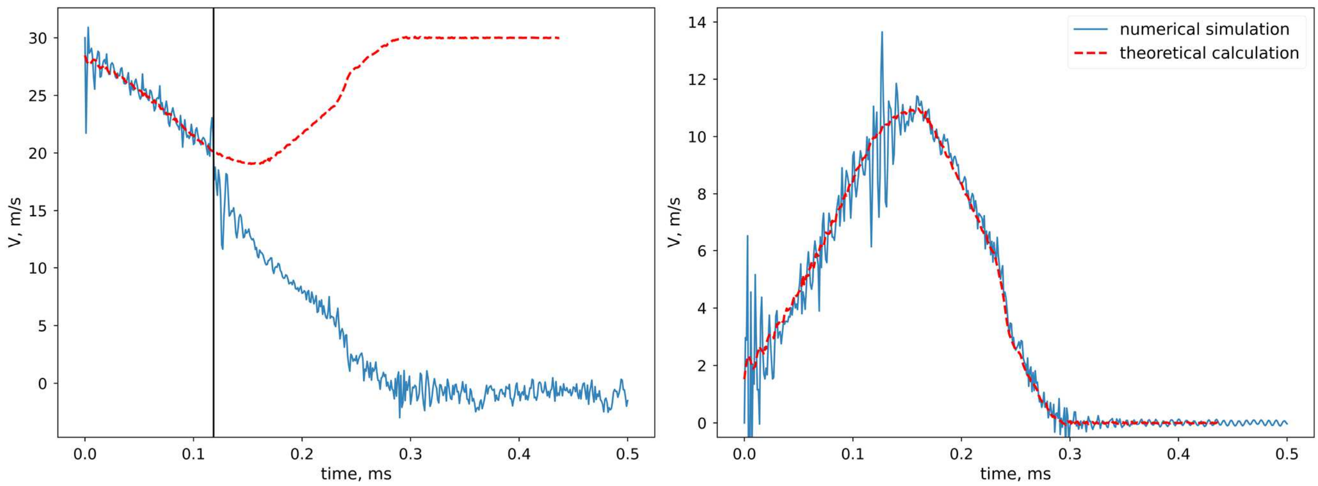

Fig. 5. Comparison of the velocities at the ends of the specimen (direct calculation and theoretical evaluation based on the strains in the measuring bar)

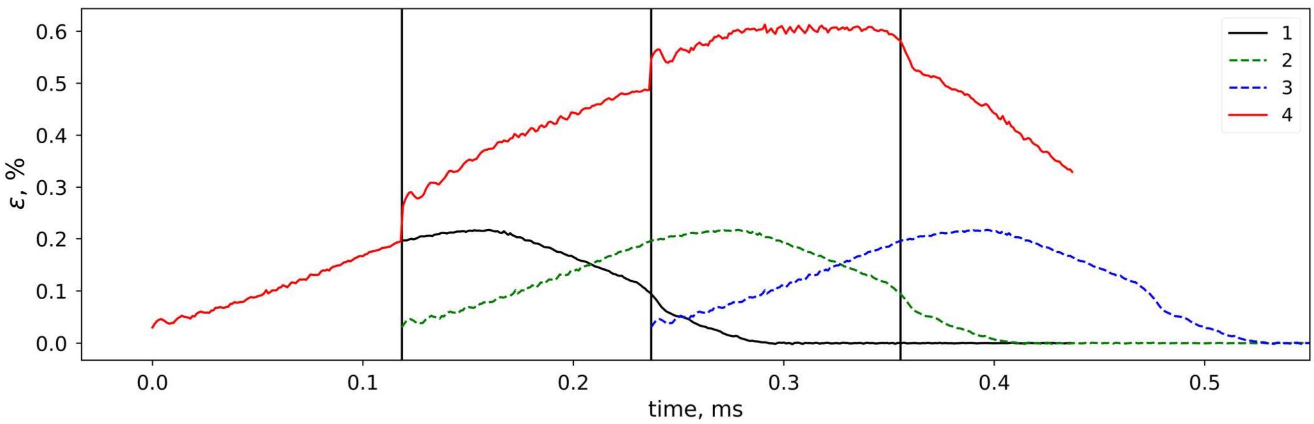

Fig. 6. Computation of a modified signal

4. The Modified Data Processing Procedure

To extend the range where the method would provide a correct result, and, hence, the strain range for constructing deformation curves, a modified procedure for processing experimental information has been developed. In this procedure, the velocity of the 'impactor-specimen' interface is determined using a modified pulse made up by adding pulses reflected from the free end of the impactor to the initial signal, i.e.

$$\varepsilon^{mod}(t) = \varepsilon_T(t) + \sum_{i=1}^{N} 2\,\varepsilon_T\left(t + 2\cdot i\cdot \frac{L_{st}}{c}\right) \tag{14}$$

where L_{st} is impactor length, c is sound velocity in the impactor material.

The described procedure is illustrated in Figure 6. Initial signal 1 is complemented with a double pulse shifted by two wave travels in impactor 2 and a double pulse shifted by four wave travels in impactor 3. The pulse 4 is the result of such superposition.

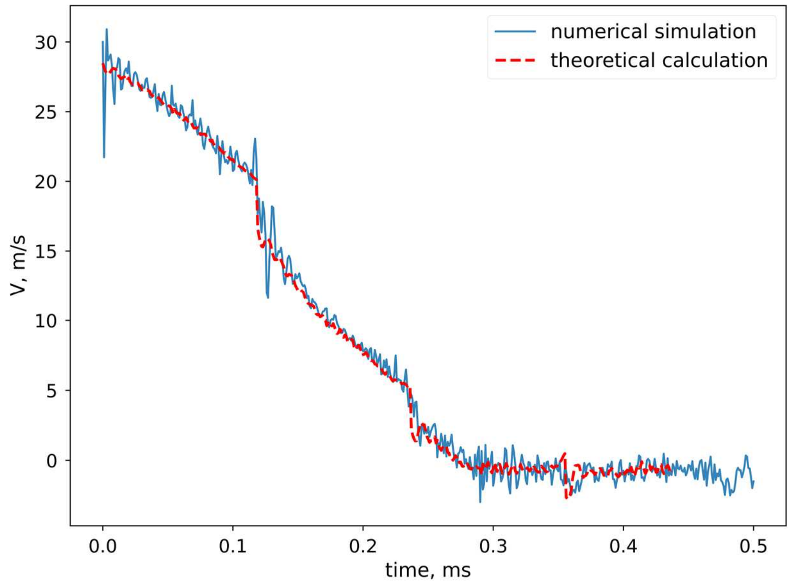

Fig. 7. Velocities at the 'specimen-impactor' interface

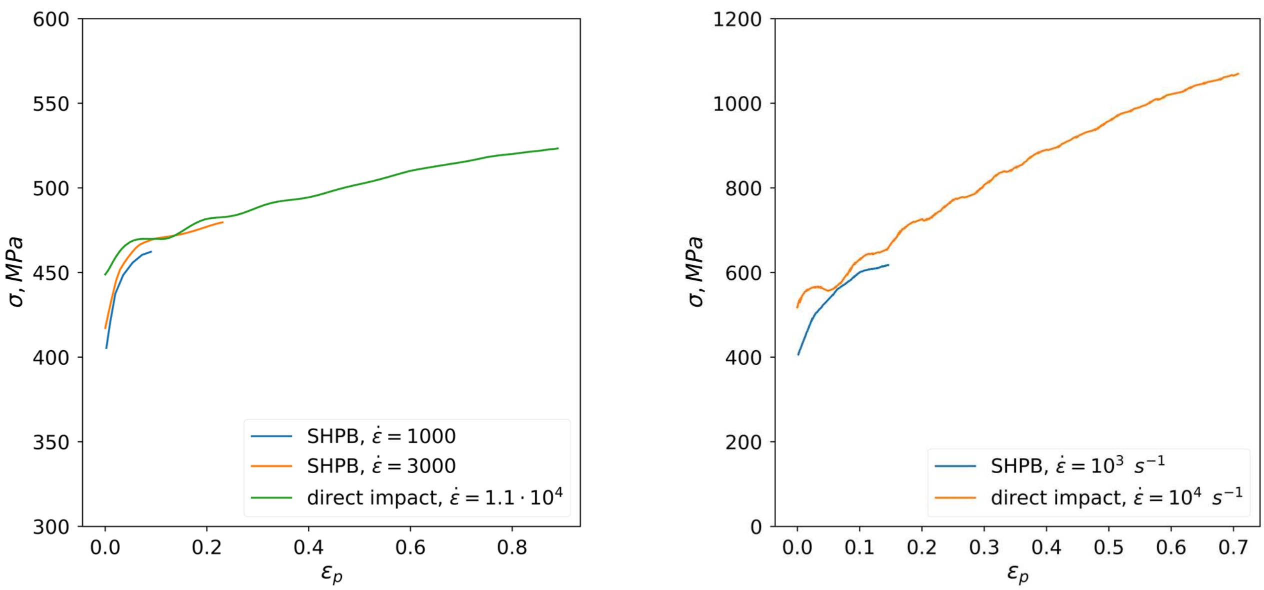

Fig. 8. Test results for copper S101 (on the left) and aluminum alloy D16T (on the right)

Velocity V_1 was found using the following formula:

$$V_1(t) = c \cdot \varepsilon^{mod}(t). \tag{15}$$

Figure 7 compares the velocities on the 'specimen-impactor' interface, obtained directly from numerical modeling, with those obtained using the modified procedure 7. It can be seen that the use of the developed procedure makes it possible to determine accurately the 'impactor-specimen' interface velocity along the entire interval of actively loading the specimen.

Now the formula for determining the rate of change of the specimen length will have the following form:

$$V_s(t) = V_0 - c \cdot \varepsilon_T(t) - c \cdot \varepsilon^{mod}(t). \tag{16}$$

Strain rates, strains and stresses in the specimen are found using formulas (6), (8) and (9). The direct impact method was used to construct deformation curves of copper S101 and aluminum alloy D16T for the strain rate of about 10^4 s^{-1}. The plastic parts of diagrams are presented in Figure 8. The vertical axes represent true effective stress accounting axial and radial components. The horizontal axes represent true effective plastic strain of the specimen. The use of the direct impact method made it possible to obtain deformation curves at strain rates an order of magnitude higher than the conventional SHPB method. The range of studied plastic deformations is increased by 4 times for the case of copper and 3 times for aluminum alloy. The obtained information in combination with the curves constructed using the traditional SHPB method, makes it possible to judge about the strain rate effect on yield strength of the studied materials in the strain rate range of 1000 to 10000 s^{-1}.

5. Conclusion

The paper described the direct impact method based on the measuring bar technique. This methodology, in combination with some other experimental investigation methods, such as standard static tests and the Split Hopkinson Pressure Bar method, made it possible to obtain information about strain-rate dependence of strength and deformation properties of structural materials in a wide range of strain rates. The above numerical analysis of the method made it possible to assess its scope of application and to define the limits within which the described method provides reliable results. A modification of the experimental data processing procedure was presented, that overcomes this limitation. Using the described methodology, deformation diagrams for copper S101 and aluminum alloy D16T for strain rates of about 10^4 s^{-1} have been constructed. The use of the direct impact method made it possible to obtain deformation curves at strain rates an order of magnitude higher than the conventional SHPB method. The range of studied plastic deformations was increased by 4 times for the case of copper and 3 times for aluminum alloy.

Author Contributions

A. Basalin and A. Konstantinov conducted experiments and analyzed the results. A. Belov engaged in numerical simulation and analysis of results. A. Bragov proposed a modified scheme for processing experimental information. L. Igumnov carried out the general management of the study. V. Eremeyev engaged in the interpretation of experimental data and the results of numerical simulation. All authors made a substantial, direct and intellectual contribution to this work. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

Acknowledgments

Not applicable.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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