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ANALYSIS OF THE IMPACT OF THE FREQUENCY RANGE OF THE TENSOMETER BRIDGE AND PROJECTILE GEOMETRY ON THE RESULTS OF MEASUREMENTS BY THE SPLIT HOPKINSON PRESSURE BAR METHOD

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Abstract

The paper presents the results of the analysis of the striker shape impact on the shape of the mechanical elastic wave generated in the Hopkinson bar. The influence of the tensometer amplifier bandwidth on the stress-strain characteristics obtained in this method was analyzed too. For the purposes of analyzing under the computing environment ABAQUS / Explicit the test bench model was created, and then the analysis of the process of dynamic deformation of the specimen with specific mechanical parameters was carried out. Based on those tests, it was found that the geometry of the end of the striker has an effect on the form of the loading wave and the spectral width of the signal of that wave. Reduction of the striker end diameter reduces unwanted oscillations, however, adversely affects the time of strain rate stabilization. It was determined for the assumed test bench configuration that a tensometric measurement system with a bandwidth equal to 50 kHz is sufficient.

Keywords: Hopkinson bar, tensometer bridge, amplifier bandwidth, strain measurement.

1. Introduction

To test the viscoplastic material properties in the range of high deformation rates, the modified Hopkinson bar method is used [1-3], the scheme of which is shown in Fig. 1. The specimen with a cylindrical shape is placed between two bars with a length of 1 m and a diameter of 20 mm made of steel with a high yield point (maraging steel). The striker bar (5) is accelerated in the pneumatic gun (1) and strikes with a velocity of V_0 against an incident bar (8), generating an elastic wave which propagates along the bar. When the wave reaches the front of the bar, causes its displacement, which plastically deforms the specimen. A part of the wave is reflected and propagates in the opposite direction along the incident bar and the remainder passes through the specimen to the transmitter bar (9) along which it propagates, until it reaches the damper mounted at its end, where it is absorbed. The initial speed of the striker is measured with a counter, which records the time in which the striker passes 80 mm. The measurement of time is triggered by an optoelectronic system, consisting of two pairs of a diode/photodiode. The course of mechanical wave is recorded by means of a tensometer bridge system [4]. In order to average the course of the mechanical wave and eliminate the effects from buckling of the bar, the measurement of the strain is carried out by means of four tensometers bonded symmetrically on the circumference of the bar. Based on the waveforms recorded by a digital oscilloscope for transmitted ε_T (t) and reflected ε_R (t) waves and the known cross sectional area of the bars A and the specimen A_S, the speed of the elastic wave propagation in the material of the bars C_0 and the test-piece length L, it is

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possible to determine the time courses of stress σ (t), strain ε (t) and strain rate $\dot{\varepsilon}(t)$ in the specimen using the formulae:

$$\sigma(t) = E\left(\frac{A}{A_S}\right)\varepsilon_T(t) \ , \tag{1}$$

$$\varepsilon(t) = -\frac{2C_0}{L}\int \varepsilon_R(t)dt \ , \tag{2}$$

$$\dot{\varepsilon}(t) = \frac{d\varepsilon(t)}{dt} = \frac{-2C_0}{L}\varepsilon_R(t) \, . \tag{3}$$

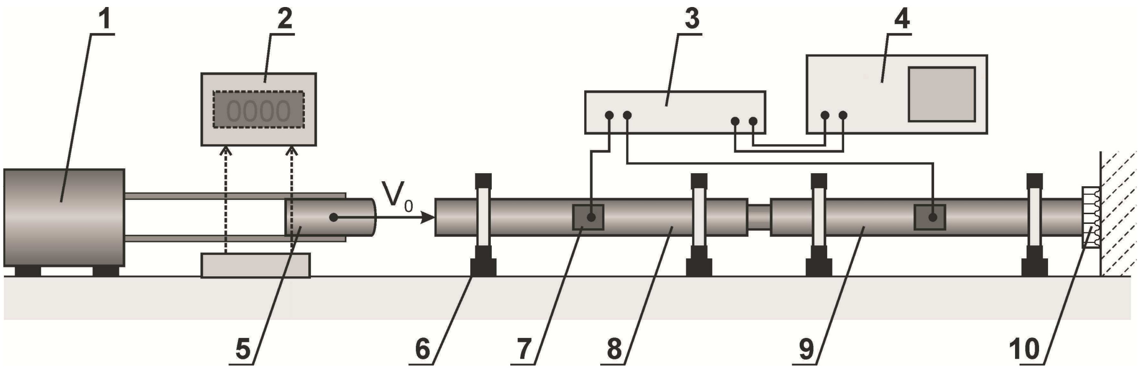

Fig. 1. Scheme of the test bench for tests by Hopkinson bar method, 1 - pneumatic gun, 2 - optoelectronic system for measuring striker velocity, 3 – broadband tensometer bridge, 4 - digital oscilloscope, 5 – striker, 6 - bar bearings, 7 - tensometers, 8 – incident bar, 9 – transmitter bar, 10 – wave damper.

The analysis of the results obtained using the Hopkinson bar method requires knowledge about the influence of the specific characteristics of the mechanical design of the test bench, as well as the measuring system on the obtained measurement result. In the literature, much attention has been paid to the issues related to the analysis of mechanics of the phenomena occurring during the tests by the Hopkinson method, but there are few studies on issues related to the acquisition and processing of measurement signals. Therefore, in this paper an analysis of the operation of the measurement system was performed, focusing on the effect of the striker shape onto the spectrum width of the generated pulses, and the bandwidth of the tensometer bridge on the measurement result.

In the Hopkinson method the course of the elastic wave recorded using tensometers is highly dependent on the shape of the striker, and the mechanical properties of the specimen. As follows from the assumptions of the measurement method, the material deformation rate should be constant, from which results the loading pulse shape similar to a rectangle. In a typical configuration of the test bench, shown in Figure 1, the measurement signal recording time is less than 1 ms which determines the need for a bridge with an amplifier with a wide bandwidth - as for the tensometric measurements. A thorough analysis of the required bandwidth values is presented later in this paper.

2. Effect of striker shape on the elastic wave propagation in the measurement bars

The course of a mechanical wave in the bars was calculated using the finite element method. The test bench model, shown in section 1, was created in an ABAQUS/Explicit environment. The method of collection and processing of data from the numerical analysis was identical as in real measurements i.e. the strain value recorded in the middle of the bar length was then processed using equations (1-3). By using FEM it was possible to trace easily a few basic cases for a variety of striker configurations while avoiding the adverse effects of such phenomena as friction, material non-homogeneity and adiabatic heating on the measurement result. In addition, it was possible to define the reference mechanical parameters of the tested material, and then compare them with the stress-strain curves determined for different parameters of the test bench. Tests were performed for three lengths of a striker, namely 10 cm, 20 cm and 30 cm and different diameters of the spherical striker end amounting to Inf (flat end striker), 3 cm and 1 cm. The test-piece material was defined as elasto-plastic with Young's modulus E = 207GPa. The hardening effect of the specimen material was taken into account as a linear dependence of flow stress on plastic strain i.e. the stress value increases linearly from 400MPa to 600MPa within the strain range from 0 to 1. The material takes account of the phenomenon of the sensitivity to deformation speed. The initial velocity of the striker was equal to 30 m/s. The axisymmetric model of the testing stand incorporating specimen of 10 mm in diameter and 5 mm in thickness was applied. All apparatus components i.e. striker, incident bar, transmitter bar and specimen were meshed with the use of CAX4R elements with reduced integration and hourglass control. The mesh size was equal to 1mm for bars and 0.2 mm for the specimen. The simulation time equal to 0.4 ms was divided into 800 steps in order to obtain a smooth shape of stress in the bars. More details of the modelling of the Hopkinson bar can be found in earlier works [5-8].

The influence of the length of the flat-ended striker on propagation of the mechanical wave recorded by tensometers is shown in Fig. 2. Along with the increase of the striker length also the width of measured impulses increases, whereas the shape of their initial part remains unchanged. The theoretical shape of impulses is rectangular, but characteristic oscillations are produced due to mechanical wave dispersion [9,10]. The length of the striker does not have any clearly visible effect on the spectral width of the measured signal [11], as shown in Fig. 3.

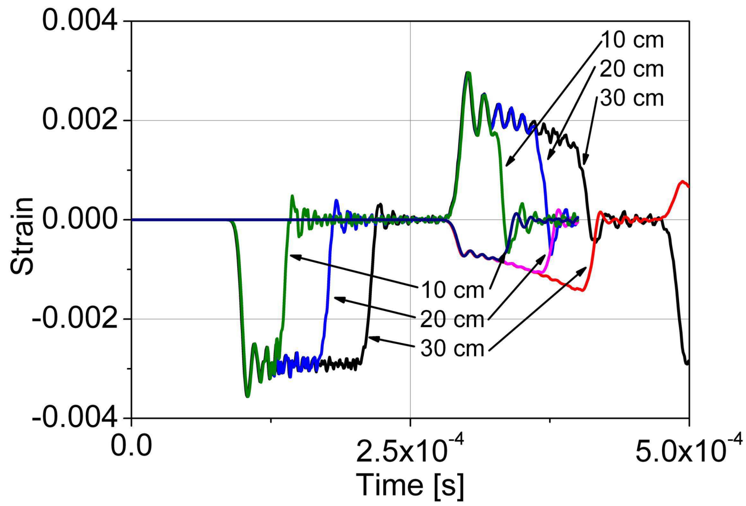

Fig. 2. Mechanical wave in bars at various striker lengths.

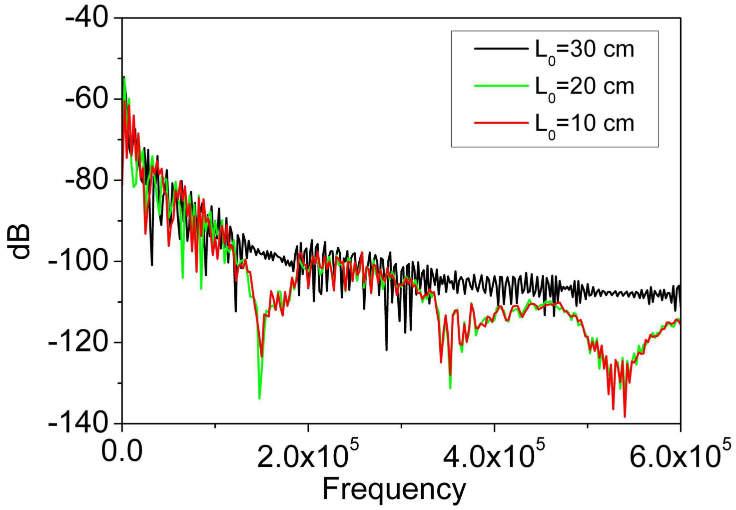

Fig. 3. Mechanical wave in bars at various striker lengths.

The curves illustrating the shape of the measuring signal for different shapes of the striker end are presented in Fig. 4. Analyzing the graph it can be concluded that with a decrease in the radius also the level of oscillation imposed on waveforms decreases significantly. The observed effect can be explained as follows: The introduction of rounding at the end of the striker causes that the shape of the generated mechanical wave pulse starts to deviate from the rectangular shape and begins to assume a sinusoidal one, which narrows the width of the signal spectrum. This can be seen in Fig. 5, which shows the spectrum of the signals for different geometries of the striker end. As one of the types of dispersion, which occurs during mechanical wave propagation along an infinitely long bar, is a different wave propagation speed for different frequencies, then the signal bandwidth limitation reduces the effect of dispersion. This is shown in Fig. 4 where the introduction of a rounded end reduces the effect of dispersion and reduces the formation of oscillation. On the other hand, the Hopkinson bar method aims to obtain the pulses as close to the rectangle as possible, so that it is possible to obtain a constant strain rate of the material, which is one of the basic assumptions of this research technique. The problem of the signal rise time is discussed later in this paper.

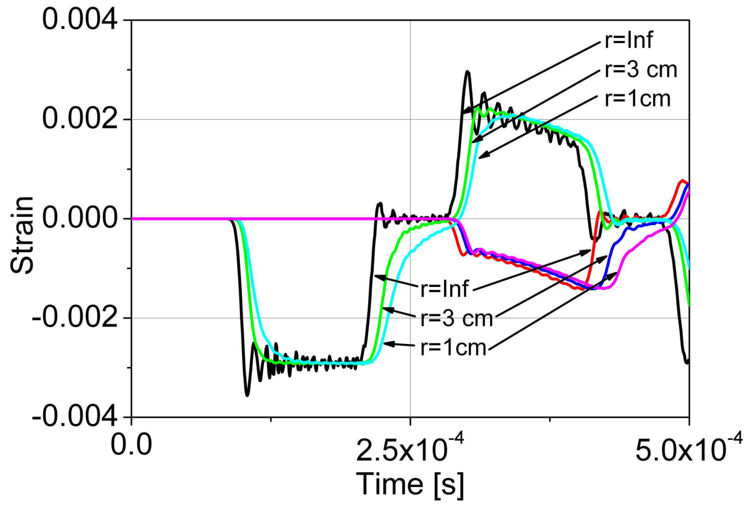

Fig. 4. Mechanical wave in bars at various striker interface radius.

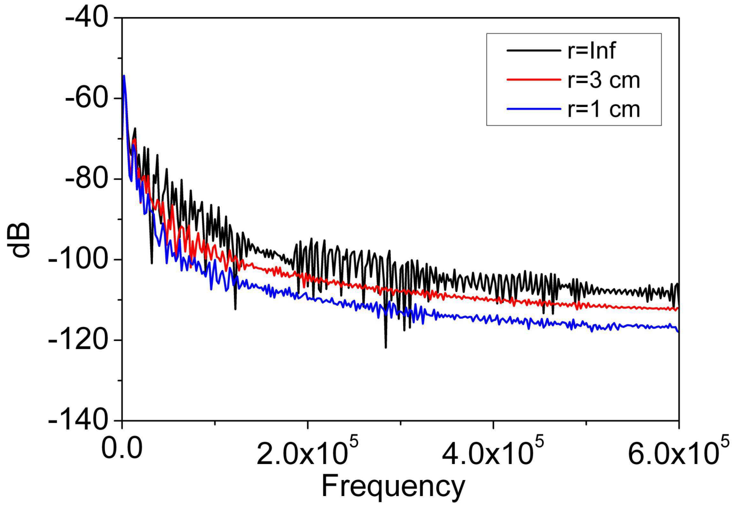

Fig. 5. Mechanical wave in bars at various striker interface radius.

3. Influence of tensometer bridge cut-off frequency on the measurement result

The basic value which is determined by the Hopkinson bar method is the stress-strain characteristics of the tested material. The shape of this curve calculated from the equations (1-3) for different lengths of the strikers has been compared with a model curve in Fig. 6. The model curve was determined on the basis of the mechanical properties of the test-piece material which was used in FEM simulations. As is the case in the course of the stress in the bars the stress-strain curves differ only in the value of the final strain, with the initial parts having the same shape.

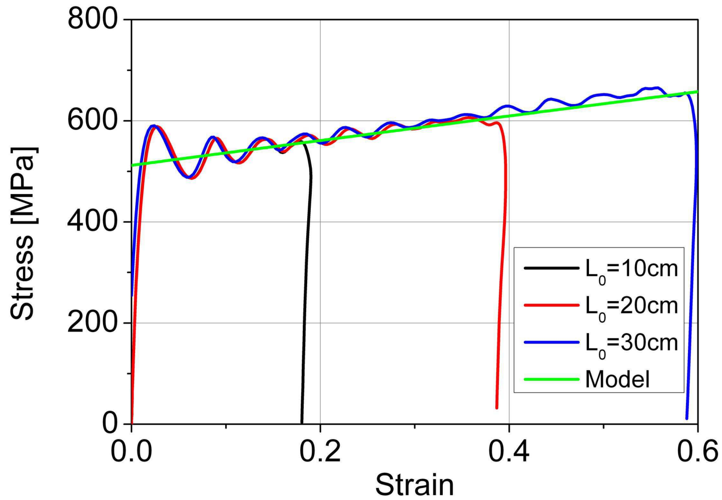

Fig. 6. Stress-strain curves at various striker lengths.

The influence of the end geometry changes on the stress-strain characteristics is illustrated in Fig. 7 It can be seen that a reduction of the radius of the end will reduce the oscillation generated while maintaining good agreement with the curve representing the reference material properties.

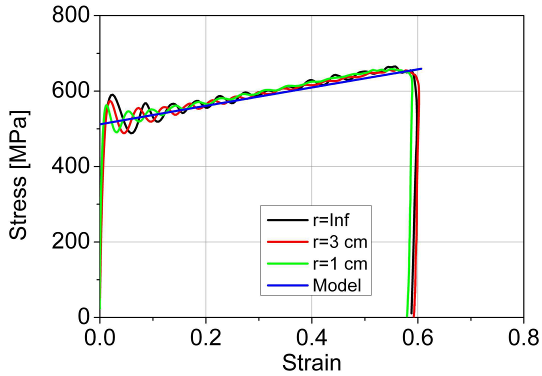

Fig. 7. Stress-strain curves at various striker interface radii.

In the next stage of the analysis the tensometer bridge bandwidth limitation was simulated. The analysis was carried out using a FFT low-pass filter function in the package Origin 8.1. The signals determined on the basis of the simulation, measured using "virtual" tensometers were then filtered with four different frequency limits of 10 kHz, 20 kHz, 50 kHz and 100 kHz. The calculations were performed for various striker end geometries. The shape of signals after filtering is shown in Fig. 8. Analyzing the shape of the waveform it can be said that according to Fourier theory a limitation of the signal bandwidth affects the limitation of oscillations and pulse smoothing. Since the reduction of the radius of the striker end reduces the loading pulse bandwidth , therefore the influence of filtration on the course of stress in the bars is smaller for the signals generated by the impact of a round-ended striker. It should be noted that for the rounding r = 1cm the smooth shape of loading impulses measured by means of tensometers results from the properties of the tested sample, while for the flat-ended striker using the bridge with a small bandwidth (10kHz or 20kHz) it is the result of signal filtration. Therefore, excessive reduction of the bandwidth may result in a loss of a part of information about the measured material parameters.

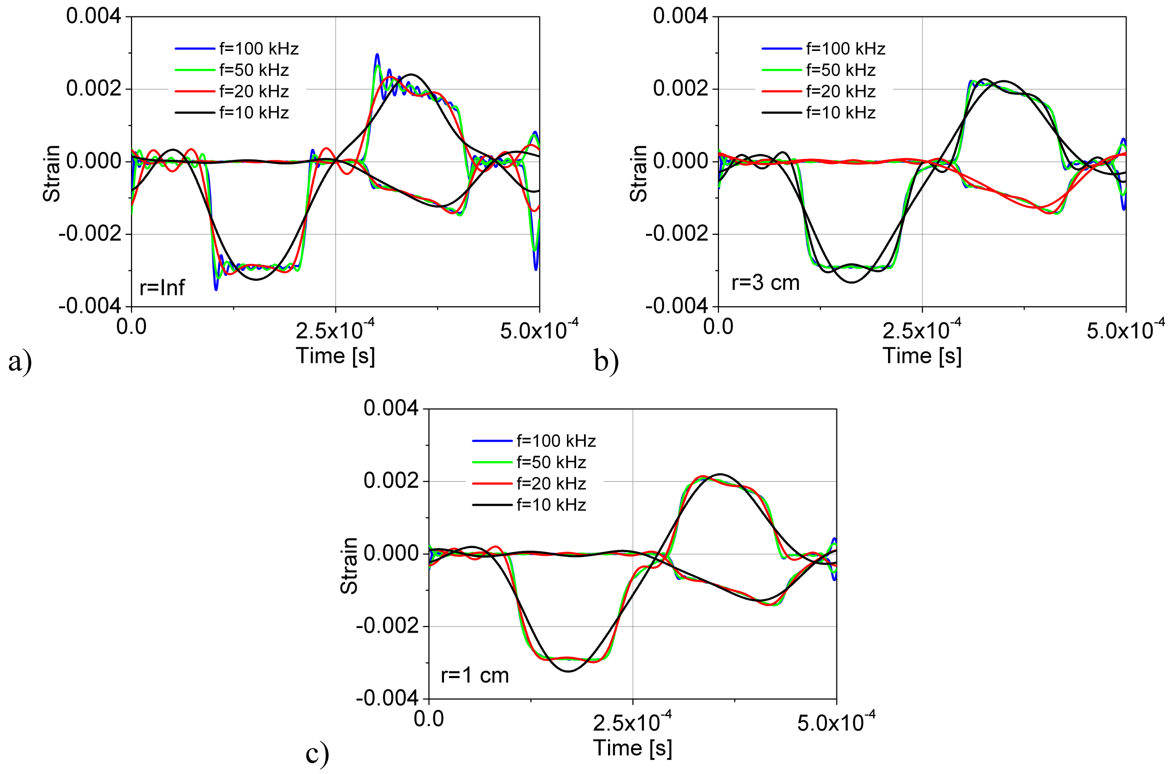

Fig. 8. Stain in bars at various bridge cut-off frequencies for: a) r=Inf; b) r=3 cm; c) r=1cm.

On the basis of the waveforms with the band limited by means of the low-pass filter, presented in Fig. 8, the material characteristics were determined using the equations (1-3). The results are presented in Fig. 9.

To make an objective assessment of the impact of the bandwidth of the measuring bridge and the geometry of the striker on the final result of the analysis performed by the Hopkinson bar method the relative measurement error was determined, described by the following equation:

$$\delta = \frac{\int_{\varepsilon=a}^{b} |\,\sigma(\varepsilon) - \overline{\sigma}(\varepsilon)\,|\, d\varepsilon}{\int_{\varepsilon=a}^{b} \overline{\sigma}(\varepsilon) d\varepsilon}, \tag{4}$$

where $\sigma(\varepsilon)$ and $\overline{\sigma}(\varepsilon)$ mean respectively the measured and reference stress-strain characteristics. The integration limits were assumed in the range from a = 0.002 to b = 0.55 that results from the yield strength of the material and the maximum plastic strain achieved during the test.

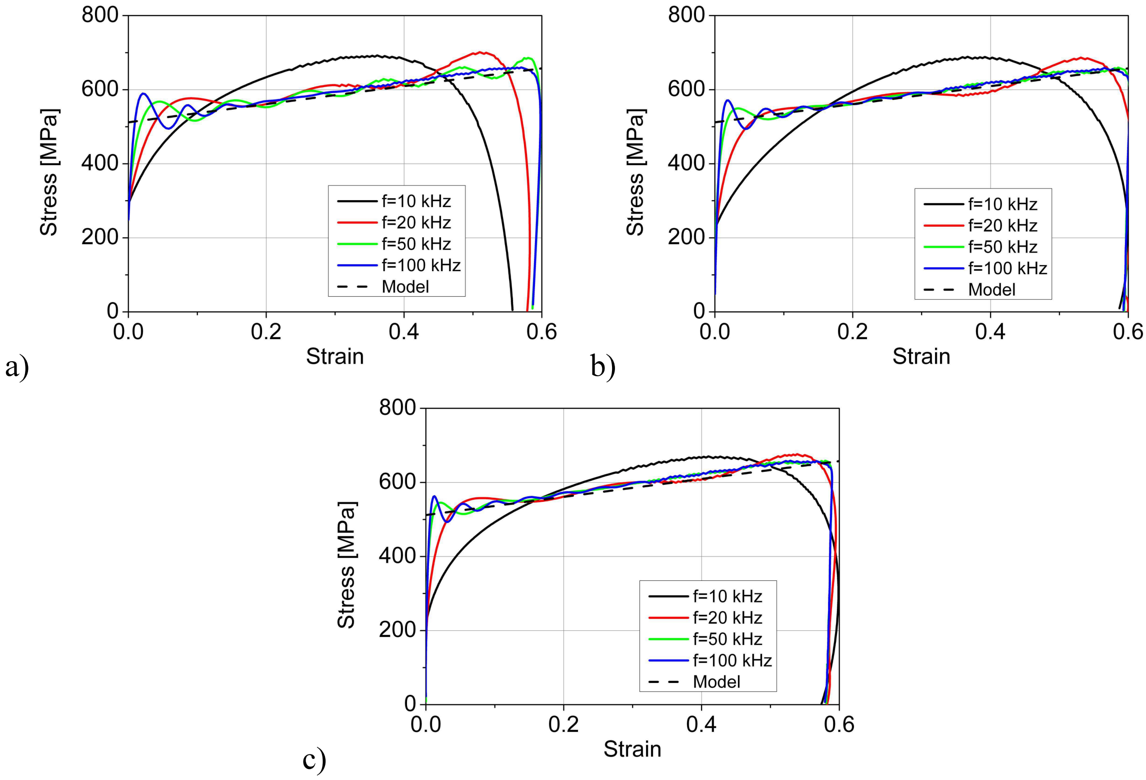

Fig. 9. Stress-Strain curves at various bridge cut-off frequencies for: a) r=Inf; b) r=3 cm; c) r=1cm.

4. Discussion

The influence of the striker geometry and bandwidth of the measuring bridge on the error of stress-strain characteristic determination is shown in Fig. 10. It can be observed that a increase in bandwidth reduces the measurement error. Increasing the bandwidth above 50 kHz does not cause an apparent reduction of discrepancy between the reference and measured characteristics. It can therefore be assumed that the tensometer measuring bridge with a bandwidth equal to 50 kHz is sufficient for use in the Hopkinson bar method in the discussed configuration.

The use of the rounded-end striker allows to reduce the error in relation to the flat-ended one, being said that a rounding radius has an effect on the resulting value of the measurement error. For the optimal bandwidth of the bridge, which was 50kHz, the lowest value of error was obtained for a rounding radius equal to 3 cm; further reduction of the radius caused an increase in the error value. Furthermore, the use of the striker with the rounding radius equal to 1 cm results in a slow rise of loading impulses thereby the time required to achieve a constant deformation rate is extended.

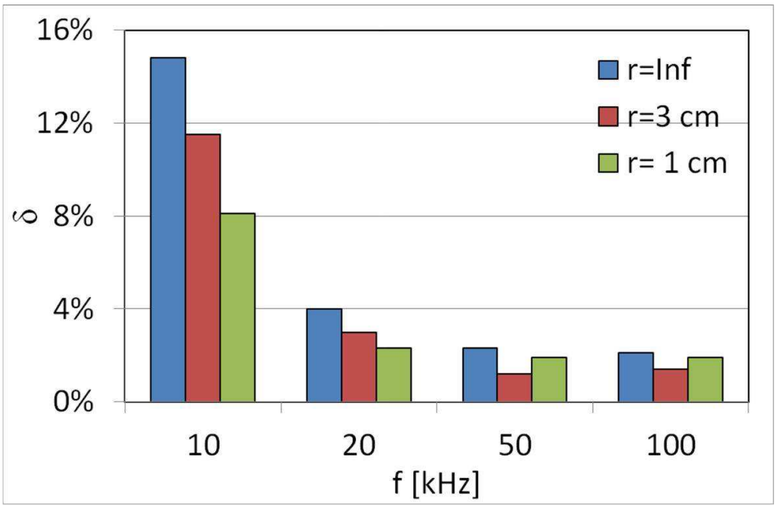

Fig. 10. Influence of striker geometry and bridge bandwidth on stress-strain error.

The influence of the striker shape on the course of the deformation rate is presented in Fig. 11. The nominal strain from equation (3) was recalculated into true values using the logarithmic formula i.e. $\varepsilon_{TRUE}=\ln(1+\varepsilon_{ENG})$ in order to determine the true strain rate value. With decreasing diameter of the rounding the shape of the loading pulses in the bar is smoother, and therefore the true strain rate curve calculated from equation (3) changes. To determine how fast the deformation rate achieves a constant value, the criterion equal to 90% of the average strain rate was introduced, which in the present case was 4500 s^{-1}. For any shape of the striker, the time after which the rate reached the assumed value was determined, as well as the plastic strain corresponding to this time. The results of analysis are shown in Table 1. As a result, a part of the stress-strain characteristics before reaching the 90% of assumed strain rate cannot be taken into account in the analysis of the results, because it was determined under specific conditions (non-constant deformation rate). In the case of the flat-ended striker and one rounded up to 3 cm in diameter the strain rate rise time was short enough to not significantly affect the measurement result. However, for 1 cm rounding the stress-strain characteristics in the range of strain less than 0.1 was determined at conditions different than the assumed ones.

Table 1. Loading impulse rise time and corresponding strain value at various striker geometries.

	r		
	Inf	3 cm	1 cm
t [μs]	0.007	0.018	0.036
ε	0.02	0.036	0.1

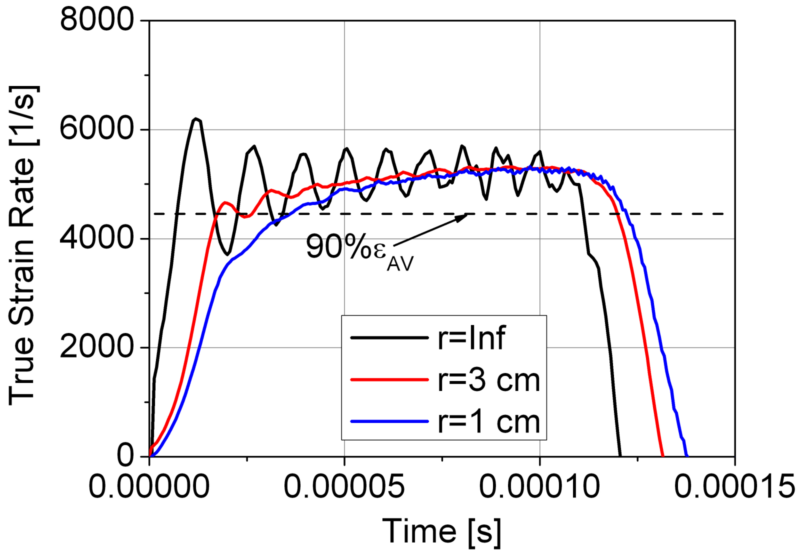

Fig. 11. I Influence of striker geometry on true strain rate curve.

Based on the carried out analyses it can be stated that:

- The optimum bandwidth of the tensometer bridge should be 50 kHz, and using broader band amplifiers cannot give a considerable improvement of the accuracy of the results, but it can significantly affect the increase in the cost of the device.
- The shape of the end of the striker has an impact on the shape of the loading pulses and their frequency spectrum. Reducing the rounding radius minimizes the waveform oscillation, but also adversely affects the signal rising time, and thus the time in which the strain rate stabilizes. Therefore, the striker ended with a radius of 3 cm was selected as the optimal shape.
- Using the Hopkinson bar method for characterizing the mechanical properties of materials at high strain rates it is necessary to perform a detailed analysis of the impact of the mechanical design of the test bench (dimensions and geometry of bars and the striker) and the measurement system (bandwidth) on the resulting stress-strain characteristics. As shown in the paper MES is a good tool for this purpose.

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