Numerical analysis of influence of length of the working part of specimen on dynamic diagrams of constructional materials obtained by the Kolsky method

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Abstract. It is known that experiments with intensive dynamic influences and high-speed deformation of specimens under tension are important in the analysis of deformations and strength of structures and their elements. The most reasonable and widely used method for obtaining dynamic stress-strain curves, characteristics of ultimate strength and deformations is the modified Kolsky method. It should be noted a small number of publications on the analysis of the influence of fillets and the length of the working part of the specimen on the most important mechanical characteristics obtained by this method. This work is aimed at increasing knowledge in this area. By numerical and experimental analysis it was established that when the working part of the specimen has a length of 5 mm, then the uniformity and one-dimensionality of the stressed state are seriously violated. When choosing the length of the specimen in the Kolsky method, there are important limitations: the length of the specimen must be much smaller than the length of the loading pulse. Therefore, in this study, two specimen lengths of 10 and 15 mm were analyzed. In this paper, we give experimental and calculated diagrams and their comparison with each other. It was shown, that for the above-mentioned lengths, the homogeneity and one-dimensionality of the stressed state is substantially improved.

1 Experimental and numerical analysis

In the dynamic testing of materials, there are complex transient processes caused by the interaction of loading and unloading waves. Consequently, the problem of numerical analysis of experimental schemes arises. During this analysis, the range of applicability of the test method can be established, as well as the main effects that can influence the interpretation of the experimental information. Also during the analysis, optimization of the loading parameters, shape and size of the specimen, optimization of materials for the units of the test installation have been carried out.

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The experiment on high-speed tension has an important place in the study of the behavior of materials. Various modifications of the Kolsky method have been proposed in [1-5] to obtain a tensile load in the working part of the specimen. This type of test is used both to determine the deformation diagrams under conditions of high-speed tension, and to determine the limiting characteristics (relative elongation δ, relative contraction at break ψ, and also time resistance $\sigma_{\hat{A}}$) used to identify the fracture models. Therefore, there is an interest in the experimental and numerical analysis of the scheme of dynamic tests, including the evaluation of the effect of the working part of the specimen length on the distribution of stress and strain fields.

It is known that in tensile tests, the length of the working part of the specimen must be of a definite size. This length should reduce the effect of the threaded part and the fixing conditions in the test machine on the uniformity of the stress-strain state in the working part of the specimen. On the other hand, in the experiments on high-speed tension in the working part of long specimens, the homogeneity of the stress-strain state is disturbed by the imposition of interacting loading and unloading waves repeatedly reflected from the fixing points and free surfaces of the specimen. Therefore, the specimen length must be sufficiently small that a homogeneous stress state is established in the working part during the time of the transition of the specimen to the plastic deformation mode. For tests using the Kolsky method and split Hopkinson bar (SHB) on uniaxial compression, there are specific recommendations for choosing the length-diameter relationship. However, the question of choosing the optimal specimen base used in the tensile test is still open.

In this regard, a series of tests of specimens with threaded heads made of aluminum alloy AK-4 with a diameter of 5 mm and a working length of 5, 10 and 15 mm was carried out, as well as numerical simulation of this type of test.

Dynamic tests were carried out at a strain rate of ~2000 s^{-1}. Figure 1 shows the stress-strain curves for different specimen geometry. The diagrams on the left illustrate the curves obtained at normal temperature, whereas on the right - at elevated temperature (200 °C).

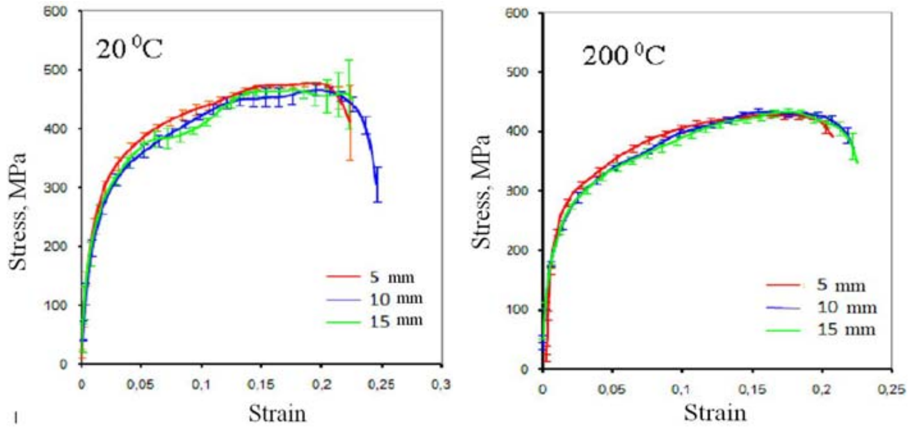

Fig. 1. The stress-strain charts obtained on specimens with different lengths of the working part

It can be seen that the diagrams obtained on specimens with a base of 5 mm are located higher than the deformation diagram of specimens with a base of 10 and 15 mm. It should be noted that on the curves with the working part of the specimen 15 mm, there are obvious oscillations.

Table 1 shows the results of determining the ultimate fracture characteristics for specimens of different geometries:

Table 1. Ultimate fracture characteristics obtained on specimens with different lengths of the working part.

Specimen length	**ψ, %**	**δ, %**	**σ_B, MPa**	**ψ, %**	**δ, %**	**σ_B, MPa**
	20 °C			**200 °C**		
5mm	36.86±2.94	23.16±1.5	476.6±8.35	34.97±1.83	24.66±2.0	468.3±16.36
10 mm	38.88±2.74	24.88±1.89	464±18.85	37.1±1.5	24.69±2.43	439.9±5.49
15 mm	38.54±2.34	28.78±1.73	457.14±9.87	43.56±0.93	26.67±1.54	445.7±12.45

Based on the results of the experimental studies, it can be concluded that the geometry of the specimen does not have a significant effect on the magnitude of the ultimate fracture characteristics.

To evaluate the influence of the length of the working part of the specimen on the uniformity of the stress-strain state, and also to evaluate the stress state index at the time of failure when specimens with different lengths of the working part were used, a numerical analysis of the impact tensile test with the use of the SHB modification was carried out.

The simulation of the process of specimen tension is shown in Fig. 2.

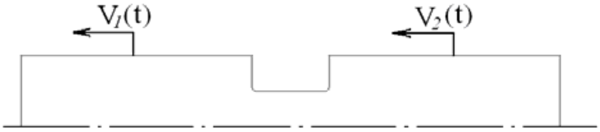

Fig. 2. Loading the specimen in the simulation

In this setting, the velocities are calculated on the threaded surface of the specimen, which are calculated from the deformation pulses in the measuring bars registered in the experiment. The velocities are determined by the formulas used in the Kolsky method, as follows [6, 7]:

$$V_1(t) = c\varepsilon_i(t) + (-c)\varepsilon_r(t) = c[\varepsilon_i(t) - \varepsilon_r(t)] \tag{1}$$

$$V_2(t) = c\varepsilon_t(t) \tag{2}$$

where c is the velocity of the longitudinal wave in the measuring bars, εi, εr и εt are the incident, reflected and transmitted deformation pulses in the measuring bars, respectively.

The force on the left end $P_1(t)$ is made up of the tensile force $P_1^i(t)$ caused by the impulse $\varepsilon_i(t)$ and the force $P_1^r(t)$ caused by the impulse $\varepsilon^r(t)$, and the force $P_2(t)$ at the right end is caused by the impulse $\varepsilon_t(t)$. Then, taking into account Hooke's law:

$$P_1(t) = EA\left[\varepsilon_i(t) + \varepsilon_r(t)\right] \tag{3}$$

$$P_2(t) = EA\varepsilon_t(t) \tag{4}$$

where *E* and *A* are the Young's modulus and the cross-sectional area of the rods, respectively. The average force in the sample is:

$$P(t) = \frac{P_1(t) + P_2(t)}{2} \tag{5}$$

Fig. 3 gives a comparison of the stress-strain curves in the calculation, as well as the ones reconstructed from it by the integral force and the average deformation of the stress-strain curve using specimen with different lengths of the working part. It can be seen that when using short specimens with a length of 5 mm, it is not possible to accurately determine the deformation diagram under the assumption of a uniaxial stress state.

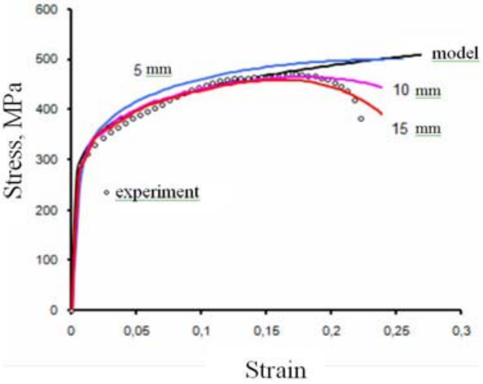

Fig. 3. Comparison of the calculated deformation diagram with the curves reconstructed from it.

Figure 4 shows the distribution of axial stresses and axial deformations on the axis of the working part of the specimen for different instants of time when using specimens with a working length of 5, 10 and 15 mm.

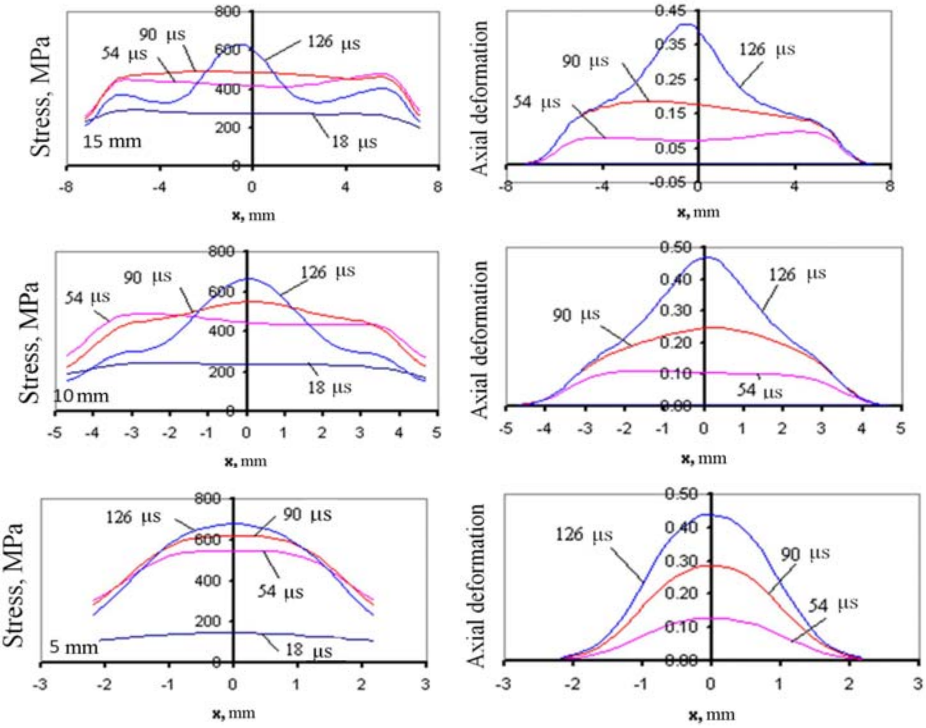

Fig. 4. Stress distribution (left) and deformations (right) along the axis of the working part of the specimen

The figure shows that by using the specimen with a small base the stress-strain state uniformity along the axis of the specimen is broken at an early tension stage.

Conclusions

Based on the results of calculations, the following conclusions can be drawn:

1. When using specimens with different lengths of the working part, the destruction occurs approximately at the same kind of stress state. However, the stress state differs for uniaxial tension, because at the time of neck formation a uniform tension is imposed on the uniaxial stressed state.
2. Equivalent deformation, calculated from the relative narrowing of the sample, adequately reflects local deformations in the neck region, while the corresponding value, determined by the relative elongation, gives an underestimate.

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