Experimental complexes for investigation of behavior of materials at a strain rate of $5{\cdot}10^2{\div}10^5$ s^{-1}

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Abstract. A description of experimental complexes, methodological and hardware means for determining the mechanical properties of materials under high-speed deformation and fracture is given in the report. Determination of mechanical properties in the strain rate range 5·102÷103 s-1 is the first direction of work in the laboratory of "Dynamic Materials Testing". These tests are done using automated complexes based on the Kolsky method and its modifications for compression, tension and shearing. It is also possible to determine the fracture toughness, the characteristics of dynamic crack resistance, as well as to obtain stress-strain curves of low-density materials under uniaxial strain. Original gas guns with a caliber of 10, 20 and 57 mm are used for creation a dynamic load. The study of the behavior of materials at strain rates of 105 s-1 and higher is the second direction of work. In this case, the methods of a plane-wave shock experiment based on gas guns of 57 and 85 mm caliber are used. Manganine and dielectric pressure sensors, as well as laser interferometry are used for measuring the parameters of elastoplastic waves and for determining such important characteristics as impact compressibility, Hugoniot yield strength, spall strength.

1 Introduction

There is considerable interest in research into the problems of high-speed deformation and the destruction of materials of various physical nature in the last ten years. This is due to the need to calculate the stress-strain state and the strength of the structures of aerospace, automotive, and power engineering. They undergo intense dynamic impacts as a result of man-made accidents, terrorist attacks and natural disasters. A technique is used that realizes a uniaxial stress state and a technique for uniaxial deformation (in plane load waves). The choice of technique depends on the speed loading conditions of the study of the dynamic properties of materials.

The Kolsky method using the Split Hopkinson Pressure Bar (SHPB) is most widely used among the dynamical methods known to date for a uniaxial stress state. It has a good

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theoretical justification and is easy to implement. The first time the method appeared in the late 1940s [1] but only after the 1970s it became very popular. This technique allows testing a wide set of materials in the strain rate range of $10^2 \div 10^4$ s^{-1}. A large bibliography describing the history of the development of this method is presented in the survey papers [2,3]. SHPB and its modifications are used to determine dynamic stress-strain curves, ultimate strength and deformation properties of a wide range of structural materials, both at normal and elevated temperatures.

Dynamic tests under conditions of uniaxial deformation are realized in plane load waves created by the charge of explosives. Another variant of the dynamic tests is carried out when the flat plates are accelerated by means of gas guns. The parameters of shock or elastoplastic waves in these experiments are determined using modern techniques, such as manganine and dielectric sensors, laser interferometers. A detailed review of the methods and means of a plane-wave experiment is presented in the book [4].

2 Experimental complex for investigation of high-speed deformation and fracture of materials

A set of experimental facilities for studying the behavior of various materials over a wide range of strain rates ($\dot{\varepsilon}=10^2$-10^5 s^{-1}) and loads up to 5 GPa was developed, manufactured and assembled (Table 1). This complex implements almost all known to date advanced testing and registration techniques. It allows to conduct a wide range of studies of materials of various physical nature: metals and alloys, composites and ceramics, soils and rocks, wood, polymers, etc.

The Kolsky universal technique is used in the strain rate range $5 \cdot 10^2$ - $5 \cdot 10^3$ s^{-1}. This technique allows to obtain stress-strain curves of materials under various types of loading (tension, compression, shear, cyclic alternating loading). It is possible to estimate the influence of the effects of the strain rate history, to investigate the dynamic crack resistance, to determine the dynamic hardness, to investigate the Bauschinger effect, and so on [5]. Dynamic compressibility and shear strength are investigated when testing materials in a rigid confining cage (the condition of one-dimensional deformation). The method of direct impact is also used to expand the speed range (up to 10^4 s^{-1}).

The technique of the plane-wave shock experiment is used at large (10^4-10^5 s^{-1}) strain rates and loads up to 3-5 GPa. This technique realizes the collision of flat plates with the recording of parameters of the shock wave in the specimen. It allows to investigate the dynamic compressibility of materials, as well as spall and shear strength.

3 A set of installations that implement the Kolsky method

Structurally, the traditional version of SHPB is made of two thin long bars with a high yield strength. Between the rods is a small sample of the material being studied. The yield point of the measuring rods is higher than the yield point of the sample. The system of sample rods is loaded with elastic pulses. Pulses are recorded using strain gauges placed on measuring rods. Then, based on the one-dimensional theory of elastic waves, a dynamic diagram of the deformation of the sample is constructed.

The Kolsky method is realized with use of gas guns and measuring bars with a diameter of 10, 20 and 60 mm to expand the spectrum of the materials investigated and to study the scale effect.

The installation of SHPB-10 allows testing only fairly uniform materials (metals and alloys, polymers) under compression and tension. The SHPB-20 has all the basic types of testing of structural materials: compression and tension under conditions of a one-dimensional stressed state, compression under uniaxial deformation, cyclic alternating loading, shear, fracture toughness studies, dynamic hardness.

Table 1. Composition of the experimental complex.

Installations that implement the Kolsky method and its modifications					
The name of the installation and the caliber of the gas gun	**Rate of throwing, m/s**	**Material of measuring bars**	**Strain rates, 1/s**	**Types of tests**	**The characteristics obtained**
SHPB-10 (10 mm)	3-100	Steel, titanium	$5\cdot10^2$ – $5\cdot10^3$	Uniaxial compression, tension	diagrams $\sigma_x \sim \varepsilon_x$, σ_{02}, $E_{упр}$, δ, ψ
SHPB-20 (20 mm)	5-50	Steel, duralumin, titanium, vinyl plastic	$5\cdot10^2$ – 10^4		
				Splitting	diagrams $\sigma_t \sim t$
				Uniaxial deformation	Compressibility $\sigma_x \sim \varepsilon_x$, $P \sim \theta$, $P \sim \rho$, shear strength $\tau \sim P$
			10^4 – 10^5	Shear	diagrams $\tau \sim \gamma$
			10^3 – 10^4	Crack resistance	K_{IC},
			$\sim10^3$	Hardness	HD
			$\sim10^4$	Direct impact	diagrams $\sigma_x \sim \varepsilon_x$
			$\sim10^3$	Coefficient of friction	f_{st}, f_{dyn}
SHPB-60 (57 mm)	5-50	Steel, duralumin, titanium	$3\cdot10^2$ – $2\cdot10^3$	Uniaxial compression, splitting, uniaxial deformation	diagrams $\sigma_x \sim \varepsilon_x$, σ_{02}, $E_{упр}$, $P \sim \theta$, $\sigma_t \sim t$, shear strength $\tau \sim P$
GG-10, GG-20	50-200	Steel	10^3 – 10^4	Modified Taylor Test	Residual form, σ_{02}, pulse $\varepsilon(t)$

Plane-wave testing plants					
The name of the installation and the caliber of the gas gun	**Thrown masses**	**Rate of throwing, m/s**	**Registration Tools**	**Measured parameters**	**The characteristics obtained**
GG-57 (57 mm)	Up to 100 g	50-450, 100-800 (helium)	Manganine pressure sensors, dielectric sensors, laser interferometer	The speed of the impactor, the velocity of plane waves, the method of reflection	Shock adiabat $D \sim U$, $\sigma_x \sim U$ и $\sigma_x \sim \varepsilon_x$
GG-85 (85 mm)					

Non-uniform materials (fine-grained concrete and mortars, bricks, rocks, ceramics, composite materials, fine-grained soils) with the size of inhomogeneities up to 2-3 mm can be tested, in addition to the above homogeneous materials. Installation SHPB-60 is designed to study structurally heterogeneous materials and media with inclusions up to 10-15 mm (ordinary concrete, real soils).

The modification of Kolsky method [6, 7] is used to carry out dynamic tests of loosely coupled materials (soils). The test soil specimen is located between the ends of the measuring bars in the rigid casing limiting the radial extension of soil. In the specimen, an axially symmetric volumetric stress state arises after some time, since a rigid cage prevents the radial deformation of the sample. This version of the Kolsky method allows one to determine the lateral pressure coefficient or Poisson's ratio, the volume compressibility curve, and the dependence of shear resistance on pressure. Also obtain diagrams of uniaxial compression of a soil specimen (under conditions of a one-dimensional deformed and volume stressed state).

4 A complex of installations realizing a plane-wave shock loading

To study the behavior of materials at strain rates of 10^5 s^{-1} or more, a set of installations is used with gas guns of caliber 57 and 85 mm as loading devices and measuring techniques based on dielectric or manganin pressure sensors and laser interferometers.

It should be noted that the stress-strain state in the shock wave is characterized by the same components as when testing materials using the modified Kolsky method in a rigid cage, i.e. one-dimensionality of deformation. This allows us to compare the results obtained by these two methods.

The VISAR laser interferometer is used to study elastoplastic properties and spall strength of metals and alloys as a method for studying the structure of plane waves. The processing of the obtained interferograms made it possible to determine the Hugoniot yield strength and the maximum tensile stress in the plane of splitting (spalling strength).

5 Researching results

As an example, the results of the investigation of the dynamic properties of some materials are given. Figure 1 shows the dynamic diagrams for oxygen-free copper M1 (analogue C101) during compression in the delivery state and after annealing.

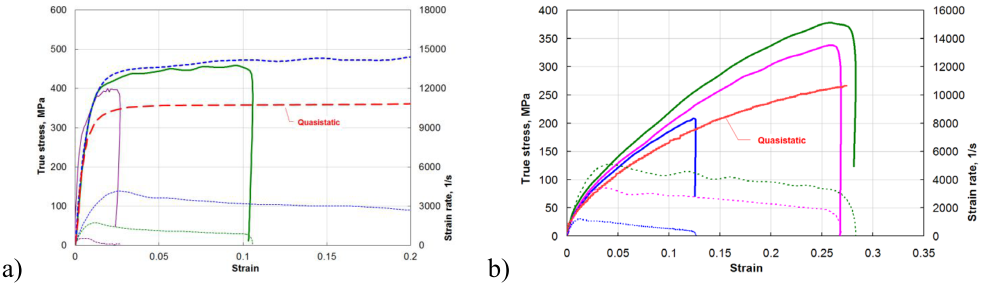


Fig. 1. The behavior of copper in the state of delivery (a) and after annealing (b).

It can be seen that in the annealed state the strain hardening curves diverge as a fan, which is typical for FCC (cubic face-centered lattice) metals.

Austenitic chromium-nickel stainless steel type 08H18N10T (analogue AISI 321) is widely used not only in the manufacture of medical and household tools, but also as a structural material of nuclear power plants. Figure 2 shows the average static and dynamic stress-strain diagrams of the steel under compression and tension at different temperatures. It can be seen that the temperature of the test has a significant effect on mechanical properties: as the temperature rises, the diagrams go lower and the steepness of the hardening section decreases slightly. Static diagrams in compression have a smaller slope of the hardening section than dynamic ones. Static diagrams are located significantly lower than the dynamic ones under tension.

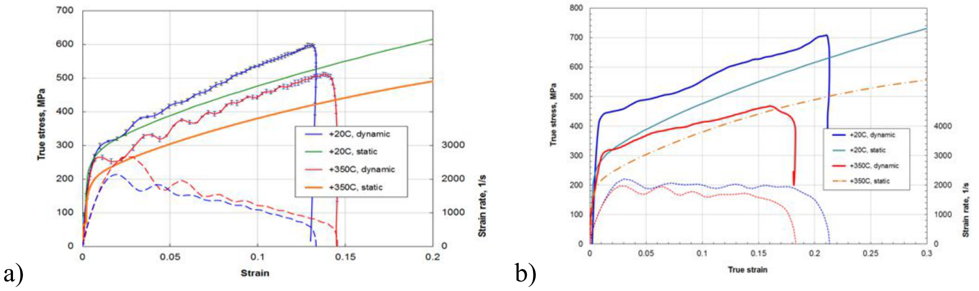
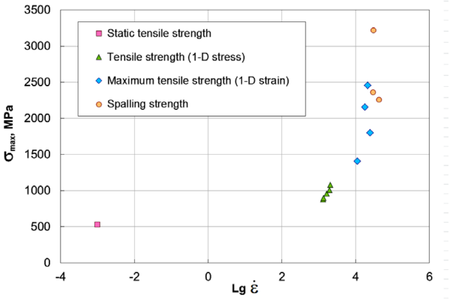


Fig. 2. Average diagrams of deformation of stainless steel under compression (a) and tension (b) at different temperatures.

The tensile strength of this steel obtained under static loading and dynamic loading by the Kolsky method in the conditions of a uniaxial stressed state is shown in Fig. 3. The spalling strength is also shown for plane-wave shock loading under uniaxial deformation.



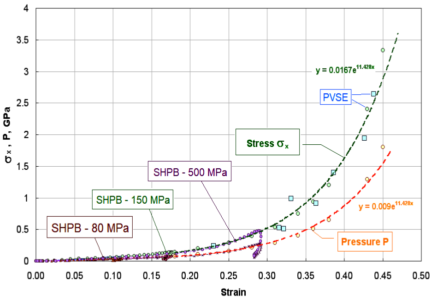


Fig. 3. Dependence of the maximum tensile stress on the logarithm of the strain rate for stainless steel.

Fig. 4. Unified curves for the dynamic compressibility of dry sand.

It can be clearly seen that the joint use of the Kolsky method and plane-wave shock experiment significantly expands the speed range of research on the dynamic strength of materials.

A method was proposed [8] for determining the basic regularities of deformation of soft soils under dynamic loading in the range of load amplitudes up to several gigapascals. This technique is based on the joint use of the results of high-speed tests under conditions of uniaxial deformation. These results were obtained by the modified Kolsky method (SHPB) and the plane-wave shock experiment (PVSE). Figure 4 shows the total curves of the dynamic compressibility of dry sand (dashed lines) in the axes σ_x~ε_x and P~ε_x.

It can be seen that the use of two complementary methods makes it possible to investigate the dynamic compressibility of low-dense media (for example, the soil) over a wide range of load amplitude changes.

Conclusions

The mechanical properties of structural materials during high-speed deformation using the described complex of experimental installations, methodical and hardware are determined. The results of the study of the behavior of oxygen-free copper, stainless steel, low-density chamotte and dry sand are presented. The effect on the mechanical properties of the strain rate, the mode of stress-strain state and the test temperature is noted.

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