STUDY OF HIGH-RATE COOPER STRAIN BY SPLIT HOPKINSON BARS METHOD

Yu.A. Garmashev, S.M. Dolgykh, A.I. Klyonov, E.A. Petukhov, K.S. Sidorov, E.B. Smirnov, M.A. Shistirikov, D.T. Yusupov

RFNC-VNIITF, Snezhinsk, Russia

Dynamic strain of materials is studied for more than half a century. However such investigations result in different, often hard-comparable characteristics. Reliability and comparability of investigation results is defined, first of all, by scientific validation of high-speed material test setup. One method, which provides clear theoretical basis, high efficiency, universality and reliability of the obtained results is the split Hopkinson bars (SHB) method or Kolsky method. This method falls within the class of tests with constant strain rate $\dot{\varepsilon}$=const; it allows one to study dynamic diagrams of compression and tension at strain rates $\dot{\varepsilon}=10^2$-10^4 s^{-1}.

Description of the facility

Operating principle of the facility is based on acceleration of cylindrical impactor (steel, titanium, aluminum alloy, etc.) of length 200-500 mm by compressed air pumped into high-pressure chamber. Air pressure accelerates the impactor, which strikes split Hopkinson bar end and excites a compression wave. Hopkinson bar comprises two bars made of high-strength steel with yield limit above 2400 MPa, test material sample being placed between them. Bar strains are measured by strain gauges bonded to loading and support measuring bars. A schematic diagram of the facility is presented in figure 1.

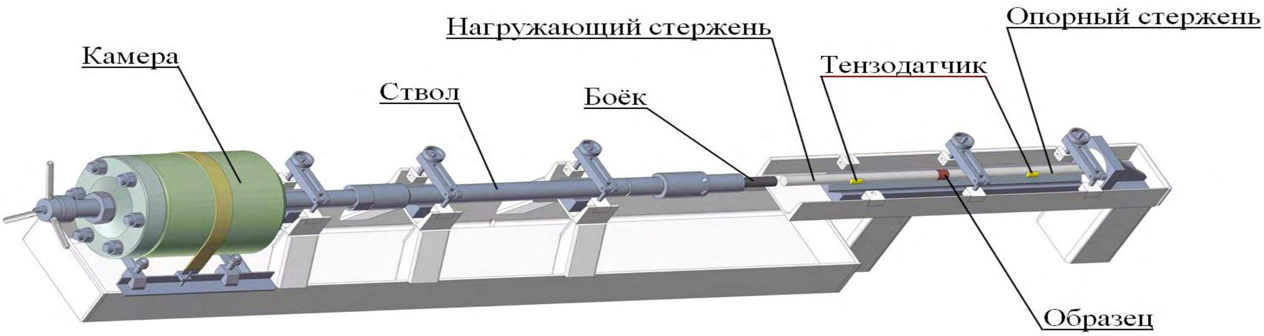

Figure 1. Schematic diagram of split Hopkinson bar

By theory [1], when developing relations to calculate sample stress σ and strain ε it is assumed that time of wave travel along the sample is substantially shorter than load pulse length and sample stress-strain state is near homogeneous. Then elastoplasic strain of the sample is a steady process (similar to quasistatic one), but it proceeds at high strain rates (up to ~10^4 s^{-1}).

In the sample parametric dependences $\sigma(t)$, $\varepsilon(t)$ $\dot{\varepsilon}(t)$ are determined based on experimental records of elastic strain in loading $\varepsilon_I(t)$ and transmitted $\varepsilon_T(t)$ stress waves (in loading and support bars, correspondingly) by the following formulas [2]:

$$\sigma(t) = \frac{ES}{S_S^0}\left[\varepsilon_T(t)\right]; \quad (1)$$

$$\varepsilon(t) = \frac{2C}{L_0}\int_0^t \left[\varepsilon_I(t) - \varepsilon_T(t)\right]\cdot dt; \quad (2)$$

$$\varepsilon(t) = \frac{2C}{L_0}\left(\varepsilon_I(t) - \varepsilon_T(t)\right), \quad (3)$$

where S_S^0 is reference cross-section area of the sample, S is cross-section area of measuring bars, E is an elasticity modulus of measuring bars, C is longitudinal wave velocity in bars, L_0 is initial sample length. Excluding time t parameter, diagrams of sample strain σ-ε, as well as strain rate vs. strain $\dot{\varepsilon}$ ~ε are plotted.

Using the facility one can analyze stress-strain and stretch diagrams, localized shift, cracking resistance, Bauschinger effect and other material characteristics at strain rates of $\dot{\varepsilon}$ ~10^2-10^4 s^{-1}. Test type mode in Hopkinson bar facilities is changed fairly easy. To do this would require another type of samples and bars with modified geometry in sample attaching point. Loading and recording modes of bar elastic strains remain as before. When needed strain-strength characteristics of structural materials can be investigated using Taylor process at strain rates $\dot{\varepsilon}$ ~10^4-10^5 s^{-1}. In this case facility assemblies slightly differ, that is, using the pneumatic system the sample is accelerated, strikes a bar and then it is strained (prior to failure, if necessary).

Measurement procedure

The test procedure involves strain measurement in stress waves in loading and support measuring bars using standard foil strain gauges. Strain gauges (see Fig. 1) are bonded to generating surface at a distance of 4-5 diameters from loading edge (loading bar) or the edge touching the sample (loading and support bars).

To provide compensation for bending vibrations in bars and to increase useful signal amplitude, two series-connected strain gauges are bonded in useful cross-sections. While the test process records only dynamic strain component, the potentiometric circuit is chosen to power strain gauges due to its simplicity and potential power supply of several measurement channels by a single source. Both groups (of strain gauges on support and loading bars) are direct-current supplied from standard stabilized power unit through original power and calibration circuits. Gauge signals are recorded by storage oscillograph.

Results of investigations

As part of investigations ten experiments were conducted with cooper samples of diameter Ø10x5 mm. The impactor velocity was 12,3-17,9 m/s, strain rate $\dot{\varepsilon}$ was 2030-2850 s^{-1}.

Figure 2 shows typical oscillogram of strain pulses in one experiment.

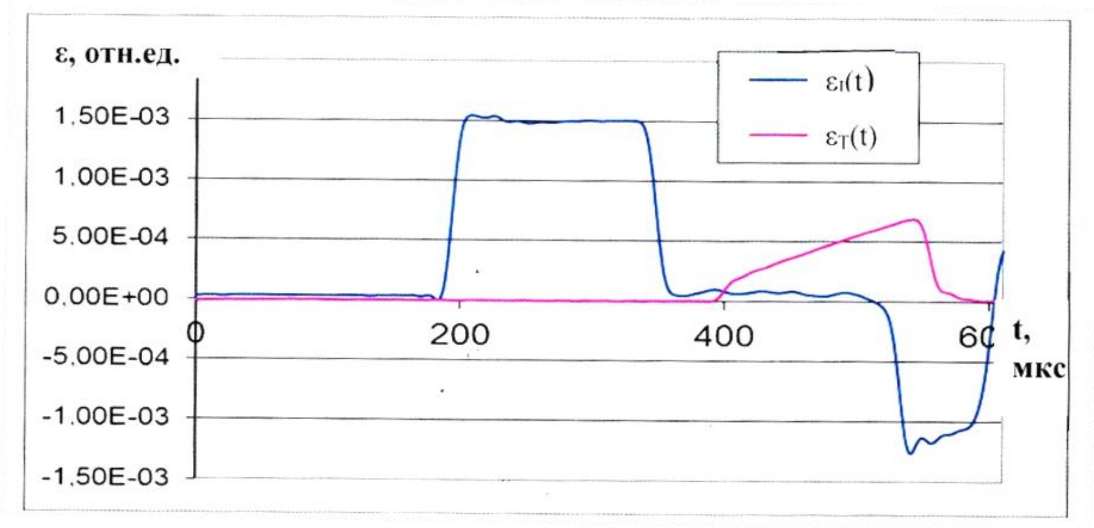

Figure 2. Typical oscillogram of strain pulses for loading $\varepsilon_I(t)$ and transient $\varepsilon_T(t)$ stress waves in one experiment

In experiments the samples suffered plastic strain without failure, being decreased in height by 1,5-2,4 mm (see Figure 3).

а б в г

Figure 3. Initial and tested samples at different strain rates $\dot{\varepsilon}$: б – 2150 s^{-1}, в – 2100 s^{-1}, г – 2360 s^{-1}

The end profile of tested samples has a form of irregular circuit with a spread in minimum and maximum diameters from 12 up to 15 mm.

Figure 4 presents σ-ε diagrams for complete set of experiments in dynamic cooper compression.

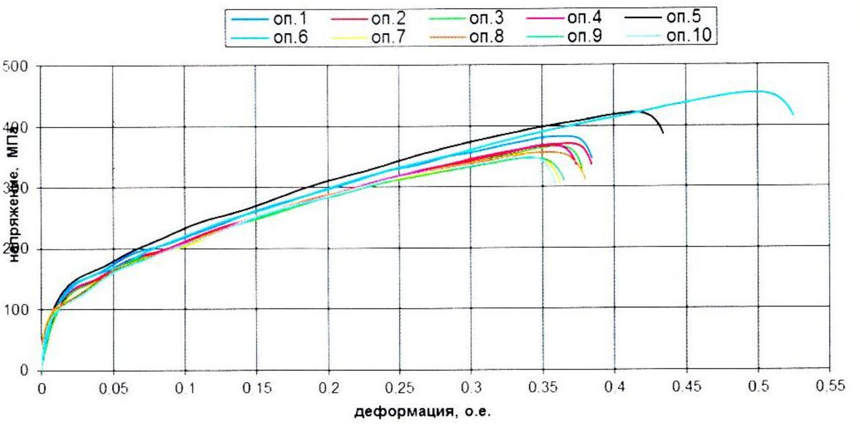

Figure 4. σ-ε diagrams for complete set of experiments

Analysis of the results

It is seen from figure 4 that under different strain rates σ-ε diagrams differ little from each other, while possessing about the same strain hardening. Diagrams for experiments No 1-4, 7-10 were plotted at $\dot{\varepsilon}$ =2030–2160 s^{-1}, and diagrams for experiments No 5 and No 6 were plotted at $\dot{\varepsilon}$ =2360 s^{-1} and 2850 s^{-1}, but in general they differ only in increased value of residual shortening at higher $\dot{\varepsilon}$: $\varepsilon_{ocm.}$=31-33 % in experiments No 1-4, 7-10 and $\varepsilon_{ocm.}$=40 % and 48 % in experiments No 5 and No 6.

The results of complete set of experiments with copper are given in Table 1. In addition to strain rate and residual shortening the Table presents yield limits $\sigma_{0,2}$ found from diagrams for each experiment.

Table 1. Experimental results

Experiment No	Strain rate $\dot{\varepsilon}$, s^{-1}	Residual shortening $\varepsilon_{ocm.}$, %	Yield limit $\sigma_{0,2}$, MPa
1	2150	32,0	68,5
2	2100	31,5	66,2
3	2100	31,0	64,0
4	2060	31,0	65,3
5	2360	40,0	73,0
6	2850	48,0	70,0
7	2080	32,3	62,8
8	2160	34,0	65,0
9	2080	32,5	71,2
10	2030	32,0	67,0

Numerical simulation commonly uses empirical constitutive relations, in which the yield surface is represented by the function of strain ε, strain rate $\dot{\varepsilon}$ and temperature T:

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T). \tag{4}$$

The simplified additive or multiplicative form of this function is most frequently used:

$$\begin{aligned} &\sigma = f_1(\varepsilon, T), \\ &\sigma = f_1(\varepsilon, T) f_2(\dot{\varepsilon}, T) f_3(T) + f_2(\dot{\varepsilon}, T). \end{aligned} \tag{5}$$

In most models the effects of high-speed hardening and thermal softening are thought to be independent and represented by individual multipliers:

$$\sigma = f_1(\varepsilon) f_2(\dot{\varepsilon}) f_3(T). \tag{6}$$

The function f_1 normally represents a linear combination of power or exponential functions of ε [3].

The most common model used in dynamic calculations is Johnson-Cook model (JC) [4]. The JC model for isotropic hardened material connects equivalent Mises stresses with equivalent plastic strain ε and strain rate $\dot{\varepsilon}$ by the following expression:

$$\sigma = (A + B\varepsilon_p^n)(1 + D\ln\dot{\varepsilon})\left(1 - T^{*m}\right), \tag{7}$$

where σ is strain, ε_p is plastic strain, $\dot{\varepsilon}$ is strain rate, A is yield limit, B is hardening response, D is strain-rate hardening constant, n is strain-hardening exponent, m is temperature dependence factor, $T^*=(T-T_{room})/(T_{melt}-T_{room})$, T is absolute instantaneous sample temperature, equal to the sum of initial absolute test temperature T_{room} and temperature increment of the sample under elastic strain (calculated from energy capacity), T_{melt} is melting temperature.

In this paper, the temperature term in equation (7) is not accounted for in approximation. Complete data set obtained during the experiments is approximated by equation (7) using the method of non-linear regression by Levenberg-Macvert algorithm. Approximation results are shown in figure 5.

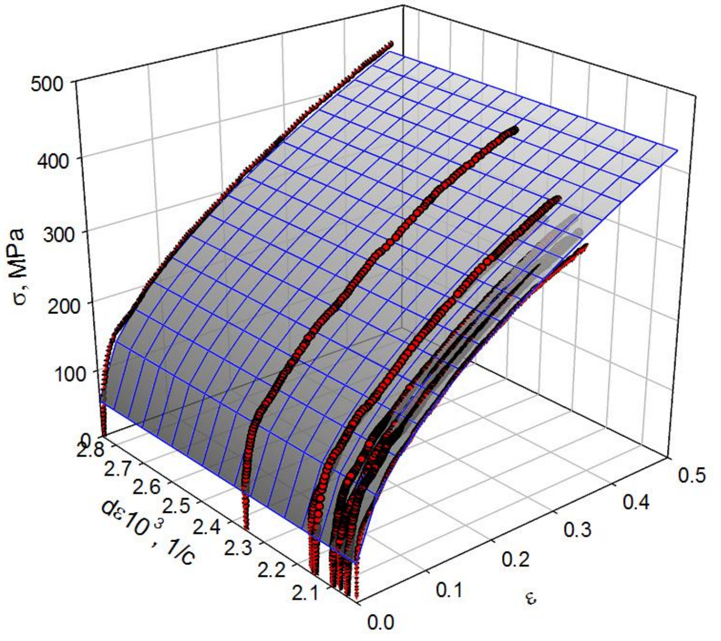

Figure 5. Cooper strain $\sigma = f_1(\varepsilon) f_2(\dot{\varepsilon})$ diagram

Figure 5 presents experimental data and approximating surface (7). Approximation has resulted in the following approximating parameters: A – 50±6 MPa, B – 544±66 MPa, D – 0,01, n – 0,572±0,006.

The derived constitutive equation in a Johnson-Cook form is expected to improve precision in describing dynamic cooper strain in numerical simulation of shock-wave processes.

References

1. Kolskii G. Study of mechanical properties of materials at high loading rates.// Mechanics, 1950, issue 4, pp. 108-128.
2. Zukas Jh. A., Nikolas T., Swift Ch. F. et al. Impact dynamics.// M.: Mir, 1985, p. 296.
3. Patrick L. Strain rate sensitivity of automotive sheet steels: influence of plastic strain, strain rate, temperature, microstructure, bake hardening and pre-strain.// Genehmigte Dissertation, April 2010.
4. Johnson G.R., Cook W.H. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures// Proceedings of the 7th International Symposium on Ballistic. Hague, Netherlands, 1983. P. 541–547.