– от $0{,}75\times10^3$ до $2{,}8\times10^3$ 1/с. В работе приведены диаграммы напряжение-деформация и скорость деформации-деформация.

Проведен сравнительный анализ результатов исследования образцов, изготовленных с помощью аддитивных технологий, с табличными данными стали, изготовленной традиционным способом.

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INVESTIGATING HIGH-RATE DEFORMATION OF STAINLESS STEEL MADE BY ADDITIVE FABRICATION (3D PRINTER) USING SPLIT HOPKINSON PRESSURE BARS TECHNIQUE

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Investigation of mechanical and physical properties of materials exposed to intensive impact loading and high-rate deformation is of great scientific and practical interest owing to development of a number of new branches of technology, and due to development and industrial introduction of new advanced material processing approaches.

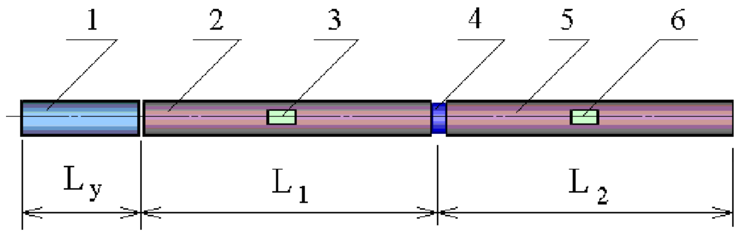
Additive fabrication is currently considered as one of the fastest growing lines of “digital” production. “Additive fabrication” (often named as 3D-technologies) indicates a general name for technologies implying that a physical object (a workpiece) is built by layer-upon-layer deposition (“adding”) of some material from digital model (CAD-model) engineering data, as opposed to conventional techniques of workpiece formation at the cost of material subtraction out of the blank array [1].

Such techniques and facilities as cam plastometers, drop-weight tests, dynamic deposition method, ring deposition driven by electromagnetic field or pulse have become very popular in practice of impact testing of the structural materials mechanic properties. Dramatic progress in impact testing was achieved in the past decades by the application of the split Hopkinson pressure bar system by Kolsky.

This technique allows a wide range of materials to be tested and stress-strain dynamic curves to be studied within the strain rate range of $\dot{\varepsilon}=10^2\text{-}10^4$ sec^{-1} [2].

A research facility comprises two long measuring bars (incident and transmitter ones) with rather high yield point and a thin pelletized specimen inbetween their angles. The elastic compression impulse of specified amplitude and duration is excited in the incident bar. Going toward the specimen this impulse, owing to the acoustic stiffness difference of the bar and specimen materials, is divided: one part of the impulse reflects from the boundary back into the incident bar, while another part passes through the specimen into the transmitter bar. Bar strains are measured with strain gauges bonded onto the incident and transmitter measuring bars.

Installation diagram is presented in Figure 1.



1 – striker bar, 2 – incident bar, 3 and 6 – strain gauges,
4 – specimen, 5 – transmitter bar

Figure 1. The schametic of SHPB technique

When deriving basic relations of SHPB technique it is suggested that in view of extreme short length of a specimen as compared with the length of loading impulse, the uniaxial stress state with uniform distribution of stress and deformation along its length is implemented in specimen during testing. Thus, in despite of the specimen high strain rates (up to ~10^4 sec^{-1}), the test can be considered as quasi-static.

The parametric dependencies $\sigma(t)$, $\varepsilon(t)$ $\dot{\varepsilon}(t)$ in the specimen are determined based on the experimental records of elastic strain in loading $\varepsilon_I(t)$ and transient $\varepsilon_T(t)$ stress waves (in incident and transmitter bars correspondingly) according to the following formulas [3]:

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

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

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

where S_S^0 – initial cross-sectional area of the specimen, S – cross-section area of measuring bars, E – elasticity modulus of measuring bars material, C – longitudinal wave velocity in bars, L_0 – specimen original length.

From the obtained parametric dependencies we exclude time and build a strain curve σ-ε of a specific specimen and strain rate versus strain curve $\dot{\varepsilon}$ ~ε.

The facility permits to explore compression and stress-strain curves, localized shift, fracture resistance, Bauschinger effect and other material properties at strain rates $\dot{\varepsilon}$ ~10^2-10^4 sec^{-1}. Changing of test mode in the split Hopkinson pressure bar facilities appears to be fairly simple. The process needs applying the other specimen types and bars of modified geometry in a specimen fixturing point. Loading and recording mode for bars elastic strain remains the same.

Strains elastic impulses in measuring bars are measured with resistance strain gauges bonded onto their side surfaces. The following strain impulses being material "responses" onto the applied load are recorded: loading $\varepsilon^i(t)$, reflected $\varepsilon^r(t)$ and passed $\varepsilon^t(t)$ through the specimen impulses. Resistance strain gauges (see Figure 1) are bonded onto the resulted surface at a distance 4-5 diameters of loading face (incident bar) or of specimen contacting face (incident and transmitter bar).

We selected a potentiometric circuit as a power source for resistance strain gauges owing to its simplicity and supply capability for several measuring channels from one source. Both groups of resistance strain gauges on transmitter and incident bars are powered with direct current from a conventional constant-current power unit via original feed and calibrating circuits. Gauge signals are recorded with a storage oscilloscope.

Additive Fabrication indicates a general name of techniques implying that objects from 3D model data (or CAD-model) are made by adding material layer upon layer as usual.

As opposed to subtractive manufacturing technologies, when material is removed step-by-step from a blank till obtaining the needed shape and size, in this case an object is fabricated layer-by-layer, stepwise by forming (in some manner or other) a material layer, hardening or fixing that layer according to the CAD-model cross-section configuration and joining each subsequent layer with preceding one.

Specimens of steel 12X18H10T were fabricated by Selective Laser Sintering (SLS) on the basis of Snezhinsk Physical and Technical Institute — Scientific and Research Nuclear University "MEPI" with a commercial 3D printer.

Figure 2. Specimens of steel fabricated with 3D printer

Table 1 presents chemical composition determinations of specimens material

Table 1. Specimens chemical composition

Specimen	Element mass content, %				
	Cr	Ni	Ti	Mn	Si
Specimen 1	17,2	10,5	0,55	0,61	0,63
Specimen 2	17,4	10,0	0,56	0,58	0,66
Specimen 3	17,3	10,7	0,56	0,60	0,72
12X18H10T GOST	17,0-19,0	11,0-13,0	5 x C-0,80	≤2,00	≤0,80

By convention, as to content of basic alloy elements, the material of specimens under investigation fits into a group of stainless steel of type X18H10T as per GOST5632-72 standard.

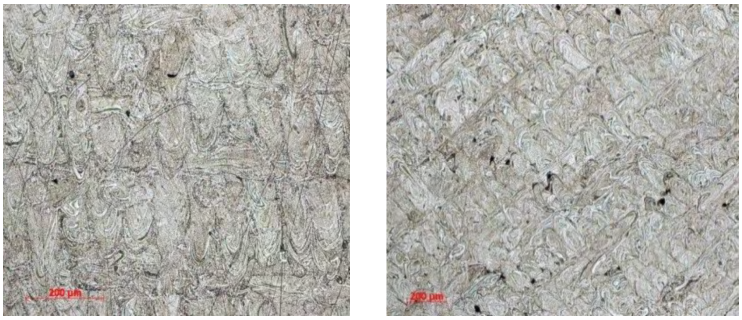


Figure 3. AT-stainless steel, material structure, optical photos

In Figure 3 one can observe the ordered structure, apparently, due to a laser movement without well-pronounced grain boundaries that could indicate a rapid-solidification process. For the same reason a grain has got smaller size as compared for 12X18H10T (see Figure 4).

As part of the study the set of experiments with specimens AT of stainless steel Ø8x4 mm was conducted. The impact velocity was 7,24-13,88 m/sec, specimen deformation intrinsic rates varied from $0{,}75\times10^3$ to $2{,}8\times10^3$ 1/sec.

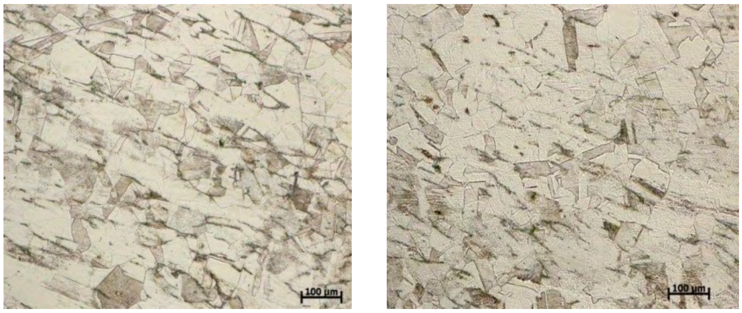


Figure 4. Conventionally fabricated stainless steeel, material structure, optical photos

Figures 5, 6 present the curves set of specimen dynamic loading obtained at different impact velocities. Solid lines indicate “stress-strain” dependencies and dashed lines indicate “strain rate” dependencies. Figures indicate specimens numbers.

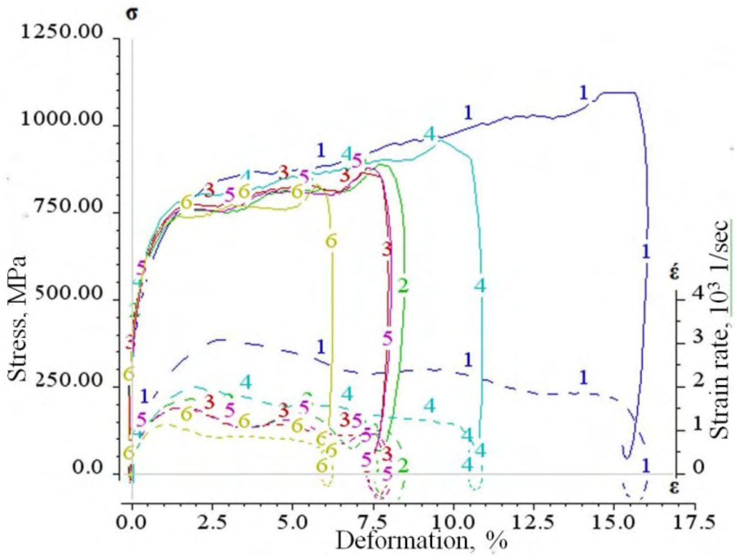


Figure 5. Curves family «σ - ε» of the first set of tests

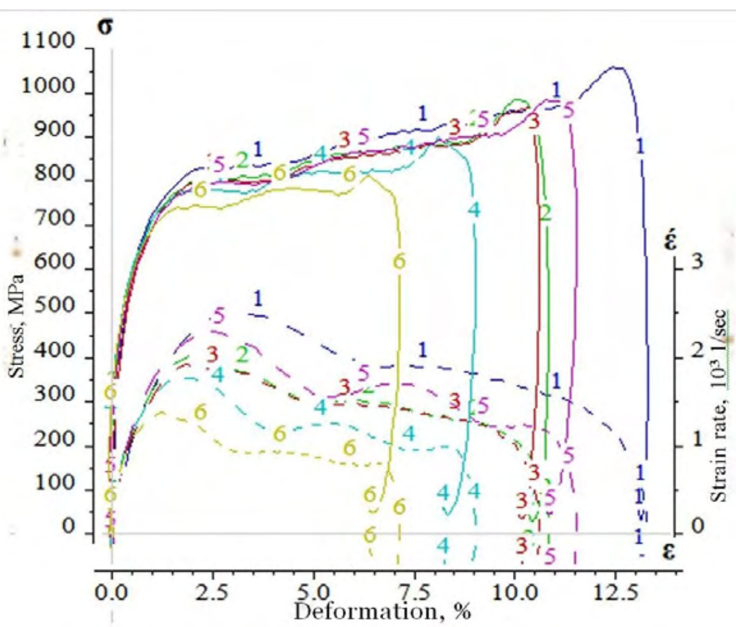


Figure 6. Curves family «σ - ε» of the second set of tests

Table 2. Specimens deformation and sizes, first set

Specimen №	Impact velocity, m/sec	Thickness, mm	Diameter, mm	Deformation, %
1	13,88	2,99	7,91	15,70
2	8,47	2,99	7,91	7,40
3	9,25	2,98	7,92	6,70
4	10,86	2,98	7,91	10,40
5	9,09	2,97	7,90	6,40
6	8,06	2,98	7,91	5,00

Table 3. Specimens deformation and sizes, second set

Specimen №	Impact velocity, m/sec	Thickness, mm	Diameter, mm	Deformation, %
1	11,90	2,91	7,92	12,70
2	10,63	2,91	7,90	10,00
3	10,41	2,91	7,90	9,60
4	9,25	2,91	7,90	6,90
5	10,86	2,92	7,91	10,30
6	8,33	2,92	7,90	5,10

Dependence curves «σ - ε» are not monotone increasing. Such kind of curves «σ - ε» is typical for dynamic curves obtained by Kolsky method.

In Figures 5 and 6 one can observe that at different rate of deformation the curves σ-ε vary little from each other developing much the same strain hardening. Yield stress (Table 4) $\sigma_{0,2}$ and stress limit $\sigma_в$ factors for specimens of AT steel are nearly twice as large as that for steel fabricated with conventional techniques (according to steel grade guide [4]).

Table 4. Yield stress $\sigma_{0,2}$ and stress limit $\sigma_в$ factors

Steel	$\sigma_{0,2}$, MPa	$\sigma_в$, MPa
12X18H10T GOST	282,43	561,14
AT stainless steel	552,15	938,6

As part of the study twelve experiments with specimens of stainless steel were conducted. Impact velocities vary from 7 to 14 m/sec, meanwhile specimens deformation intrinsic rates vary from $0{,}75\times10^3$ to $2{,}8\times10^3$ 1/sec. The paper includes the stress-train and strain rate-strain curves.

Comparative analysis was carried out for the results of investigation of the specimens made with additive fabrication with provided steel tabular information fabricated with conventional techniques.

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