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The Spall Strength and Hugoniot Elastic Limit of Iron-Nickel Alloys of Meteoritic Origin

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The results of measurements of critical fracture stresses (spall strength) and parameters of the elastic-plastic transition of samples of four iron meteorites: Chinga, Sikhote-Alin, Seymchan and Dronino under shock wave loading are presented. The experiments were carried out on a pneumatic gun at a shock compression intensity of ~ 5.5 and ~ 11 GPa and a strain rate before spall fracture of $\sim 10^5\,s^{-1}$. The strength characteristics were determined from the analysis of complete wave profiles recorded during the loading of samples using a VISAR laser interferometer with high spatial and temporal resolution. It was found that the samples of the Sikhote-Alin meteorite demonstrated the highest Hugoniot elastic limit of all the tested samples, which was 1.6 GPa. The highest value of the spall strength ($3.92-4.04$ GPa) was measured on the samples of ataxite Chinga. A comparative analysis of the strength characteristics of the studied meteorites with the strength properties of the iron-nickel alloy H6, which has a composition close to meteorite, as well as with a number of modern structural steels for various purposes, was carried out. The comparison has shown that the strength characteristics of iron meteorites under these loading conditions are close to the strength properties of the steels and iron-nickel alloys of terrestrial origin.

Keywords: iron meteorite, shock wave loading, spall strength, Hugoniot elastic limit, microstructure.

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Introduction

Research of the structure and properties of an extraterrestrial substance is of much interest to both the researches in the field of cosmochemistry and mineralogy, and in the field of condensed matter physics and material science, since most meteorites contain iron-based alloys, which are the materials of structural and functional purpose. Besides, the issues of the Earth protection against potential collision with space bodies of significant size with catastrophic consequences have remained relevant and open for many recent decades. Research of the structure and mechanical properties of extraterrestrial materials (meteorites and asteroids) has recently become especially important in connection with the awareness of actual asteroid-comet danger for the Earth and searching for the opportunities of its prevention. Currently several main methods are proposed to prevent such collisions, one of which suggests using strong explosion loads at a space body, in particular, with the help of a nuclear explosion or a large charge of an industrial explosive (IE) with the purpose to fragment the meteoroid body into fine pieces that are not dangerous for the Earth or to deviate its trajectory [1–8]. Until now all these methods are at the stage of theoretical developments, numerical estimates and laboratory experiments that simulate impulse exposure at space body imitators. The research in this area is complicated by lack of valid data on the strength properties of such space objects, especially under impulse exposures. Such measurements are only possible in the found fragments of meteorites that reached the Earth surface, since only they are currently available for laboratory studies of the asteroid substance. Therefore, the substance of meteorites is the only material available on the Earth to assess the physical and mechanical properties of meteoroids [9]. The available individual fragments of meteorites passing through the Earth atmosphere are exposed to ablation, strong force impact and intense heating of the surface layer, causing thermal impact at the initial structure of the meteorite substance [1,5,10]. However, as multiple measurements have shown, the depth of such impact is small and depends on the thermophysical characteristics of the substance. The visible zone of the thermal impact and related internal stresses at the structure and properties of meteorites is detected by metallographic methods, and, for example, for iron meteorites it is $0.1-10$ mm [11–13]. Therefore, the inner volumes of the available substance from the meteorites that reached the Earth remain practically unchanged by their structure and properties, and the information obtained from their tests may serve as the basis for prognostic calculations of the efficiency for crushing of bulky bodies under explosive or other impulse exposure. Without any doubt, the nature of damage from collision of bodies in space and damage of meteor bodies in the Earth atmosphere or when hitting the Earth surface first of all depends on their strength characteristics [14]. However, by this moment of time the scientific literature contains limited data on mechanical properties of meteorites [9], and no research was done on impact of chemical composition and structure of the meteorite substance on its deformation and strength characteristics under shock-wave impact.

The objective of this paper included measurements of features of the elastic-plastic transition and critical breaking strains (spallation strength) under short impulse loads of large amplitude for the specimens of iron meteorites found at different times in the territory of Russia by the meteorite expedition of the Ural Federal University.

1. Materials and research techniques

The research materials were the fragments of four iron meteorites: Chinga, Sikhote-Alin, Seymchan and Dronino. Fig. 1 presents the microstructure of studied meteorites. The first specimens of Chinga meteorite were found near the Tannu-Ola ridge (now the Republic of Tyva) in 1911. The fragments of this meteorite investigated in this paper were collected in 1986, by the meteorite expedition of the Ural Federal University. Content of Ni in the specimens varies from 15.5 to 18.0 wt.%. Microstructure of Chinga meteorite specimens mainly represents a submicroscopic two-phase mixture of α-phase (kamacite) Fe(Ni) and γ-phase (taenite) Fe(Ni) — with rare nuclei of α-phase (kamacite) and crystals of daubreelite $FeCr_2S_4$, troilite FeS, shreibersite $(Fe,Ni)_3P$ (Fig. 1, *a*) [15].

Seymchan meteorite is an iron stone meteorite, even though its first specimen of around 300 kg was found in 1967 in the tributary of the Yasachnaya River in Magadan Region and consisted of metal only [16]. By now several tons of iron and iron-stone fragments of this meteorite were collected. For this paper a specimen of Seymchan meteorite was selected from the collection of the Ural Federal University, the main part of which is an iron and nickel alloy with 9.1% Ni. Microstructure of the specimen consists of widemanstatten „beams“ of α-phase (kamacite) Fe(Ni), γ-phase (Fe,Ni-taenite) and sections with a two-phase mix of $\alpha + \gamma$-phases (plessite) Fe(Ni) (Fig. 1, *b*).

Iron meteorite Sikhote-Alin is one of few meteorites, whose impact is on February 12, 1947 was observed by multiple witnesses. The bolide swept in the sky above Primorye and fell as heavy meteorite shower, and also formed several impact craters. Content of Ni in the studied fragments of the Ural Federal University collection is 5–7 wt.%. By its structure the specimen of Sikhote-Alin meteorite consists of α-phase (kamacite) Fe(Ni) and rod-like fragments of rhabdite $(Fe,Ni)_3P$ (Fig. 1, *c*) [17,18].

Fragments of the meteorite shower called „Dronino“, were found in 2003 in Kasimovsky district of Ryazan Region. In sand soil at the depth of down to 3 m more than three tons of meteorite substance were found. Ancient fall into moist environment caused significant oxidation of fine fragments, but bulky specimens preserved unoxidized metal base. The researched specimens of Dronino meteorite represent an iron alloy with 9.3 wt.% Ni and 0.47 wt.% Co. The meteorite structure consists of a disperse mixture of α-phase (kamacite) Fe(Ni) and γ-phase (Fe,Ni-taenite) with large inclusions of sulfides FeS (Fig. 1, *d*) [19].

The structure of all meteorites was studied on thin sections made using standard methods, after etching in 2–4 vol.% solution of HNO_3 in ethyl alcohol. Microstructural research was carried out on certified equipment of the scientific and educational center of „Nanotechnology and Nanomaterials“ of the Ural Federal University: using inverted top-light microscope Carl Zeiss Axiovert 40MAT.

Specimens for shock-wave experiments in the form of plane-parallel plates with thickness of ~ 2 mm with linear dimensions $\sim 12 \times 12$ mm were cut on an electrospark discharge machine from internal parts of iron meteorites with microstructures described above (Fig. 1). Both planes of the specimens were polished using fine polishing paper to the necessary purity. Rear surface of the specimens after the additional thin polishing provided for proper diffuse reflection of the probing laser emission from an interferometric velocity meter necessary to record full wave profiles of time after exposure to the shock wave. The method of hydrostatic weighing was used to measure density ρ_0 of all specimens using analytical scale ME204T („Mettler Toledo“) in automatic mode, their longitudinal sound velocity — with the help of an instrument to measure velocity of propagation of acoustic waves (MGNIVP „Akustika“). Since the meteorite specimens had thickness of around 2 mm, the error of sound velocity measurements by ultrasonic method was ± 10 m/s.

Mechanical characteristics of meteorites measured under static loads, as well as their density and longitudinal velocity of sound are given in Table 1. Static strain tests were performed at room temperature using universal machine INSTRON 3382 on flat specimens with length of 75 mm, thickness of 2 mm and width of 15 mm, cut from Chinga and Seymchan meteorites. Impact viscosity tests were carried out on standard prismatic Mesnager specimens, on an instrumented impact tester Tinius Olsen IT542. Vickers microhardness was measured using PMT-3M instrument at load of 0.49 N, the error was determined by 15 measurements.

For comparison, similar experiments were carried out on cast iron-nickel alloy H6. Chemical composition, structure and properties of the alloy after special thermal treatments are close to characteristics of the studied meteorite specimens. Specimens of alloy H6 for shock-wave experiments were prepared in a similar manner. The investigated alloy contained (wt.%): 0.01 C; 5.8 Ni; 0.2 Si; 0.1 Mn; 0.02 Ti; balance Fe. The microstructural study was carried out on microscope Neophot-32. Thin sections were made using

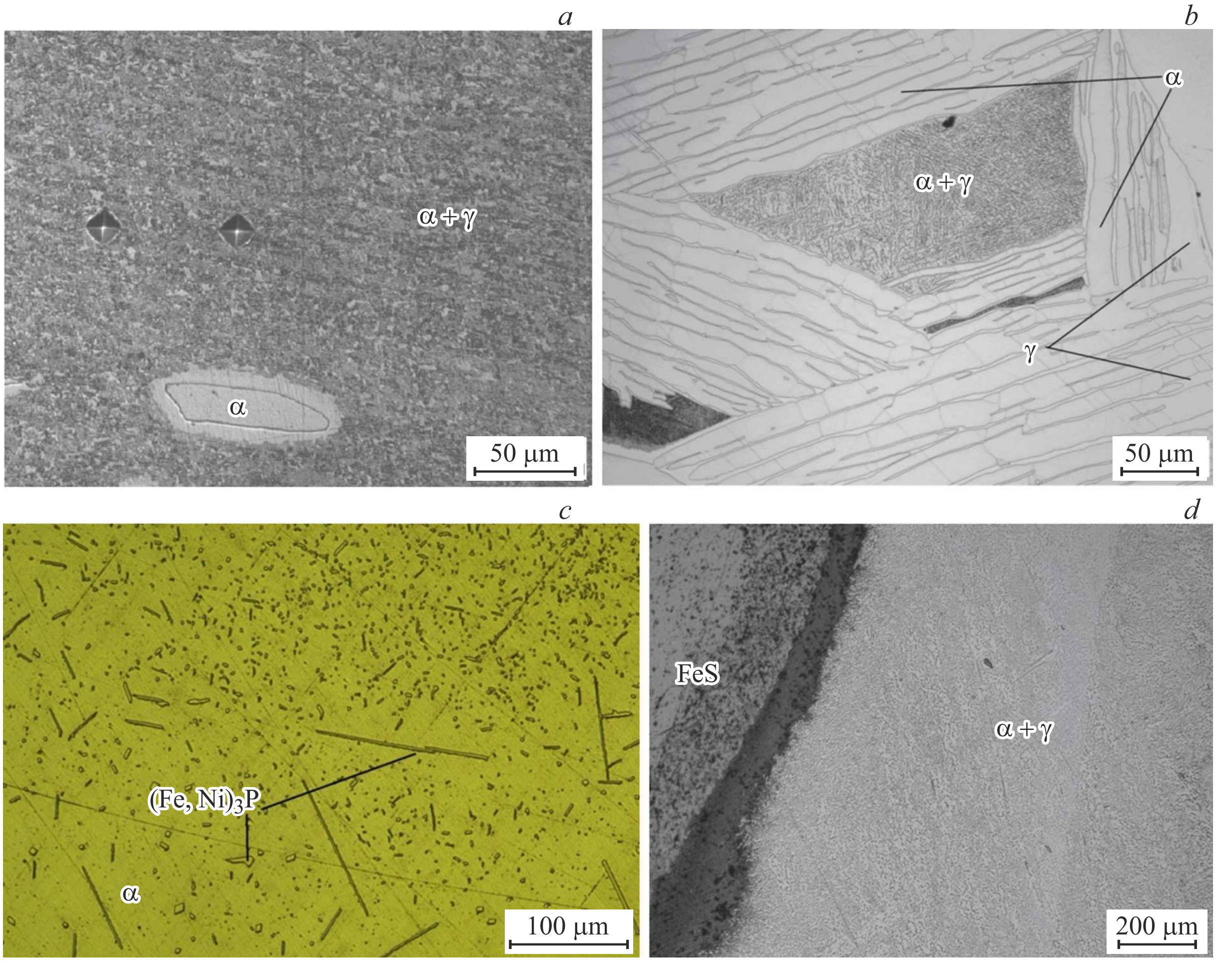

Figure 1. Structure of initial specimens of iron meteorites: *a* — Chinga [15], *b* — Seymchan [16], *c* — Sikhote-Alin [17,18], *d* — Dronino [19]; α-phases (kamacite) Fe(Ni), γ-phases (taenite) Fe(Ni) γ-phase (Fe,Ni-tetrataenite), $\alpha+\gamma$ (plessite) Fe(Ni); FeS — (troilite); $(Fe,Ni)_3P$ — (rhabdite and/or shreibersite).

Table 1. Characteristics of iron meteorites

№	Meteorite	Average/measured density, g/cm^3	Impact viscosity (KCU), kJ/m^2 [20]	Microhardness HV$_{50}$, MPa	Longitudinal velocity of sound C_l, m/s
1	Chinga	7.9/7.95	1486	2550–2650	5872
2	Seymchan	7.7/7.85	670	1500–1600	5715
3	Sikhote-Alin	7.5/7.58	103	1500–1600	5770
4	Dronino	7.6/7.59	1500	1600–1700	5350

a standard method with subsequent etching by 4 vol.% solution of HNO_3 in ethyl alcohol.

Fig. 2 presents a ferrite structure of alloy H6, obtained by recrystallization in α-state at 630°C for $21.6\cdot10^3$ s (Fig. 2, *a*), and also two-phase ferrite-martensite structures formed as a result of slow ($6.7\cdot10^{-3}$ degree/s) and fast ($13\cdot10^{-2}$ degree/s) heating in $(\alpha+\gamma)$ area to temperature of 735°C, soaking of $1.8\cdot10^3$ s and subsequent tempering (Fig. 2, *b, c*). Therefore, the change in the heating velocity in $(\alpha+\gamma)$ area by an order causes formation of two morphological types of ferrite-martensite structures in the alloy: plate or widemanstatten (Fig. 2, *b*) and globular (Fig. 2, *c*).

Mechanical properties of the investigated alloy with different microstructures measured at static loads are presented in Table 2 [21]. As expected, the strength properties and microhardness of the alloy with the globular ferrite-martensite structure is 1.6–1.7 times higher, and the impact viscosity is 3 times lower than in an alloy with ferrite structure. The alloy with widemanstatten ferrite-martensite

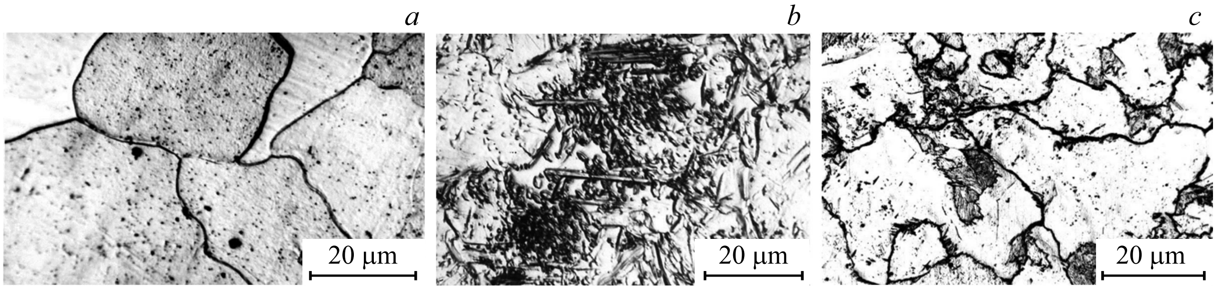

Figure 2. Microstructure of alloy H6 in the initial α-state (a) and after heating in two-phase ($\alpha \to \gamma$) area to 735°C with the following velocities: $V_{\mathrm{H}} = 6.7 \cdot 10^{-3}$ (b) and $13 \cdot 10^{-2}$ degree/s (c).

Table 2. Characteristics of alloy N6 with structures obtained after heating with different velocities (V_{H}) in the intercritical interval of temperatures

№ specimens	V_{H}, degr/s	Types of structures obtained after of tempering from two-phase ($\alpha + \gamma$) area	Microhardness, HV, MPa	Impact viscosity (KCU), kJ/m^2	σ_{B}, MPa	$\sigma_{0.2}$, MPa
1	–	initial ferrite	1620	2500	550	350
2	$6.7 \cdot 10^{-3}$	plate ferrite-martensite	1750	1300	900	550
3	$13 \cdot 10^{-2}$	globular ferrite-martensite	2520	800	950	600

structure also has higher values of microhardness and strength characteristics compared to the alloy with ferrite structure with preservation of satisfactory values of impact viscosity.

The measured density of alloy H6 specimens is $\sim 7.84\,\mathrm{g/cm^3}$, longitudinal C_l and shear C_s velocities of sound are accordingly equal to 5507 and 3098 m/s. The volume velocity of sound $C_b = 4190$ m/s, used to determine the critical damaging stresses, was calculated using equation

$$C_b = \sqrt{C_l^2 - \frac{4}{3}C_s^2}.$$

Experiments for shock-wave loading of specimens of iron meteorites and iron-nickel alloy H6 were conducted on a pneumatic gun PP50 with caliber of 50 mm. A copper impactor with thickness of 0.47 mm speeded up to velocity of 335 ± 10 m/s or 660 ± 10 m/s prior to a collision with a specimen. Casting velocity depended on the working gas pressure, which in these experiments was air compressed to 80 atm or helium compressed to 150 atm. Flat metal impactors were located at the end of a hollow aluminum or magnesium cylinder with length of 100 mm, which was accelerated int he gun barrel by compressed air or helium, providing for flat collision with the specimen located in the receiving chamber. In every experiment the impactor velocity and its slant were measured by two pairs of electric contact sensors. All experiments were performed at room temperature. The gun barrel and the receiving chamber, where the specimen was located, were vacuumized prior to the experiment. In all experiments the velocity of the surface of the studied specimens was registered (full wave profiles $u_{fs}(t)$) using laser Doppler interferometric meter of velocity VISAR [22], having temporal resolution ~ 1 ns and spatial resolution $\sim 0.1\,\mathrm{mm^2}$.

Studies of the mechanical properties of materials under dynamic exposures in submicrosecond range of impact durations at strain rates $> 10^4\,\mathrm{s^{-1}}$ are carried out under the conditions of shock-wave loading of the tested samples. Measurements are based on the fact that the structure of waves and dynamics of wave interactions are determined, apart from the thermodynamic equation of state of the substance, by processes of elastic-plastic deformation and damage in the material. Analysis of evolution (form change) of the shock compression wave as it passes in the specimen provides high quality information on the nature of deformation and damage processes, and the possibility to obtain quantitative data on the strength properties of the material [23].

2. Results of the measurements and their discussion

Fig. 3 presents the velocity profiles of free surface of specimens in all studied meteorites under shock compression pressure ~ 5.5 GPa (collision velocity 335 ± 10 m/s) and ~ 11 GPa (collision velocity 660 ± 10 m/s). In profiles the release of an elastic precursor (elastic compression wave), a plastic shock wave and subsequent part of an unloading wave on the surface is registered to the moment of spallation fracture. The velocity of propagation of the elastic precursor in these experiments is almost equal to the measured longitudinal velocity of sound c_l, and the velocity of the plastic shock wave is determined by the

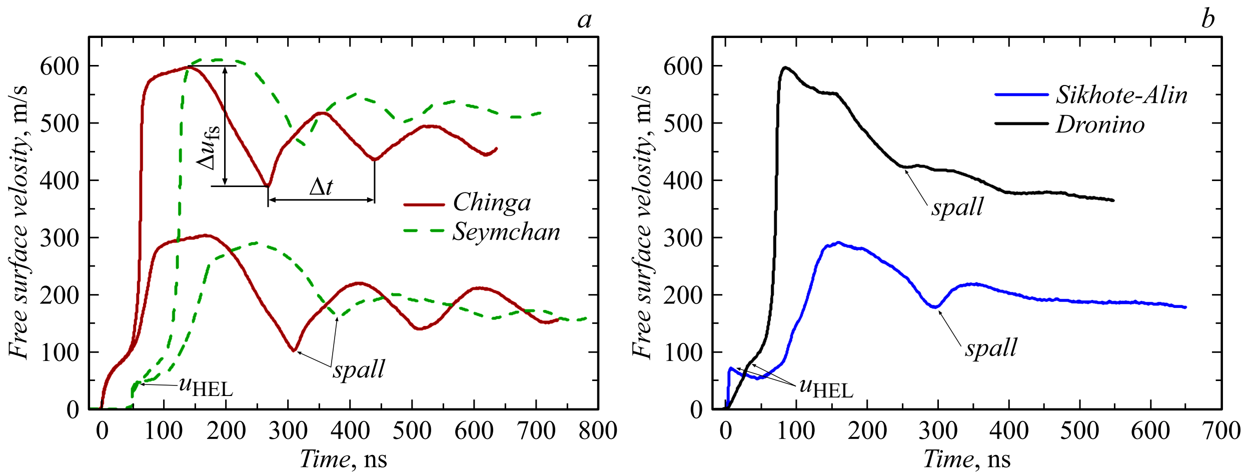

Figure 3. Velocity profiles of free surface of iron meteorite specimens at different impact velocity.

bulk compressibility of the material and, accordingly, must be close to the volumetric velocity of sound C_b [24] at moderate compression wave amplitudes.

For specimens of Sikhote-Alin and Dronino meteorites it was not possible to do the experiments at different pressures of shock compression. Probably, it is related to the presence of even visually noticeable large mechanical defects in the specimens in the form of micro- and macro-imperfections. After passage of the shock wave in the specimen and its release to the free surface, the latter drastically lost reflecting capacity, and it was not possible to register its velocity by a laser interferometer.

The amplitude of the elastic precursor is determined by the Hugoniot elastic limit of the material HEL (Hugoniot Elastic Limit), which is calculated using its measured value u_{HEL} (Fig. 3) as

$$\sigma_{\mathrm{HEL}} = 0.5\, u_{\mathrm{HEL}}\, \rho_0 C_l.$$

Hugoniot elastic limit at one-dimensional deformation is related to yield strength of the material Y of ratio

$$Y = \frac{3}{2}\sigma_{\mathrm{HEL}}(1 - C_b^2/C_l^2).$$

When the extension wave coming from the rear side of the impactor interacts with the extension wave reflected from the free surface of the specimen, inside of it the tensile stresses are generated, and when they exceed the value critical for this material, a damage is initiated in the specimen — a spall. In this case, the relaxation of tensile stresses occurs and a compression wave (spall pulse) is formed, the output of which to the surface of the sample usually causes a second rise in its velocity — a compression wave, so called „spall pulse". The decrement of the surface velocity Δu_{fs} (Fig. 3) at its decline from the maximum to the value before the front of the spall pulse is proportional to the magnitude of the destructive stress — the spallation strength of the material under these loading conditions.

In the acoustic approximation the spallation strength of the material is calculated using ratio

$$\sigma_{sp} = \frac{1}{2}\rho_0 C_b(\Delta u_{fs} + \delta),$$

where δ — correction for the distortion of the velocity profile due to the difference in the velocities of the front of the spall pulse and the velocity of the plastic part of the incident discharge wave in front of it [23,25].

By time of single oscillation of the spall pulse Δt in the spall plate its thickness may be determined as $h_{sp} = C_l\Delta t/2$.

Maximum amplitude of the plastic compression wave is determined as $P_{\max} = \rho_0 U_s u_{fs}$, where ρ_0 — density of specimens, U_s — shock wave velocity, u_{fs} — particle velocity determined from velocity profiles. To process experimental data, a shock adiabat was used in the form of $U_s = C_0 + s u_p$ [km/s], where U_s — shock wave velocity, u_p — particle velocity behind the shock wave front, C_0 takes on a value of bulk sound speed C_b, s — slope of shock adiabat. Coefficient s for meteorite specimens and iron-nickel alloy H6 with the close composition was taken on as equal to 1.14 [26–28].

Here, the strain rate implies substance expansion in the expansion wave prior to spall that is defined as follows

$$\frac{\dot{V}}{V_0} = -\frac{\dot{u}_{fsr}}{2C_b},$$

where $\dot{u}_{fsr}$ — measured velocity of decrease in velocity of free surface of the tested specimen in the unloading part of the shock compression impulse, V_0 — specific volume, $\dot{V}$ — gradient of velocity in the unloading part of the compression impulse.

From comparison of wave profiles obtained for meteorite specimens one can see that evolution of shock waves for specimens of Chinga and Seymchan meteorites is typical for metals and alloys. Elastic-plastic transition takes place smoothly with material strengthening, and the process of spallation destruction is specific for metal materials [22,25].

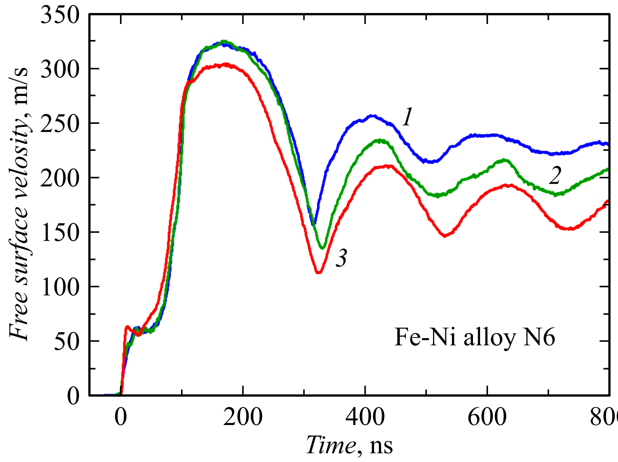

Figure 4. Velocity profiles of free surface of iron-nickel alloy H6 specimens in different structural states.

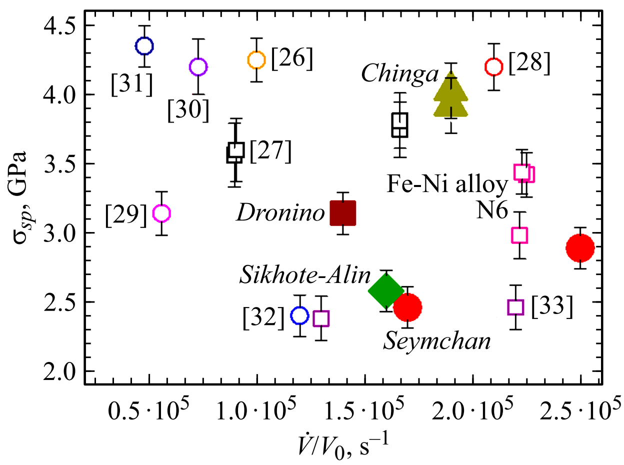

Figure 5. Spallation strength of meteorites and structural steels under close conditions of shock-wave loading. [26] — steel 45; [27] — steel 15Kh2NMFA; [28] — steel 09G2Sa-A; [29] — highly alloyed TRIP steel; [30] — steel 40Kh; [31] — steel 35Kh3NM; [32] — pure iron; [33] — stainless steel 12Kh18N10T.

Profiles obtained for specimens of Dronino and Sikhote-Alin meteorites are somewhat different from the previous ones. For a specimen of Sikhote-Alin meteorite the elastic precursor is a so called „yield drop“ with quick relaxation of strain downstream the elastic compression wave, which is related to quick reproduction of dislocations in an elastic wave. After formation of a spallation impulse the free surface velocity oscillations are not registered, but its quick attenuation is observed due to slower process of fracture and formation of a strongly developed spall surface.

Measurements of the dynamic elastic precursor demonstrated that its maximum value ~ 1.6 GPa is shown by Sikhote-Alin meteorite specimen, slightly lower HEL values (~ 1.5 GPa) are obtained on specimen of Dronino meteorite. Minimum values of Hugoniot elastic limit ~ 0.9 GPa are measured on the specimens of Chinga meteorite. Accurate values of Hugoniot elastic limit for all iron meteorites are presented in Table 3.

Fig. 4 presents velocity profiles of free surface of alloy H6 specimens with initial ferrite structure (profile *1*) and with two morphological types of ferrite-martensite structures: widemanstatten (profile *2*) and globular (profile *3*). You can see that measured wave profiles reflect all above features of high velocity strain and damage of such alloys under the spall conditions. I. e. change of the alloy microstructure during thermal treatments practically did not influence the evolution of the shock wave as it passed in the specimen and did not change the Hugoniot elastic limit and dynamic yield strength of this alloy. Spallation strength of alloy with two-phase ferrite-martensite structure of various morphology (Fig. 2, *b, c*) increased approximately by 13% compared to spallation strength of alloy with the initial ferrite structure (Fig. 2, *a*).

Results of processing of wave profiles obtained on specimens of meteorites are presented in Fig. 5 as dependences of spallation strength of studied specimens on strain rate prior to a spall and in Table 3.

Fig. 5 shows the results of measurements of spallation strength of the investigated specimens of meteorites and iron nickel alloy H6, and also for comparison the data obtained previously for the spallation strength of various structural steels and pure iron [26–33]. As you can see from the figure, all specimens of meteorite iron demonstrate spallation strength close to the presented steels under similar loading conditions.

Comparative analysis of the obtained data on spallation strength demonstrated that the damage of the meteorite substance occurs in quite a wide range of critical damaging loads from ~ 4 to ~ 2.5 GPa, which is related to both their initial structure and the quantity of induced defects inside the specimen. However, their strength, as you can see from Fig. 5, *b*, remains close to the strength of structural steels of various purposes, being only slightly inferior to the ones having the highest strength.

Conclusion

Therefore, for the first time the measurements of spallation strength and parameters of elastic-plastic transition were carried out on specimens of meteorites known as Chinga, Seymchan, Sikhote-Alin and Dronino, found in different areas in the territory of Russia in XXth century. Measurements are made under impact load with intensity of ~ 5.5 and ~ 11 GPa and average material strain rate prior to spallation fracture $10^5\,s^{-1}$. Specimens of all studied iron meteorites demonstrate the elastic-plastic behavior specific for most structural alloys and steels at high velocity strain under impact compression. Maximum value of the Hugoniot elastic limit ~ 1.6 GPa is measured on the specimen of Sikhote-Alin meteorite, its minimum value ~ 0.9 GPa is demonstrated by specimens of Seymchan meteorite. By comparative analysis it is shown that the spallation strength

Table 3. Conditions of experiments and results of measurements of Hugoniot elastic limit and spallation strength of meteorite specimens and alloy H6

Meteorite, alloy	P_{max}, GPa	u_{HEL}, m/s	σ_{HEL}, GPa	Y, GPa	Δu_{fs}, m/s	σ_{sp}, GPa	Strain rate, $\times 10^5$ s^{-1}	Δt, ns	h_{sp}, mm
Chinga	5.51	52	1.21	0.79	201	3.92	1.9	205	0.59
	11.30	54	1.26	0.83	207	4.03	1.9	176	0.50
Seymchan	5.22	41	0.92	0.56	128	2.46	1.7	190	0.53
	11.40	39	0.87	0.53	151	2.89	2.5	173	0.48
Sikhote-Alin	5.24	74	1.62	1.02	139	2.58	1.6	165	0.47
Dronino	11.30	73	1.48	0.72	175	3.14	1.4	160	0.42
H6 (1)	5.55	63	1.36	0.86	164	2.98	2.2	200	0.53
H6 (2)	5.60	61	1.32	0.83	189	3.42	2.3	193	0.52
H6 (3)	5.20	64	1.38	0.87	190	3.44	2.2	205	0.55

of all studied meteorites under these loading conditions was close to the strength of the iron-nickel alloy H6, having a close elemental chemical composition, and steels and alloys of various purpose, including pure iron. The results of the measurements completed in the paper indirectly confirm the previously obtained data and conclusions that the meteorite substance preserves as practically unchanged its strength properties in the volume of the fragments that maintained their integrity after passage through the Earth atmosphere and collision with its surface. The obtained experimental data on the nature of the spallation fracture and assessment of the impact from the defects in the structure of iron-nickel alloys of cosmic origin on their resistance to deformation and damage under submicrosecond durations of the load will make it possible to expand the existing ideas on their strength properties under strong dynamic exposures and to become the basis for adequate model estimates of the response from the real space bodies representing a serious threat upon their potential collision with the Earth, when the suggested protection methods are implemented.

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Conflict of interest

The authors declare that they have no conflict of interest.

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