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Submicrosecond strength of $(\alpha + \beta)$ titanium alloy VT22 under plane shock wave loading

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The measurements results of the Hugoniot elastic limit and spall strength of high strength $(\alpha + \beta)$ titanium alloy VT22 under shock-wave loading with a impactor velocity of 850 ± 30 m/s are presented. Experimental results on the decay of the decay of the elastic precursor depending on the distance passed by the wave are described by a power-law dependence. New data on the spall strength of the VT22 alloy in the range of strain rates in a rarefaction wave have been obtained $10^4 - 10^6$ s⁻¹.

Keywords: titanium alloy, shock waves, strength, interferometer.

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Owing to their unique properties (low weight and high strength), high-strength titanium alloys are used widely to produce of parts or armor in the aerospace and defense industries [1]. Since the mechanical properties of alloys depend strongly on alloying elements (Al, V, Mn, Mo, Cr, Fe, etc.), the design and modeling of products and structures potentially subjected to strong pulse loads during operation require data on the mechanical properties of a specific alloy under impact loads (namely, the Hugoniot elastic limit and spall strength at deformation rates of $10^4 - 10^7$ s⁻¹). Data in the form of temperature-rate dependences of flow stress under the conditions of high-rate fracture for low-strength (VT1-0) and medium-strength (VT6) titanium were presented in [2–4]. Similar studies for structural titanium alloy VT22 have not been performed to date.

The purpose of experiments was to obtain new experimental data needed for determining the dependencies of the Hugoniot elastic limit and spall strength and to compare them with literature data on the strength of medium-strength titanium alloys. Measurements are based on the fact that the structure of waves and dynamics of wave interactions are governed by the processes of elastic-plastic

deformation and fracture. The strength at short load times is determined by analyzing the spallation phenomena observed when a compression pulse is reflected from the surface of a body [5].

In the present study, we report the results of shock-wave tests of hot-rolled titanium alloy VT22 produced by VSMPO-AVISMA. The chemical composition of this alloy specified in the delivery certificate is presented in Table 1.

Its density ρ was measured using the Archimedes method and an ME204T analytical balance. Longitudinal c_l and shear c_s sound speeds were measured using an MGNIVP „Akustika“ instrument with a transducer frequency of 2.5 MHz by through scanning. The bulk sound speed was calculated as $c_b = \sqrt{c_l^2 - 4c_s^2}/3$. The results of phase analysis performed using a DRON-4 diffractometer in the Bragg–Brentano geometry provided an opportunity to determine the overall volume fraction (%) of α and β phases. The Rockwell hardness (HRB) of alloy was also measured with a TN-300 automated stationary equipment. The measured characteristics of titanium alloy VT22 are listed in Table 2.

An ARTA electrical discharge machine was used to cut

Table 1. Chemical composition (wt.%) of titanium alloy VT22 (Ti — base)

Al	Mo	V	Zr	Cr	Si	Fe	C	O ₂	N ₂	H ₂
5.3	4.5	4.75	4.62	1.04	0.034	0.67	0.009	0.074	0.015	0.004

Table 2. Measured parameters of titanium alloy VT22

Phase composition	Volume fraction of phase, %	σ_B , MPa	HRB	c_l , m/s	c_s , m/s	c_b , m/s	ρ_0 , g/cm ³
α (HCP)	52.3	1170	113	5962	3095	4772	4.608
β (BCC)	47.7						

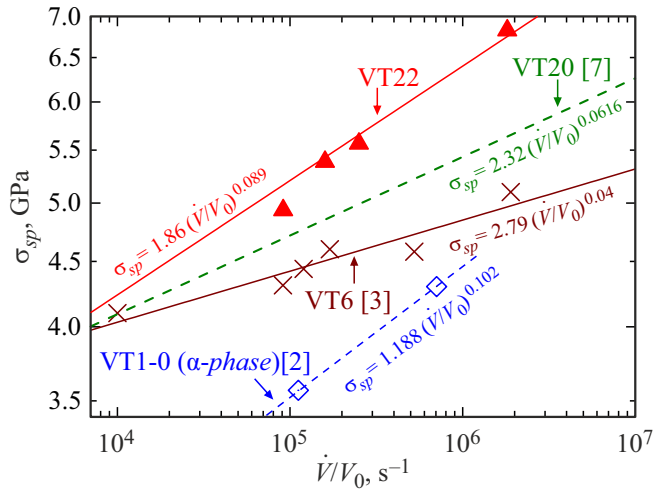


Figure 3. Measurement results of spall strength of high-strength titanium alloy VT22 as a function of the expansion rate in an incident rarefaction wave in comparison with the data for commercially pure titanium alloy VT1-0 [2], VT6 [3], and VT20 [7]. Lines represent the results of approximation of experimental data.

The precursor decay may be characterized by empirical power-law relation $\sigma_{\text{HEL}} = \sigma_0(h/h_0)^{-\alpha}$ [5], where σ_0 is the Hugoniot elastic limit for targets with thickness $h_0 = 1$ mm. Quantities $\sigma_{0(\text{peak})} = 4.75$ GPa and $\sigma_{0(\text{min})} = 3.76$ GPa and power index $\alpha = 0.072$ are adjustable parameters and are determined by verification against our experimental data. It should be noted that the elastic precursor decay in technically pure titanium VT1-0 is 2 times slower ($\alpha = 0.036$); in the VT6 alloy, the decay follows relation $\sigma_{\text{HEL}} = 3.05(h)^{-0.135}$.

Figure 3 summarizes the results of measurements of the dynamic (spall) strength for titanium alloy VT22 in comparison with similar data for commercially pure titanium alloy VT1-0 [2], VT6 [3], and VT20 [7]. The magnitude of fracture stress at spallation in the linear approximation is written as $\sigma_{sp} = 0.5\rho c_b(\Delta u_{fs} + \delta u)$ [5]. The values of spall strength were obtained by processing the measured wave histories (Fig. 1). The results are presented in the form of dependences of the spall strength of titanium alloys on material expansion rate \dot{V}/V_0 in the rarefaction wave before the spall pulse [5], which is defined as $\dot{V}/V_0 = -\dot{u}_{fsr}/2c_b$, where \dot{u}_{fsr} is the measured wave profile decay rate in the unload-

ing part of the shock compression pulse. Measurement data on the spall strength of high-strength titanium alloy VT22 were characterized within a wide range of deformation rates by power-law dependence $\sigma_{sp} = 1.86(\dot{V}/V_0)^{0.089}$. It should be noted that the spall strength of the VT22 alloy is significantly higher than the strength of technical titanium VT1-0 and exceeds the strength of VT6 and VT20 alloys at deformation rates of 10^4 – 10^6 s $^{-1}$. The high strength of alloy VT22 is attributable to a significant heterogeneity of the structure with a large number of dislocations and the presence of strengthening phases (due to alloying).

Table 3 lists the experimental conditions and the results of processing and analysis of free surface velocity histories, where

$$U_s = c_l(2h - c_l\Delta T)/(2h + c_l\Delta T)$$

is the plastic wave velocity. Here, ΔT is the difference in the time it takes for the middle part of elastic and plastic waves to reach the free surface. The maximum compression stress was determined as

$$\sigma_{\text{max}} = \sigma_{\text{HEL}} + \rho_{el}U_s(u_{\text{max}} - u_{\text{HEL}})/2,$$

where $\rho_{el} = \rho c_l/(c_l - u_{\text{HEL}}/2)$ is the density after elastic compression, $\Delta u_{fs} = u_{\text{max}} - u_{\text{min}}$ is the surface velocity decrement (Fig. 1), and $H_{sp} = c_l\Delta t/2$ is the thickness of the spall plate, where Δt is the time of compression pulse circulation in the spall plate.

Thus, experimental of the free surface velocity histories of high-strength α (52.3%) + β (47.7%) transition titanium alloy VT22 with a thickness of 0.4–10 mm were recorded. The results of measurements of full wave histories were analyzed to reveal the nature of decay of the elastic precursor propagating along the sample (i.e., the dependence of the Hugoniot elastic limit on distance traveled by the wave). It was demonstrated that the Hugoniot elastic limit and the spall strength of high-strength titanium alloy VT22 exceed the values obtained for VT1-0, VT6, and VT20 alloys under the same loading conditions. The dynamic (spall) strength of titanium alloy VT22 varies from 4.95 to 6.3 GPa within the range of deformation rates from 10^4 to 10^6 s $^{-1}$.

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Table 3. Experimental conditions and results of wave profile processing

h , mm	H_{imp} , mm	H_{bp} , mm	U_s , m/s	σ_{max} , GPa	$u_{\text{HEL}(\text{peak})}$, m/s	$u_{\text{HEL}(\text{min})}$, m/s	Δu_{fs} , m/s	H_{sp} , mm
0.39	0.19	—	5312	9.3	371	303	496	0.18
1.99	0.95	1.92	5459	9.8	356	250	447	0.87
4.56	1.99	1.98	5485	9.4	321	263	420	1.75
9.65	2.02	1.99	5457	8.8	296	209	407	1.73

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Conflict of interest

The authors declare that they have no conflict of interest.

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