from [7]. The regime designation is that of [1]. For the regime with "splattering" the estimate gives Re $\sim$ 11; for the regime without "splattering" Re $\sim$ 7.

We note that the change in the parameters Re and β is apparently related not only to Joulean heating of the powder, but also the electroplastic effect of current pulse action [8], which reduces the yield point of the material.

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INFLUENCE OF TEMPERATURE ON THE CRITICAL CONDITIONS OF SPALLING FRACTURE OF METALS

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The question of the influence of temperature on the spalling fracture of metals has still been studied insuficiently at this time. The results of a few experimental investigations of this equation [1-4] are extremely limited and quite contradictory. If a reduction in the spalling strength of steel St.3 and copper M1 with the temperature rise to 500°C is noted in [2, 4], then no influence of the temperature on the spalling fracture of aluminum was noted in [1, 3].

Results of an experimental investigation of the influence of temperature on the critical spalling fracture conditions for a number of construction metals are represented in this paper: AD1 aluminum, D16 and AMg6 aluminum alloys, St.3 and 12Kh18N10T steels, VT14 titanium, M1 copper, and NP2 nickel in a broad temperature range (−196- +800°C). The experimental method used is based on determining the critical velocity of impact of a plate on the specimen of material being investigated, that results in the formation of macroscopic spalling fracture, and was successfully used to investigate the time regularities of spalling fracture ([5, 6], for instance). In application to the problem posed in this paper, the method of determining the critical impact velocity permits us to obtain a clear boundary between the spalling fracture zones, and to conserve the macroscopic continuity of the material in the temperature range under study for identical time conditions of the impulsive mechanical loading.

Knowledge of the mechanical properties of the specimen and impactor materials under shockwave loading permits a comparison between the critical impact velocity and the magnitude of the critical tensile stress in the specimen. The selection of a geometry of the impactor—

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specimen system such that the elastic unloading wave would not succeed in overtaking the shock front before its emergence on the specimen free surface is expedient. In this case the error in design estimates of the magnitude of the tensile stress and the time of its action in the spall plane, as based on knowledge of the shock adiabat and the elastic-plastic properties of the material, does not exceed the error in existing indirect experimental methods of continuous recording of the history of the stress state in the spall plane.

The diagram for conducting the experiments is presented in Fig. 1 (1 is a nichrome heater, 2 is the loading unit, 3 is the specimen of material being investigated, 4 is a Chromel—Copel thermocouple). The specimens are heated by the radiant flux from the tape nichrome heater. The temperature was measured by the Chromel—Copel thermocouple. The time to heat the specimen to the maximum temperature did not exceed 20 min. Cooling the specimens to —196°C was by submersion in a vessel with liquid nitrogen. After the necessary temperature had been reached, the specimen was advanced remotedly under the loading unit. Pulsed mechanical loading of the specimens of metals under investigation was performed by the impact of a plate from the aluminum alloy AMts that was 4 mm thick and 110 × 150 mm in size. Acceleration of the plate impactor to the velocity needed was by the grazing detonation of a layer of plastic explosive material. To prevent spalling fracture of the plate, a layer of technical cloth was placed between the plate and the explosive layer. The detonation front in the explosive charge was produced during simultaneous initiation of the explosive along one of the plate sides.

A change in explosive layer thickness permits altering the velocity of plate—impactor motion within broad limits. Measurement of the velocity and symmetry of plate motion on bases corresponding to the collision with the specimen was carried out in a special series of tests by optical and contact methods. The dependence obtained for the velocity of plate motion on the explosive layer thickness permits giving the collision velocity to an accuracy no worse than 3%.

For a 500-m/sec collision velocity the difference in the time of impact does not exceed 0.3 μsec in the area of a 70-mm-diameter circle.

The experimental specimens were fabricated from rod materials, i.e., the direction of the pulsed mechanical loading agreed with the direction of technological rolling. Preliminary heat treatment of the materials was not performed. To clarify the influence of the preliminary heat treatment, specimens of M1 copper were fabricated from material in two initial states, in the state of factory delivery, and subjected to preliminary annealing for an hour at a 600°C temperature. The annealed material was cooled in water. Experimental specimens had an 80-mm loading surface diameter and a 20-mm thickness. Titanium, nickel, and the aluminum alloy AMg6 specimens had a 60-70-mm loading surface diameter and 10-mm thickness. For convenience in the attachment and for reduction of the influence of edge effects, the specimen lateral surface had a conical section. The specimen free surface had a 40-mm diameter.

After the pulse mechanical loading, the specimen was cut along the axis, the exit surface was polished, andthe fact of the presence or absence of macroscopic spalling fracture was observed visually. To find the critical collision velocity governing the boundary between the spall rupture zones and the preservation of the macroscopic continuity of the material, it was required to perform several tests with a subsequent change in the collision velocity. The determination of this velocity with an accuracy no worse than 5% required performance of 3-5 tests depending on the accuracy of the preliminary prediction of the experiment. The maximal collision velocity at which no spalling fracture of the material is observed visually was taken as the magnitude of the critical velocity. Exceeding this velocity by not more than 5% already resulted in partial spalling fracture of the specimen, characterized by the presence of separate moderate cracks in the spalling fracture zone. A further increase in the collision velocity results in complete spalling fracture, characterized by the presence of a mainline spall crack passing through the whole section of the

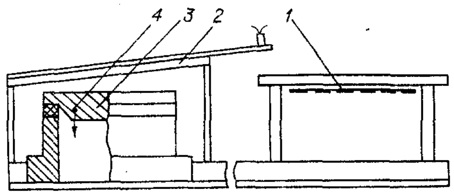

Fig. 1

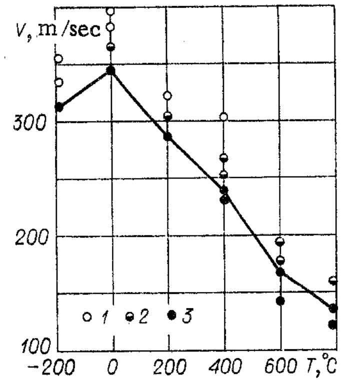

Fig. 2

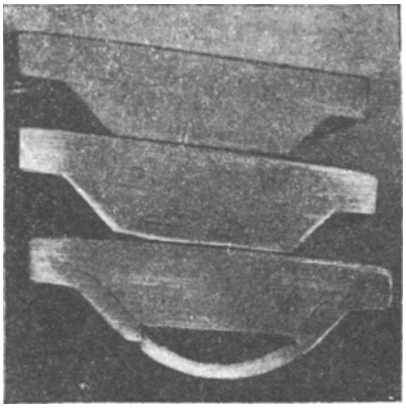

Fig. 3

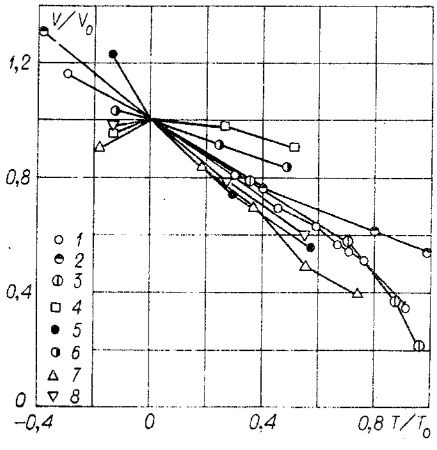

Fig. 4

specimen. For instance, results of test with copper specimens are shown in Fig. 2 (1 is complete spalling fracture; 2 is partial spalling fracture; 3 is the absence of visually observable spalling fracture), and the shape of the loaded specimens in the appropriate states in Fig. 3.

The results of the experiments performed are represented in Fig. 4 in dimensionless form. Values of the critical collision velocity V_0 for $T \simeq 0°C$ (the specimen temperature was not recorded in this case, and corresponded to a temperature at which the experiments were performed (—5– +15°C)) and the melting point of the materials T_0 (the solidus temperature for the aluminum alloys D16 and AMg6) are presented in the table. The numbers of the points in Fig. 4 correspond to the numbers of the materials in the table. Also presented in the table are properties of the materials which are needed to determine the force conditions of the pulsed mechanical loading; the density ρ and the coefficients of the linear D—u relationships between the wave and mass velocities c_0 and λ, taken in the appendix to [7]. The same shock adiabat is used for the impactor material, the aluminum alloy AMts, as for the aluminum alloys being investigated, where the density of the alloy AMts is 2.73 g/cm^3.

Analysis of the pulse mechanical loading conditions for the materials is approximate in nature. It is assumed that expansion of the materials is explained satisfactorily by their shock compression adiabats, including even the negative pressure domain. The geometry of the impactor—specimen system is selected in such a way that the elastic unloading wave does not succeed in overtaking the shock front in the material; consequently, the pressure behind the shock front that emerges on the free surface of the specimen agrees with the collision pressure. Critical values of the collision pressure p_0 and the tensile stress σ_0 in the materials at $T \simeq 0°C$ are presented in the table. Approximate temperature dependences of the critical collision pressures and tensile stresses in the case of not taking account of the influence of the temperature on the mechanical properties of the material correspond, with a high degree of accuracy, to the temperature dependences of the critical collision velocities presented in Fig. 4. A reduction in the values of the pressure and tensile stress because of a change in the material properties at high temperatures is insignificant

TABLE 1

No.	Materials being investigated	Properties of the materials				Critical fracture conditions for T≃ 0°C		
		ρ, g/cm^3	c_0, km/sec	λ	T_0, °C	V_0, kbar	p_0, kbar	σ_0, kbar
1	AD1 aluminum]	2,71	5,25	1,39	660	253	18,7	17,5
2	D16 Al alloy	2,78	—	—	502	336	25,4	23,2
3	AMg6 Al alloy	2,64	—	—	570	365	27,0	24,4
4	St. 3	7,85	4,57	1,49	1535	385	41,9	38,9
5	12Kh18N10T	7,80	—	—	1400	540	60,0	54,0
6	VT 14 titanium	4,52	5,22	0,77	1668	539	51,2	48,1
7	M1 copper	8,90	3,95	1,50	1083	344	37,0	34,3
8	NP2 nickel	8,86	4,62	1,52	1453	444	50,6	46,8

and can be estimated easily because of taking account of the influence of the temperature on the material density on the volume speed of sound, which is close to the coefficient c_0 of the shock adiabat in magnitude and physical meaning. The characteristic time of the impulsive mechanical loading of the materials is estimated at 1.3 μsec, as the time for elastic wave circulation in the plate—impactor.

As was noted above, to clarify the influence of the preliminary heat treatment on the spalling fracture conditions, the copper specimens were also fabricated from material subjected to annealing at a 600°C temperature. Experiments with specimens from annealed material showed that the critical collision velocity V_0 of 344 m/sec for material not annealed was reduced to 308 m/sec for annealed material, and the values of p_0 and σ_0 corresponding to this velocity were 33.0 and 30.7 kbar. The temperature dependence of the critical collision velocity for annealed copper gradually approached the dependence for the unannealed copper as the temperature rose, and converged to it at the point V = 168 m/sec at the temperature 600°C.

The experimental results obtained in this paper (see Fig. 4) indicate an explicit and quite substantial role for the temperature during spalling fracture of metals, which does not agree with the deduction in [3] that the process of metal fracture is close to athermal for microsecond band durations. Certain individual features of the strength properties of the metals and alloys under investigation in both heating and cooling must be noted. This is the significant high-temperature strength of titanium and St.3 steel during heating, the significant strength of the aluminum alloy D16 at a 500°C temperature, which practically agrees with the solidus temperature. During cooling this is the reduction in the spall strength of St.3 steel, of copper and nickel, and the increase in the spall strength of titanium, the aluminum alloys, and especially the steel 12Kh18N10T.

As has been shown in [8], the process of spalling fracture of metals can be both viscous, as for instance for aluminum, and brittle, as for instance for armco iron. The level and duration of the acting stresses substantially influence the process of microdamage formation, pores in the viscous, and cracks in the brittle fracture cases, and the process of their further growth. The experimental results obtained indicate that the temperature also substantially influences the process of rupture generation and development with spall. This influence is apparently dual in nature: On the one hand a rise in temperature results in some activation of the dislocation mechanisms of microdamage generation, resulting in a reduction in the critical level of the fracturing stresses, and on the other hand, a temperature reduction results in a change in the nature of the fracture from viscous to brittle, that specifies a reduction in the critical level of the fracturing stresses for certain metals during cooling to the temperature —196°C and the behavior of the temperature dependence of the steel St.3.

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DEPENDENCE OF THE CRITICAL STRESSES ON THE LOADING TIME PARAMETERS DURING SPALL IN COPPER, ALUMINUM, AND STEEL

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Intensive shock and explosive pulse loads, used extensively in a number of modern engineering areas, result in the origination of a specific kind of fracture, called spall, in the construction material which is caused by the appearance of tensile stresses during interaction of opposing loading waves [1-4].

In this connection, an investigation of the operability of materials, and the clarification of those conditions under which they do not fracture under the action of pulse loads, are of practical interest. The independent scientific interest in the investigation of spall is due to the possibility of setting up a strength-time relation for short-range actions (to 10^{-7} sec) of high stress levels.

The development of loading facilities and methods of recording parameters behind shocks (precisely there does spall occur), and the application of continuous recording methods [5-8] permit advancement in this area. From the authors' viewpoint, investigations [9] using laser interferometers permitting the experimental recording of the wave profile during loading and determination of the force and time characteristics of the spalling fracture thereby, were substantial progress. However, use of an acoustic approximation by the authors of this paper during processing of the experimental data should apparently be considered just the first step to obtaining the information needed. In the pressure range to 150 kbar, as is known, the shocks are elastic—plastic in nature in the majority of structural materials for which the presence of an elastic part, an elastic predecessor, anda plastic wave being propagated at different velocities, is characteristic. The acoustic approximation does not take this circumstance into account and can induce a significant error, especially in determining the load time parameters [8]. Moreover, knowledge of experimentally determined properties of the materials used as parameters in these problems is necessary for a numerical examination of the different problems associated with the elastic—plastic wave propagation and the fracture of the bodies ([10], for instance). Hence, the appropriate models of the medium should be used in processing the experiments.

A method and the results of determining the load force and time characteristics during the spalling fracture of copper, the aluminum alloy B95, and steel subjected to the action of plane shocks of intensity up to 160 kbar, are presented in this paper. The material is considered an elastic—plastic body under loading and unloading.

Because of the practical impossibility of recording the load parameters in the spall domain, they are assessed by means of the change in state on the interface of the material being tested and a material of low dynamic stiffness. The diagram of the experiment is represented in Fig. 1. The impactor 1 of 90-mm diameter was accelerated in an air-passage apparatus assuring extreme planarity of the collision, to a velocity V_0 of around 900 m/sec, t—x

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