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CRITICAL STRESSES IN SPALLING AND DYNAMIC RUPTURE OF METALS

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Results of dynamic rupture tests of a series of metals obtained using a composite Hopkinson bar and shock-wave loading of plane specimens are described. It is shown that the actual rupture strength at a strain rate of $5 \cdot 10^3$ sec^{-1} *is very close to the spall strength at higher strain rates. Results of testing the same metals using a composite Hopkinson bar within a temperature range of* 20–350°C *are given.*

Key words: *spall strength, rupture strength, composite Hopkinson bar.*

Despite numerous papers that have been published on the strength of materials under shock-wave loading and certain progress in general understanding of the physical processes that occur therein, the problems of correct determination of the spall strength and comparability of data obtained with results of other types of dynamic and quasi-static tests are still unsolved.

The main results, which are believed to be most reliable, on determining the spall strength are obtained by methods based on continuous recording of the free-surface velocity of a specimen (target) under uniaxial strain conditions. In the acoustic approach, the spall strength of an ideal material (amplitude of tensile stresses σ_{tens} acting in the spall section inside the specimen) is [1]

$$\sigma_{\text{tens}} = 0.5\rho_0 c_0 (V_0 - V_m), \tag{1}$$

where ρ_0 is the initial density of the material, c_0 is the volume velocity of sound, V_0 is the maximum free-surface velocity, V_m is the free-surface velocity at the first minimum of the dependence $V(t)$, and t is the time.

In the case of materials with explicit manifestation of elastoplastic properties in both incident and reflected waves, a correction factor associated with the determination of the difference in velocities $\Delta V = V_0 - V_m$ is introduced into formula (1) to take into account that the unloading part of the incident compressive pulse with a velocity $\approx c_0$ catches up with the leading part of the spalling pulse that propagates with a velocity of the longitudinal elastic wave c_{lead}:

$$\sigma_0 = 0.5\rho_0 c_0 (\Delta V + \delta V). \tag{2}$$

Various types of relations for δV can be found in [1–3].

The existing models for spall fracture are based on the stage nature of the spalling process. Most authors consider two to four stages: "explosion-like" formation of numerous single micro- and mesocracks, combination of them into groups (finite clusters), growth and merging of clusters into one macrocrack (infinite cluster) extending over the entire specimen, and, finally, total failure of the specimen into fragments (so-called formation of a spalling "plate"). All the stages are considered in the zone of the extension-wave action; nevertheless, even in the case of a low-intensity shock wave, there is a possibility of formation of micro- and mesodefects with dimensions $l_{1,2} \geqslant 10^{-6}$ m, which can be parallel or perpendicular to the shock-wave front (l_1 and l_2 are the lengths of the perpendicular and parallel defects, respectively). The reason is that, as was shown in a number of papers (see, e.g., [4] and the literature cited therein), the motion of micro- and mesoflows of particles of the material under shock-wave loading possesses

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velocity inhomogeneity in both loading and unloading waves, i.e., this motion is characterized not only by the mean velocity of particles but also by dispersion and amplitude of velocity. Because of this velocity inhomogeneity, micro-(meso) defects of the shear type can be formed between neighboring micro-(meso) flows under certain conditions [5]. Moreover, it is known that mode I (shear) and II (spalling) cracks can be initiated in the compressive-stress field even in the absence of velocity inhomogeneity [6].

Thus, the spall strength determined in this case by formula (1) or (2) is the characteristic of the material with a defect structure rather than the characteristic of the initial material.

It is therefore expedient to use either an alternative method for determining the strength of a material under shock-wave loading, which would allow one to obtain the characteristic required directly, or comparative-correlation relations between the spall strength and other characteristics of dynamic or static strength of materials.

An attempt to find a relation between the spall strength and the critical (actual) rupture strength $S_{\rm cr}$ of the material was made in [7]. Based on the data available (mainly those published in the literature), Kanel' [7] concluded that $\sigma_{\rm tens}$ exceeds $S_{\rm cr}$ by a factor of 2 or less and that the results differ owing to the stress–strain state (SSS) that occurs in spalling and in the neck of a specimen in tension: in the first case, strictly uniaxial strain is realized, whereas in the second case, uniaxial load produces a three-dimensional SSS.

However, the strain of a specimen in tension is of complex nature, varies permanently, and in most cases its concentration and gradient are so much pronounced that the critical strain rates increase abruptly and the SSS changes. At the final stage of extension, the strain is concentrated in a certain cross section and ceases to be uniform, thus, becoming almost adequate to the strain that occurs under spalling conditions. Moreover, numerous experiments showed that the critical rupture strength is twice the shear strength [8], which is in complete agreement with the theoretical determination of the spall strength.

It is therefore of interest to compare extension tests of materials for strain rates close to those that occur in plane specimens under shock-wave loading. A method that allows one to perform these tests is, in our opinion, shock extension of specimens using a composite Hopkinson bar (CHB). For strain rates $\dot{\varepsilon} \approx 10^4$ sec^{-1}, this bar is commonly used to determine the following characteristics: ultimate dynamic strength $\sigma_{\rm t}^{\rm dyn}$, critical rupture strength $S_{\rm cr}^{\rm dyn}$, specific elongation δ, and contraction ratio ψ.

In the present study, the CHB tests using bars 18 mm in diameter were performed at a strain rate $\dot{\varepsilon} = 5 \cdot 10^3$ sec^{-1}. Of importance is the specimen size, in particular, its working (gauge) length (l_0). It is known that the absolute elongation of a specimen immediately after rupture can be decomposed into two components: absolute uniform elongation $\Delta l_{\rm t}$ and absolute concentrated elongation Δl_u, i.e., $\Delta l_{\rm cr} = \Delta l_{\rm t} + \Delta l_u$. Since we are interested only in the concentrated elongation Δl_u, which extends over a small part of a specimen (1.5 to 2 diameters of its cross section d_0), we used a shortened specimen with $l_0/d_0 = 2.0$ as the working part.

To determine the spall strength $\sigma_{\rm tens}$, the tests were performed using a 37 mm-caliber pneumatic gun. Specimens were disks 52 mm in diameter and 5–10 mm thick. The free-surface velocity was recorded by a differential laser interferometer. The experimental technique was described in [4].

An analysis of the values of $\sigma_{\rm tens}$ calculated by formula (1) and the values of $S_{\rm cr}^{\rm dyn}$ listed in Table 1 shows that the critical rupture strength at the strain rate $\dot{\varepsilon} = 5 \cdot 10^3$ sec^{-1} is very close to the spall strength at the strain rate $\dot{\varepsilon} = 10^4$–10^5 sec^{-1}. This result supports once again the importance of taking into account the compression of a material under shock-wave loading.

Kanel' and Chernykh [9] compared experimental data and theoretical models in which the compression process was ignored and showed that the real spalling process occurs faster and more abruptly. To describe the experimental data, these authors used an exponential dependence of the microcrack-accumulation rate on their volume concentration.

As a whole, we can state that the spall strength of materials is determined by relation (1) and the role of the correction factor in (2) is reduced by decreasing the parameters entering into this relation owing to the formation of a system of defects at the compression stage. Moreover, it should be noted that the spall strength depends on the strain rate only slightly and is equal to the actual rupture strength of materials subjected to shock extension with the use of a CHB setup.

It was of interest to study the effect of the initial temperature of a specimen on $S_{\rm cr}^{\rm dyn}$ and, hence, on $\sigma_{\rm tens}$. The corresponding results are listed in Table 2. With an increase in the initial temperature, $S_{\rm cr}^{\rm dyn}$ decreases moderately for most materials tested and substantially for 12Kh18N10T steel and M2 copper. We dwell on the phenomenon of

TABLE 1

Metal	Standard mechanical characteristics	S_{cr}^{dyn}, GPa	σ_{tens}, GPa	$\dot{\varepsilon} \cdot 10^{-4}$, sec^{-1}
St. 4 steel	$\sigma_{0.2} = 250$ MPa, $\sigma_t = 525$ MPa, $\delta_5 = 26\%$	1.72	1.87	3.75
40Kh steel	$\sigma_{0.2} = 415$ MPa, $\sigma_t = 680$ MPa, $\delta_5 = 7.7\%$	1.5	1.6 1.72	3.6 8.2
45 steel	$\sigma_{0.2} = 330$ MPa, $\sigma_t = 610$ MPa, $\delta_5 = 24\%$	1.66	1.79 1.58	3.1 4.25
12Kh18N10T steel	$\sigma_{0.2} = 350$ MPa, $\sigma_t = 560$ MPa, $\delta_5 = 56\%$	1.96	1.77 1.95 1.63	2.45 3.9 6.1
Sp. 28 steel	$\sigma_{0.2} = 540$ MPa, $\sigma_t = 745$ MPa, $\delta_5 = 23\%$	2.38	1.32 1.64 2.22 2.80*	1.35 3.5 4.25 5.5
30KhN4M steel	$\sigma_{0.2} = 925$ MPa, $\sigma_t = 1310$ MPa, $\delta_5 = 22\%$	2.23	2.06 2.21 2.98*	4.8 5.5 6.6
KhN75BMYu alloy	$\sigma_{0.2} = 890$ MPa, $\sigma_t = 1385$ MPa, $\delta_5 = 45\%$	2.52	2.6 2.58 3.43*	3.85 5.25 7.1
M2 copper	$\sigma_{0.2} = 140$ MPa, $\sigma_t = 220$ MPa, $\delta_5 = 58\%$	0.93	0.87 1.22 1.03	1.88 3.68 5.22
VT6-C titanium alloy	$\sigma_{0.2} = 650$ MPa, $\sigma_t = 745$ MPa, $\delta_5 = 16\%$	1.14	1.31	2.97

Notes. 1. The error in determining stresses does not exceed 7% for a confidence probability of 0.95.
2. The values of σ_{tens} that refer to spalling plate formation are marked by an asterisk.

TABLE 2

Metal	S_{cr}^{dyn}, GPa			
	$T = 20°$C	$T = 150°$C	$T = 250°$C	$T = 350°$C
St. 4 steel	1.72 ± 0.062	1.61 ± 0.049	1.485 ± 0.043	1.35 ± 0.052
40Kh steel	1.5 ± 0.064	1.45 ± 0.061	1.31 ± 0.071	1.2 ± 0.059
45 steel	1.66 ± 0.038	1.54 ± 0.049	1.48 ± 0.025	1.41 ± 0.044
12Kh18N10T steel	1.956 ± 0.082	1.45 ± 0.056	1.21 ± 0.039	1.1 ± 0.07
Sp. 28 steel	2.38 ± 0.071	2.38 ± 0.068	2.374 ± 0.074	2.28 ± 0.092
30KhN4M steel	2.23 ± 0.058	2.21 ± 0.061	2.18 ± 0.052	2.0 ± 0.069
M2 copper	0.925 ± 0.031	0.929 ± 0.025	0.619 ± 0.009	0.468 ± 0.028
VT6-C alloy	1.14 ± 0.063	1.13 ± 0.057	1.12 ± 0.064	1.08 ± 0.068

12Kh18N10T steel. Formally, this steel refers to the class of high-temperature steels; however, as can be seen from Table 2, the quantity S_{cr}^{dyn} decreases abruptly at $T = 150°C$. With a further increase in temperature, a decrease in this characteristic is less pronounced. As a whole, this does not contradict the data of other researchers. For example, Polukhin et al. [10] offered data for 12Kh18N9T steel [with an identical chromium content (≈18%) that determines the high-temperature strength of steels of this type] at a strain rate of 90 sec^{-1}, which show that a decrease in σ_t exceeds 50% with an increase in temperature. Similar data are available for the results of static tests. The effect of reduction in strength within the range of 150–200°C is still to be studied.

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