STUDY OF MICRODAMAGE ACCUMULATION WITH SPALLING IN TITANIUM ALLOY VT14

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In describing spalling, i.e., failure of material with intense shock-wave loading, recently the idea has been adopted of damage accumulation taking account of the change in material microstructure during deformation in the region of rarefaction wave reaction. Two main stages of spalling are separated: appearance and growth of nucleated cracks; merging of microcracks [1-3]. In the first, precritical stage of material spalling failure with sufficient accuracy it is possible to consider it as continuous. Initial microdefects arise in local overstressed zones, and their size is 10^{-8}-10^{-7} m [4, 5]. Achievement of a limiting number of microdefects in a unit volume leads to failure of a microvolume and formation of defects with typical sizes of 10^{-6} and 10^{-4} m, which determines the start of the second, post-critical stage of spalling failure. In the first stage the growth of defects has a thermal activation nature [1]. It is possible to suggest that in the second stage failure propagation and reaction of microcracks will be described by the rules of fracture mechanics. A study of specimen microsections stored after shock-wave loading by means of an optical microscope made it possible to reveal reliably defects (pores, cracks) with sizes less than 10^{-6} m. Quantitative analysis of their distribution with different levels of tensile stresses in the region of spalling makes it possible to obtain information about the whole of the second stage of failure close to its boundary with the precritical stage.

Results are given in the present work for quantitative estimates of the degree of damage for specimens of titanium alloy VT14 with spalling. The specimens studied were prepared from bar 50 mm in diameter previously annealed at 750°C for 60 min with air cooling. After annealing alloy VT14 had the following mechanical characteristics: ultimate strength $\sigma_f = 100$ kgf/mm^2, relative elongation $\delta_5 = 8.5\%$, relative reduction of area $\psi = 42.5\%$, impact strength $a_n = 8.4$ kg·cm/cm^2. Alloy microstructure is characterized by an equiaxed $\alpha + \beta$ structure having two typical features: coarse polyhedral grains of transformed β-phase, and the lamellar character of the intragranular structure. The main specimen dimensions are shown in Fig. 1.

Loading was carried out with impact of an aluminum alloy AMts plate 4 mm thick accelerated by detonation of thin layers of explosive. Typical loading time was $1.3 \cdot 10^{-6}$ sec (time for circulation of the elastic wave in the striker). The geometry of the striker–specimen system was selected so that the elastic unloading wave did not overtake the shock-wave front in the specimen, and therefore the pressure behind the shock-wave front emerging at the free specimen surface coincided with pressure at the impact surface. Tests were carried out at 10°C. Sections cut along the specimen axis after grinding, polishing, and chemical etching in a reagent (hydrofluoric acid 2.5 ml, nitric acid 7.5 ml, water 15 ml) were microanalyzed using a MIM-8M metallographic microscope at magnifications up to ×1000. In order to exclude the effect of side loading the central part of specimens in a zone 30 mm in diameter was studied. For convenience of compiling data defects of the cross section working area were divided into 24 rectangular zones as shown in Fig. 1. Estimation of pressure in the compressive loading pulse was carried out using known shock adiabats for titanium and aluminum, and it was assumed that in the acoustic approximation tensile stresses in the spalling zone equaled in absolute value pressure in the compression wave. In tests with an increase in layer of explosive substance there was a subsequent increase in pressure in the loading pulse and correspondingly an increase in tensile stresses. The overall qualitative characteristics of the degree of specimen damage in the pressure loading range 3.9-4.9 GPa are given in Table 1.

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TABLE 1

Test no.	p, GPa	Degree of damage for specimens in the test cross section
1	3,9	Absence of damage
2	4,0	Single microcrack
3	4,26	Several individual microcracks
4	4,33	Weak microdamage in local zones
5	4,45	Moderate microfailure in local zones
6	4,7	Intense microfailure in local zones
7	4,9	Intense microfailure over the whole spalling zone

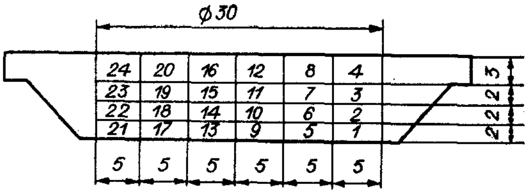

Fig. 1

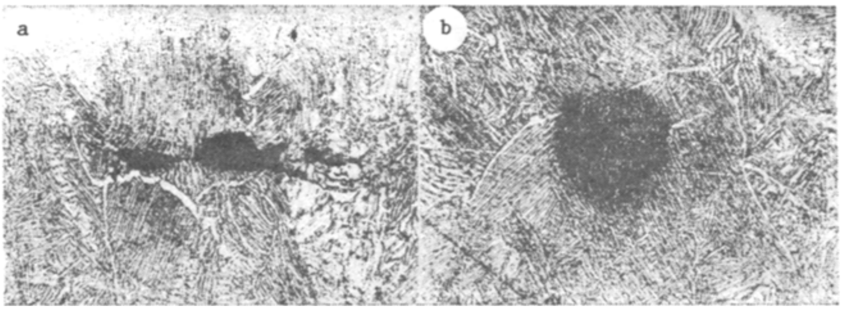

Fig. 2

The pressure with which in the working cross section of the specimen no visible microdamage is observed at a magnification of ×1000 is 3.9 GPa. Formation of microspalls (merging of several cracks) occurs with a pressure of 4.9 GPa. Failure initiation proceeds mainly in the form of microcracks close to the boundary of transformed β-phase along its precipitates (Fig. 2a). Pores also form (Fig. 2b), but their contribution to the overall picture of failure is small. It is significant for alloy VT14 that with a subsequent increase in pressure in the shock wave in the test range the increase in the number of microcracks formed is very small. The total length of microcracks in a cross section of the test specimen was selected as a criterion for the degree of damage. On the basis of results obtained for each of the specimens (see Table 1) histograms were plotted for the distribution of overall extent of cracks $\Sigma \ell$ in relation to distance x from the loaded surface and recording to specimen diameter.

Typical histograms (tests 2, 6, 7), characterizing the change in $\Sigma \ell$ through the specimen thickness with an increase in pressure, are given in Fig. 3. Shown in Fig. 4 is the dependence of overall extent of cracks in the spalling zone (as follows from Fig. 3, found at a distance of 5-7 mm from the loaded surface) on tensile stresses. Attention is drawn to the fact that up to a stress of ≈4.5 GPa there is almost no increase in the value of $\Sigma \ell$, but with a further increase in stress it increases sharply. The dependence obtained points in favor of the suggestion that in the second stage development of spalling failure proceeds in accordance with the assumptions of linear fracture mechanics (LFM). In fact, according to LFM a crack in a brittle material starts to propagate rapidly on reaching a certain critical value

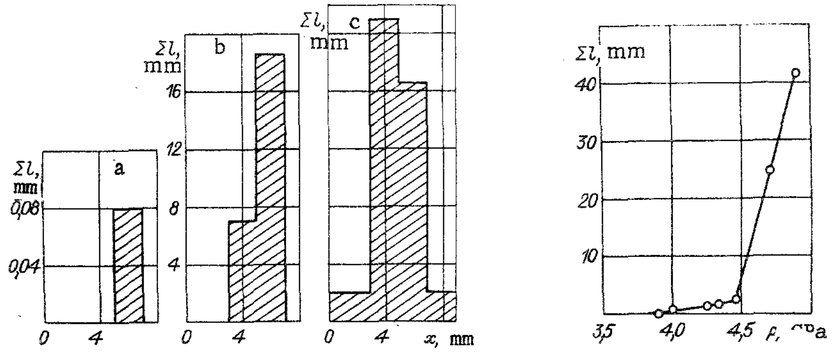

Fig. 3

at the mouth of the crack determining the critical stress intensity factor, which is a parameter for a given material.

In the case of spalling, the process is undoubtedly complicated: there is not one, but a whole series of cracks orientated perpendicular to the shock-wave front. For complete description of the failure process it is necessary to consider their reciprocal effect (experimentally it is demonstrated in studying the reaction of high-velocity colliding cracks in organic glass with dynamic loading [6]). For a number of materials, for example, zinc, in which damage accumulation in the spalling zone occurs by growth and merging of almost spherical pores [7], the LFM assumptions are not applicable.

Nonetheless, the fact detected in this work of a sharp increase in the degree of damage in alloy VT14 on reaching a certain critical tensile stress in the spalling zone merits attention in describing the phenomenological picture of the process of spalling failure for similar structural materials.

LITERATURE CITED

1. L. D. Volovets, N. A. Zlatin, and G. S. Pugachev, "Occurrence and development of submicrocracks in polymethyl methacrylate with dynamic tension (spalling)," Pis'ma Zh. Tekh. Fiz., No. 18 (1978).
2. A. N. Dremin and A. M. Molodets, "Kinetic characteristics of spalling failure," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1980).
3. A. M. Molodets and A. N. Dremin, "Two stages of the spalling failure process," Dokl. Akad, Nauk SSSR, 249, No. 6 (1979).
4. V. R. Regel', A. I. Slutsker, and É. I. Tomashovskii, Kinetic Nature of the Strength of Solids [in Russian], Nauka, Moscow (1975).
5. V. T. Tamuzh and V. S. Kuksenko, Failure Macromechanism for Polymeric Materials [in Russian], Zinatne, Riga (1978).
6. A. S. Eremenko, S. A. Novikov, and A. P. Pogorelov, "Study of the propagation and reaction of high-speed cracks in organic glass," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1979).
7. V. K. Golubev, S. A. Novikov, et al., "Failure and ductility of zinc with spalling," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1982).