DEFORMATION AND FRACTURE OF A THIN DISC UNDER COMPRESSION

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The results of an investigation into the behavior of thin testpieces of two organic solids (succinic acid and oxalic acid) under the conditions of slow compression and compression by impact are presented. The character of deformation and the mechanism of brittle fracture are considered.

For deformation of thin layers, as we know, stresses are required which considerably exceed the yield point of the material. This circumstance,which makes working of metals by pressure difficult, at the same time enables us to apply the simplest methods for the investigation of the properties of the material under pressure. Thus, to study the effect of pressure on certain properties of materials, Bridgman extensively used the method of compressing a thin disc between plane rigid surfaces [1-3]. Under these conditions the stress distribution in a deforming testpiece has been found for rigid-plastic and elastic-plastic media [4, 5]. Here the value of the mean pressure P_* is connected with the yield point σ of the material, the thickness h of the testpiece, and the diameter D (for $h/D < 0.125$) as follows:

$$P_* = \sigma\left(1 + \frac{D}{3\sqrt{3}h}\right) \tag{1}$$

For ductile metals both the stress distribution and the relation (1) are experimentally confirmed [4]. The relation (1) is also satisfied for a brittle fracture of a disc in the case where it solidly adheres to punches; here σ signifies the ultimate strength [5].

Low-strength organic materials were chosen as the objects of the investigation: succinic acid (SA) and crystalline hydrate of oxalic acid (COA). Bearing rollers with a diameter of 10 mm were used as punches. They exceeded the modulus of elasticity of the materials under investigation by two orders. The testpieces were obtained from a dispersed mass by applying pressure up to 5000 atm. Before application of pressure SA was dried out up to a constant weight. In the case of impact the lower roller with a bifilar winding of constantan wire was a strain gage pressure transducer. The construction of the transducers, measurement of pressure,and procedure of interpreting oscillograms are described in [6]. The tests were carried out on a vertical drop hammer; the height of dropping a load of 10 kg was varied from 5 to 80 cm. The pressure oscillogram on the impact of the rollers without the testpiece is presented in Fig. 1a. (The time markings appear at each 200 μsec.) The compression process in the drop hammer is quasistatic, since the time of passage of sound along the rollers ($\sim 10^{-6}$ sec) is much less than the time of impact.

During the impact on the testpiece (Fig. 1b) a sudden pressure drop takes place at a certain time instant; this signifies the fracture of the testpiece. The fracture is accompanied by ejection of a part of the material from the compression region. The strain of the testpiece before fracture, as the analysis of the pressure oscillogram shows, usually does not exceed 10%. Therefore, with a good degree of accuracy we can identify the thickness for which fracture occurs with the initial thickness of the testpiece. No less than 5-10 tests were carried out for each thickness. From measured values of pressure P_* which lead to a fracture and from the relation (1) the values of σ were found and subsequently averaged. Strength curves (Fig. 2) were plotted from the expression (1) and the averaged values $\langle\sigma\rangle$. For SA and COA they are respectively equal to 730 (curve 1) and 580 kgf/cm^2 (curve 2). The dots on the graph correspond to the values $\langle P_*\rangle$ which are the result of averaging the quantities P_* obtained for each thickness. The deviation

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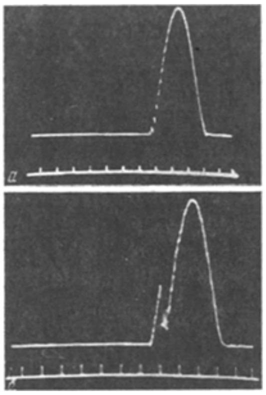

Fig. 1

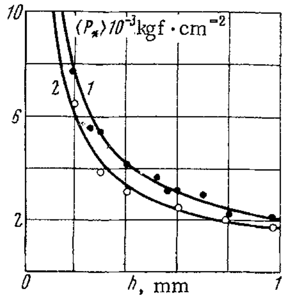

Fig. 2

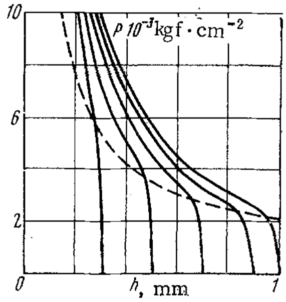

Fig. 3

of $\langle P_* \rangle$ from the curves does not exceed 10%. The results of individual measurements independently of the thickness of the disc can deviate from the strength curve right up to 25%. The cause of such a large scatter in the strength of the testpieces, obviously, is their inhomogeneity. This is confirmed by the fluctuation of the density of the testpieces, which in a number of cases falls short by 15% from the density of the monocrystal.

As experiments showed, the values of $\langle P_* \rangle$ and $\langle \sigma \rangle$ within the limits of measurement errors (10%) do not depend on the dispersion of the material and the velocity of the load during impact (the velocity was altered four times). Thus, we can draw the conclusion that the quantities $\langle P_* \rangle$ depend only on the strength and thickness of the testpieces and are fairly well described by the relation (1). The measurement of the quantity $\langle \sigma \rangle$ during an impact on a thin disc can be recommended as a method of measuring the strength of brittle low-strength materials.

The magnitude of the residual strain, dependent on the pressure (Fig. 3), was measured for SA testpieces of various thickness under slow loading in a press. The strength curve of SA obtained for an impact is marked on the graph by the dotted line. For pressures below the strength curve the residual strain is fairly small; then, as pressure increases, it substantially increases. The plastic strain thus observed is accompanied by hardening, since the curves of slow loading run higher and more steeply than the strength curve. At the same time the fracture of the testpiece can also occur above the strength curve. It is observed more often and at lower pressure for a thicker testpiece and for more rapid loading. Similar fractures for an increased thickness of the layer, for a broad range of materials, were obtained by Bridgman [2].

An explanation of the different behavior of materials during impact and slow loading, apparently, should be sought in two factors: the effect of the rate of loading, which, in the cases being compared, differs by 4-5 orders, and the effect of the pressure. The possibility of flow of relaxation processes, as is known, depends on the rate of loading; if it is sufficiently increased, then a transition into brittleness must take place. However, the effect of the rate alone is insufficient, since testpieces with $h/D \approx 1$ behave as brittle both under impact and under slow loading. The pressure also influences the mechanical properties of solids: it increases the value of plastic deformation of metals before fractures, while many materials (marble, for example) which are brittle under the usual conditions become ductile under high pressure [3]. If, however, the material is plastically deformed under pressure and the latter is removed, then brittleness is restored. In view of this the following experiments are of interest: testpieces deformed along the strength curve under slow loading up to a certain thickness h_1 which noticeably differs from the initial value h, and up to a pressure which greatly exceeds $P(h_1)$, were subsequently subjected to an impact. Here values of $P(h_1)$ were obtained which correspond to the strength curve. Thus, the plastic strain hardening of the testpieces is also reduced when the pressure is removed.

It should be noted that the correspondence of the ultimate strength of the testpieces measured under impact to the relationship (1) indicates that $\langle \sigma \rangle$ does not depend on pressure. In view of this we consider the experiments of Bridgman [2], where the force of rotation of one of the punches was measured dependent on the applied pressure. A strong growth of this force for an increase in the pressure was interpreted by Bridgman as an increase in the yield point of the material under pressure. Such interpretation gave rise to an objection in [7], where it was shown that the connection of the yield point with the rotation force and

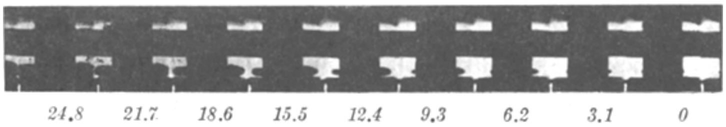

Fig. 4

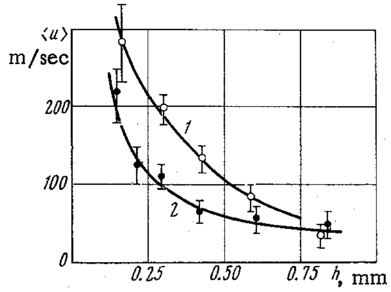

Fig. 5

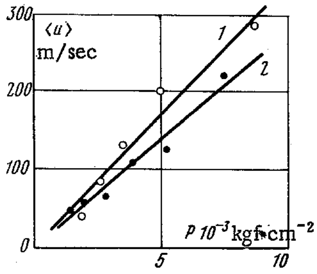

Fig. 6

pressure is more complex than suggested by Bridgman. Consideration of this circumstance, however, cannot explain such a strong dependence of the rotation force on pressure as was obtained in the experiment. This effect, proceeding from the tests under slow loading described above, can be explained by an increase in the yield point as a result of plastic hardening in the shear deformation of the material under pressure. Such hardening must take place on the initial stage of rotation, while the specific friction force on the contact plane must be equal to the increasing limiting shear strength for the material. It should be noted that numerous "flicks" observed for a majority of materials during rotation precisely characterize a brittle type of behavior of the material.

The fracture of thin testpieces can also take place for a rapid pressure drop after preliminary slow loading. The fracture is observed the more often the more rapidly the load is removed. This indicates a kinetic character of the process. A fracture of preliminary loaded testpieces for a rapid pressure drop was obtained in [8] for a large number of different materials.

In all cases, be it under impact, slow loading, or subsequent pressure drop, the fracture of a thin disc leads to intense ejection of a part of the material from the pressure region and to a sharp pressure drop. Often the fracture is accompanied by a strong sound effect, particularly at high pressures, and takes place as an explosion. Having been discovered by Bridgman, this phenomenon attracted great interest from the viewpoint of the effect of pressure on the stability of chemical compounds, especially organic compounds. As it turned out, however, hydrostatic pressure has practically no effect on the chemical stability of organic materials, and the phenomenon under consideration takes place only in the presence of shear stresses. Focusing attention on the fact that during compression of the disc this phenomenon substantially depends on the thickness, Bridgman [9] explained it by purely mechanical causes, while the cases of partial chemical decomposition encountered were explained by a secondary process: heating of the material due to the friction during the fracture. Nevertheless, in an article published not long ago [10], two explanations of the "sugar detonation" were proposed; the cause of this, apparently, was an "explosive" fracture of a thin layer. An experimental refutation of this is presented in [8].

To explain the dynamic pattern of the fracture, tests were set up concerned with the measurements of the rate of rejection of the material from the pressure region during the fracture of a thin disc. A high-speed cine film record of the process of departure of the material during an impact was taken. A ZhLV-2 waiting time lens was used. The case of impact enables the illumination in pulse to be synchronized with the process being observed [6]. The generality of the investigation of the fracture of a thin disc is not violated here, since compression during an impact has a quasistatic character. The filming was carried out in two versions: from one side, in penetrating light so that a shadow pattern was observed, and from below, through a glass anvil in reflected light. In Fig. 4 we have presented sequential frames of film, taken from one side, of the behavior of an SA testpiece having a width of 0.3 mm. The numbers under the frames indicate time in μsec.

In the initial stage of the impact, which corresponds to the portion of gradual increase in the pressure up to the value P_* (Fig. 1b), practically no squeezing out of the material is observed. When P_* is reached, the material is suddenly ejected in a radial direction from the space between the rollers. After a small interval of acceleration ($\lesssim 1$ mm) the motion of the material being ejected takes place with velocities of the order of 100 m/sec. The value of the velocity is the higher, the thinner the fracturing disc. In Fig. 5 we have presented the results of measurements of the velocity of motion of the front of the ejection for SA (curve 1) and COA (curve 2) dependent on the initial thickness of the testpieces. When the fracture is registered, a certain time difference is observed for the ejection from opposing sides of the testpiece. This increases as the thickness decreases and, as the film taken from below showed, can reach 10-15 μsec. The velocity of motion of the material is higher from the side where the ejection is delayed. The difference of velocities in a majority of experiments did not exceed 20%, but in certain cases on the thinnest testpieces it reached 50%. The values of $\langle u \rangle$ shown in Fig. 5 correspond to values of the velocity which have been averaged over the number of tests (3-5) and over opposite sides of the ejection. In Fig. 5 we have shown also the maximum existing deviations of the velocity from the values of $\langle u \rangle$. The measurement of velocities was carried out on a base which was approximately equal to the radius (5 mm) of the testpiece. The accuracy of measurement for all tests amounted to 10%. When thrown out into the free space, the material diverged at an angle of 35° (±10°). No connection between this angle and the velocity of ejection was noted. It should also be mentioned that an examination of the material ejected and collected after the tests showed no traces of chemical decomposition.

Thus, we see that in the fracture of thin layers indeed explosion-like mechanical processes take place. The measured values of the velocities signify a wave character of the ejection process in which a major part of the elastic energy stored during compression is transformed into kinetic energy. The ejection process under investigation can be considered as one of the most convenient cases for testing models of the wave of self-sustained fracture in a stressed brittle body [11, 12]. Indeed, in a thin layer shear stresses are very small in comparison with the bulk stresses. We consider the simplest form of the connection between the velocity of mass and the pressure

$$u = p / \rho c$$

where ρ is the density of the material and c is the velocity of sound. In Fig. 6, we have presented the values $\langle u \rangle$ for SA and COA, dependent on the difference $p = (\langle P_* \rangle - \frac{2}{3} \langle \sigma \rangle)$, which corresponds to the pressure averaged along the radius, of the hydrostatic compression. As we see, a proportionality between them is fulfilled perfectly satisfactorily. The calculation of the velocity of sound from the angle of slope here gives 1900 m/sec for SA and 2200 m/sec for COA, the values which are very characteristic to such materials.

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