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MECHANICAL PROPERTIES OF MATERIALS STUDIED FROM KINETIC DIAGRAMS OF LOAD VERSUS DEPTH OF IMPRESSION DURING MICROIMPRESSION

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The mechanical properties of the technological layers formed near the contact surfaces of different materials considerably affect the durability of constructions manufactured from composite materials such as bimetals prepared by soldering or welding. Owing to the brittleness and the small sizes of the layers, their properties usually cannot be determined by utilization of the normal procedures. The method of microimpression by an indentor and plotting of the results of the tests along two coordinates, viz., plotting the load on the indentor along the abscissas and the depth of the impression along the ordinates [1] is one of the few methods permitting the mechanical properties of such materials to be estimated. For "uniform" materials this method should be considered a highly efficient micromechanical test procedure.

TABLE 1. Some Physicomechanical Properties of the Materials Examined

Sample No.	Material	σ_b, kgf/mm²	P_{max}, gf	HV, kgf/mm²	$\sqrt{H/HV}$	$E\cdot10^{-3}$, kgf/mm²	$E_d\cdot10^{-3}$, kgf/mm²	δH, %	ψ, %
1	30KhGSA	79	250	250	1,07	20,5	21,0	5	20
2	30KhGSA	130	365	446	1,10	20,0	21,6	2	9
3	Steel 45	90	365	246	1,11	19,5	19,5	4	20
4	L62	46	250	133	1,09	9,5	9,8	0	12
5	D16T	60	250	161	1,06	7,8	8,02	2	6
6	Ti alloy	—	250	247	1,085	—	13	9	9,5
7	Glass	—	90	625	0,91	—	7,37	—	12
8	Fe_2Al_5	—	200	915	0,91	—	13	0	1,5
9	$FeAl_3$	--	300	718	0,88	—	11,0	0	1,5

Note. 1. P_{max} denotes the load on the indentor at the moment of unloading; HV and H are the hardnesses calculated from the diagonal and the depth of the impression of Bikkers pyramid; E and E_d are the values of Young's modulus calculated from the stretching and impression tests. 2. Each value is the result of five to ten impression tests carried out in an equipment analogous to that described in [3, 4].

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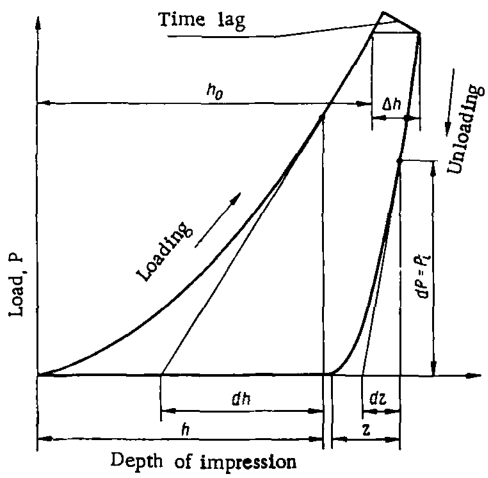

Fig. 1

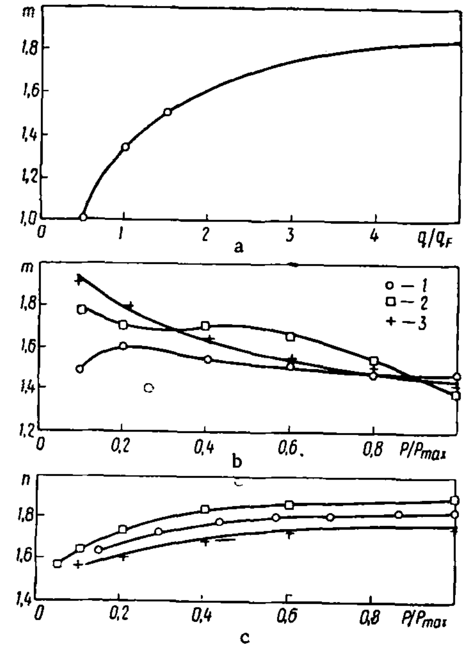

Fig. 2

Fig. 1. Diagram of impression by an identor and some parameters.

Fig. 2. Plots of m and n vs the relative pressure in the center of the impression (a) and the relative load on the indentor (b, c): 1) 30KhGSA steel, σ_b = 79 kgf/mm^2, P_{max} = 250 gf; 2) 30KhGSA steel, σ_b = 130 kgf/mm^2, P_{max} = 365 gf; 3) glass, P_{max} = 90 gf.

One of the important characteristics of the material – the Young's modulus – can be found from the unloading branch of the impression diagram (Fig. 1). If the load is relieved after the relaxation processes under the impression have come to an end, the initial stage of unloading is a purely elastic process. In this stage loading and unloading are reversible processes and can be described by the theory of elasticity. The sample can be considered to be an elastic semispace if its linear sizes exceed the diameter (diagonal) of the impression by a factor of about ten or more. Then during elastic impression of a rigid cylinder with a plane end face of diameter d (when the pressure on the contour of the area of contact tends to infinity) the load P distributed over the surface of the impression is related to the vertical displacement z of the center of the impression by the relationship [2]

$$P = \frac{d}{e} z, \tag{1}$$

where $e = (1-\mu)/E$ (μ and E are Poisson's coefficient and Young's modulus of the semispace). For elastic impression of a spherical punch of radius R the formula reads

$$P = \frac{4}{3} \cdot \frac{\sqrt{R}}{e} z^{3/2} \tag{2a}$$

The formula for a cone with the apex angle 2φ reads:

$$P = \frac{2}{\pi} \cdot \frac{1}{\operatorname{ctg} \varphi e} z^2. \tag{3}$$

We shall determine the derivatives dP/dz of these functions. Since in the first function d = const., it follows that dP/dz = d/e.

For function (2a) $dP/dz = (2/e)\sqrt{Rz}$. Since

$$R = \frac{d^3}{6Pe}, \tag{2}$$

and z = (3/2)(Pe/d), only two of the parameters P, z, d, and R are independent; we may take, e.g., P and d as independent parameters. After substitution we get dP/dz = d/e.

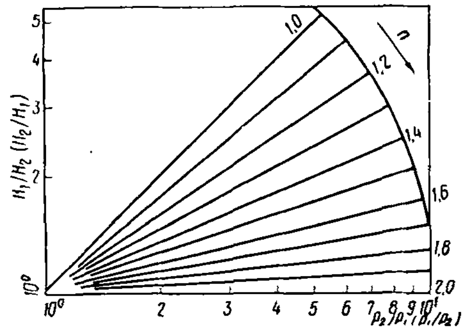

Fig. 3. Monogram suited for calculating the microhardness from the function n = f(P).

For the third function (second limiting case where the pressure in the center of the impression tends to infinity) $dP/dz = (4/\pi) \cdot (z/\text{ctg}\,\varphi e)$. On the other hand [5], $z = (\pi/4) d\,\text{ctg}\,\varphi$. After substitution we find the same value $dP/dz = d/e$.

Consequently, the finding that the slope of the initial unloading branch of the loading–impression diagram is independent of the distribution of the pressure under the impression is an important practical property of the curve of elastic unloading of a plastic impression. We shall express the linear size d of the impression by the area F of its projection:

$$dP/dz = \frac{d}{e} = \frac{2}{\sqrt{\pi}} \cdot \frac{\sqrt{F}}{e}. \tag{4}$$

Taking into account the elastic properties of the indentor we find $e = e_1 + e_2 = (1-\mu^2)/E + (1-\mu_a^2)/E_a$, where μ_a and E_a denote the elastic constants of the indentor. Solving Eq. (4) with respect to E, we derive

$$E = \frac{1-\mu^2}{\frac{2}{\sqrt{\pi}}\sqrt{F}\,dz/dP - e_2}. \tag{5}$$

Assuming $\mu = 0.3$, we determine E to an accuracy of $\pm 3\%$, if $0.25 \leq \mu \leq 0.35$.

In order to apply the proposed procedure to a square impression in a plane, we compare the values of z for a round ($z_{\bigcirc}$) and a square impression ($z_{\square}$) at identical areas F. In the case of a uniform pressure on round and square areas, respectively, we find [2]

$$z_{\bigcirc} = \frac{2(1-\mu^2)}{E} \cdot \frac{P}{\sqrt{\pi F}};$$

$$z_{\square} = \frac{2(1-\mu^2)}{\pi E} \ln \frac{\sqrt{2}+1}{\sqrt{2}-1} \cdot \frac{P}{\sqrt{F}}.$$

It is easily shown that $z_{\bigcirc} \simeq 1.0056\, z_{\square}$. Consequently, the processes and equations which describe them are almost identical. Since the actual distribution of the pressure under the indentor is not uniform but increases upon passing towards the center of the impression and, owing to the decreasing difference between the moments of the forces with respect to the impression axis, the equations differ still less, it can be concluded that Eqs. (4), (5) are applicable both to a round and to a square impression.

An experimental check of the procedure proposed showed that Young's modulus E determined from stretching tests agrees fairly well with Young's modulus E_d determined from impression tests. It should be noted that the value E_d is slightly higher than E for two theoretical reasons. If F denotes the area of the impression and F_K denotes the area of the contact between the indentor and the sample, the latter area slightly exceeds the area of the impression, owing to the elastic contact at the contour of the impression. Therefore, $E_d > E$ in formula (5). The presence of a hydrostatic pressure which raises Young's modulus is typical of the stressed state under the indentor. According to data of [5, 6] this rise equals 5% when the pressure is increased by 0.01 E. From this it follows that $E_d = E(1 + k(HV/E))$. According to tabulated data, $k \simeq 2$-0.

The capability of the material to relax the stresses in the course of the time δH was calculated from the formula

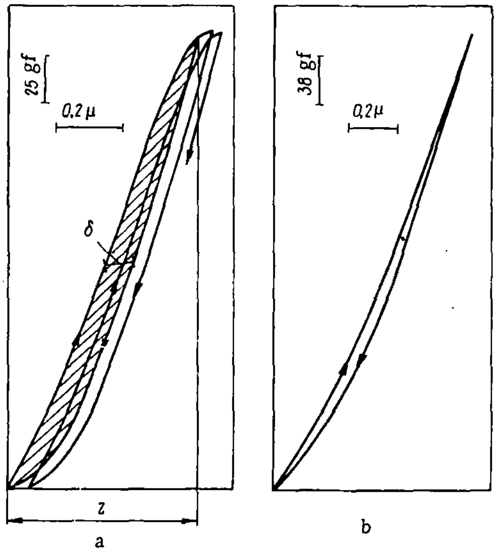

Fig. 4. Hysteresis in the samples No. 1 (a) and No. 2 (b) of 30KhGSA steel (the area of the loop of the first cycle (a) is hatched).

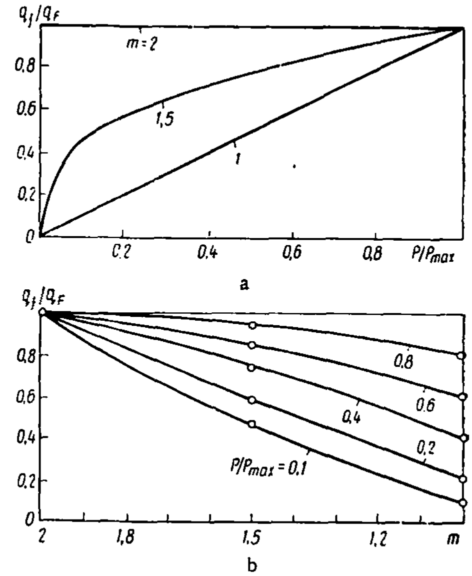

Fig. 5. Variation of the mean pressure under the impression during unloading.

$$\delta H = \frac{H_0 - H_t}{H_0} \simeq \frac{2\Delta h}{h_0 + \Delta h},$$

where $H_0 = c(P/h_0^2)$ (see Fig. 1) denotes the hardness found from the loading branch; H_t is the hardness at the moment t (the rise of the loading being stopped at t = 0) after which the hardness practically did not change further. The time t for the various materials varied from a few seconds to several minutes. The slope of the arc which corresponds to the time lag is not correlated to the properties of the material (the latter are determined by the parameter δH) and characterizes the rigidity of the spring in the equipment with which the forces are measured.

Table 1 contains several properties of the two metal alloys Fe_2Al_5 and $FeAl_3$, which have been hardly examined so far; since they are brittle, they cannot be studied by means of the usual methods.

Relationships (1)-(3) derived above permit a general exponential function $P = a_m z^m$ to be introduced for describing the actual elastic process of unloading; in this function $1 \leq m \leq 2$, as follows from the two limiting cases, the value of m characterizing the distribution of the pressure under the indentor [2, 7]. If the pressure in the center of the impression and the mean pressure are denoted by q and q_F, respectively, $q/q_F = 0.5$ at m = 1 (for this case we take z = 1); at m = 1.5, $q/q_F = 1.5$, z = 1.5; at m = 2, $q/q_F \to \infty$, z = 2; at $q = q_F$, $z = 4/\pi$. The plot of $q/q_F = f(m)$ in Fig. 2a was constructed from these data.

To determine the value of m in any point of the unloading curve characterized by the parameters P, z, and dP/dz, we have two equations $P = a_m z^m$ and $dP/dz = m a_m z^{m-1}$. Solving the first equation with respect to a_m, substituting the expression thus obtained for a_m in the second equation, and solving the latter with respect to m, we find:

$$m = dP/dz : P/z. \tag{6a}$$

In the case of graphical determination of dP/dz the differential $dz = \Delta z$. Th. , the difference Δz should be so chosen that $dP = P_i$ (see Fig. 1), where P_i denotes the value of the load in the considered point of the curve. Then

$$m = z/dz. \tag{6b}$$

Figure 2b and c shows the variation of parameter m for three materials during unloading, from which the distribution of the pressure under the indentor can be estimated.

This evaluation of the unloading branch is a universal procedure and can be used in many practical studies, e.g., in the consideration of the unloading branch when the latter is described by the equation

$P = ah^n$ [8]; however, in the latter case n is variable. Consequently, the functions $n = f(p)$ or $n = \varphi(h)$ can be found experimentally. This function essentially describes the effect of the scale factor during impression. The equation which is analogous to Eq. (6b) (see Fig. 1) reads

$$n = h/dh. \tag{6c}$$

From a comparison of the data obtained by evaluating the loading and unloading branches for the material 30KhGSA in two structural states and those for industrial glass (see Fig. 2b and c, where every point represents the average over five to ten tests) it is evident that m increases as the index n decreases (the rise of the hardness increases when the size of the impression decreases), i.e., the pressure under the apex of the indentor increases, which is especially noticeable for glass. This is related to a considerable extent to the effect of the rate of unloading and the dependence of the geometry of the unloading branch on this rate. This dependence does not occur in metals.

The continuous function $H = \psi(P)$ can be constructed from the function $n = f(P)$ and a single known value of the hardness. To do this, it is convenient to utilize a simplified procedure consisting in division of the function $n = f(P)$ into parts to which a constant value is assigned. Then by applying some transformations we derive from the power function $P = ah^n$ the expression $dH/H = [(n-2)/n]dP/P$. Integrating the latter expression and substituting the integration limits, we find

$$\ln H_1/H_2 = \frac{2-n}{n} \ln P_2/P_1 \quad \text{at} \quad P_2 > P_1; \tag{7a}$$

$$\ln H_2/H_1 = \frac{2-n}{n} \ln P_1/P_2 \quad \text{at} \quad P_2 < P_1. \tag{7}$$

A plot of these equations along logarithmic coordinates is a straight line and the slope of this line, equaling $(2-n)/n$, indicates the ratio between the change of the logarithm of the hardness and the change of the logarithm of the load, e.g., at $n = 1.9$ this ratio equals 1/19 and at $n = 1.5$ it equals 1/3. Figure 3 shows a nomogram suited for calculating the hardness from known values of n. Such a nomogram may be constructed also along the coordinates H_1/H_2 vs h_2/h_1, and then the slope of the rays will equal $2-n$.

In the case of unloading of metals the variation of m has a complex character (see Fig. 2b), which, evidently, is related to the Bauschinger effect, which is revealed by the hysteresis loop found upon renewed loading of the impression. Figure 4 shows the hysteresis loops for 30KhGSA steel (see Table 1), where sample No. 1 shows an increase of the depth of the impression, whereas in several tests on sample No. 2 the depth of the impression remains constant and the hysteresis loops coincide. "Explosion" of the impressions in the first cycles is typical of brittle materials. The hysteresis

$$\psi = \delta/z \tag{8}$$

(see Table 1) for samples No. 1 and No. 2 equaled 20 and 9%, respectively. The value of ψ thus determined is an analogue of the measure which characterizes internal friction and the so-called absorption coefficient [9].

Our investigations proved the general validity of some regularities of cyclic loading during impression and in few-cycle fatigue tests on samples of the usual shape when the durability is predicted from the width of the hysteresis loop [10]. With regard to the magnitude, the hysteresis during impression is of the same order as the Bauschinger effect. Therefore, we shall consider the physical nature of the latter effect in more detail.

The Bauschinger effect appears when the direction of the effective stresses is altered, while the magnitude is kept constant or slightly reduced. During unloading of an impression this situation may occur, if the mean pressure on the contact area left remains constant or is slightly reduced. We shall analyze how the pressure changes in the three cases described by Eqs. (1)-(3).

If $P = d/ez$, where $d = \text{const}$, then $q_F = 4P_{max}/\pi d^2$. We shall denote the mean pressure and the load during unloading by q_f and P, respectively: $q_f = 4P/\pi d^2$, from which it follows that

$$q_f/q_F = P/P_{max}, \tag{9}$$

i.e., in this case the mean pressure decreases proportionally to the reduction of the load on the indentor.

During elastic unloading of a spherical punch the following equation holds:

$$P = d^3/6Re, \tag{2b}$$

from which it follows that

$$P/P_{max} = (d/d_{max})^3,$$

where d_{max} denotes the diameter of the contact area at the moment of unloading; d the diameter of the contact area during the unloading process. On the other hand, we can always write $P = \pi d^2/4q_f$ or $P/P_{max} = q_f/q_F(d/d_{max})^2$. Consequently, $P/P_{max} = (d/d_{max})^3 = q_f/q_F(d/d_{max})^2$. Substituting P from Eq. (2b) for d and d_{max}, we get

$$q_f/q_F = (P/P_{max})^{1/3}, \tag{10}$$

i.e., the mean pressure decreases considerably slower than the load.

In the third case by substituting $z = (\pi/4)d\cot\varphi$ in Eq. (3) we find $P = (\pi/8)\cdot(\cot\varphi)d^2/e = cF$, from which it follows that

$$c = P/F = \text{const} = q_F, \tag{11}$$

or, in other words, in this limiting case the pressure remains constant during the unloading process.

Figure 5 shows how the mean pressure q_f/q_F depends on P/P_{max} at three fixed values of m and m at fixed values of P/P_{max}.

Since Eqs. (1)-(3) hold both for round and for square impressions, the plots shown in Fig. 5 are evidently applicable also to a square impression in a plane.

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