JOURNAL OF MATERIALS SCIENCE 15 (1980) 2331–2334

Surface layer hardening of polycrystalline copper by multiple impact

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A near-rigid indenter is used to impact repeatedly a fixed location on a target material. The process of work-hardening in copper targets was revealed by the change of the value of the coefficient of restitution during a sequence of impacts. It was found that for a series of impacts on a single point the ratio of the rebound energy to the impact energy approaches a constant value which is independent of the impact energy and appears to be related to the dislocation density. Repeated impacts on a fixed location result in (1) plastic deformation decreasing with successive impacts because of work-hardening, (2) increasing volume of work-hardening material that contributes to the elastic rebound, and (3) bowing of dislocations. The process is similar to cyclic hardening associated with fatigue.

1. Introduction

The aim of this work is to study the complex problem of erosion and impingment fatigue caused by particle bombardment by investigating the effect of multiple impacts produced on a single point on the surface of a target material.

The effect of the impact of a particle on a solid surface depends on the physical and mechanical properties, geometries, masses and relative velocities of striker and target. These experiments involve the impact of a free falling indenter of hard spherical surface against the flat surface of a softer target. "Hard" implies that the indenter will suffer no plastic deformation and only negligible elastic deformation during experimentation. The impact energy is the kinetic energy of the indenter at the time of contact with the target represented by $w^0 = mv_0^2/2$, where m is the indenter mass and v_0 is the impact velocity. The energy of rebound or elastic energy is given by $w^e = mv_r^2/2$, where v_r is the velocity of rebound. The coefficient of restitution [1] is defined as $e = v_r/v_0$, or $e^2 = w^e/w^0$. When all the energy is used in plastic deformation, $e = 0$. For a perfectly elastic impact all the energy is regained by the rebounding particle, and thus $e = 1$. When the surface properties change as a consequence of repeated impacts, variations of e are indicative of the change in the relative amount of elastic and plastic energy of the deformation.

2. Experiments

The flat surface of a copper target was impacted repeatedly by a hardened-steel indenter of spherical surface with a radius of curvature of 1.5 mm, and mass of 100 g, at velocities ranging up to 50 cm sec^{-1}. The position of the indenter during impact was detected by an LVDT and displayed as a function of time on a digital oscilloscope; the impact and rebound velocities were measured in the display. The coefficient of restitution was calculated at v_r/v_0 with an error of less than 3.5%. Optical and scanning electron microscopy was used to analyse the deformation of the impacted surface.

3. Results

Impact loading produces a permanent indentation. Repetitive impacts result in major deformation of the volume underneath the indentation and minor deformation in the adjacent region. Fig. 1 is a graph of the depth of the indentation as a function of the number of impacts. The deformation produced during each impact is proportional to the difference between two consecutive points.

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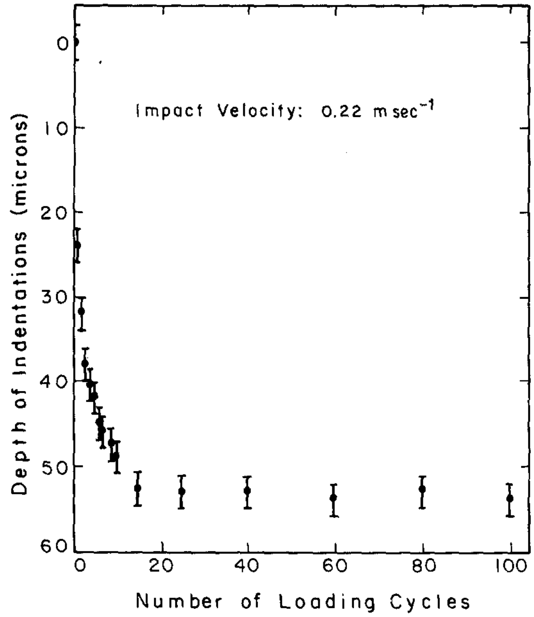

Figure 1 Depth of identation as a function of number of impacts for an impact velocity of 25 cm sec^{-1}.

The increments of plastic deformation decrease with the number of impacts, and the depth of the crater increases only slightly after 20 impacts. The coefficient of restitution is plotted as a function of the number of impacts as in Fig. 2. For the first impact its value is approximately equal to 0.3, it increases with the number of impacts, and approaches the value 0.75 by approximately the 20th impact. For subsequent impacts (up to 10^6) the value of e remains essentially unchanged. Figs. 1 and 2 clearly show an initial stage of rapid work-hardening, and an approach to a state of saturation by the 20th impact. The value of the coefficient of restitution for impacts occurring after the stage of rapid hardening is independent of indenter mass and velocity. This fact is seen in Fig. 3 where the coefficient of restitution is plotted as a function of the number of impacts for 3 sets of impacts produced on the same point on the target surface at different impact velocities. Each increase of impact velocity produces more plastic deformation and the consequent decrease of the value of e. After rapid hardening the same saturation value is approached.

The dependence of the coefficient of restitution on the value of impact velocity for an impact-hardened and a non-hardened surface is shown in Fig. 4. The open circles represent the coefficient of restitution measured for a single impact produced on an undeformed area. The solid circles represent the value of the coefficient of restitution measured when the indenter impinged an area that was previously impacted 150 times. Tabor [1] developed the following expression for the relation between impact velocity and rebound velocity for a single elastic–plastic impact

$$v_r = k(v_0^2 - 3/8v_r^2)^{3/8} \tag{1}$$

with k given by the relation

$$k = 1.96\frac{\mathscr{P}^{5/8}}{m^{1/8}}\left(\frac{1}{E_1}+\frac{1}{E_2}\right)^{1/2} \tag{2}$$

where m is the mass of the indenter and R its radius of curvature, E_1 and E_2 are the Youngs' modulus of indenter and indented materials, and $\mathscr{P}$ is the dynamic yield stress. The predicted dependence of the coefficient of restitution with v_0 follows from Equation 1 and is shown for two values of k in Fig. 4. The two values of k were chosen to give the best fit of the two sets of experimental points. The lower curve in Fig. 4 is in reasonable agreement with the experimental

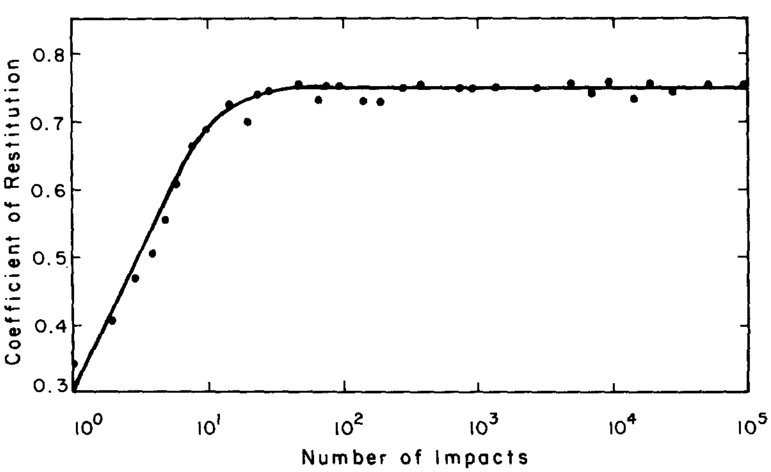

Figure 2 Coefficient of restitution as a function of number of impacts for an impact velocity of 25 cm sec^{-1}.

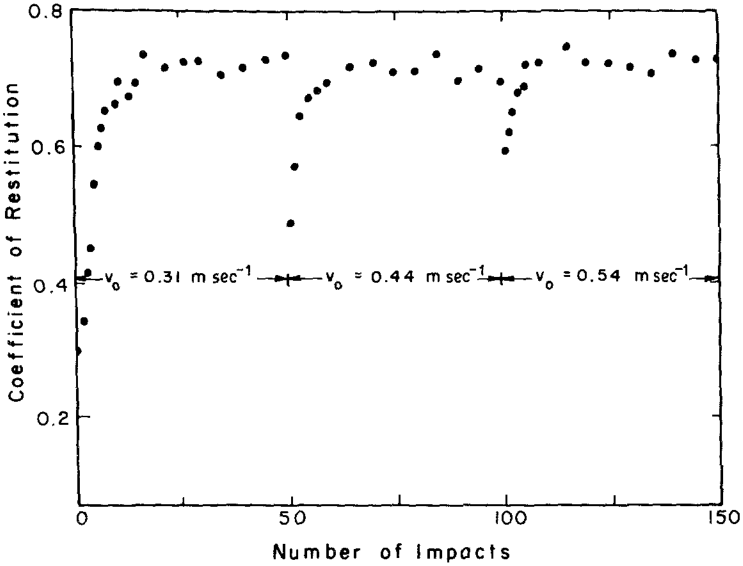

Figure 3 Coefficient of restitution as a function of number of impacts for impact velocities of 0.30, 0.45 and 0.55 m sec^{-1}.

data for annealed specimens. The solid circles corresponding to the impact-hardened surface do not fit any curve of the family of Equation 1, but instead they spread around a value of 0.73.

The crater depth produced by a number of impacts up to 10^6 is plotted in Fig. 5; these data show that crater depth increases at a rate of 30 micrometers per decade of impacts and that the plastic deformation process does not cease even after a large number of impacts.

Patterns of slip lines form around the indentation during the stage of rapid hardening. For single crystals these patterns are similar to those produced by static indentation of copper [2] and are not indicative of cyclic straining. The appearance of surface slip traces is a manifestation of the development of a high density of dislocations adjacent to the crater.

4. Comments

A diagram of the energy distribution for the first 50 impacts is shown in Fig. 6. The solid curve represents the fraction of energy expended in elastic deformation derived from Fig. 2. The difference between the dashed curve and the solid curve represented by the vertical hatched region is the amount of energy expended in

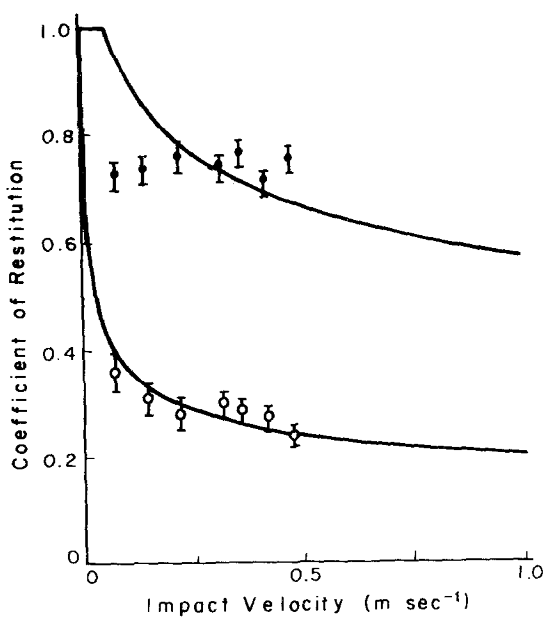

Figure 4 Coefficient of restitution as a function of number of impacts for a work-hardened surface (solid circles) and for a non-hardened surface (open circles).

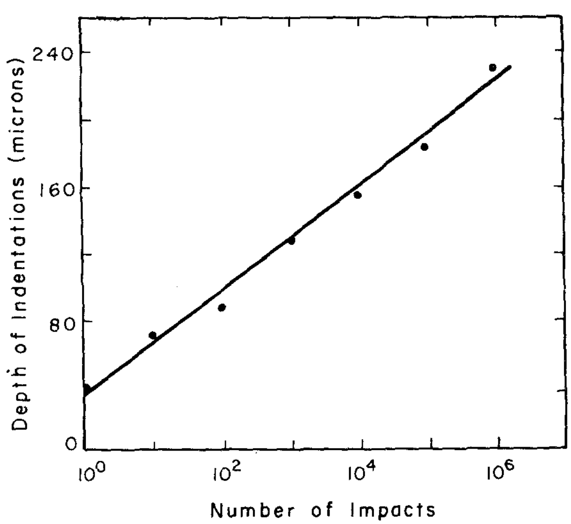

Figure 5 Depth of indentation as a function of the number of impacts in a semilogarithmic graph for an impact velocity of 25 cm sec^{-1}.

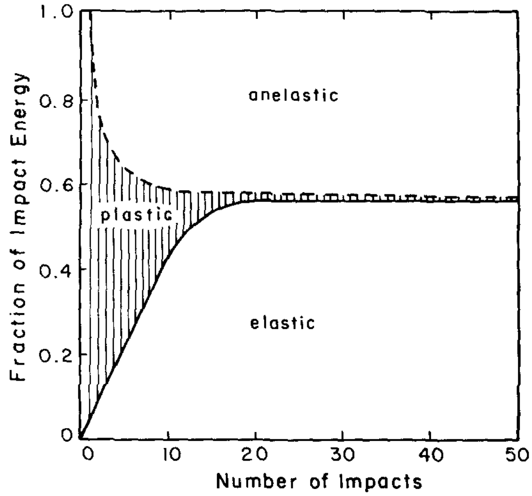

Figure 6 Energy distribution during impacts as a function of number of impacts for an impact velocity of 25 cm sec^{-1}.

plastic deformation w^p. w^p is estimated based on the volume V_c of the crater, using the relationship [1]

$$w^p = PV_c \tag{3}$$

where P is a mean pressure estimated as follows

$$P = F/S_0 = \frac{1}{S_0} m \frac{dv}{dt} = \frac{1}{S_0} m \frac{(v_0 + v_r)}{\Delta t} \tag{4}$$

where S_0 is the projected surface of the indentation, m is the mass of the indenter and Δt is the duration of the impact or contact time.

After the stage of rapid hardening approximately 55% of the impact energy is expended in elastic deformation.* A fraction of the energy in Fig. 6 cannot be accounted for by plastic or elastic deformation. This condition appears to be a characteristic of work-hardening materials [3, 4]. We attribute this expenditure of energy to the bowing of the high density of dislocations produced during work-hardening.

The density of active dislocations necessary to absorb 45% of the impact energy can be estimated based on the work W required to move a dislocation with Burgers vector $\boldsymbol{b}$ a distance $\bar{x}$ by an external applied stress σ

$$W = \sigma b \bar{x} \bar{\rho} V_d \tag{5}$$

where $\bar{\rho}$ is an average density of active dislocations and V_d is the volume of the deformed region under the crater. V_d was revealed by etching cross sections of the indentation. The applied stress is taken as the impact average pressure estimated according to Equation 4, and the average distance a dislocation moves is taken as $\bar{x} = \sqrt{1/\bar{\rho}}$. For an impact energy of $w^0 = 10^{-3}$ J corresponding to $m = 100$ g and $v_0 = 25$ cm sec^{-1}, we obtain from Equation 5

$$\bar{\rho} = 10^{-11} \text{ cm}^{-2}.$$

This calculated density is consistent with the range of values of dislocation densities measured in cold worked materials [7].

5. Conclusions

Repeated impacts normal to the flat surface of a copper target by a near-rigid indenter with impact velocity ranging up to 50 cm sec^{-1} produces a permanent indentation on the target surface. Two stages can be identified.

(1) Rapid work-hardening is produced during approximately the first 20 impacts. A region of high density of dislocations develops underneath the crater. Most of the impact energy is expended in plastic and elastic deformation.

(2) Impacts following the stage of rapid hardening produce slight plastic deformation. The impact energy is used in elastic deformation and the bowing of dislocations in approximately equal amounts. The coefficient of restitution remains equal to 0.75 for impacts up to 10^6, and it is independent of impact velocity and indenter mass. Its value appears to be related to the density of dislocations.

Acknowledgement

This work was supported by the National Science Foundation under grant no. DMR 7914779.

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Received 24 May 1979 and accepted 18 February 1980.

*Calculations based on the work of Hunter [4] and Kirchner and Gruver [5] indicate that in the present case the energy dissipated in stress waves is less than 1%.