EXPERIMENTAL INVESTIGATION OF PLASTIC WAVES IN COPPER PLATES

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A large number of theoretical and experimental articles have been devoted to the study of the propagation of elasticoplastic waves in thin bars. In these articles the main stress is laid on the verification and comparison of the one-dimensional theories of Rakhmatulin, Taylor, and Karman and Sokolovskii, and Malvern.

The present article considers plastic waves in copper plates, when the transverse components of the deformation cannot be neglected. The propagation of the longitudinal and transverse components of the plastic deformations is demonstrated experimentally. No effect of the deformation rate was observed. A number of curves characterizing a plastic pulse are plotted.

From the well-known experiments of Bell, and those of Clifton and Bodner [1] and of a number of other authors, as well as from the results of experiments with wave-type loading [2, 3], the conclusion can be drawn that the spectrum of the rates of propagation of deformations in a plastic pulse depends only very slightly on the deformation rate. This has explained the good agreement between the experimental data and the Rakhmatulin–Taylor–Karman theory, and has permitted a number of authors to modify it, introducing the deformation rate into the equations as a parameter.

The assumption adopted here with respect to the equality to zero of the transverse deformation is rather rough, and is rougher the greater the ratio of the diameter of the bar to its length. To evaluate the effect of the scheme of the stress-deformation state on the propagation and properties of plastic waves, the authors of the present article made a series of experiments on the elongation of copper plates by a pulsed discharge of explosives. The experimental scheme made it possible to record the dynamics of the principle deformations ε_1 and ε_2 in the plane of the plate.

1. Experimental Method

To record the deformations, a high-speed moving-picture streak camera (rate $5 \cdot 10^5$ frames/sec) was used to photograph the picture of the moiré bands forming on the basal surface of the sample. An emulsion having a grating with a line ruling of 40 lines/mm was glued to the polished surface of the plate with an epoxy-based resin. The control grating was pressed closely against the basal surface through a thin layer of glycerin. The moiré pictures were interpreted using the method of [4].

Samples of M2 cold-rolled copper were cut along the direction of rolling. The working surface of the samples was 75×10 mm^2, and their thickness 2.5 mm. The normal elastic modulus E = 11,100 kg/mm^2.

A schematic diagram of the loading is shown on Fig. 1. The sample 1, with a rectangular notch in its tip, one side of which was rounded off to conform to the radius of the firing pin, the half-cylinder 2, was loaded by the explosion of a charge of explosive 4, placed in the chamber 3. The cheekpiece 5, fitting into the notch in the sample, was attached to the rigid support 6. A regular gap 8 was left between the cheekpiece and the edge of the notch. The plate 9 prevented the explosion products from getting into the field of the photography. The charge of explosive (0.7 g PETN, poured density 1.3 g/cm^3) was detonated by the discharge of a battery of high-voltage condensers through the wire 7. The advantage of the scheme consisted in the possibility of regulating the amplitude, the duration, and the slope of the charge pulse by means of the gap 8, and by a change in the mass of the charge. The rear part of the sample was held in a special clamp.

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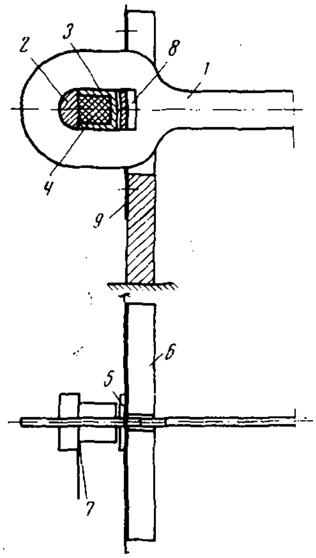

Fig. 1

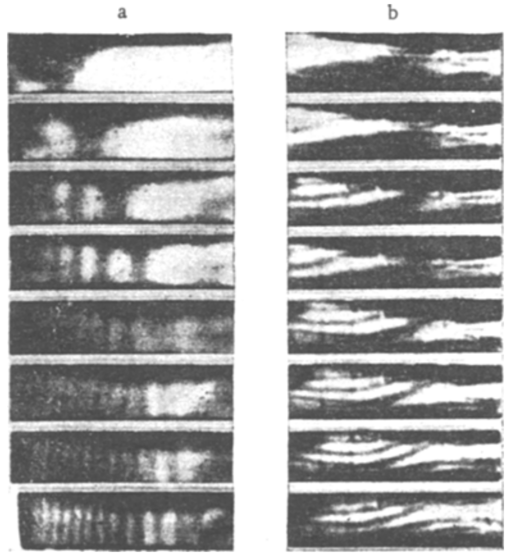

Fig. 2

2. Results and Discussion

The loading consisted in a monoaxial plane-parallel state with two principal deformations, longitudinal ε_1 and transverse ε_2. A linear grating with lines across the sample was used to bring out ε_1, and a grating with lines along the sample to determine ε_2; an orthogonal grating was used for the combined recording of ε_1 and ε_2. Unfortunately, the orthogonal grating considerably worsened the quality of the image, and only the ε_2 components were visible on the moving-picture photos. We note that the deformations measured by the moiré method are of the Euler type.

Figures 2a and b give moving-picture photos illustrating the propagation of ε_1 and ε_2. The time between frames was 12 μsec, and the exposure time 1 μsec. The distribution of the profile of the plastic waves was determined by photography in several cross sections along the length of the sample. The dependence $\varepsilon = \varepsilon(t)$ was determined.

Figure 3 gives profiles of plastic waves. The rates of propagation of the longitudinal components of the deformation $c_1 = c_1(\varepsilon_1)$ and the transverse components $c_2 = c_2(\varepsilon_2)$ were determined from known profiles and from the distances between cross sections. It was found that the rates of propagation of the deformations do not depend on the position of the cross section. Since, along the length of the sample, with increasing distance from the origin the curves $\varepsilon = \varepsilon(t)$ become flatter and flatter, the deformation rate decreases in the same direction. An evaluation of the dependence of the deformation rate on the position of the cross section of the sample shows that it is close to hyperbolic. It can be concluded that, within the limits of error of the photography, the velocities c_1 and c_2 do not depend on the deformation rate. (This error is from 7% with small deformations to 3% with upper values of the deformation). It must be noted that the very form of the visualization of the deformations ε_2 made it possible to use a positive differential moiré to record the whole spectrum of the deformations, starting with elastic deformations. It is more difficult to plot the profile of the wave ε_1, due to the superposition of elastic waves of the shock front reflected from

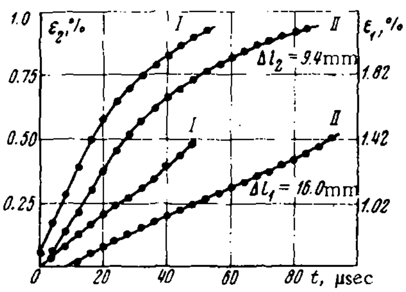

Fig. 3

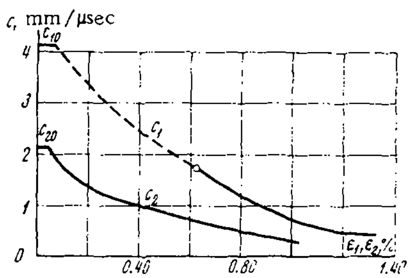

Fig. 4

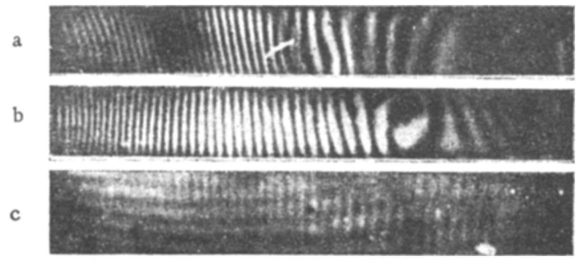

Fig. 5

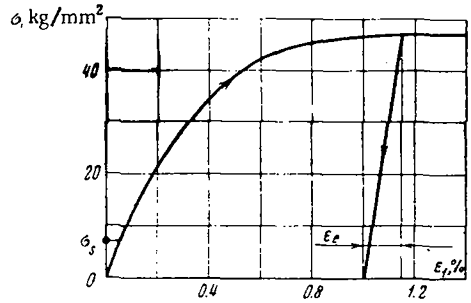

Fig. 6

the capture and the direct plastic wave. For purposes of reliability, the profile of the wave ε_1 (the lower curves on Fig. 3) is given starting from $\varepsilon_1 = 0.62\%$.

On the figure, the curve $c_1 = c_1(\varepsilon_1)$ is extrapolated from $\varepsilon_1 = 0.62\%$ to the value of the longitudinal shock wave in the plate, under the assumption that there are no points of inflection on the curve (Fig. 4), starting from the form of the dependence $c_2 = c_2(\varepsilon_2)$.

According to the results of an analysis, the greatest transverse deformation, propagating at the velocity of the shock waves, is 0.042%, and the greatest longitudinal deformation is 0.063% (extrapolated value).

Attention must be drawn to the effect of the length of the sample on the data obtained. In the region of the transition from elastic deformations to plastic they become thinner, with a considerably greater length of the working section. However, one of the aims of the experiments was to obtain the degree of reflection of a plastic wave from capture. The photographs (Fig. 5) illustrate moiré pictures of the distribution of the residual deformations. Figure 5a corresponds to the case of complete exhaustion of the plastic waves; in Fig. 5b, the wave arrives at capture and is reflected. The reflected plastic wave has the sign of the direct wave and, with capture, the residual deformation increases. Figure 5c shows the combined distribution of ε_1 and ε_2.

It was of interest, using the curve of c_1 and $c_1(\varepsilon_1)$, to plot the dynamic curve $\sigma = f(\varepsilon_1)$ in a manner similar to that used in the investigation of bars. It is well known that in bars the rate of propagation of a given deformation $c = (E_t/\rho)^{1/2}$; where $E_t = E$ with $\varepsilon \leq \varepsilon_0$, $E_t = d\sigma/d\varepsilon$ with $\varepsilon > \varepsilon_0$; ρ is the density; ε_0 is the greatest value of the deformation, propagating at the velocity of the elastic perturbation.

An analogous dependence was adopted as a basis in the case of a plate

$$c_1 = \sqrt{\frac{E_t}{\rho(1-\nu^2)}}, \qquad \begin{array}{l} E_t = E \text{ with } \varepsilon_1 \leqslant \varepsilon_{10} \\ E_t = d\sigma/d\varepsilon \text{ with } \varepsilon_1 > \varepsilon_{10} \end{array}$$

Here the quantity ν plays the role of a simplifying factor, due to the existence of considerable transverse deformation. Assuming ν to be the ratio of the transverse deformation to the longitudinal at a given moment of time, and on the basis of experimental data, it was postulated that $\nu = 0.5$. The instantaneous value of ν is relatively stable in the investigated range of deformations ε_1 and ε_2 (0.30-2%), although this is contradicted by the fact that $\varepsilon_{10} = 0.063\%$, and $\varepsilon_{20} = 0.042\%$.

From the known value $E_t = E_t(\varepsilon_1)$, the method of numerical integration was used to plot the curve $\sigma = f(\varepsilon_1)$ (Fig. 6)

$$\sigma = \sigma_0 + \int_{\varepsilon_{10}}^{\varepsilon_1} E_l(\varepsilon_1)\, d\varepsilon_1, \quad \sigma_0 = \varepsilon_{10} E = 7 \ \text{kg/mm}^2$$

An analysis of the moving-picture photos shows that, in the range of longitudinal deformations from 0.6 to 2%, the elastic load is equal to 0.14-0.18%, which corresponds to a dynamic model of the loading, exceeding by three times the value of E with $\varepsilon_1 = 1\%$, and approaching the value of E with a decrease of ε_1 to ε_{10}.

In conclusion there must be noted the presence of a region of constant residual deformation at the start of a sample, with an extension of ~10 mm (Fig. 5). This relatively large-size region must be explained by the washing-out of the rear front of the pulse applied to the zero cross section of the working part of the sample, due to the special character of the loading scheme.

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