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PREPRINT

THE ELASTO-PLASTIC RELEASE BEHAVIOUR OF MAGNESIUM AT 80 Kb

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ABSTRACT

A technique has been developed, based on the manganin wire transducer, which enables the stress-time profiles of shock and release waves produced in a block of magnesium by the impact of an explosively driven flying plate to be recorded. The profiles presented differ from those that would be predicted by hydrodynamic theory; in particular, the top of the release wave is traveling approximately 30% faster. A release stress-strain path is derived from the results and it is shown that this can be interpreted in terms of elasto-plasticity.

INTRODUCTION

There has been considerable discussion in the literature recently suggesting that the behaviour of solids under high shock stresses cannot be adequately described by hydrodynamic theory, and that the effects of yield strength are important [1]. Several experimenters have reported the initial parts of release waves behind intense shocks travelling faster than hydrodynamic theory would predict [2-5].

We have attempted to match the manganin wire transducer to a metal so that it can be used to record the stress-time profile of a plane wave inside the material, instead of observing a free surface. The advantage of this method is that, in principle, the interpretation of the results is simplified, and a complete mathematical analysis is possible, uncomplicated by lateral strain effects which have plagued much of the earlier work on plastic waves using rods and wires [6], or by the need to assume a particular theory of plasticity. Our preliminary results with magnesium show that stress-time profiles can be observed and that these can be used to calculate the stress-strain path of the release process.

TECHNIQUE

A transducer based on the linear pressure-resistance characteristic of manganin has already been used to measure stress as a function of time in electrical insulators [7]. To extend this technique to a metal it is necessary to insulate each manganin wire and its leads from the surrounding metal without invalidating the stress-time profiles obtained. This may be attempted by using an insulator whose shock impedance approximates to that of the metal used, and by making the insulating layer so thin that any significant reverberations in it are over in a time which is short compared with that being measured.

Figures 1 and 2 show the design used. The manganin wire, of 0.005-inch diameter coated with glass to 0.008-inch overall diameter, is cast in the middle of a 0.025-inch layer of epoxy resin, loaded with powdered lead borate glass of density 6.1 gm/cc. The copper support tubes are 0.050-inch diameter, surrounded by 0.250-inch diameter soda lime glass tubing, which is a fairly good shock impedance match ~~to~~ magnesium. The loading of the epoxy resin was chosen so that the proportional sum of the compressed volumes of the constituents was equal to the specific volume of magnesium at the pressure of the experiment. Glass and epoxy resin were used because in previous work they have been found to be adequate insulators when shocked. The effectiveness of the insulation was shown by the agreement obtained between the measured peak pressure and that predicted from the shock and flying plate impact velocities. In addition the accuracy with which the wire resistance returned to its initial value after the passage of the stress wave indicated that the insulation remained satisfactory and that good contact with the wire was probably maintained.

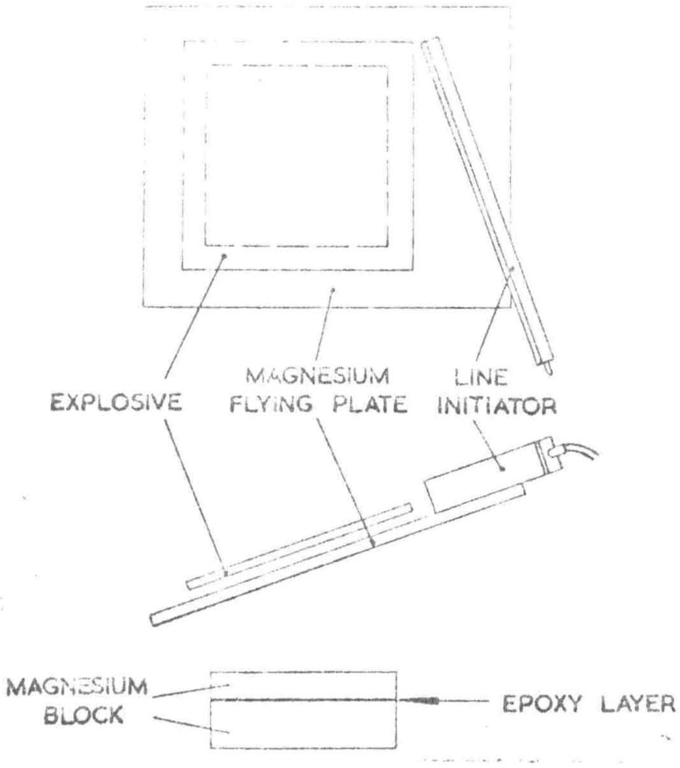

Fig. 1 - Arrangement of magnesium block and flying plate

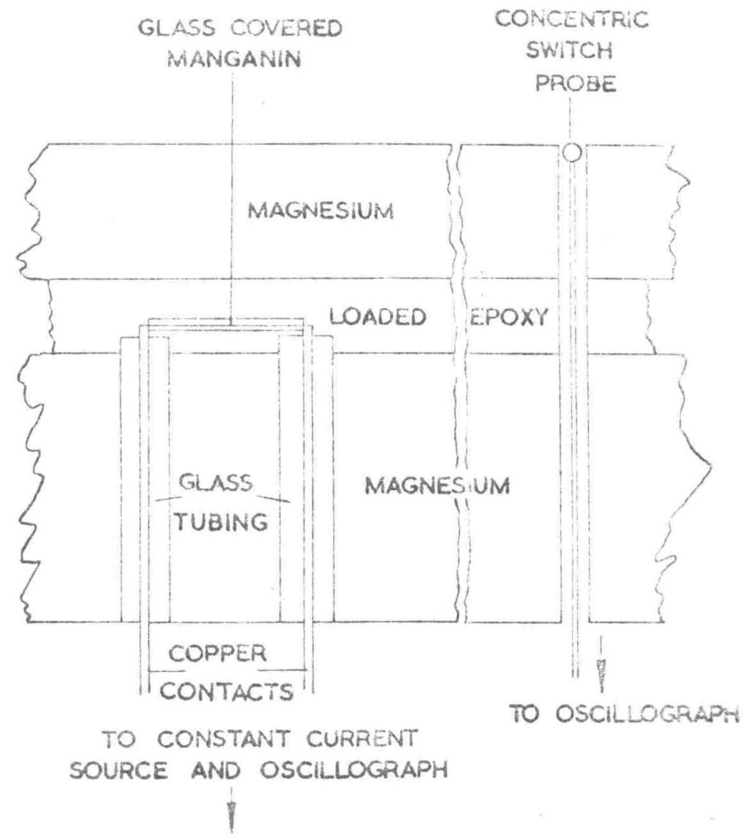

Fig. 2 - Details of transducer and insulator (not to scale)

The angle between the flying plate and the block is adjusted so as to achieve plane collision. Figure 3 shows how the shock and release waves propagate. The sides and back of the block are sufficiently remote from the transducers for reflected waves not to reach them until the measurements are completed; plane wave conditions are therefore maintained. The impact of the plate on the block is detected by capped concentric switch probes flush with the surface. In each round the square region of the flying plate striking the block is recovered in one piece and does not show any sign of scabbing.

Initially the experiments have been carried out at a comparatively low pressure of 80 Kb, a region where the strength of the metal would be expected to be important and conduction in the insulators less troublesome. The metal used was the magnesium alloy ZW 3 which has 2.9% zinc and 0.63% zirconium as its main alloying elements.

RESULTS

Figure 4a shows a typical oscillogram taken with the transducers one flying plate thickness (0.250-inch) into the block. It will be noticed that this stress-time profile is not flat-topped; there is a slight fall in stress of about 6 Kb lasting for about 0.5 microseconds after the initial rise in stress. This fall is not due to a release wave, which would have to travel at nearly infinite velocity, but is somehow associated with the shock front. Attempts to relate this fall in stress to features of the design of the experiment, such as the shock impedance of the insulator or its thickness for example, have not been successful. It could, therefore, be due to either some other property of the epoxy resin insulator or to the magnesium alloy. In a few experiments the glass tubing and the resin were replaced by thin PTFE sheet; the profiles from these shots tended to show a similar slope, but not when the magnesium was replaced by aluminium. A similar pressure-time profile has been reported in steel [8].

The stress drop due to the release wave begins at about 1.2 microseconds. The front of the release wave has a velocity of 7.3 ± 0.2 km/sec relative to the material, which is 30% higher than hydrodynamic theory would predict, about the same increase as has been estimated for other materials [2-5]. This higher velocity means that the top of the release wave should catch up with the shock at about five flying plate thicknesses into the block instead of fifteen as predicted by hydrodynamic theory. Figure 4b shows a typical oscillogram at five flying plate thicknesses.

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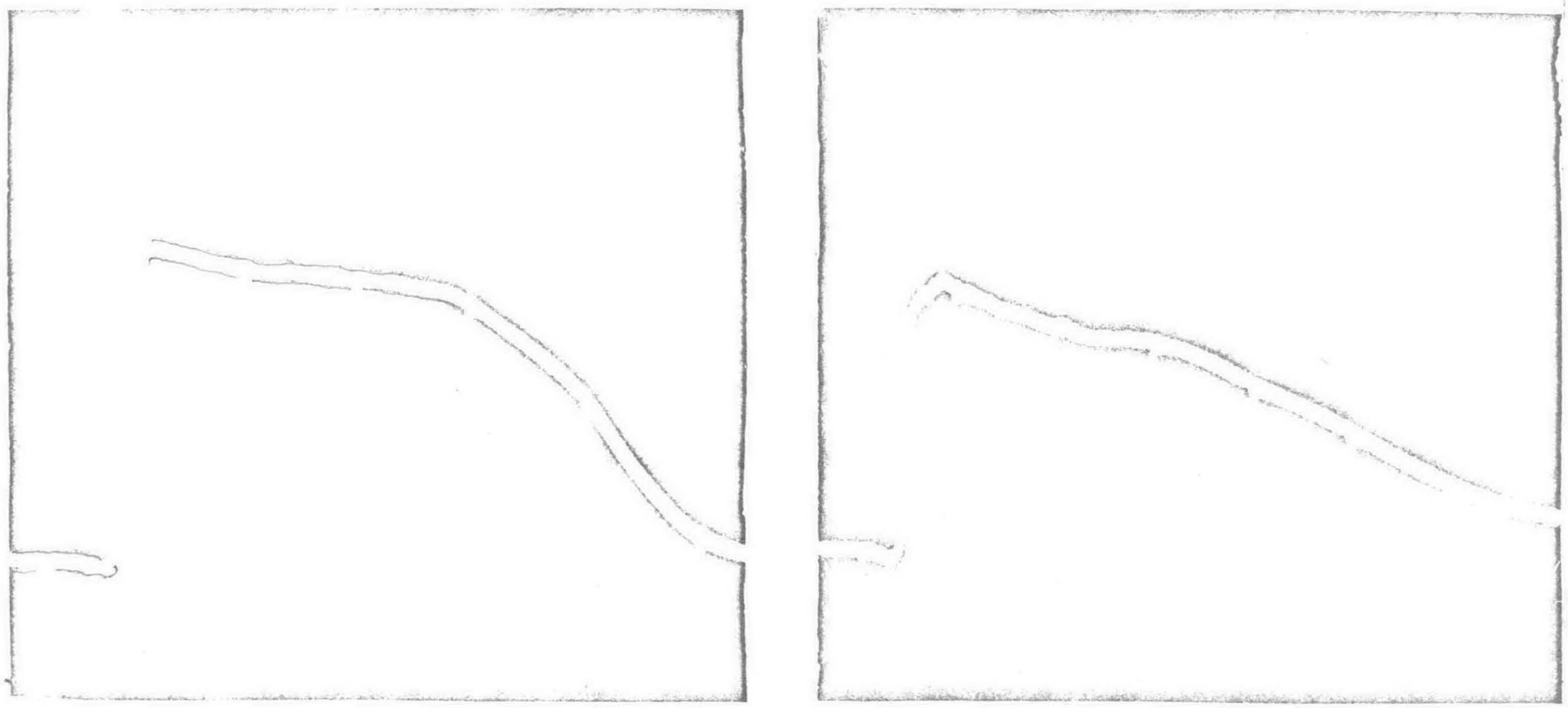

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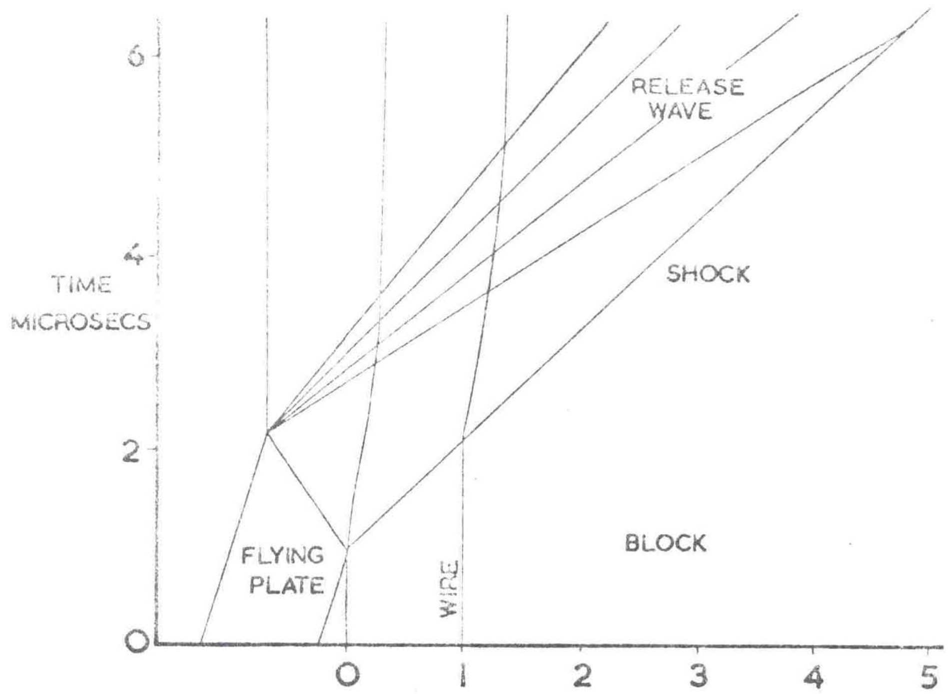

Figure 3

Fig. 4 - Pressure-time oscillograms at 1 and 5 flying plate thicknesses (0.5 microsecond time markers)

Interpretation

Despite the general similarity of shape shown by the profiles at one and five flying plate thicknesses it is not possible to interpret them in the same way. Following the previous interpretation and regarding the release wave at five flying plate thicknesses as beginning only after the constant stress region leads to a release velocity eight standard deviations lower than that previously measured. Hence it is concluded that the initial fall in stress in Fig. 4b represents the front of the release wave but is possibly perturbed by the falling-stress effect seen in Fig. 4a. The initial fall followed by a constant stress region and then a further fall, is regarded as evidence of the separation of the release wave into elastic and plastic components, but is unresolved at short distances as in Fig. 4a.

Method of Calculation

From the impact time measured by the probes and the time of shock arrival at the transducers, the shock velocity can be calculated. In each round the peak stress and measured shock and impact velocities had values which were consistent with published data for magnesium. From the impact time and the shock velocity, the distance-time point is calculated where the shock in the flying plate is reflected from its back surface as a release wave. This point, together with the stress-time profile, enables the velocity of the release wave to be found as a continuous function of stress. From this, density and particle velocity are calculated using the following equations [7] based on conservation of mass and momentum:

$$\rho_1 - \rho_0 = \int_{p_0}^{p_1} \frac{dp}{c^2}$$

$$\int_{u_0}^{u_1} du = \int_{p_0}^{p_1} \frac{dp}{\rho c} .$$

Here ρ represents the density, p the stress in the direction of wave propagation, c the wave velocity relative to the local material (for a continuous wave), and u the particle velocity. This calculation is done at small stress decrements down the release wave. The wave velocity is corrected for movement of the transducer and expressed relative to the local material, using the calculated particle velocity. Density and particle velocity at the top of the release wave are taken from published Hugoniot data for magnesium corresponding to the measured stress.

Stress-strain Curve

Figure 5 shows the resulting release velocities and Fig. 6 the corresponding stress-strain relation taken from experiments at one flying plate thickness. These are again markedly different from the hydrodynamic predictions. The stress-strain curve first falls steeply below the Hugoniot and then becomes shallower. This is attributed to elasto-plastic behaviour of the metal [9]. The results at five flying plate thicknesses have not been used in this type of calculation because of the possible difficulty in interpreting the initial fall in stress. However, an elasto-plastic release path would predict a discontinuity of release wave velocity at the reverse yield point, and hence a stress plateau. The period of almost constant stress shown at five flying plate thicknesses is identified with this plateau, and the regions above and below it with the elastic and plastic parts of the release process. The size of the elastic stress release is, therefore, 16 Kb, determined by the stress difference between the plateau and the beginning of the release process as recorded by one flying plate thickness experiments. Single experiments at six and eight flying plate thicknesses support this interpretation.

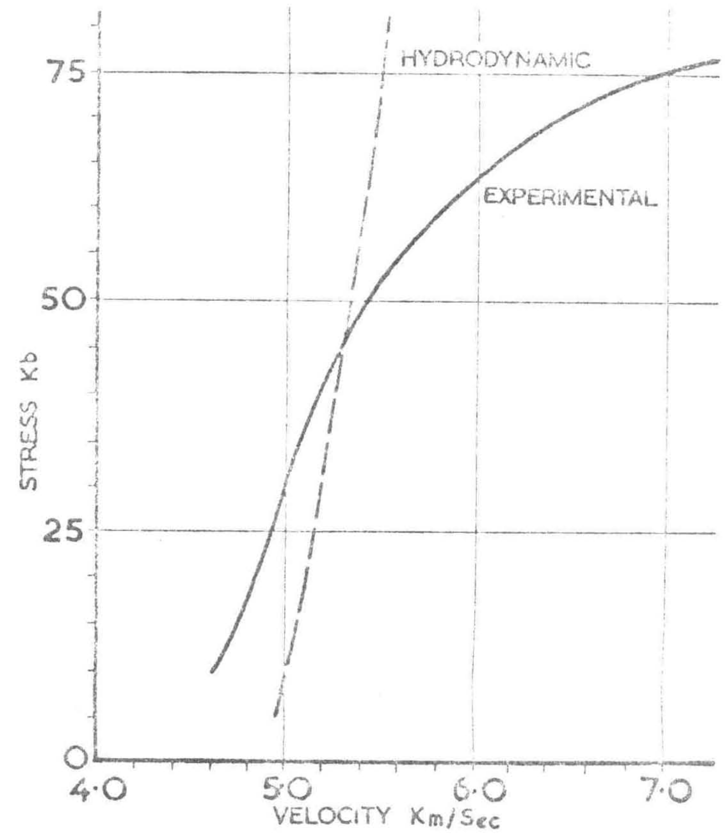

Fig. 5 - Mean velocities measured from 28 stress profiles at one flying plate thickness

Elastic Properties

Some elastic properties can now be calculated from the elastic and plastic wave velocities c_e and c_p. Bulk modulus is found in the plastic region using

$$c_p^2 = k/\rho$$

(Fig. 7); a considerable increase with stress is obtained. The curve is consistent with the small stress bulk modulus for magnesium [10].

While the initial fall in stress of the profiles at five flying plate thicknesses may be difficult to interpret, the ratio of the elastic and plastic wave velocities at the yield point nevertheless allows an estimate to be made of Poisson's ratio r. Using

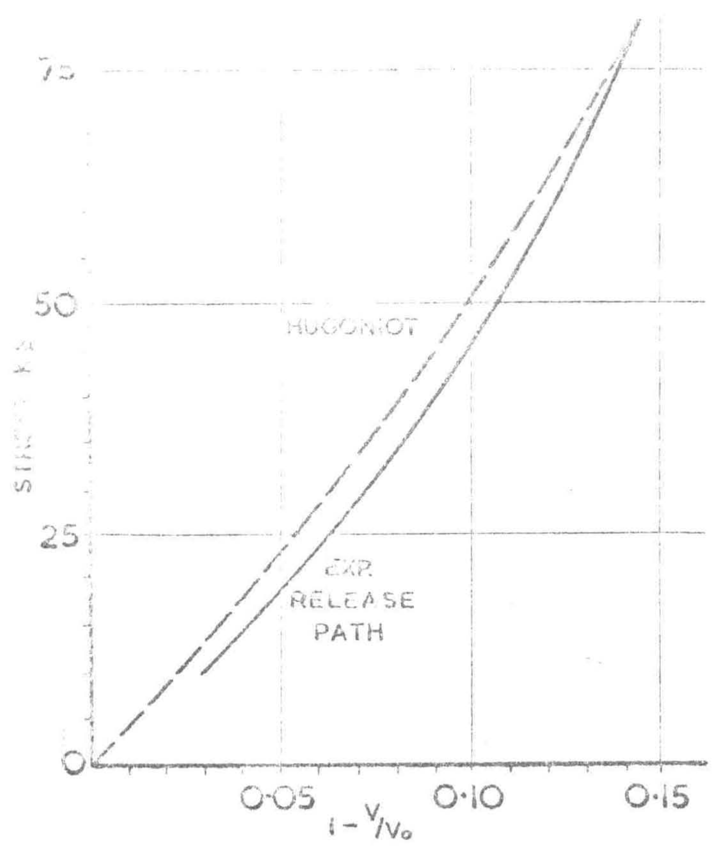

Fig. 6 - Stress-strain curve calculated from Fig. 5

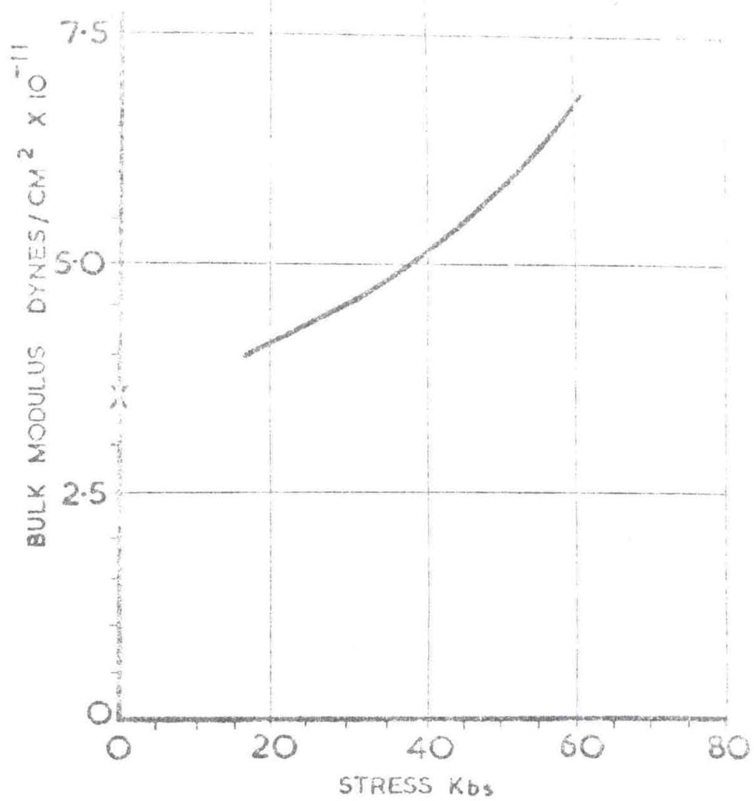

Figure 7

$$\frac{c_c^2}{c_p^2} = 3\,\frac{(1-r)}{(1+r)}$$

we obtain what may be regarded as an upper limit for Poisson's ratio of 0.42: the small stress value is 0.30 [10]. An expression for the fall in elastic stress is

$$2Y_s\,\frac{(1-r)}{(1-2r)}$$

where Y_s is the yield stress, assumed to be equal in tension and compression. Substitution of 16 Kbs for the elastic stress release, and the above values of Poisson's ratio gives yield strengths of 2.2 or 4.6 Kbs respectively; the results therefore suggest an increase in yield strength with stress above the static value of 1 Kb.

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