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Effects of High Hydrostatic Pressure on the Plastic Properties of Metals

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INTRODUCTION—THE GENERAL NATURE OF PLASTIC FLOW

SINCE this is a symposium for physicists, it will probably be well to begin by indicating briefly the qualitative characteristics of the plastic state in solids, for these phenomena are outside the conventional range of physics and, in general, are familiar only to engineers. I have found that many physicists are inclined to think of a solid in the plastic state as similar to a highly viscous liquid, with perhaps the difference that the phenomena of flow in the solid occur only when stress exceeds some critical value, whereas in the liquid, some flow occurs for any stress no matter how small. This, however, is not an adequate description, for there are phenomena in the plastic state for which there are no analogues in the viscous liquid. Consider, for example, a unit cube of metal, subject to uniform compressive load along the z axis. If the load is large enough, the metal will flow plastically, shortening along the z axis, and expanding uniformly along the transverse x and y axes. Since metals show the phenomenon of strain hardening, the flow will presently cease if the load is kept constant. If at the same time that the load is applied along z a transverse load is applied along x, the transverse expansion along x will be diminished, and if the load along x is made sufficiently great, expansion along x may be entirely suppressed, with the result that the flow consists entirely of a shortening along z and a lengthening along y. In general, the stress along x necessary to suppress flow along x completely is approximately one-half the stress along z. Imagine now an experiment in which a load beyond the plastic limit is applied along z, and one-half the stress is applied along x, so that the z axis shortens and the y axis lengthens by an equal amount. After the flow has ceased, increase the force along x, say by 25 percent, maintaining the force along z constant. One result of the increase of force along x is that the shortening along z is resumed with corresponding lengthening along y.

This phenomenon has no counterpart in the viscous liquid. Roughly, in the solid there is a "plastic state." Whether or not the solid is in the plastic state is determined by the intensity of *all* the stress components (and also by the strains), but in the plastic state the dominant direction of flow is determined by the direction of dominant stress. In the example above, after flow had ceased because of strain hardening, the metal was brought back again into the plastic state by an increase in the x stress, but when once again in the plastic state, the direction of dominant flow was still the direction of dominant stress, which remained the same as initially in spite of the increase of the x stress.

The relations in plastic flow are suggested in a rough qualitative way by the equations:

$$\frac{\dot{\epsilon}_x}{\sigma_x-\frac{1}{2}(\sigma_y+\sigma_z)}=\frac{\dot{\epsilon}_y}{\sigma_y-\frac{1}{2}(\sigma_z+\sigma_x)}=\frac{\dot{\epsilon}_z}{\sigma_z-\frac{1}{2}(\sigma_x+\sigma_y)}=\varphi,$$

where, in general, φ is some function of the state of the body and, in particular, of the stresses and strains. However, in certain degenerate limiting cases, φ may not be a function of the physical parameters at all but may vary from point to point in a way determined by the geometry of the particular situation. In these equations the ϵ's and σ's are strains and stresses referred to principal axes, and the dots indicate differentiation with regard to time.

GENERAL NATURE OF EFFECTS OF PRESSURE ON PLASTICITY

With this introduction concerning the nature of plastic flow, we turn to the general question of the effect of completely immersing the specimen undergoing plastic deformation in a liquid carrying hydrostatic pressure. For ordinary metals there is one general outstanding and spectacular result of the hydrostatic pressure; namely, the amount of plastic deformation which the metal will tolerate without fracture may be much increased. It is as if cracks were prevented from forming in the metal by the pressure which pushes the parts together. Most of my experiments on plastic deformation under pressure have been made with conventional tension specimens since the manipulations and measurements are easiest for them. At hydrostatic pressures of 25,000 to 30,000 kg/cm^2, tension specimens of ordinary mild steels may show elongations of hundreds of fold without fracture, against elongations at atmospheric pressure of only two- or threefold. This is illustrated in Fig. 1, showing a cylindrical tension specimen broken at atmospheric pressure and another specimen of the same steel pulled to a much greater reduction of area without fracture under high pressure.

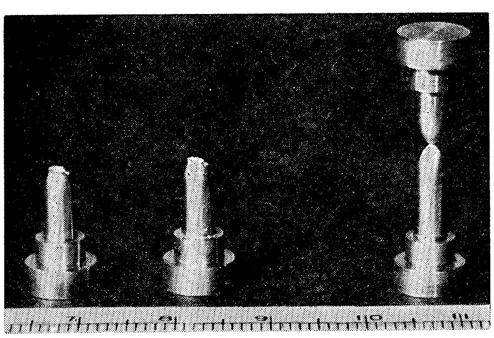

FIG. 1. At the left, a tension specimen pulled to fracture at atmospheric pressure; at the right, a specimen of the same steel pulled to a much greater reduction of area without fracture in a medium under a hydrostatic pressure of approximately 25,000 kg/cm^2.

Two different sorts of phenomena may be investigated under these conditions: the phenomena of flow and, in particular, the relation between stress and strain or strain hardening, and the phenomena of fracture. The strain under these conditions is best expressed in terms of natural strain according to the equation $\epsilon = \log_e A_0/A = \log_e l/l_0$, where A_0 and A are the initial and final areas of the section of the tension specimen at the neck, and l_0 and l are the initial and final lengths of elements lying along the axis at the neck. Whereas normally the stress-strain curve at atmospheric pressure is terminated by fracture at a strain of the order of magnitude of unity, under pressure the curves may be carried to strains of 4 or 5. Even then it is not fracture which prevents following the curves further, but incidental effects, such as diminution of accuracy of the measurement of stress because of diminution of the total tensile load due to reduction of cross section, and failure of geometrical regularity due to the dominating role of the individual crystal grains when the cross section is much reduced.

THE EFFECT OF NON-UNIFORMITY OF STRESS AT THE NECK

Under the drastic reductions of area attained under pressure, it becomes necessary to consider certain corrections which are conventionally neglected under the small deformations found in testing under normal conditions at atmospheric pressure. It is usually assumed that the tensile stress is constant all the way across the neck of the tension specimen, and the so-called "true stress" at the neck is defined as the total tensile load divided by the area of the neck. It has, of course, been recognized that the assumption of constant stress is only an approximation. The correction for departure of stress from uniformity could be made if the problem of the plastic distortion at the neck could be solved. The complete solution of this problem would appear to be impossible at present, both for physical and mathematical reasons, but I have recently ob-

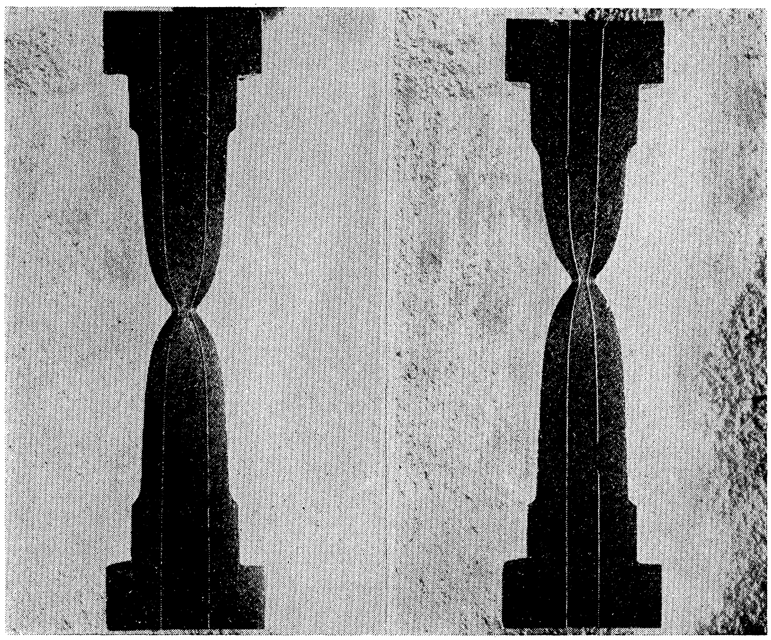

FIG. 2. Cored sectioned tension specimens from which the radial distribution of strain at the neck may be obtained.

tained a partial and approximate solution,[1] which gives the stress distribution at the neck in terms of a parameter which defines the shape of the neck. This parameter is the ratio of the radius of curvature of the contour of the neck to the radius of the cross section of the neck and may be determined by independent measurement if necessary. In obtaining the solution it was assumed that the strain, as distinguished from the stress, remains constant across the neck. This appeared plausible on geometrical grounds, but it has recently been possible to give an experimental justification for it. By silver soldering cores of various diameters into the tension specimen and by pulling to various reductions of area under pressure, it is possible to study the distribution of distortion across the neck. Figure 2 shows longitudinal sections of two cored tension specimens which were pulled under pressure. From measurements of the external and core diameter, it is possible to show that any departure of strain from uniformity is too small to introduce appreciable error into the mathematical solution.

The distribution of stress at the neck of a tension specimen pulled under normal conditions at atmospheric pressure may be analyzed into two systems: one is a tension uniform all the way across the neck and the second is a hydrostatic tension (three equal components of principal stress) increasing in magnitude from zero at the outer surface of the neck to a maximum on the axis. If the specimen is pulled in a medium under hydrostatic pressure, the complete stress system includes this hydrostatic pressure in addition to the two systems just described. The problem now arises how to represent the flow conditions at the neck in view of the complicated state of stress there. The implication of the ordinary stress-strain diagram is that there is only one principal component of stress, and it is the corresponding principal component of strain which is plotted against it. In a tension specimen pulled at atmospheric pressure, the stress reduces to a single component only at the outer surface of the neck, which means that the stress-strain curve should be so constructed as to represent the relation between stress at the outer surface of the neck and the corresponding strain. Since the strain is uniform across the neck, the strain at the

[1] P. W. Bridgman, Trans. A.S.M.E. **32**, 553 (1944).

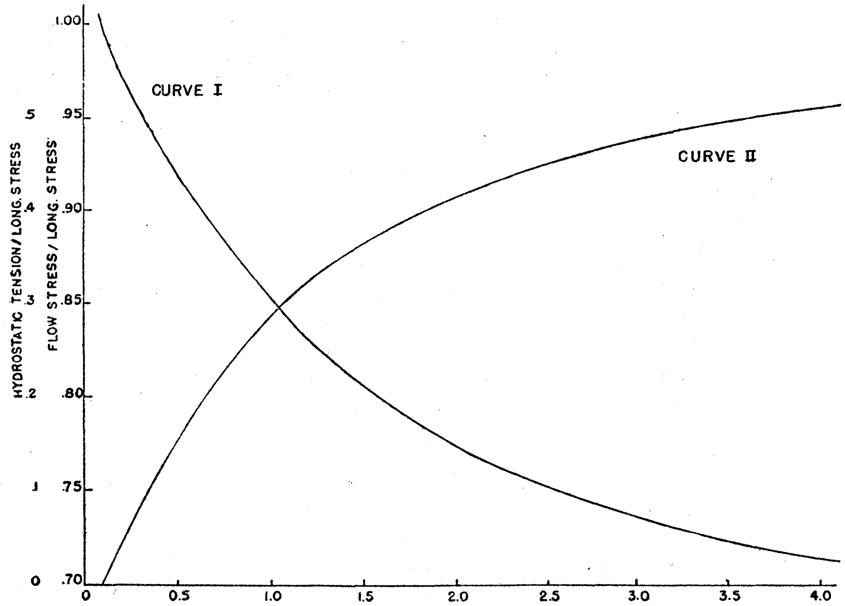

FIG. 3. Curves from which the flow stress and the hydrostatic tension on the axis may be obtained in terms of the average longitudinal stress in necked tension specimens as a function of the strain at the neck. Curve I shows ratio of flow stress to average longitudinal stress. Curve II shows ratio of hydrostatic tension on axis to average longitudinal stress.

outer surface is the same as the mean strain, which is $\log A_0/A$. The stress at the outer surface is, however, less than the mean stress, or total load divided by A (referred to above as "true stress") by a factor which may be obtained from the mathematical analysis. The correction factor for converting mean stress to "flow stress" or stress at the outer surface of the neck is shown in Fig. 3 as a function of the strain. It is possible to represent the correction as a function of the strain instead of as a function of the geometrical parameter which determines the shape of the contour at the neck because of an empirical relation between the two, which will not be described further here.

If the specimen is pulled under pressure, there is, in general, no region in the neck where the stress reduces to a single component, so that the meaning of the "stress-strain" curve has to be set by convention. A very simple convention is suggested by the elementary theory of plastic flow; according to this, a pure hydrostatic pressure is without effect on plastic flow so that it would be legitimate and significant to describe the stress-strain relations by entirely neglecting the hydrostatic pressure in the ambient liquid and by treating the specimen as if it were being pulled at atmospheric pressure. This is the convention adopted in all the following. The "flow stress" plotted in the stress-strain diagrams is the longitudinal component of the stress system at the outer surface of the neck which remains after the hydrostatic pressure is subtracted from the total stress. As a matter of fact, when pressures are pushed to the magnitudes reached here, it is possible to establish experimentally the existence of an effect of pure hydrostatic pressure on the conditions of plastic flow, but the effect remains small, and the simple convention adopted above proves to be a sufficiently good first approximation.

The correction for the stress distribution at the neck is not, under the conditions of these experiments, large enough to change qualitatively the nature of the flow phenomena, the corrected flow stress at worst being 70 percent of the uncorrected stress. When it comes to phenomena of fracture, however, the effect of stress distribution at the neck is much more important. Fracture is not a homogeneous phenomenon like strain, but is initiated at the point where the local conditions reach some critical limit, and it should be possible to characterize these local conditions in order to characterize adequately the conditions of fracture. When a tension specimen breaks at the neck under the conditions of these experiments, the break is initiated on the axis. The reason the fracture starts on the axis is that on the axis the hydrostatic tension part of the total stress reaches a maximum. It is well recognized that hydrostatic tension predisposes to brittle fracture. In fact it is generally accepted that at a sufficiently high hydrostatic tension and with no other component of stress, fracture must occur with no plastic deformation, although such conditions have not been achieved in practice because of technical difficulties of applying the stress system. In reporting the fracture of a tension specimen, the complete stress system at the point of fracture should be reported, and this involves not only the main tension but also the hydrostatic tension on the axis generated by the geometry of the neck. The hydrostatic tension on the axis is shown also in Fig. 3. Under the conditions of these experiments, it may rise to 70 percent of the main tension and is therefore important.

EFFECT OF PRESSURE ON STRAIN AT FRACTURE

We are now ready to discuss certain aspects of the plastic behavior of metals, in particular, that of various grades of steel under hydrostatic pressures up to 30,000 kg/cm^2. The most striking effect, as already mentioned, is the great increase of ductility. The strain at fracture may be determined with considerable accuracy as a function of the hydrostatic pressure in the ambient liquid from measurements on the fractured specimen. The relation between strain and hydrostatic pressure at fracture proves to be linear within the errors of measurement. This is shown in Fig. 4 for a single heat treatment of a 1045 steel. The linear relation is seen to hold up to strains of 4.6 or elongations of 100-fold. It is difficult to follow the curve to higher strains because of error arising from loss of circular cross section at the neck and because of geometrical distortions introduced by the act of fracture.

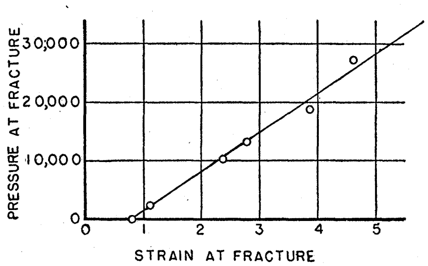

FIG. 4. The strain at fracture of a 1045 steel as a function of hydrostatic pressure in kg/cm^2.

The linear relation holds for steels heat-treated to give a wide range of hardnesses. The harder the steel, the greater the slope of the line, or in other words, the smaller the increase of ductility produced by a given increase of hydrostatic pressure. Even glass hard steel shows a measurable ductility at pressures of 30,000 kg/cm^2. The steel of Fig. 4 fractures at atmospheric pressure with an elongation of 2.2-fold and at 27,000 kg/cm^2 with an elongation of 100-fold. A similar great increase of ductility under pressure has been established for copper, aluminum, brass, and bronze. On the other hand, cast iron shows no appreciable ductility in tension even up to 30,000 kg/cm^2.

FLOW STRESS AS A FUNCTION OF STRAIN

The strain hardening curve, or the curve of strain *versus* flow stress, cannot be followed to as high strains as the strain *versus* pressure curves at fracture represented by Fig. 4 because of greater experimental error arising from uncertainty in the total load. In Fig. 5 the stress-strain curve for the same steel, as in Fig. 4, is shown up to a strain of 3.2 or an elongation of 25-fold. Since at atmospheric pressure this steel fractures at a strain of 0.8, it is obvious that by pulling under pressure the stress-strain curve can be followed to much higher strains than would otherwise be possible. In Fig. 5 the pressure of pulling corresponding to the different points is different, in

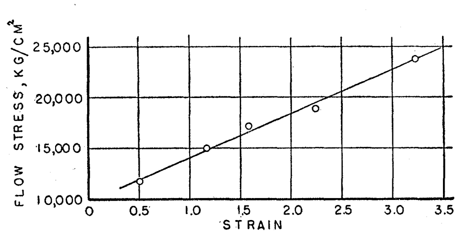

FIG. 5. The strain hardening curve (flow stress as a function of strain) for the same steel as in Fig. 4.

general the pressure being higher at the higher strains. It is permissible to plot the points without specifying more exactly the corresponding pressures because of the experimental fact that to a first approximation, the flow stress corresponding to a given strain is independent of the pressure of pulling. I have lately, however, by using all improvements in technique and by making measurements on a large number of specimens, been able to establish that this is only a first approximation. There are measurable effects of pressure on the relation between flow stress and strain, and furthermore, the stress-strain curve for measurements all at the same pressure deviates perceptibly from linearity. These second-order effects are in the direction that might be anticipated. At constant strain the flow stress increases somewhat with increasing pressure. Furthermore, this pressure effect is not linear, but the percentage effect of a given hydrostatic pressure in raising the flow stress is greater, the greater the absolute value of the strain. The deviation from linearity is in the direction of a slightly less rapid rise of flow stress under constant pressure with strain at the higher strains, or in other words, the curve shown in Fig. 5 as straight is actually, when points all at the same hydrostatic pressure are plotted, slightly concave toward the strain axis. This departure from linearity is small and has been certainly established only for a few varieties of steel. For a steel similar to that of Fig. 5, the effect of a pressure of 30,000 kg/cm² is to make the flow stress greater by 20 percent than would be indicated by a linear extrapolation to this strain of the results at atmospheric pressure. The deviation from linearity is of such magnitude that at the middle of a strain range reaching up to 3.5 the actual flow stress is of the order of 5 percent higher than would be given by a linear connection between the points at the extremes of the range. The qualitative nature of the effects is shown in Fig. 6. The single parameter family of curves of flow stress *versus* strain for different hydrostatic pressures forms a fan-shaped aggregate; at low strains the flow stress is independent of pressure, and at high strains the curves for different pressures diverge more and more.

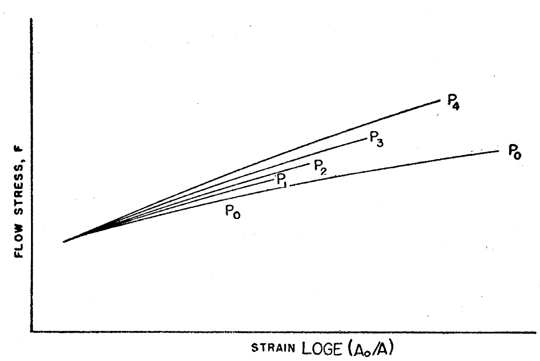

FIG. 6. This figure indicates qualitatively the nature of the deviations from linearity in the relations between flow stress, strain, and hydrostatic pressure of pulling.

At any single pressure the stress-strain curve is terminated by fracture. Since the strain at fracture is a linear function of the pressure, the length of the stress-strain curve is greater at the higher pressures, as indicated in Fig. 6, in which increasing subscripts on the P's denote increasing pressures. The curve for P_0 (atmospheric pressure) in Fig. 6 is an exception, being drawn longer than all the others. This is because the significance of the complete P_0 curve in Fig. 6 is different from that of the others, as will be explained in detail later.

EFFECT OF PRESSURE ON CHARACTER OF FRACTURE

Not only is the strain at fracture drastically changed by hydrostatic pressure, but the whole character of the fracture is altered. Figure 7 shows six fractures of the same steel under successively higher pressures. At atmospheric pressure the fracture is of the well-known cup-cone type, and the general character of the fracture is coarsely granular. As the pressure of fracture increases, the tensile part of the break, that is, the flat bottom of the cup, at first occupies a progressively smaller part of the total area of the break. For most of the steels which I have examined, the ratio of the area of the bottom of the cup to the total area of the neck is a decreasing linear function of pressure. This means that above a certain pressure the tensile part of the break vanishes and the fracture becomes entirely shearing in character. It is possible to establish by suitable control experiments that this is a legitimate pressure effect and is not an incidental result of the altered geometry of the neck which usually accompanies fracture at high pressures. The pressure at which the tensile part of the

(A) (B) (C) (D) (E) (F)

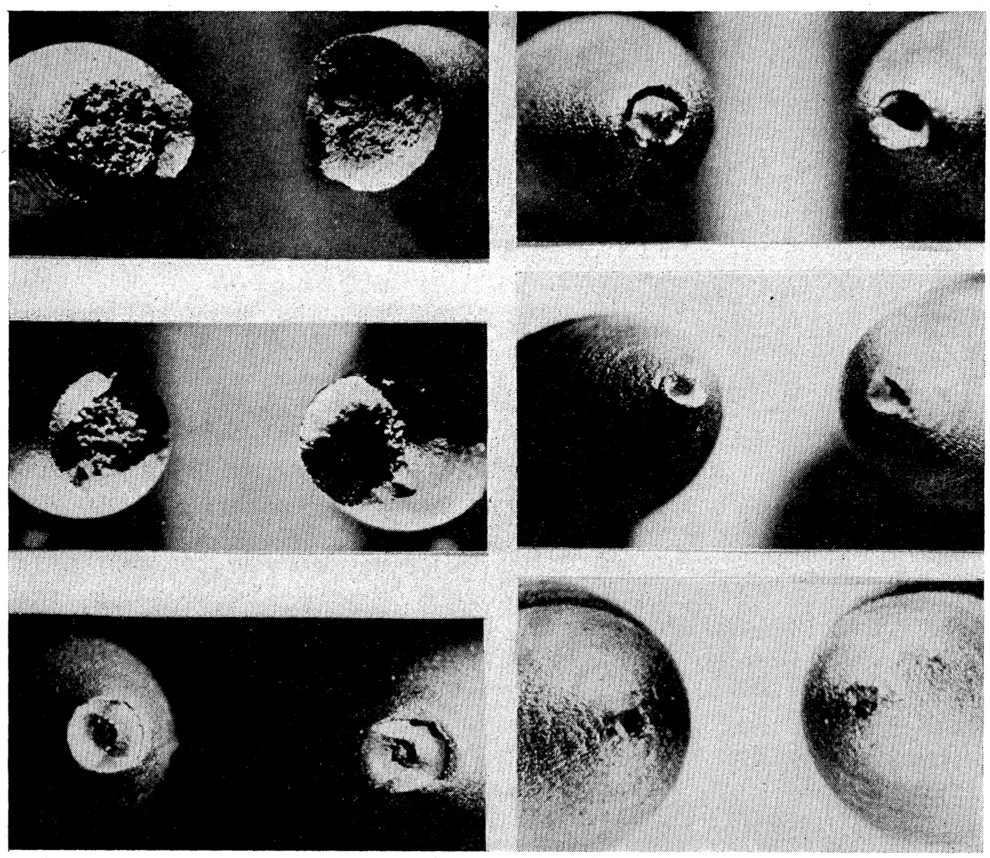

FIG. 7. Fractures of the same steel made at various pressures, showing the progressive change in the character of the fracture with increasing pressure. (A) Broken at Atmospheric Pressure ×10. (B) Broken under 34,000 p.s.i. ×10. (C) Broken under 145,000 p.s.i. ×12. (D) Broken under 186,000 p.s.i. ×12. (E) Broken under 268,000 p.s.i. ×12. (F) Broken under 387,000 p.s.i. ×18.

break vanishes depends on the nature of the steel, in general being greater the harder the steel. I have observed it to vanish anywhere between 5,000 and 25,000 kg/cm^2, and for the hardest steels it has not yet vanished at 30,000. Along with the vanishing of the tensile part of the fracture goes a progressive refinement in the granular character of the fracture until at the highest pressures all trace of the original granular structure disappears. Above the pressure of disappearance of the tensile break the appearance of the shearing break undergoes progressive changes, which may vary strikingly with the nature of the steel. A common type of variation is from a single vortex-like crater of shearing slip at pressures immediately above the disappearance of tensile break to shearing failure on a single plane of slip extending all the way across the neck at the highest pressures. Sometimes several shearing vortices develop at higher pressures, the axes of the vortices being distributed at random across the section of the neck. It is curious that the linear relation between strain and hydrostatic pressure at fracture continues without appreciable change in direction through the pressure at which the tensile part of the break disappears.

GENERAL CRITERIA OF FRACTURE

A question which naturally arises is what light these results throw on the general criterion which may determine fracture. Measurements on fracture are notoriously capricious, so that no great accuracy can be expected, but it is nevertheless possible to draw several conclusions, mostly negative, which are certainly beyond experimental error. Thus the maximum tensile stress is certainly not the determining factor in fracture. The maximum tensile stress, meaning the *total*

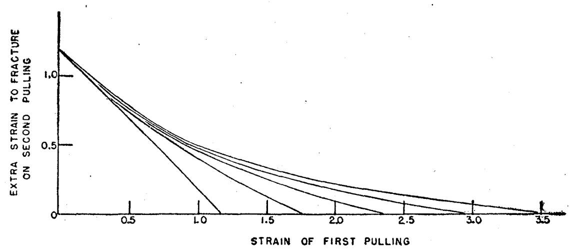

FIG. 8. The effect of prepulling to various strains and at various pressures on the strain at fracture on a second pulling at atmospheric pressure. The curves in rising order are for successively higher pressures.

tensile stress, and therefore including the hydrostatic pressure in the stress system, in general rises rapidly as fracture occurs at higher pressures. The rise is much more rapid than the rise of hydrostatic pressure. This means that the maximum tensile stress diminished by the external hydrostatic pressure, which may be visualized in terms of a weight hung on the specimen in the liquid, also rises rapidly. It is not uncommon for this to increase by a factor of three or four in the present pressure range. It hardly needs to be said that any of the ordinary criteria on strain, such as the maximum extension criterion for fracture, fail utterly under these conditions. There is one criterion, however, which is approximately satisfied under a wide range of conditions; this is that fracture occurs when the sum of the three principal stress components reaches a critical value. The physical meaning of this is that fracture occurs when the volume is expanded to a critical amount beyond its normal value. From certain points of view this criterion appears not unreasonable, but it is not completely general, and it is possible to set up experimental situations in which it definitely fails. The subject of fracture is most complicated, and it is highly doubtful whether any single criterion can be formulated in terms of simple physical parameters.

VARIOUS EFFECTS OF PRESTRAINING

The physical condition of a metal which has been severely deformed under high pressure is obviously much altered from that of the original crystal lattice. This may be established by x-ray examination of the specimen after release of pressure. Very great distortions of the lattice are disclosed, much greater than are obtainable under ordinary conditions of plastic flow. The ordinary physical properties of such severely strained metal may be profitably examined; in particular, tension experiments may be made at atmospheric pressure on specimens which have been previously pulled under hydrostatic pressure. The lower curve in Fig. 6 gives the stress-strain curve at atmospheric pressure of tensile specimens prestrained under pressure. From certain points of view it is surprising that such a curve even exists, for an argument can be made for the expectation that the prestrained specimen will break brittlely at atmospheric pressure with no further plastic deformation if the amount of prestrain under pressure is beyond the amount at which fracture normally occurs for the virgin specimen at atmospheric pressure. Not only does such a curve exist at atmospheric pressure, but the relations can be represented by a *single* curve. This means that irrespective of the pressure of prepulling, the stress-strain relation at atmospheric pressure can be represented by the same curve, which is naturally the prolongation beyond the normal fracture point of the stress-strain curve at atmospheric pressure of the virgin material.

Although the stress for any given strain is independent of the pressure of prepulling, the amount of additional strain which can be imparted before fracture occurs is not independent of the previous pressure, but is greater the greater the pressure. The relations are indicated diagramatically in Fig. 8 in which the extra strain to fracture on the second pulling is plotted as a function of the maximum strain of the first pulling for different hydrostatic pressures of the first pulling. The 45° line is for atmospheric pressure, and the pressure increases toward the right. The diagram indicates the qualitative nature of the effects for the steel already described in Figs. 4 and 5, for pressures spaced roughly uniformly in the range from atmospheric to 30,000 kg/cm^2. The curves for all pressures intersect in the same point on the vertical axis in virtue of the experimental fact that a previous exposure to pure hydrostatic pressure, without tension, produces no permanent change in any of the physical properties. The curve for atmospheric pressure is the 45° line as shown because of the experimental fact that at atmospheric pressure the final strain at fracture is the same whether the specimen is pulled in one or two stages.

Figures 6 and 8 contain one very important implication which must be emphasized. On the atmospheric pressure line the specimen may or may not have fractured at a given strain depending on the pressure of the prepulling. That is, fracture is not determined solely by the current stress and current strain, but also involves the past history. This means that a precise and rigorous characterization of the conditions which determine fracture must be more complicated than ordinarily supposed. Incidentally, this shows that the criterion proposed above for fracture, namely, that the sum of the three principal components of stress reach a critical value, can not be correct under all circumstances.

In addition to the conventional tension tests just described, other sorts of test have been made at atmospheric pressure on specimens prestrained in tension under hydrostatic pressure, namely torsion tests and simple compression tests. The stress for plastic flow in either torsion or simple compression is raised by the previous straining in tension materially beyond the value for the virgin material. In fact it appears to be a general rule that the stress of plastic flow for any particular type of stress is raised by a previous straining under another type of stress. The validity of this result is confined to large distortions; at low distortions the opposite sort of thing may occur, as typified by the Bauschinger effect, for example, in which the elastic limit in compression or tension is *lowered* by a previous overstrain in tension or compression respectively.

TWO-DIMENSIONAL STRAIN

In the tension tests hitherto described, the specimen has rotational symmetry, and the distortion consists of a longitudinal extension and two equal transverse contractions of one-half the amount. The two-dimensional type of distortion is also important, in which there is a longitudinal extension in one direction, a numerically equal contraction in one direction at right angles, and zero strain in the second perpendicular direction. These conditions can be approximately realized by subjecting thin tubes to axial tension. Tests on such tubes have been carried out under hydrostatic pressure. Figure 9 shows photographs of the exterior of such a tube in the virgin condition, an exterior of a similar tube pulled nearly to fracture under hydrostatic pressure, and a longitudinal section of such a tube pulled nearly to fracture. Qualitatively the phenomena are similar to those for three-dimensional tension. There is a great increase of ductility and strain, and the accompanying reduction of cross section may be carried much further under pressure than at atmospheric pressure. Corrections for the stress distribution in the neck may be made analogously to the corrections in the three-dimensional case, and a stress-strain curve may be similarly constructed. This again is linear.

The fundamental problem here is to correlate the stress-strain curve for two-dimensional flow with that for three-dimensional flow. Various

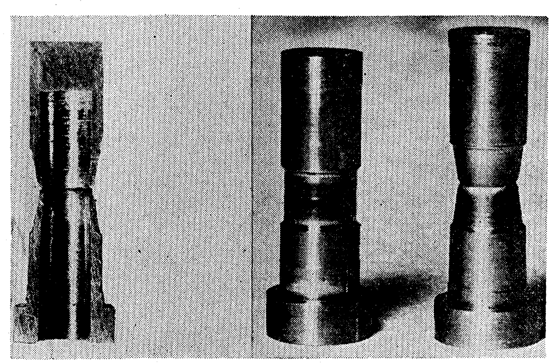

FIG. 9. Thin tubes for the study of two-dimensional strain under pressure. In the center is a tube before pulling, at the right an external view after pulling nearly to fracture under pressure, and at the left a longitudinal section of a similar tube.

conditions of plastic flow have been proposed which permit such a correlation. Two of the most prominent of these are the maximum shearing stress criterion and the so-called octahedral stress-strain relation. Both of these are about equally successful in effecting the correlation, in this case, the maximum shearing stress criterion being slightly better. However, neither is entirely satisfactory; both would predict from the stress-strain curve in two dimensions values for the stress in the three-dimensional case which are from 5 to 10 percent too low. The phenomena of fracture are much more capricious and difficult to control in two dimensions than in three, and it was not possible to establish the relation between strain and pressure at fracture. In general, fracture occurs at much smaller strains in two dimensions than in three.

PUNCHING UNDER PRESSURE

If a metal is punched under pressure, it shows the same enormous increase of ductility that is shown in the tension tests. Under hydrostatic pressure it is possible to move a punching through almost the entire thickness of a steel plate with no fracture or loss of cohesion. In fact, if a plate which has been nearly punched through under high hydrostatic pressure is restored to atmospheric pressure, it will require several times more force to complete the punching process at atmospheric pressure than to punch a piece of the virgin material machined to the same configuration. From such punching experiments, it has been possible to get a rough idea of the nature of the stress-strain curve for shear. The results are not inconsistent with what might be anticipated from the tension experiments according to the octahedral stress-strain criterion, but the experimental accuracy is not at all high.

EFFECTS AT SMALL STRAINS—"TENSILE STRENGTH"

The effects discussed hitherto have been associated with large plastic deformations. It is to be expected that hydrostatic pressure will also have effects in the region of small deformations. The initial part of the stress-strain curve, that is for strains less than the general order of 0.2, is known to be concave toward the axis of strain instead of straight; this part of the stress-strain curves has not been shown in the diagrams. In general, any effect of hydrostatic pressure on this part of the curve is too small to be measured by present methods. There is, however, one effect not too small to measure, namely, the effect of pressure on the technical "tensile strength." This is by definition the maximum tensile load divided by the *original* cross section. It is simply connected with the true stress at the maximum load, because the maximum load marks the initiation of necking where there is no correction for stress distribution across the neck. It turns out that the tensile strength increases under pressure, but by a comparatively small amount, the increase being of the general order of 5 percent for 10,000 kg/cm². It also appears that the elastic limit, or the stress at which plastic flow begins, is also increased by pressure. However, the elastic limit itself is not sharp, and it is not possible to make any statement about the magnitude of this effect other than that it is small. In fact, the general statement that there is an increase can be justified only as a statistical conclusion from many experiments.

SIMPLE COMPRESSION

Examination has also been made of the effect of hydrostatic pressure on the behavior under simple compressive stresses. There are technical difficulties here which have prevented the study from being carried to large strains: the cross section and therefore the total load increases instead of decreasing with increasing strain, and in consequence, the correction for frictional drag on the ends becomes continually more important and also more uncertain. It is possible to establish, however, that in the region of small strains in simple compression, up to a shortening of 10 to 15 percent, the effect of an increase of hydrostatic pressure of 10,000 kg/cm² is to increase the compressive flow stress by roughly the same

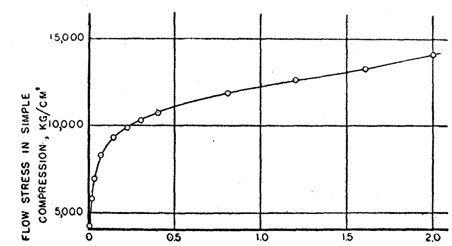

FIG. 10. Stress-strain curve for steel in simple compression by the method of successive refiguring.

amount as the increase of tensile strength, that is, by about 5 percent.

The study of simple compression at atmospheric pressure may, however, be carried into the region of large strains by a procedure first applied by Taylor and Quinney[2] to the study of copper. This procedure is to perform the experiment in successive, comparatively small stages, machining the specimen back to the original proportions between stages. In this way the effects of barrelling and the extraneous stress components arising from terminal friction are avoided. By applying this technique, the behavior of various steels in simple compression has been studied up to compressive strains reaching in some cases to 3.2, or shortenings of 25-fold. The results of one such experiment, in this case to a maximum strain of only 2, is shown in Fig. 10. This is typical of all my results for steel; in the initial stages the stress-strain curve in simple compression is concave toward the strain axis; at high strains it becomes approximately straight and continues to rise. The strain at which it becomes linear is in general markedly higher than the strain at which the corresponding stress-strain curve in tension becomes linear. Furthermore, the rate of rise for simple compression is less than for tension. To a second approximation, there is a light inflection at higher strains, and the curve eventually becomes slightly concave upwards. This behavior for steel is in marked contrast to that found by Taylor and Quinney for copper; here the stress-strain curve approaches a horizontal asymptote for high strains. I have repeated this result of Taylor and Quinney.

FAILURES OF ISOTROPY AFTER SIMPLE COMPRESSION

The nature of the material resulting after straining in simple compression may be further studied by making various mechanical tests on it. Specimens have been cut transversely to the original direction of compression and subjected again to simple compression. Such specimens do not remain circular in cross section but become elliptical. The transverse strain corresponding to the major axis of the ellipse may be anywhere from 1.5- to 1.8-fold greater than the strain along the minor axis. In at least most cases, the minor axis corresponds to the direction of extension in the previously strained material, the major axis to the previous compression. It thus appears that there may be rather large failures of isotropy.

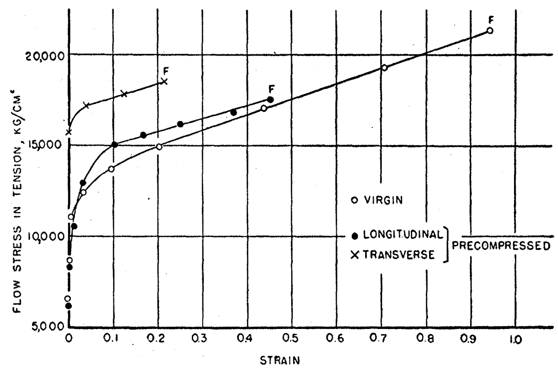

FIG. 11. Shows the effect of prestraining in simple compression on subsequent tension.

The simple equations of plasticity theory in general assume isotropy. Tension specimens cut in different directions from material previously strained in simple compression show a similar failure of isotropy. This is shown in Fig. 11. Except at the very lowest strains where the Bauschinger effect is exhibited, the material is strain-hardened for tension by a previous strain in simple compression. The strain-hardening is greatest for the transverse specimen in which two of the three principal strains on the second pulling are in the same direction as on the first straining. That is, although a material is hardened for any type of strain by a previous straining of any other type, the hardening is greater if the second strain is in the same direction as the first. Figure 11 shows that the slope of the strain-hardening curve for the longitudinal specimen is distinctly less than for the transverse specimen and the virgin specimen. This is to be ascribed to a partially reversible component in the plastic flow. It further appears from Fig. 11 that specimens prestrained in simple compression may fracture on subsequent tension at strains and stresses both markedly lower than for the virgin material. On the other hand, tension specimens prestrained in tension under hydrostatic pressure

[2] Taylor and Quinney, Proc. Roy. Soc. **143**, 323 (1933–34).

fracture at stresses and total strains much greater than for the virgin material. This again emphasizes the complicated nature of the phenomena of fracture and their qualitative difference from the phenomena of plastic flow.

SUMMARY

In summary, this must be regarded primarily as a qualitative description of the general nature of the phenomena to be found in this domain. It is obviously too early, in view of the great complexities, for any precise quantitative theory. The general nature of the phenomena is not different from what might be expected from rough qualitative considerations. For example, the great increase of ductility under pressure appears reasonable when it is considered that the external pressure tends to prevent the formation of internal cracks from which fractures might be initiated. The increase of tensile strength under pressure might be expected in view of the closer approach of the atoms and the consequent intensification of the atomic forces. But the existence of such phenomena as the dependence of fracture on past history in addition to stress and strain indicates that any precise theory must delve much deeper into the detailed structure of the metal than is necessary for the explanation, for example, of the ordinary bulk properties within the elastic limit.

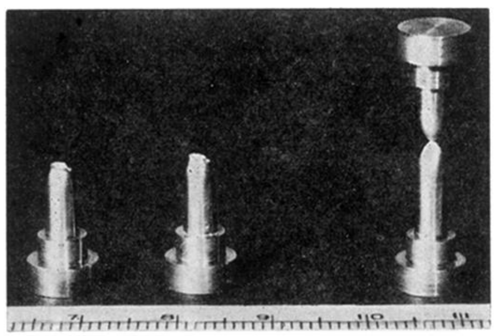

FIG. 1. At the left, a tension specimen pulled to fracture at atmospheric pressure; at the right, a specimen of the same steel pulled to a much greater reduction of area without fracture in a medium under a hydrostatic pressure of approximately 25,000 kg/cm².

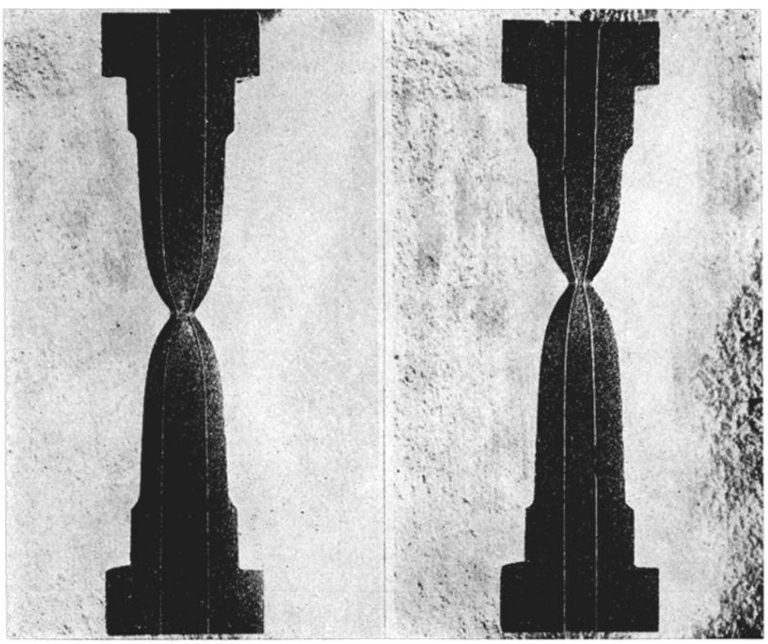

FIG. 2. Cored sectioned tension specimens from which the radial distribution of strain at the neck may be obtained.

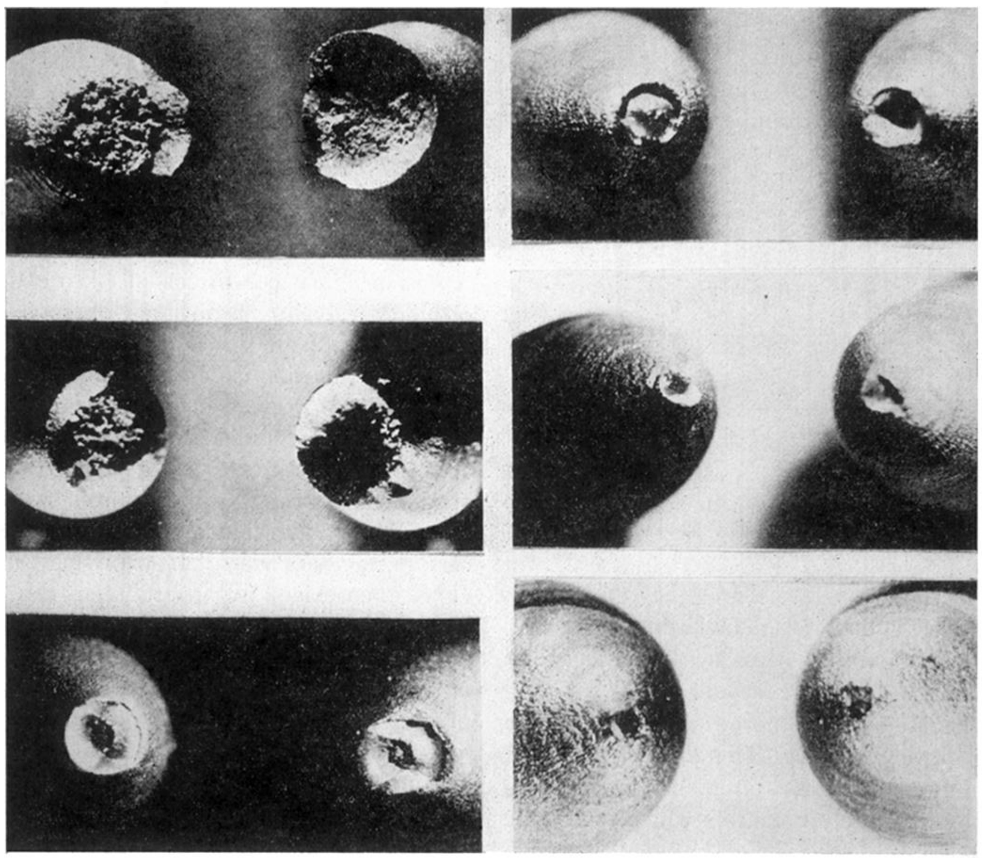

FIG. 7. Fractures of the same steel made at various pressures, showing the progressive change in the character of the fracture with increasing pressure. (A) Broken at Atmospheric Pressure ×10. (B) Broken under 34,000 p.s.i. ×10. (C) Broken under 145,000 p.s.i. ×12. (D) Broken under 186,000 p.s.i. ×12. (E) Broken under 268,000 p.s.i. ×12. (F) Broken under 387,000 p.s.i. ×18.

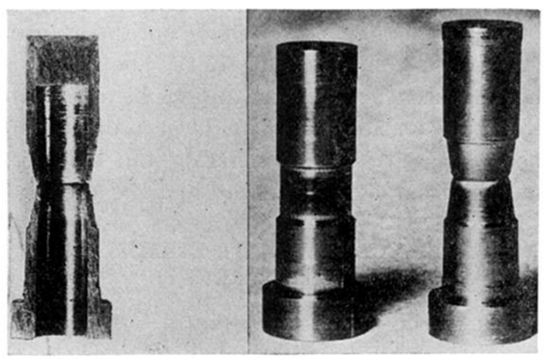

FIG. 9. Thin tubes for the study of two-dimensional strain under pressure. In the center is a tube before pulling, at the right an external view after pulling nearly to fracture under pressure, and at the left a longitudinal section of a similar tube.