SSC-127

INFLUENCE OF SPEED OF DEFORMATION ON STRENGTH PROPERTIES IN THE POST LOWER YIELD STRESS-STRAIN CURVE OF MILD STEEL

by

J. M. Krafft

and

A. M. Sullivan

SHIP STRUCTURE COMMITTEE

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December 9, 1960

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring an investigation at the Naval Research Laboratory to determine what occurs when steel is stressed at a high strain rate, and how this may relate to brittle fracture.

Herewith is a copy of the second progress report of this investigation, Serial No. SSC-127, entitled Influence of Speed of Deformation on Strength Properties in the Post Lower Yield Stress-Strain Curve of Mild Steel by J. M. Krafft and A. M. Sullivan.

The project is being conducted under the advisory guidance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

Please address any comments concerning this report to the Secretary, Ship Structure Committee.

Yours sincerely,

E H Thiele

E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure
Committee

Serial No. SSC-127

Second Progress Report
of
Project SR-142

to the

SHIP STRUCTURE COMMITTEE

on

INFLUENCE OF SPEED OF DEFORMATION ON STRENGTH PROPERTIES IN THE POST LOWER YIELD STRESS-STRAIN CURVE OF MILD STEEL

by

J. M. Krafft and A. M. Sullivan

U. S. Naval Research Laboratory
Washington, D. C.

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Washington, D. C.
National Academy of Sciences-National Research Council
December 9, 1960

ABSTRACT

The essence of the correlation procedure attempted here is to associate the average strain-rate sensitivity in plastic flow with the growth speed of the individual plastic zone. Flow is considered to be accomplished by a continuing series of yield initiations in the elastic stress field of such a zone. The non-linear relationship between upper yield stress and stress rate suggests that rate sensitivity will increase directly with zone velocity or inversely with the density of operative zones. Zone density is thought to vary as a function of both strain and strain rate. The influence of the speed of lower yield strain on the distribution of operative slip bands accounts for observed deviations from an equation of state.

CONTENTS

Page

Introduction. 1

- Effect of Number of Luders' Bands on Lower Yield Rate Sensitivity 1
- Plastic Zone Growth Rate 3
- Conditions Affecting Operative Plastic-Zone Density . . 4
- Tests at High Rates of Strain 5
- Changes in Rate Sensitivity with Strain 7
- Deviations from an Equation-of-State 9
- Termination of Rate-Sensitivity 14

Conclusions 14

Acknowledgments 16

References 17

Appendix 18

INTRODUCTION

Of the rate or time sensitivities of the various regions in the stress-strain curve, the upper yield stress is perhaps best understood. The deductions of Elam[1] and experimental measurement of Clark and Wood[2] give firm basis for identifying the upper yield point dependency upon rate of loading with the delay-time effect for yield initiation. The former effect can usually be predicted from the latter by assumption of linearly cumulative damage: that when the summation of fractions of the delay time expended at a particular stress level reach unity, yield will be initiated.[3] If the loading rate is increased, the magnitude of "fractions" spent at each stress level is decreased so that a higher stress can be reached before unit damage is accumulated.

In plastic flow, individual regions of elastic material can be subjected to continuously increasing stress in the combined stress environment of growing zones of plastic deformation. Such stress gradients are not primarily a function of the average stress level. Other things fixed, the local stress rate will depend upon the growth speed of the plastic zone. However, the growth process is identified with the yielding of elastic material at the zone boundary. Increases in the local stress required to accomplish this will be felt as an increase in the average stress required to continue plastic deformation. Evidence that supports this explanation of rate sensitivity for the case of Lüders' strain propagation during the lower yield strain has been obtained by Taylor.[4] This paper suggests the extension of this model to the interpretation of rate-of-strain sensitivities in post lower yield plastic flow where the slip band is thought to represent the applicable zone of plastic strain.

Effect of Number of Luders' Bands on Lower Yield Rate Sensitivity

The importance of the velocity of plastic-zone growth can be demonstrated by observing the rate-sensitive characteristics of the Lüders strain at conventional testing speeds. The load-head-displacement record of Fig. 1 was obtained from a flat specimen (6 x 1 1/2 x 3/16 in.) of mild steel sheet

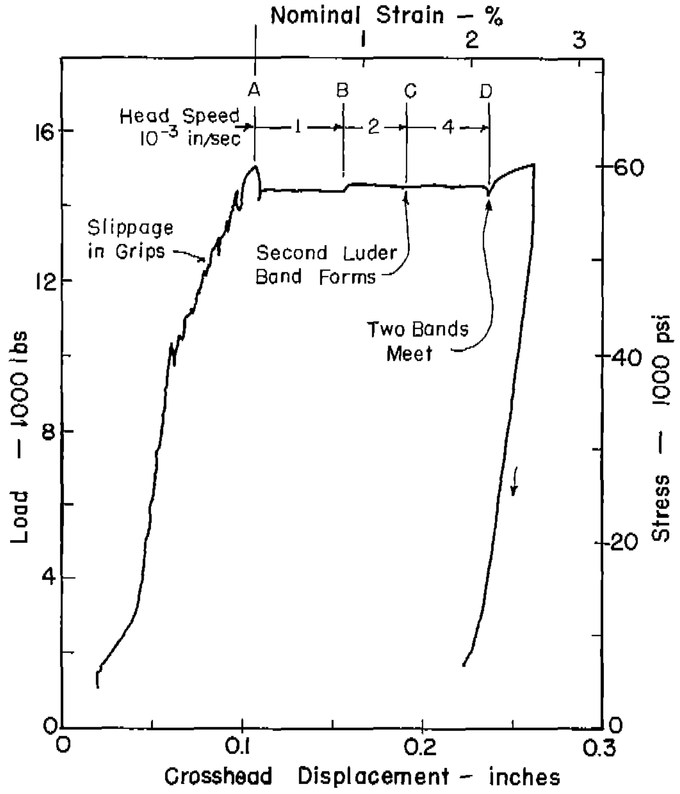


Fig. 1. Autographic record of load versus head displacement for 0.10 per cent C hot-rolled sheet steel tested in tension. Formation of second Lüder's band at point C negates stress rise expected from doubling of head speed, such as observed at B.

(SAE 1010) pulled in a conventional 120,000-lb capacity hydraulic testing machine.

After the upper yield point A, a Lüders band has been established across the specimen near one shoulder. As head motion continues, this wave-like band grows into the elastic regions of the specimen. The load or stress required to drive this band remains fixed as long as the head speed is not varied. At point B, the head speed is doubled to 2×10^{-3} in./sec. On the specimen, the strain-front velocity roughly doubles, the increased speed requiring about 1000 psi increased driving stress. A further doubling of head-speed at point C produces no stress change, starting instead a new Lüders band at the opposite shoulder. Each band then propagates at a velocity equal to that of the single band between B and C. When the two bands, which have parallel fronts converge at D, the machine load drops, an effect previously noted by Taylor.[4] It is apparent that the stress required to drive the Lüders band bears a unique relationship to its velocity but not necessarily to machine head speed unless the number of bands remains constant.

Plastic Zone Growth Rate

For the case of Luders' band propagation, the band-front velocity v_L may be expressed as a function of the head speed $d\ell/dt$:

$$v_L = \frac{1}{\epsilon_L N} \frac{d\ell}{dt} \tag{1}$$

where ϵ_L is the lower yield strain and N is the number of operative Lüders' band fronts. The stress elevation resulting from delayed yield effects should be a function of v_L, as it determines the stress rate imposed on elastic material in front of the band.

If instead of one or more zones covering the whole section area a plurality of zones having the area of a grain size accommodate the external deformation, then constancy of volume requires that

$$A d\ell = \epsilon_P \alpha n V dx \tag{2}$$

where A is specimen area, $d\ell$ is head displacement, ϵ_P is the plastic strain within the zone, α is the area of the zone front, $\underline{n}$ is the number of active zones per unit volume, V is the specimen volume, and dx is zone-front displacement. Since for cylinder specimens $V/A = \ell$, Eq. 2 becomes

$$\frac{d\ell}{\ell} = \epsilon_P \alpha n dx \tag{3}$$

or

$$\mathring{\epsilon} = \epsilon_P \alpha n \frac{dx}{dt}$$

where $\mathring{\epsilon}$ is the over-all average straining speed and ℓ is the specimen length. A crude continuity requirement would suggest a flow unit formed by interconnection of sufficient elemental areas α to cover the cross section of the specimen, in which case

$$\frac{dx}{dt} \equiv v_S = \mathring{\epsilon}/\epsilon_P \; N/\ell \tag{4}$$

Thus it is seen that the effective plastic zone speed v_S varies inversely as the number of deformation bands per unit length N/ℓ, which may be called the operative slip-band density. The plastic strain ϵ_P would be equal to that in a slip band and thus much larger than the lower yield strain ϵ_L of Eq. 1.

Conditions Affecting Operative Plastic-Zone Density

Two variables of the dynamic deformation process are thought to influence the density of operative slip bands: the average strain and the average strain rate. Changes in slip density with strain can affect rate sensitivity because of the way in which this sensitivity is measured. An absolute value for local strain rate in plastic flow is not known. It can only be assumed that if the external deformation rate is varied by a certain factor the local strain rate should vary by the same factor. Accordingly, the average straining speed is plotted as a speed ratio or on a logarithmic scale. The flow-rate sensitivity is thus taken as the absolute change of strength level for a given ratio of average straining speed. Measured in corresponding units, the rate sensitivity of the upper yield, which is thought to be the controlling process, increases with the level of straining speed. The upper yield relationship is linear in a log-log plot.[5] If the level of local straining speed is increased by a decreased operative slip density, a corresponding increase in rate sensitivity should result. An example of the variation in sensitivity that might be expected for a steel is shown in Fig. 2. (This variation in sensitivity will be discussed later.)

Measured values of flow-rate sensitivity are actually somewhat lower than might be expected from Fig. 2. The more direct effect of slip density increasing with straining speed is suggested. It is not unreasonable that rapid plastic flow should be influenced both by effects of strain and of strain rate on operative slip density. Although the relative importance of each effect is dif-

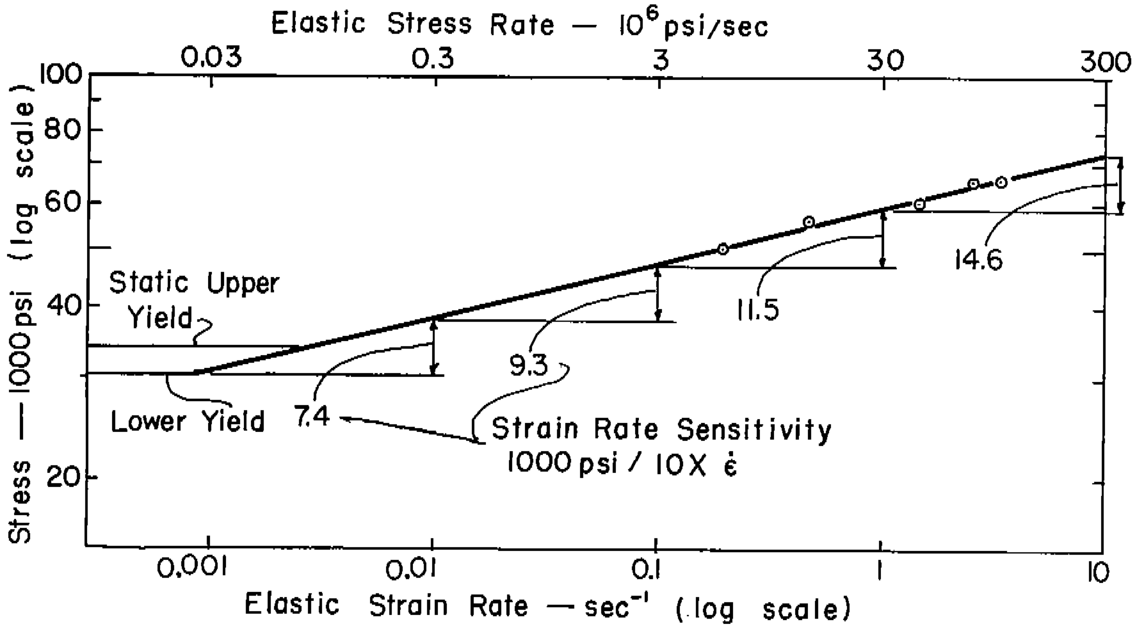


Fig. 2. Log upper yield stress versus log elastic strain rate showing that absolute strain rate sensitivity decreases with decreasing strain-rate level.

ficult to separate, certain test procedures are thought to favor indication of a particular effect. These will now be discussed.

Tests at High Rates of Strain

The stress concentration effect at the Lüders' band plastic-elastic boundary makes it possible to observe lower-yield rate sensitivity at conventional testing speeds. General flow-stress rate-sensitivity for mild steel is only observed at much higher head speeds. A device for obtaining strain rates from about 1 to 100 per second is described in the appendix.

Typical data obtained with the dynamic loading apparatus are plotted in Fig. 3, which shows compressive engineering stress against both strain and strain rate. The material used was an 0.2% C steel, furnace cooled from 870 C, designated C-3; details of its composition and microstructure have already been published.[5] Cylindrical specimens 1/2 in. long and of 1/2-in. radius were used for this plot.

The upper yield stress is plotted as a function of elastic strain rate (stress rate divided by Young's modulus) on the zero-strain plane. Applicability

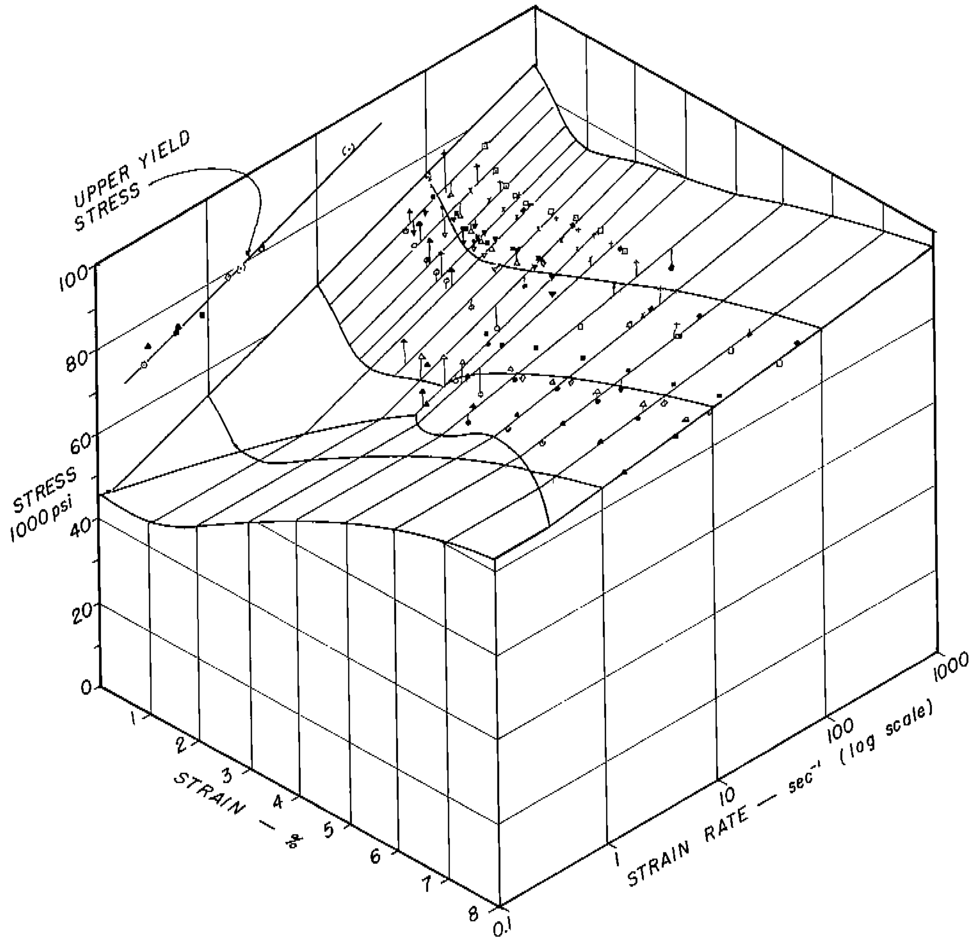


Fig. 3. Effect of strain rate on the stress-strain curve for an 0.20 per cent C steel tested in compression. Upper yield stress is plotted on zero strain plane as a function of elastic strain rate with bracketed points predicted from constant-stress delay time measurements. Data points designated ▽ ▼ x + are obtained with Hopkinson Bar Impact as in Ref. 5; remainder with device of Fig. 10.

of the cumulative-damage hypothesis is demonstrated by the fact that yield points predicted from yield-delay-time data (those shown in brackets at 2 and 20 per second) lie on the extension of this curve.

At increasing strain values, the stress is plotted at the instantaneous head speed. The variation of head speed with strain can be followed from the similar symbols used for points of a given test. It is characteristic in a low-stiffness loader for the head speed to vary inversely with the slope of the load-deflection curve. Prior to yield when this slope is high, low head speeds on

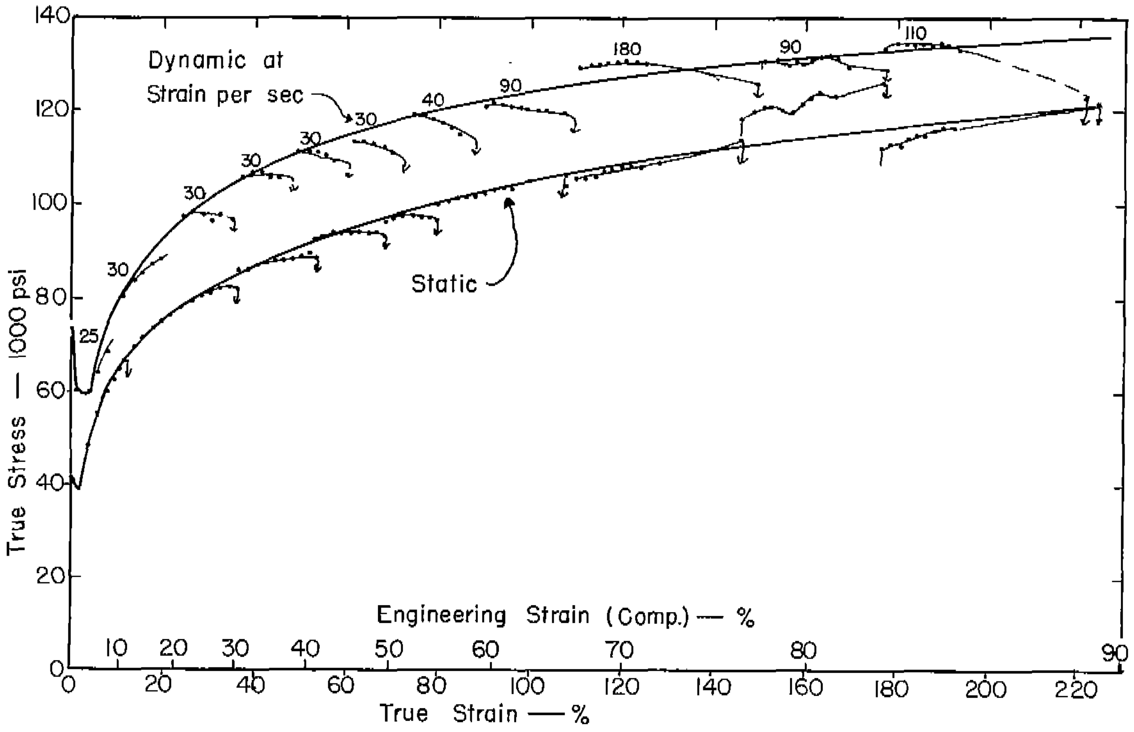


Fig. 4. True Stress - True Strain curves for repeated tests of 0.11 per cent C steel at static and dynamic (strain rates noted) compression.

the order of 1 in./sec are obtained; for zero slope during yield point strain, speeds a factor of 100 greater are typical; for the work-hardening range, a normal increase is by a factor of 10.

Although the rate sensitivity (slopes in Fig. 3) is about twice as great for upper yield stress as for plastic flow, the two are necessarily unrelated. Increased density of operative slip zones with strain and strain rate should lead to a reduced flow-stress sensitivity in plastic flow, in accordance with the previously outlined reasoning.

Changes in Rate Sensitivity with Strain

Substantial variation in the density of operative slip bands is thought to occur during straining of mild steel and to account for part of a corresponding change in flow-stress sensitivity to strain rate. The variation in rate sensitivity is suggested by an intercomparison of static and dynamic compression tests continued to high values of strain. Typical behavior is illustrated in Fig. 4, which shows stress-strain curves for successive compression tests on specimens 0.925-in. long to nearly unit engineering strain. The material

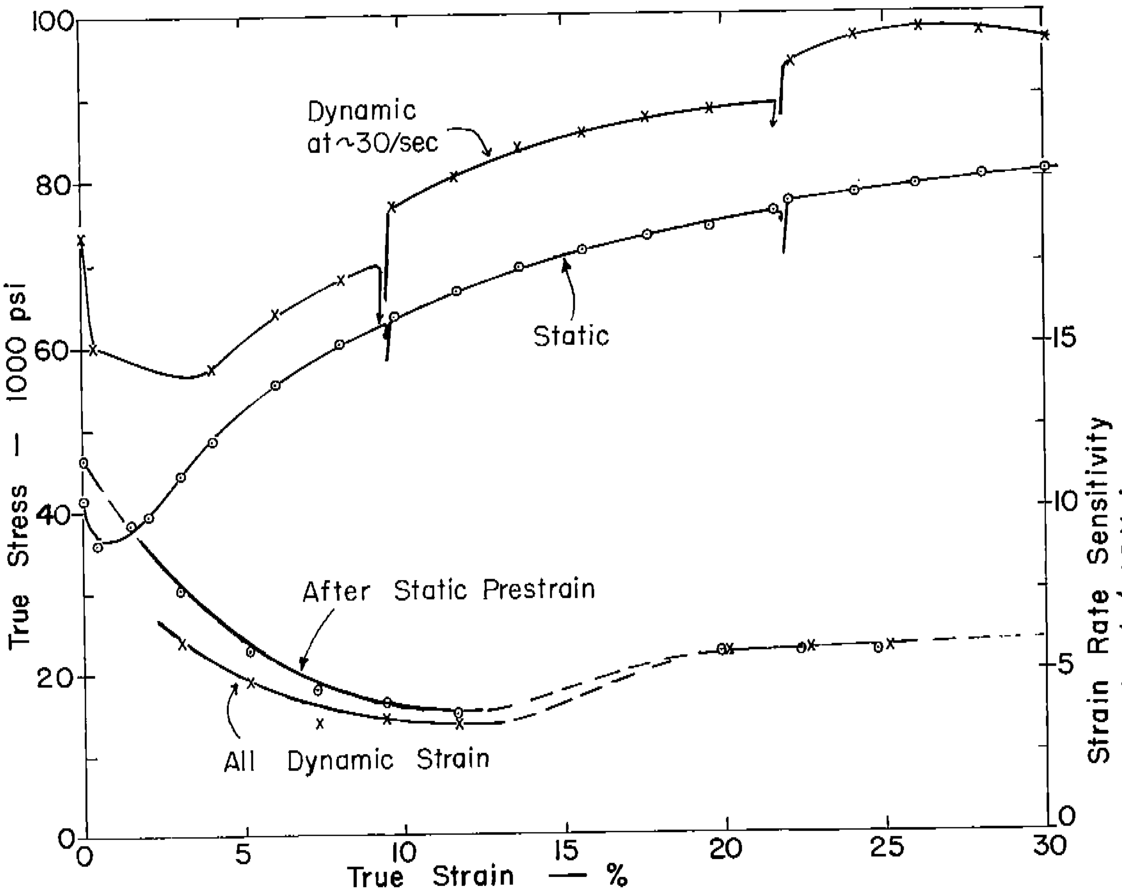


Fig. 5. Expanded portion of Fig. 4 (to 30 per cent true strain) together with corresponding variation in strain rate sensitivity taken from Fig. 9. Point on zero strain ordinate represents upper yield stress strain-rate sensitivity. Static traverse of yield point strain increases rate sensitivity.

shown here (and in Fig. 2) is a 0.11% C. steel designated 1010 in an earlier publication.[5] After each strain cycle, the specimen bulge was turned off to restore the cylindrical form and initial diameter. When the specimens were compressed to less than a diameter in length (0.50 in.), the outside diameter was turned down to maintain at least unit length-to-diameter proportions.

Static and dynamic curves are seen from Fig. 4 to draw closer together in the region of maximum strain hardening and then to diverge. A similar observation can be made from the data of Manjoine[6] for mild steel at room temperature. An examination of tests over a range of straining speeds near that for the dynamic curve of Fig. 4 shows the rate sensitivity of plastic flow to vary roughly in correspondence with the separation of static and dynamic stress-strain curves. Values of rate sensitivity (taken from slope measurements in Fig. 9) are also plotted in Fig. 5.

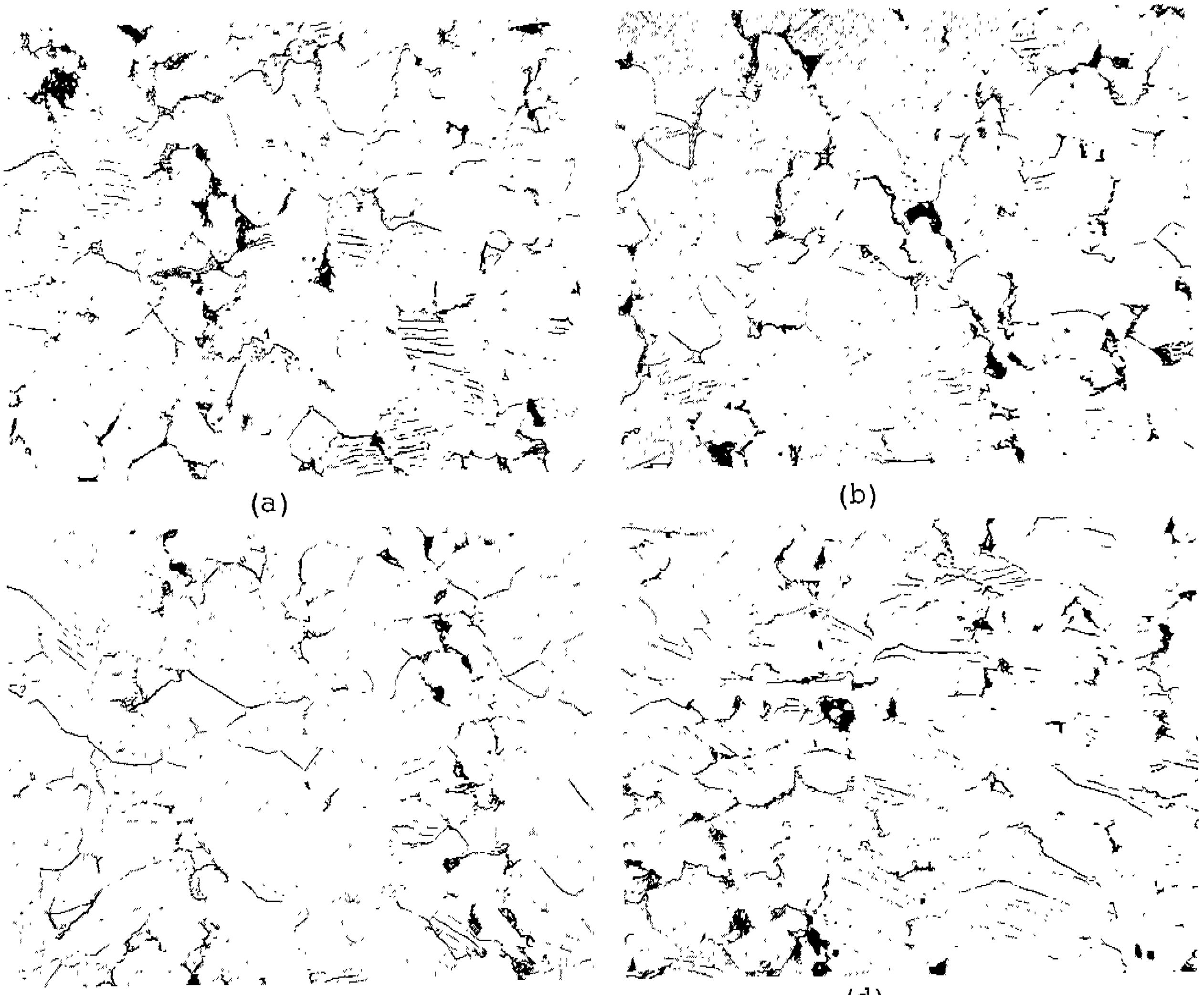
The density of operative slip bands could reasonably vary in a way which would correlate with the observed changes in rate sensitivity. During early work hardening, slip occurs preferentially in the grains most favorably oriented. As the easy glide planes are exhausted, deformation will tend to be accommodated on slip planes in less favorably oriented grains. These new slip lines increase the density of active deformation bands and thus decrease the rate sensitivity.

Evidence for variation in slip band density was sought by polishing specimens that had been prestrained (compression up to 20%) to selected levels, and then continuing deformation with small equal increments of true strain (2%). The deformation markings should indicate only those slip bands that were active at the selected strain level as prior markings are erased by the polishing. It is thought that increased number of slip bands operative to accommodate the strain may be associated with a decreased amount of strain observed in each band.

The photomicrographs of Fig. 6 do show slip traces to become narrower for prestrains up to 10 per cent. At higher prestrain levels there is a tendency for wider slip traces to reappear, an effect which is reasonably related to the increase in rate sensitivity. An analagous tendency in another delay-time sensitive material, α-brass, is indicated by the work of Barnby, Steel, and Calnan.[7]

Deviations from an Equation-of-State

With a neglect of the strain-rate (and temperature) history during plastic deformation, a graphical form of an equation-of-state is represented by Fig. 3. A single surface fits the data rather satisfactorily. If the lower yield strain is carried out at very low straining speeds rather than at excessively high speeds, deviations from this surface become substantial. These deviations are of interest here as they can be reasonably interpreted, in terms



(a) (b)

(c) (d)

Fig. 6. Photomicrographs of 0.11 per cent C steel showing an additional 2.0 per cent strain after indicated approximate amounts of prior strain. (a) 0 per cent; (b) 2 per cent; (c) 4 per cent; (d) 20 per cent (500X)

of the proposed model of rate sensitivity, as a function of operative slip-band density, which here varies largely as a function of straining speed.

Extreme effects of lower yield-strain history can be demonstrated by comparing flow curves following static lower yield with those following lower yield at the highest head speed possible with the present machine. A reduction in static flow-stress is seen in Fig. 7a after yield-point strain has been completed at such a high head speed. This effect has been observed for steel by Campbell and Duby[8] and by Smith and Vigness.[9] For the reverse order of strain history shown in Fig. 7b, the yield point strain is traversed statically

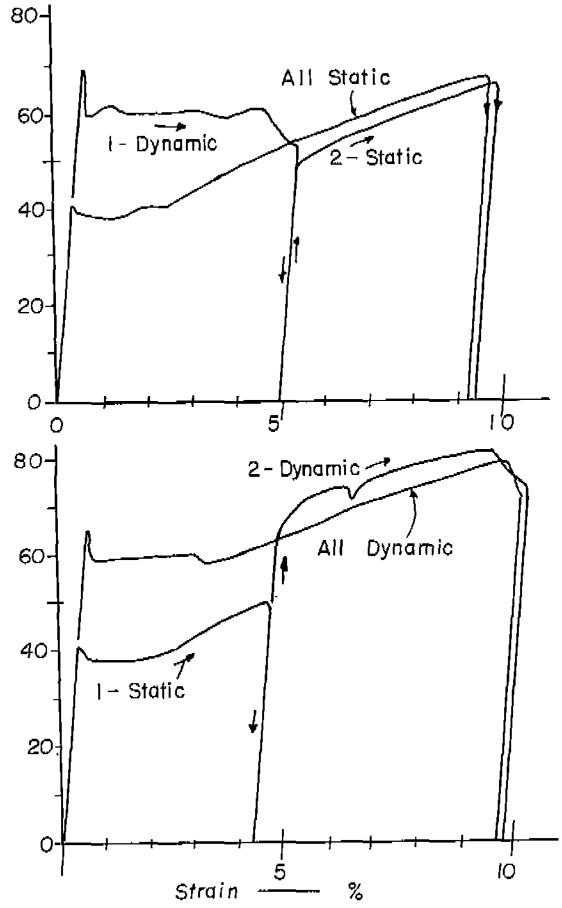


Fig. 7. Load versus head displacement (Tracings of X-Y Oscilloscope records) for 0.11 per cent C steel.

(a) Effect of dynamic lower yield strain on static curve

(b) Effect of static lower yield strain on dynamic curve

and deformation is then continued at a high rate for which the stress level appears greater than in the all-dynamic test. If a series of more moderate "dynamic" strain rates follows the static prestrain, it is found (Fig. 8) that an increased rate of strain sensitivity may be associated with the static prestrain. Further, the increase in stress level associated with static lower yield straining becomes smaller as the speed of the dynamic test (and presumably its lower-yield-strain head speed) is reduced.

The speed of Lüders band propagation is thought to account for the observed deviations from an equation of state because the straining speeds associated with its strain gradient are so high. Using values suggested by the work of Taylor,[4] a strain rate the order of 1000 per sec or 10 times the flow strain rate values can be calculated for the present tests when considered as single-band propagation. Marked differences in appearance of deformation markings (Fig. 9) are observed to follow such rapid lower yield strain and suggest increased operative slip density. Slow deformation to 4 per cent (Fig. 9a) is accomplished by relatively wide slip traces while the corresponding deformation with a head speed of about 100 in./sec accomplishes the same strain with

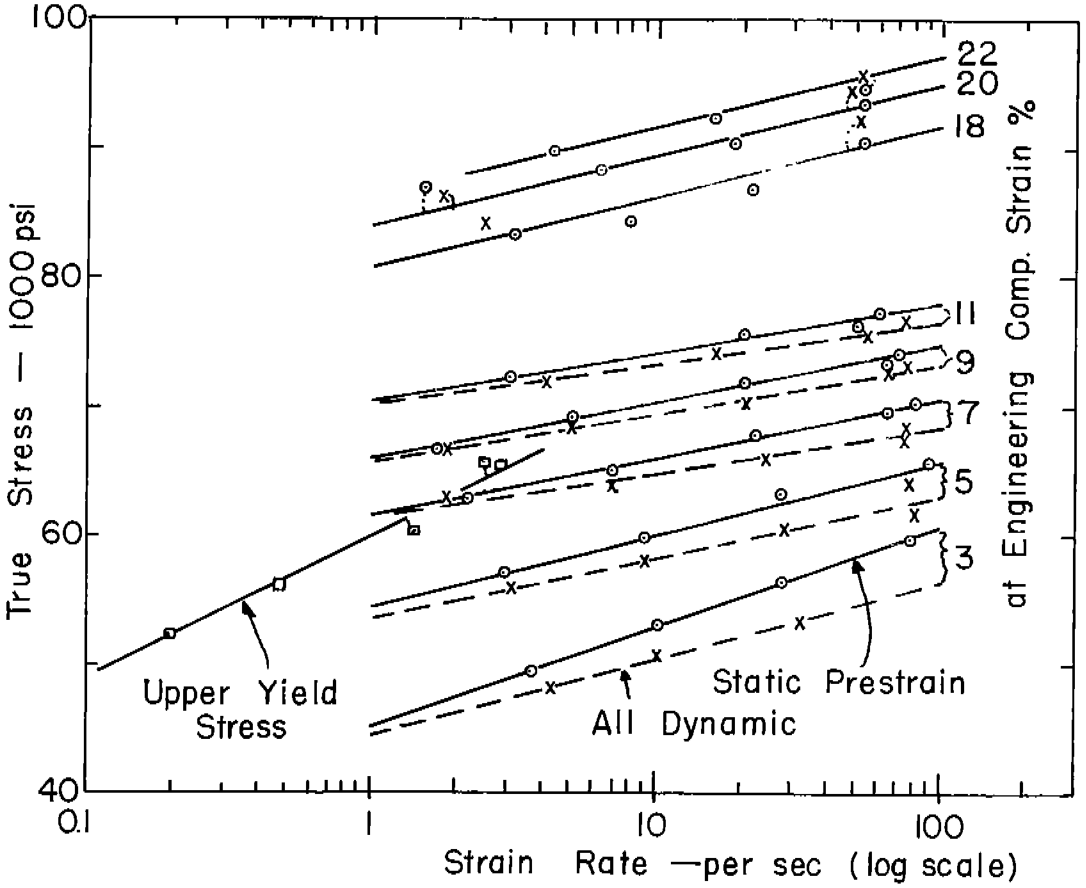
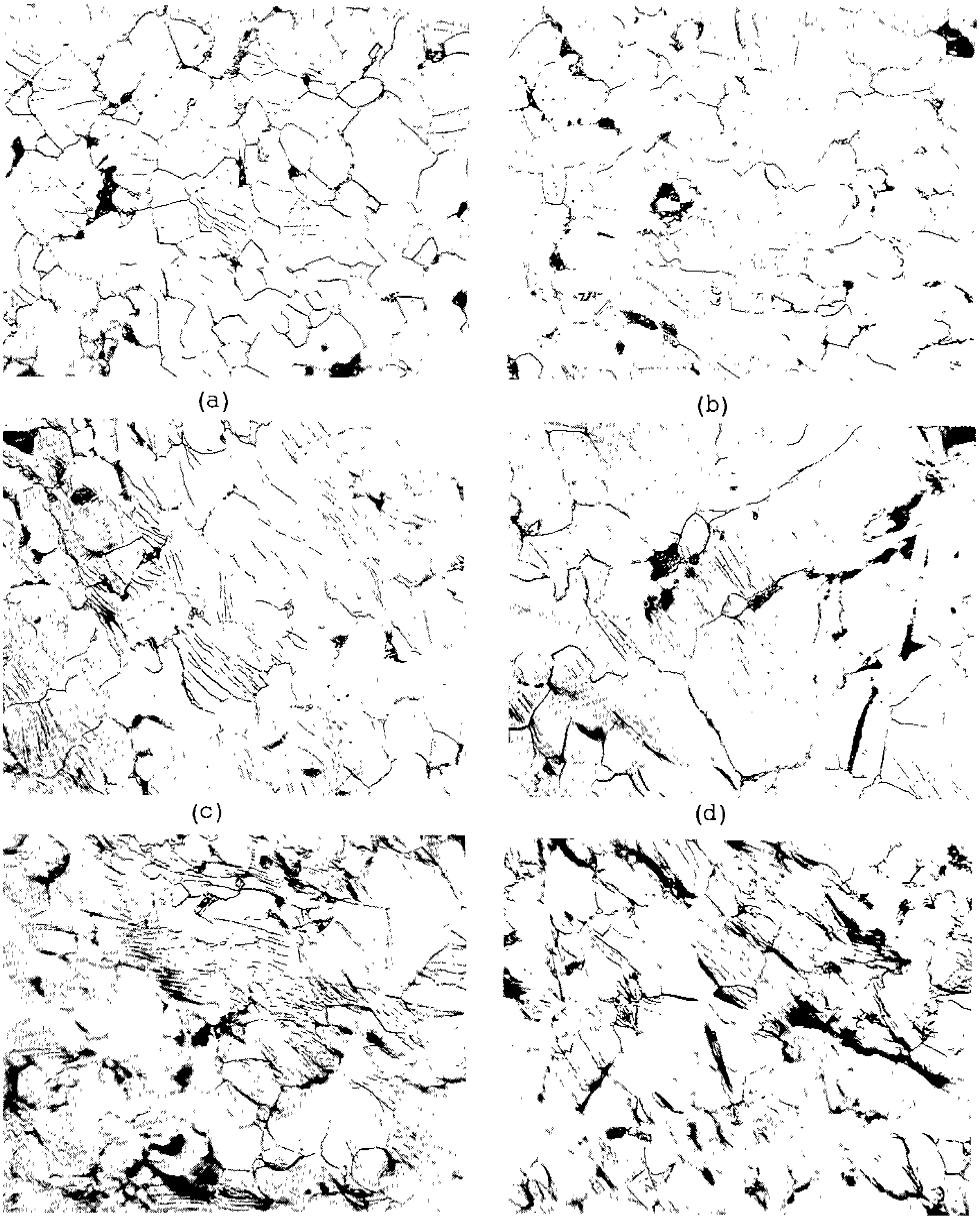


Fig. 8. True stress versus log strain rate at selected strain levels showing effect of static lower yield strain on strain rate sensitivity. Slopes of these curves are plotted in Fig. 5.

narrower slip traces (Fig. 9b) which would necessarily be more numerous or have higher density.

In the general flow region up to about 10 per cent strain where the strain rate sensitivity factor continually decreases, more numerous deformation sites in the dynamic test are still reflected in the different appearance of the slip bands (Figs 9c and 9d). At 20 per cent, however, little difference can be detected (Figs. 9e and 9f), a fact nicely coincident with the disappearance of history effects on rate sensitivity. At this level, strain in the dynamic test is thought to be accomplished by growth of the previously existing slip lines which now coarsen and resemble the normal slip line for static strain. Similar appearance trends have been noted by Campbell and Duby.[8]

The observed increase in slip density following high speed of Lüders



(a) (b)

(c) (d)

(e) (f)

Fig. 9. Photomicrographs of 0.11 per cent C steel after various deformation histories: Static a, c, e; 4, 9, 18 percent strain
Dynamic b, d, f; 4, 9, 18 percent strain

straining is not unreasonable. It is plausible that such rapid strain should disturb the normal static slip distribution; that because increased deformation rate tends to suppress easy glide, slip planes that would normally await higher stress levels caused by work hardening are brought into action at subnormally low average strain levels. When speed of deformation is slowed on the return to static testing, the "easy glide" planes, on which deformation has been inhibited to subnormal levels, tend to accommodate the ensuing strain at lower than normal stress levels as observed in Fig. 7.

The converse explains Fig. 7b; since flow on the easy glide (low stress) planes has been favored during the earlier static strain, fewer glide planes are available for the dynamic plastic flow which, for this reason, requires a stress higher than that for the all-dynamic test.

The observed changes in flow strain rate-sensitivity seen in Fig. 8 may be reasonably associated with the above noted variations in appearance. Relatively lower values of the strain rate-sensitivity factor occur in the all dynamic deformation where the high strain rate of the lower yield point deformation has resulted in a persistence of more numerous deformation sites or higher operative slip band density into plastic flow regions.

Termination of Rate-Sensitivity

Continued strain should eventually exhaust all sites in which yield had not been initiated; static and dynamic stress-strain curves would then converge and stress rate-sensitivity would vanish. The data of Fig. 5 show instead that the increased separation of static and dynamic curves after about 10 per cent strain thereafter remains constant. The data of Work and Dolan[10] for dynamic torsion tests, which are preferred for this determination because of constancy of specimen form do show vanishing rate-sensitivity at rupture strains of the order of 2.5, while it still exists for strains of 0.05 and 0.30.

Conclusions

1) All regions of the stress-strain curve of mild steel possess a degree of sensitivity to rate of strain which is suggestive of control by a single process.

2) The upper yield point sensitivity is known to be controlled by the delayed yield effect. It is thought that the growth rate of zones of plastic flow into elastic regions could be resisted by yield strength elevation and thus by the yield delay process.

3) During the lower yield strain, the plastic deformation zone of interest is the Lüders band; the stress elevation is a function of the velocity of its front; and the velocity varies inversely as the number of bands which are simultaneously growing.

4) In post lower yield plastic deformation, the plastic deformation zone of interest is thought to be the slip band--or possibly aggregations of such bands in a single grain. The growth velocity of slip bands is inversely proportional to the operative slip density.

5) Corresponding to the strain region of maximum strain hardening in the stress-strain curve, strain rate sensitivity reached a minimum value. The decrease is attributed to increasing operative slip density with cold work. Somewhat increased strain rate sensitivity is observed at higher strain levels.

6) Because of the high strain gradient at the Lüders band front and soft machine characteristics, traverse of the lower yield strain at high machine speeds produces abnormal effects on post lower yield stress-strain characteristics: a) it reduces the flow stress in the static as well as in the dynamic test and b) it decreases the rate sensitivity of plastic flow.

7) Departures from an equation of state noted above are thought to be due to a tendency for the density of operative slip zones to increase with strain rate. The normal pattern of slip growth preferentially on planes of easy glide is suppressed by rapid deformation. The material seeks a less rate-sensitive deformation pattern by increases in operative slip density. When slower deformation rates are restored, strain hardening on easy glide planes is subnormal so that strain may proceed at reduced stress levels. The effect of increased slip density persists, nonetheless, and reduces the rate of strain sensitivity. Evidence from appearance of deformation markings in the microstructure corroborate

this interpretation.

8) Significant rate of strain sensitivity is maintained to the vicinity of 90 per cent engineering strain. It is expected that near unit strain no unyielded zones of material would remain and rate sensitivity would cease. Although not concluded from this work, other data suggest this possibility.

Acknowledgments

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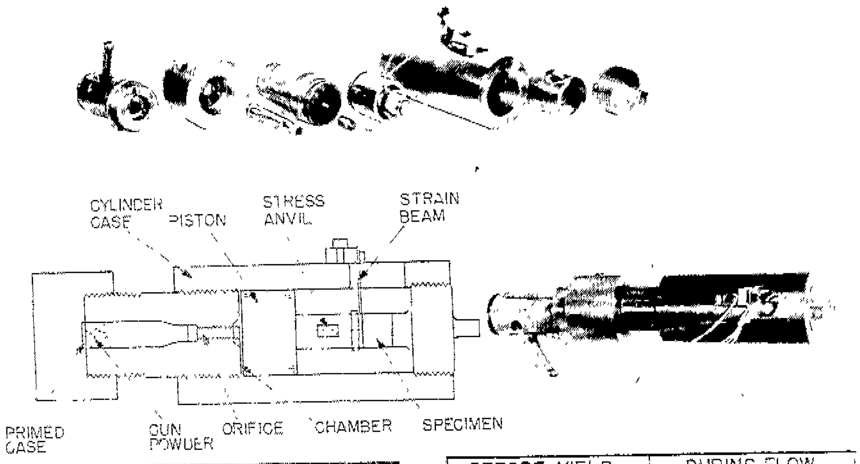
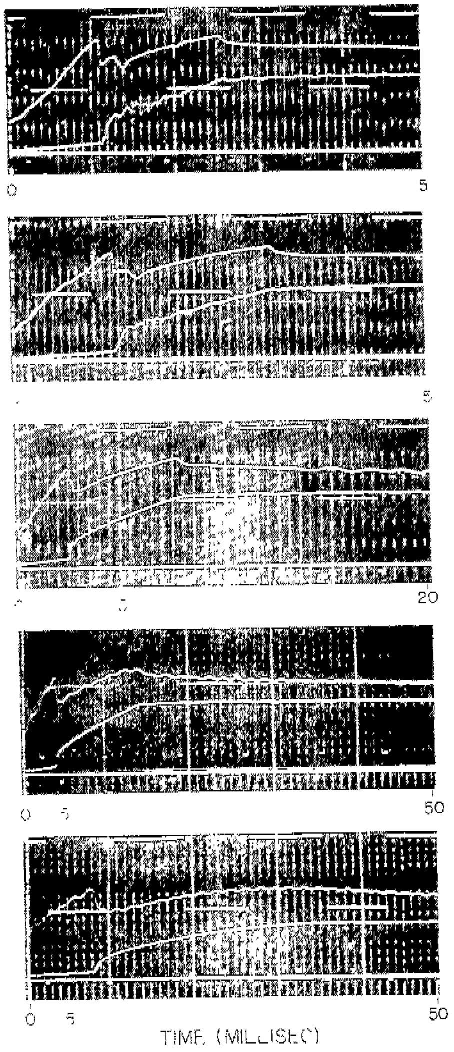
Appendix

The machine developed for attaining head speeds to produce the strain rate range of 1 to 100 per second is illustrated in Fig. 10, together with typical data obtained by its use. A small charge of rifle powder (usually about 1 gram of Dupont 4064) burned in a standard primed-brass cartridge case (.300 Magnum) provides a sudden and intensive source of high pressure. The high-pressure gas drives a piston at a rate controlled by the size of a restrictive orifice (drilled holes, wire drill standard sizes: 57, 60, and 70, 5/8 in. long; 75 and 80, 3/16 in. long). Opposite the pressure source, a short, hard, stress anvil rod embedded in the piston presses against the specimen, which in turn is backed up by a threaded base. The stress anvil is instrumented with wire strain gages. A heavy walled tube (portion of a 37-mm gun barrel) provides a cylinder case for the piston and a rather rigid loading frame. It is sufficiently rigid to permit strain measurement directly between the stress anvil and the frame by detecting the bending in a short, tapered, cantilever beam with wire strain gages.

Cathode ray oscillographs were employed to record the wire strain-gage signals. The photographs (Fig. 10) show both stress and strain signals recorded on a common linear time base (Tektronix 530 oscillograph with dual-beam pre-amplifier) for decreasing restrictive orifice size. Direct presentation as a stress-strain curve may also be obtained with an X-Y oscillograph (Tektronix Model 536) as shown in Fig. 7.

Speed of response is limited by the strain beam which, with one end in contact with the stress anvil, has a natural period of about 300 μ sec. Straining rates as high as 100 per second in a 1/2-in. long specimen can be measured with accuracy. Specimens twice this length can be accommodated in the loader. An analysis of machine characteristics will appear in a forthcoming publication.[11]





BEFORE YIELD		DURING FLOW AT 6% STRAIN	
STRESS RATE 10^6 LBS/IN^2/SEC	UPPER YIELD STRESS 10^3 LBS/IN^2	STRAIN RATE SEC^{-1}	STRESS 10^3 LBS/IN^2
61	78	40	67
46	75	34	65
16	68	12	62
9	67	6	61
4	64	1	58

Fig. 10. Photograph and schematic drawing of test apparatus. Oscillograms of load and head displacement versus time together with tabulated data typify the effect of variations in speed obtained by reducing orifice diameter.

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Institute for the Study of Metals
University of Chicago

Mr. Paul Ffield
Assistant Manager of Research
Bethlehem Steel Company

Professor Maxwell Gensamer
Professor of Metallurgy
School of Mines
Columbia University

Dr. J. R. Low, Jr.
Metallurgy Research Unit
Research Laboratory, General Electric Company

Mr. T. S. Washburn
Manager, Quality Control Department
Inland Steel Company

Mr. T. T. Watson
Director of Research
Lukens Steel Company