MATERIAL PROPERTIES AT MEDIUM STRAIN RATES

by

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INTRODUCTION

The influence of rate of strain on material properties has been under study by several investigators during the past decade. Most of these investigations have been made using tensile test specimen. The methods of loading the specimen and recording the results varied, but the type of test specimen was essentially the same.

Clark and Duwez [1]* have shown that the strain rate in impact tensile tests varies from point to point along the specimen and for a given point is also dependent upon time. This is because of the phenomenon of the propagation of plastic strain. It is therefore apparent that there is a need for a test in which plastic strain propagation is not a limiting factor.

This report is concerned with a method of testing that has been developed to study the influence of a pure strain rate on material properties. A description of the equipment used and some sample results are presented.

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*[ ] Refers to bibliography.

TESTING EQUIPMENT

The method used to obtain a uniform medium strain rate was to use a hollow thin-wall cylindrical specimen loaded by internal fluid pressure. The circumferential strain versus time was recorded as a measure of the strain rate. The ability of the test fixture to produce a desired constant strain rate depended upon the incompressibility of the fluid used, the ability to compress the fluid by means of a piston moving at a constant velocity, and the stress-strain relation for the material being tested.

The device used in this investigation was a slight modification of the fixture designed by Chen [2]. The general assembly is shown in Fig. 1. Number ten turbine oil was used to fill the inside of the specimen and cylinder. The piston was placed in contact with the oil in the cylinder and the air bled out. The piston was then driven by the stem of a Screw-type Testing Machine at a velocity to produce the desired strain rate.

Equation for Strain Rate

The equation for strain rate using this fixture and assuming an incompressible fluid is as follows:

$$\dot{\epsilon}_t = \left(\frac{r_p}{r_o}\right)^2 \frac{V_p}{2L} \qquad (1)$$

where $\dot{\epsilon}_t$ = strain rate

r_p = radius of piston

r_o = original inside radius of specimen

L = length of specimen

V_p = velocity of piston

The derivation of the formula is given in Appendix I.

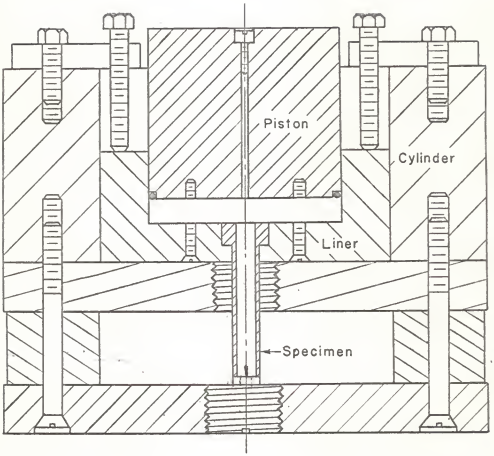


Fig. 1 Test Fixture

An attempt was made to use mercury as the fluid because it was readily available and had a low compressibility coefficient, $k = 4 \times 10^{-6}$ atmospheres^{-1}. However, the pressure needed to rupture the specimen could not be attained because of leakage of the mercury between the piston and the cylinder wall.

Oil was found to be satisfactory since it would eliminate the excessive leakage problem, but its compressibility effect would tend to give a strain rate that was not constant throughout a test. Another consideration in the selection of a fluid was the propagation of elastic waves in the fluid. This will become troublesome if the time required for the pressure wave to travel the length of fluid contained within the specimen and cylinder is of the same order of magnitude as the time required for the specimen to rupture. The velocity of propagation of an elastic wave in oil is approximately 5×10^{4} inches per second. The length of the column of fluid involved in these tests was about 3 inches. Therefore, the time required for a wave to travel this distance is 0.6×10^{-6} seconds. At the rate of strain achieved in these tests, which was 0.001 in./in./sec., the specimen ruptured in 4.0 seconds. From this consideration it was shown that pressure wave propagation in the fluid was not troublesome. However, if this fixture were used for higher rates of strain, this effect should be considered.

As shown by Equation 1, the strain rate can be changed by various means. For a given sized specimen, as used in this investigation, the strain rate was changed by varying the piston velocity. In general, it is clear that either by increasing the piston diameter or piston speed, or by decreasing the diameter or length of the specimen, an increase in strain rate is obtained.

TEST FIXTURE

The fixture was made of C1018 steel. It consisted of four main parts: a base, four spacers, cylinder block, and piston arrangement. A safety device was used to protect the operator from the spray of oil when the specimen ruptured.

The base was made of one-inch steel plate. The plug in the base was used to support the end of the specimen, making it possible to use shorter specimen without using spacers of corresponding lengths.

The spacers were made of two-inch square bar stock. Square spacers were used to facilitate the attachment of the safety device to them. Also, they provided a large enough cross-sectional area to withstand the weight of the testing machine, while not restricting the space near the test specimen.

The cylinder block consisted of three sections of steel pipe that were shrunk together. A further explanation of this structure is given in Appendix III. A one-inch steel plate was bolted to the cylinder block, forming its base. The cylinder wall was ground, as were the walls of the pistons. A device was attached to the top of the cylinder to provide a means of clamping the outer section of the piston arrangement to the bottom of the cylinder when using the inner piston.

The piston arrangement provides both a six-inch and a four-inch diameter piston with which the strain rate can be regulated. The two pistons could be fastened together, and the effective area against the oil would be the area of the six-inch piston. Used separately, the effective area of the four-inch piston can be utilized when the outer portion is clamped to the bottom of the cylinder block. A bleed hole is provided to

remove the air from the cylinder before a test. The four-inch piston was used on the tests that were made. An O-ring was used to provide a seal between the piston and the cylinder wall. If the six-inch piston were to be used, it would also have to be equipped with an O-ring.

The safety device is shown in Appendix IV. The holding plates were machined from 3/4 x 3 inch bar stock. Three-eighths inch plexiglass was used on opposite sides so the specimen could be safely viewed during a test. The holding plates were attached to the spacers with C-clamps. This device not only protected the operator, but it confined the oil to a small area so that it could be collected following rupture of the specimen.

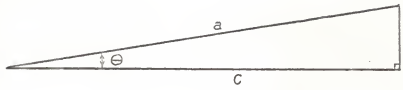
INSTRUMENTATION

It was desired from this investigation to obtain stress-strain relationships for C1020 cold-rolled steel at medium strain rates. As previously shown in Equation 1, the strain rate during a test could be calculated if an incompressible fluid were used and the piston velocity known. However, the equation was not used to determine the strain rate for this investigation. Instead, two SR-4 wire strain gages were attached around the circumference of the test specimen. The indication of strain versus time, obtained from the gages, was photographed from an oscilloscope screen. From these data the strain rate was calculated, and it could be determined whether or not the rate remained constant during test.

The strain gages used were Baldwin-Lima-Hamilton wire resistance gages. Each has a single strand resistance element long enough to wrap around the circumference of the specimen. Two of them were attached to the specimen, and twice the average value of strain recorded. It was assumed that the specimen would not deform uniformly along its length; therefore, better results and an increase in sensitivity were obtained by using the two gages.

The gages were connected in series into one arm of a Wheatstone bridge circuit. The resistance of each gage was 60 ohms, and being in series gave a total resistance of 120 ohms in the external arm. The bridge in the amplifier used was rated for use with this value of resistance.

Because the strain gage leads could not be placed exactly on top of one another, the resistance element was not precisely on the circumference of the specimen. The element was in a spiral, like the thread on a bolt. Correction could be made as shown below.



a = gage length

b = distance between gage leads along longitudinal axis of specimen

c = gage length in circumferential direction around specimen

Actual Strain = Indicated Strain x cos Θ

If the gages are carefully attached, cos Θ approaches unity, and no correction need be made. The existence of this condition was assumed in this work, since the largest value of θ involved was of the order of 5 degrees.

Temperature compensation was not used in the bridge. It was assumed that the resistance change in the gages, because of increasing temperature during a test, was negligible. The basis for this assumption was that the test was dynamic and that there was insufficient time for the heat from the specimen to be transferred to the gages.

The circumferential stress in the specimen was calculated using thin-wall cylinder theory. From the derivation shown in Appendix II:

$$\sigma = \frac{F_p}{A_p} \frac{r_o}{t}$$

where r_o, A_p, and t are constant values for a particular test. Therefore, it was desired to record F_p versus time and from this information to calculate σ.

Two foil resistance strain gages were attached to the four-inch piston at diametrically opposite positions, from which leads were connected to opposite external arms of a Wheatstone bridge. This was done to nullify the effect of possible eccentric loading of the piston. Calibration was accomplished before each test by loading the piston in the Screw-type Testing Machine and recording the load versus the change of position of the oscilloscope trace. Again, using two gages increased the sensitivity of the arrangement.

A Tektronics 535 cathode ray oscilloscope was utilized to display the output of the strain gages. A dual trace feature was employed so that both the traces from the gages on the specimen and the piston could be shown simultaneously on the same oscilloscope. The traces were chopped so that they moved across the oscilloscope screen simultaneously. Using this method, there was no problem of synchronization of events. The load and strain traces were both on a common time datum. The traces were photographed using the oscilloscope camera with Type 55 P/N Polaroid film.

Triggering of the oscilloscope was accomplished by utilizing the initial rise characteristic of the signal from the strain gages on the specimen. The triggering proved to be somewhat unreliable because the triggering sensitivity had to be manually adjusted and depended chiefly upon the proficiency of the operator. Another disadvantage was that an entire load trace was not obtained. A small portion of the trace at the beginning of each test was omitted, because the oscilloscope would not trigger at the instant the specimen started to deform. This loss was of minor importance, however, since information was desired only at the yield point and at the fracture of the specimen. The trace of the oscilloscope could be

photographed at a condition of no load, before the test was begun, in order to establish a datum.

The signals received by the oscilloscope were amplified outputs from the Wheatstone bridge arrangements. A Brush dual channel amplifier and a Tektronics type Q strain gage transducer and amplifier were used to provide the proper amplification. Figure 2 shows the test fixture placed in the Testing Machine along with the accompanying instrumentation.

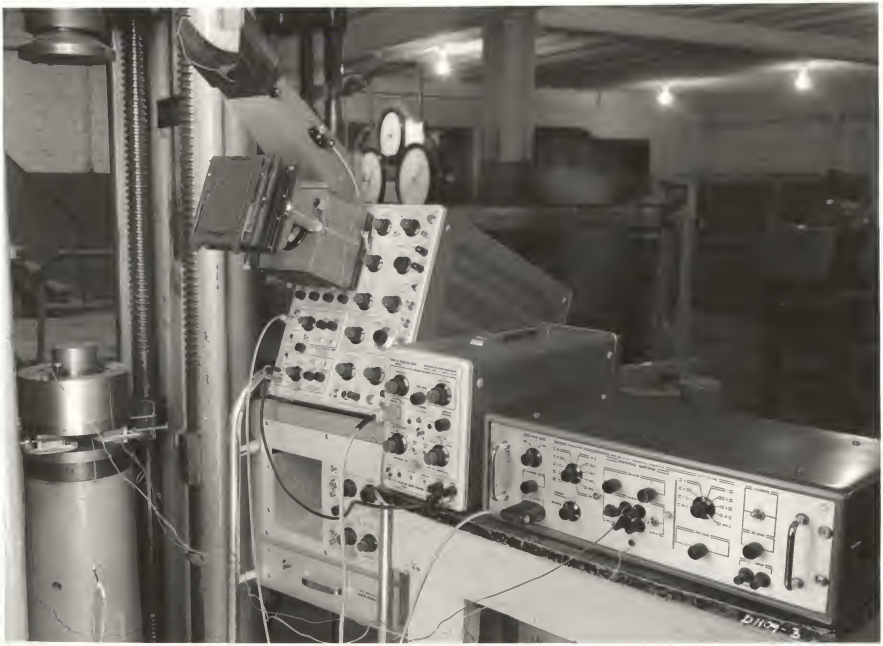


Fig. 2. Testing Apparatus.

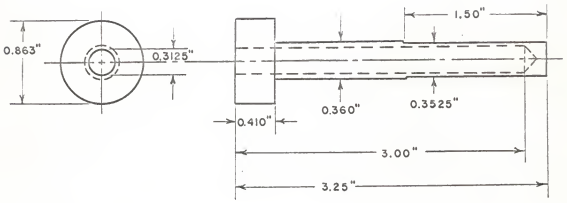
SPECIMEN

The specimen used for the dynamic tests are shown in Fig. 3. It was attempted to use specimen B during the initial phases of the experimentation. This type of specimen is described in greater detail by Chen. Small O-rings were used to provide a preventive seal against leakage at both ends of the specimen. This arrangement proved to be unsatisfactory because the seal was inadequate for the high pressures during these tests.

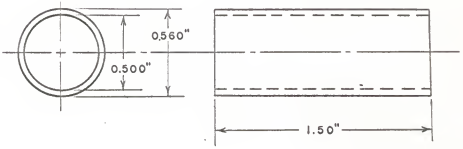
Therefore, a modification in the test fixture was made to accommodate the use of specimen A. This specimen reduced the possible leakage points to two, between the piston and cylinder and around the outside of the specimen at the bottom of the cylinder block. The O-ring provided a sufficient seal between the piston and the cylinder; a forced-fit was made between the specimen and the cylinder block. Thus, this specimen proved satisfactory.

The specimen were machined from bar stock. The hole was drilled first and then reamed to the correct size. The outside surfaces were machined smooth but were not ground.

Concentricity of the hole and the outside of the specimen was an important consideration, which, together with the homogeneity of the material, determined if the specimen would deform uniformly. Because of the design of specimen A, measurements were not taken of the wall thickness to determine the concentricity. Figure 4 shows a specimen with attached strain gages mounted in the test fixture.



Specimen A



Specimen B

Fig. 3 Test Specimen

Fig. 4. Test Specimen with Mounted Strain Gages.

TEST RESULTS

The results of these tests were largely qualitative instead of quantitative. A photograph of the traces on the oscilloscope screen during one test is shown in Fig. 5. This test was made using an unloaded piston velocity of 2.75 in./min.

For this velocity and specimen used, a strain rate of 3.05 in./in./sec. was calculated using Equation 1. However, the strain rate obtained from the test results shown in Fig. 5 was 0.00136 in./in./sec. There are several factors that would account for this difference.

1. Concentricity of hole with outside of specimen.
2. Compressibility of the fluid.
3. Decreasing velocity of the tester under load.

The hole and the outside of the specimen were not concentric. Measurements of the wall thickness were made on the ruptured specimen. The maximum thickness was 0.023" diametrically opposite the point of rupture. This would indicate that the minimum wall thickness was 0.017". Therefore, it was probable that the specimen did not have a uniform circumferential strain. This would affect the strain gage output since the gage is calibrated for a uniform strain over its entire length.

Using a modulus of elasticity for the oil as 230,000 lb/in^2, a total volume of oil as 9.75 in^3, and a maximum pressure change of 5,000 psi, the calculated decrease in volume of the fluid was 0.212 in^3. This would indicate a strain rate of the order of 2.26 in./in./sec.

The tester stalled before the specimen ruptured when driven at an unloaded velocity of 3.56 in./min. This would indicate a decrease in piston velocity when loaded during a test. A decrease in strain rate would result.

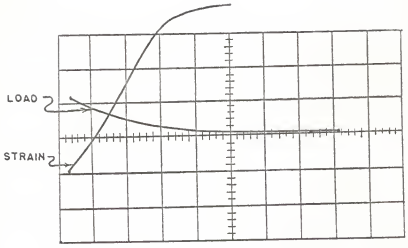
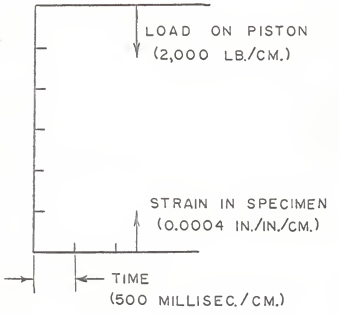


Fig. 5 Test Results

Calibration:



The yield point of the material determined from the test results was 34,500 psi, assuming no eccentricity in the specimen. Using the minimum wall thickness of 0.017 in., the value calculated was 40,600 psi. A yield point of 48,000 psi was the handbook value for a static test. However, no tensile tests were made of the actual material used to determine its yield point.

Internal triggering of the oscilloscope was found to be quite unreliable. External disturbances, such as vibration from the testing machine would trigger the sweep before any straining occurred in the specimen. Manual triggering of the sweep was used in the results shown in Fig. 5.

Previous tests were made to collect information concerning the prevention of fluid leakage and to make the system operational. A specimen which was ruptured during these tests is shown in Fig. 6.

Fig. 6 Ruptured Specimen

DISCUSSION OF RESULTS

The test fixture was constructed, instrumented, and shown to be a workable system. The original design by Chen had to be altered to eliminate some of the problems encountered during this work. The sealing of the fluid in the specimen and test fixture was the cause for most of the revision. The pressure required for these tests was approximately 10,000 psi.

Mercury was used as a fluid for the first attempts. It was found to be very difficult to confine and was replaced by oil. Although the oil was compressible, the leakage problem was solved. However, compensation was needed for the effect of compressibility.

Concentricity of the hole and outside of the specimen was found to be an important consideration. The method of machining the specimens needs to be refined, with emphasis on the lowering of the eccentricity. Also, the surface finish should be smooth. The wall thickness of the specimen should be measured before a test.

The actual piston velocity during a test should be recorded. This could be accomplished by using a differential transformer as a transducer and recording its output on an oscilloscope.

Using the workable system provided by this investigation, it will be possible to obtain quantitative results for various materials at medium strain rates. Those data can be attained by refinement of testing techniques and additional research and testing.

ACKNOWLEDGMENTS

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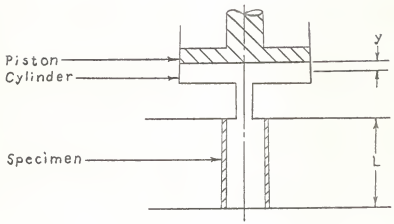
APPENDICES

APPENDIX I

Calculation of Strain Rate



The inside of the cylinder and of the specimen was filled with oil. The lower end of the piston was placed in contact with the oil column. After the piston moved y distance, the change of volume in cylinder and specimen would be:

$$\Delta V_p = \pi r_p^2 y$$

$$\Delta V_s = \pi r^2 L - \pi r_o^2 L = \pi (r^2 - r_o^2) L$$

where ΔV = change of volume

p = piston

s = specimen

r_o = original inside radius of specimen

r = inside radius after deformation

L = length of specimen

$$\Delta V_p = \Delta V_s$$

$$\pi (r^2 - r_o^2)L = \pi r_p^2 y$$

$$(r - r_o)(r + r_o) = \frac{r_p^2}{L} y$$

$$(r_o + \Delta r - r_o)(r_o + \Delta r + r_o) = \frac{r_p^2}{L} y$$

$$2r_o \Delta r = \frac{r_p^2}{L} y - \Delta r^2$$

$$\Delta r = \frac{r_p^2}{2r_o L} y \text{ - infintesimal of higher order}$$

$$\Delta r = \frac{r_p^2}{2r_o L} y$$

$$\frac{\Delta r}{\Delta t} = \frac{r_p^2}{2r_o L} \frac{y}{\Delta t}$$

$$\frac{dr}{dt} = \frac{r_p^2}{2r_o L} V_p$$

where V_p = velocity of piston

ϵ_t = strain in tangential direction = $\dfrac{r - r_o}{r_o}$

$\dot{\epsilon}_t$ = strain rate

$$\dot{\epsilon}_t = \frac{d\epsilon_t}{dt} = \frac{d}{dt}\left(\frac{r - r_o}{r_o}\right) = \frac{d}{dt}\left(\frac{r}{r_o} - 1\right)$$

$$= \frac{1}{r_o}\frac{dr}{dt} = \frac{1}{r_o}\frac{r_p^2}{2r_o L} V_p = \left(\frac{r_p}{r_o}\right)^2 \frac{V_p}{2L}$$

APPENDIX II

Calculation of Circumferential Stress in Cylinder

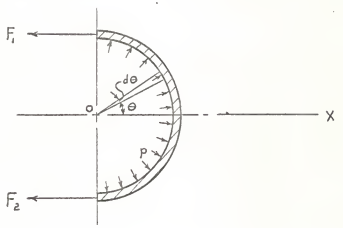


Fig. 7

Figure 7 is a free body diagram of one-half of a specimen cut along the longitudinal axis.

F_1, F_2 - forces on cut

p - fluid pressure

r_o - original radius of specimen

$d\theta$ - infinitesimal angle

σ - circumferential stress in cylinder

A - area acted upon by F_1 and F_2

t - wall thickness of specimen

L - length of specimen

Summing moments about point 0:

$$F_1 r - F_2 r = 0$$

$$\therefore F_1 = F_2$$

Summing forces in X-direction:

The force on an infinitesimal area, $Lr_o d\theta$, of the cylinder caused by the internal pressure acting normal thereto is $pLr_o d\theta$. The component of this force in the X-direction is $(pLr_o d\theta)\cos\theta$.

$$2F_1 - 2\int_0^{\frac{\pi}{2}} pLr_o \cos\theta d\theta = 0$$

$$F_1 = pr_oL$$

Tangential Stress:

$$\sigma = \frac{F_1}{A} = \frac{pr_oL}{tL} = \frac{pr_o}{t}$$

To obtain this stress in terms of the physical quantities measured, it is noted that the pressure is caused by the force of the piston, F_p. The area of the piston is denoted as A_p.

$$p = \frac{F_p}{A_p}$$

$$\text{therefore, } \sigma = \frac{F_p r_o}{A_p t}$$

APPENDIX III

Construction of the Cylinder Block

The cylinder block was constructed of three sections of C1018 steel shrunk together. The diametral interference between cylinders 1 and 2 was 0.0006 in. and 0.0014 between cylinders 2 and 3.

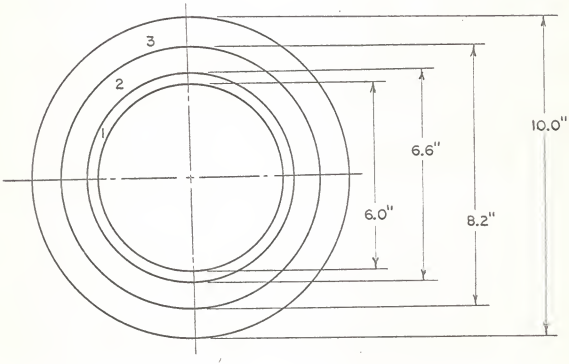


Fig. 8

This shrinking was done because of the inability to obtain a single piece of stock which was large enough to construct the entire block. Also, the interference fits gave "locked-in" stresses in the cylinder block. Using thick wall cylinder theory, the fits were calculated to give the locked-in stresses which increased the factor of safety above that achieved by a single piece when subjected to an internal pressure. For an internal pressure of 10,600 psi., the safety factors based on the yield strength were 1.99 for a single piece and 2.61 with interference fits.

APPENDIX IV

Figure 9 is the top view of the safety device used to contain the fluid upon rupture of the specimen. It is shown clamped to the four spacers of the test fixture.

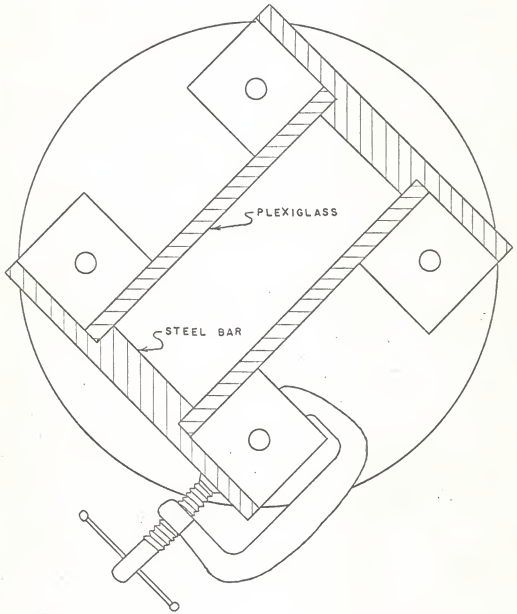


Fig. 9

APPENDIX V

Dynamic Test Techniques

In preparation for a test, the first consideration was mounting the test specimen in the fixture. The base plate and spacers were removed to give access to the specimen. The outer portion of the piston arrangement was positioned and clamped to the bottom of the cylinder. The specimen was then placed in position by forcing it into the hole in the bottom of the cylinder. Two SR-4 strain gages were attached to the specimen using Duco cement. They were then wired in series, and lead wires attached. The base plate and spacers were reassembled, and the plug in the base plate tightened snug against the specimen.

Instrumentation was the next step. The strain gages on both the piston and on the specimen were connected to separate amplifiers. The amplifier outputs were indicated by separate traces on the oscilloscope. Wheatstone bridges in the amplifiers were balanced by adjusting internal resistance and capacitance. The use of shielded leads eliminated much interference from the surroundings.

Calibration of the gages on the piston was achieved by loading the piston in a testing machine and recording the deflection of the oscilloscope trace. The trace deflection could be adjusted to correspond to a given line on the oscilloscope for a given load. The gages on the specimen were calibrated using an internal calibration device. An unbalance could be put into the bridge to correspond to a given strain and the deflection on the oscilloscope recorded.

Oil was then poured into the cylinder with care being taken not to trap air in the specimen. An O-ring was placed on the four-inch piston and inserted into the cylinder block. The piston was forced down until all the air was bled out. After clamping the protective device into position, the fixture was placed in the testing machine. A spacer was put on top of the piston to contact the driving head of the testing machine.

Adjustment of the triggering sensitivity was made until a slight disturbance at a gage on the specimen would trigger the trace. Sweep speed was set at 500 millisec/cm for the test shown. The camera aperature setting used was 4.0; Polaroid film, type 55 P/N was placed in the camera and the shutter opened. A zero reference trace was triggered.

The piston was then loaded by the Screw-type Testing Machine until the specimen failed. The Polaroid film was then developed, yielding the results of a completed test.

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Manhattan, Kansas

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A knowledge of material properties at medium rates of straining is needed in order to achieve a good design where high impulsive type loads are encountered. Missile structure and explosive forming are examples of the application of this kind of loading.

Several investigations concerning the influence of strain rate on material properties have been made during the past decade. Most of these studies were made using tensile test specimen. The strain rates were not constant because of the phenomenon of the propagation of plastic strain, which causes the strain rate to vary from point to point along a tensile specimen and a given point also to be dependent upon time.

This report is concerned with a method of testing which has been developed to study the influence of a pure strain rate on material properties. A uniform medium strain rate was obtained by loading a hollow thin-wall cylindrical specimen by internal fluid pressure.

A description of the testing device and instrumentation used is given. The experimental procedure and some sample results using C1020 steel specimen are also shown.