

# New Approach to the Autofrettage of High-strength Cylinders

An oversize mandrel is forced through a 4340 steel tube to plastically deform the walls and, thereby, produce favorable residual stress patterns

by T. E. Davidson, C. S. Barton, A. N. Reiner and D. P. Kendall

**ABSTRACT**—The usual method of autofrettage (cold working) for gun tubes utilizes hydraulic pressure applied directly to the bore in order to plastically deform the wall of the tube so that favorable residual-stress patterns are produced. The strength of the tube is effectively increased, providing many associated benefits; however, ultra-high hydraulic pressures are required for high-strength steels since plastic-flow pressure is directly proportional to the yield strength of the material.

A new method for the autofrettage of high-strength steel cylinders requiring greatly reduced pressures is developed and described herein. An oversize mandrel is forced through the tube to plastically deform the walls. Three methods of forcing the mandrel are investigated. Mechanical-push swaging is used in the autofrettage of short 5-in. long specimens with pull swaging and hydraulic-push swaging being used on specimens 40 in. long.

All specimens are made from 4340 steel heat treated to various strengths. Cylinders with wall ratios ranging from 1.5 to 2.8, yield strengths ranging from 90,000 to 180,000 psi, and percent enlargements at the bore ranging from 1.0 to 5.0 are utilized.

An engineering analysis is made investigating such factors as percent enlargement and elastic recovery at the bore, the ratio of pressure required for pushing the mandrel to the yield strength of the material, the effects of various lubricants on the frictional forces involved, and the induced three-dimensional stresses in the cylinder walls.

Sach's boring-out technique is used to evaluate induced residual-stress patterns. Strains are recorded with electric-resistance strain gages and the associated dynamic and static instrumentation is described. Results are presented in graph form.

## List of Symbols

- $E.R.$  = elastic recovery
- $FD_b$  = final diameter of the bore after compression
- $ID_b$  = initial diameter of the bore before compression
- $ID_m$  = initial diameter of the mandrel before compression
- $FD_m$  = final diameter of the mandrel during compression
- $P$  = internal hydrostatic pressure, psi
- $W$  = wall ratio (ratio of outside to inside diameters)
- $E$  = Young's modulus of elasticity
- $\Delta$  = change in diameter
- $\sigma_{ys}$  = yield strength, psi

- $\tau$  = shear stress
- $\epsilon_y$  = strain at yield on the outer surface
- $\epsilon_b$  = tangential elastic strain at the bore
- $\epsilon_m$  = tangential elastic strain at mandrel surface
- $\mu$  = Poisson's ratio

## Introduction

### The Autofrettage Process

Autofrettage is a process for inducing elasticity in a gun tube at pressures which otherwise cause plastic strains. The conventional process is one of subjecting a monobloc tube to internal pressure of sufficient magnitude to permanently enlarge the bore a predetermined amount. As the internal pressure is released, the outer portion of the tube attempts to resume its original dimension, however, the material near the bore resists this movement. Consequently, tangential compressive stresses are induced in the material near the bore and tangential tensile stresses remain in the outer material.

The strength of the tube is thus effectively increased and may be utilized as follows, (1) a non-autofrettaged monobloc tube may safely have the wall ratio  $W$  reduced for a given maximum internal pressure, or (2) without changing the wall ratio the internal pressure may be safely increased.

The autofrettage principle can be applied to steel cylinders of very high yield strengths. For these materials, the small increase in strength caused by strain hardening associated with plastic deformation is negligible compared to the increased strength resulting from the residual stresses induced by the autofrettage process.

The conventional hydraulic method utilizes a press to restrain pressure-retaining packings, and also external restraining containers whose internal diameter is used to control the amount of radial plastic deformation. In view of many problems encountered utilizing the conventional hydraulic method of autofrettage of high-strength cylinders, an alternate method has been developed. Experiments on this new method, known as the swaging method, are presented and described.

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to the back surface of the mandrel. Figure 2B presents a typical hydraulic swaging assembly. The specimen was counterbored to a diameter slightly smaller than the mandrel and deep enough to admit the mandrel and the end packing through which the fluid was passed. The mandrel was pressed into the position shown to obtain an initial seal; thereafter, contact with the cylinder walls provided a continuous forward seal. Pressure was recorded by means of a Manganin wire pressure cell and a Foxboro Dynalog recorder.

#### Mechanical-push Swaging

A hydraulic press was used to mechanically force the mandrel through the cylinders while a simple fixture supported the specimen and guided the ram and mandrel. The mandrel moved at constant velocity since the required force was, in general, much less than the 75-ton capacity of the press.

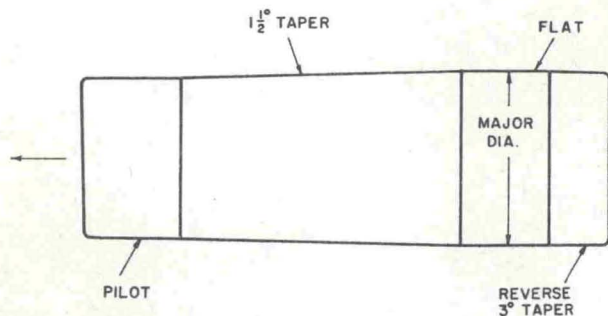


Fig. 1—Typical swaging mandrel

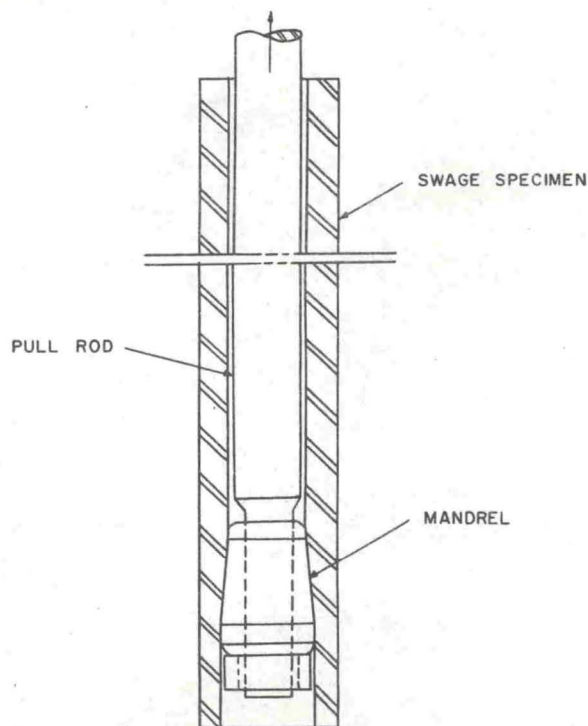


Fig. 2A—Mechanical-pull swaging assembly

SR-4 strain gages, Types AX-5 and A-7, were placed on some specimens at the mid-length section on the exterior surface to record the tangential strains during the swaging process. In this way the maximum strains which occurred, the residual strains, and the effects of the cylinder ends on the strain at the mid-length section were recorded. Brush and Edin continuous strain recorders were utilized for these measurements.

Radial elastic recovery and permanent enlargement at the bore were determined by measuring the bore diameter before and after test using a dial bore indicator. The change in average surface finish was evaluated with a Profilometer using rms values.

To provide data for evaluating the longitudinal, tangential and radial residual stresses in the cylinder walls, SR-4 Type A-5 and/or A-7 strain gages were placed diametrically opposite and oriented in the longitudinal and transverse directions at the mid-length section. These data were obtained by successively removing material from the bore and noting the accompanying change in strain.

A special jig was designed to facilitate the machining of the specimens. This fixture permitted the specimen to be removed from the lathe and jig during the period required for the specimen temperature to return to its initial value. In this way, the jig was used continuously in the machining of other cylinders. Certain specimens were strain gaged very completely to evaluate the effects of the ends on the residual strains. A cylinder with strain gages is shown in the jig in Fig. 3.

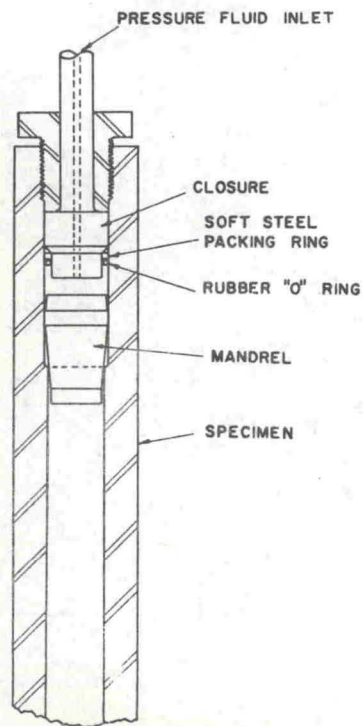


Fig. 2B—Hydraulic-push swaging assembly

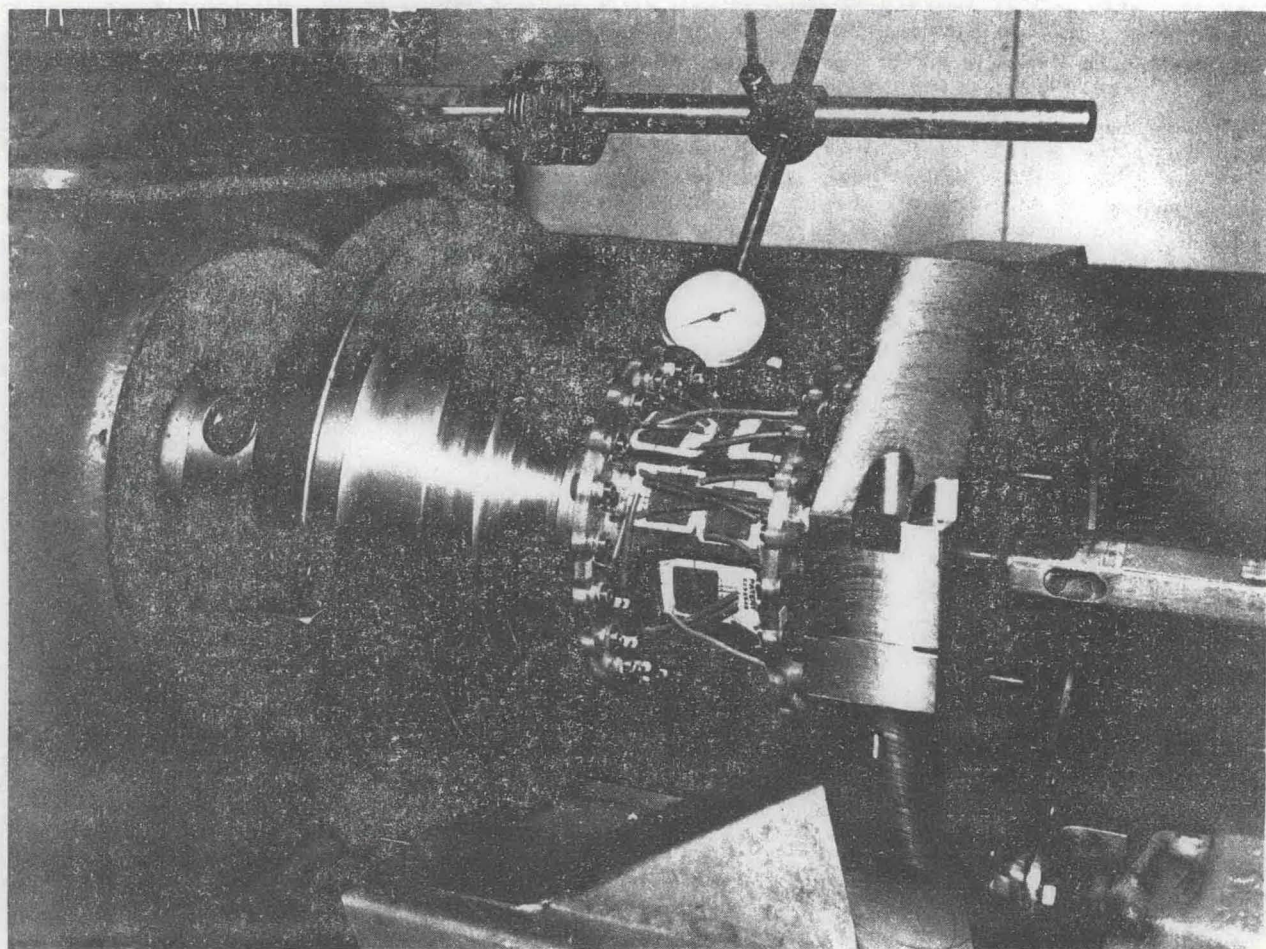


Fig. 3—Residual-stress evaluation fixture and specimen

## Results and Discussion

### *Lubrication and Surface Finish*

The greatest amount of plastic flow during the swaging process occurred in the bore of the tube where the radial pressure and the longitudinal forces were applied by the mandrel. Photomicrographs on transverse sections at 100 and 500 times enlargement were made comparing swaged and non-swaged cylinders. No evidence of structural change or damage was found.

The basic mandrel configuration was found to be, in general, satisfactory for all percent enlargements at the bore and for all yield-strength values. Slight changes were made from time to time to alleviate minor difficulties encountered. The velocity of the mandrel was constant at approximately 17 21 ipm which was established by the particular press used.

The need of dimensional control before swaging in order to measure accurately percent enlargement and elastic recovery at the bore required good initial bore finishes. These initial ground finishes averaged 27.6 rms micrometers for all tested specimens before swaging, and 13.2 after swaging. This yielded an average finish improvement in the bore of 52%.

The data showed that rougher initial bore surfaces resulted in correspondingly larger improvement in surface finish than did the relatively smoother initial bore surfaces. In general, the finish before swaging was too smooth to permit the maximum improvement in finish to be realized. This was unavoidable due to the dimensional-control requirements. The data revealed no correlation of finish with percent bore enlargement and wall ratio for any mandrel and yield strength.

A study of suitable lubricants was carried only far enough to make possible the use of existing facilities to mechanically push the mandrel through the shorter cylinders. A molybdenum disulfide suspension in oil and copper plating were tried as lubricants, first separately and, then, in combination. The best lubrication as determined from the least force required to swage was obtained from using the two in combination. However, the basic lubricant was apparently supplied by the copper in the form of a film of relatively soft material between the two sliding surfaces.

### *Force Requirements*

In order to describe the force requirements of the

swaging method of autofrettage, a conversion was made to an equivalent hydraulic pressure in psi acting on the rear face of the mandrel. A typical comparison of pressure-yield strength relations for the swaging and the conventional methods is graphically shown in Fig. 4 for a 2.8 wall-ratio cylinder with 2.5% bore enlargement. Some nonlinearity is indicated for the swaging method, whereas the conventional method shows linearity. The pressure required in the conventional process for complete yielding was computed from the empirical relation

$$P = 1.08 \sigma_{ys} \log W \quad (1)$$

It is also seen that the magnitude of the pressures required for swaging is much less than the conventional method for any given yield strength. For low yield strengths, the swaging force is almost constant. At higher yield strengths, the required pressure increases but remains much less than that for the conventional method.

Figure 5 shows a plot of hydraulic pressure as a function of wall ratio and compares the two methods for one typical yield-strength value. It is important to note that swaging and the conventional process pressures are dependent on percent bore enlargement for any given wall ratio. For comparison purposes, however, only that curve for the condition of complete yield through the wall for the conventional process is shown. This curve is given by eq (1). Again, the low-pressure advantage for the swage method is clearly indicated.

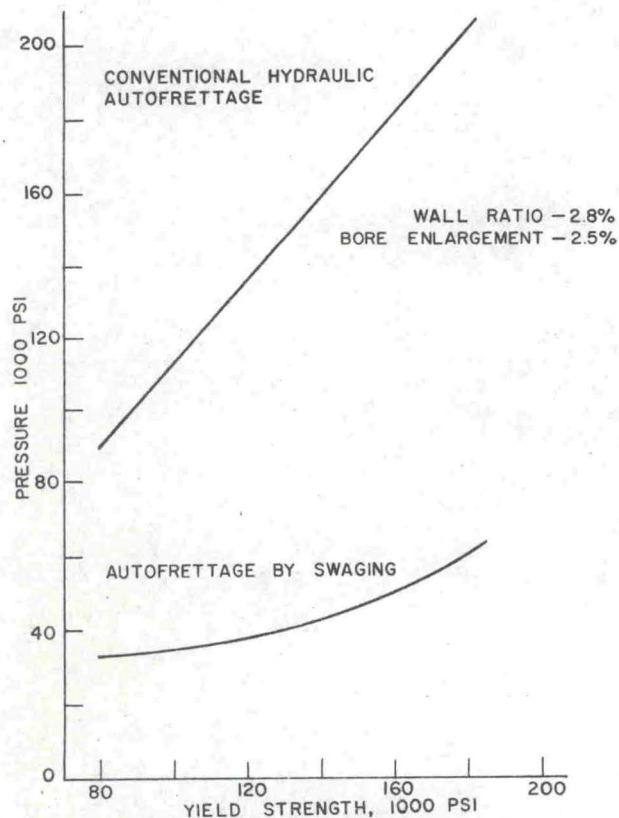


Fig. 4—Hydraulic pressure vs. yield strength

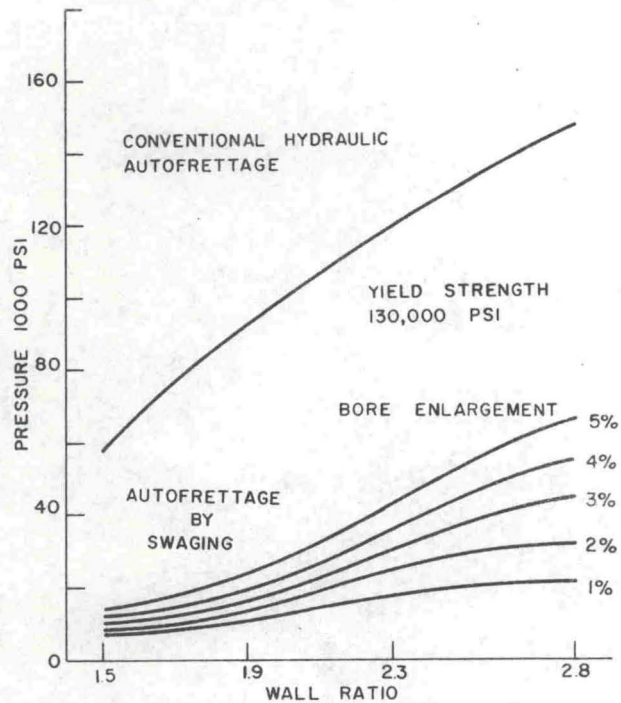


Fig. 5—Hydraulic pressure vs. wall ratio

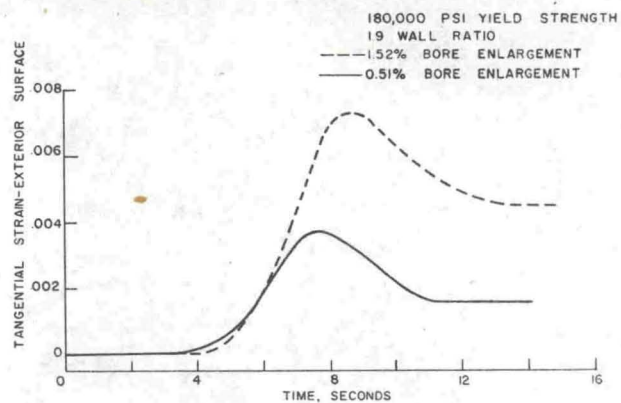


Fig. 6—Exterior surface strain during swaging

#### Elastic Recovery

Typical plots of tangential exterior-surface strains as a function of time at the mid-length section of the short specimens are shown in Fig. 6. Zero time on the graph corresponds to the entry of the mandrel into the bore. It is seen that the effects of the ends of the cylinders on the strain at the mid-point is negligible since the curves are horizontal at the beginning and end. This validated the assumption that the specimens were long enough to eliminate end effects on the induced residual stresses at mid-length section. This assumption was validated by this method for wall ratios of 1.5, 1.9 and 2.3 for bore enlargements ranging from 0.3 to 5.6% and for all yield strengths.

Figure 6 visibly demonstrates typical elastic recovery and residual strain which occur as the mandrel passes through the bore. The peak strain

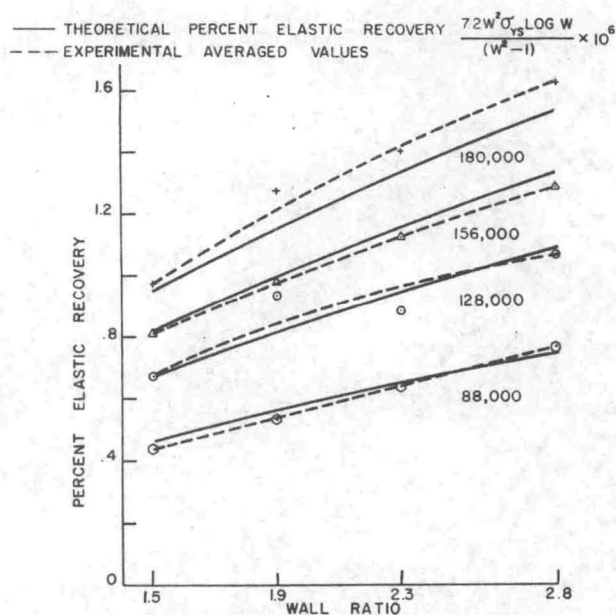


Fig. 7—Percent elastic recovery at the bore vs. wall ratio

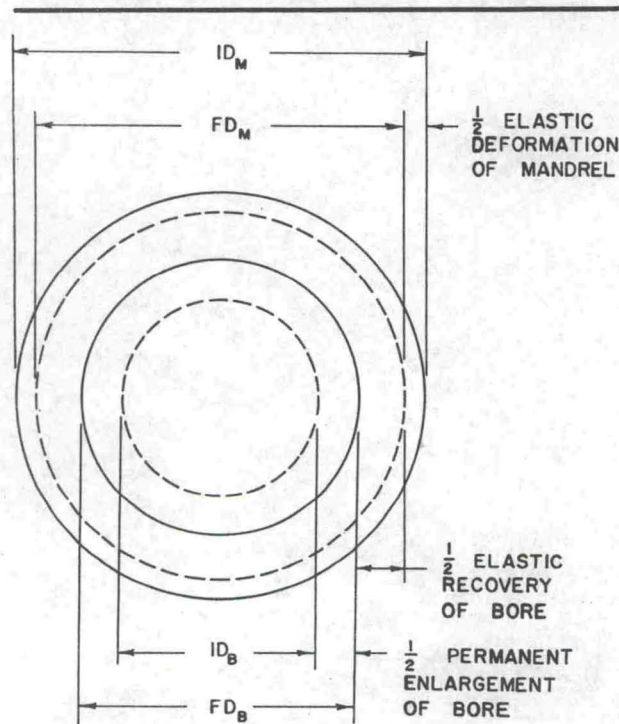


Fig. 8—Schematic diagram of bore and mandrel surface deformations

less the residual strain is the elastic recovery at the exterior surface. It may also be determined if the cylinder walls have been completely yielded by comparing the peak strain with that calculated from Hooke's law. An example of over yielding and under yielding is indicated in this figure by the 1.52 and 0.51% bore enlargements respectively.

Elastic recovery is defined in percent as:

$$\% \text{ E.R.} = \frac{(ID_m - FD_b)}{ID_b} \times 100 \quad (2A)$$

Elastic recovery at the bore plotted as a function of wall ratio is shown in Fig. 7 where each experimental point is the average value for all cylinders at a given wall ratio and yield strength regardless of percent enlargement. The data indicated a slight trend for an increase in elastic recovery with an increase in percent enlargement for a given yield strength and wall ratio; however, the spread at any point was less than  $\pm 0.1\%$ . This substantiated the same observation made with the outside-surface measurements. The variation of elastic recovery with percent enlargement appeared to be random with no determinable correlation from one wall ratio to another. The  $\pm 0.1\%$  spread in elastic recovery seemed to have no practical significance for the bore diameters of these tests since machining inaccuracies produced greater variations in the final bore dimensions than did the elastic-recovery variation.

Elastic recovery was also observed to vary along the cylinder length, being larger at the mid-length than at the ends. The lower values at the ends are attributed to an observed longitudinal displacement of metal out of the bore as the mandrel passed. However, the center 2 in. of the 5-in. cylinder possessed a constant value of elastic recovery where the least longitudinal flow was expected. This physical phenomenon again revealed no end effects at the mid-length position.

The elastic recovery as defined in eqs (2) is composed of two factors: (a) the elastic compression of the mandrel due to radial pressure exerted by the specimen, and (b) the elastic recovery of the specimen after the mandrel has passed. The magnitude of these two factors may be computed from the Lamé equations for thick-walled cylinders with the following assumptions:

(1) The pressure existing between the mandrel and the specimen is equal to the internal hydrostatic pressure required to completely yield the specimen. This pressure is given in the form of eq (1). The value of  $K$  depends on the theory of plasticity which is used. Tresca's maximum shear criterion gives a value of  $K = 1$ , and the Von Mises criterion gives a value of  $K = 1.15$ . Extensive experimental work in hydrostatic autofrettage of miniature cylinders shows a value of  $K = 1.08$  for the type of steel used in these tests.

(2) The mandrel may be considered as a solid circular cylinder under radial hydrostatic pressure only. The effect of longitudinal loading on the mandrel may be neglected.

(3) Both mandrel and cylinder are steel with a Poisson's ratio ( $\mu$ ) of 0.3 and an elastic modulus ( $E$ ) of  $30 \times 10^6$  psi.

Figure 8 illustrates a superposition of the elastic and plastic deformations of the mandrel and cylinder during the swaging operation. This relates and clarifies eqs (2) and (3).

By definition (Fig. 8),

$$\% \text{ elastic recovery (E.R.)} = \frac{\Delta D_m + \Delta D_b}{ID_b} \times 100 \quad (2B)$$

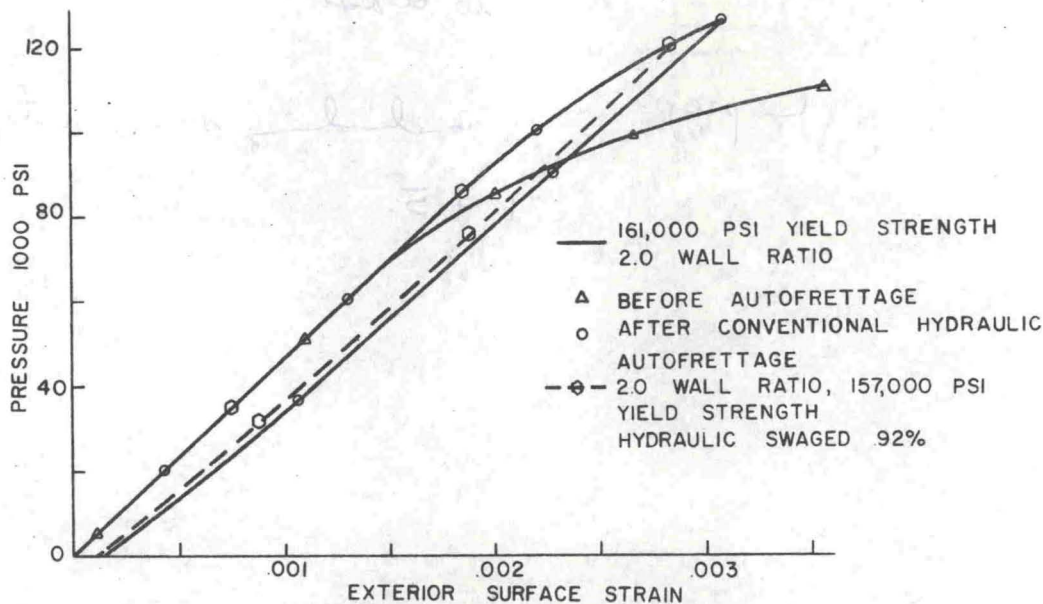


Fig. 9—Pressure-strain response for hydraulic-push-swaged specimen

or

$$\% \text{ E.R.} = \frac{\epsilon_m (ID)_m + \epsilon_b (FD)_b}{(ID)_b} \times 100 \quad (3)$$

where:

- $\Delta$  = change in diameter
- $\epsilon_b$  = tangential elastic strain at the bore
- $\epsilon_m$  = tangential elastic strain at mandrel surface

For small deformations, eq (3) becomes

$$\% \text{ E.R.} = (\epsilon_m + \epsilon_b) \times 100 \quad (4)$$

From Lamé's equations,

$$\epsilon_b = \frac{P[(1 - \mu) + (1 + \mu)W^2]}{E(W^2 - 1)} \quad (5)$$

and

$$\epsilon_m = \frac{P(1 - \mu)}{E} \quad (6)$$

Putting eqs (5) and (6) into (4) yields:

$$\% \text{ E.R.} = \frac{P}{E} \left[ \frac{200 W^2}{W^2 - 1} \right] \quad (7)$$

and finally by using

$$\begin{aligned} P &= 1.08 \sigma_{ys} \log W \\ E &= 30 \times 10^6 \text{ psi} \end{aligned}$$

eq (7) becomes:

$$\% \text{ E.R.} = \frac{7.2 W^2 \sigma_{ys} \log W}{(W^2 - 1)} \times 10^{-6} \quad (8)$$

Equation (8) is shown as solid lines and compared with experimental results in Fig. 7. The good agreement indicated permits eq (8) to be utilized for design purposes if the deformation of the cylinder is sufficient to produce yielding throughout the wall.

#### Mechanical-pull and Hydraulic-push Swaging

The utilization of the pull swaging and hydraulic-push swaging methods made it possible to study (1) the effectiveness of the lubricants under sustained high pressure and friction forces, (2) the ability of

the mandrel to withstand these conditions over a longer period of time, (3) the general over-all effectiveness of the induced residual stresses in a long cylinder, and (4) the mechanical problems associated with these two methods. For these tests, four 40-in. specimens were swaged by pull swaging and two 40-in. specimens by hydraulic pushing. Each specimen was later cut into three equal lengths for the hydrostatic-yield comparison tests.

The pull-swaging-force records indicated force fluctuations varying in intensity according to the velocity of loading and the cylinder-wall ratio. These fluctuations were attributed to the elastic nature of the loading equipment and its inability to maintain a constant force. Reducing the wall ratio and increasing the velocity reduced the force required to overcome static friction and minimized the magnitude of the fluctuations.

In the specimen lengths tested, no apparent damage was done to the mandrel or the bore surfaces which, along with the small force magnitudes required, verified the practicality of the lubricants and the mandrel design.

The hydraulic-push method utilized hydraulic pressure applied directly to the back face of the mandrel in order to push it as shown in Fig. 2. The mandrel contact with the cylinder walls provided a very good forward movable seal with the initial seal being obtained from pressing the mandrel into position. The required pressure for this method was obtained from a 200,000 psi high-pressure system used for conventional autofrettage. Considerable fluctuations in pressure revealed the inadequacy of the system to compress the liquid in sufficient volume to maintain a constant force against the mandrel. This condition, together with the higher force requirement needed to overcome static friction as compared with moving friction, resulted in nonuniform motion