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
Δ = change in diameter
σ_{ys} = yield strength, psi
τ = shear stress
ϵ_y = strain at yield on the outer surface
ϵ_b = tangential elastic strain at the bore
ϵ_m = tangential elastic strain at mandrel surface
μ = Poisson's ratio

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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.

Autofrettage by Swaging

The swaging method of autofrettage basically consists of passing an oversize swaging tool (mandrel) through the bore of the cylinder. The mechanical advantage gained from the sliding cone is used to expand the cylinders until yield conditions are obtained throughout the walls.

Three different methods of forcing the mandrel were studied, (1) the mandrel was mechanically pushed by means of a ram and hydraulic press, (2) an overhead crane pulled the mandrel and (3) the mandrel was pushed by applying hydraulic pressure directly to the end of the mandrel.

The majority of this paper is concerned with experiments utilizing the mechanical-push method on specimens approximately 5 in. long. Longer specimens were tested in order, (1) to examine the feasibility of swaging by mechanically pulling the mandrel and by pushing the mandrel using direct fluid contact, (2) to determine the effects of longer contact distances and (3) to provide specimens of sufficient length for hydrostatic yield tests.

Four basic wall ratios: 1.5, 1.9, 2.3 and 2.8, and four nominal yield strengths: 90,000, 130,000, 150,000 and 180,000 psi were tested and evaluated. Nominal predicted increments of bore enlargement were: 1.0, 2.5, 3.7 and 5.0%

Copper plate and molybdenum disulfide were used as lubricants to prevent seizure and scoring between the mandrel and bore surfaces which were in contact under very high pressure and friction conditions. Instrumentation included the use of dial bore gages, rms surface-finish indicators, SR-4 electric-resistance gages, Baldwin strain indicators and Brush and Edin dynamic strain recorders. Radial, tangential and longitudinal stresses were evaluated using Sach's boring-out technique. Percent enlargement and elastic recovery at the bore, surface finish changes, and the ratio of pressure required to push the mandrel to the yield strength of the material were also evaluated.

Description of Tests and Test Apparatus

Swage Specimens

All specimens were prepared from the same heat of Type 4340 steel forgings $4^1/_4$ in. in diameter and 80 in. long. The chemical analysis showed the following content:

Carbon	0.37	Nickel	2.39
Manganese	0.72	Chromium	0.98
Silicon	0.28	Molybdenum	0.38
Sulfur	0.035	Phosphorous	0.016

Specimen lengths cut from the forgings were drilled to $1^1/_4$ in. internal diameter before heat treatment. One specimen from each heat-treated lot was used to determine the mechanical properties of the material.

The before-swaging bore dimensions of the 5-in. mechanical-push specimens were obtained by machining and grinding. Outside and inside diameters were varied to obtain the desired permanent bore enlargements for the various wall ratios. Tests on the short specimens included all four basic yield strengths of 90,000, 130,000, 150,000 and 180,000 psi.

The 40-in. pull-swaging specimens were heat treated to 127,000 psi yield strength and machined to obtain a nominal 2.5% bore enlargement. The wall ratios were kept the same as the 5-in. specimens. The 40-in. direct-hydraulic-push specimens were heat treated to a nominal 160,000 psi yield strength, machined to a 2.0 wall ratio, and threaded at one end to receive a special high-pressure seal fitting.

Swage Mandrels

Several mandrel designs varying from spherical to cylindrical were considered. Such factors as friction, localized enlargement of the specimen bore, lubrication and tool alignment were considered in arriving at the final configuration. Figure 1 illustrates a typical design.

Several combinations of materials and surface treatments, along with minor changes in the length of flat surface and in the rear taper, were investigated. An angle of approach of 1.5 deg was maintained for all mandrels and a ground and polished mandrel surface finish of 2–15 microinches was provided to reduce friction. Other nominal dimensions consisted of $1^1/_2$ in. major diameter, $^3/_4$ in. flat width, and a rear taper of 3 deg to facilitate elastic recovery.

Mechanical-pull Swaging

The mandrel used in pull swaging was made in the form of a cylinder and attached to a long pull rod by shrinking. Figure 2A shows an assembly of the pull rod, attached mandrel and 40-in. long specimen. An overhead crane provided the power source.

The holding fixture for the specimen was composed of a steel cylinder of 10 in. outside diameter and 1-in. wall thickness. The ends were capped and possessed holes just large enough for the mandrel and pull rod to pass through. External cones at the ends centered the specimen and buckling was prevented by set screws at two points along the length of the specimen. This fixture was mounted on the bottom of the yoke of a 10-million pound press with the pull bar extending upward through a hole in the yoke.

To measure the force in the pull bar, SR-4 Type A-1 strain gages were attached to the pull rod diametrically opposed at the quarter points to form one arm of a Wheatstone bridge. In this manner, induced bending strains were eliminated and only axial strains were recorded. Calibration of this circuit directly into tons was accomplished using a tensile-testing machine. Continuous recording was made possible with a Baldwin dial strain recorder.

Hydraulic-push Swaging

Several longer specimens were swaged with hydraulic (glycerine and water) pressure applied directly 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.

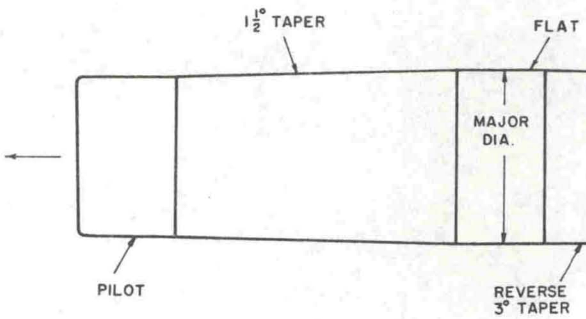

Fig. 1—Typical swaging mandrel

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.

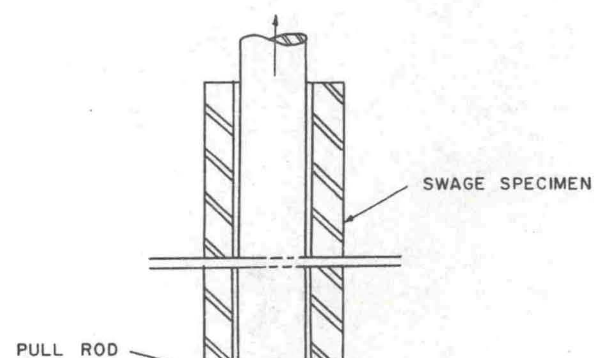

Fig. 2A—Mechanical-pull swaging assembly

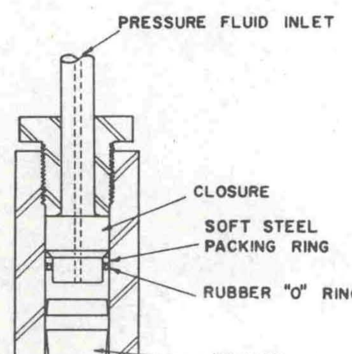

Fig. 2B—Hydraulic-push swaging assembly

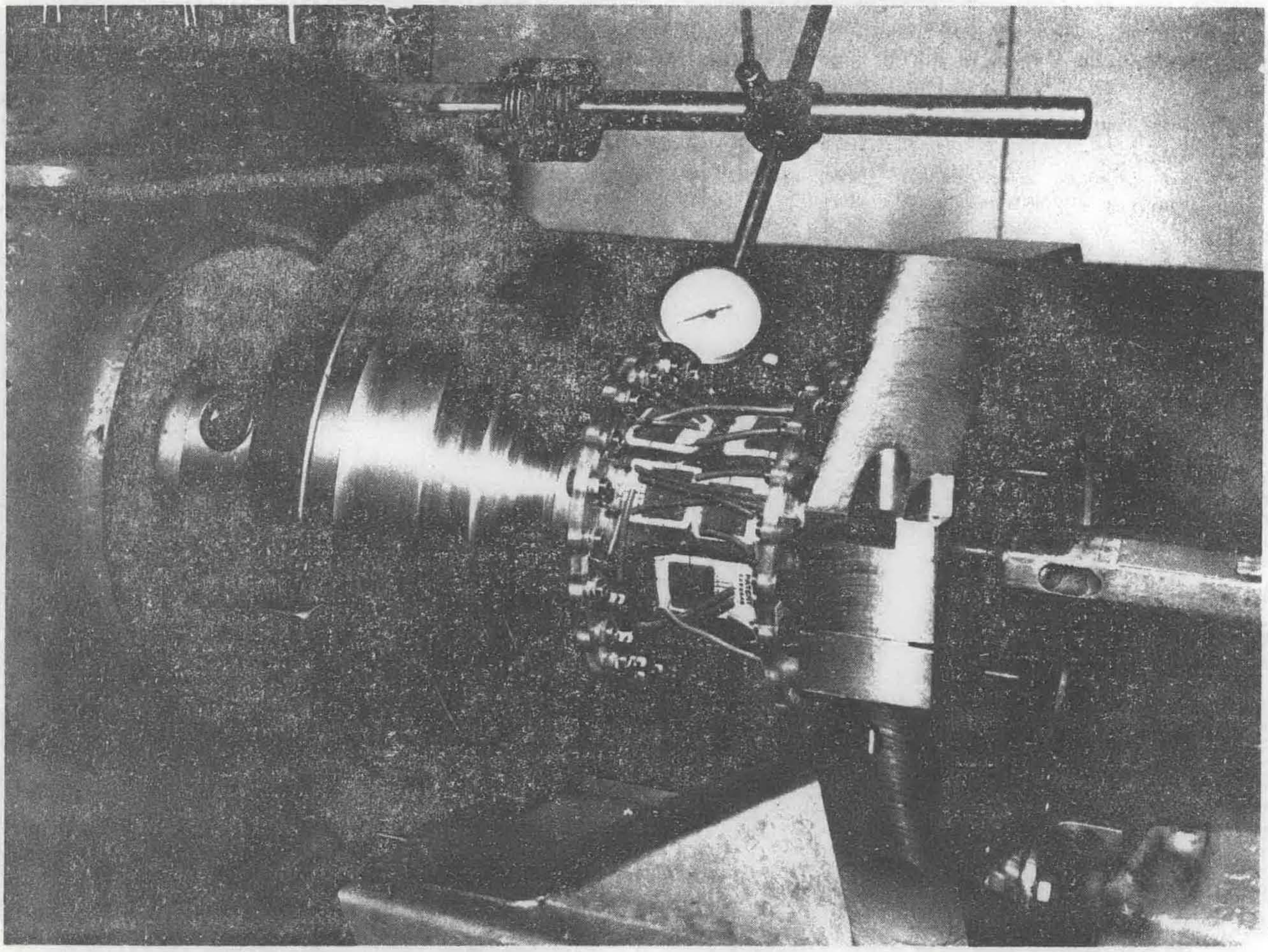

Fig. 3—Residual-stress evaluation fixture and specimen

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 microinches 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

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

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.

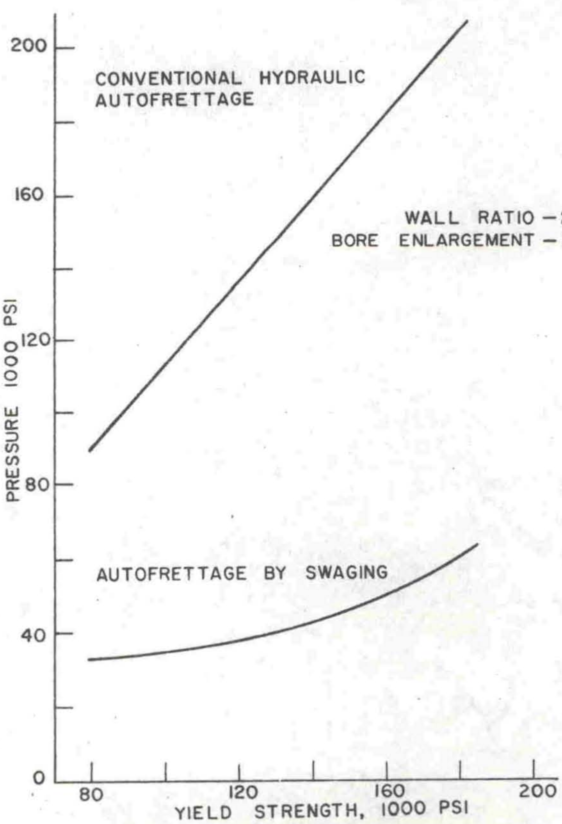

Fig. 4—Hydraulic pressure vs. yield strength

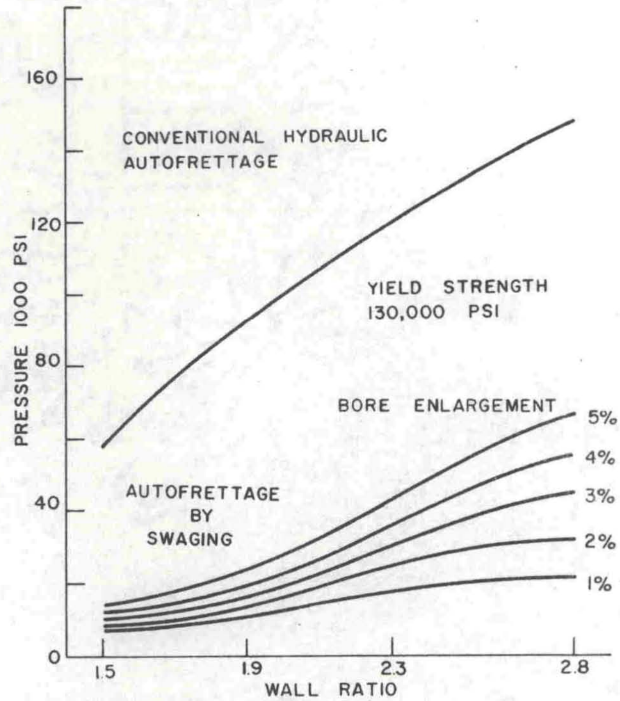

Fig. 5—Hydraulic pressure vs. wall ratio

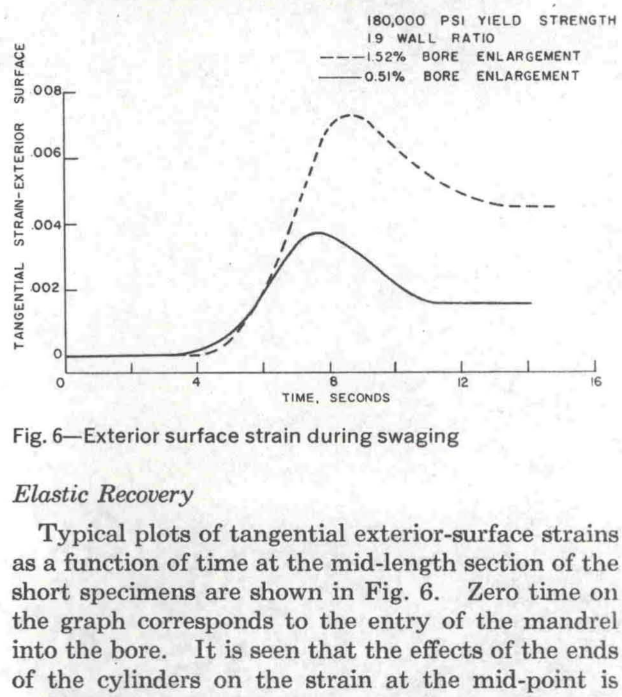

Fig. 6—Exterior surface strain during swaging

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

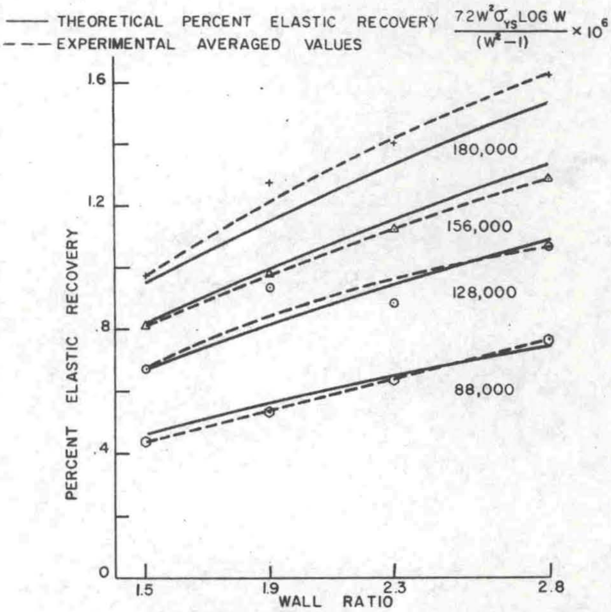

Fig. 7—Percent elastic recovery at the bore vs. wall ratio

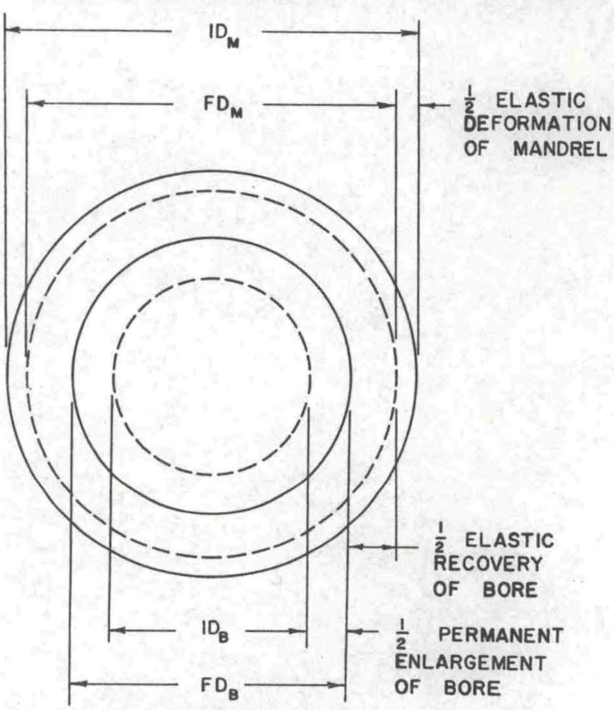

Fig. 8—Schematic diagram of bore and mandrel surface deformations

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 Hookes' 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:

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

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 ±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 ±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 (μ) of 0.3 and an elastic modulus (E) of 30×10^6 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),

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

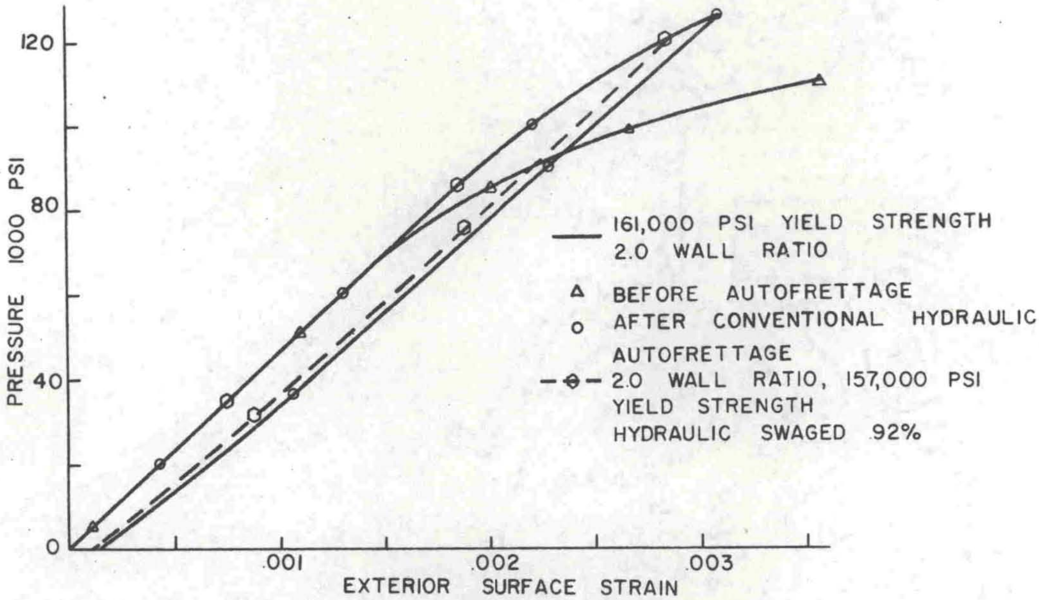

Fig. 9—Pressure-strain response for hydraulic-push-swaged specimen

or

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

where:

Δ = change in diameter
ϵ_b = tangential elastic strain at the bore
ϵ_m = tangential elastic strain at mandrel surface

For small deformations, eq (3) becomes

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

From Lamé's equations,

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

and

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

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

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

and finally by using

$$P = 1.08\,\sigma_{ys} \log W$$
$$E = 30 \times 10^6 \text{ psi}$$

eq (7) becomes:

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

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

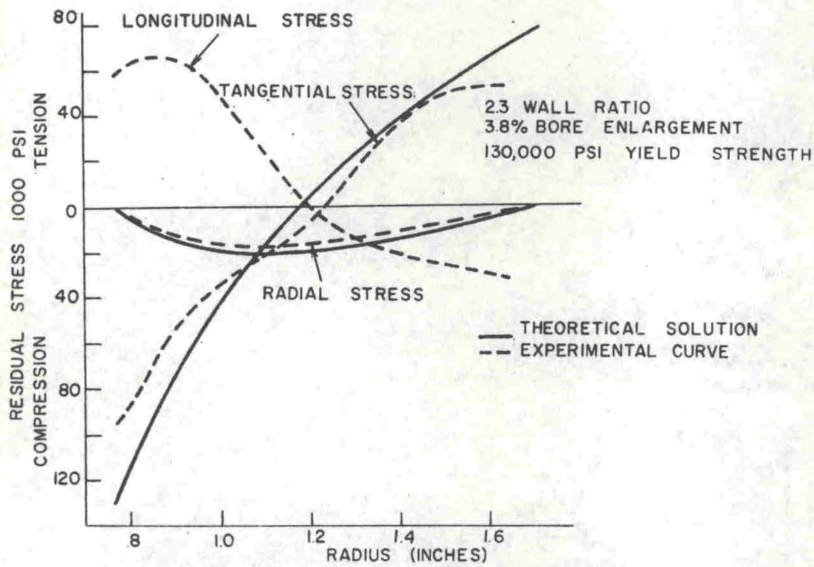

Fig. 10—Residual stresses in mechanical-push-swaged specimen

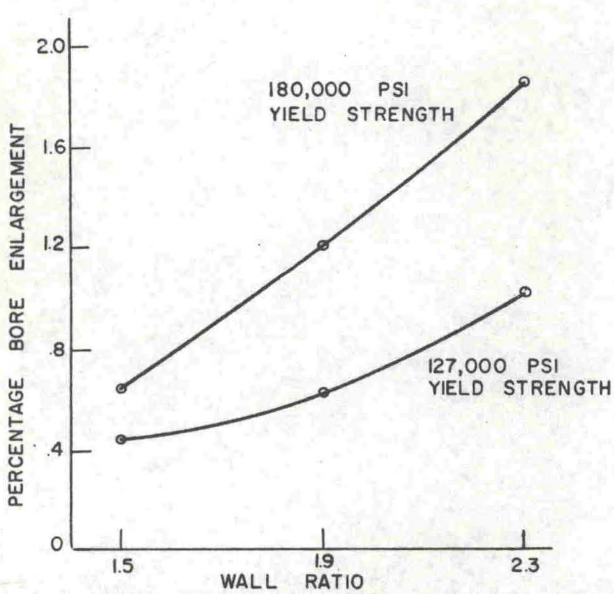

Fig. 11—Percent bore enlargement to yield exterior surface. Empirical data

of the mandrel through the specimen. However, an examination of the bore surfaces revealed no damage.

An immediate evaluation of the effectiveness of the residual stresses induced by both pull and hydraulic-push methods was provided by subjecting test cylinders to hydrostatic pressure until yielding resulted. A comparison is made in Fig. 9 of the internal pressure versus exterior surface strain for a typical hydraulic push-swaged specimen, a nonswaged specimen, and a specimen of conventional autofrettage. It is seen that the hydraulic-push swage method produces an autofrettaged condition which was as effective in increasing yield pressure as the conventional hydrostatic method. The results shown in Fig. 9 are also typical for the pull-swaging method.

Residual Stresses

The induced three-dimensional residual stresses were evaluated and compared at five transverse sections. The Sach's boring-out method was used. Figure 3 shows a specimen mounted in a special jig designed to facilitate this evaluation. Two SR-4 strain gages were oppositely placed on diameters at mid-length, $\pm 1/2$ in., and ± 1 in. from mid-length. Uniform results from these locations indicated that the center inch of length was free from end effects, which verified the previous dynamic records.

Experimental curves of the stress distribution through the cylinder wall at the mid-length section are shown in Fig. 10 for tangential, radial and longitudinal stresses. A summary of the data indicated that the experimental distribution which most nearly coincided with the theoretical distribution is that associated with yield just to the outer surface. Yielding less than or greater than this changed the residual-stress distribution significantly. The theoretical curves compared with the experimental in Fig. 10 are based on the autofrettage of a monobloc open-end tube using conventional internal hydraulic pressure. Good agreement is shown.

Figure 11 summarizes the experimental data for the 120,000 and 180,000 psi yield-strength materials, and expresses percent bore enlargement as a function of wall ratio to just yield the outer surface.

Acknowledgments

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