Instrumentation. 1 **Pressure Control and Recording.** In the 80,000 pounds per square inch system, pressure measurement is by means of Manganin wire-type pressure transducers. Two such transducers are used. One serves as input to the "Rotax" control unit which regulates the automatic cycling of the pressure system through a self-balancing "servo" system equipped with electrical contacts and recording pen. The setting of control contacts relative to the desired indicated pressure determines the point of opening and closing of the dump valve as well as stopping the main intensifier at the end of each pressure peak. The second transducer is used to monitor and record the total pressure cycle on an oscillographic recorder.

The second basic type of pressure transducer, known as a bulk modulus cell, is used in the 150,000 pounds per square inch system. It is a mechanical device designed to sense the linear motion produced by a cylinder with one end closed and exposed to the pressure being measured. This particular system uses a low pressure air transmitter and receiver unit to remotely record and control peak and minimum specimen pressure.

The error in the measurement and recording of pressure is estimated to be approximately one percent in the calibration of the pressure transducer and two percent in the recording system due to the cyclic conditions.

2 **Strain Measurement and Recording.** To insure that each specimen is at the anticipated test pressure, two strain gauges are mounted diametrically opposite each other at the mid-length of each specimen. The output of one gauge on each specimen is monitored on an oscillographic recorder. In normal operation the instruments are set to record the full elastic strain cycle.

Theory

Fatigue failure can be divided into two phases. The first phase consists of the microscopic initiation of the crack. The second stage consists of the propagation of the fatigue crack to the point where the specimen or component can no longer support the applied cyclic load and failure occurs. To a great extent, this second stage is dependent upon the applied tensile stress and, therefore, would be affected by superimposed mean or residual stresses and stress gradients. It is this second stage that will be of primary concern in this paper.

It is well known that a compressive mean stress increases the allowable cyclic-stress amplitude for a given fatigue life. Conversely, a mean tensile stress decreases the allowable amplitude stress as shown qualitatively in Fig. 3, the fatigue strength diagram from H. Sigwart [4] where σ_m is the mean and σ the cyclic stress.

In an overstrained thick-walled cylinder, the tangential and radial residual-stress distribution is described by the relationships [3] based on the Tresca yield criterion:

$$\sigma_{trp} = \frac{\sigma_y}{2}\left[\frac{b^2 + R^2}{b^2} + 2\log\frac{r}{R} - \frac{a^2}{b^2 - a^2}\left(\frac{b^2 - R^2}{b^2} + 2\log\frac{R}{a}\right)\left(1 + \frac{b^2}{r^2}\right)\right] \quad (1)$$

and

$$\sigma_{rrp} = \frac{\sigma_y}{2}\left[\frac{b^2 - R^2}{b^2} + 2\log\frac{r}{R} - \frac{a^2}{b^2 - a^2}\left(\frac{b^2 - R^2}{b^2} + 2\log\frac{R}{a}\right)\left(1 - \frac{b^2}{r^2}\right)\right] \quad (2)$$

For the 100 percent overstrain condition, i.e., $R = b$, these relationships become:

$$\sigma_{trp} = \frac{\sigma_y}{2}\left[2 + 2\log\frac{r}{b} - \frac{a^2}{b^2 - a^2}\left(2\log\frac{b}{a}\right)\left(1 + \frac{b^2}{r^2}\right)\right] \quad (3)$$

and

$$\sigma_{rrp} = \frac{\sigma_y}{2}\left[2\log\frac{r}{b} - \frac{a^2}{b^2 - a^2}\left(2\log\frac{b}{a}\right)\left(1 - \frac{b^2}{r^2}\right)\right] \quad (4)$$

Equations (3) and (4) are shown in Fig. 4 for a 2.0-diameter ratio in the 100 percent overstrain condition. As can be seen, the tangential residual stress is compressive at the bore.

In view of the compressive residual stress, it would be expected that the overstrained, or autofrettaged, cylinder will withstand a higher cyclic pressure for a given life or a longer life for a given stress level than the nonautofrettaged cylinder. Since, for the 100 percent overstrain condition, the magnitude of the residual stresses increases with diameter ratio, it would also be expected that the increased life due to autofrettage would also increase with diameter ratio.

By equating the tangential residual stress to the yield strength of the material in compression, it is found for the 100 percent overstrain condition, assuming the simplified maximum shear-stress yield criterion, that beyond a diameter ratio of approximately 2.2, the cylinder will reverse yield upon the release of the overstrain pressure. Theoretically then, the increase in fatigue characteristics due to autofrettage will approach a maximum at the 2.2-diameter ratio level. As will be shown, however, due to what appears to be the Bauschinger effect, this critical diameter ratio appears to be in the range of 1.8–2.0 instead of 2.2.

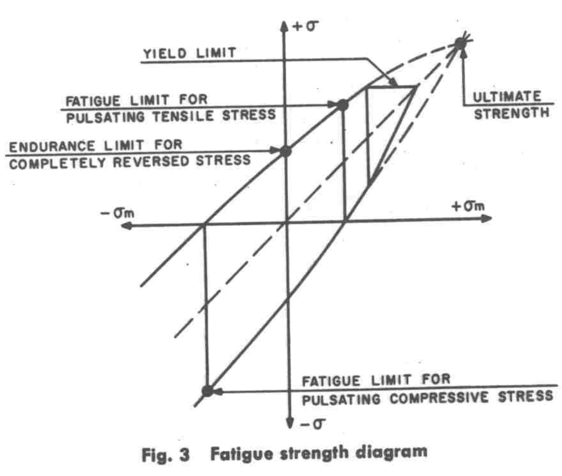

Fig. 3 Fatigue strength diagram

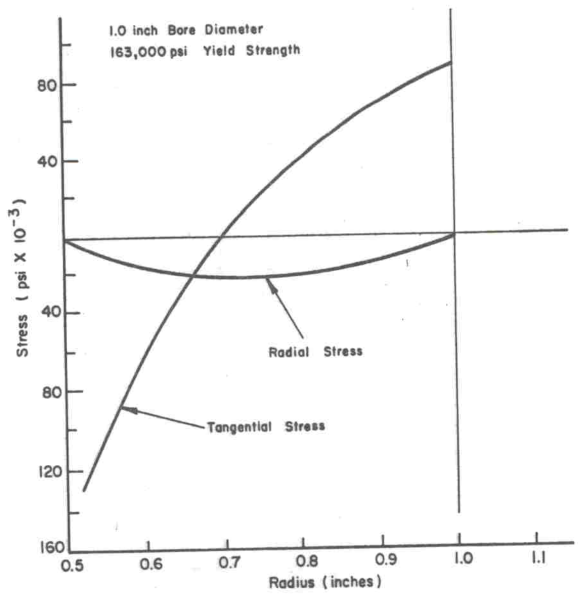

Fig. 4 Residual stress distribution for a 2.0-diameter ratio, 100 percent overstrained cylinder

Results and Discussion

Analysis of Various Cyclic Parameters for Use in Presenting Fatigue Data. In the presentation of fatigue data for thick-walled cylinders, several cyclic parameters may be plotted against life in terms of cycles to failure. How the fatigue data for the non-autofrettaged cylinders appear when plotted in terms of various cyclic parameters is shown in Figs. 5 through 8. For simplicity in comparing the various cyclic parameters, only the least-squares line for each diameter ratio corresponding to the regression of the cycles to failure on the pressure or stress level, along with the correlation coefficient, equation (6), for all of the data in terms of the pertinent cyclic parameter, will be shown in this series of figures.

Based on conventional statistical theory, the general relationship describing the least-squares line for the regression of x on y is:

$$x = a + b(y - \bar{y}) \quad (5)$$

where for the purposes of this investigation

$$y = \log \text{(cyclic parameter)}$$

$$a = \bar{y} = \frac{\Sigma y}{n}$$

$$\bar{x} = \frac{\Sigma x}{n} = \frac{\Sigma \log \text{(no. cycles to failure)}}{n} \text{ and}$$

$$b = \frac{\Sigma(x - \bar{x})(y - \bar{y})}{\Sigma(y - \bar{y})^2}$$

The correlation coefficient (r) is defined by

$$r = \frac{\Sigma(x - \bar{x})(y - \bar{y})}{\sqrt{\Sigma(x - \bar{x})^2(y - \bar{y})^2}} \quad (6)$$

and is a measure of the effectiveness or probability of the data being described by the defined least-squares line and, as will be shown, is an indication of the relative data spread for the various cyclic parameters.

The data could also be statistically analyzed in terms of the regression of y on x. However, because of the high correlation coefficients of the experimental results, varying from 0.91 to 0.986, there are only minor variations between the regressions, and only one will be shown.

For the purpose of minimizing the effects of minor property variations in the test specimens, and to enable comparison of the results of this work with those of other investigators, all cyclic parameters and the data presented herein will be normalized with

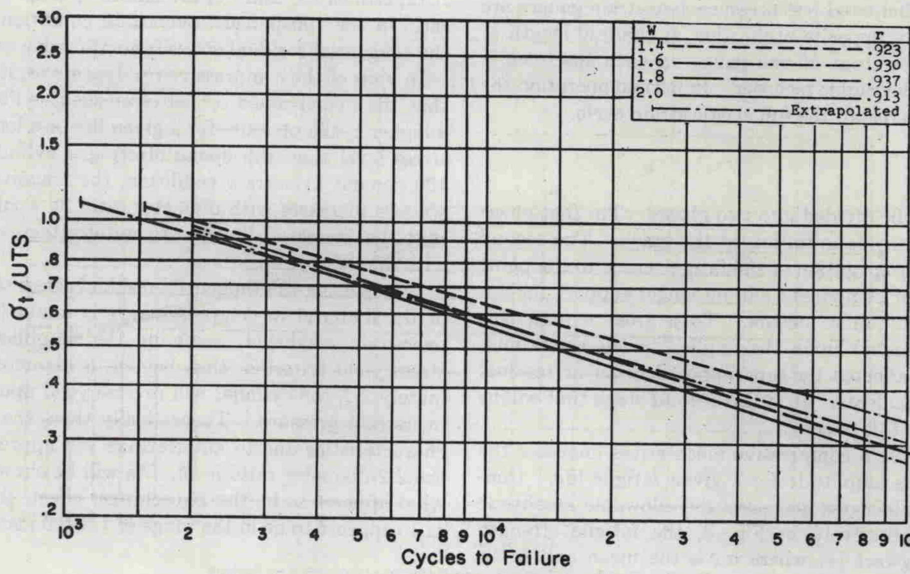

Fig. 5 Tangential bore stress versus cycles to failure

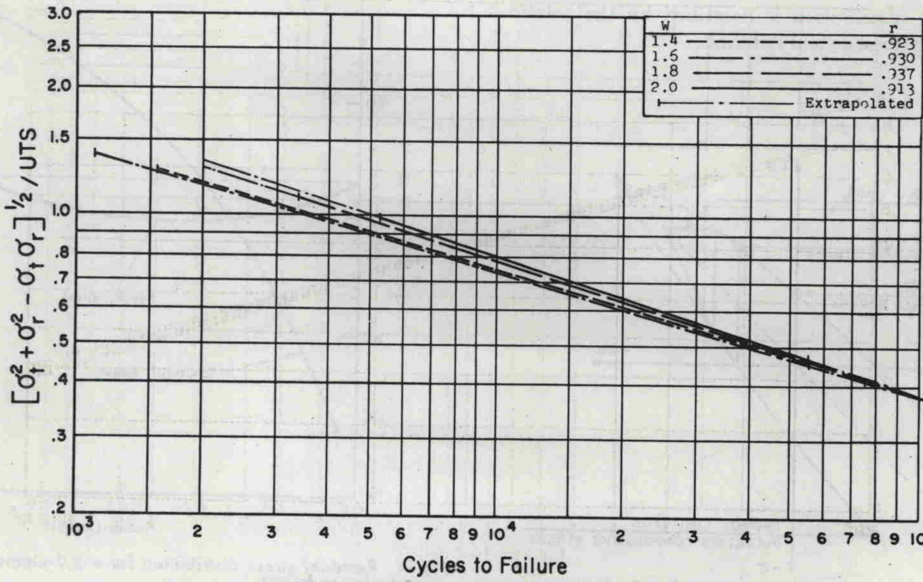

Fig. 6 Difference in principal bore stress versus cycles to failure