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THE BAUSCHINGER AND HARDENING EFFECTS ON RESIDUAL STRESSES IN AN AUTOFRETTAGED THICK-WALLED CYLINDER

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Most of the earlier solutions for residual stresses were based on the assumption of elastic unloading and only a few considered reverse yielding. In this report a new theoretical model for a high strength steel is proposed and a closed-form solution for calculating residual stresses in autofrettaged tubes has been obtained. The new results indicate that the influence of the combined Bauschinger and hardening effects on the residual stress distribution is significant.

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INTRODUCTION

To increase the maximum pressure a cylinder can contain, it is common practice to produce a more advantageous stress distribution involving residual compressive hoop stresses near the bore by autofrettage treatment of the cylinder prior to use (ref 1). The determination of residual stresses is important in the fracture analysis and the fatigue life estimation (refs 2-6). There is, however, considerable disagreement over solutions obtained by different investigators for the residual stress distribution in the cylinder after the autofrettage process (refs 7-12). This discrepancy in residual stress is a result of different mathematical methods, end conditions, and material models. Different assumptions for the material properties such as compressibility, yield criterion, flow rule, hardening rule, Bauschinger effect, etc., can lead to many material models. Most of the earlier solutions for residual stresses were based on the assumption of elastic unloading and only a few considered reverse yielding (refs 8,11). For unloading with reverse yielding, there is no general agreement in the literature over which material model should be used. Many plasticity theories have been proposed and reviewed (ref 13), yet no theory is completely adequate. In particular, it seems that no theoretical model has been given to represent accurately the actual material behavior in a high strength steel as reported by Milligan, Koo, and Davidson (ref 14).

References are listed at the end of this report.

In this report a new theoretical model is proposed with one attempt to give a better representation of the actual loading/unloading behavior in a high strength steel. A closed-form solution for calculating residual stresses in autofrettaged thick-walled cylinders is obtained, and some numerical results will show the influence of the Bauschinger and hardening effects.

MATERIAL BEHAVIOR AND MODELING

The material chosen for this investigation was a modified 4330 steel having a martensitic structure. A description of its chemical composition and various heat treatments is given in Reference 14 by Milligan, Koo, and Davidson. They studied material behavior by utilizing a uniaxial tension-compression specimen. Figure 1 shows the stress-strain curve during loading and unloading after overstrains in tension. The stress-strain curve during loading was assumed to be elastic-perfectly plastic. This was a good approximation since the tensile test exhibited very little strain-hardening during loading. This would also be true for other steels used such as in References 6 and 9.

Initially the yield stresses in tension and compression are approximately equal so that the material can be considered as isotropic. However, the ratio of the yield stress upon reverse yielding to the initial yield stress is strongly affected by overstrain as shown in Figure 1. The values of the Bauschinger effect factor (BEF) also depend on the offset, and the 0.1 percent offset was chosen for the present study. Figure 2 shows the Bauschinger effect factor (f) as a function of percent tensile overstrain (ε^p). The graph shows a decrease of the BEF with an increasing amount of tensile prestrain up to approximately two percent, at which point it becomes effectively constant (ref 14).

The Bauschinger effect factor is very important in determining the range of elastic unloading. After reverse yielding occurs, a very large slope of strain-hardening will develop, even though the initial tensile test exhibits very little strain-hardening. A bilinear model for elastic-plastic unloading is proposed here, as shown in Figure 1. Choosing a new coordinate system (σ',ε') with the origin at the point before unloading, we have for the plastic portion of the reverse yielding curve

$$\sigma'/\sigma_o = 1 + f + m'\zeta'/(1-m') \tag{1}$$

where $\zeta' = (E/\sigma_o)\varepsilon'^P$, E is Young's modulus, σ_o is the initial yield stress, $m'E$ is the slope of the strain-hardening after reverse yielding, and ε'^P is the additional plastic strain during unloading.

ELASTIC-PLASTIC LOADING

Consider a thick-walled cylinder, inner radius a, and external radius b, which is subjected to inner pressure p. The material is assumed to be elastic ideally plastic, obeying the Tresca's yield criterion and the associated flow theory. The elastic-plastic solution during loading has been found by Koiter (ref 7). The expressions for the stresses and strains are:

$$\left.\begin{matrix}\sigma_r/\sigma_o \quad (2a)\\ \sigma_\theta/\sigma_o \quad (3a)\end{matrix}\right\} = \frac{1}{2}\left(\mp 1 + \frac{\rho^2}{b^2}\right) - \log\frac{\rho}{r}, \quad \text{in } (a < r < \rho)$$

$$\left.\begin{matrix}\sigma_r/\sigma_o \quad (2b)\\ \sigma_\theta/\sigma_o \quad (3b)\end{matrix}\right\} = \frac{1}{2}\left(\frac{\rho^2}{b^2} \mp \frac{\rho^2}{r^2}\right), \quad \text{in } (\rho < r < b)$$

$$\sigma_z/\sigma_o = \nu(\sigma_r+\sigma_\theta)/\sigma_o + E\varepsilon_z/\sigma_o \tag{4}$$

$$\frac{E}{\sigma_o}\frac{u}{r} = (1-2\nu)(1+\nu)\frac{\sigma_r}{\sigma_o} + (1-\nu^2)\frac{\rho^2}{r^2} - \nu\frac{E}{\sigma_o}\varepsilon_z \tag{5}$$

and

$$(E/\sigma_o)\ \varepsilon_z = (\mu-2\nu)(p/\sigma_o)/(b^2/a^2-1) \tag{6}$$

where $\mu = 0$ (open-end), 1 (closed-end), and ρ is the elastic-plastic boundary relating to the internal pressure p by

$$p/\sigma_o = \frac{1}{2}(1-\rho^2/b^2) + \log(\rho/a) \tag{7}$$

The equivalent plastic strain can be calculated by

$$(E/\sigma_o)\varepsilon^p = \varphi = \varphi_1(\rho^2/r^2-1) \quad , \quad \text{in } (a \leq r \leq \rho)$$

and

$$\varphi_1 = (2/\sqrt{3})(1-\nu^2) \tag{8}$$

REVERSE YIELDING

If the pressure p given by Eq. (7) is subsequently completely removed with no reverse yielding, the unloading is entirely elastic and the solution is given by

$$\left.\begin{matrix}\sigma_r' \\ \sigma_\theta'\end{matrix}\right\} = \frac{p}{b^2/a^2-1}\left[\pm\frac{b^2}{r^2} - 1\right] \tag{9, 10}$$

$$\sigma_z' = \nu(\sigma_r'+\sigma_\theta') + E\ \varepsilon_z' \tag{11}$$

$$E\ \varepsilon_z' = -(\mu-2\nu)p/(b^2/a^2-1) \tag{12}$$

$$E\ u/r = -[(1-\nu-\mu\nu) + (1+\nu)b^2/r^2]p/(b^2/a^2-1) \tag{13}$$

Let a double prime denote a component in the residual state, i.e., $\sigma_\theta'' = \sigma_\theta + \sigma_\theta'$. Assuming a reduced compressive yield strength as a result of the Bauschinger effect and using Tresca's criterion subject to $\sigma_r'' > \sigma_z'' > \sigma_\theta''$, the reverse yielding will not occur if

$$\sigma_r'' - \sigma_\theta'' \overset{<}{=} f\,\sigma_o \qquad (14)$$

Substituting the loading and unloading solutions into Eq. (14), we can determine the minimum pressure (p_m) for reverse yielding to occur. The equation for p_m is given by

$$p_m/\sigma_o = \frac{1}{2}\,(1+f)(1-a^2/b^2) \qquad (15)$$

Equating Eq. (7) to Eq. (15), we can calculate p_m and determine the maximum amount of overstrain for reverse yielding not to occur.

ELASTIC-PLASTIC UNLOADING

Now suppose that the loading has been such that the internal pressure is larger than p_m given by Eq. (15). On unloading, yielding will occur for $a \leq r < \rho'$ with $\rho' < \rho$. Taking into account the Bauschinger effect (f) and the strain-hardening during unloading (m'), we have

$$\sigma_r'' - \sigma_\theta'' = f\,\sigma_o + m'E\epsilon'^{p}/(1-m') \qquad (16)$$

assuming that $\sigma_r'' > \sigma_z'' > \sigma_\theta''$ in $a \leq r \leq \rho'$.

The material is assumed to be elastic-plastic, obeying the Tresca's yield criterion, the associated flow theory, and a linear strain-hardening rule during unloading. Following the procedure in Bland's work (ref 8), a closed-form solution for elastic-plastic unloading can be obtained. The stresses in the reverse yielding zone ($a \leq r \leq \rho'$) are given by

$$\sigma_r'/\sigma_o = p/\sigma_o - \frac{1}{2}\,\beta_2'\,(1+f)(\rho'/a)^2(1-a^2/r^2) - (1-\beta_2')(1+f)\,\log(r/a) \qquad (17)$$

$$\sigma_\theta'/\sigma_o = \sigma_r'/\sigma_o - (1+f) - m'\zeta'/(1-m') \qquad (18)$$

$$\zeta' = \beta_1'(1+f)(\rho'^2/r^2-1) \qquad (19)$$

where

$$\beta_1' = (1-m')/[m' + \frac{\sqrt{3}}{2}\frac{(1-m')}{(1-\nu^2)}] \quad , \quad \beta_2' = m'\beta_1'/(1-m') \tag{20}$$

The stresses in the elastic zone ($\rho' \leq r \leq b$) are

$$\left.\begin{array}{l}\sigma_r'/\sigma_o \\ \sigma_\theta'/\sigma_o\end{array}\right\} = \frac{1}{2}(1+f)[\pm(\rho'/r)^2 - (\rho'/b)^2] \qquad \begin{array}{r}(21)\\(22)\end{array}$$

The other expressions for the entire tube ($a \leq r \leq b$) are

$$\sigma_z'/\sigma_o = \nu(\sigma_r'+\sigma_\theta')/\sigma_o + E\ \varepsilon_z'/\sigma_o \tag{23}$$

$$E\ \varepsilon_z'/\sigma_o = -(\mu-2\nu)(p/\sigma_o)/(b^2/a^2-1) \tag{24}$$

$$(E/\sigma_o)\ u'/r = (1-2\nu)(1+\nu)(\sigma_r'/\sigma_o) + (1-\nu^2)(1+f)(\rho'/r)^2 - \nu E\ \varepsilon_z'/\sigma_o \tag{25}$$

The residual stresses and the residual displacement are found by addition

$$\sigma_r'' = \sigma_r + \sigma_r' \quad , \quad \sigma_\theta'' = \sigma_\theta + \sigma_\theta' \quad , \quad \sigma_z'' = \sigma_z + \sigma_z'$$

$$\text{and } u'' = u + u' \tag{26}$$

NUMERICAL RESULTS AND DISCUSSION

The numerical results for two closed-end thick-walled cylinders with $b/a = 2$ and 3 were obtained. Various values of f and m' were used for the purpose of showing the Bauschinger and hardening effects on residual stresses. Although the numerical results for all the stresses, strains, and displacement were obtained, only those for the residual hoop stresses will be shown here. The material constants used in all cases were $\nu = 0.3$, $E/\sigma_o = 200$. The slope of unloading after reverse yielding was estimated to be 0.3E for a high strength steel (ref 14).

The residual stress distributions in an autofrettaged thick tube of wall ratio two are shown in Figure 3 for $\rho/a = 1.4$ and 1.8. For a 40 percent autofrettaged tube, we have shown the results for three cases (a) $f = 1$, $m' =$

0; (b) $f = 0.50$, $m' = 0$; (c) $f = 0.50$, $m' = 0.3$. The first case represents no Bauschinger effect with no reverse yielding. The second case shows the Bauschinger effect only (ref 11). The third case shows the influence of the combined Bauschinger and hardening effects. For an 80 percent autofrettaged tube, we have shown the residual stress distributions for three cases (a) $f = 1$, $m' = 0$; (b) $f = 0.42$, $m' = 0$; (c) $f = 0.42$, $m' = 0.3$. Now the influence of the Bauschinger and hardening effects is more significant. Comparing the residual hoop stress at the bore given by cases (a) and (b) with case (c), the results indicate that neglecting both effects will overestimate by 46 percent, while including the Bauschinger effect only will underestimate by 25 percent.

The residual stress distributions in an autofrettaged thick tube of wall ratio three are shown in Figure 4 for $\rho/a = 1.4$ and 2.2. The values of f used for the 20 and 60 percent autofrettage are 0.54 and 0.40, respectively. If the hardening effect (m') is neglected, we would have a smaller compressive stress at the bore. If we neglect both the Bauschinger and hardening effects, i.e., $f = 1$ and $m' = 0$, we would have a larger residual compressive stress at the bore. At 60 percentage autofrettage, reverse yielding still occurs but in a smaller portion of the tube around the bore.

In order to further discuss the Bauschinger and hardening effects on the residual stress distributions, we have used other values for f and m' in a thick tube with wall ratio three and 100 percent autofrettage. Figure 5 shows the Bauschinger effect ($f = 0.36$, 0.68, 1.00) only with no hardening ($m' = 0$). Figure 6 shows the effect of hardening ($m' = 0$, 0.1, 0.2, 0.3) with $f = 0.36$. Figure 7 shows the Bauschinger effect ($f = 0.36$, 0.68, 1.00) with hardening ($m' = 0.3$). These results indicate that the influence of the combined

Bauschinger and hardening effects on the residual stress distribution is significant.

CONCLUSIONS

A new theoretical model for a high strength steel has been proposed. The real Bauschinger effect factor can be used to determine the range of elastic unloading. The small strain-hardening during loading is neglected, but the large strain-hardening after reverse yielding is taken into account.

A closed-form solution for calculating the residual stresses and strains with reverse yielding has been obtained. The numerical results for the residual stress distributions in two autofrettaged thick-walled cylinders have been given. The new results indicate that the influence of the combined Bauschinger and hardening effects on the residual stress distribution is significant.

Comparing the residual hoop stress at the bore for an 80 percent autofrettaged tube with wall ratio two, Koiter's model neglecting both effects (ref 7) will overestimate by 46 percent, while Parker's model including the Bauschinger effect only (ref 11) will underestimate by 25 percent when compared with the present model taking into account both the Bauschinger and hardening effects.

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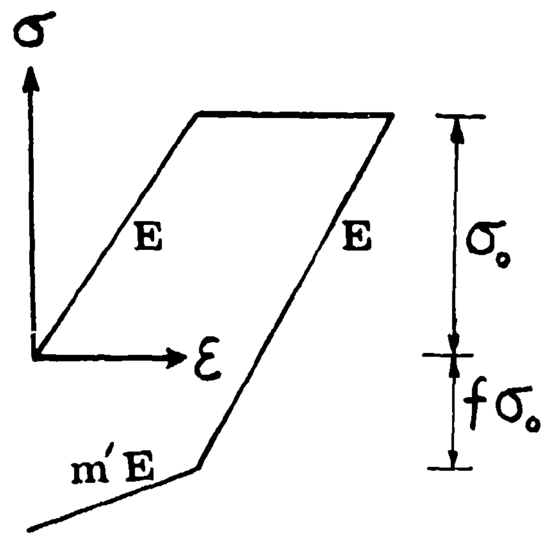

Figure 1. Stress-strain curve during loading and unloading.

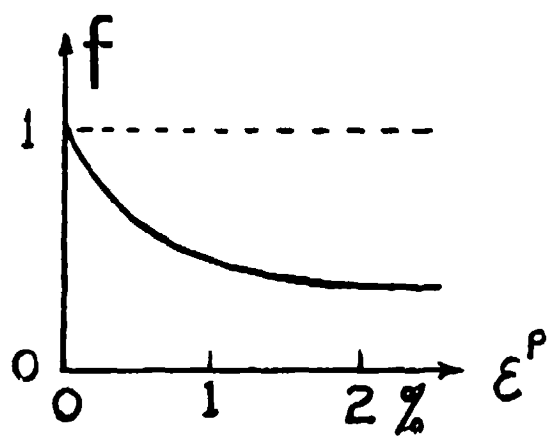

Figure 2. Bauschinger effect factor as a function of pre-strain.

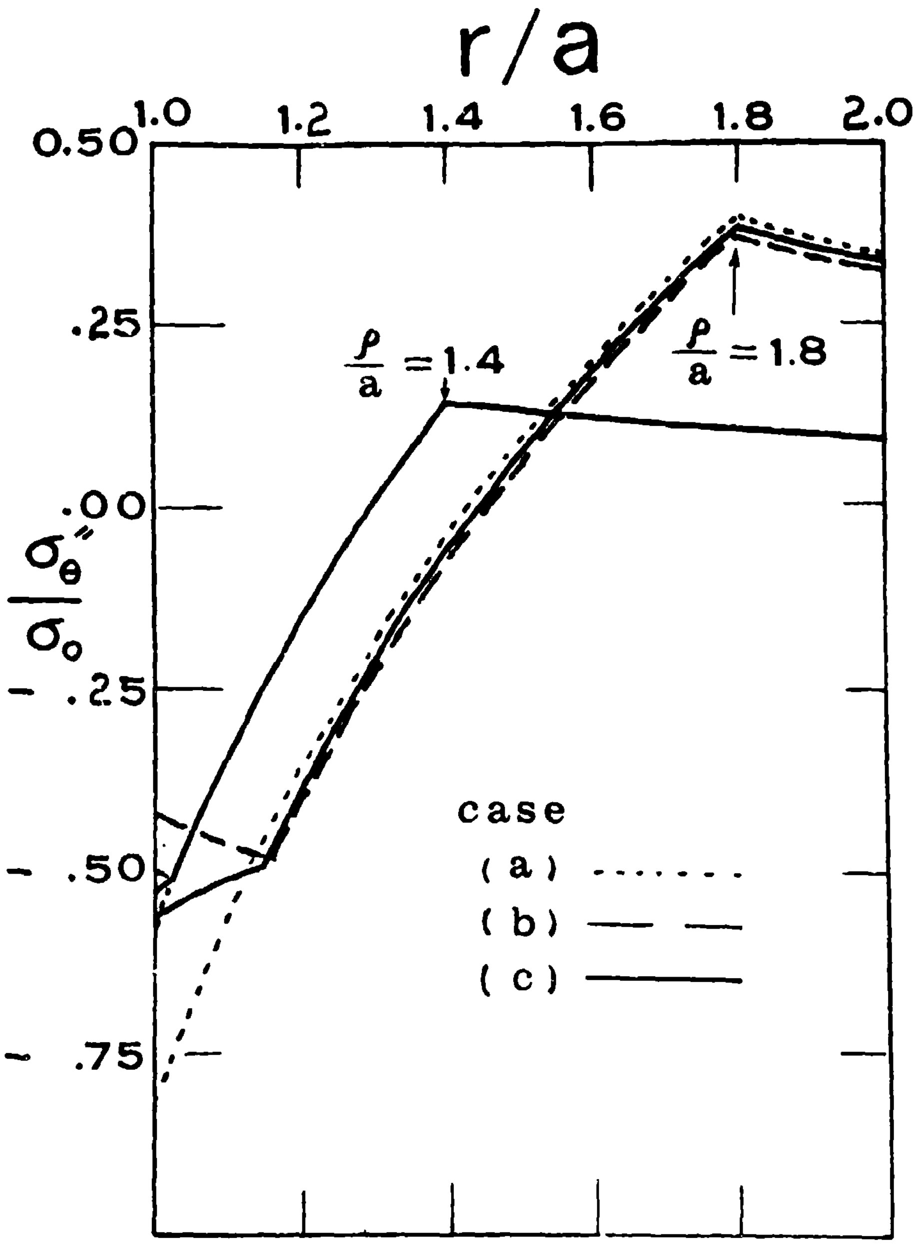

Figure 3. Residual stress distribution in an autofrettaged tube ($b/a = 2$, $\rho/a = 1.4$ and 1.8).

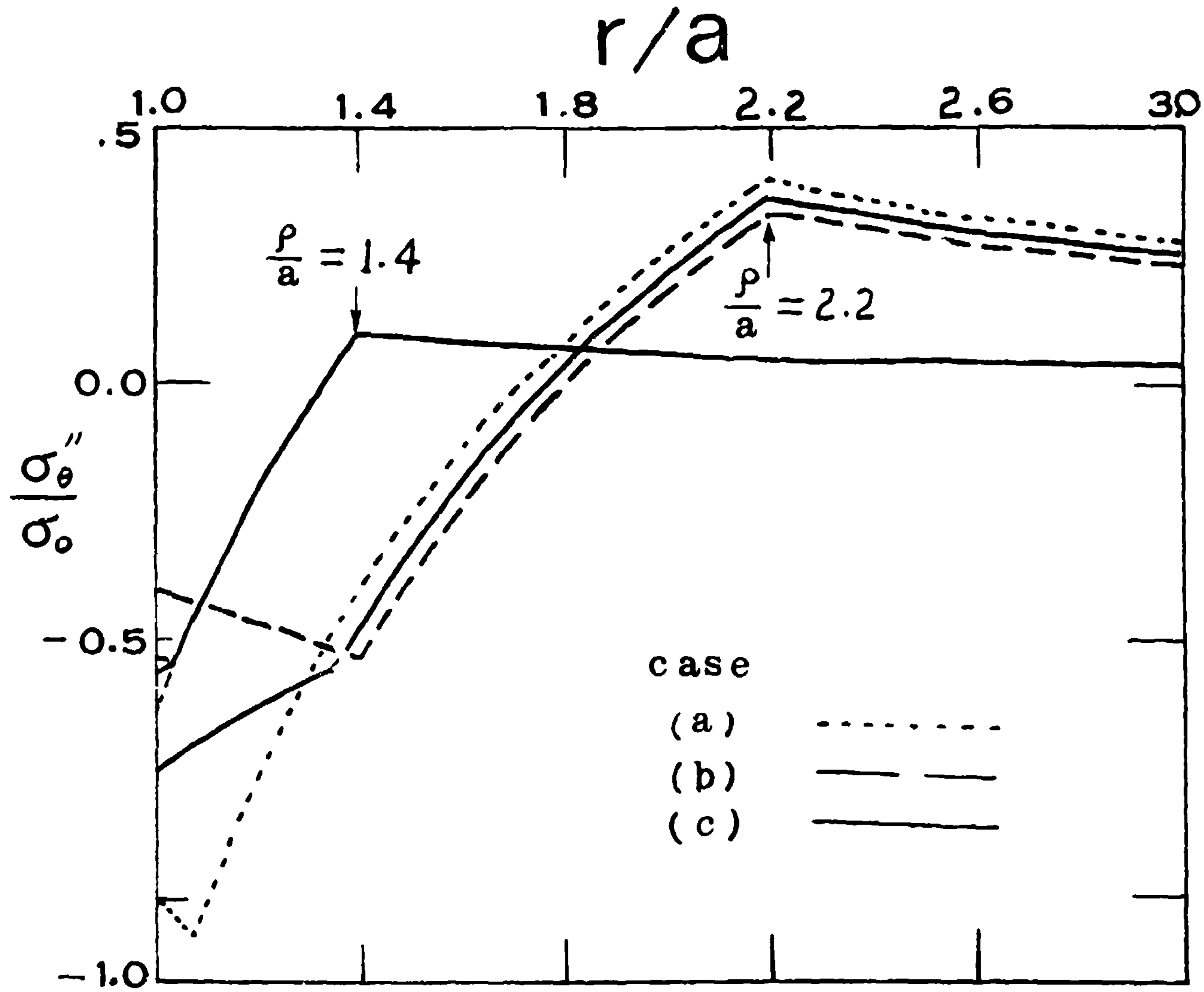

Figure 4. Residual stress distribution in an autofrettaged tube (b/a = 3, ρ/a = 1.4 and 2.2).

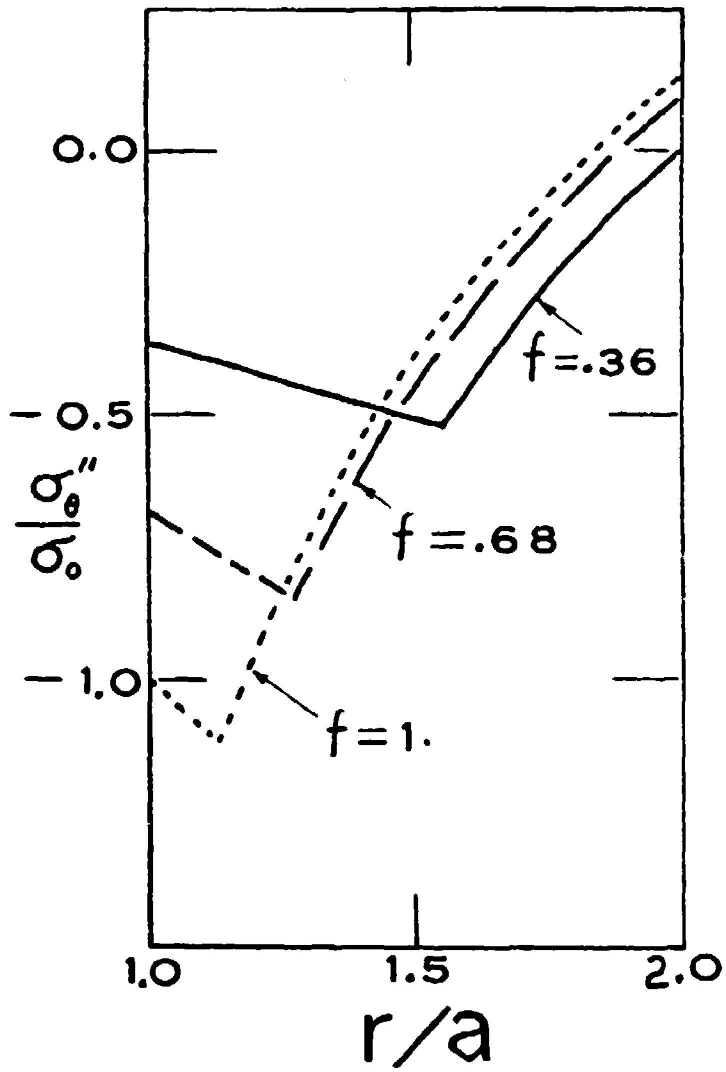

Figure 5. Bauschinger effect on residual stress distribution ($b = \rho = 3a$, $m' = 0$).

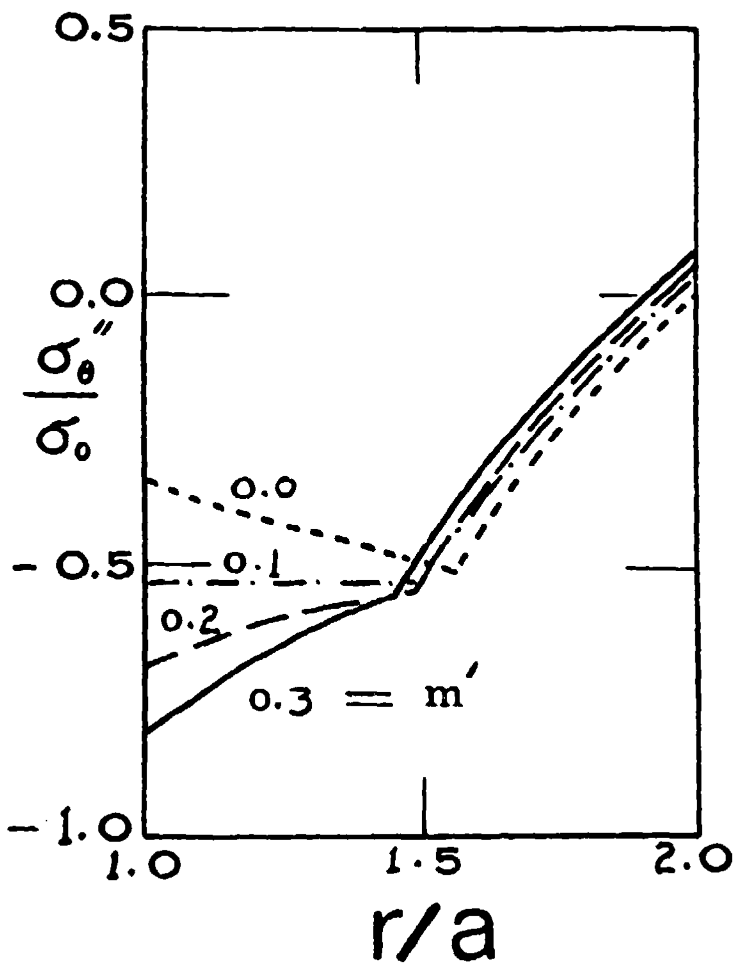

Figure 6. Hardening effect on residual stress distribution
($b = \rho = 3a$, $f = 0.36$).

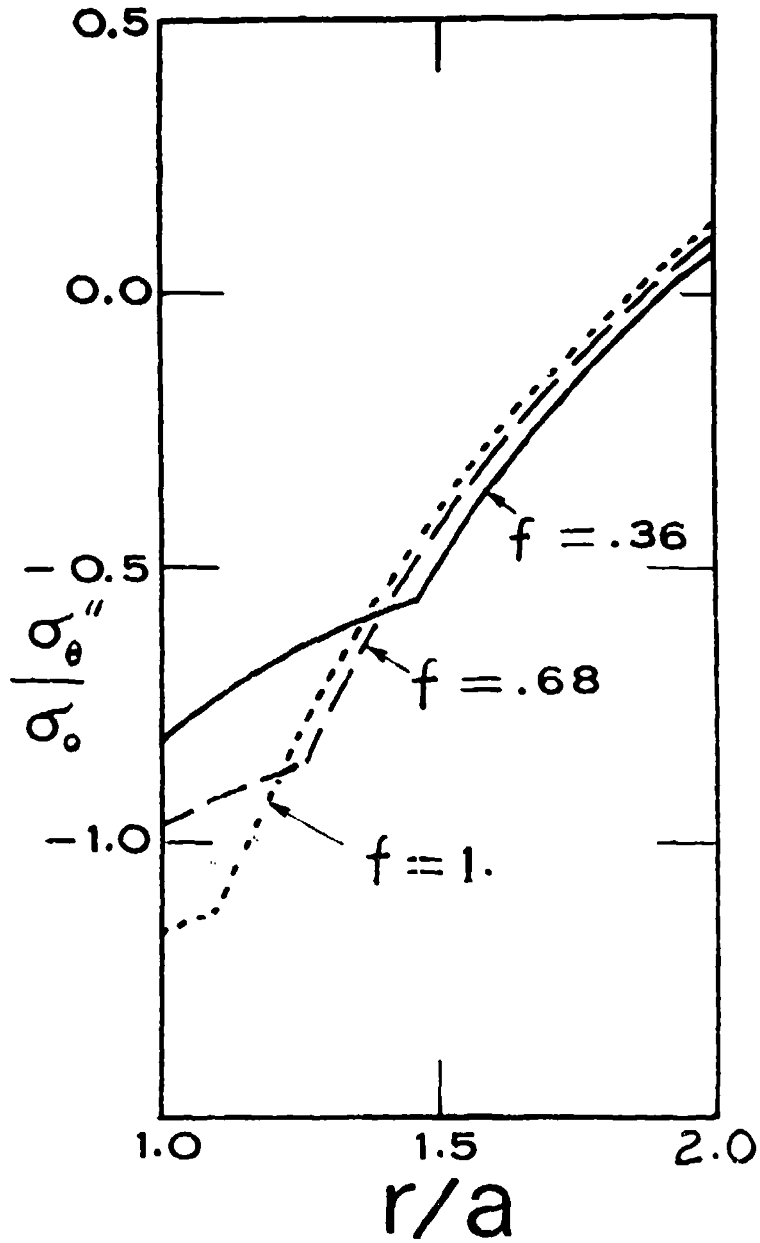

Figure 7. Combined Bauschinger and hardening effects on residual stress distribution ($b = \rho = 3a$, $m' = 0.3$).

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