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SIMULATION OF PARTIAL AUTOFRETTAGE RESIDUAL STRESSES BY THERMAL LOADS

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P. O'Hara

February 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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WATERVLIET, N. Y. 12189

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The effect of favorable residual stresses of an autofrettaged tube is well known. In many instances there is a redistribution of these stresses due to changes of geometrical configurations such as the presence of keyways, riflings, cracks, etc. The problem, in general, can be studied by discretization carried out either by finite elements or by finite differences; however, it is usually not possible to incorporate the redistributed residual stress patterns due to the presence of such geometrical changes. This

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20. Abstract (Cont'd)

difficulty is overcome by simulation of residual stresses by certain active loadings.

The simulation by dislocation and equivalent thermal loading for a fully autofrettaged tube is well known. In this report we extend the thermal loading to simulate a partially autofrettaged case. The simplicity of the method is illustrated by comparing numerical results to those obtained from finite elements (NASTRAN) and finite differences.

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ILLUSTRATIONS

NOTATIONS AND NUMERICAL VALUE USED

a	inner radius, 1"
b	outer radius, 2"
r,θ	cylindrical coordinates
σ	normal stress
σ_o	yield stress, 170 ksi
ϕ	Airy stress function
A,B,C,D	superposition constants
u	displacement
d	coefficient of dislocation
G	shear modulus
ν	Poisson's ratio, 0.3
ψ	thermoelastic potential
T	temperature at r
T_a, T_b	temperature at r=a, r=b
E	Young's modulus, 30×10^6 psi
α	coefficient of thermal expansion, 6.8×10^{-6} in/in/°F
ρ	radius of the autofrettaged interface
T_ρ	temperature at $r=\rho$

FULLY AUTOFRETTAGED CASE

The plane strain stress distribution of a fully autofrettaged tube using von Mises yield condition and the incompressibility condition is given by

$$\sigma_r = \frac{2\sigma_o}{\sqrt{3}} \{\log \frac{r}{b} - \frac{a^2}{b^2-a^2} (1 - \frac{b^2}{r^2}) \log \frac{b}{a} \} \tag{1}$$

$$\sigma_\theta = \frac{2\sigma_o}{\sqrt{3}} \{1 + \log \frac{r}{b} - \frac{a^2}{b^2-a^2}(1 + \frac{b^2}{r^2}) \log \frac{b}{a} \} \tag{2}$$

This distribution can be simulated either by a dislocation, Figure 1, or by a steady state thermal loading.

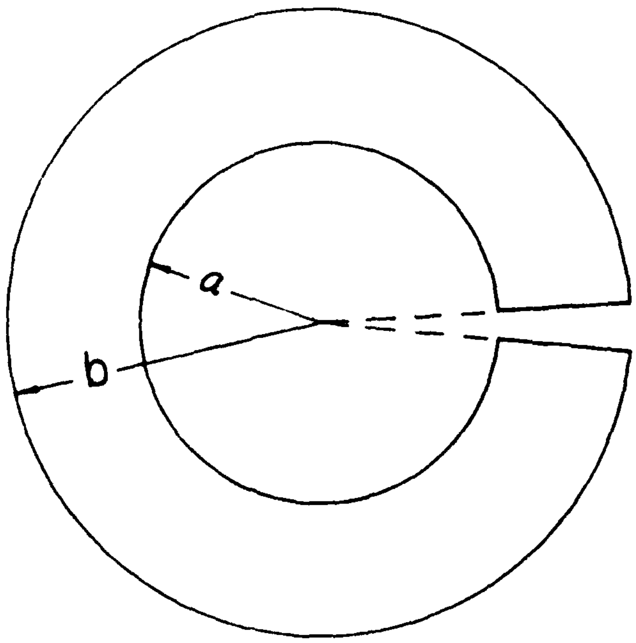

Figure 1. A portion of the ring between two adjacent cross sections is cut out. If the ends of the ring are joined again, stresses thus produced may simulate the residual stresses due to autofrettage.

Dislocation Solution:

Using biharmonic Airy stress function[1] the dislocation solution can be obtained by

$$\phi = A \log r + Br^2 + Cr^2 \log r \tag{3}$$

The dislocation is expressed by the jump condition

$$[2Gu_\theta]_{\theta=0}^{\theta=2\pi} = d \cdot r \tag{4}$$

This condition together with traction free conditions at the inner and outer radii gives

$$A = \frac{d}{4\pi(1-\nu)} \frac{a^2b^2}{b^2-a^2} \log \frac{b}{a}$$

$$B = -\frac{d}{16\pi(1-\nu)} \left\{\frac{2a^2}{(b^2-a^2)} \log \frac{b}{a} + 1 + 2 \log b\right\}$$

$$C = \frac{d}{8\pi(1-\nu)} \tag{5}$$

Using the formulas

$$\sigma_r = \frac{1}{r^2} \frac{\partial^2\phi}{\partial\theta^2} + \frac{1}{r} \frac{\partial\phi}{\partial r}$$

$$\sigma_\theta = \frac{\partial^2\phi}{\partial r^2} \tag{6}$$

[1]Timoshenko, S. and Goodier, J. N., Theory of Elasticity, McGraw-Hill Co., 1951, 2nd Edition, p. 56.

The stress distribution is then obtained from (3) and (5) as

$$\sigma_r = \frac{d}{4\pi(1-\nu)} \{\log \frac{r}{b} - \frac{a^2}{b^2-a^2} (1 - \frac{b^2}{r^2}) \log \frac{b}{a}\} \tag{7}$$

$$\sigma_\theta = \frac{d}{4\pi(1-\nu)} \{\log \frac{r}{b} + 1 - \frac{a^2}{b^2-a^2} (1 + \frac{b^2}{r^2}) \log \frac{b}{a}\} \tag{8}$$

The equivalence between (7), (8) and (1), (2) is easily seen with dislocation and yield stress related by

$$\frac{d}{4\pi(1-\nu)} = \frac{2\sigma_o}{\sqrt{3}} \tag{9}$$

Solution of Thermal Loading:

Using the superposition of Airy stress function ϕ and thermo-elastic potential ψ (ref. 2), the solution can be symbolically written as

$$[S] = A_1[\psi-r^2] + B_1[\psi-r^2\log r] + C_1[\psi-\log r] + D_1[\phi-r^2] \tag{10}$$

with T_a and T_b as steady state temperatures at the inner and outer radii respectively and using the traction free boundary conditions we have

$$\begin{aligned} A_1 &= \frac{E\alpha}{4(1-\nu)} [T_a + \frac{(1+\log a)(T_a-T_b)}{\log(b/a)}] \\ B_1 &= \frac{-E\alpha}{4(1-\nu)} \frac{(T_a-T_b)}{\log(b/a)} \\ C_1 &= -\frac{2a^2b^2}{b^2-a^2} B_1 \log(b/a) \\ D_1 &= A_1 + \frac{1}{2} B_1 [1 + 2\log b + \frac{2a^2}{b^2-a^2} \log (\frac{b}{a})] \end{aligned} \tag{11}$$

[2]Sadowsky, M. A. and Hussain, M. A., "Thermal Stress Discontinuities in Microfibers," Watervliet Arsenal Technical Report WVT-RR-6401, April 1964.

Using the formulas

$$\sigma_r = -\frac{1}{r^2}\frac{\partial^2\psi}{\partial\theta^2} - \frac{1}{r}\frac{\partial\psi}{\partial r}$$

$$\sigma_\theta = -\frac{\partial^2\psi}{\partial r^2} \tag{12}$$

The stress distribution is obtained from (6), (10), (11) as

$$\sigma_r = \frac{E\alpha(T_a-T_b)}{2(1-\nu)\log(b/a)}\{\log\frac{r}{b} - \frac{a^2}{b^2-a^2}(1-\frac{b^2}{r^2})\log\frac{b}{a}\} \tag{13}$$

$$\sigma_\theta = \frac{E\alpha(T_a-T_b)}{2(1-\nu)\log(b/a)}\{1 + \log\frac{r}{b} - \frac{a^2}{b^2-a^2}(1+\frac{b^2}{r^2})\log\frac{b}{a}\} \tag{14}$$

The equivalence between (13), (14) and (1), (2) is easily seen with the temperature gradient and yield stress related by

$$\frac{E\alpha(T_a-T_b)}{2(1-\nu)\log(b/a)} = \frac{2\sigma_o}{\sqrt{3}} \tag{15}$$

PARTIALLY AUTOFRETTAGED CASE

The plane strain stress distribution of a partially autofrettaged tube, using the same von Mises and incompressibility conditions as before, is

$$\sigma_r = \begin{cases} \frac{\sigma_o}{\sqrt{3}}\{(2\log\frac{r}{\rho} - 1 + \frac{\rho^2}{b^2}) - P_1(\frac{1}{b^2} - \frac{1}{r^2})\} & a\le r\le\rho \quad (16) \\ \frac{\sigma_o}{\sqrt{3}}(\rho^2-P_1)(\frac{1}{b^2} - \frac{1}{r^2}) & \rho\le r\le b \quad (17) \end{cases}$$

$$\sigma_\theta = \begin{cases} \frac{\sigma_o}{\sqrt{3}}\{(2\log\frac{r}{\rho} + 1 + \frac{\rho^2}{b^2}) - P_1(\frac{1}{b^2} + \frac{1}{r^2})\} & a\le r\le\rho \quad (18) \\ \frac{\sigma_o}{\sqrt{3}}(\rho^2-P_1)(\frac{1}{b^2} + \frac{1}{r^2}) & \rho\le r\le b \quad (19) \end{cases}$$

where $P_1 = \frac{a^2b^2}{(a^2-b^2)}[(1 - \frac{\rho^2}{b^2} + 2\log(\rho/a)]$.

<u>Solutions of Thermal Loading</u>:

Using the superposition of Airy stress function ϕ and thermoelastic potential ψ, it is sufficient to write the solution symbolically as

$$[S] = \begin{cases} A_2[\psi-r^2] + B_2[\psi-r^2\log r] + C_2[\psi-\log r] + D_2[\phi-r^2] \ , & a\leq r\leq\rho \quad (20) \\ A_3[\psi-r^2] + C_3[\psi-\log r] + D_3[\phi-r^2] \ , & \rho\leq r\leq b \quad (21) \end{cases}$$

In order to obtain stress distribution given by (16)-(19) we must have

$$\begin{aligned} A_2 - D_2 &= \frac{1}{2}\ [2 + 2\log\rho - \frac{1}{b^2}\ (\rho^2-P_1)]\ \frac{\sigma_o}{\sqrt{3}} \\ B_2 &= -\frac{\sigma_o}{\sqrt{3}} \\ C_2 &= -P_1\ \frac{\sigma_o}{\sqrt{3}} \qquad (22) \\ A_3 - D_3 &= -\frac{1}{2b^2}\ (\rho^2-P_1)\ \frac{\sigma_o}{\sqrt{3}} \\ C_3 &= (\rho^2-P_1)\ \frac{\sigma_o}{\sqrt{3}} \end{aligned}$$

The temperature profile from (20) and (21) is

$$\frac{E\alpha T}{(1-\nu)} = \begin{cases} 4A_2 + 4B_2(1 + \log r) \ , & a\leq r\leq\rho \\ 4A_3 & \rho\leq r\leq b \end{cases} \qquad (23)$$

It is seen that the temperature is constant in the outer region, $\rho\leq r\leq b$, and logarithmically distributed in the inner region, $a\leq r\leq\rho$. Let T_a, T_ρ be the temperatures at r = a, and r = ρ respectively. These temperature boundary conditions give the equivalence between the temperature gradient and the yield stress

$$\frac{E\alpha(T_a - T_\rho)}{2(1-\nu)\log(\rho/a)} = \frac{2\sigma_o}{\sqrt{3}} \qquad (24)$$

The temperature profile of (23) is then given by

$$T = T_a - \frac{(T_a - T_\rho)}{\log(\rho/a)}\log(r/a) \qquad a \leq r \leq \rho$$

$$T = T_\rho \qquad \rho \leq r \leq b \qquad (25)$$

Once the temperature distribution is known, all the remaining superposition constants can be specifically determined. It should be noted that we have neglected the axial stress computation which can easily be taken care of by the method discussed on page 409 of Reference 1.

A NUMERICAL EXAMPLE

Consider a tube of inner radius a = 1, outer radius b = 2, with material constants $E = 30 \times 10^6$ psi, $\nu = 0.3$, $\alpha = 6.8 \times 10^{-6}$ in/in/°F, $\sigma_o = 170 \times 10^3$ psi; the temperature distribution was computed from (25) for 30%, 60% and 100% autofrettaged cases, shown in Figure 2. Using these temperature distributions as temperature input in a finite difference computer program based on the theory of thermal stress in section 9-10 of Reference 3 we obtain the stress distributions. The results are compared in Table I with the exact solution given by (14), and are also graphically shown in Figure 3.

[1]Timoshenko, S. and Goodier, J. N., Theory of Elasticity, McGraw-Hill Co., 1951, 2nd Edition, p. 56.

[3]Boley, B. A. and Weiner, J. H., "Theory of Thermal Stresses," John Wiley & Sons, 1960.

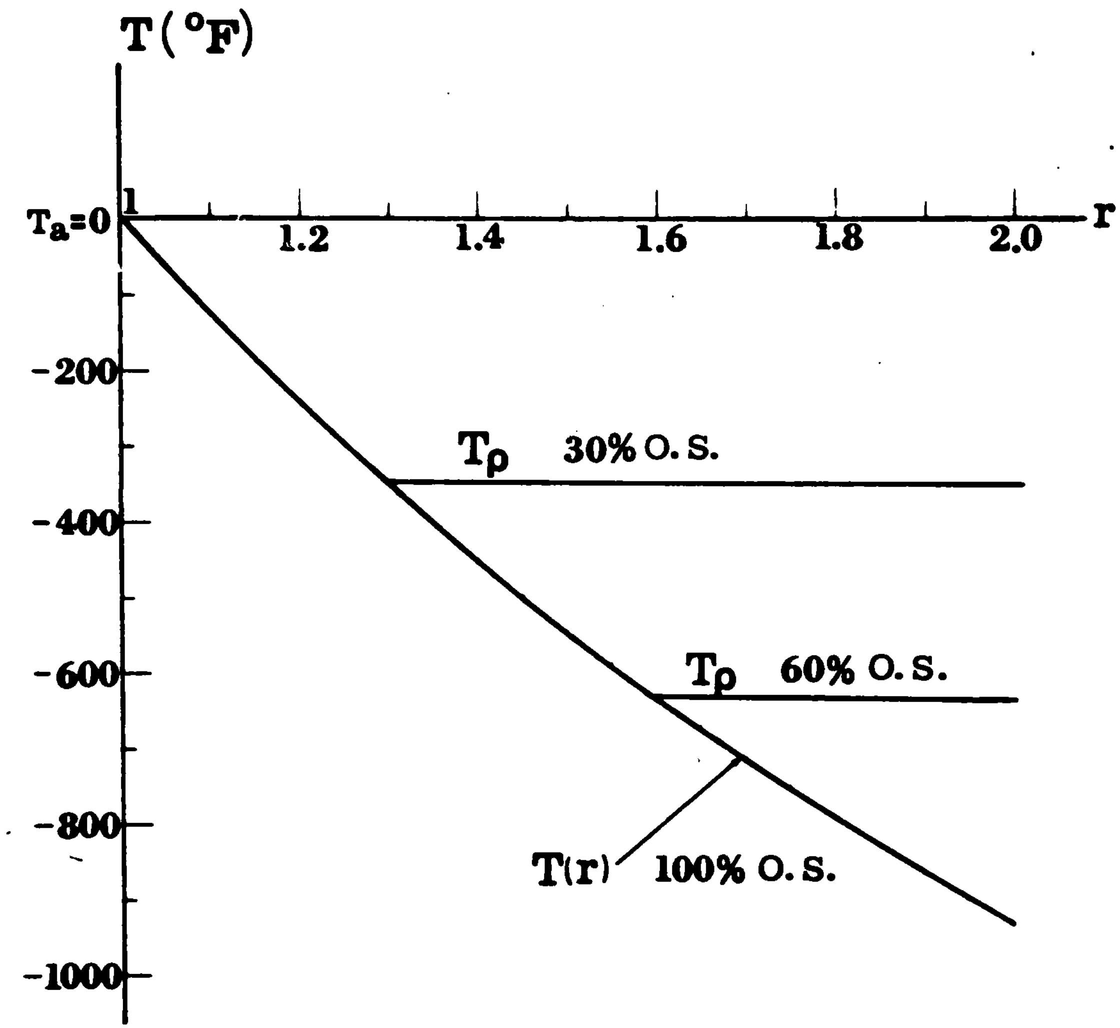

Figure 2. Temperature distributions to simulate residual stresses caused by 30%, 60%, and 100% overstrain in a cylinder with a = 1, b = 2, $\nu = 0.3$, $E = 30 \times 10^6$ psi, $\sigma_o = 170$ ksi, $\alpha = 6.8 \times 10^{-6}$ in/in°F.

TABLE I. COMPARISON OF σ_θ (PSI) WITH FINITE DIFFERENCES

Percent Overstrain	r	Exact Solution	Finite Difference
30%	1.0	- 92190	- 92897
	1.1	- 48446	- 49567
	1.2	- 12325	- 13636
	1.3	18205	16825
	1.4	16442	15236
	1.5	15020	13948
	1.6	13856	12890
	1.7	12891	12010
	1.8	12083	11271
	1.9	11398	10643
	2.0	10814	10106
60%	1.0	-143955	-145316
	1.1	- 95719	- 97552
	1.2	- 56182	- 58225
	1.3	- 22993	- 25102
	1.4	5422	3323
	1.5	30153	28107
	1.6	51978	50007
	1.7	48359	46593
	1.8	45326	43724
	1.9	42759	41289
	2.0	40568	39205
100%	1.0	-166539	-168854
	1.1	-116343	-119099
	1.2	- 75316	- 78246
	1.3	- 40966	- 43929
	1.4	- 11631	- 14550
	1.5	13842	11005
	1.6	36275	33539
	1.7	56267	53640
	1.8	74269	71749
	1.9	90621	88206
	2.0	105590	103274

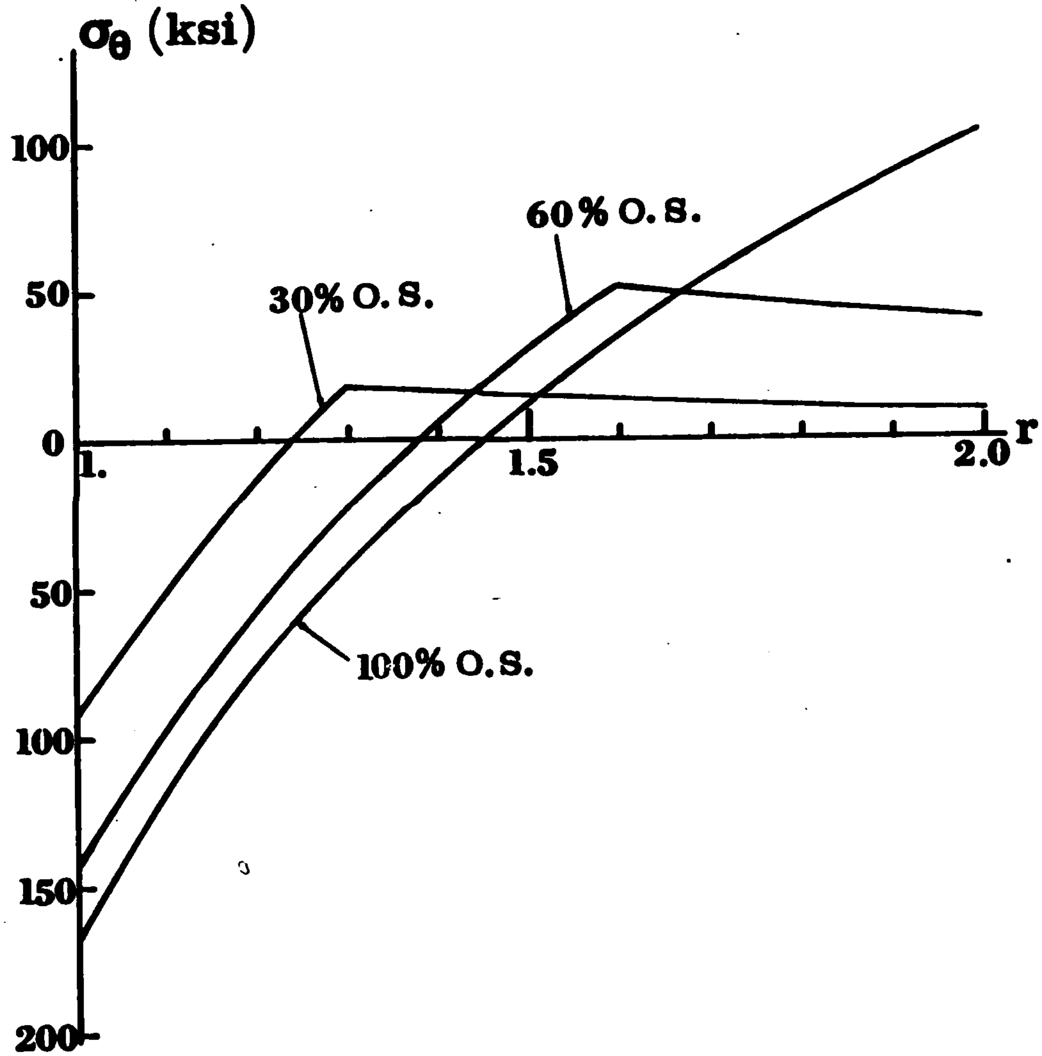

Figure 3. Thermal stresses obtained from Eq. (14) using temperature distributions shown in Figure 2 simulating 30%, 60%, and 100% overstrain.

The same temperature distribution was also used in the finite element NASTRAN program using a TEMP (LOAD) request in the case control deck. The results are again compared with the exact solution in Table II.

CONCLUSION

A simple method has been devised to simulate partial autofrettage residual stresses in thick walled cylinders.

TABLE II. COMPARISON OF σ_θ (PSI) WITH FINITE ELEMENTS

Percent Overstrain	r	Exact Solution	Finite Element (NASTRAN)
	1.025	- 80392	- 80638
	1.125	- 38795	- 38981
	1.225	- 4231	- 4375
	1.325	17727	17818
	1.425	16058	16143
30%	1.525	14707	14782
	1.625	13597	13671
	1.725	12675	12740
	1.825	11900	11964
	1.925	11243	11307
	1.025	-130910	-131102
	1.125	- 85128	- 85261
	1.225	- 47361	- 47454
	1.325	- 15490	- 15558
	1.425	11915	11872
60%	1.525	35856	35827
	1.625	51010	51136
	1.725	47551	47660
	1.825	44645	44754
	1.925	42179	42283
	1.025	-152950	-153095
	1.125	-105342	-105430
	1.225	- 66178	- 66228
	1.325	- 33215	- 33240
	1.425	- 4938	- 4941
100%	1.525	19709	19716
	1.625	41482	41496
	1.725	60939	60972
	1.825	78500	78538
	1.925	94484	94519

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1. Timoshenko, S. and Goodier, J. N., Theory of Elasticity, McGraw-Hill Co., 1951, 2nd Edition, p. 56.
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3. Boley, B. A. and Weiner, J. H., "Theory of Thermal Stresses," John Wiley & Sons, 1960.

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