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Finite Element Analysis of Thermally Autofrettaged Strain- Hardening Spherical Vessels

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Abstract

This study includes thermal residual stress prediction on an uniaxial loading-unloading stresses of strain hardening material model. FE analysis of thermal autofrettage process has been conducted for spherical vessel considering von Mises yield criterion to predict behaviour within the plastic zone of bilinear kinematic hardening material. The effect of changing load is investigated. Feasibility of Centrifugal and Centripetal autofrettage for kinematic hardening material are discussed and compared with elastic perfectly plastic material. Effect of re-autofrettage and Bauschinger effect on the FE model is examined in this study. The finite element results have been validated with previous work cited in the literature.

Keywords: Thermal Autofrettage, Re- Autofrettage, Spherical vessel ,Strain hardening, FE Analysis, Residual stress, Bauschinger effect.

INTRODUCTION

The autofrettage process can also be achieved by means of thermal stresses. Parker, A. P.[1] 2001, discussed Autofrettage of Open End Tubes. Paolo Livieri & Paolo Lazzarin[2], 2002, reportedanalytical solutions valid for residual stresses in cylindrical pressure vessels subjected to autofrettage. The influence on residual stresses, both of the hardening law and of the shape of the unloading σ-ε curve, is discussed. R.Thumse, J.W.Bergmann & M.Vormwald, [3] 2002, addressed the calculation of residual stresses due to autofrettage and the resulting increase of the endurance limit. It is shown that large plastic penetrations arising from bending and autofrettage can residually stress the section beyond its yield point in tension and in compression across both its halve. Anthony P. Parker[4]2004,In his procedure involved initial autofrettage; one or more ‘‘heat soak plus autofrettage’’ sequences and an optional final heat soak. Stresses are calculated numerically for traditional, single autofrettage and compared with those created by the new procedure. X. P Huang & W. C. Cui [5], 2006 ,showed an autofrettage model considering the

material strain-hardening relationship and the Bauschinger effect, based on the actual tensile-compressive stress-strain curve of material, plane-strain, and modified yield criterion, has been proposed. Hamid Jahed, Babak Ahmadi Moghadam & Mojtaba Shambooli ,[6],2006, conducted at plastic strains up to 3.4% for unloading and reloading. Re-autofrettage is the process of reapplication of overload pressure on an already autofrettaged tube.C. Levy a,*, M. Perl b,1, S. Kotagiri a , [7]2006 studies influence of the Bauschinger effect on the three-dimensional, Mode I, stress for arrays of longitudinal coplanar, surface cracks emanating from the bore of a thick walled cylinder is investigated. A. P. Parker & X. Huan [8]2007, numerically solved the analogous problem of a spherical, thick walled steel vessel. An equivalent new analytical solution for the case of a spherical vessel is also formulated. R. Adibi-Asl1& P. Livieri [9] ,2007 studied thedifferent material models incorporating the Bauschinger effect depending on the loading phase are considered in the present study. Some practical analytical expressions in explicit form are proposed for a bilinear material model and the modified Ramberg–Osgood model. M.H. Hojjati, A. Hassani,[10] 2007,studied the optimum autofrettage pressure and the optimum radius of the elastic–plastic boundary of strain-hardening cylinders in plane strain and plane stress theoretically and by finite-element modeling.Gibson, Amer Hameed, Anthony P. Parker, John G. Hetherington[13] discussed that general purpose finite element analysis for a range of end conditions: plane stress and several plane-strain states. Huang has developed a von Mises solution of an elastic-plastic tube. Thermal stress for spherical and cylindrical vessels in the elastic range are given in [14–17]. In [18] the behaviour of thick-walled spherical and cylindrical vessels under thermal and mechanical load is considered. The exact solution for the stress distribution in a thick-walled sphere made of elastic-perfectly plastic material and under a steady state, radial temperature gradient is obtained in [19]. Spherical vessels for various combinations of temperature and pressure and various radius ratios is studied in [20]. Elasto-plastic thermal stresses in a spherical vessel under a temperature gradient across the wall thickness are studied in [21]. M.H. Kargarnovin A. Rezai Zarei, H. Darijani. optimize the Wall thickness of thick-walled spherical vessel using thermo-elasto-plastic concept[22].

The autofrettage process can also be achieved by means of thermal stresses. The tests carried out were intended to determine whether the physical process of autofrettage was accurately simulated by the ANSYS model of strain hardening material, hence a simple bi-linear material representation was used, a simplistic bi-linear kinematic hardening material is used, as well as keeping the Young's and Tangent moduli constant in loading and unloading.

THEORETICAL CONCEPT

In the case of kinematic hardening, if the tensile stress reaches the value of σ_i during plastic deformations, then on unloading the yielding stress comes to a constant value of $2\sigma_y$ as shown in Fig.2.The strain -stress relations can be written in terms of the stresses, the coefficient of thermal expansion(α),the free-thermal strain and the plastic strain The radial and tangential stresses σ_r and σ_t must satisfy the equilibrium equation ,

$$\frac{d\sigma_r}{dr} - 2\frac{\sigma_t - \sigma_r}{r} = 0 \ldots\ldots\ldots\ldots\ldots (1)$$

The strain -compatibility relation,

$$\frac{d\varepsilon_t}{dr}+\frac{\varepsilon_t-\varepsilon_r}{r}=0.....(2)$$

The steady state temperature in the case of spherical symmetry is given by the well-known formula,

$$T=T_{r_o}+\left(T_{r_i}-T_{r_o}\right)\frac{r_o/r-1}{r_o/r_i-1}.....(3)$$

Accordingly to satisfy the Mises yield criterion'

$$\sigma_t-\sigma_r=\sigma_y.....(4)$$

For bilinear material ,Equivalent stress,

$$\sigma_i=\sigma_y+E_p\varepsilon_i^p.....(5)$$

$$E_p=\frac{E_tE}{E-E_t}.....(6)$$

$$\varepsilon_r^p=\frac{1}{E_p}(\sigma_r-\sigma_t).....(7)$$

$$\varepsilon_t^p=\frac{1}{2E_p}(\sigma_t-\sigma_r).....(8)$$

$$\varepsilon_r=\frac{1}{E}\left(\sigma_r+2\vartheta^e\sigma_t\right)+\alpha T+\varepsilon_r{}^p.....(9)$$

$$\varepsilon_t=\frac{1}{E}\left\{\left(1-\vartheta^e\right)\sigma_t-\vartheta^e\sigma_r\right\}+\alpha T+\varepsilon_t^p.....(10)$$

For the elastic-plastic sphere, the total strain in terms of stresses,

$$\varepsilon_r=\frac{1}{E}\left(\sigma_r+2\vartheta^e\sigma_t\right)+\alpha T+\frac{1}{E_p}(\sigma_r-\sigma_t).....(11)$$

$$\varepsilon_t=\frac{1}{E}\left\{\left(1-\vartheta^e\right)\sigma_t-\vartheta^e\sigma_r\right\}+\alpha T+\frac{1}{2E_p}(\sigma_t-\sigma_r).....(12)$$

The thermal strain -stress relations can be written in terms of the stresses, the coefficient of thermal expansion(α),

$$\sigma_r=\frac{E}{\left(1+\vartheta^e\right)\left(1-2\vartheta^e\right)}\left[\left(1-\vartheta^e\right)\left(\varepsilon_r-\alpha T-\varepsilon_r^p\right)+2\vartheta^e\left(\varepsilon_t-\alpha T-\varepsilon_t^p\right)\right].....(13)$$

$$\sigma_t=\frac{E}{\left(1+\vartheta^e\right)\left(1-2\vartheta^e\right)}\left[\left(\varepsilon_t-\alpha T-\varepsilon_t^p\right)+\vartheta^e\left(\varepsilon_r-\alpha T-\varepsilon_r^p\right)\right].....(14)$$

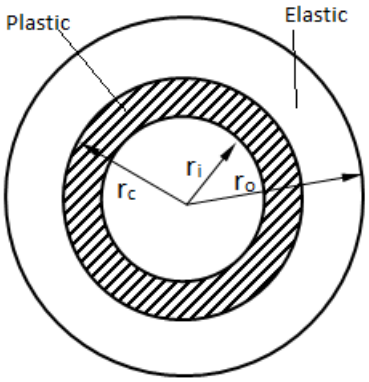

Figure1. First Elastic and plastic zone during loading

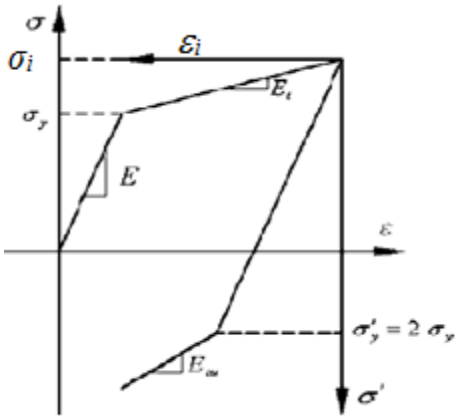

Figure 2. Stress Strain diagram : kinematic hardening

COMPARISON AND DISCUSSION

A bilinear kinematic hardening quadratic axis symmetric 8-node elements have been used for inelastic finite element analysis. The material properties used here, *E*=206 GPa, *Et*=*Etu*=10 GPa, σ_y=850 MPa, and ϑ =0.3,α=17.1×10^{-6}°C. An FEA procedure for simulating bilinear kinematic stress-strain behaviour during Thermal autofrettage has been implemented and investigated.

During first stage of centrifugal thermal loading The maximum positive values of σ_t occur in correspondence to the external fibre and The maximum negative values of σ_t occur to the internal fibre. radial stress is compressive and zero at inside and outside fiber. As the inner surface temperature Ti, increases for centrifugal flux, keeping To fixed, first elastic stresses occur throughout the entire thickness then, yielding initiates at the inner surface because the largest difference between σ_t and$\sigma_r$obviously occurs at the inner surface. next the yielding moves outward from the inner surface creating a plastic region between $r = r_o$ and $r = r_c$ (the elastic plastic interface radius),i.e., the region$r_i \leq r \leq r_c$.This first elastic/plastic boundary is shown fig.1. However, this plastic region does not just simply continue to grow until the entire shell is plastic as in the collapse analysis for inner- surface pressurization. The elastic- plastic interface radius is less than outside radius $(r_c < r_o)$. The plastic region expands outward with

increasing temperature gradient until a second yield surface develops at the outer surface. The two elastic- plastic boundaries grow closer as the inner temperature increases. For centrifugal flux unloading radial stress is tensile and zero at inside and outside fiber . Here maximum positive values of σ_t in correspondence to the internal fiber and negative to the external fiber. The residual stress distribution can be determined by using loading stress minus corresponding unloading stress ,i.e., $\sigma^R = \sigma^{load} - \sigma^{unload}$. Residual stresses for centrifugal flux (fig.3) are not suitable for increase in the pressure capacity of the component even at high temperature gradient because the centrifugal residual hoop stress is positive at the inner surface and negative near the outer surface, its change sign from positive to negative between r_i and r_o. The centrifugal residual radial stress is also positive sign and increase with temperature gradient.

For centripetal flux as the outer surface temperature, To, increases keeping inner surface temperature Ti fixed, maximum positive value of σ_t in correspondence to the internal fiber and negative to the external fiber . Loading centripetal thermal hoop and radial stress is shown in[Fig.5 and Fig.6]. The radial stress is zero at the inner surface and at the outer surface. In between the inside and outside surfaces, σ_r always tensile. first elastic stresses occur throughout the entire thickness then, yielding initiates at the inner surface. So For the centripetal flux also yielding initiates at the inner surface and then yielding moves outward from the inner surface creating a plastic region from $r = r_o$ to some growing radius $r = r_c$ in which$(r_c < r_o)$ until a second yield surface develops at the outer surface. So for centrifugal flux and centripetal flux yielding behaviour is identical for bilinear kinematic model. Von mises stress during centripetal loading is shown in figure.10 . After loading when temperature gradient is removed(Unloading) compressive residual stress is produced in sphere. But like loading during unloading also first reverse yielding is start near the bore but this re-auttofrettage radius is smaller than first the yielding radius of loading.

After loading when temperature gradient is removed(Unloading) compressive residual stress is produced in sphere. When considering Elastic -plastic loading with double plastic zone and unloading is Elastic -plastic unloading, four different zone along the thickness of vessel is created. The zones are following

i)At the outside radius loading plastic- unloading elastic,

ii)After the outside first zone loading elastic- unloading elastic ,it is second zone from outside.

iii)After the second zone from outside, loading plastic-unloading elastic, it is the third zone from outside, and

iv)Last or forth zone from outside ,loading -plastic-unloading plastic.

If we consider the loading is Elastic -plastic thermal loading with single plastic zone inside the bore and Unloading is completely elastic Unloading , then loading ,unloading and residual stress pattern from the ANSYS model for centripital temperature gradient. are showing in Fig. 3.8,3.10,and 3. 12 . A very close agreement can be seen between the mechanical and thermal autofrettage at the wall thickness, including at the bore. Now if we consider Elastic -plastic loading with single plastic zone and Elasto-plastic unloading ,it increase the residual

hoop stress near the bore and there is no considerable increase in hoop stress at the outside of the vessel. But when considering Elastic -plastic loading with double plastic zone[Fig.11] and Elasto-plastic unloading noticing considerable increase in hoop stress at the outside of the vessel. The yielding pattern of thermal load are not similar with the mechanical yielding .In thermal loading we are not able to increase the percentage of over strain so long during loading because yielding is start on outside radius and loosing benefits of autofrettage.fig.5. shows the residual hoop stress different condition of yielding. Fig.8.shows the residual hoop stresses and residual radial stresses for different temperature gradient.

Effect of Bauschinger effect on Thermal Residual stress

During loading only strain hardening occurs as the Bauschinger effect does not influence yield stress until load reversal commences, but in unloading both strain hardening and the Bauschinger effect influence yield stress. The Bauschinger effect is an unloading phenomenon. The Bauschinger effect occurs solely during unloading after plastic strain and defines the Bauschinger Effect Factor, β.This phenomenon is measured by the Bauschinger effect factor(BEF or bef),which is defined as the ratio of the yield strength after reverse loading to the initial yield strength:

$$BEF = \frac{\sigma_{\text{comp.y.p.after overstrain in tension}}}{\sigma_{\text{comp.y.p. initially}}}$$

Fig.9. showing effect of different Bauschinger effect factor on residual hoop stress and a large reduction in bore hoop stresses as a result of Bauschinger effect.With increasing Bauschinger effect factor residual compressive hoop stress is increase near bore.

CONCLUSION

Autofrettage procedure, previously proposed for kinematic hardening material by mechanical load, may also be created by Thermal load and Centripetal temperature gradient are more suitable for thermal Autofrettage than centrifugal thermal load. At higher temperature gradient yielding start at outside of the sphere, thus losing much of the potential benefit of autofrettage, because of the significant increase in tensile residual hoop stress at the outside diameter. During thermal autofrettage for kinematic hardening material ,Elastic- plastic unloading increase residual stress near the bore than only elastic unloading .The residual thermal stresses are also highly dependent on the Bauschinger effect. A large reduction in bore hoop stresses as a result of Bauschinger effect.

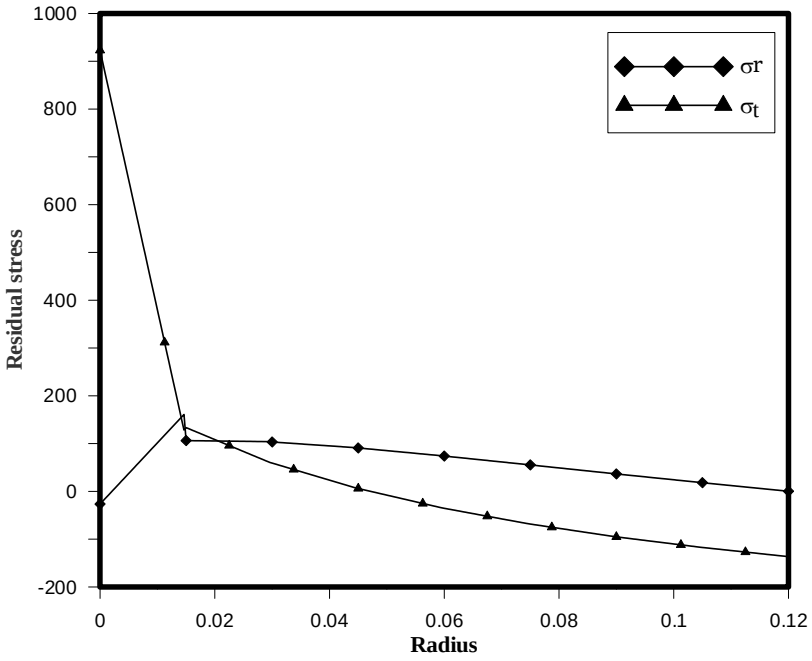

Figure3.Centrifugal Residual hoop and radial stress for k=2, T_O =41°C andT_i=482°C

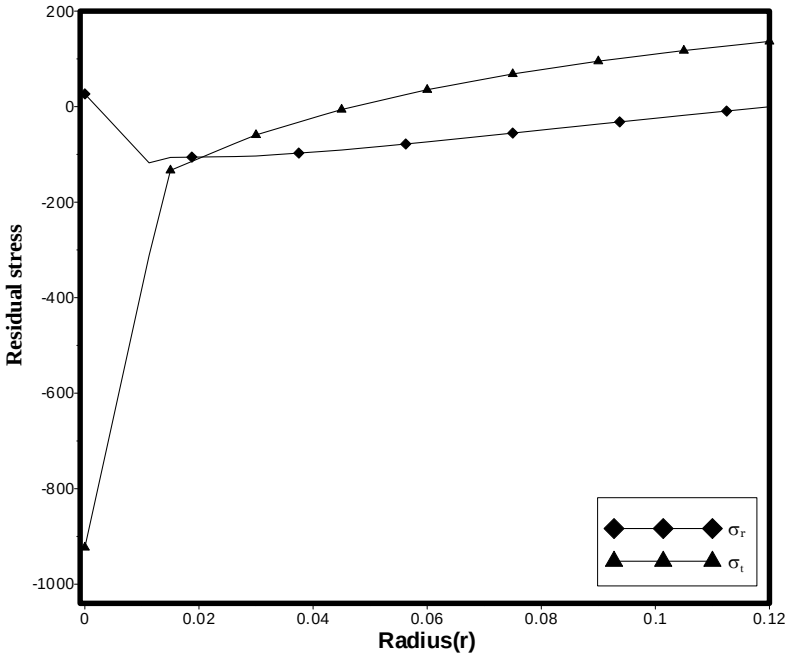

Figure 4.Residual stresses for centripetal flux,k=2,T_0=482°Cand T_i=41°C

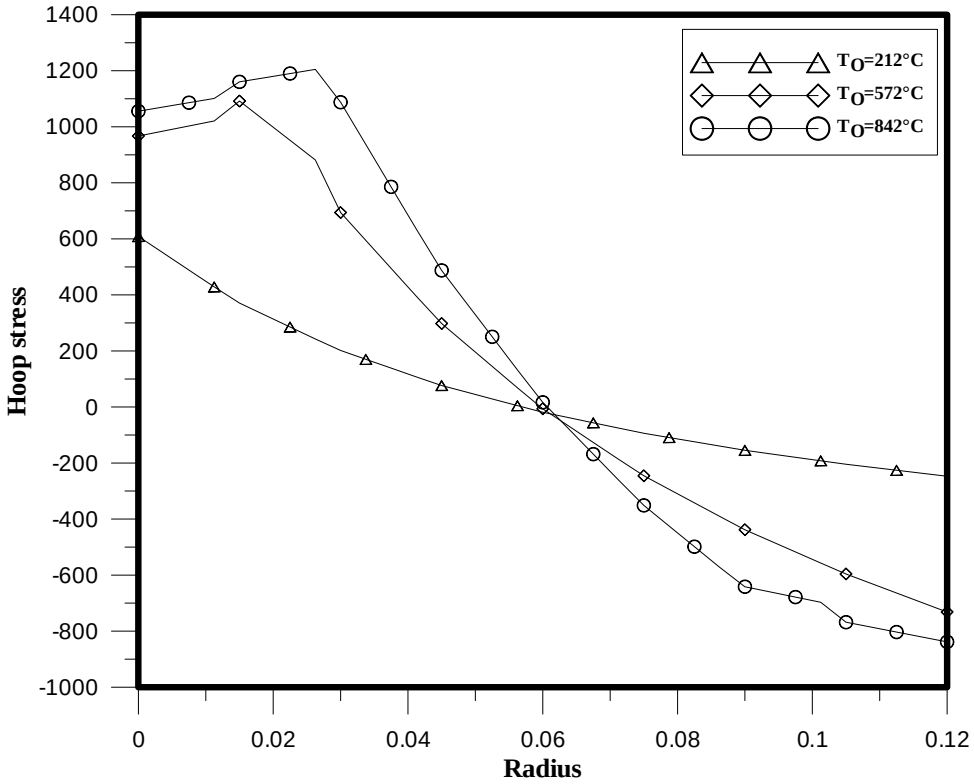

Figure 5.Different type of loading hoop stress for different type of loading condition .

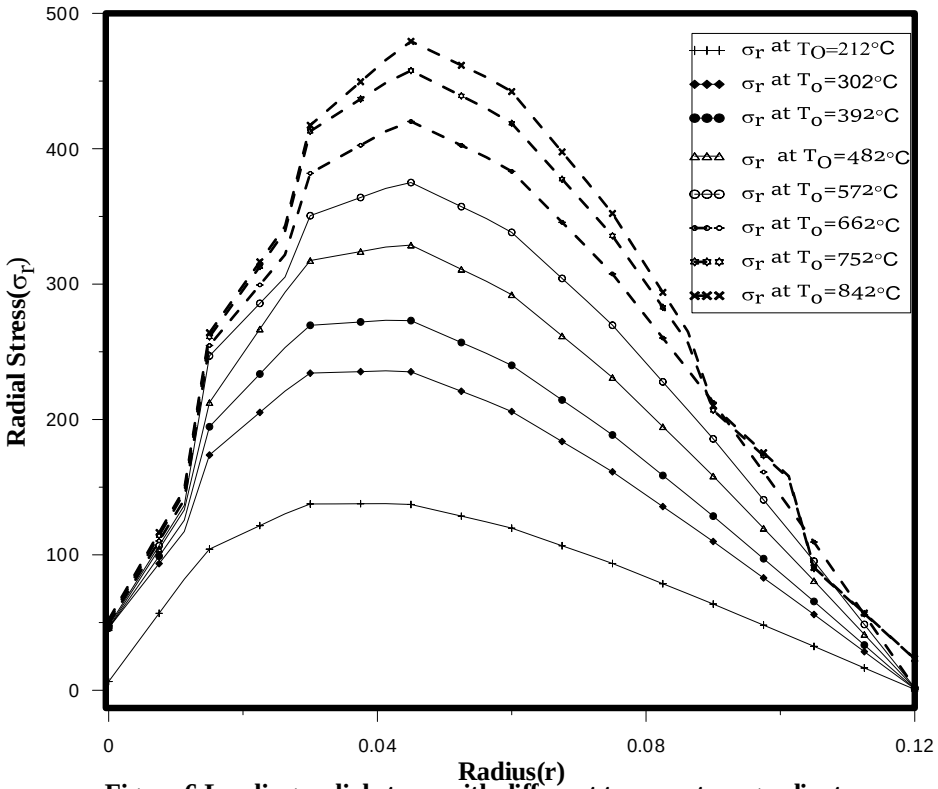

Figure 6.Loading radial stress with different temperature gradient, k=2 andT_i=41°C

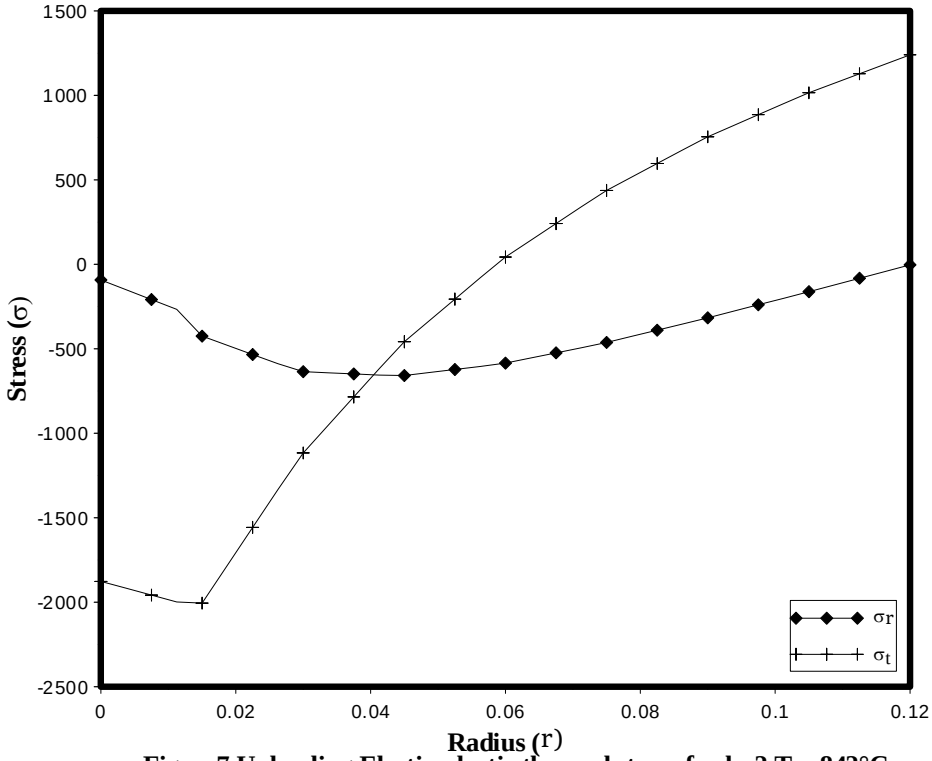

Figure7.Unloading Elastic-plastic thermal stress for k=2,T_o=842°C and T_i=41°C

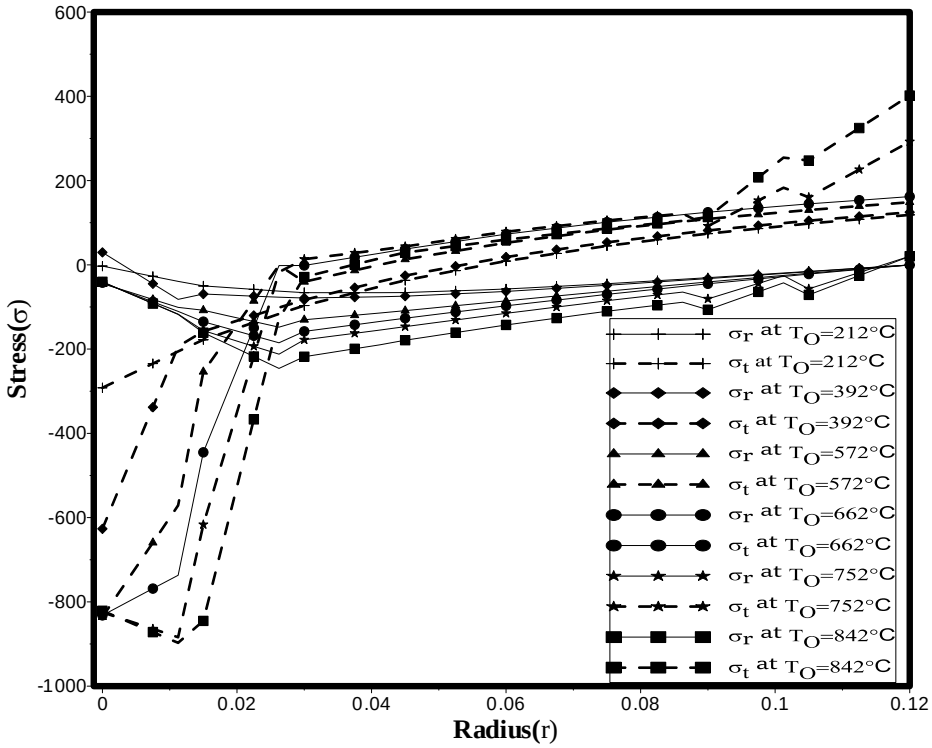

Figure8.Residual centripital thermal hoop and radial stresses with different temperature gradient,k=2,T_i=41°C

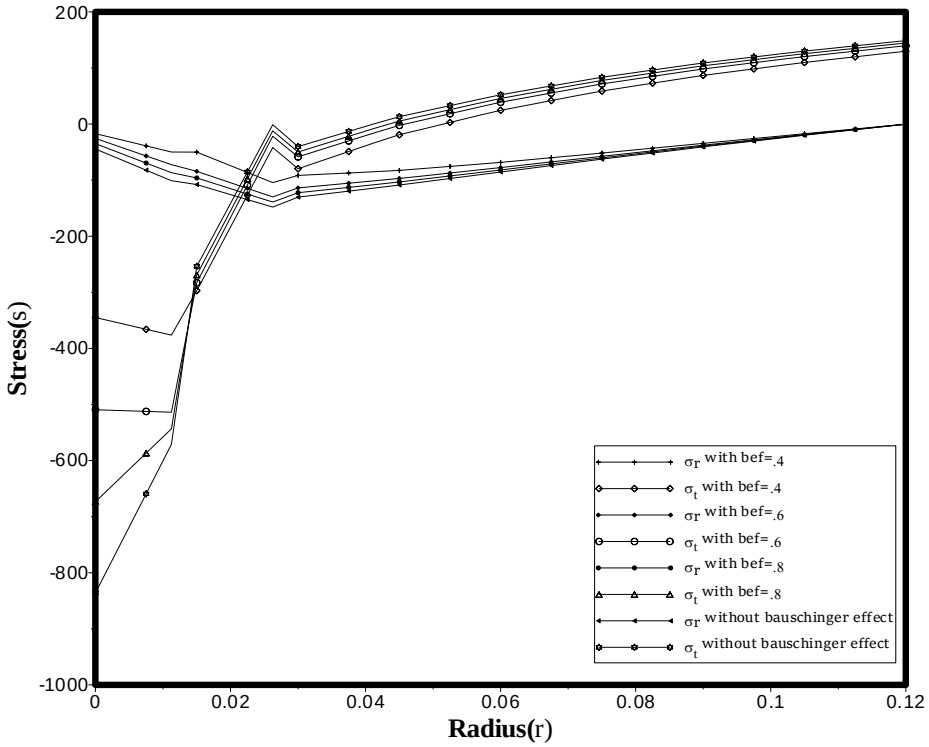

Figure.9. Residual thermal hoop and radial stresses with different Bauschinger effect factor

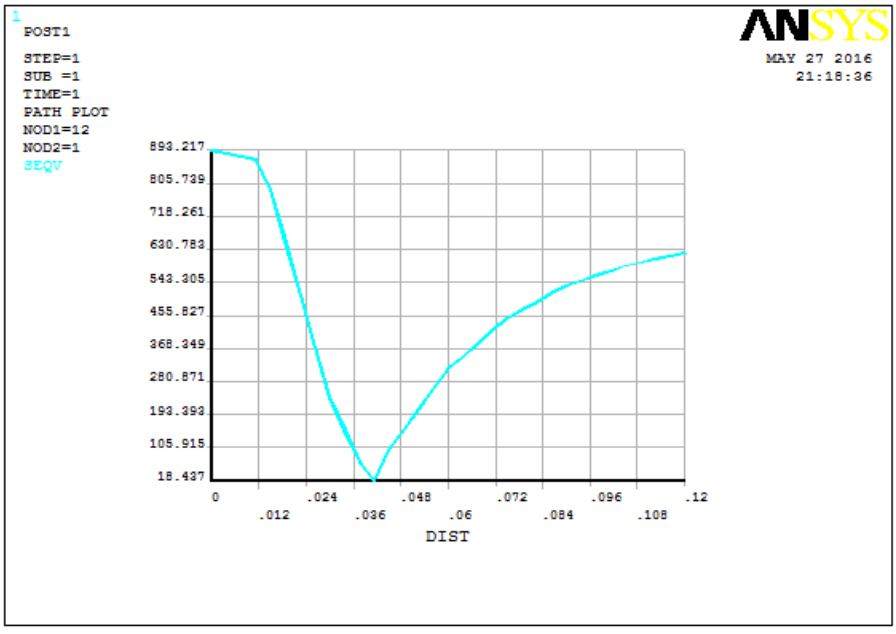

Figure10.Loading Von mises stress for centripetal flux To=482°C and Ti=41°C

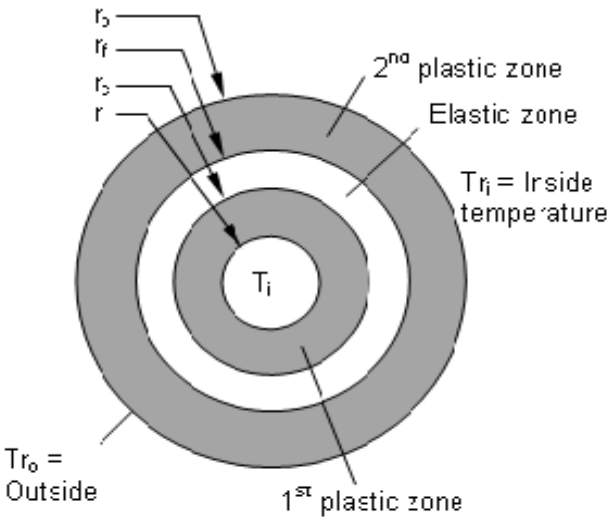

Figure11. Loading with two plastic zone

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NOMENCLATURE

r : Radius

r_o : Outside Radius

r_i : Inside Radius

r_c : Loading first yield radius

r_f : Loading second yield radius

r_d : Unloading yield radius

T_{r_o} : Outside radius temperature

T_{r_i} : Inside radius temperature

ε : Deformation (strain)

$\sigma_t, \sigma_\phi, \sigma_r$: Principal stresses

$\varepsilon_t, \varepsilon_\phi, \varepsilon_r$: Principal strain

σ_i : Equivalent stress

ε_i :Equivalent strain

σ_r : Radial stress

σ_t : Hoop stress,

ϑ : Poisson's ratio

E :Young's modulus / modulus of elasticity

E_t :Tangent modulus(loading phase)

E_{tu} :Tangent modulus (unloading phase)

E_p : Plastic modulus

u : Displacement

α : Coefficient of thermal expansion

σ_y : Loading Yield stress in tension

σ_y' : Unloading yield stress in compression

k : r_o / r_i