Manoj Sahni, Parth Dinesh Mehta

THERMO-MECHANICAL ANALYSIS OF SANDWICH CYLINDER WITH MIDDLE FGM AND BOUNDARY COMPOSITE LAYERS

TERMOMEHANIČKA ANALIZA SENDVIČ CILINDRA SA SREDNJIM SLOJEM OD FGM I GRANIČNIM SLOJEVIMA OD KOMPOZITA

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Adresa autora / Author's address:
Department of Mathematics, School of Technology, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat, India email: manojsahani117@gmail.com ; mehtaparths@gmail.com

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- functionally graded materials (FGM)
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Abstract

The study deals with finite element analysis of sandwich cylinder made up of functionally graded (FG) material in the middle layer and outer layers as composite materials. The cylinder is under the effect of mechanical and thermal loading. Young's modulus (i.e. elasticity modulus), thermal conductivity and coefficient of thermal expansion are varied in nonlinear form in functionally graded domain of the cylinder. The effect of thermo-mechanical loading, different material composition, and varying material properties on the behaviour of radial displacement, radial and tangential stresses is analysed. Performance of functionally graded cylinder with inner and outer composite layers is discussed with the help of graphical representation of stresses and displacement.

Ključne reči
- funkcionalni kompozitni materijal (FGM)
- Jungov modul elastičnosti
- termičko širenje
- koeficijent termičkog širenja
- unutrašnji pritisak
- napon
- pomeranje

Izvod

U radu je obrađen sendvič cilindar analizom konačnim elementima, a koji je sačinjen od funkcionalnog kompozitnog materijala (FGM) u srednjem sloju, i od kompozitnog materijala u vanjskim slojevima. Na cilindar deluju mehanička i toplotna opterećenja. Jungov modul elastičnosti, toplotna provodnost i koeficijent termičkog širenja se menjaju nelinearno unutar funkcionalnog kompozita cilindra. Analiziran je uticaj termomehaničkog opterećenja, različitog sastava materijala, kao i promenljivih osobina materijala, na ponašanje radijalnog pomeranja, radijalnih i tangencijalnih napona. Diskusija obuhvata performanse cilindra od funkcionalnog kompozitnog sloja i od slojeva kompozita, obrađena prema grafičkim rezultatima napona i pomeranja.

INTRODUCTION

An innovative class of composite material also known as functionally graded material (FGM) is an inhomogeneous material with combination of two or more materials with varying properties over the dimension of the body. FGMs have completely revolutionized the idea of composite materials by continuously varying the material properties and thereby effectively utilizing the material properties of combined materials. This innovative idea of functionally graded materials originated in 1984 during a space plane project in Sandai, Japan in which scientists were looking for a material that could provide thermal barrier to space plane body surface under severe temperature environment of 2000 K with temperature gradient of 1000 K across 10 mm section of the space plane body. Functionally graded materials provide both thermal resistance and strength to the structure by effectively utilizing the properties of combined materials. Functionally graded materials have wide application to many areas such as aerospace, defence, medical, automobile, energy sector, etc. By the virtue of material properties such as low density, high strength to weight ratio, high stiffness and elevated thermal capabilities, FGMs with metal matrix (such as Al, Ti, Mg) and ceramic (SiC, Al_2O_3, TiB_2) reinforcement are used in aircraft structures, diesel engine pistons, cylinder liners, brake drums, brake rotors, pressure vessels, etc. The continuous variation of material properties can be achieved by gradually varying the content of ceramic reinforcement in the metal matrix. The reinforcement phase of the material provides strength to the material by improving material strength and toughness whereas matrix phase required for transferring the load to reinforcement phase, provides temperature and chemical resistance. Thus, by using functionally graded materials instead of traditional composites, superior performance of engineering components can be achieved. Banking on the promise of these materials, scientists across the world have analysed the behaviour of functionally graded (FG) materials under different working environments such as temperature gradients, thermal, internal-external pressure, body forces such as rotating force, magnetic field, etc. The performance of engineering components such as cylinder (used in pressure vessels, turbine rotors, flywheels, delivery pipes, gun barrels, etc.) and disc (turbojet engines, centrifugal compressors, turbo generators, gears, etc.) made up of functionally graded materials are analysed. Literature review encompassing some of the notable work on analysis of functionally graded materials under severe working conditions are given below.

Hajisadeghian et al. /1/ evaluated the effect of magnetic field on thermo-mechanical elastic stresses in an axisymmetric double walled FG cylinder and presented closed form stress field solution. The study focused on reduction of stress quantity in cylinder with inner FG layer and outer composite layer. Mehta and Sahni /2/ reported an analysis validating the above study and presented a numerical solution for thermo-mechanical elastic stress field in such a sandwich cylinder with an exponential gradation of material properties. Dini et al. /3/ worked on sandwich disk composed of inner metal layer, middle FG layer and outer ceramic layer. The paper presented stress distribution in closed form for sandwich disk subjected to thermal, magnetic field, convection heat transfer and internal heat generation. Researchers have employed finite element method (FEM), variational asymptotic method (VAM), finite difference method (FDM) and various other numerical, analytical, and semi-analytical methods to obtain stress field in rotating FG cylinders and disks. A novel approach to obtain steady state 1D thermo-mechanical stress solution in a hollow thick FG cylinder using complementary functions method (CFM) was also found in the literature /4/. Habib et al. /5/ presented an analytical solution for stresses in FG cylinder subjected to thermo-mechanical loadings. Researchers /6-7/ extended the study of stress for FG rotating disc in plastic stage and reported thermo-elastic-plastic stresses using finite difference method (FDM) and Seth's transition theory. Engineering components that work under elevated temperatures undergo plastic and creep deformation. Study on performance of functionally graded rotating and internally-externally pressurized cylinder/disc under steady state creep stresses and strain rates provides significant amount of knowledge to avoid structure failure /8-9/. Sadrabadi et al. /10/ derived an analytical solution for estimating the yield onset related to elastic limit of stress in a thick-walled FG cylinder. The study highlighted effects of FGM parameters on yielding in cylinder under thermo-mechanical loading. Yıldırım /11/ provided comprehensive literature consisting of different material grading rules for annular structures under rotation and mechanical loading. The complementary functions method (CFM) illustrated the effectiveness of increasing ceramic layer towards the outer surface of the structure under internal pressure and under the influence of elastic stress fields. Mehta and Sahni /12/, conducted analytical and numerical analysis for studying the impact of linear and quadratic temperature distribution profile on behaviour of internally pressurized FG rotating disc with tailored material properties. FGMs can be used as an interfacial zone to improve material performance by continuous gradation of different material phases, where one or two of them are ceramics and the others are metal alloy phases. In our study, a sandwich cylinder with functionally graded material as middle layer, whereas composite material at inner and outer layer is analysed. The material in central layer is graded exponentially and the behaviour of stress field in sandwich cylinder with different material composition, and subjected to thermal loading together with internal pressure, is studied using finite element method.

MATHEMATICAL FORMULATION OF STRESS ANALYSIS

Consider an axisymmetric cylinder with three material domains as shown in Fig. 1. The domains of cylinder are divided in such a way that inner and outer layers are made up of composite material Al-SiC_p 10%, whereas the middle layer is of functionally graded material, reinforced with 30%, 35% and 40% of ceramic SiC_p in Al metal matrix at $r = b$ and 10% SiC_p ceramic at $r = c$. The sandwich cylinder has inner and outer composite layers of radius $r = a$ to $r = b$ and $r = c$ to $r = d$, respectively. The material properties in middle functionally graded layer of the cylinder, namely, Young's modulus, thermal conductivity and coefficient of thermal expansion are varied exponentially from radial points $r = b$ to $r = c$, given as

$$Y(r) = Y_F \exp\left(p_1 \left(\frac{r}{b}\right)^{m_1} \right), \tag{1}$$

$$\lambda(r) = \lambda_F \exp\left(p_2 \left(\frac{r}{b}\right)^{-m_2} \right), \tag{2}$$

$$\alpha(r) = \alpha_F \exp\left(p_3 \left(\frac{r}{b}\right)^{-m_3} \right), \tag{3}$$

where: $Y(r)$, $\lambda(r)$ and $\alpha(r)$ are Young's modulus, thermal conductivity, and coefficient of thermal expansion, respectively, defined for functionally graded domain of the sandwich cylinder, i.e. from $r = b$ to $r = c$. Also, m_1, m_2 and m_3 are material gradient parameters, whereas p_1, p_2 and p_3 are control parameters. Also, Y_F, λ_F and α_F are Young's modulus, thermal conductivity and coefficient of thermal expansion, respectively, for functionally graded part of sandwich cylinder, reinforced with 30%, 35% and 40% of SiC_p in Al matrix. In first and third domain of the cylinder, Young's modulus Y_C, thermal conductivity λ_C and coefficient of thermal expansion α_C are considered for Al–SiC_p 10 % composite material which remain homogeneous throughout the first and third domain of the sandwich cylinder.

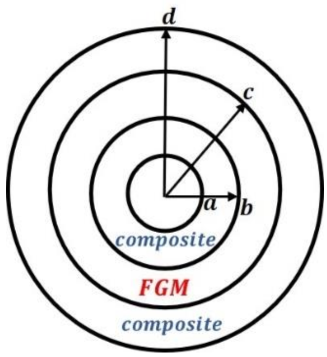

Figure 1. Functionally graded sandwich cylinder with boundary composite layers.

The governing differential equation for FG and homogeneous part of cylinder is given by /2/,

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0\,, \tag{4}$$

where: σ_r, σ_θ are radial and tangential stresses, respectively, varying with radial coordinate r.

The strain displacement relation /9/ is given as

$$\varepsilon_r=\frac{du}{dr} \quad\text{and}\quad \varepsilon_\theta=\frac{u}{r}\,, \tag{5}$$

where: ε_r, ε_θ and u are radial strain, tangential strain, and displacement, respectively. The compatibility condition obtained by eliminating u from the above equation is

$$\varepsilon_r=\varepsilon_\theta+r\frac{d\varepsilon_\theta}{dr}\,. \tag{6}$$

The constitutive relation for thermoelastic behaviour of sandwich cylinder under the plane stress condition $\sigma_z = 0$, can be given as /1/,

$$\varepsilon_r=\frac{1+\upsilon_k}{Y_k(r)}[(1-\upsilon_k)\sigma_r-\upsilon_k\sigma_\theta]+(1+\upsilon_k)\alpha(r)T(r)\,, \tag{7}$$

$$\varepsilon_\theta=\frac{1+\upsilon_k}{Y_k(r)}[(1-\upsilon_k)\sigma_\theta-\upsilon_k\sigma_r]+(1+\upsilon_k)\alpha(r)T(r)\,, \tag{8}$$

where: $T(r)$ is temperature field; and ν_κ is Poisson's ratio. Also, Poisson's ratio, $\nu_k = \nu_F = \nu_C = 0.3$, where $k = F$, or $k = C$ represents relation for functionally graded and composite part of the cylinder.

Using Eqs.(5), (7) and (8), stress components in radial, tangential and axial directions, respectively, can be obtained as,

$$\sigma_{r_k}=Y_k(r)[C_1\varepsilon_r+C_2\varepsilon_\theta-C_3\alpha(r)T(r)]\,, \tag{9}$$

$$\sigma_{\theta_k}=Y_k(r)[C_1\varepsilon_\theta+C_2\varepsilon_r-C_3\alpha(r)T(r)]\,, \tag{10}$$

where: $C_1=\dfrac{(1-\upsilon_k)}{(1+\upsilon_k)(1-2\upsilon_k)}$; $C_2=\dfrac{\upsilon_k}{(1+\upsilon_k)(1-2\upsilon_k)}$; and $C_3=\dfrac{1}{1-2\upsilon_k}$.

Thermal loading in radial direction in sandwich cylinder induced by temperature difference and thermal conductivity can be modelled using heat conduction equation given by /1/,

$$\frac{1}{r}\frac{d}{dr}\left[r\lambda(r)\frac{dT(r)}{dr}\right]=0\,, \tag{11}$$

where: $\lambda(r)$ is variable thermal conductivity in radial direction of functionally graded domain of the cylinder. As shown in Fig. 2, temperature field $T(r)$ is uniform for composite domains, whereas for functionally graded domain, it varies nonlinearly and can be obtained with the help of thermal conductivity given by Eq.(2), as well as by temperature difference at radial points b and c, respectively, given as

$$T(r)=T_b \quad\text{at}\quad r=b \quad\text{and}\quad T(r)=T_c \quad\text{at}\quad r=c\,. \tag{12}$$

The pressure boundary conditions on sandwich cylinder are defined as,

$$\sigma(r)=-P_a \quad\text{at}\quad r=a \quad\text{and}\quad \sigma(r)=-P_d \quad\text{at}\quad r=d\,, \tag{13}$$

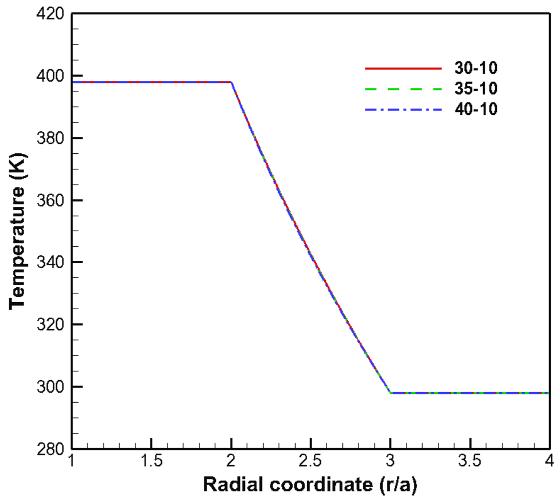

Figure 2. Temperature distribution in sandwich cylinder.

From Eqs.(4), (5), (9), and (10) we get,

$$C_1\left[\frac{dY_k}{dr}\frac{du}{dr}+Y_k(r)\frac{d^2u}{dr^2}\right]+C_2\left[\frac{dY_k}{dr}\frac{u}{r}+Y_k(r)\left(\frac{ru'(r)-u(r)}{r^2}\right)\right]+$$
$$+C_3\left[\frac{dY_k}{dr}\alpha_k(r)T(r)+\frac{d\alpha}{dr}Y_k(r)T(r)+\frac{dT}{dr}Y_k(r)\alpha_k(r)\right]+$$
$$+(C_1-C_2)\left[\frac{1}{r}\frac{du}{dr}Y_k(r)-\frac{u}{r^2}Y_k(r)\right]=0\,. \tag{14}$$

Using the above Eq.(14) together with Eqs.(1)-(3), radial displacement for functionally graded and composite domains of sandwich cylinder can be obtained. Using the relation between displacement and stresses given by Eqs.(5), (9) and (10), we can obtain stresses in radial and tangential directions. Due to different compositions of material at interface layer, continuity conditions in terms of radial stress and displacement at interface points $r = b$ and $r = c$ in functionally graded and homogeneous part are defined as,

$$\sigma_{r_C}(r=b)=\sigma_{r_F}(r=b)\,,$$
$$u_{r_C}(r=b)=u_{r_F}(r=b)\,,$$
$$\sigma_{r_F}(r=c)=\sigma_{r_C}(r=c)\,,$$
$$u_{r_F}(r=c)=u_{r_C}(r=c)\,. \tag{15}$$

NUMERICAL ANALYSIS

The above differential Eq.(14) with appropriate pressure, temperature boundary conditions Eqs.(12)-(13), and continuity conditions Eq.(15) have been solved numerically by using FEM based solver, COMSOL Multiphysics (5.4). The material properties, namely Young's modulus, thermal conductivity and coefficient of thermal expansion are defined using global analytical functions for the functionally graded domain of the sandwich cylinder. The governing differential Eq.(14) for sandwich cylinder is solved using axisymmetric geometric condition. The domain of sandwich cylinder is discretized with triangular elements of extremely fine element size. A coarser meshing of sandwich cylinder with 15462 domain elements and 1228 boundary elements is considered. The displacement and temperature field are discretized using quadratic shape function. Thermo-mechanical stresses are evaluated using heat transfer and solid mechanics module with appropriately defined pressure and temperature boundary conditions. The model is solved using linear direct PARDISO solver (capable of solving symmetric and nonsymmetric matrices) and results for stresses and displacement are obtained with relative tolerance of 10^{-6}. Finally, parametric sweep is applied to the model for obtaining plots of stresses and displacement in cylinder with different material compositions, i.e. 30%, 35% and 40% SiC_p reinforcement.

RESULTS AND DISCUSSION

Radial graphical representation of thermo-mechanical radial stress, tangential stress, and radial displacement for different particulate ceramic reinforcement of SiC is presented. Here, internal pressure P_a =25 MPa, whereas temperature loading in first and third domain made up of composite material is uniform, i.e., $T_a = T_b =$ 398 K, and $T_c = T_d =$ 298 K. The material constants /1/ in functionally graded domain for material with 30-10% SiC_p reinforcement are: m_1 = -0.779, m_2 = 0.236, m_3 = 0.253, p_1 = 1.2528, p_2 = -0.3806, p_3 = -0.4076, Y_F = 32.2 MPa, λ_F = 187.735 W/mK, and $\alpha_F = 27.81\times10^{6}$ K^{1}, whereas for 35-10% SiC_p reinforcement, m_1 = -0.922, m_2 = 0.302, m_3 = 0.324, p_1 = 1.4834, p_2 = -0.4864, p_3 = -0.5215, Y_F = 25.57 MPa, λ_F = 208.68 W/mK, $\alpha_F = 31.165\times10^{6}$ K^{-1}, and for 40-10% SiC_p reinforcement, m_1 = -1.052, m_2 = 0.371, m_3 = 0.398, p_1 = 1.6938, p_2 = -0.5972, p_3 = -0.6413, Y_F = 20.73 MPa, λ_F = 233.14 W/mK, and $\alpha_F = 35.133\times10^{-6}$ K^{-1}. Also, the parameters for homogeneous material properties in the first and third domain made up of composite material Al-10% SiC_p are considered as, Y_c = 112.7 MPa, λ_c = 128.3 W/mK, and $\alpha_c = 18.5\times10^{-6}$ K^{-1}.

EFFECT OF MECHANICAL LOADING

Radial stresses in sandwich cylinder with inner and outer composite layers, whereas middle domain made up of functionally graded material, are compressive under the effect of internal pressure as observed from Fig. 3. It can be seen that the compressiveness is higher at inner radius of the cylinder but starts to decrease in its magnitude as it goes along the outer radius of the cylinder. The effect of functionally graded material in middle region of cylinder can be clearly seen where the magnitude of radial stresses decreases and is lowest for the cylinder with 40-10% reinforcement of SiC_p.

Figure 4 presents tangential stress in FG cylinder with composite layers on its inner and outer side, respectively. It can be observed that tangential stresses are tensile in nature and decrease from r/a = 1 to r/a = 3. In third domain from r/a = 3 to r/a = 4, there is a slight increase in magnitude of tangential stresses at interface radii and decreases thereby. It can be noted that tangential stress in a cylinder with 40-10% reinforcement of SiC_p has higher magnitude in first and third domain but lower in the second domain. Also, discontinuity at the interface of second and third domain of the cylinder can be seen from the figure due to mismatch in material properties at that point. Displacement in the cylinder under internal pressure, as shown in Fig. 5, decreases throughout the radius of the cylinder. It can be observed that cylinder with higher reinforcement of SiC_p has higher magnitude of displacement along the entire radius of cylinder.

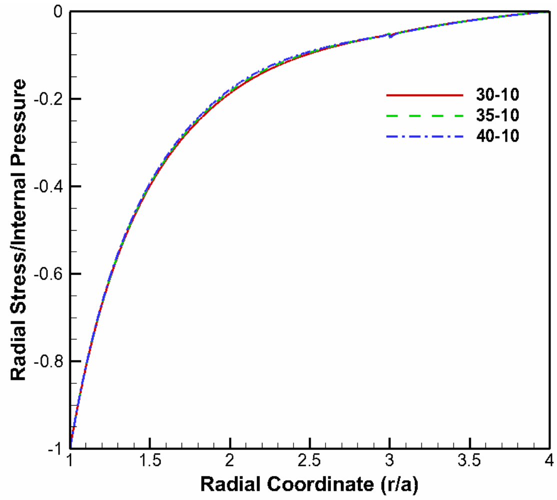

Figure 3. Radial stress under internal pressure P_a = 25 MPa.

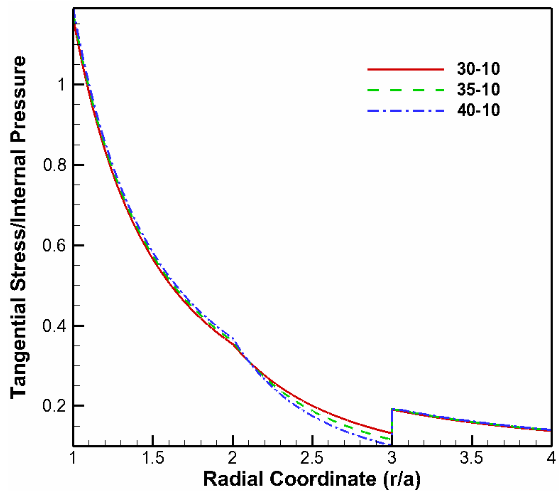

Figure 4. Tangential stress under internal pressure P_a = 25 MPa.

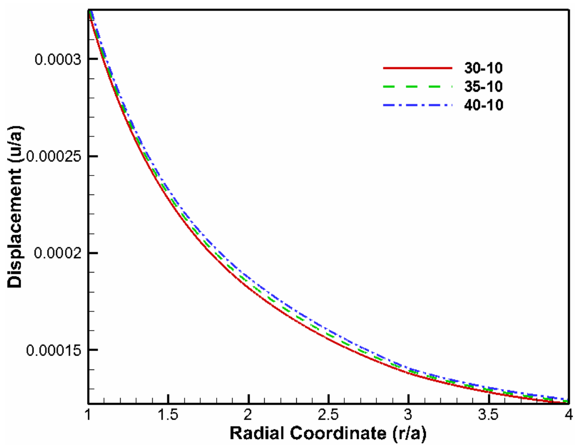

Figure 5. Displacement under internal pressure P_a = 25 MPa.

EFFECT OF THERMO-MECHANICAL LOADING

Radial stresses in cylinder under thermo-mechanical loading is depicted in Fig. 6. Radial stresses under thermo-mechanical loading become convex with presence of discontinuity at the interface of third domain. The magnitude of radial stress increases in first domain and decreases along the outer domains of the cylinder. The compressiveness of radial stress is found to be higher in the first domain of the cylinder. It is interesting to note that magnitude of radial stress from *r/a* = 2.8 in cylinder with 30-10% reinforcement of SiC_p is lowest as compared to 35-10% and 40-10% reinforcement cases. Figure 7 presents tangential stresses in a cylinder under thermomechanical loading. Tangential stresses under thermomechanical loading are compressive at inner radial points and become tensile towards the outer radius of the cylinder. It can be observed that compressiveness of tangential stress is higher for cylinder with 30-10% reinforcement case but decreases along the radius of the cylinder. The discontinuity at *r/a* = 3, due to mismatch of material properties, is found to be higher under thermomechanical loading. Displacement in a cylinder under thermomechanical loading increases from inner to outer radius and has lower magnitude under 30-10% reinforcement case at outer radial points, as seen in Fig. 8.

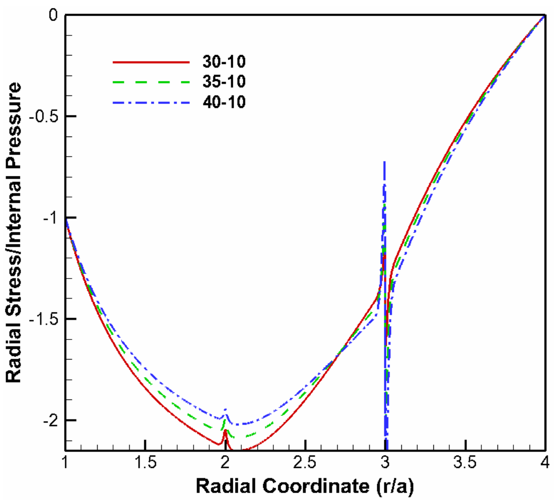

Figure 6. Radial stress under P_a = 25 MPa, $T_a = T_b$ = 398 K, and $T_c = T_d$ = 298 K.

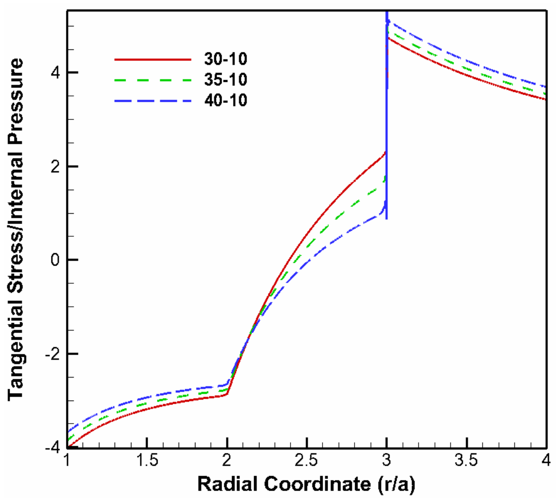

Figure 7. Tangential stress under P_a = 25 MPa, $T_a = T_b$ = 398 K, and $T_c = T_d$ = 298 K.

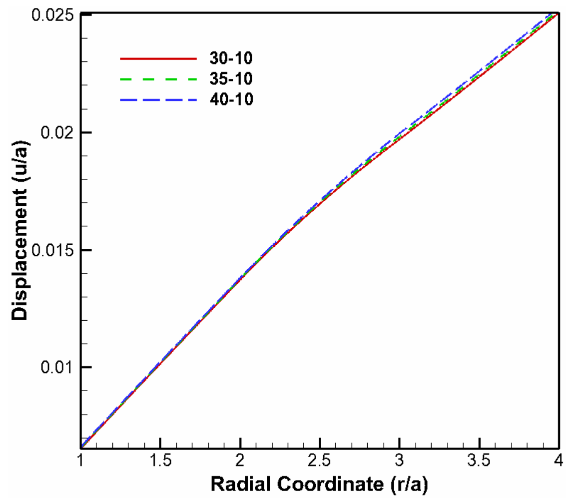

Figure 8. Displacement under P_a = 25 MPa, $T_a = T_b$ = 398 K, and $T_c = T_d$ = 298 K.

CONCLUSION

The study presents analysis of thick-walled functionally graded cylinder with inner and outer composite layers. Radial stress, tangential stress and radial displacement in an internally pressurized sandwich cylinder under thermo-mechanical loading are plotted and discussed. From the study, following outcomes can be concluded:

– Radial stress in a cylinder under mechanical loading and harder material reinforcement, i.e. 40-10% reinforcement of SiC_p at inner radii of second domain and outer domain of second domain, respectively, has lowest magnitude. Under thermo-mechanical loading, radial stresses are highly compressive at inner radial points of the cylinder. Also, magnitude of radial stress in cylinder with 40-10 % reinforcement of SiC_p is lower at inner radial points as compared to other reinforcement cases.
– Tangential stresses in sandwich cylinder under internal pressure, are tensile in nature. Tangential stress in cylinder with 40-10% reinforcement of SiC_p has the lowest magnitude in the second domain. Under thermo-mechanical loading, tangential stresses are compressive at inner radial points and become tensile at outer radial points. Magnitude of tangential stresses increase in the third domain of the cylinder. Also, due to mismatch of material properties at *r/a* = 3, singularity can be observed.
– Displacement in a sandwich cylinder under internal pressure, decreases from inner to outer radius but under thermo-mechanical loading, it increases from inner to outer radius.

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