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CREEP ANALYSIS IN COMPOSITE DISC IN THE PRESENCE OF THERMAL GRADIENTS

ANALIZA PUZANJA U KOMPOZITNOM DISKU U PRISUSTVU TEMPERATURSKIH GRADIJENATA

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Abstract

In the present work, an effort has been made to study the creep response in the isotropic/anisotropic FGM disc with constant thickness made of aluminium alloy based metal matrix composite containing silicon carbide particles in the presence of thermal gradients in the radial direction. The thermal gradient experienced by the disc is the result of breaking action as estimated by finite element method. The steady state creep behaviour of disc is analysed by Sherby's constitutive model. The creep response of rotating disc is expressed by a threshold stress with stress exponent value of 8. The creep parameters characterizing difference in yield stresses have been used from the available experimental results in literature. The results indicate that the stress and strain distributions in an isotropic/anisotropic rotating FGM disc are affected by thermal gradients. It is concluded that for designing a functionally graded material disc (FGM), the presence of thermal gradients needs attention from the point of view of steady state creep and the creep response in isotropic/anisotropic discs operating under thermal gradients are observed to be significantly lower than those observed in a disc without thermal gradients.

Izvod

U radu je prikazano ispitivanje ponašanja puzanja izotropnog/anizotropnog FGM diska konstantne debljine, napravljenog od kompozita sa matricom na bazi legure aluminijuma, sa česticama silicijum karbida, u prisustvu temperaturskih gradijenata u radijalnom pravcu. Temperaturski gradijent kojem je disk izložen je rezultat procesa loma, prema proračunu primenom metode konačnih elemenata. Ponašanje u uslovima stabilnog puzanja diska je analizirano primenom Šerbijevog konstitutivnog modela. Ponašanje pri puzanju rotirajućeg diska je izraženo preko praga napona sa eksponentom napona od 8. Parametri puzanja koji karakterišu razlike u naponima tečenja su dobijeni na osnovu eksperimentalnih rezultata dostupnih u literaturi. Ovi rezultati ukazuju na uticaj temperaturskog gradijenta na raspodelu napona i deformacija u izotropnom/anizotropnom rotirajućem FGM disku. Zaključuje se da je za projektovanje diska od funkcionalnog kompozita (FGM) potrebno obratiti pažnju na temperaturski gradijent, a u tim uslovima su ravnomerno puzanje i otpornost materijala značajno manji u odnosu na uslove bez temperaturskog gradijenta kod izotropnog/anizotropnog diska.

INTRODUCTION

Aluminium matrix composites reinforced with silicon carbide particles are attractive materials for a broad range of engineering applications: automotive, aircraft, sports, aerospace, rotors, turbines, pumps, compressors, flywheels, braking systems of automotive, railway and aerospace, and computer disc drives. All these engineering applications are usually operated at high thermal gradient and higher angular velocity. This gives rise to sufficiently high stresses and subsequent creep damaging effects in disc. Therefore, a number of functionally graded materials with property of superior heat resistance have been developed. Wahl et al. /1/ were the first to theoretically investigate steady state creep behaviour by a power function in a rotating turbine disc made of 12% chromium steel using von Mises and Tresca yield criteria, theoretically describing creep behaviour and comparing the results with experimental values. Arya and Bhatnagar /3/ studied creep deformation and stress distribution in rotating discs of orthotropic materials by assuming the creep rate to be a function of stress multiplied by a function of time (time-hardening law), expressions for stresses and creep-rates in radial and tangential directions. Mishra and Panday /4/ proposed that steady-state creep in aluminium-based composites could be described in a better way by Sherby's constitutive creep model, as compared to Norton's creep model. The steady-state creep behaviour of Al-SiCp composites under uniaxial loading condition in the temperature range between 623 K and 723 K for different combinations of particle size and volume fraction of reinforcement has been studied and found that the composite with finer particle size has better creep resistance than that containing coarser ones (Pandey et al., /5/). Durodola and Attia /6/ investigated the benefits of using different forms of fiber gradation in rotating hollow and solid FGM discs with constant thickness. It is noticed that the stress and deformation distribution can be modified by the different forms of property gradation with the same nominal volume fraction of reinforcement modification in FGM discs compared to uniformly reinforced discs. Singh and Ray /7/ studied creep analysis in an isotropic FGM rotating disc at uniform elevated temperature by using Norton's power law and concluded that the steady state creep response in FGM disc is significantly superior compared to a non-FGM disc. Orcan and Eraslan /8/ have studied that the stresses in rotating composite discs having variable thickness, with thickness decreasing from the centre towards the periphery, are much lower than those observed in a constant thickness disc. Gupta et al. /9/ have analysed steady state creep behaviour in isotropic disc by using Sherby's law and concluded that the strain rates in the constant thickness disc reduce significantly with decreased particle size and operating temperature and increasing particle content. Gupta et al. /10/ have analysed creep behaviour of a rotating isotropic disc made of FGM containing varying amounts of silicon carbide in the radial direction in presence of each type of gradient and concluded that steady-state strain rates in the rotating disc with the presence of gradients are significantly lower than that observed in an isotropic disc without gradients. The effect of anisotropy on stress and strain rates have been studied and concluded that the anisotropy of the material has a significant effect on creep of a rotating disc (Chamoli et al., /11/). The steady-state creep response of an isotropic FGM disc with constant thickness by using Sherby's constitutive model has been analysed and the results obtained for nonlinear variation of particle distribution along the radial distance of the disc are compared with that of discs containing the same amount of particle distributed uniformly or linearly along the radial distance (Rattan et al., /12/). Callioglu et al. /13/ studied stress analysis of functionally graded rotating annular discs subjected to temperature distributions parabolically decreasing with radius. They concluded that with increase in temperature, the tangential stress component gets decreased at the inner surface but increased at the outer surface, whereas the radial stress component gets reduced gradually for all the temperature distributions. The problem of rotating disc with variable thickness, thermal effect, heat generation effect and pressure by using Seth's transition theory has been studied (Thakur et al., /14-18/). Deepak et al. /19/ investigated the effect of varying disc thickness gradient (TG) on creep behaviour of rotating discs made of functionally graded materials with linearly varying. The discs contain silicon carbide particles in a matrix of pure aluminum. The study shows that with the increase in disc TG, the stresses decrease throughout the disc and the strain rates in the disc also reduce significantly. Gupta et al. /20/ discussed variation of Poisson ratios and thermal creep stresses and strain rates in an isotropic disc. Kaur et al. /21/ studied steady thermal stresses in a thin rotating disc of finitesimal deformation with edge loading. An attempt has been made to investigate steady state creep behaviour of thermally graded isotropic discs rotating at elevated temperatures. The results are compared with the disc having a uniform temperature profile from inner to outer radius and are displayed graphically in designer friendly format for the said temperature profiles. It is observed that there is a need to extend the domain of thermal gradation for designing rotating discs (Bose et al. /22-23/). A theoretical solution for time-dependent thermo-elastic creep analysis of a functionally graded thick-walled cylinder based on the first-order shear deformation theory is presented. The effects of the temperature gradient and FG grading index on the creep stresses of the cylinder are investigated. A numerical solution using finite element method is also presented and good agreement is found (Kashkoli et al. /24/). Keeping this in mind, the study ends with an effort to determine the plastic stress and strain analyses for the particle reinforced isotropic/anisotropic disc with constant thickness in the presence of thermal gradients and compare it with the isotropic/anisotropic disc operating under isothermal conditions. The analysis has been done by using von Mises criteria/Hill's criterion for yielding. The creep response of the disc under stresses developing due to rotation has been determined using Sherby's law. The material parameters of creep vary along the radial direction in the disc due to varying composition.

FINITE ELEMENT ANALYSIS OF THERMAL GRADIENT IN A COMPOSITE DISC

The temperature gradient originating due to the braking action of the discs has been obtained by Finite Element Analysis. For this purpose, the disc with inner radius of 31.75 mm, outer radius 152.4 mm, and thickness 5 mm is supposed. The FGM disc is assumed to rotate with an initial 15,600 rpm which is reduced to 15,000 rpm due to breaking action. An estimated heat flux of 130 kW/m^2 is applied over an annular area with inner radius of 142.4 mm and outer radius of 152.4 mm, while the remaining surfaces of the FGM disc are exposed to ambient conditions with convective heat transfer coefficient of 25 kW/m^2 and an ambient temperature of 303 K. For a particular ring, the thermal conductivity $K(r)$ is assumed to be constant and calculated using the rule of mixture as given below:

$$K(r)=\frac{[100-V(r)]K_m+V(r)K_d}{100}, \qquad (1)$$

where: matrix conductivity is K_m = 247 W/mK; and the dispersoid conductivity is K_d = 100 W/mK. The temperature $T(r)$, obtained at any radius r is presented below in the form of a regression equation as

$$T(r)=a_0+a_1r+a_2r^2+a_3r^3+a_4r^4+a_5r^5 \qquad (2)$$

where: coefficients a_0, a_1, a_2, a_3, a_4 and a_5 for different disc are taken from Gupta et al. /10/.

ASSUMPTIONS IN COMPOSITE DISC

Consider an aluminium silicon-carbide particulate composite disc of constant thickness h, having inner radius a and outer radius b, rotating with angular velocity ω (radian/s). From symmetry considerations, principal stresses are in the radial, tangential and axial directions. For the purpose of analysis, the following assumptions are made:

1. Stresses at radius of the disc remain constant with time i.e. steady state condition of stress is assumed.
2. Elastic deformations are small for the disc and can be neglected as compared to creep deformation.
3. Biaxial state of stress (σ_z = 0) exists at any point of the disc.
4. Frictional shear stress induced due to braking action is estimated to be 10^{-5} MPa, which is very small compared to creep stresses and, therefore, can be neglected.

5. The composite shows a steady state creep behaviour which may be described by following Sherby's law /21/,

$$\dot{\bar{\varepsilon}} = \left[M(r)(\bar{\sigma} - \sigma_0(r))\right]^n , \quad (3)$$

where: $M(r) = \frac{1}{E}\left(\frac{AD_\lambda \lambda^3}{|b_r|^5}\right)^{1/n}$ is the creep parameter; and $\dot{\bar{\varepsilon}}$, $\bar{\sigma}$, n, $\sigma_0(r)$, A, D_λ, λ, b_r, E are the effective strain rate, effective stress, stress exponent, threshold stress, a constant, lattice diffusivity, sub-grain size, magnitude of burgers vector, and Young's modulus, in respect.

The values of material parameters $M(r)$ and $\sigma_0(r)$ in terms of P, $T(r)$ and V are obtained from the creep results by using experimental results reported by Pandey et al., /3/ for Al-SiCp composite under uniaxial loading, using the following regression equations,

$$M(r) = e^{-35.38} P^{0.2077} T(r)^{4.98} V^{-0.622} , \quad (4)$$

$$\sigma_0(r) = -0.03507P + 0.01057T(r) + 1.00536 - 2.11916 . \quad (5)$$

In an FGM disc, creep parameters $M(r)$ and $\sigma_0(r)$ will vary radially due to variations in temperature $T(r)$. In the present study, the particle size (P) and particle content (V) are taken as 1.7 μm and 20 % over the entire disc. Thus, for a given FGM disc under known temperature, both creep parameters are functions of radial distance and their values $M(r)$ and $\sigma_0(r)$ at any radius r could be determined by substituting the values of particle size, particle content and temperature distribution into Eqs.(4) and (5), respectively.

MATHEMATICAL FORMULATION

The generalized constitutive equations for creep in an isotropic/anisotropic FGM disc under multiaxial stress take the following form

$$\dot{\varepsilon}_r = \frac{\dot{\bar{\varepsilon}}}{2\bar{\sigma}}\left\{(G+H)\sigma_r - H\sigma_\theta - G\sigma_z\right\} , \quad (6)$$

$$\dot{\varepsilon}_\theta = \frac{\dot{\bar{\varepsilon}}}{2\bar{\sigma}}\left\{(H+F)\sigma_\theta - F\sigma_z - H\sigma_r\right\} , \quad (7)$$

$$\dot{\varepsilon}_z = \frac{\dot{\bar{\varepsilon}}}{2\bar{\sigma}}\left\{(F+G)\sigma_z - G\sigma_r - F\sigma_\theta\right\} , \quad (8)$$

where: F, G and H are anisotropic constants of the material; $\dot{\varepsilon}_r$, $\dot{\varepsilon}_\theta$, $\dot{\varepsilon}_z$, and σ_r, σ_θ, σ_z are the strain rates and stresses, respectively in directions r, θ and z; $\dot{\bar{\varepsilon}}$ be the effective strain rate; and $\bar{\sigma}$ be the effective stress.

For biaxial state of stress (σ_r, σ_θ), the effective stress is

$$\bar{\sigma} = \left\{\frac{1}{\left(\frac{G}{F}+\frac{H}{F}\right)}\left[\sigma_\theta^2 + \frac{G}{F}\sigma_r^2 + \frac{H}{F}(\sigma_r - \sigma_\theta)^2\right]\right\}^{1/2} . \quad (9)$$

Using Eqs.(3) and (9), Eq.(6) can be rewritten as

$$\dot{\varepsilon}_r = \frac{d\dot{u}_r}{dr} = \frac{\left[\left(\frac{G}{F}+\frac{H}{F}\right)x(r) - \frac{H}{F}\right]\left[M(r)\left(\bar{\sigma} - \sigma_0(r)\right)\right]^8}{\sqrt{\frac{G}{F}+\frac{H}{F}}\left[\left(\frac{G}{F}+\frac{H}{F}\right)x(r)^2 - 2\frac{H}{F}x(r) + \left(\frac{G}{F}+\frac{H}{F}\right)\right]^{1/2}} \quad (10)$$

Similarly, from Eq.(7),

$$\dot{\varepsilon}_\theta = \frac{\dot{u}_r}{r} = \frac{\left[\left(1+\frac{H}{F}\right) - \frac{H}{F}x(r)\right]\left[M(r)(\bar{\sigma} - \sigma_0(r)\right]^8}{\sqrt{\frac{G}{F}+\frac{H}{F}}\left[\left(\frac{H}{F}+\frac{G}{F}\right)x(r)^2 - 2\frac{H}{F}x(r) + \left(1+\frac{H}{F}\right)\right]^{1/2}} , \quad (11)$$

$$\dot{\varepsilon}_z = -(\dot{\varepsilon}_r + \dot{\varepsilon}_\theta) , \quad (12)$$

where: $x(r) = \sigma_r/\sigma_\theta$ is the ratio of radial and tangential stresses at any radius r.

Dividing Eq.(10) by Eq.(11), we get

$$\phi(r) = \frac{\left(\frac{G}{F}+\frac{H}{F}\right)x(r) - \frac{H}{F}}{\left(1+\frac{H}{F}\right) - \frac{H}{F}x(r)} . \quad (13)$$

The equation of equilibrium for a rotating disc with varying thickness can be written as

$$\frac{d}{dr}(r\sigma_r) - \sigma_\theta + \frac{\rho(r)\omega^2 r^2}{g} = 0 , \quad (14)$$

where: $\rho(r)$ is the density of FGM disc.

Boundary conditions are

$$\sigma_r(a) = 0 = \sigma_r(b) . \quad (15)$$

Tangential stress (σ_θ) is obtained from Eq.(14) by using Eqs.(10) and (11),

$$\sigma_\theta = \frac{\psi_1(r)\left[A_0\sigma_{\theta_{avg}} - \int_a^b \psi_2(r)dr\right]}{M(r)\int_a^b \frac{\psi_1(r)}{M(r)}dr} + \psi_2(r) , \quad (16)$$

where:

$$\psi_1(r) = \frac{\psi(r)}{\left\{\left(\frac{1}{\frac{G}{F}+\frac{H}{F}}\right)\left[\left(\frac{G}{F}+\frac{H}{F}\right)x(r)^2 - 2\frac{H}{F}x(r) + \left(1+\frac{H}{F}\right)\right]\right\}^{1/2}} \quad (17)$$

$$\psi_2(r) = \frac{\sigma_0(r)}{\left\{\left(\frac{1}{\frac{G}{F}+\frac{H}{F}}\right)\left[\left(\frac{G}{F}+\frac{H}{F}\right)x(r)^2 - 2\frac{H}{F}x(r) + \left(1+\frac{H}{F}\right)\right]\right\}^{1/2}} \quad (18)$$

$$\psi(r) = \left\{\frac{\sqrt{\frac{G}{F}+\frac{H}{F}}}{r} \cdot \frac{\left[\left(\frac{H}{F}+\frac{G}{F}\right)x(r)^2 - \frac{2Hx(r)}{F} + \left(1+\frac{H}{F}\right)\right]^{1/2}}{\left[\left(1+\frac{H}{F}\right) - \frac{H}{F}x(r)\right]} \times \exp\int_a^r \frac{\varphi(r)dr}{r}\right\}^{1/8} \quad (19)$$

The average tangential stress may be defined as

$$\sigma_{\theta_{avg}} = \frac{1}{b-a}\int_a^b \sigma_\theta dr . \quad (20)$$

Now, $\sigma_\theta(r)$ can be obtained by integrating Eq.(13) within limits a to b,

$$\sigma_r(r) = \frac{1}{r}\left[\int_a^r \sigma_\theta dr - \frac{\omega^2 \rho (r^3 - a^3)}{3}\right]. \tag{21}$$

Thus, the tangential stress σ_θ and the radial stress σ_r are determined by Eqs.(16) and (21), respectively, for anisotropic disc with constant thickness. Then the strain rates $\dot{\varepsilon}_r$, $\dot{\varepsilon}_\theta$ and $\dot{\varepsilon}_z$ are calculated from Eqs.(10)-(12).

NUMERICAL COMPUTATION

The stress distribution is evaluated from the above analysis by iterative numerical scheme of computation. For rapid convergence, 75 % of the value of $\sigma_\theta(r)$ obtained in the current iteration is mixed with 25 % of the value of $\sigma_\theta(r)$ obtained in the last iteration for the use in the next iteration.

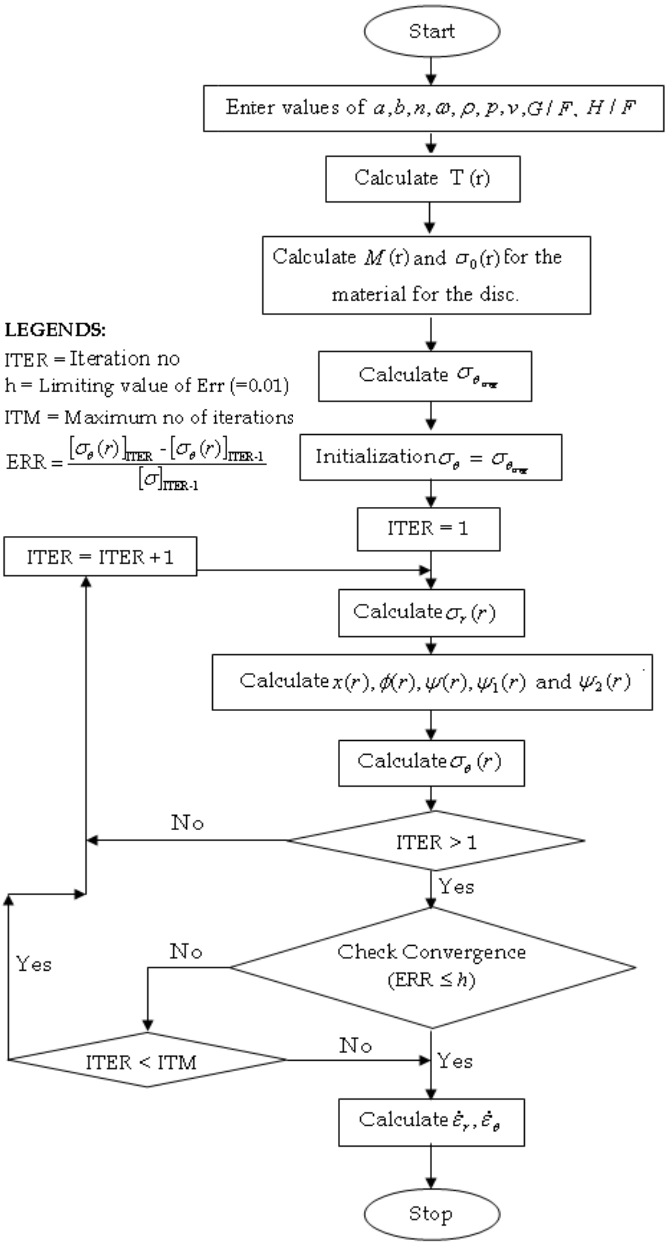

Figure 1. Numerical scheme of computation.

RESULTS AND DISCUSSION

A computer program based on the mathematical formulation has been developed to obtain the steady-state creep response of rotating isotropic/anisotropic FGM discs operating under thermal gradient. The ratios of anisotropic constants of a composite disc taken in this study as G/F = 1.34, H/F = 1.64, each deviating from isotropic constants G/F = 1, H/F = 1. For all the discs, the inner radii a and outer radii b are taken respectively as 31.75 mm and 152.4 mm. The stress exponent and density of disc material are taken as n = 8 and ρ = 2812.4 kg/m^3, respectively.

The disc is assumed to rotate at 15,000 rpm and operate under constant temperature of 623 K. To obtain the plastic stresses and strain rates, the results for a rotating steel disc are obtained by following the current analysis scheme for disc and operating conditions mentioned in Table 1. An excellent agreement between strain rates estimated using current analysis and those reported by Wahl et al. /1/ implies the validity of the present analysis as well as the software developed, as shown in Fig. 2.

Table 1. Experimental data from Wahl et al. /1/.

Parameters for steel disc	
Density of disc material	ρ = 2862.1 kg/m^3
Inner radius of disc	a = 31.75 mm
Outer radius of disc	b = 152.4 mm
Particle size	P = 1.7 μm
Uniformly distributed particle content	V_{avg} = 20 %
Young's modulus for Al	E_{Al} = 70 GPa
Young's modulus for SiC	E_{SiC} = 47 GPa
Density for Al	ρ_{Al} = 2713 kg/m^3
Density for SiC	ρ_{SiC} = 3210 kg/m^3
Isotropic constants	G/F = 1, H/F = 1
Anisotropic constants	G/F = 1.34, H/F = 1.64
Operating conditions	
Angular velocity of disc	ω = 15,000 rpm
Average temperature of disc	T = 623 K
Values of coefficients operating under thermal gradients	a_0 = 619.69, a_1 = 0.6083, a_2 = -0. 0208, a_3 = 3.27·10^{-4}, a_4 = -1.96·10^{-6}, a_5 = 4.43·10^{-9}

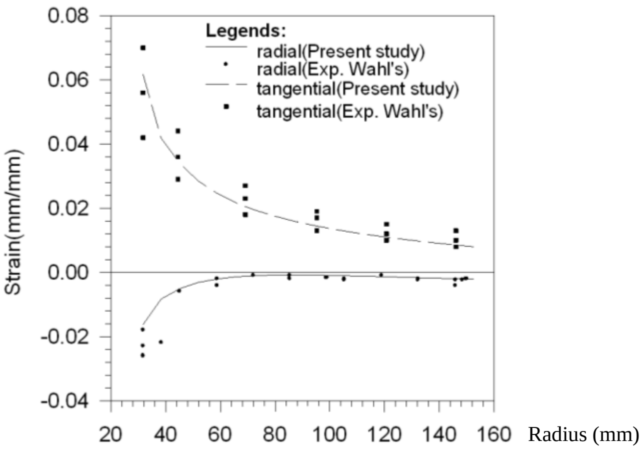

Figure 2. Comparison of theoretical (present study) and experimental strains in a rotating steel disc.

Figure 3 shows the distribution of temperature for composite discs in the presence of thermal gradients. The temperature observed in the FGM disc shows maximal variation near the outer radius. In the disc with thermal gradient, the temperature is highest at the outer radius and lowest at the inner radius, due to the heat flux towards the outer radius of the disc. The uniform disc has relatively lower values of temperature, compared to the values of the functionally graded disc in presence of thermal graded disc.

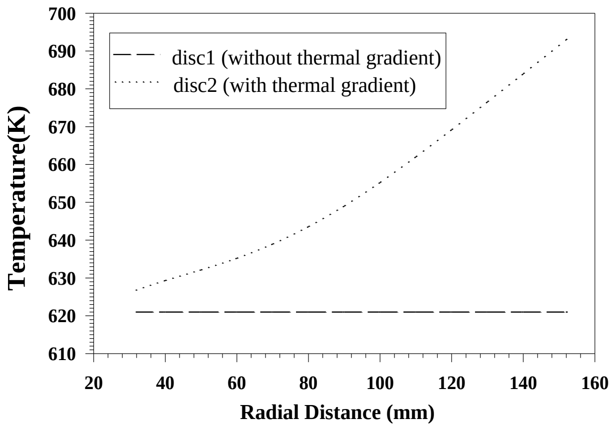

Figure 3. Variation of temperature in composite discs.

Figures 4 and 5 show the variation of material parameters $M(r)$ and $\sigma_0(r)$, respectively, along radial distance for different (non-FGM and FGM) composite discs.

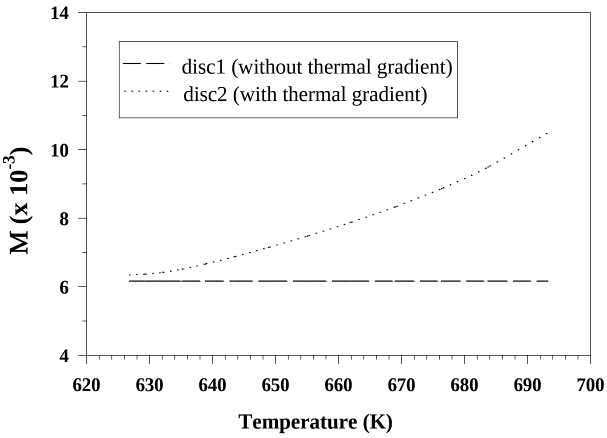

Figure 4. Variation of creep parameter in composite discs.

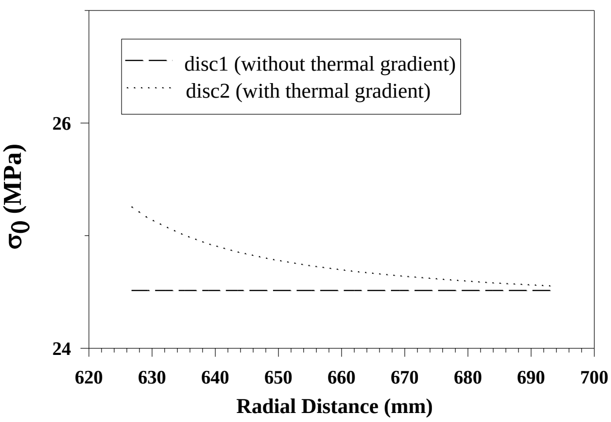

Figure 5. Variation of creep parameter in composite discs.

The parameter $M(r)$ is proportional to temperature. That is why a relatively higher temperature in FGM disc near the outer radius, compared to that observed near the inner radius, leads to slightly higher values of $M(r)$ near the outer radius, compared to that observed near the inner radius. Both material parameters, $M(r)$ and $\sigma_0(r)$ are observed to be constant over the entire non-FGM disc. But in the presence of the thermal gradient, the creep parameter $\sigma_0(r)$ decreases with increasing temperature along the radial distance. The threshold stress $\sigma_0(r)$ in the FGM disc decreases linearly by moving from inner to outer radius. The threshold stress in the presence of thermal gradient is maximum at inner radius and minimum at the outer radius in the composite disc shown in Fig. 5.

Figure 7 shows the tangential stress in an isotropic/anisotropic rotating FGM disc in the presence of thermal gradients and the results are compared with those without thermal gradients. It is concluded that in the isotropic/anisotropic discs, the tangential stress is a little higher in the region near the inner radius and slightly lower in the region near the outer radius in the presence of the thermal gradient as compared to the disc without thermal gradients. The primary reason for these changes in the distribution of tangential stress depends on the ratio of $\psi(r)$ at a given radial distance to its average value and multiplied by the average value of $\sigma_{\theta\,\mathrm{avg}}$ which depends on density, as shown in Eq.(16). The average value of $\sigma_{\theta\,\mathrm{avg}}$ does not depend on radial distance and so the variation of tangential stress will reflect only the variation of σ_θ. It is observed that the distribution of $\psi(r)$ in the non-FGM disc is higher near the inner radii and lower at the outer radii, compared to other FGM disc, as shown in Fig. 6.

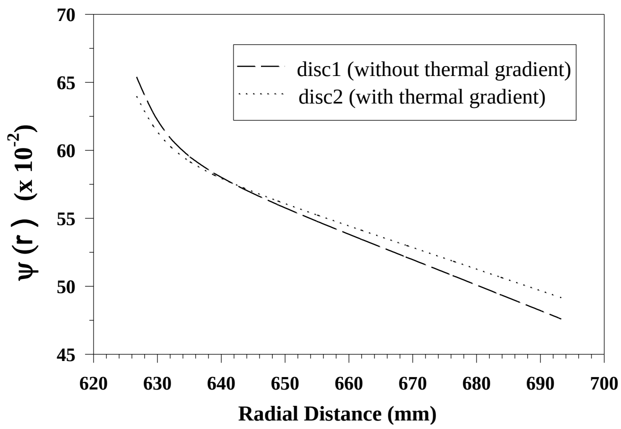

Figure 6. Variation of function $\psi(r)$ in composite discs.

Figure 9 shows that tangential strain rates decrease significantly over the entire radius in both isotropic/anisotropic discs operating under thermal gradients developed, compared to discs without thermal gradients. Clearly, the temperature over the entire radius of disc-2 dominates the creep behaviour compared to those observed in disc-1 under isothermal condition. Secondly, it is also noticed that change in magnitude due to thermal gradients in an anisotropic disc is somewhat smaller compared to that for an isotropic disc.

Although, the trend of variation of tensile strain rate in the tangential direction remains the same in the isotropic/anisotropic disc in the presence/absence of thermal gradients, but the magnitude can be reduced in an anisotropic disc.

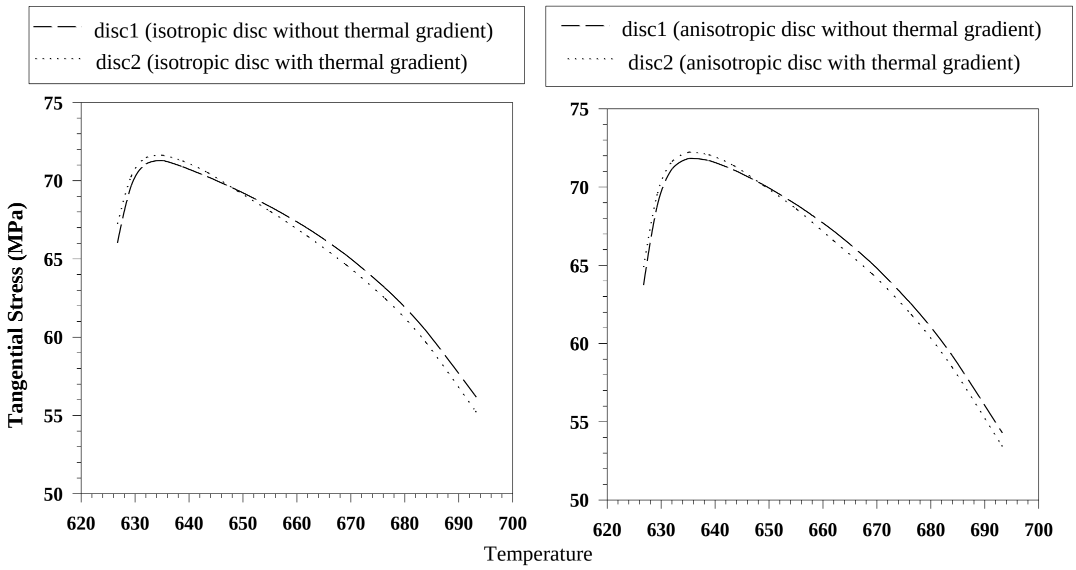

Figure 7. Variation of tangential stress along the temperature in composite discs with/without thermal gradient.

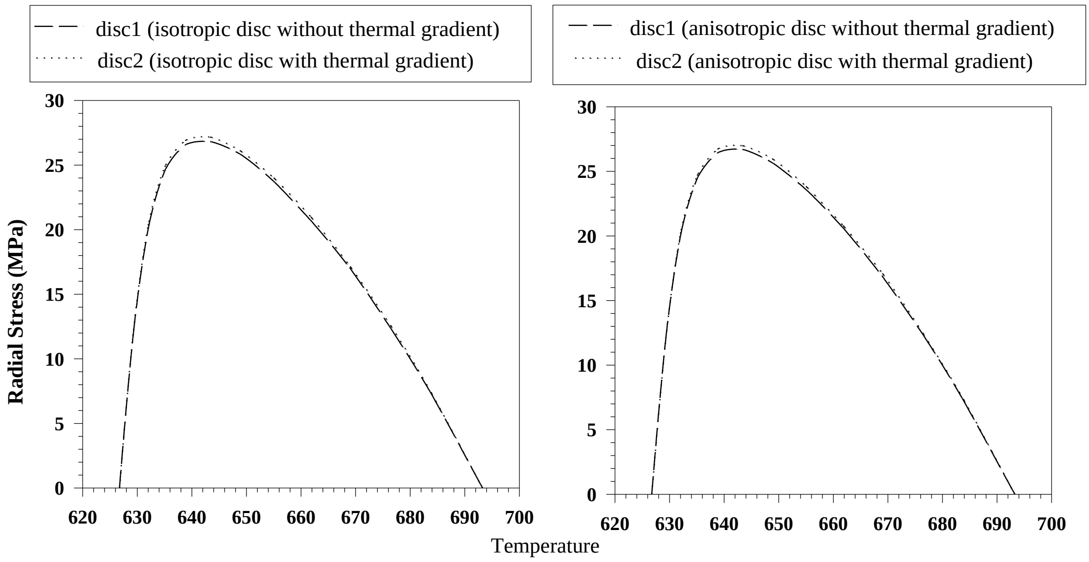

Figure 8. Variation of radial stress along the temperature in composite discs with/without thermal gradient.

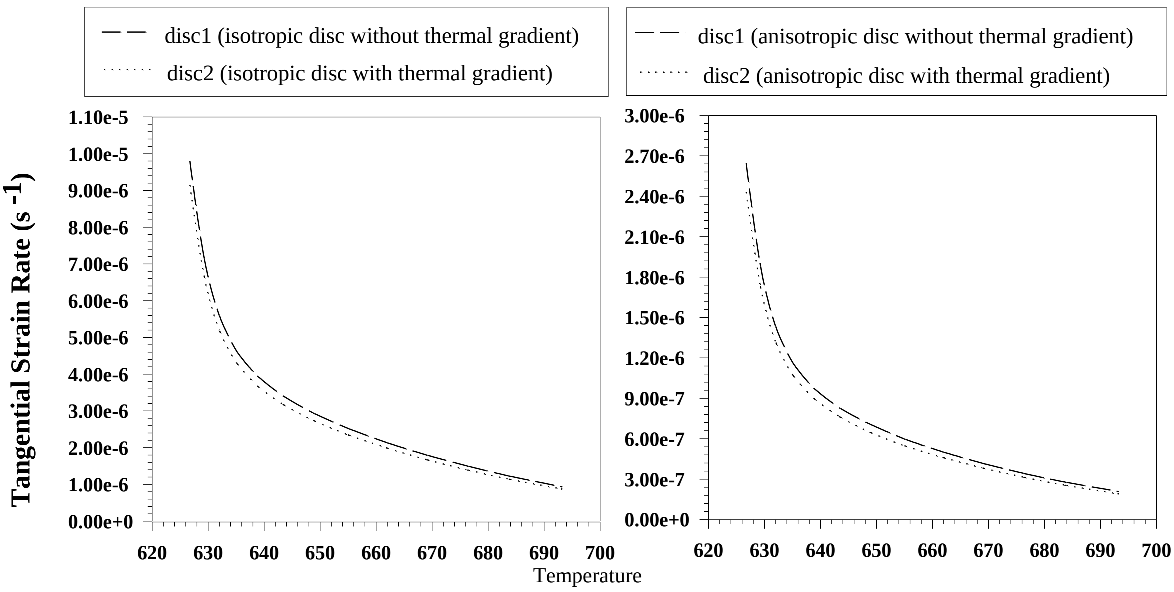

Figure 9. Variation of tangential strain rate along the temperature in composite discs with/without thermal gradient.

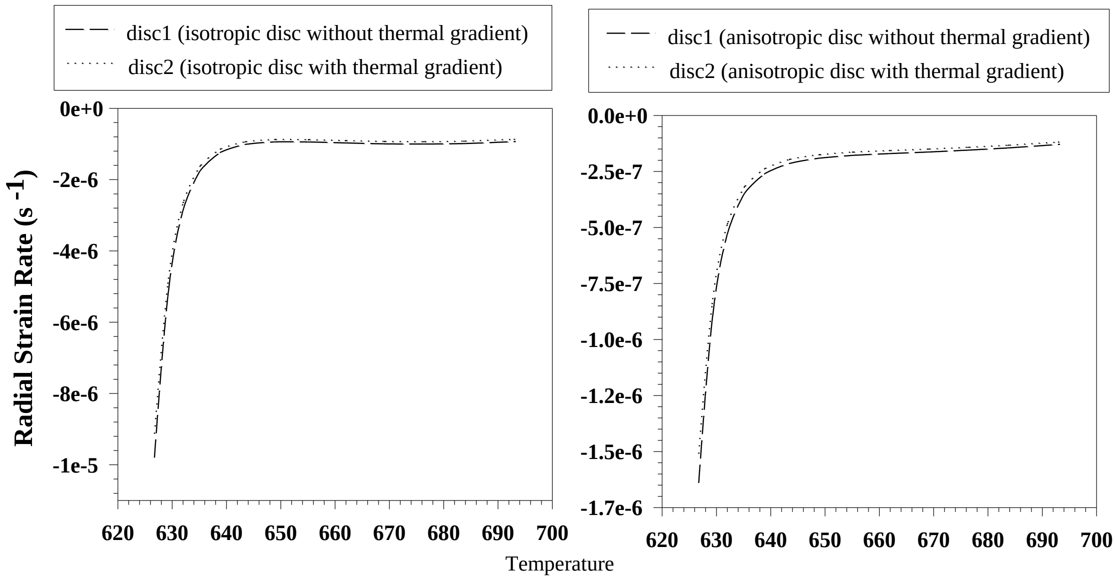

Figure 10. Variation of radial strain rate along the temperature in composite discs with/without thermal gradient.

Figure 10 shows that the effect of imposing thermal gradients on the radial strain rate in isotropic/anisotropic discs is similar to that observed for tangential strain rate. The magnitude of radial strain rate firstly increases rapidly with radial distance, and then starts decreasing. It reaches a minimum before increasing again towards the outer radius in both isotropic/anisotropic discs in the presence/absence of thermal gradients.

From the above discussion, it can be concluded that the strain rates decrease significantly over the entire radius in both isotropic/anisotropic discs operating under the thermal gradients, and it may lead to reducing the extent of distortion.

CONCLUSION

Based on the above results and discussion, the following main conclusions may be drawn:

- thermal gradients significantly affect the strain rate distribution in an isotropic/anisotropic particle reinforced disc having constant thickness, but its effect on the distribution of stresses is relatively small,
- the trend of variation of strain rates in tangential direction remains the same in both isotropic/anisotropic discs in the presence/absence of thermal gradients, but by taking the anisotropic disc under thermal gradients, the magnitude of strain rates is reduced by about one or two orders of magnitude compared to those for isotropic/anisotropic discs operating under isothermal conditions.

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