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Steady state creep behavior of thermally graded isotropic rotating disc of composite taking into account the thermal residual stress

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ABSTRACT

The present paper investigates the steady-state creep behavior of thermally graded isotropic disc rotating at elevated temperature. The composite discs are made of aluminum matrix reinforced with silicon-carbide particulate. The creep analysis is carried out using isotropic Hoffman yield criterion. The stress and strain rate distributions have been calculated for the discs. The creep parameters vary along the radius of the disc and have been estimated by regression fit of the available experimental data. Investigations for disc operating under linearly decreasing temperature from inner to outer radii has been done taking into account the phase-specific thermal residual stress. Further work has been done for discs operating under linearly increasing, parabolically decreasing and parabolically increasing temperatures. The results are displayed and compared graphically in designer friendly format for the above said temperature profiles. It is observed that there is a significant change in the stress distribution due to the presence of thermal residual stress. The radial strain rate is compressive for the discs operating at elevated temperature in the absence of residual stress, but due to the presence of residual stress the strain rate becomes tensile as one gradually moves along the radial distance and again becomes compressive near the outer radius. However, the presence of residual stress led to an increase in the tangential strain rate in the discs as compared to the discs without residual stress. Thus it is concluded that there is a need to extend the domain of thermal gradation in designing rotating discs.

1. Introduction

Processing of the composites often involves cooling from higher temperature resulting in thermal residual stresses in the matrix due to restraint imposed by reinforcements. Thermal residual stresses determinately affect the responses of materials thereby shortening their lifetime (Arsenault and Taya, 1987). The residual stress analysis is an important stage in the design of parts and structural elements as it significantly affects the engineering properties of materials and structural components, notably fatigue life, distortion, dimensional, corrosion resistance, brittle fracture, and so forth (Lohe et al., 2002). Thermal residual stresses exist within a body in the absence of external loading or thermal gradients. Residual stresses may be reduced or eliminated by annealing, by plastic deformation, or just by letting the piece at room temperature for enough time (Dieter, 1988). Because of its influence on the properties, the residual stress in composites has been the subject of several studies, both experimentally and analytically. During cooling, the alloy around ceramic particles contract more than the ceramic constituent and thus, there is a compressive thermal residual stress on the ceramic and a tensile thermal residual stress in the surrounding alloy (Singh and Rattan, 2010; Arsenault and Taya, 1987). A part of the matrix residual stress is relaxed by plastic deformation increasing the density of the matrix dislocation, which contributes to the strengthening of the composite. These residual stresses result in difference in yield stresses in tension and compression, which has led to the application of isotropic Hoffman yield criterion to describe yielding in isotropic materials Singh and Gupta (2013). A number of studies (Singh and Ray, 2003; Singh and Rattan, 2010; Singh and Gupta, 2011; Garg et al., 2013) on the creep analysis of rotating discs have been done because the creep deformation and stress distribution in a turbine disc have practical importance for gas turbine

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designers. Most of the studies are on the steady-state creep deformations. Few experimental data have been published on the creep of rotating discs (Wahl et al., 1954; Arsenault and Taya, 1987; Pandey et al., 1992).

Wahl et al. (1954) conducted creep tests for a rotating discs made of 12 percent chrome steel and simulated the results theoretically using von Mises and Tresca yield criteria. It was observed that, by using Norton's creep law, the creep deformation in a rotating disc based on Mises criterion yield slightly lower values as compared to the experimental values. However, the theoretical results based on maximum-shear theory, was found to be in a better agreement with the test values. Arsenault and Taya (1987) investigated the magnitude of the thermal residual stresses by determining the difference of the yield stresses between tension and compression resulting from the thermal residual stresses. Singh and Ray (2003) studied the processing of composite containing whiskers and short fibers, often resulting in anisotropy preferentially due to alignment of reinforcing element during flow of extrusion and proposed a new yield criterion which reduces to Hill anisotropic and Hoffman isotropic yield criterion. Singh and Gupta (2011) analyzed the steady state creep behavior of a functionally graded thick composite cylinder subjected to internal pressure in the presence of residual stress where the yielding of composite material was described by Hoffman's yield criterion. The results obtained were compared with a similar cylinder having yielding according to von-Mises yield criterion ignoring the presence of residual stress. It was revealed that the presence of residual stress in the FG cylinder, having linearly varying whisker content in the radial direction, the radial stress decreases slightly over the entire radius of the cylinder, whereas the tangential and axial stresses increased considerably near the inner radius but showed a significant decrease towards the outer radius. The presence of thermal residual stress in the cylinder lead to increase in the tangential as well as radial strain rate throughout the cylinder. Gupta et al. (2004) carried out the steady state creep in a rotating disc made of isotropic aluminium-silicon carbide particulate composite. The radial and tangential stresses and steady state creep rates in the disc have been calculated and presented for various combination of material parameters and temperatures. The study revealed that for given operating conditions, the strain rates in the disc could be controlled by selecting optimum particle content or particle size of the reinforcement.

Rattan et al. (2009) investigated the effect of stress exponent on steady state creep in an isotropic rotating disc made of aluminium silicon-carbide particulate composite. The creep behavior has been described by Sherby's model and the analysis of steady state creep was carried out by using von Mises' yield criterion. The stress and strain rate distributions developed due to rotation have been calculated and the study revealed that the stress exponent of 8 gave better approximation to experimental results than those of 3 and 5. Further, Singh and Rattan (2010) carried out the analysis of steady state creep in a rotating disc made of aluminum-silicon carbide particulate ($Al-SiC_p$) composite using isotropic Hoffman yield criterion and the results obtained were compared with those using von Mises yield criterion ignoring difference in yield stresses. It was observed that the stress distribution was not too much affected due to presence of phase specific thermal residual stress. The presence of residual stress has contributed to an increase in the tangential strain rate particularly in the region near the outer radius of the disc, as compared to the tangential strain rate in the disc without residual stress. The radial strain rate, which was compressive, changed significantly due to the presence of residual stress and even became tensile in the middle of the disc. It was thus concluded that the presence of residual stress significantly affected the creep in an isotropic rotating disc.

Garg et al. (2013) analyzed the steady state creep in a rotating disc made of composite containing silicon carbide particles (SiC_p) in a matrix of pure aluminium having linearly varying thickness in the presence of linear thermal gradient. It was indicated that the tangential stress increased near the inner radius but decreased towards the outer radius and the radial stress increased throughout when the functionally graded materials (FGM) disc was assumed to operate under a linear thermal gradient.

Rotating disc is a commonly encountered component in aero-engines, automobiles, turbines, pumps, compressors, flywheels and in a number of other dynamic applications. Thermal stress analysis in the composite discs is very important because of the wide range of applications. Thus, the present paper throws light on the steady state creep behavior of thermally graded rotating isotropic disc in the presence of thermal residual stress. The composite discs are made of aluminium matrix reinforced with silicon-carbide particulate. The creep analysis is carried out using isotropic Hoffman yield criterion.

2. Disc profile

Let us consider transversely isotropic annular disc of aluminium, Al, matrix reinforced with silicon carbide particles, SiC_p, having inner radius, $a = 0.03175$ m and outer radius, $b = 0.1524$ m. The volume fraction, V, of the reinforcement is considered to be 10 vol% fraction of the constituent material $Al-SiC_p$. Using the law of mixtures, the density variation in the composite is expressed as

$$\rho(r) = \rho_m + (\rho_d - \rho_m)\frac{V}{100} \tag{1}$$

where $\rho_m = 2713$ kg/m^3 and $\rho_d = 3210$ kg/m^3 are the densities of the matrix alloy and of the dispersed silicon carbide particles, respectively.

For the present study, the following types of discs have been considered;

(I) Disc D_1 operating at uniform temperature of 623 K.
(II) Discs D_2 and D_3 operating at linearly decreasing and linearly increasing temperature along the radial distance has distribution, $T(r)$ given as:

$$T(r) = A - Br,\ a \le r \le b \tag{2}$$

where

$$A = \frac{bT_a - aT_b}{b-a} \tag{3}$$

and

$$B = \frac{T_a - T_b}{b-a} \tag{4}$$

Here T_a and T_b are the imposed temperatures for linearly decreasing profile at the inner radius and outer radius respectively. The values of T_a and T_b for discs D_2 and D_3 are given in Table 1.

(III) Discs D_4 and D_5 operating at parabolically decreasing and parabolically increasing temperature along the radial distance has distribution, $T(r)$ given as:

$$T(r) = C - Dr^2,\ a \le r \le b \tag{5}$$

where