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CREEP RESPONSE OF ROTATING FUNCTIONALLY GRADED AL–SIC COMPOSITE DISCS UNDER THERMAL LOADING

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ABSTRACT

The present research paper investigates the creep deformation and stress distribution behavior of rotating functionally graded metal matrix composite (FGMMC) discs operating under elevated temperature conditions. Functionally graded materials (FGMs), particularly aluminum matrix composites reinforced with silicon carbide particles, have attracted significant attention in aerospace, automotive, and high-temperature engineering applications because of their superior thermal resistance, high strength-to-weight ratio, and improved creep resistance. The study focuses on the theoretical modeling and analysis of creep behavior in rotating composite discs subjected to thermo-mechanical loading and material composition gradients. A detailed review of classical creep theories, including Norton's law, Bailey–Norton law, time hardening, and strain hardening approaches, has been incorporated to establish the constitutive framework for creep analysis. The influence of threshold stress, stress exponent, activation energy, and reinforcement distribution on creep response has also been examined. The functionally graded characteristics of the composite disc are considered through gradual variation of reinforcement concentration along the radial direction, which helps in minimizing stress concentration and enhancing structural performance. The analysis demonstrates that creep strain rate, radial stress, tangential stress, and displacement distribution are strongly influenced by rotational speed, temperature gradient, reinforcement geometry, and material gradation profile. It is observed that functionally graded composite discs exhibit improved creep resistance and reduced stress concentration as compared to homogeneous discs. The study further highlights the significance of optimized reinforcement distribution for enhancing the service life and reliability of rotating components operating in severe thermal environments. The outcomes of this investigation may provide useful guidelines for the design and development of advanced rotating machinery components made from FGMMCs.

KEYWORDS: Functionally Graded Materials (FGMs), Creep Deformation, Rotating Composite Discs, Metal Matrix Composites (MMCs)

1.0 INTRODUCTION

Rotating discs are important structural components widely used in gas turbines, aircraft engines, turbochargers, flywheels, compressors, and other high-speed rotating machinery. During service, these components are frequently exposed to high rotational speeds and elevated temperatures, which generate significant thermal and mechanical stresses. Under such severe operating conditions, creep deformation becomes one of the major causes of structural failure and reduction in service life. Therefore, an accurate analysis of creep behavior and stress distribution in rotating discs is essential for safe and efficient design. In recent years, metal matrix composites (MMCs), particularly aluminum-based composites reinforced with ceramic particles such as silicon carbide (SiC), have gained considerable attention due to their superior mechanical properties, low density, improved wear resistance, and excellent high-temperature performance. Furthermore, the development of Functionally Graded Materials (FGMs), in which the composition of constituent materials varies continuously along a particular direction, has provided an effective solution to reduce stress concentration and improve thermal resistance. FGMs combine the advantages of both metallic and ceramic materials and are especially suitable for rotating components operating under thermo-mechanical loading.

A number of researchers have investigated creep behavior in homogeneous and composite rotating discs using different constitutive models such as Norton's law and Bailey–Norton creep law. However, studies related to creep deformation in functionally graded rotating composite discs are comparatively limited. The present study focuses on the theoretical investigation of creep behavior and stress analysis in rotating functionally graded metal matrix composite discs under elevated temperature conditions. The influence of reinforcement distribution, thermal gradients, and material parameters on creep response has been analyzed to improve the structural reliability and performance of advanced rotating systems.

2.0 CREEP MODELS

Most of the models representing uniaxial creep of metals and alloys are empirical, established after years of experimentation. These models have been widely used and implemented as options in several finite element codes. The models express uniaxial creep strain or creep strain rate as a function of stress, time and temperature, and some models also use the accumulated creep strain to model strain hardening. The mathematical form of these models is as given below,

$$\varepsilon = f(\sigma, t, T) \tag{1}$$

where ε is the creep strain, σ is the applied stress, t is the time period and T is the temperature of application.

The Eqn. (1) can also be written in the following form,

$$\varepsilon = f_1(\sigma).f_2(t).f_3(T) \tag{2}$$

Since the temperature during creep test is constant, therefore, Eqn. 2 becomes,

$$\varepsilon = f_1(\sigma).f_2(t) \tag{3}$$

Many empirical expressions, as a function of $f_1(\sigma)$ and $f_2(t)$, have been developed in the past. The most commonly used stress function law is Norton's law given as,

$$f_1(\sigma) = B\sigma^n$$

where B and n are the material constants. The approximation of a creep curve to a straight line is possible if secondary creep region is predominant, and elastic as well as primary creep is negligible. Under such conditions, it can be assumed that the creep strain rate depends upon stress function only. The time dependence of creep has been expressed in terms of Bailey's empirical law given by,

$$f_2(t) = A_1 t^m$$

where A_1 and m are the material constants.

For practical applications creep does not usually occur at a fixed temperature and stress over the entire life of component. Therefore, it is not possible to compute the creep strain directly from a uniaxial creep equation. The rules of time hardening and strain hardening have been developed to extend the constant stress and temperature creep equations to time-varying stress and temperature histories. The creep strain is determined by integrating the creep strain rate equations for changing stress and temperature conditions. To compute the creep strain rate at a particular instant, the mechanical and thermal loads as well as the material history must be known. Hardening rules specify the state of material as a function of loading history. In its simplest form, a creep-hardening rule might be looked upon as a method of moving between constant stress and temperature creep curves as the stress and temperature change. Two different hardening rules have been used with classical creep models: time hardening and strain hardening. When the creep rate equations are integrated for conditions of constant stress and temperature, both the hardening rules produce identical results, namely the uniaxial creep curve for that stress and temperature.

The time hardening theory states that for a constant temperature and variable stress condition, creep rate ($\dot{\varepsilon}_c$) is a function of stress and time *i.e.*,

$$\dot{\varepsilon}_c = f(\sigma, t) \qquad (4)$$

However, in case of strain hardening theory it is assumed that the creep rate is a function of stress and accumulated strain *i.e.*,

$$\dot{\varepsilon}_c = f(\sigma, \varepsilon) \qquad (5)$$

The particular forms of these laws can be obtained by assuming that the creep curve can be represented by Bailey-Norton law, which is a common representation of creep in the primary and secondary creep ranges under isothermal conditions and is given below,

$$\varepsilon_c = A\sigma^n t^m \qquad (6)$$

where A, m and n are constants whose values depend upon the type of material. The constant A, and exponents m (>1) and n (<1), should be functions of temperature. The form of Bailey Norton given by Eqn. (6) could be used to describe creep in both tension and compression, but it would be reasonable to expect that the parameters would be different in tension and compression. Since the value of exponent $n < 1$, therefore the creep rate at $t = 0$ could not be defined.

Differentiating Eqn. (6) with respect to time, the time hardening law can be obtained as,

$$\dot{\varepsilon}_c = \frac{d\varepsilon_c}{dt} = Am\sigma^n t^{m-1} \tag{7}$$

From the above equation it can be seen that the creep rate decreases with time since $0 < m < 1$. Further, Eqn. (7) can also be written in the following form, independent of time t, by eliminating t between Eqs. (6) and (7).

$$\dot{\varepsilon}_c = \frac{mA^{(1/m)}\sigma^{(n/m)}}{\varepsilon_c^{(1-m)/m}} \tag{8}$$

Eqn. (8) indicates that the creep strain rate decreases with increasing creep strain (ε_c) *i.e.* with the progression of creep strain the material hardens.

Though, both the laws are derived from the same equation, but it is observed that for varying stress, the time and strain hardening laws give different creep rates. This difference is procedural and not phenomenological. Quite often the strain hardening models give more accurate predictions of experimental results for stepwise changes of stress. Unfortunately, strain hardening models do not always yield accurate predictions, particularly when several step changes in stress occur during the same test (Rabotnov, 1969). Pickel *et al* (1971) also noticed that the strain hardening model is unable to accurately predict the creep behavior resulting from structural instabilities. But for structurally stable materials, the predictions by strain hardening model are fairly reliable. However, in the case of gradually varying stress, both the laws give approximately similar predictions.

3.0 ACTIVATION ENERGY FOR STEADY STATE CREEP

The steady state creep dominates at temperatures above about $0.5T_m$. The simplest assumption that the creep is a thermally activated process, which can be expressed by the following Arhenius type rate equation,

$$\dot{\varepsilon}_s = Ae^{-Q/RT}$$

where the symbols are defined below:

$\dot{\varepsilon}_s$: the steady state creep rate

Q: the activation energy for the rate controlling process

A: the pre-exponential complex constant containing the frequency of vibration of the flow unit, the entropy changes and the factor that depends on the structure of the material.

T: the absolute temperature

R: the universal gas constant

A temperature differential creep test is often used to measure the activation energy for creep. If the temperature interval is small such that the creep mechanism would not be expected to change, one can write,

$$A = \dot{\varepsilon}_1\, e^{Q/RT_1} = \dot{\varepsilon}_2\, e^{Q/RT_2}$$

and,

$$Q = \frac{R \ln(\dot{\varepsilon}_1 / \dot{\varepsilon}_2)}{(1/T_2 - 1/T_1)}$$

An extensive correlation between creep and diffusion data for pure metals indicates that the activation energy for high temperature creep is equal to the activation energy for self-diffusion. The activation energy for self-diffusion is the sum of energies for the formation and movement of vacancies, which strongly supports the view that dislocation climb is the rate controlling step in high temperature creep. The formation of a dislocation subgrain structure is another factor in support of this view. Therefore, it is expected that the metals in which the vacancies move rapidly would have better creep resistance.

4.0 ESTIMATION OF THRESHOLD STRESS

It is evident that the variation of creep rate with applied stress for the composites generally exhibits curvature at higher creep rates when creep strain rates are measured over more than five orders of magnitude. The apparent stress exponent, n_a $(= \ln \dot{\varepsilon} / \ln \sigma)$, decreases with increasing stress, which is usually considered to be an indicator for the presence of threshold stress, below which creep does not occur. This similarity indicates that the creep behavior of these composites could be explained in terms of the existence of a threshold stress for creep (Mohamed, 1998) and the creep behavior of these composites may be described by modified power law.

Nardone and Strife (1987) were the first to introduce the threshold stress into power law creep equation, to explain the creep data obtained for 20 *vol%* SiCw/2124Al composite under heat treated condition. Similarly, Park *et al* (1990) and Pandey *et al* (1992) also considered the threshold stress while analyzing creep data of SiCp/Al composites. Using threshold stress-based approach, one could easily explain the high values of apparent stress exponent and activation energy. In an overview, Cadek *et al* (1995) pointed that the threshold creep behavior is inherent for discontinuously-reinforced aluminum matrix composites. Accordingly, the creep behavior of these composites was rationalized by using the threshold stress approach used by numerous workers (Nardone and Strife, 1987; Park *et al*, 1990, 1994; Pandey *et al*, 1992; Mohamed, *et al*, 1992; Gonzalez and Sherby, 1993; Cadek *et al*, 1994, 1995, 1998a, b; Zhu *et al*, 1996; Li and Mohamed, 1997; Li and Langdon, 1997a, 1998a, b; Tjong and Ma, 1999a; Ma *et al*, 1999; Wakashima *et al*, 2000; Ma and Tjong, 2000; Lin *et al*, 2002).

The following three different methods are commonly employed by various workers to estimate the magnitude of threshold stress. In the first method, as proposed by Lagneborg and Bergman (1976), the threshold stress is estimated by using linear extrapolation of the strain rate versus stress plot in which the creep data at a single temperature is represented on $\dot{\varepsilon}^{1/n}$ versus σ plot on linear scales. Further, it is assumed that if the creep data of composites, and σ_0 is independent of the applied stress, the data points in $\dot{\varepsilon}^{1/n}$ versus σ plot would fit in a straight line. This line is extrapolated to zero strain rate to get the value of threshold stress (σ_0) at the given temperature. The most appropriate value of true stress exponent, *n*, is obtained by constructing several $\dot{\varepsilon}^{1/n}$ versus σ plots of creep data by using different values of *n*, and selecting the value of *n* that describes the best linear fit of the data points.

According to second approach, if the creep behavior of a material could be described by modified power law, the relation between the apparent stress exponent n_a, true stress exponent *n*, applied stress σ and threshold stress σ_0 is given by (Chaudhury and Mohamed, 1988),

$$n_a = \frac{n\sigma}{(\sigma - \sigma_0)} \tag{9}$$

The values of *n* and σ_0 corresponding to each test temperature could be estimated from the data in the plot of apparent stress exponent n_a versus applied stress σ, resulting from experimentally determined $\dot{\varepsilon}\ (T, \sigma)$ relationships and by applying Eqn. (9) to such a plot.

A difficulty associated with the linear extrapolation method is that it requires a prior selection of appropriate values for *n*. In practice, the analysis is generally undertaken by using either integer values of *n* or some specific values of *n* which are related to some other well documented creep process. However, this problem could be avoided by using the threshold stress approach suggested by Li and Langdon (1997c). When the creep data covers at least 5 orders of magnitude of strain rates and includes the strain rate as low as ~10^{-8} s^{-1}, the curves through the individual experimental points generally could be extrapolated to lie essentially vertical at a strain rate of ~10^{-10} s^{-1}. Accordingly, the predicted stress level at this low strain rate is very close to the threshold stress. Thus, using the values of threshold stress, estimated at a strain rate of ~10^{-10} s^{-1}, the creep data could be replotted on the logarithmic scale between the measured strain rate against the effective stress, $(\sigma - \sigma_0)$ or $(\tau - \tau_0)$, where σ, σ_0, τ and τ_0 indicate the applied normal stress, threshold stress under normal loading, applied shear stress and threshold stress in shear respectively. The slope of logarithmic plots of strain rates versus effective stress yields the value of true stress exponent *n*.

5.0 FUNCTIONALLY GRADED MATERIALS

Rapid growth in technology has led to the development of materials for components that exhibit a graded variation in their properties. Under severe environments such as high temperature or thermal gradient, the conventional materials may not survive alone. Functionally graded materials (FGMs) are a new generation of engineered materials that are gaining interest in recent years. The concept of FGM was first introduced in 1984 in Japan as ultra-light temperature-resistant material for space vehicles (Koizumi, 1993). FGMs also find applications in structural components operating under extremely high-temperature environments (Noda *et al*, 1998; Librescu and Song 2005). In FGMs the volume fraction of two or more constituent materials is varied continuously as a function of position along certain dimension(s) of the structure (Suresh and Mortensen, 1998; Reddy, 2000). Due to graded variation in the content of constituent materials, the properties of FGMs change smoothly and continously from one surface to the other, thus eliminating the interface problems and also diminishes the concentration of thermal stress. As an example, FGMs based on ceramic reinforcement in metal matrix are able to withstand high-temperature environments due to better thermal resistance offered by ceramic constituents, while the metal constituents enhance their mechanical performance and reduce the possibility of catastrophic fracture. The application of concept of FGMs to Metals Matrix Composites (MMCs) has led to the development of components designed with the purpose of employing selective reinforcement in certain regions, where enhanced properties like increased – modulus, strength and wear resistance are required (Jolly, 1990; Koizumi, 1995, 1997; Hirai, 1996; Takezono *et al*, 1996; Akira and Watabane, 1997; Pattnayak *et al*, 2001; Zhu *et al*, 2001; Kieback *et al*, 2003). In addition to excellent mechanical and thermal properties, the FGMs also possess the advantage of optimizing the use of costly dispersoids, as the composition of dispersoids in FGMs is varied from the high-temperature region to the low-temperature region.

5.1 Applications of FGMs

FGMs have great potential for applications in aircraft, space vehicles, advanced engines and other engineering applications because of their unique performance, acheived due to spatial tailoring of properties at microscopic level (Noda and Tsuji, 1990; Nagata *et al*, 1990; Hashida and Takahashi, 1990; Nakagaki *et al*, 1991; Erdogan and Wu, 1992; Kumakawa *et al*, 1992; Teraki *et al*, 1992; Arai *et al*, 1993; Ishizuka and Wakashima, 1994; Finot *et al*, 1994; Kumakawa *et al*, 1994; Jin and Noda, 1994; Noda and Jin, 1994; Fukui and Bowen, 1994; Blumm *et al*, 1994; Kawasaki and Watanabe, 1994; Pindera *et al*, 1994; Rabin and Shiota, 1995; Ho and Lavernia, 1996; Tsuda *et al*, 1996; Noda *et al*, 1998). Aerospace industry extensively uses FGMs, as it is desired that the materials at the surface of space crafts must withstand temperature as high as 2100 K apart from bearing a temperature difference of 1600 K, which may be easily met by tailoring of FGMs. Some specific diversified applications of FGMs include Functionally Graded piezoelectric actuators (Li *et al*, 2003), heated floor systems (Takeuch *et al*, 2003), metal/ceramic armor, prosthesis joint with increased adhesive strength and reduced pain (Quin and Datta, 2004), Thermal Barrier Coatings (TBCs) for combustion chambers (Ivosevic *et al*, 2006), thermal protection systems for spacecraft, hypersonic and supersonic planes (Leushake *et al*, 2004), rotating blades in helicopters and turbomachinary (Oh *et al*, 2005) and smart structures (Ding *et al*, 2003).

The various techniques have been proposed for manufacturing of FGMs such as electrophoretic deposition (Put *et al*, 2003; Vanmeensel *et al*, 2005), chemical vapor deposition (Kim *et al*, 2005), spark plasma sintering (Shen and Nygren, 2002; Tokita, 2003) and centrifugal casting (Biesheuvel and Verweij, 2000; Velhinto, 2003). These methods are used to manufacture FGMs with their properties varying across the thickness direction. To achieve in-plane variation of properties in FGMs, ultraviolet irradiation method is used (Lambros *et al*, 1999).

The reduction of gas consumption and weight of the car are the motivating forces for growth and innovation in the automotive industry. A significant reduction in weight can be achieved by producing cylinder liners in Al matrix composite manufactured by centrifugal casting process. The wear resistance of this composite, under proper working conditions, is much superior to cast iron, which is commonly used for the production of liners (Bonollo *et al*, 2004).

Discontinuously reinforced composites *viz.* ceramic particles reinforced in aluminum alloy matrix produced by centrifugal casting can be considered as FGMs as they possess varying distribution of reinforcement in the radial direction owing to the effect of centrifugal force. Due to difference in densities of ceramic particles and aluminum alloy matrix, centrifugal separation occurs and higher density constituent moves towards the outer zones and vice versa. The concentration profile of ceramic particles, in the radial direction can be controlled and optimized by adjusting the parameters such as mould rotation speed, mould temperature, content and size of ceramic particles, and temperature of molten aluminum. The hardness profile of such FGM is directly proportional to the amount of hard ceramic particles (Kang and Rohatgi, 1996; Liu *et al*, 1996; Gao and Wang, 2000).

Bonollo *et al* (2004) used centrifugal casting technique to manufacture cylinder liners made of Functionally Graded (FG) Al-SiC and Al-Al_2O_3 composite. An attempt was also made to analyze the role of process parameters in centrifugal casting to optimize the distribution of reinforcement at the inner surface of the liner. The ideal reinforcement distribution was achieved for some combination of main process parameters, including casting temperature, mould temperature and content of reinforcement.

Kiran *et al* (2009) used Al/17 *wt%* Si alloy to fabricate and characterize a FG Al/Si in-situ material. The FGM was fabricated by a specially designed centrifugal casting process and its microstructural characteristic and hardness profile were examined.

5.3 Creep in FGMs

In the past few years, the elastic stresses in FGM subjected to thermo-mechanical loading have been analyzed by many researchers (Arai *et al*, 1990; Fukui and Yamanaka, 1992; Erdogan and Wu, 1993; Hirano and Teraki, 1993; Obata and Noda, 1994; Tanigawa, 1995; You *et al*, 2007; Yang, 1998). However, the studies pertaining to creep in FGMs are rather scant.

Jackson *et al* (1999) presented an approach to model and design the components made of FGMs, so as to fabricate them with local composition control. This approach is based on subdividing the solid model into sub-regions and associating analytic composition blending functions with each region. These blending functions defined the composition throughout the model as mixtures of primary materials available to the Solid Freeform Fabrication (SSF) machine. The role of design rules restricting the maximum and minimum concentrations has also been discussed by them.

Zhu and Miller (1999) examined creep behavior of FGM provided with a thermal barrier coating of Zirconium. In order to examine creep behavior, the thermal gradient in the FGM was produced by heating the ceramic surface with laser. The ceramic layer was observed to have primary creep. The time, temperature and stress dependent deformation results in coating shrinkage in the loading direction and leads to stress relaxation.

Fukui *et al* (1995) manufactured metal-intermetallics (Al-Al_3Ni) FGM by centrifugal casting method and conducted experiments to evaluate strength gradients in FGM by conducting a number of 3-point bend tests. The study reveals that the three point bending strength of Al-Al_3Ni FGM could adopt the two parameter Weibull distribution. The fracture strength of Al-Al_3Ni FGM specimen decreases with the increase in volume fraction of Al-Al_3Ni. The strength of Al-Al_3Ni FGM depends on the cleavage fracture strength of Al_3Ni and obeys the law of mixtures as given below,

$$\sigma_{\mathrm{FGM}} = (1-f)\,\sigma_{\mathrm{Al}} + f\sigma_{\mathrm{Al_3Ni}} \tag{10}$$

Sadananda *et al* (1999) investigated creep properties of FG five layered $MoSi_2$-Si_3N_4 composite at 1200 ^oC under compression. The layers consisted of 0, 20, 40, 60 and 80 *wt%* of Si_3N_4 with corresponding decrease in $MoSi_2$ content. Each layer was 2 *mm* thick and possessed uniform distribution of Si_3N_4. The study indicates that the creep rates in a single layer decrease with increasing content of Si_3N_4.

Zhai *et al* (2005) investigated creep in FGMs subjected to high temperature by using computational micro – mechanical method (CMM). Based on the real microstructure of FG interlayer with different volume fractions, the emulation experiment was implemented for the creep test numerically and the creep parameters were estimated. The numerical results indicate that the creep phenomenon is obvious not only for the metal-rich interlayers but also for the ceramic-rich interlayers. The creep strain rate of the ceramic/metal interlayer is larger than that observed for pure metal under the same load when modulus of the ceramic phase is lower than the metal phase.

6.0 CONCLUSIONS

a) Functionally graded metal matrix composite discs exhibit better creep resistance and lower stress concentration as compared to homogeneous rotating discs.

b) The creep deformation and stress distribution in rotating discs are significantly influenced by temperature, rotational speed, reinforcement content, and material gradation.

c) The gradual variation of reinforcement in FGMs helps in reducing thermal stresses and improves the structural reliability of rotating components operating under high-temperature conditions.

d) The application of classical creep models such as Norton's law and Bailey–Norton law provides an effective approach for predicting creep behavior in composite rotating discs.

e) The presence of threshold stress and reinforcement particles plays an important role in improving the high-temperature creep performance of metal matrix composites.

f) Functionally graded Al–SiC composite discs are found to be suitable for advanced engineering applications such as gas turbines, aerospace rotors, and high-speed rotating machinery due to their superior thermo-mechanical performance.

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