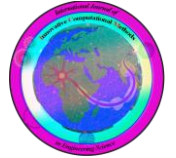


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Investigation of Thermoelasticity and Creep Behavior of Functionally Graded Materials (FGMs)

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ABSTRACT

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Functionally graded materials (FGMs) have a heterogeneous and advanced structure, and their properties change gradually and continuously from one surface to another. This continuous structure eliminates the delamination problems of layered composite materials. On the other hand, they perform better under various environmental and operational conditions, especially in applications that require high resistance to temperature and pressure. This article examines the thermoelasticity and creep behaviour of functionally graded materials along with their governing structural equations.

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1. Introduction

The study of thermoelasticity and creep in functionally graded composite materials (FGMs) involves analyzing the mechanical and thermal properties of these materials, where the material properties gradually change from one region to another. These property variations enhance the material's strength, reduce stress concentration, provide high resistance to mechanical loads and severe temperature gradients, and prevent crack propagation.

In thermoelastic analysis, the temperature distribution and its effect on stresses and strains in FGMs are typically examined. The temperature-dependent mechanical properties and their spatial distribution change according to power-law or exponential functions, which are significant in numerical modeling methods such as the finite element method.

The creep behavior of FGMs is also studied under long-term loading and elevated temperatures, considering the effects of gradual property variations and thermal conditions on time-dependent creep characteristics. This is crucial for predicting the service life and long-term performance of structures made from FGMs.

FGMs are typically composed of a combination of ceramic and metal, providing desirable thermal and mechanical properties based on a continuous compositional distribution. These materials find applications in

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specific areas such as heat-resistant coatings, aerospace components, and machinery parts exposed to severe thermal and mechanical stresses. This article reviews the research conducted in this field.

1.1. Creep Concept

Creep is a time-dependent deformation that occurs gradually and continuously under a constant load. This phenomenon is temperature-dependent, with increasing temperature accelerating the creep rate. Creep occurs at all temperatures, but the temperature at which creep becomes significant depends on the material type and varies for different materials. This temperature is related to the material's melting point and typically becomes noticeable at temperatures above approximately 40% of the melting point. Structural components subjected to creep undergo time-dependent changes including stress redistribution, continuous deformation and transition of material behavior from isotropic to anisotropic, and localized reduction in material strength.

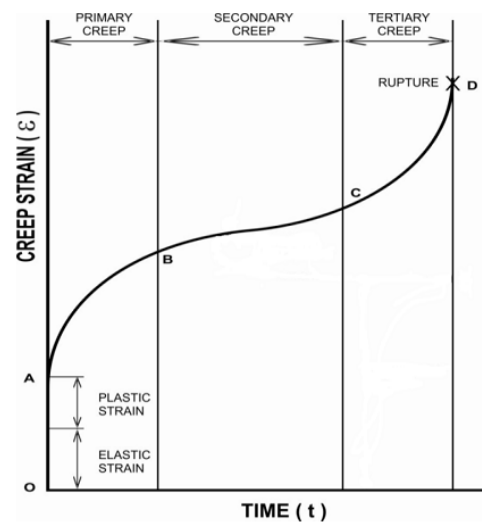


Fig. 1. Standard Creep Curve [1]

Strain variation over time is depicted by a standard creep curve, where the creep rate corresponds to the slope of the curve at any point. Even under constant load, creep causes a continuous increase in strain, ultimately leading to creep fracture or failure. The creep curve consists of three distinct stages (Figure 1-1): The primary or transient creep stage, where the creep strain rate decreases over time; the secondary or steady-state creep stage, where the creep strain rate remains approximately constant; and the tertiary creep stage, characterized by an accelerating creep strain rate leading to failure. The slope of the tertiary creep stage is increasingly rapid and occurs just before failure.

Due to microstructural changes such as the formation of sub-grains and obstacles to dislocation motion, the creep rate decreases in the primary stage. A balance between work hardening and recovery processes and a stable microstructure maintains a constant creep rate in the secondary stage. The loss of balance between hardening and softening processes, along with the activation of metallurgical weakening factors such as grain boundary sliding, necking, corrosion, void formation, intergranular fracture, recrystallization of work-hardened grains, coarsening of secondary phase particles, and precipitation of brittle phases, occurs in the tertiary stage. Typically, the primary creep region lasts for a short time, and the tertiary stage quickly leads to rupture; therefore, the secondary stage is of greater importance.

Not all rapid initial strain in the primary stage is elastic, even when the stress is below the material's yield strength. Part of the strain is elastic and fully recoverable after unloading, while another part is plastic and

irreversible. In some cases, because the initial strain is small compared to creep strains, it is sometimes not considered part of the creep strain, and the creep curve starts from the origin.

This translated text accurately conveys the detailed explanation of creep including its stages, microstructural influences, and significance related to temperature and material properties. Let me know if any adjustments or further refinements are wanted. Creep is a time-dependent deformation that occurs slowly and continuously under a constant load. It is temperature-dependent, with increasing temperature accelerating this process. Creep occurs at all temperatures, but the temperature at which it becomes significant depends on the material and usually relates to the melting point; it is typically notable above about 40% of the melting temperature. Structural components experience time-dependent effects such as stress redistribution, continuous deformation, changes from isotropic to anisotropic behavior, and local reductions in strength.

The strain versus time relationship is shown by a standard creep curve, where the creep rate is the slope at any point. Even under constant load, creep continuously increases strain, eventually leading to creep failure. The creep curve has three main stages: primary (transient) creep with decreasing strain rate, secondary (steady-state) creep with nearly constant strain rate, and tertiary creep where the strain rate accelerates before failure. Microstructural changes slow down creep in the first stage, a balance between work hardening and recovery stabilizes the rate in the second stage, and metallurgical weakening mechanisms activate causing rapid creep in the third stage. The primary stage is short, and tertiary creep quickly causes rupture, so secondary creep is considered most important. Initial strain in the primary stage includes both elastic (recoverable) and plastic (irreversible) parts, though sometimes the initial strain is so small it is not counted as creep.

2. Shear Deformable Plate Theory

Thin-walled sheets made from functionally graded materials (FGMs) possess unique properties that enable their use in special conditions. Some of these properties include the ability to withstand very high temperatures, large temperature differences, corrosion resistance, wear resistance, and fracture resistance. These sheets have extensive applications in industries such as aerospace, power plants, petrochemicals, and more, with many researchers focusing on their high-temperature performance.

Extensive research has been conducted on thin sheets. Considering their mostly thin dimensions and thicknesses, their formulation is more complex than typical beam or other engineering structures. For designers, determining stresses and displacements in sheets holds a special place. Due to the diverse and widespread applications of sheets in industries, various geometries are considered, each possibly having different boundary and loading conditions. Many loadings on sheets are static; therefore, bending and normal and shear stresses are important concerns for sheets. In mechanical systems, bending and stress lead to wear, structural failure, cavity formation in parts, cracks, looseness in joints, repeated maintenance, expensive repairs, and many other issues in machinery. By measuring system displacement and stresses, many adverse effects due to stress and bending can be prevented.

As mentioned, in recent decades with vast developments in industries, especially aerospace, the need for materials resistant to stresses, especially thermal stresses, has increasingly been felt, which led to the production of functionally graded materials.

Classical theory was the first accurate analysis of sheet behavior, developed by Euler and Bernoulli. Since this theory neglects transverse shear deformation, classical theory is accurate for thin sheets but does not yield precise results for thick sheets. In 1921, Timoshenko first included correction effects such as inertia

and shear deformation in the classical theory, known as the first-order shear deformation theory. This theory is now widely applied.

3. Previous research

In 1999, Reddy and colleagues investigated the relationship between classical plate theory and first-order shear deformation theory (FSDT) in the symmetrical bending of circular plates [2]. Subsequently, in 2000, Reddy analyzed rectangular FGM plates using a third-order shear deformation theory combined with the Navier and finite element methods [3].

In 2004, Ma and Wang studied bending and buckling of symmetrical circular plates made from FGMs, also establishing the relationship between Kirchhoff's classical theory and Reddy's third-order shear deformation theory [4]. In 2007, Nai and Zhong analyzed vibrations of circular FGM plates based on three-dimensional elasticity theory using generalized differential quadrature and state-space methods [5].

Zhan and Shan provided a three-dimensional exact solution for simply supported rectangular plates with material properties varying through the thickness direction [6]. Using stress functions, Li et al. derived elasticity solutions for transversely isotropic circular plates under load conditions where the mode number is zero or an even integer [7]. Chang and Batra developed field equations based on first- and third-order shear deformation theories for polygonal plates, presenting simplified relations linking plate deflections to equivalent homogeneous Kirchhoff plates [8]. Lou et al. offered semi-analytical bending analysis of multi-directional orthotropic plates with simple supports [9]. Bina and Pouratti introduced a finite strip method for bending analysis of plates using classical plate theory [10].

In 2008, Brischetto et al. analyzed deformation of simply supported rectangular plates under thermo-mechanical loads using theories and finite element formulations applicable to composites and multilayered plates [11].

In 2005, Ching et al. conducted thermodynamic analyses of two-dimensional elastic FGMs using local Petrov-Galerkin methods and applied penalty methods for geometric boundary conditions, comparing results to theoretical and numerical solutions [12].

Zencor (2009) investigated rectangular FGM plates subjected to uniform mechanical and thermal loading on an elastic Pasternak foundation using sinusoidal shear deformation theory [13]. In 2018, he studied bending of thin homogeneous rectangular plates with variable thickness in hot and humid environments [14].

Kaur and Lata (2019) researched thermoelastic deformation of transversely isotropic thin circular plates, examining the rotational effects under thermal boundary and insulation conditions, and solved governing equations using Laplace and Hankel transforms. Their temperature, displacement, and thermal stress results are applicable to designing pressure sensors, microphones, gas flow meters, optical telescopes, radar antennas, and other engineering devices [15].

In 2020, Lai and Ma investigated free vibrations of micro FGMs with thermoelastic damping based on Kirchhoff theory [16].

In 2021, Swamy et al. analytically examined thermoelastic bending of composite multilayer plates under linear and nonlinear thermal loads using trigonometric shear deformation theory [17].

El-Hify et al. (2021) studied large displacements of poroelastic graded plates on nonlinear elastic foundations employing generalized differential quadrature, showing porosity and foundation coefficients affect plate displacement [18].

Ghoelil et al. (2021) analyzed effects of porosity distribution and boundary conditions on the mechanical bending response of FGM plates on Pasternak foundations [19].

Ali-Bigli (2010) solved thermoelastic problems for FG plates using an exponential model for property variation [20].

Plate theory governing equations [21, 22] are solved via numerical methods (e.g., Ritz, finite element, quadrature differential, Galerkin), semi-analytical methods [23, 24] (e.g., power series), and exact analytical methods [25, 26] (e.g., state-space and 3D elasticity) [27]. Exact solutions, though few, are sought without simplifications for complex FG plate problems to validate approximate and numerical methods [28].

Singh and Rai studied creep in rotating FGM Al-SiC disks using Norton's structural equation, finding that linear SiC distribution leads to less stable radial and circumferential creep rates than uniform distribution [29].

Loqman and Wahab examined creep damage in thick-walled pipes under thermal and internal pressure loads using theta projection creep equation and Mendelson's method, analyzing creep behavior until failure [30].

Loqman and Shekouhi studied creep behavior and damage in thick-walled spheres with structural equations [31].

Loqman et al. researched time-dependent stress histories in thick FGM cylinders under internal, external pressure, heat, and magnetic field, considering mechanical and thermal properties as power functions of radius [32].

They also analyzed time-dependent creep behavior semi-analytically for steel thick-walled cylinders under internal pressure [33].

Arefi et al. investigated creep behavior in porous FGM cylinders under asymmetric loading via semi-analytical methods based on Norton's structural equation [34].

Loqman et al. evaluated time-dependent creep in thick-walled FGM cylinders using first-order shear deformation theory with Yang's analytical method [35].

Jorfi and Akhlaghi (2017) analyzed creep in rotating FGM disks using Sherby's structural equation, solved by generalized differential quadrature, extracting governing secondary creep equations for different boundary conditions and linear SiC distributions [36].

Mirzaei et al. (2019) conducted creep analysis of variable thickness beams via Sherby's structural equation and Mendelson's elastic sequential method, showing stress and displacement converge after approximately 50,000 hours [37].

Few studies address creep in plates; notable are works by Vladimir et al. (1999) on polymer plates creep, and Altenbach et al. (1999) using Ritz and finite element methods for creep damage [38].

Yoo et al. used Mendelson's method to study steady-state creep in thick cylindrical FG tanks under internal pressure with Norton's equation, examining stress components, creep strain rates, and applying von Mises criteria for effective stresses. They derived closed-form solutions for radial, circumferential, and axial stresses satisfying boundary conditions [39].

Loqman and colleagues investigated time-dependent creep stress redistribution in rotating FGM disks under thermal loading, considering radial variation of mechanical/thermal properties based on SiC volume fraction, with creep modeled by Sherby's equation from experimental results. Loading included centrifugal inertia and thermal gradients in steady state, with SiC volume fraction linearly varying along thickness. They employed plane stress assumptions with total strains as elastic, thermal, and creep parts. Governing

differential displacement equations were discretized into finite intervals to obtain solutions using boundary and continuity conditions. They showed uniform SiC distribution has minimal effect on stresses, with optimal thermoelastic stress distribution achieved in disks having 40% SiC on the outer surface and 0% on the inner [40]. Creep strain, displacement, and stress changes decrease over time, reaching steady state after 50 years. Amiri and etc. investigated thermoelastic analysis of rectangular plates with variable thickness made of FGM based on TSDT using DQ method [41], they also analyzed Creep analysis of plates made of functionally graded Al-SiC material subjected to thermomechanical loading [42]. Samaisim and etc. examined a detailed account of thermoelastic and creep properties of FG cylindrical shells [43].

4. Governing Equations for Functionally Graded Materials

The properties of functionally graded materials (FGMs) change purposefully based on a function along a specific direction. This function depends on the application, structural design, operating conditions, applied forces, and the designers' perspectives. Below are some of the most important functions used to describe the properties of FGMs.

To represent the variation of mechanical properties in the materials, four models have been proposed, including the power-law model, the exponential model, the sigmoid model, and the volume fraction model.

4.1. Power-law Model

In the power-law model for FGMs, the volume fraction of a constituent material follows a power-law relation.

$$g(z) = \left(\frac{z+h/2}{h}\right)^p \quad (1)$$

The power-law exponent and material parameters can be adjusted to tailor the material properties. The thickness of the plate is h . The material properties are obtained by the following relations:

$$H(z) = g(z)H_1 + [1 - g(z)]H_2 \quad (2)$$

Where the material properties at the top and bottom surfaces of the plate are denoted by H_1 and H_2 . For example, for Young's modulus:

$$E(z) = g(z)E_1 + [1 - g(z)]E_2 \quad (3)$$

In the above equation, the elastic modulus of the functionally graded material varies from E_1 at the bottom to E_2 at the top surface.

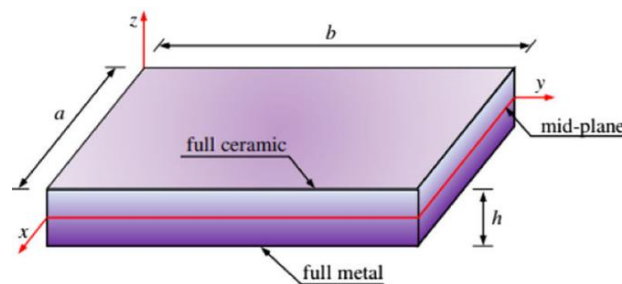


Fig. 2. Plate made of functionally graded materials [51].

The variations of Young's modulus along the thickness direction are shown in Figure (3). The variations of other properties are similar to the changes in Young's modulus.

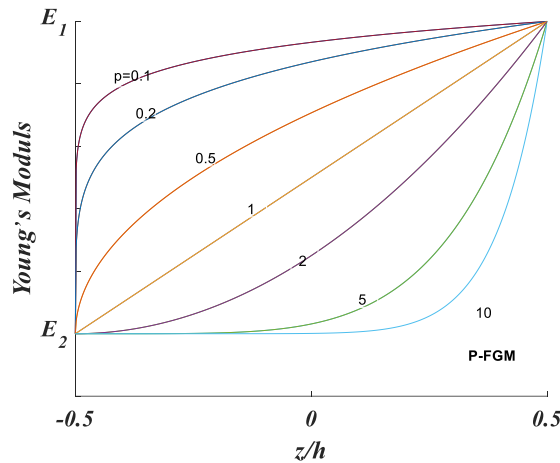


Fig. 3. Variation of Young's modulus along the thickness in an FGM)

4.2. Exponential Model

In this model, the properties vary exponentially from one surface to another (see Figure 4). As shown, the mechanical properties of the functionally graded material in z direction transition exponentially from the properties of material 1 to those of material 2. The variation of the elastic modulus or mechanical properties along thickness in the positive z-axis direction is expressed by the following relationship[50]:

$$E(z) = Ae^{B(z+\frac{h}{2})} \tag{4}$$

Where:

$$A = E_2, \quad B = \frac{1}{h} \ln\left(\frac{E_1}{E_2}\right) \tag{5}$$

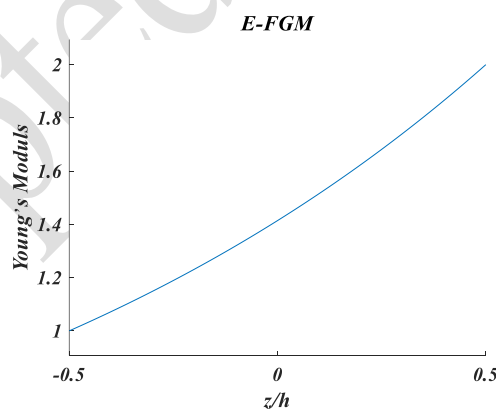


Fig. 4. Variation of Young's modulus in an FGM

4.3. Sigmoid Model

In the sigmoid model, the properties of FGMs vary between layers in a power-law manner and the property profile along the thickness resembles a sigmoid shape. Figure 5 shows the variation of Young's modulus in this model.

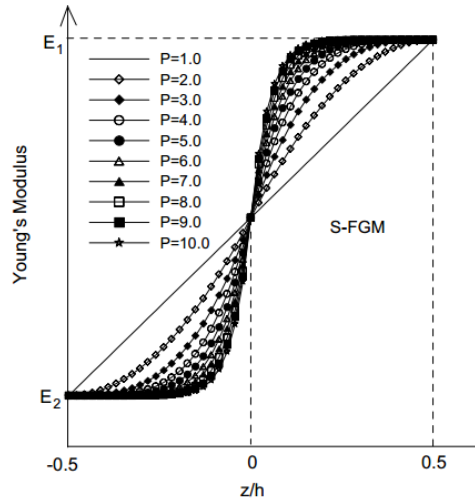


Fig. 5. Variation of Young's modulus in an FGM [52]

According to the figure, the mechanical properties of material 1 are in region A and those of material 2 in region B.

$$E(z) = g_1(z)E_1 + [1 - g_1(z)]E_2, \quad 0 \leq z \leq h/2 \quad (6)$$

$$g_1(z) = 1 - \frac{1}{2} \left(\frac{h/2 - z}{h/2} \right)^p$$

and

$$E(z) = g_2(z)E_1 + [1 - g_2(z)]E_2, \quad -h/2 \leq z \leq 0 \quad (7)$$

$$g_2(z) = \frac{1}{2} \left(\frac{h/2 + z}{h/2} \right)^p$$

(Equations 6 and 7 describe the property variations in different regions A and B)

Unlike the previous two models, two separate relations are used in this model to represent the mechanical property variation along the thickness.

4.4. Volume Fraction Model

In the volume fraction model, the material properties depend on the volume fraction ratio of SiC, which changes along the thickness.

The distribution of silicon carbide changes linearly from the minimum amount at the bottom surface to the maximum amount at the top surface of the plate.

$$C(z) = C_{\min} + (C_{\max} - C_{\min})V_c \quad (8)$$

$$V_c = \frac{z}{h} + \frac{1}{2}$$

Represents the distribution of silicon carbide particles along the thickness direction. C_t and C_b denote the volume fractions of silicon carbide at the top and bottom surfaces of the plate, respectively, and their values range between zero and one. The mechanical and thermal properties of the FGM material, besides Poisson's ratio, depend on the silicon carbide distribution and are expressed as follows:

$$P(z) = P_{Al} + (P_{SiC} - P_{Al})C(z) \quad (9)$$

Includes all material properties (except Poisson's ratio), where P_{Al} and P_{SiC} are the properties of aluminum and silicon carbide, respectively. $P(z)$ comprises Young's modulus, thermal conductivity coefficient, and thermal expansion coefficient. For example, Young's modulus is given by:

$$\begin{aligned}
 E(z) &= E_{Al} + (E_{SiC} - E_{Al})C(z) \\
 E(z) &= E_{Al} + (E_{SiC} - E_{Al})C(z) \\
 E(z) &= E_{Al} + (E_{SiC} - E_{Al}) \left[C_{\min} + (C_{\max} - C_{\min}) \left(\frac{z}{h} + \frac{1}{2} \right) \right]
 \end{aligned} \tag{10}$$

Poisson's ratio is assumed constant due to its much smaller effect on deformation compared to Young's modulus.

5. The Structural Equation of Creep

In this section, one of the well-known structural equations of creep is examined. This equation is the Norton structural equation, which was proposed by Singh and Ray based on the experimental results of Pandey [42].

The equation is as follows:

$$\dot{\epsilon} = B(z)\sigma_e^{n(z)}(z) \tag{11}$$

The symbols $\dot{\epsilon}$ and σ_e represent the effective strain rate and effective stress, respectively. The parameters $B(z)$ and $n(z)$ are creep parameters determined from the following relations.

$$\begin{aligned}
 \log B &= -29 + 1729.38 \text{Log}e - 274.71 \text{Log}T(z) - 1.98 \text{Log}P - 15.88 \text{Log}C(z) \\
 \text{Log}(n) &= -21.54 \text{Log}e + 3.08 \text{Log}(T(z)) + 0.07 \text{Log}P + 0.07 \text{Log}C(z)
 \end{aligned} \tag{12}$$

Here, T denotes the temperature at any point along the Z -direction in Kelvin, and P represents the size of silicon carbide particles in micrometers (μm).

Table 1. Creep parameters used for FGM materials made of Al-SiC.

Particle Size(μm)	Temperature (K)	B	n	Particle Content (%)
1.7	623	9.282×10^{-32}	16.37	10
14.5		5.319×10^{-32}	16.1	
45.9		3.175×10^{-32}	21.60	
1.7	623	9.282×10^{-32}	16.37	10
		1.120×10^{-32}	17.91	20
		1.141×10^{-32}	16.69	30
1.7	623	1.120×10^{-32}	17.91	20
	673	1.378×10^{-32}	22.35	
	723	3.679×10^{-32}	29.73	

6. Conclusion

With the remarkable advancement of science and technology, the urgent need for heat-resistant materials is inevitable. Among high-temperature materials, functionally graded materials (FGMs) show satisfactory performance. The creep and thermoelasticity of functionally graded materials are examined in this article.

There are many functions for FGMs, with the volume fraction function being the most widely used in these materials. The advantage of the volume fraction equation over other formulations is that it allows the percentage of the reinforcing material to be varied at any point through the thickness, such that the material properties at any point can transition smoothly from that of a pure metal to a pure ceramic. The main advantage of FGMs is that they eliminate the problem of delamination, which is the greatest weakness of laminated composites, because there is no abrupt or sharp physical interface between the two materials; the property variation occurs in a smooth, continuous, and functional manner. This characteristic makes them ideal for applications involving high stresses and severe thermal gradients (such as turbine blades, rocket nozzles, and advanced engine components).

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