Abstract

Functionally Graded Materials (FGMs) are advanced engineering materials characterized by a gradual variation in composition and structure over volume, enabling tailoring of mechanical and physical properties for specific functional requirements. Due to their spatially tailored properties, these materials offer superior performance in applications involving thermal barriers, wear resistance, and fracture-critical environments. However, the fabrication, characterization, and accurate modeling of FGMs remain critical challenges, especially in ensuring microstructural homogeneity and predicting failure behavior. This research addresses the above-mentioned challenges through a multi-pronged approach combining experimental synthesis, advanced image processing, and numerical modeling. A novel Python-based image analysis framework that leverages computer vision libraries such as `OpenCV` and `Matplotlib` has been developed to quantify the homogeneity of metal powder mixtures using microscopic color images. The framework segments regions of interest (ROIs), extracts color-shade distributions, and calculates homogeneity metrics, offering a cost-effective and efficient alternative to traditional tomographic and spectroscopic techniques. This methodology was successfully applied to Al-Cu and Al-SiC powder blends. It demonstrates the utility in evaluating material uniformity, a crucial factor influencing the mechanical properties of functionally graded materials (FGMs). Furthermore, functionally graded Al-Al_2O_3 and Al-SiC composites were synthesized using the powder metallurgy route, with gradation in reinforcement content across multiple layers. Microstructural analysis revealed the challenges of achieving smooth transitions at interfaces, particularly at lower aluminum content. The homogeneity at the interfaces was quantitatively assessed using image-based oxygen distribution mapping. Mechanical tests, including hardness, wear, porosity, and coefficient of friction, established a direct relationship between gradation and performance, highlighting the significance of precise compositional control.

To complement the experimental findings, finite element models were developed to investigate the influence of spatial variation of the elastic modulus on fracture behavior. Nanoindentation-based modulus profiles were fitted to various mathematical gradation laws (cubic, power, sigmoidal, tan-hyperbolic, etc.), and their impact on stress Intensity Factors (SIFs) was analyzed under different gradation patterns, including 1D, 2D, and radial distributions. The results underscore the significance of heterogeneity on fracture parameters, providing valuable insights for designing damage-resistant FGM structures. This work presents an integrated framework for the synthesis, characterization, and modeling of FGMs, offering practical tools and theoretical insights for future advancements in materials engineering and structural integrity assessment.

Keywords: Functionally graded material, powder metallurgy, homogeneity, image processing, nano-indentation, stress intensity factor, multi-directional gradation, and goodness factor.