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A new process for design and manufacture of tailor-made functionally graded composites through friction stir additive manufacturing

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ABSTRACT

Motivated by the recent use of friction stirring in the manufacture of *in-situ* composites, a new additive manufacturing method for the design and manufacture of tailor-made functionally graded composites is presented.

The existing literature on the subject matter is limited to creating functional grades in the vicinity of the weld nugget without direct control on composition and property gradients. A mathematical model is developed for achieving a compositional gradient over a predefined length in a metal matrix composite and subsequently demonstrated through the manufacture of aluminum + TiC functionally graded composite. Progressive gradients are observed in hardness and local mechanical properties, namely, Young's modulus, stain hardening exponent, and yield stress obtained using the digital image correlation technique. The process mechanism is elucidated by correlating results of mechanical tests and electron backscatter diffraction analysis. A specific process condition vis-à-vis the number of passes, volume fraction, and particle size combination may promote one or more phenomena such as continuous dynamic recrystallization, particle fragmentation, and breaking of initial matrix grains, which eventually affect particle mixing and matrix grain size and thus cause property gradients. The findings are expected to enable the manufacture of functionally graded composites products of larger size.

1. Introduction

Functionally graded materials (FGM) are heterogeneous materials characterized by a gradual variation in properties over volume. FGM can withstand very high thermal gradients, making them suitable for use in high-stress structures such as space plane bodies [1]. They have the ability to inhibit crack propagation that makes them useful in defense applications as penetration resistant materials used for armor plates [2] and bullet-proof vests [3]. Wang et al. [4] showed that thermal buckling, a design feature of hypersonic vehicles, can be achieved by FGM. The FGM are also suitable for biomedical applications wherein tailored mechanical properties are required to achieve biomechanical performance in patient-specific implants [5]. Other areas of application include medicine, energy, cutting tools, insert coatings, automobile engine components, turbine blades, heat exchangers etc. Several methods, such as powder metallurgy [6], centrifugal method [7], chemical and physical vapor deposition techniques, solid free-form fabrication (SFF) techniques [8], laser deposition methods [9], selective laser sintering, 3-d printing, selective laser melting [10] etc. are all used for the fabrication of FGM [11]. FGMs are also produced by casting route, e.g., Singh and Singh [12] developed Al/Al2O3 composite as an FGM by using an alternative reinforced fused deposition modelling pattern in investment casting process. Vapor deposition techniques can also be used for depositing thin surface coatings but are not suitable for producing bulk FGM [13]. The Powder metallurgy technique produces discrete gradients and thus gives rise to a step-wise structure. The Centrifugal method gives a continuous grading but limits structures to cylindrical shapes and type of gradient that can be produced [14]. SFF techniques have an edge over other methods as they are capable of producing complex shapes and have greater design freedom, since parts are made directly from CAD data but are characterized by a poor surface finish and this necessitates secondary finishing operations [15].

Welding processes have an inherent feature of creating localized functional grade in micro or micro scale. Weld metal and the heat affected zone have functionally graded microstructures that

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facilitate distributive mechanical properties [16]. The buttering layer in hardfacing applications is an example of macro – functionally graded material wherein the butter layer has an intermediate thermal expansion to that of the substrate and hardfacing [17]. Recently, friction stirring has been introduced as an additive manufacturing process to control microstructure [18]. The friction stir processing (FSP) in also a mean to produce metal matrix composites, e.g. Al/SiC surface composites [19,20] wherein a localized plastic deformation is produced by forcing a non-consumable revolving tool on the workpiece surface. The FSP is controlled mainly by rotation and traversing speeds of the tool. Kumar et al. [21] and Panaskar et al. [22] used friction stir processing for nano-composite layering. The FSP can be used in manufacture of functionally graded composite material (FGCM) [23–25] wherein reinforcement particles are packed in a longitudinal groove along which friction stirring is conducted. Friction stirring based FGCM manufacturing as reported in the existing literature is limited to creating functional grades in the vicinity of the weld nugget and compositional, microstructural and property gradients are not predictive and controllable. Such control is essential for FGM to act as a reliable component in certain assemblies.

Previous investigations in FGM manufacture have primarily employed conventional methods of characterization that include qualitative (i.e. microscopy) and quantitative (i.e. hardness measurement) methods. However, FGM in general and FGCM in the present case, in order to ascertain efficacy of process and product, must be evaluated for change in localized mechanical properties such as Young's modulus, strain hardening exponent, yield stress etc. Such measurement is possible with advance techniques such as Digital Image Correlation (DIC), in which images of specimens under loading are taken at frequent time intervals and the relative displacement of image features from one image to another is determined and used to obtain strain maps. Some authors, e.g. Leita˜o et al. [26] determined local constitutive properties of aluminum friction stir welds using digital image correlation.

Keeping observations as forgoing in consideration, the overall objective of this investigation is to develop and characterize a new method of tailor-made FGM manufacture based on additive friction stirring. It is aimed to achieve a pre-defined property gradient of over a given length through systemic change in volume fraction of reinforcement particles. Three specific objectives of the investigation incudes (i) evaluation of the efficacy of the developed process in achieving gradients in mechanical properties, namely, hardness, Young's modulus, stain hardening exponent, and yield stress (ii) quantification of localized change in mechanical properties and constitutive parameters of FGM using digital image correlation, and (iii) elucidate a process mechanism of the developed method through correlating the effect of changes in process parameters and corresponding microstructures. The following section describes the process model of the proposed approach that is followed by descriptions of the materials and method. The result and discussion are presented in final section.

2. Process model

In order to get compositional variation through FSP, blind holes are pre-drilled in a linear fashion in a plate such that the center-to-center distance changes in successive holes. The hole drilling electric discharge machine is used to blind-holes of precise diameter and depth. The holes are filled-up with reinforcement particles. Subsequently, single/multi-pass friction stirring is carried out by a traversing stirring tool along line connecting centers of the holes, as shown in Fig. 1 (a). A mathematical model for positioning of the holes is developed to achieve a linear variation in volume faction of particles from maximum composition ($C_{\max}$) to a minimum composition ($C_{\min}$) over a length L. The i^{th} hole is situated at distance x_i form the starting point as shown in Fig. 1 (b).

The volume fraction at the i^{th} hole (i.e. C_i) is calculated considering a hole of diameter d placed at center of a rectangular grid having length Δx_i and width equal to diameter of FSP tool pin (P_d). The volume fraction can be calculated as follows:

$$C_i = \frac{\pi \times d^2 \times P_l \times 100}{4 \times \Delta x_i \times P_d \times P_l} \tag{1}$$

where P_l is the length of the pin which is equal to depth of hole. For a linear change in volume fraction

$$C_i = b - a x_i \tag{2}$$

where $b = C_{\max}$ and $a = \frac{C_{max} - C_{min}}{L}$.

Eq. (1) can be written as

$$C_i = \frac{K}{\Delta x_i} \tag{3}$$

Where $K = \frac{\pi \times d^2 \times 100}{4 \times P_d}$

Combining Eqs. (1) and (2) we get

$$\frac{K}{\Delta x_i} = C_{max} - a \times x_i \tag{4}$$

From Fig. 1(b)

$$x_{i+1} - x_i = \frac{\Delta x_i}{2} + \frac{\Delta x_{i+1}}{2} \tag{5}$$

Using Eq. (2) in Eq. (5)

$$C_i - C_{i+1} = \frac{a}{2} \times (\Delta x_i + \Delta x_{i+1}) \tag{6}$$

Using Eq. (3) in Eq. (6) and simplifying

$$\Delta \mathrm{x_{i+1}}^2 + \Delta \mathrm{x_{i+1}} \times \left(\Delta \mathrm{x_i} - \frac{2\mathrm{K}}{\Delta \mathrm{x_i a}} \right) + \frac{2\mathrm{K}}{\mathrm{a}} = 0 \tag{7}$$

solving Eq. (7) for .

$$\Delta \mathrm{x_{i+1}} = \frac{\left(\frac{2\mathrm{K}}{\Delta \mathrm{x_i a}} - \Delta \mathrm{x_i} \right) \pm \sqrt{\left(\left(\frac{2\mathrm{K}}{\Delta \mathrm{x_i a}} - \Delta \mathrm{x_i} \right)^2 - \frac{8\mathrm{K}}{\mathrm{a}} \right)}}{2} \tag{8}$$

Eq. (8) gives a recursive function in inter-hole distance. The initial grid length can be computed for a known volume fraction C_1 and subsequent grid lengths and hole positions can be computed using Eqs. (8) and (5), respectively. The inter-hole distance that controls the volume fraction and property gradient depends on pin diameter and hole diameter (Eq. (1)). Thus, for a fully and uniformly filled holes, as assumed, the pin diameter and hole diameter become critical additive parameters for the process under consideration.

A representative distribution, considering $C_{\max}$ = 8% to $C_{\min}$ = 2% over a length L = 40 mm is shown in Fig. 2. It can be seen that the inter-hole distance changes in such a way that the volume fraction of reinforcement particles changes linearly. Using limiting case of Δx_i = d = P_d in Eq. (1), a maximum possible concentration of 78.85% can be theoretically achieved. However, in practice, the achievable maximum possible concentration strongly depends on ability of matrix and reinforcement materials to mix with each other and produce a composite without any defect. The process model is implemented in manufacture of FGCM and subsequently characterized as presented in subsequent sections.

3. Material and methods

In the present study, commercial pure Aluminum with a thickness of 6 mm was chosen as the base plate and TiC particles of