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Development of Friction Stirred Functionally Graded Material using a Numerical Model Analysis

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Abstract – Functionally Graded Material (FGM) belongs to a new class of advanced material characterized by gradual variation in composition and the mechanical properties. The overall properties of the FGM are unique and different from the individual material used. Previous investigations show that various techniques such as powder metallurgy, centrifugal method, vapor deposition techniques, solid freeform fabrication methods and friction stir processing etc. have been used to fabricate the FGM. In order to overcome the control over the composition, the present study presents a method to fabricate Functional Graded Material using Friction Stir Processing (FSP) and hole drilling electrical discharge machine (EDM). Holes are drilled on an aluminum plate and filled with Alumina nano-particles of size (<50nm) and stirred using FSP. A mathematical model for positioning of holes in order to acquire a range of maximum to minimum composition of nano particles over a given length is presented. By aligning FSP seem tool center to hole center, multi-pass FSP is carried out to understand the material flow and mixing. The hardness variation along the direction parallel to the surface and perpendicular to the surface and along the depth is measured. The mathematical model is applied to different combinations of composition ranges and is evaluated under different conditions.

Index Terms – Functional Graded Material, FGM, FSP, Numerical Model.

1. INTRODUCTION

Functionally Graded Material (FGM) is a new class of advanced material with gradual variation in composition and mechanical properties with dimension. The resultant properties of FGM are different from the individual material that forms it. FGMs came into existence in 1980’s and founded by an organization “Functionally Graded Materials Forum, Japan”. They occur in nature as bones, teeth etc.

FGM has advantages over the composite materials.FGM eliminates the stress concentration i.e. sharp interfaces existing in the composite material. An ordinary composite material presents a sudden change in properties at interface whereas FGM contains a gradual change in it. FGM has wide applications in aerospace, automobile, medicine, energy, defense, sensors, optoelectronics etc. The property gradients of FGM formed are intentionally introduced so as to meet the specific performance and the functional requirements in various fields.

FGMs can be classified based on their applications such as (functional graded joints, functional graded coatings and functional graded materials), according to their components (ceramics-ceramics, ceramics-metal, metal-metal etc.), by the nature of gradient (physical, chemical), by gradient distribution (one-, two- and three dimensional), and so on.

Friction Stir Processing (FSP), a solid state joining process which has been attracted for the last few decades due to its several advantages in which high strength alloys can also be joined, whereas in conventional fusion welding it is difficult. The FSP, a non-consumable welding process which has a rotating tool with a pin and a shoulder plunges onto the surface and moves transversely along the path. The rotating tool impels the viscoplastic deformation at the interface between the tool and work piece, causing heat generation which softens the material without reaching the melting point. The material flow is stirred and forged under shoulder pressure during the process [1]. It was invented by The Welding Institute of technology (TWI) of UK in 1991.

Friction Stir Processing provides the defect free welds which includes hot cracking, distortion etc. The joining process occurs below the melting temperature of weld material. No toxic fumes or arc flashes has been evolved in this process unlike in the fusion welding process.

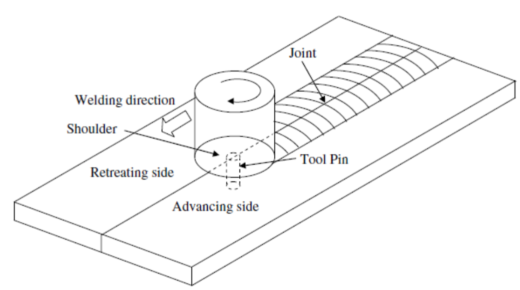


Fig. 1 Friction Stir Welding (Nandan et. al)

Electric Discharge Machining (EDM) is a machining process whereby a desired shape is obtained using electrical charges (sparks). In Hole EDM the holes have been drilled using the same principle, the material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid. One of the electrodes is the tool-electrode and the other is the work piece electrode. When the two electrodes come in contact, the material is removed from both the electrodes.

From the previous investigations there are different kinds of processes to fabricate FGM using gases, liquids and solids as the starting materials such as Powder Metallurgy method[2, 3], Rapid Prototyping technique[6, 7], Centrifugal Method[4, 5], Vapor Deposition Technique[8], friction Stir Processing [9, 10]. Considering the past work carried out in the study of fabrication of Functionally Graded Materials, the present work explores the other aspects which include the developing a detailed mathematical model for 1-Dimensional Functionally Graded Material with a linear change in composition of nano-particles under different conditions and Predicting the possible composition ranges i.e. from maximum to minimum composition for different hole diameters and Presented the effect of multi-pass FSW in the same direction with a cylindrical pin tool.

2. NUMERICAL MODEL

A mathematical model for the linear change in composition of Functionally Graded Material has been presented as follows:

Let us assume a rectangular grid of dimensions $2 * \Delta x_i * P_d$

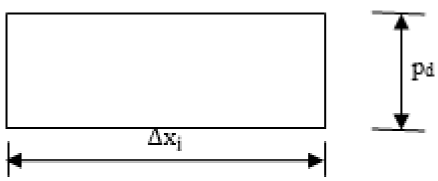


Fig. 2 Grid size

Where P_d - Pin diameter

Δx_i- Length of the grid

The percentage volume composition is defined as:

$$C_i = \frac{\pi d^2 * 100 * P_l}{4 * \Delta x_i * P_d * P_l} \quad (1)$$

Where d - Diameter of hole

C_i - %Composition

P_d- Pin diameter

Δx_i - Length of the grid

P_l - Pin length

2.1 PROCESS CALCULATIONS:

Let the equation be $C_i = b - ax_i$ in the form of y=mx+c

Where $C_i = \frac{\pi d^2 * 100 * P_l}{4 * \Delta x_i * P_d * P_l}$ (From Eq. (1))

$$b = C_{max} \quad (2)$$

$$a = \frac{C_{max} - C_{min}}{l} \quad (3)$$

Substituting Eqn's. (1), (2) & (3), we get

$$C_i = C_{max} - \left(\frac{C_{max} - C_{min}}{l}\right) x_i \quad (4)$$

i.e. $$\frac{\pi d^2 * 100 * P_l}{4 * \Delta x_i * P_d * P_l} = C_{max} - \left(\frac{C_{max} - C_{min}}{l}\right) x_i \quad (5)$$

$$\frac{k}{\Delta x_i} = C_{max} - H * x_i \quad (6)$$

Where $k = \frac{\pi d^2 * 100 * P_l}{4 * P_d * P_l}$

$H = \frac{C_{max} - C_{min}}{l}$

$$x_{i+1} - x_i = \frac{\Delta x_i}{2} + \frac{\Delta x_{i+1}}{2} \quad (7)$$

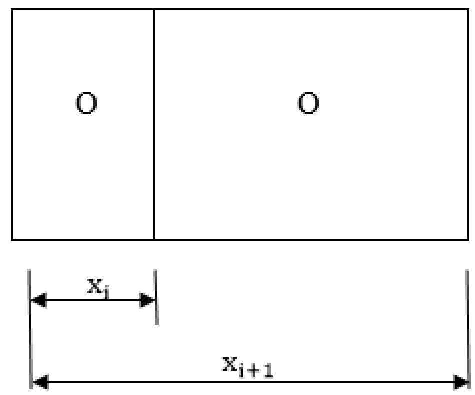


Fig. 3 x_I and x_{i+1} values

Here $$C_{max} = \frac{\pi * d^2 * 100}{4 * d * P_d} \quad (8)$$

Therefore,

$$C_{i+1} - C_i = a * (\Delta x_{i+1} + \Delta x_i)/2 \quad (9)$$

$$\frac{k}{\Delta x_{i+1}} - \frac{k}{\Delta x_i} = a * (\Delta x_{i+1} + \Delta x_i)/2 \quad (10)$$

$$\frac{2k}{a} * \left(\frac{\Delta x_i - \Delta x_{i+1}}{\Delta x_i * \Delta x_{i+1}}\right) = \Delta x_{i+1} + \Delta x_i \quad (11)$$

$$\Delta x_i * \Delta x_{i+1}{}^2 + \left(\Delta x_i{}^2 - \frac{2k}{a}\right) * \Delta x_{i+1} + \frac{2k}{a} * \Delta x_i = 0 \quad (12)$$

Let $f = \Delta x_i{}^2 - \frac{2k}{a}$

$g = \frac{2k}{a}$

Solving the Eq. (12), we get the values of Δx_{i+1}as:

$$\Delta x_{i+1} = \frac{-f \pm \sqrt{(f^2 - 4 * \Delta x_i * g)}}{2 * \Delta x_i} \quad (13)$$

These values are found out up to it reaches the value of total calculated length L_i

$$L_i = \sum \Delta x_{i+k} + \frac{\Delta x_{i+k}}{2} \quad (14)$$

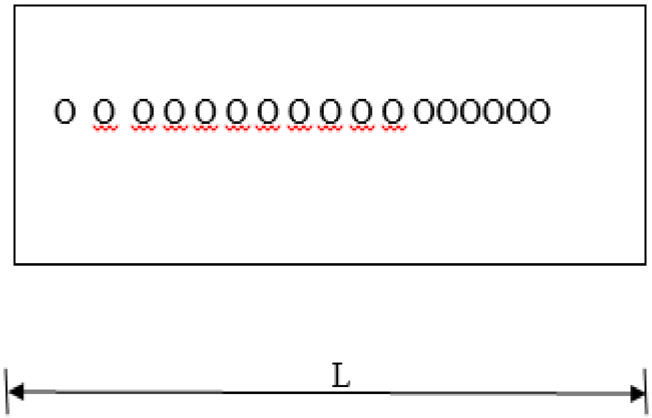


Fig. 4 Holes representing maximum to minimum composition variation

Results from the model:

In the present numerical model, we consider the different electrode diameters i.e. hole diameter such that the maximum composition can be defined for the fixed pin diameter.

Table 1

Cmax values for different diameters without overlap of holes

Diameter (mm)	1.5	1.2	1	0.8	0.6	0.4
Cmax (%comp.)	19.001	15.201	12.667	10.134	7.6	5.067

3. EXPERIMENTAL PROCEDURE

3.1 SPECIMEN PREPARATION:

In this process, 6 mm thick plate of Commercial pure Aluminium was used as base material and Alumina nano-particles of size (<50nm) was used as shown in Fig.4. The chemical composition of the specimens used is shown in Table

Table 2 Chemical composition

Material	Al	Cu	Fe	Mn	Si	Zn
Commercial Pure Aluminium	98.95	0.005	0.457	0.014	0.564	0.006

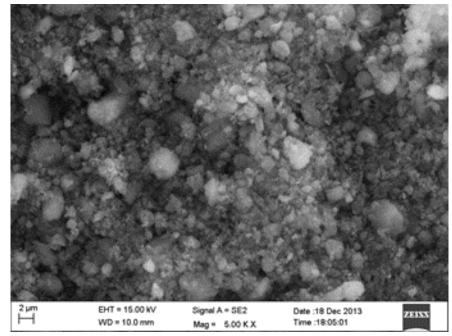


Fig. 4 SEM observation of Alumina nano particles

The experiments were conducted in the CNC vertical milling machine with a FSW seem tool and Hole EDM with a brass electrode of diameter 1 mm. The FSW tool has the following geometry.

FSP Tool geometry:

H13 Tool steel of cylindrical pin is used

Pin diameter – 6.2 mm

Pin length - 5.2 mm

Shoulder diameter – 27 mm

From the numerical model, the Δx_i values have been firstly calculated as shown in Table 1.Considering the maximum composition (Cmax) as 8 % and the minimum composition (Cmin) as 2 % such that the linear change in composition occurs over a length of 40 mm as shown in graph 1. The Δx_i have been calculated such that the % volume fraction of the hole and the grid changes linearly over a length 40 mm.

Table 1 Grid length and composition values

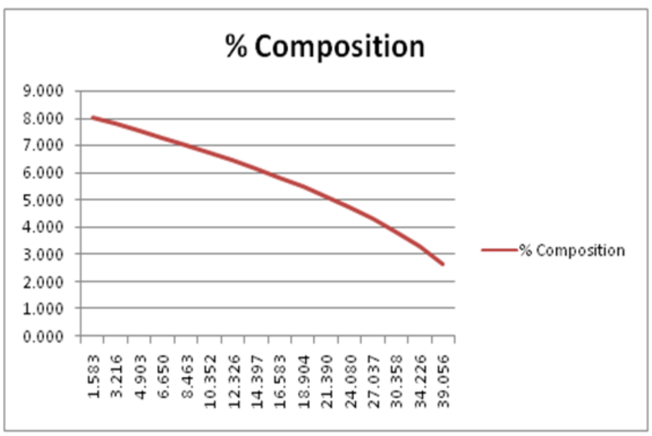
Hole no. (i)	Δx_i	Composition
1	1.583	8.000
2	1.633	7.759
3	1.687	7.510
4	1.747	7.252
5	1.813	6.985
6	1.889	6.708
7	1.974	6.418

8	2.072	6.115
9	2.186	5.795
10	2.321	5.457
11	2.485	5.097
12	2.690	4.708
13	2.956	4.285
14	3.321	3.814
15	3.868	3.275
16	4.830	2.623

Therefore,

Error in Length - 0.944

Error in Composition – -0.263



Graph 3 Length vs. Composition

The holes have been drilled on the Aluminium plate in an order using Hole EDM with a brass electrode of diameter 1 mm with the calculated Δx_i values. These holes were filled with Alumina (Al_2O_3) of particle size (<50nm). Hence the grid size changes in such a way that the % composition of nano particles changes accordingly i.e. linearly. Three samples have been prepared as shown in Fig. 4 in order to perform multi-pass FSP.

Fig. 5 Holes filled with Alumina nano-particles

Friction Stir Processing has been carried out on the filled holes in different number of passes as shown in Fig. 6 with the stated FSW tool geometry and the following parameters.

Process parameters:

Spindle speed – 1000 rpm

Travel speed - 50 mm/min

Tilt angle - 0°

During which the localized heating is produced which rises the viscoplastic behavior at the interface and welding takes place. The work piece material flow takes place from front to the back of the pin, where it is forged under shoulder pressure forming the bead.

4. RESULTS AND DISCUSSION

The multi-pass FSP (double and triple pass) provides a good material flow and weld of continuous rings than single weld FSW in both the cases with and without Alumina nano particles. The outlook of these materials shows information about the weld quality as shown in Fig. 6. Since FSW joints are accompanied by the defects like tunnel defect, cracks etc. The double and triple pass weld joints provide defect free welds than the single pass weld as shown in Fig. 7.

(a)

(b)

(c)

Fig. 6 Macroscopic pictures of Multi-pass FSPed samples (a) Plain single pass FSP (b) plain double pass FSP (c) Plain triple pass FSP

(a)

(b)

(c)

Fig. 7 Cross sectional view of Multi-FSPed samples (a) Single pass (b) Double pass (c) Triple pass

From the figure it is clear that the double and triple pass nano weld joints results in good material flow with continuous rings than the single pass nano welded joints. Defects such as cracks and voids reported in the first and second passes on the FSP surfaces as well as at the longitudinal cross sections were eliminated in the third pass.

5. CONCLUSIONS

A numerical model for 1-Dimensional Functionally Graded Material with a linear change in composition of Alumina nano-particles under different conditions is developed. Effect of multi-pass FSP has been presented that the double and triple pass nano stirred joints results in good material flow with continuous rings than the single pass nano stirred joints.

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