FABRICATION OF FUNCTIONALLY GRADED METAL MATRIX COMPOSITE USING MULTI-PASS FRICTION STIR PROCESSING

Himasekhar sai B.V

Assistant Professor, Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad-500075.

Abstract— Functional Graded Materials (FGM) are innovative materials in which final properties varies gradually with dimensions. It is the recent development in traditional composite materials which retains their strengths and eliminates their weaknesses. It can be formed by varying chemical composition, microstructure or design attributes from one end to other as per requirement. 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.

Keywords— Functional Graded Materials, Friction Stir Processing, multi-pass FSP, mathematical model, Hardness variation

I. INTRODUCTION

Friction Stir Processing (FSP), a solid state processing technique that uses the same principle as friction stir welding (FSW) 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 joining 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].

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. 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.

There are different kinds of processes to fabricate FGM using gases, liquids and solids as the starting materials such as Powder Metallurgy method, Rapid Prototyping technique, Centrifugal Method, Vapor Deposition Technique, friction Stir Processing [2, 3].

Vapor deposition technique includes chemical vapor deposition and physical vapor deposition. These vapor deposition methods are used for depositing the thin surface coating by continuously changing the ratios of reactions in the starting mixture [4]. Powder metallurgical method is known to be a cost efficient technique used to produce bulk FGM. Complex structures can be developed with more than two components but powder metallurgy technique gives rise in stepwise structure [5]. If continuous structure is preferred, then centrifugal method which is similar to the centrifugal casting was used. Centrifugal method is limited to circular shapes and type of gradient produced since the gradient is formed through the natural process (centrifugal force and density difference) [6]. Rapid prototyping technique is an additive manufacturing process which has ability to design and produce complex shapes due to the liberty provided, as parts are developed directly from CAD data. This method provides manufacturing flexibility but characterized by poor surface finish followed by a secondary finishing operation [7]. Friction stir processing (FSP), a solid state processing technique that uses the same principle as friction stir welding (FSW). The authors produced composites in a AA5xxx series placing in pre-prepared shaped grooves placed in three different locations: under the tool center, in advancing and in retreating sides. The material flow in presence of the reinforcing particles was studied. It was intended to produce a localized change in mechanical properties and gradients in its distribution [8]. In order to overcome the control over the composition, the present study aims in developing a functionally graded material metal composite using friction stir processing and hole electric discharge machining. A mathematical model was developed for positioning of holes in order to acquire a range of maximum to minimum composition of reinforcement particles over a given length under different conditions. The holes filled with Alumina nano-particles and TiC reinforcement particles were positioned under the tool center and multi pass FSW has been carried out. The multi pass effect and material flow and mixing in the presence of reinforcement particles was studied.

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

II. MATHEMATICAL BASIS OF FABRICATION METHOD

A mathematical model for the linear change in composition of Functionally Graded Material is expressed by the equation $C_i = b - ax_i$ which is in the form of $y=mx+c$
Where \( C_i = \frac{\pi d^2 \times 100 \times P_l}{4 \Delta x + P_d \times P_l} \) (1)

- \( d \): Hole diameter
- \( P_l \): Pin length
- \( P_d \): Pin diameter
- \( \Delta x_i \): Length of the grid

\( b = C_{\text{max}} \) (2)

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

Assuming a grid of \( 2 \times \Delta x_i \times P_d \)

**Figure 2 Grid size**

Where \( P_d \): Pin diameter

\( \Delta x_i \): Length of the grid

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

\[ C_i = C_{\text{max}} - \left( \frac{C_{\text{max}} - C_{\text{min}}}{l} \right) x_i \] (4)

\[ \text{i.e.} \quad \frac{\pi d^2 \times 100 \times P_l}{4 \Delta x + P_d \times P_l} = C_{\text{max}} - \left( \frac{C_{\text{max}} - C_{\text{min}}}{l} \right) x_i \] (5)

\[ \frac{k}{\Delta x_i} = C_{\text{max}} - H \times x_i \] (6)

Where \( k = \frac{\pi d^2 \times 100 \times P_l}{4 \times P_d \times P_l} \)

\( H = \frac{C_{\text{max}} - C_{\text{min}}}{l} \)

From the fig 3

\[ x_{i-1} - x_i = \frac{\Delta x_i}{2} + \frac{\Delta x_{i+1}}{2} \] (7)
III. EXPERIMENTAL PROCEDURE

3.1 Specimen preparation:
In this study, 6 mm thick plate of Commercial pure Aluminium was used as base material and Alumina nano-particles of size (<50nm) and TiC reinforcement particles of size 325 mesh were used as shown in Fig.4. The chemical composition of the specimens used is shown in Table

| Chemical composition of the specimens used is shown in Table |
|--------------------|---|---|---|---|---|---|

| Material                  | Al  | Cu  | Fe  | Mn  | Si  | Zn  |
|---------------------------|-----|-----|-----|-----|-----|-----|
| Commercial Pure Aluminium | 98.95 | 0.005 | 0.457 | 0.014 | 0.564 | 0.006 |
The experiments were conducted in the CNC vertical milling machine with a FSP seem tool and Hole EDM with a brass electrode of diameter 1 mm. The FSP tool has the following geometry and as shown in Fig 5.

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 Δxi values have been firstly calculated as shown in Table 3. 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 Δxi have been calculated such that the % volume fraction of the hole and the grid changes linearly over a length 40 mm.

| Hole no. (i) | Δxi | 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

**Figure. 6 Graph of 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 $\Delta x_1$ 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. 7 in order to perform multi-pass FSP.

**Figure. 7 Holes filled with Alumina nano-particles**

**Figure. 8 Holes filled with TiC reinforcement particles**

Friction stir processing has been carried out on the filled holes in different number of passes as shown in Fig. 7 and Fig. 8 with the stated FSW tool geometry and the following 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.

**IV. RESULTS AND DISCUSSION**

4.1 Fabrication issues- No of passes:

The multi-pass FSP (double and triple pass) provides a good material flow and weld of continuous rings than single weld FSP in both the cases with and without reinforcement 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. 8.

Figure. 8 Macroscopic pictures of Multi-passed samples (a) Plain single pass FSP (b) plain double pass FSP (c) Plain triple pass FSP (d) Alumina single pass FSP (e) Alumina two pass FSP (f) Alumina three pass FSP

Figure 9 Macroscopic pictures of Multi-passed samples (a) TiC single pass FSP (b) TiC two pass FSP (c) TiC three pass FSP
4.2 Hardness:

The hardness survey along the longitudinal direction of the stirred samples was done. It was observed from the hardness profile along the longitudinal section from Cmax side that a decrease in hardness values both with Alumina and TiC reinforcement particles to the Cmin side.

V. CONCLUSIONS

A numerical model for Functionally Graded Material metal composite with a linear change in composition of reinforcement particles under different conditions is generated. Three pass FSP samples results in good material flow with continuous rings than the single pass and two pass FSP samples. Decrease of hardness values in all the cases (one pass, two pass, three pass) along the longitudinal section at center from Cmax side is observed whereas a gradual decrease is observed in two pass stirred gradient material.

REFERENCES

[1] Mishra R.S., Ma Z.Y., 2005, “Friction Stir Welding and processing”, Material Science and Engineering, R 50 (1-2), 1-78.

[2] Mahamood R.M., Esther T. Akinlabi Member, IAENG, Shukla M. and Pityana S., "Functionally Graded Material: An Overview", Proceedings of the World Congress on Engineering 2012, Vol. III,WCE 2012, July 4 - 6, 2012, London, U.K.
[3] Kawasaki A., Cherradi N., Gasik M., 1994, “Worldwide trends in functional gradient material research and development”, Composites Engineering, Vol. 4, No. 8, pp.883-894.

[4] Kawase M., Tago T., Kurosawa M., Utsumi H., Hashimoto K., 1999, “Chemical vapor infiltration and deposition to produce a silicon carbide carbon functionally gradient material”, Chemical Engineering Science, Vol. 54, 3327-3334.

[5] Zhu J., Lai Z., Yin Z., Jeon J., Lee S., 2010, “Fabrication of ZrO2–NiCr functionally graded material (FGM) by powder metallurgy”, Materials Chemistry and Physics, Vol. 68, 130-135.

[6] Zhai Y., Liu C., Kai W., Zou M., Yong X., 2010, “Characteristics of two Al based functionally gradient composites reinforced by primary Si particles and Si in situ Mg2Si particles in centrifugal casting, Transactions of Nonferrous metals society of China”, Vol. 20, 361-370.

[7] Zhang Y., Han J., Zhang X., Xiaodong H., Li Z., Shanyi Du, 2001, “Rapid prototyping and combustion synthesis of TiC/Ni functionally gradient materials, Materials Science and Engineering”, Vol. 299, 218-224.

[8] Gandra J., Miranda R., Vilaca P., Velhinho A., Pamies Teixeira J., “Functionally graded materials produced by friction stir processing”, Journal of Materials Processing Technology, Vol. 211, 1659–1668.