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Short communication

Development of Functionally Graded Materials by Ultrasonic Consolidation

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ABSTRACT

Development of Functionally Graded Materials (FGM) using Ultrasonic Consolidation (UC) needs the joining of different metallic foils together. The present work deals with the joining of stainless steel, Al and Cu foils. Optimum experimental parameters for welding various combinations of materials have been found for making a sample of a minimum of 62 foils of width 2″ and length 13″. Optical microscopy and mirohardness test have been performed thereupon for the characterization.

1. Introduction

An extensive research has been done in the area of Functionally Graded Materials (FGM) using conventional manufacturing but the application of Rapid Prototyping (RP) technology for developing FGM is few [1].

The RP technologies which are mainly used for making metal–metal or metal–ceramic FGM are Selective Laser Melting [2,3], laser cladding-based techniques [1,4–7], Laminated Object Manufacturing [8] and Ultrasonic Consolidation (UC) [1] while for fabricating polymer–polymer or polymer–ceramic, ceramic–ceramic FGM, Selective Laser Sintering [9–12], Three Dimensional Printing [13,14] and Inkjet Printing [15–17] have been mainly used.

Out of all RP techniques, UC gives an advantage (such as solid state bonding, low temperature processing and surface texture retaining) to fabricate precisely a graded layer metal–metal FGM which has potential to furnish a metallic product with pre-defined properties gradient. To this date, a product made up from this technique contains either just two types of materials [1,18] or one/two types of materials plus an insert (fibre, sensor or mesh) [18–22].

The present work goes beyond the past work and deals with the formation of a graded layer product of approximately 13″ × 2″ × 0.25″ dimension containing Al, Cu and Stainless steel. It is aimed to fabricate a sample having graded strength (or thermal conductivity) in the direction of the deposition of foils. The present paper deals with the optimization of experimental parameters such as weld force, speed, amplitude, substrate temperature and, the characterization using an optical microscope and a micro-hardness tester.

2. Experimental

2.1. Machine and materials

Foils are joined by ultrasonic welding using a UC machine named Formation, manufactured by Solidica Inc., USA. Formation is a hybrid additive layer manufacturing machine which consists of following main parts: (1) a computer program to generate toolpaths for welding and cutting as per an STL file of a 3D CAD, (2) a base plate and attached heater, (3) an automatic foil-feeding system to lay foils, (4) an ultrasonic welding system to join foils, (5) a 3-axis CNC milling machine to shape and trim joined foils.

The machine works by joining two foils (layers) using mechanical vibrations of a welding head (sonotrode) at 20 kHZ and removing the extra part of the foil/build by a milling machine. For joining foils, a foil is laid on a base plate which could be maintained at a higher temperature, if needed. Another foil is manually fixed on top of it as automatic feeding is used only for aluminium foils. A rolling welding head, forced on the foils travels along the length of the foils. During travel, the head vibrates ultrasonically with a small amplitude normal to the direction of the travel. This vibration plus normal force helps foils bond metallurgically [18,22,23]. Fig. 1 shows the principle of the bonding of foils in a UC machine. The machine is equipped with a sonotrode of size 5.8″ of titanium alloy, and a base plate of size 14″ × 14″ × 0.5″ of Al 3003 is used. Foils are taken from the following materials: stainless steel (SS) 316L, annealed, thickness 0.004″; Cu 110 annealed, 0.005″; Al 3003 H19, 0.006″ and Al 1100 annealed, 0.002″. Al 1100 foil is used only to facilitate joining of two SS foils by placing it between the two foils.

2.2. Problem statement

In order to make the FGM out of SS, Cu and Al foils, it is necessary to have optimized parameters for joining SS–SS, Cu–Cu,

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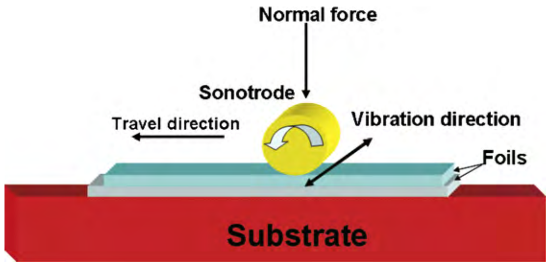

Fig. 1. Principle of the bonding of foils in a UC machine.

Al–Al, SS–Cu, SS–Al, Cu–SS, Cu–Al, Al–SS and Al–Cu foils. The optimized parameters for any two foils change when their sequence of placement/deposition changes. The earlier optimized parameters could not be applicable anymore when the dimension and/or number of foils was changed. When the layer width increases more than the width of the circumference of the sonotrode, the dividing line between two subsequent welds becomes visible. This was avoided by taking 20–50% offset during welding.

The high normal force led to the wear of the sonotrode and made the processed foils brittle. This caused non-functioning of the optimized parameters and delay in the fabrication. Increase in a substrate temperature or its variation during the build-up led to the delamination of the foils or of a half-built section.

3. Results and discussion

3.1. Parameters and strategy

A trial and error method was adopted to search for a set of optimized parameters for all possible permutations and combinations of foils. It was realized that it was not possible to find parameters for all setting sequence of the foils. The final layer sequence adopted for making an FGM sample of 62 layers is as follows:

10SAS + 4.5Al + 5SAS + 5.5Al + 25Cu
Meaning of the term used:
10SAS = Al 1100 + SS + Al 1100 + SS+—repeated 10 times
5SAS = Al 1100 + SS + Al 1100 + SS+—repeated 5 times
4.5Al = Al 1100 + 4Al
5.5Al = Al 1100 + 5Al

Parameters for SS–SS and SS–Al welding could not be found. Therefore, in order to weld SS–SS, an intermediate layer of thin Al 1100 was used between each two SS foils. In order to deposit according to the layer sequence plan, it was required to weld SS–Al. In the absence of an optimized parameter for SS–Al, SS from the previous deposition was removed by milling which gave the way for an underneath Al layer. This helped the welding to be resumed using the known Al–Al parameters.

Thin Al 1100 was again deposited in order to compensate for the loss of the Al 3003 foil which was partially milled off along with the SS foil.

The optimized parameters used are given in Table 1. The substrate temperature maintained was 150 °F (66 °C).

Fig. 2 shows a frontal view of the product formed.

Table 1
Optimized parameters used for making FGM in UC.

Foils	Force (N)	Speed (ipm)	Amplitude (μm)
SS–Al 1100–SS	1250	26	28
Al 3003–Al 3003	1750	56	19
Al 3003–Cu	1500	26	28
Cu–Cu	1500	25	25

Fig. 2. Frontal view of an FGM sample made using a UC machine.

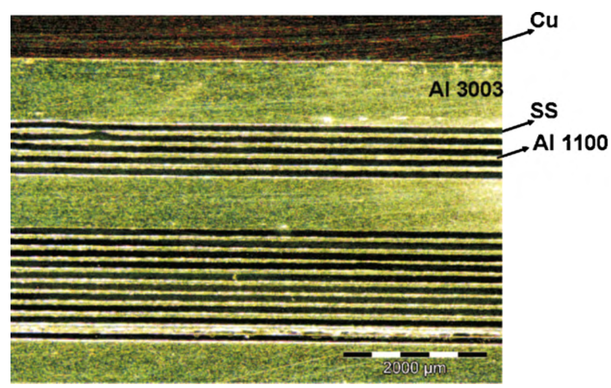

Fig. 3. Side view of the FGM sample.

3.2. Metallography

A sample is polished in a direction normal to its growth direction and is observed using an optical microscope. Fig. 3 illustrates the Al substrate, all SS foils, all Al foils and some Cu foils. This is a clear evidence of the successful fabrication of the FGM using a UC machine. Fig. 4 is a magnified micrograph of the same built section. It shows from the top to the bottom: a region comprising some Cu foils plus another region of five Al 3003 foils plus one SS foil plus one Al 1100 foil plus one SS foil. The boundary between any two Cu foils in the first region or between any two Al foils in the 2nd region is not seen in the micrograph showing the formation of a flawless strong bond free from any porosity.

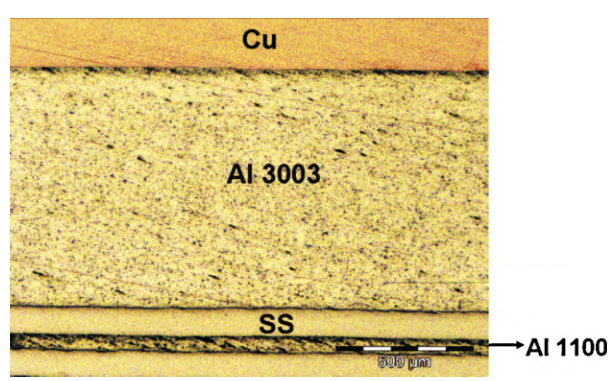

Fig. 4. From top: Cu + Al 3003 + SS + Al 1100 + SS.

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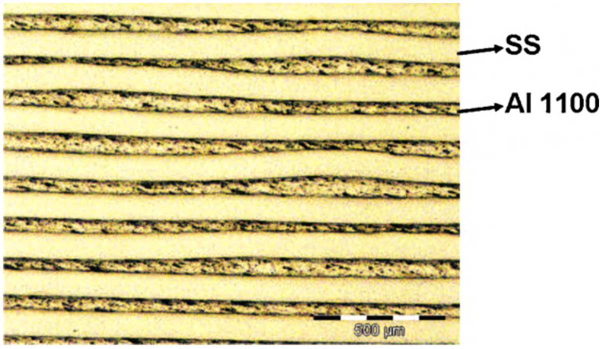

Fig. 5. Repetition of SS and Al 1100 in an FGM sample, showing the deformation of a soft Al foil.

Fig. 5 shows a magnified view of the deposited SS and Al 1100 foils. Al foils are bent and plastically deformed. It is because they are softer than SS, and UC processing has caused Al to flow. This in turn makes SS and Al bond together without causing any melting. Microhardness tests are used to observe the relative strength of the foils and their boundaries. It is found that the size of the indentation at the boundaries are smaller than for Al and bigger than for SS. The indentation could not result in any microdelamination at the boundaries showing again the strong nature of the bond.

4. Conclusion

The successful fabrication of the FGM using UC brings new confidence in the development of the metallic FGM. Although, the materials processed by UC are limited and the parameters that could be effectively varied are restricted, the processing could be successfully performed by adopting the machining strategy or by using an intermediate glue layer.

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