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Thermo-Mechanical Analysis of Dissimilar Al/Cu Foil Single Lap Joints Made by Composite Metal Foil Manufacturing

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Abstract**—**The paper presents an additive manufacturing process for the production of metal and composite parts. It is termed as composite metal foil manufacturing and is a combination of laminated object manufacturing and brazing techniques. The process has been described in detail and is being used to produce dissimilar aluminum to copper foil single lap joints. A three dimensional finite element model has been developed to study the thermo-mechanical characteristics of the dissimilar Al/Cu single lap joint. The effects of thermal stress and strain have been analyzed by carrying out transient thermal analysis on the heated plates used to join the two 0.1mm thin metal foils. Tensile test has been carried out on the foils before joining and after the single Al/Cu lap joints are made, they are subjected to tensile lap-shear test to analyze the effect of heat on the foils. The analyses are designed to assess the mechanical integrity of the foils after the brazing process and understand whether or not the heat treatment has an effect on the fracture modes of the produced specimens.

Keywords**—**Brazing, Laminated Object Manufacturing, Tensile Lap-Shear Test, Thermo-Mechanical Analysis.

I. Introduction

ADDITIVE MANUFACTURING (AM) technologies have become mainstream in the last decade majorly due to their ability to provide efficient and reliable solutions to their customers. A large number of AM processes are commercially available and are being used to produce parts using plastics, polymers, resin, flour, metals etc. The reason behind their immense success is that they can produce parts quickly and are cost-effective. Manufacturing industries are mostly interested in processes capable of producing metal parts because they can provide an environment for testing and can give real world results rather than approximations of how a part might behave in a particular situation. The ease with which AM processes can produce metal parts led to the advent of composite or dissimilar metal parts. Composites are known to provide alternatives and better solutions to industrial problems.

Producing a metal composite is a difficult process as each metal has its own unique set of properties. When a composite is made, different metals are used in such a way that each metal can contribute to the structural integrity of the product. This is not an easy task when dissimilar metals are joined because two unique sets of properties are joined together to form something that is different from both parent metals. It is because of the ever increasing demand of innovation that a composite of aluminum and copper makes a good substitute to traditional products. Copper has a number of prominent qualities that make it a very good candidate for industrial use including corrosion resistance, high thermal and electrical conductivity, strength, excellent solderability etc. Aluminum, on the other hand, has a number of important properties including low weight, high strength, superior malleability, easy machining, excellent corrosion resistance, good thermal and electrical conductivity. The idea of producing a composite of aluminum and copper is very viable but at the same time, it is a difficult endeavor as aluminum is one of the toughest metals to join. The oxide layer on aluminum surface is responsible for its failure to join with other metals. Conventional methods are not very efficient and do not always give very good results. There are a few additive manufacturing processes capable of producing metal composites, namely Selective Laser Melting/Sintering (SLM/ SLS), Laser Engineered Net Shaping (LENS), Three Dimensional Printing (3DP), Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), and Ultrasonic Consolidation (UC) [1]-[6]. They use metals in different forms including metal sheets, powder, wire etc. There has been an addition to the list that uses metal foils for the production of parts and the new process is termed as Composite Metal Foil Manufacturing (CMFM) [7]-[9]. It is a new and unique process that combines the simplicity of LOM with the flexibility of brazing that makes it a very efficient process (Fig. 1). The cutting and stacking mechanisms are similar to the LOM process whereas a special brazing paste is utilized for joining the metal foils together. The paste has a very high metal content consisting of 80% zinc, 20% aluminum by weight and a strong flux suspended in a binder. The melting point of the solder paste in use ranges between 410-470°C and it becomes liquid in this range. However, it should not be kept at these temperatures for longer periods of time as the flux would burn off and the paste would not be able to penetrate the tenacious oxide layer on the surface of the aluminum foil. The process starts with the 3D CAD model of the part to be produced being transferred to layer data, using 3D Slicer software. The machine on receiving this information moves the metal foil on top of the platform.

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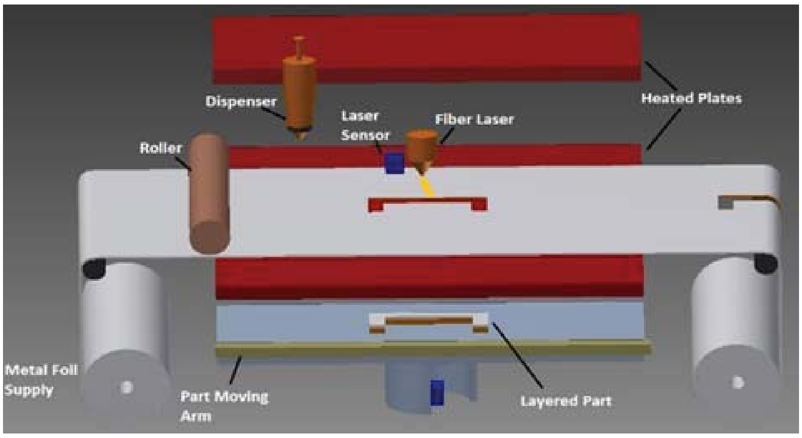

Fig. 1 Composite metal foil manufacturing process

A 300W fiber laser from MIYACHI cuts the outline of the part based on the layer data. It is a sophisticated piece of equipment capable of cutting metal foils as thin as 0.05mm with high dimensional accuracy.

After the outline cutting of the first layer, the brazing paste is deposited by the Model 710 Automatic Applicator from Fusion Automation Inc. according to the defined geometry and the platform stays at its original position. The feed mechanism moves upward and takes the remaining of the foil to the waste take-up roll. Another foil is then advanced on top of the previously deposited layer. It is placed on top of the first layer by the feed mechanism. Before the laser cutting, a roller rolls on the surface of the foil to make a uniform layer of the paste between the first and second layer. The heat produced during the cutting process melts the brazing paste at the edges that keeps the two foils in perfect alignment. The platform is then moved down according to the thickness of the foils and the layer of paste between them. The thickness is measured by Microtrak™ 3 TGS system which is designed specifically for thickness applications. The two sensors are mounted on either sides of the platform to ensure accuracy in thickness measurement and have a measuring speed of 9400Hz.

After the cutting, dispensing and stacking has been done, a stacked structure of paste-coated layers is left behind. The structure is stable enough to be moved and so an arm moves the structure onto the heated plate. It is then heated from top and/or bottom, depending on the part to be produced, by a heated plate that applies pressure and heat to produce the desired part. The heating plates are set to a temperature of 470°C so as to allow for quick heating of the part. The plates are of stainless steel 316 and are fitted with FIREROD cartridge heaters from Watlow and can go up to a maximum of 750°C. After heating the paste-coated layers for a certain amount of time depending upon their thickness, the part is taken off and is now ready to be used.

II. Experimental Procedure

Single lap joints were produced using 0.1mm thin Aluminum 1050 grade foils with a H14 ½ hard temper and pure copper foils. The elements included in the analysis are shown in Fig. 2. Thermo-mechanical analysis of the composite Al/Cu single lap joint was carried out by developing a three dimensional model and carrying out a transient thermal analysis of the heat transfer process. Thermal stress and strain on the lap joints gave an indication of the effect of heat on the foils. Foils of copper and aluminum were subjected to tensile testing prior to joining. The foils were joined together in a single lap joint by the use of heated plates. The joints were then subjected to tensile lap-shear test to analyze the effect of heat. The joints were produced and the tests were conducted according to British and International Standards.

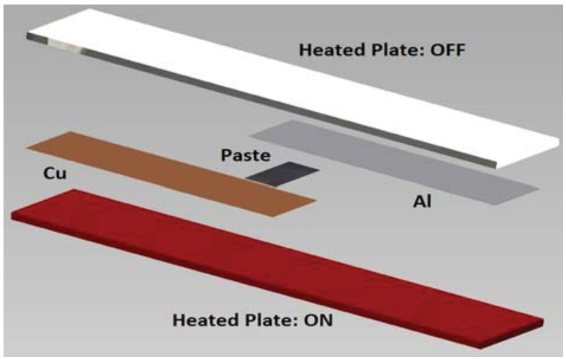

Fig. 2 Elements of the analysis

A. Modelling for Numerical Analysis

A three dimensional model has been developed in ANSYS 15.0 to analyze the heat transfer process. The properties of the materials are shown in Table I. They change with temperature and the values given are at room temperature (20°C). The temperatures obtained in thermal analysis have been applied for the structural analysis to analyze the effect of thermal stress and strain. CMFM requires foils to be joined by sandwiching them between two stainless steel plates (each 250mm long, 100mm wide, and 8mm thick). Heat flux has been calculated and applied as input to the model. One of the plates has been set to a temperature of 470°C. The reason for using only one plate is because both plates will heat up the 0.1mm thin metal foils too quickly resulting in pitting or damaging the mechanical integrity of the foil as a whole. The heating element is the FIREROD cartridge heater and it is fitted in the center of the plate and maintains a uniform temperature distribution over the entire length. Fig. 3 shows the mesh of the Al/Cu single lap joint with copper on the left hand side and aluminum on the right hand side.

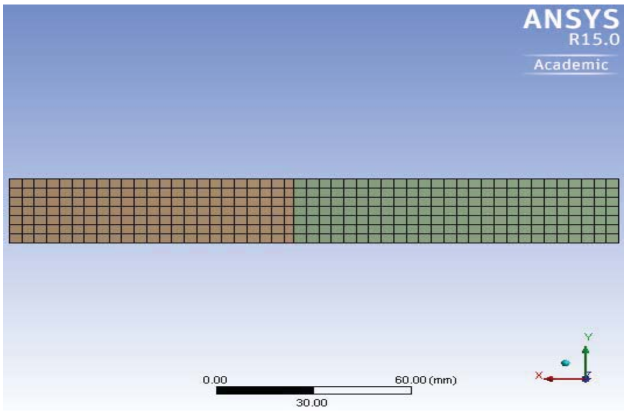

Fig. 3 Mesh of Al/Cu single lap joint

TABLE I
PROPERTIES OF MATERIALS

Material	Thermal Conductivity (W/m °C)	Specific Heat (J/kg °C)
Brazing Paste	130	480
Stainless Steel 316	17	530
Aluminum 1050	205	900
Copper	385	387

B. Tensile Lap-Shear Test

There are no current lap-shear standards for foils at the thickness of 0.1mm. The BS EN 1465: 2009 [10] was followed where possible even though it relates to thicker foils of metal (1.6±0.1mm). The Hounsfield Tinius Olsen Tensile Testing machine was used for carrying out the lap-shear testing. The dimensions of the foils were a*b*t= 25*100*0.1mm (Fig. 4) and they were subjected to a cross-head speed of 10mm/min. The lap joint length (l) was 12.5mm and the thickness of the brazing paste (s) was always kept at 0.1mm.

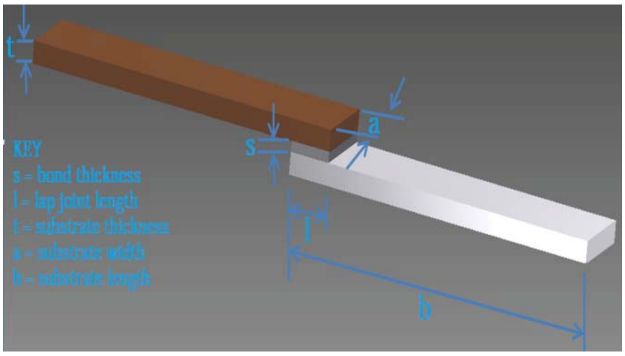

Fig. 4 Single lap joint

III. RESULTS AND DISCUSSIONS

A. Temperature Distribution

The thermal model has been developed to find the appropriate heating time for the Al/Cu single lap joint. Fig. 5 shows the temperature distribution on the plates sandwiching the lap joint between them and Fig. 6 shows the temperature distribution on the single lap joint. It is evident that the temperature of the lap joint is at 470°C after 5 seconds. As soon as the lap joint comes into contact with the heated plate, its temperature gets to 470°C but it has to stay there for three to four seconds to allow the brazing paste to remove the tenacious oxide layer otherwise there will be no bond. But it is allowed to stay there for longer periods of time, one of two things can happen; (i) the flux in the paste will burn off rendering the paste useless and unable to create a bond and (ii) pitting of the foils because of their thickness. The maximum temperature is less than the melting temperatures of the base metals but it is close to the annealing temperature of aluminum and copper but the attention will be given to aluminum as being the weaker of the two metals. The foils of aluminum are grade H14 which are work hardened by rolling to half hard and are not annealed afterwards. Upon reaching the annealing temperature (300-410°C), the crystalline structure of the material starts to relax making it more malleable. There is also a danger of over-heating which may result in stress relieving, sagging or warping, change in temper, surface conditioning, re-alloying, hot cracking and a worst case scenario is a meltdown of the material in use. The process of brazing uses heat in a localized area (to be joined) and stresses in aluminum from shearing and drawing can change, and result in distortion or deformation. To analyze this effect, structural analysis has been carried out to find out thermal stress, strain, and deformation due to the heat transfer process.

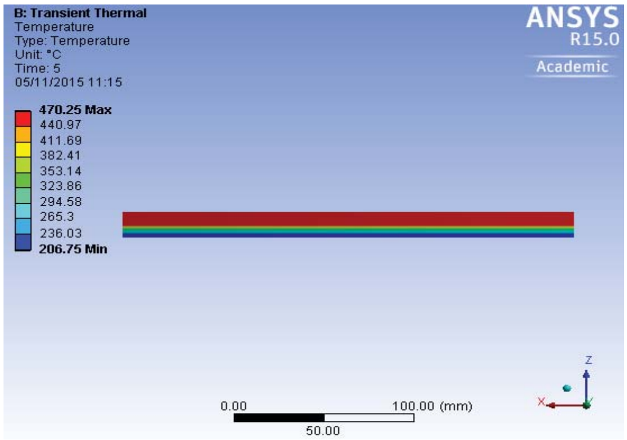

Fig. 5 Temperature distribution on the plates

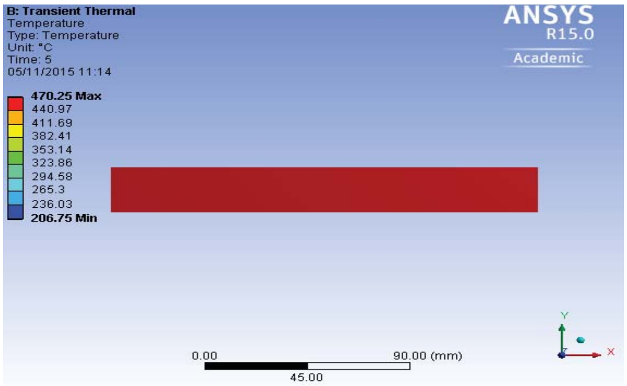

Fig. 6 Temperature distribution on the Al/Cu joint

The transient thermal analysis was carried out because the temperature is varying with time and to characterize this transient behavior, the full unsteady equation is needed:

$$\frac{1}{\alpha}\frac{\partial T}{\partial \tau} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} \qquad (1)$$

$\alpha = \frac{k}{\rho c}$ = Thermal diffusivity and $\frac{q}{k}$ is the heat source.

In the current scenario, a composite of aluminum, copper and brazing paste is being produced. The equation would have to be solved for each layer separately and then the boundary conditions could be applied. Thermal expansion of the two materials would also result in different set of conditions. The density and viscosity of the brazing paste would have to be incorporated as well. These parameters can be solved analytically but the thermal contact resistance between the layers is a big issue. When it is introduced then the analytical solution becomes significantly more complex. Numerical solutions can, however, be obtained in a relatively simple manner. For these reasons, simulation of the heat transfer process as transient and three dimensional is preferred which can be used as a reference model for future parts.

B. Thermal Stress and Strain

The temperature values obtained from the thermal model has been used as input for the mechanical simulation for predicting thermal stress, strain, and deformation. Fig. 7 shows the deformation caused by the brazing process.

The values range from 0.000076731 mm to 0.0055414mm which is very small in terms of deformation considering foils of 0.1mm thickness were utilized. Furthermore, major part of the joint is in the lower range of deformation whereas the maximum value can be seen at the edges of the joint far away from the center where the bond is present joining the two foils together.

The effect of thermal stress is shown in Fig. 8. In the five seconds that it took to make the single lap joint, the thermal stress value ranges from 0.00094787MPa to 369.59MPa. As was the case with deformation, majority of the joint lies in the low rage and the maximum value can only be observed at the starting edge of the copper foil far away from the bonded area. This goes to show that thermal stress is minimum in the surrounding area of the bond and that the brazing process did not have a significant impact on the mechanical integrity of the foil or the joint. The tensile lap-shear test will show the area where failure occurs and a comparison of the thermal stress distribution and the failure area will shed more light on the matter.

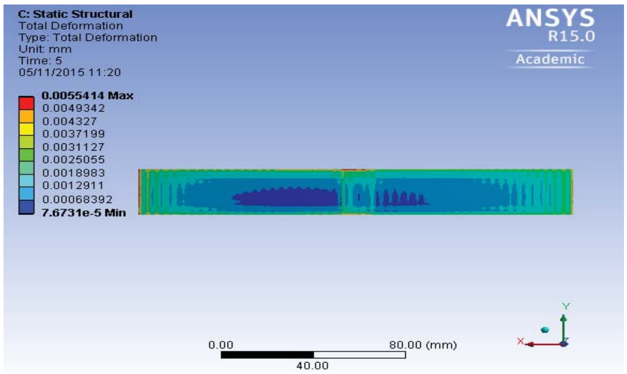

Fig. 7 Deformation of Al/Cu single lap joint

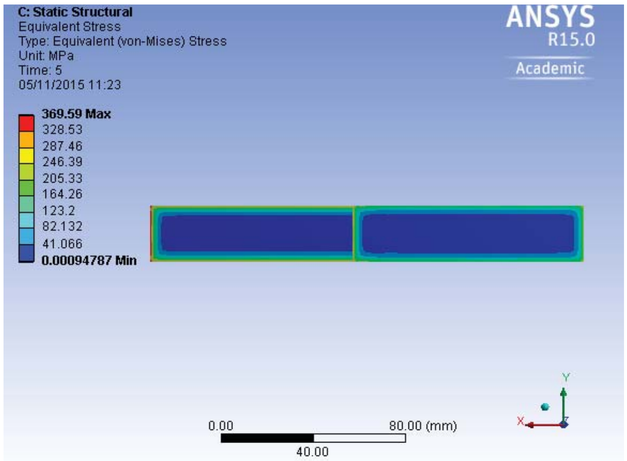

Fig. 8 Thermal stress in Al/Cu single lap joint

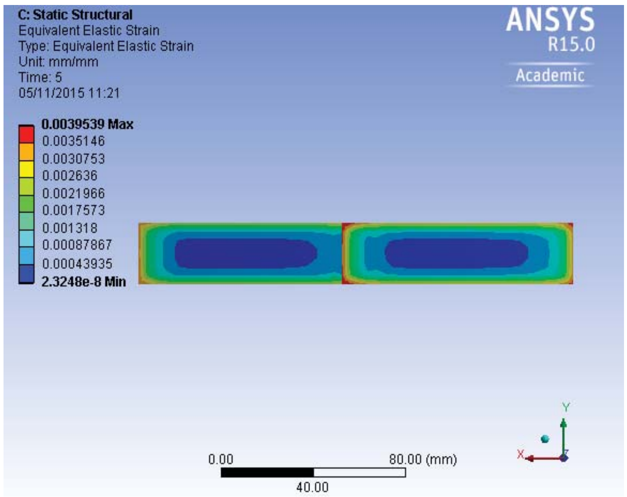

Fig. 9 Thermal strain in Al/Cu single lap joint

Thermal strain distribution is shown in Fig. 9. It shows a different distribution as compared to the deformation and thermal stress analyses. However, even in this case, majority of the lap joint is at a low value of strain. The maximum value is 0.0039539 and it is observed at both the short edges of the aluminum foil. The reason behind aluminum experiencing the maximum value is its low strength as compared to copper which makes it more vulnerable to changes in thermal strains. On the other hand, copper did experience the maximum strain value but not to the extent that aluminum had.

C. Tensile Lap-Shear Test Results

There are a number of factors that can affect the outcome of the test results. They include lap joint length, gauge length and asymmetric loading. To make sure that repeatability was observed in the test results, careful measures were taken. The lap joint was kept at a length of 12.5mm for the samples according to the standard. The test specimens were symmetrically placed in the grips, with each grip (50 ± 1) mm from the nearest edge of the overlap. Additional foils were used in the grips so that the applied force will be in the plane of the bond (Fig. 10 (b)).

A simple tensile test was carried out on an aluminum foil and then after the lap joint has been made, five specimens were tested to analyze the effect of the brazing process on the mechanical integrity of the foils. Since copper is stiffer and stringer than aluminum, it was held in the movable gripper as recommended by the standard (Fig. 10 (a)). All the specimens fractured within the base metal and not at the bonded area. As in tensile testing, specimens failed at locations with minimum cross-sectional area (i.e. the base metal, instead of the lapped region which had twice the cross-sectional area). Aluminum foil fractured in each test because copper is stronger than aluminum having a greater modulus of elasticity. This is also the reason why only Al 1050 has been shown in Fig. 11 along with the tensile lap-shear test results, and not copper. All the specimens fractured at values approaching the tensile load for aluminum 1050 (250N). In all the specimens, the failure was recorded according to BS EN ISO 10365:1995 [11]. The failure pattern was always substrate failure (SF) meaning that the substrate fractured before the bond.

Fig. 12 shows the failure mode of one of the lap-shear specimens being compared to the thermal stress analysis model obtained in Fig. 8. As it is evident that thermal stress did not play any part in the fracture of the specimen and the failure occurred as expected adjacent to the bond where the cross-section was minimum.

IV. Potential of Application

Composite Metal Foil Manufacturing is an efficient and flexible process. It has minimized the limitations related to existing metal prototyping processes in terms of materials and ease of operation. It can produce composites with the same ease as single material parts without the use of expensive equipment, machinery, or additional processes. There is an ever-growing market for composites and the prospect of having a technology able to deliver high quality parts is very promising.

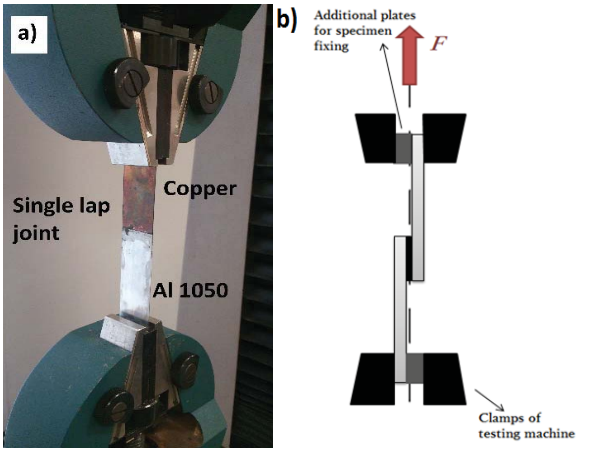

Fig. 10 Al/Cu single lap joint; (a) Specimen in clamps of the testing machine; (b) Specimen with additional foils

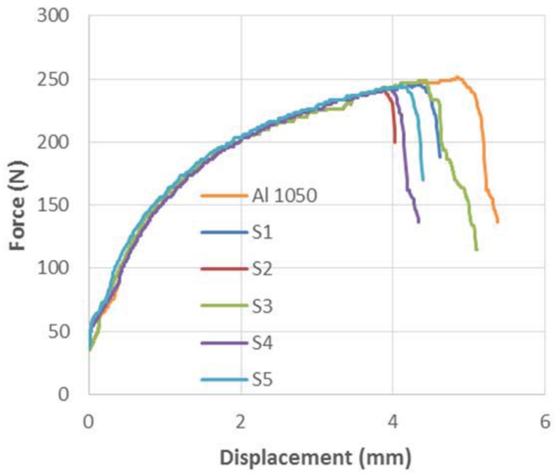

Fig. 11 Tensile lap-shear test of single lap joint

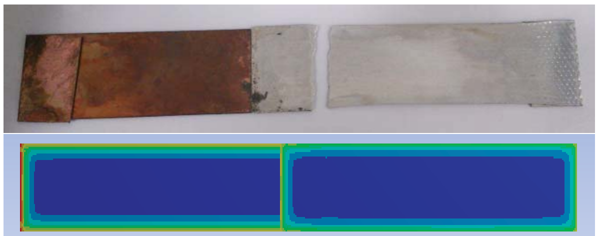

Fig. 12 Comparison of fracture model to thermal stress model

Fig. 13 Composite spanner produced by CMFM

The process can easily join tough metals like aluminum that have a very tenacious oxide layer with the use of a special brazing paste. Foils of different thicknesses have been joined using this process. This goes to show the flexibility of the process dealing with varying thicknesses that could be used to produce a variety of metal and composite products. Complex geometries with good mechanical properties are easily produced using CMFM. Fig. 13 shows an open-ended spanner being compared to a spanner produced by conventional methods and it goes to show that the composites produced by the proposed process can be used in the real world immediately after production as there is no post-processing involved and no further treatment is needed to enhance the strength of the produced composites. Furthermore, the three dimensional model presented in this paper can be used to know the heating time for future parts. This is an added advantage and most additive manufacturing processes don't offer such sophistication and ease in their operation.

V. Conclusion

Thermal and mechanical analysis has been carried out on Al/Cu single lap joint produced by CMFM to analyze the effect of temperature, thermal stress and strain distribution in base metals. The maximum temperature of 470°C does not reach the melting temperature of the base metals but is high enough for annealing to take place particularly in aluminum but there are no adverse effects on the mechanical integrity of the foil or the joint. Deformation, thermal stress and strain analyses have shown that the maximum values lie on the edges of the foils away from the bonded area. Tensile lap-shear tests show fracture values and failure modes as expected and are not affected by the brazing process.

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