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Finite Element Modeling and Mechanical Testing of Metal Composites Made by Composite Metal Foil Manufacturing

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Abstract: Foils of aluminum 1050 H14 $\frac{1}{2}$ hard temper and 99.9% copper with 500-micron thickness have been used to manufacture similar and dissimilar composites by composite metal foil manufacturing (CMFM). The metal foils are bonded to each other using a special 80% zinc and 20% aluminum by weight brazing paste. A 3D finite element model has been developed to numerically analyze the time required to heat the metal foils so that a strong bond can be developed by the paste. The numerical simulations run in ANSYS 19.1 have been validated through experiments and rectangular layered composite products have been developed for flexural testing. The flexural test results for layered Al and Al/Cu composites are compared with solid samples of Al 1050 and 99.9% pure copper made by subtractive method. The results show that the layered Al composite is 5.2% stronger whereas the Al/Cu sample is 11.5% stronger in resisting bending loads compared to a solid Al 1050 sample. A higher bend load indicates the presence of a strong intermetallic bond created by the brazing paste between the metal foils. Corrosion testing was also carried out on the composite samples to assess the effect of corrosion on flexural strength. The tests revealed that the composites made by CMFM are not affected by galvanic corrosion after 7 days of testing and the flexural loads remained consistent with composites that were not immersed in a solution of distilled water and NaCl.

Keywords: composite metal foil manufacturing; laminated object manufacturing; brazing; three-point flexural test; metal composites; British standards

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1. Introduction

Composite metal foil manufacturing (CMFM) is an additive manufacturing (AM) process that makes use of metal foils and brazing/soldering paste to produce metal and metal composite parts [1–4]. The parts made by this process have shown better mechanical properties compared to parts made by traditional methods such as CNC (Computer Numerical Control) machining. Parts made by AM methods typically have comparable mechanical properties to those made by conventional manufacturing methods [5,6] but CMFM exceeds those expectations and can manufacture parts with improved strength [7,8]. Compared to metal AM methods, CMFM is cost effective on two fronts i.e., raw material and additional processes. The raw material is metal foil whereas commercial AM processes such as direct metal laser sintering (DMLS) and electron beam melting (EBM) makes use of metal powder that is comparatively expensive. Furthermore, these processes require a considerable amount of time for pre and post processing whereas CMFM requires minimal auxiliary processes before the part is ready to be used for real world applications [9].

There is another AM method that makes use of metal foils to produce metal parts and is termed as metal foil LOM (Laminated Object Manufacturing). The major application for this process is in the production of large molds but the process has some critical issues. For the handling of the metal sheet contours, a sufficient self-stiffness of the sheet is necessary. Therefore, the thickness has to be more than approximately 0.5 mm. As a consequence of the relatively thick metal foils, parts made from this process suffer from a significant staircase effect [10]. On the other hand, CMFM can work with foils of various thickness and does not face the same issues [11]. The surface quality of the parts made by metal foil LOM is not good, and the products require post processing such as milling, build-up welding, or shot peening where necessary [12]. On the other hand, the parts produced by CMFM have good surface finish and require minimal post-processing to improve their aesthetics. CMFM has also manufactured functional products such as spanners made from similar (aluminum) as well as dissimilar metals (aluminum/copper) to demonstrate its effectiveness [13,14]. It has the capability to produce complex geometries which might not have been possible using traditional manufacturing techniques, such as undercuts, channels through sections, tubes within tubes, and internal voids etc. It can also be used to produce large molds with grooves as well as complex cooling systems with cavities and sliders. Generally, in such cases the cost for tooling or injection molding is very high and CMFM can provide cost-effective means of production. Plates press brazing (PPB) is an AM method that also uses metal foils and has been aimed at the manufacturing of large metallic molds with customized temperature control. Like metal foil LOM, this process also cannot use metal foils of various thickness values and relies heavily on pre/post processes for appropriate adhesion which reduces its efficiency [15]. Ultrasonic consolidation (UC) is another method that makes use of metal foils and has demonstrated its capabilities to produce metal and metal composites. The bonding largely depends on the ultrasonic oscillations to induce plastic flow in the metal foils being bonded. However, the setup is expensive, time-consuming, and difficult for the manufacture of high-quality composites [16–18]. On the other hand, CMFM is easy to setup and works well with a variety of different metal foils with no surface treatment to manufacture layered composites [19,20].

Two different composites have been manufactured for this work; one is the made from Al 1050 grade foils (500-micron thick) with a H14 $\frac{1}{2}$ hard temper and the other is made from the same grade of Al foils and 99.9% pure copper foils (500-micron thick). The metal foils for both composites have been bonded together using 80% zinc and 20% aluminum by weight brazing paste. The paper focuses on developing a simple 3D finite element model that can provide the time required to heat the composites. Such a model can remove trial and error when manufacturing composites of different geometries using foils of varying thicknesses. It is crucial to analyze the mechanical properties of the resulting composites as this is a major area of research [21]. The reason is two folds; they provide insight into the bonding mechanisms of the composites and help in quantifying their usage for engineering applications. Several different tests can be carried out on composites to characterize their mechanical properties e.g., tensile, flexural, corrosion resistance, hardness, fatigue, torsion etc., but the choice of a test largely depends on the properties to be investigated. In this work, the focus is on flexural testing.

Flexural testing of a part allows for the determination of its ductility, flexural strength, fracture strength, and resistance to fracture. These are crucial factors that need to be considered before a part can be put into practical use. Two types of flexural tests are quite common namely three-point and four-point [22]. A three-point test allows for a localized stress due to the force being applied on a smaller contact area and is ideal to test for specific isolation of stress on the specimen. On the other hand, a four-point test produces peak stresses along an extended region of the specimen surface. Hence, exposing a larger area of the specimen is possible with more potential for defects and flaws to be highlighted [23].

Corrosion is a big issue for metals and becomes a serious concern when dissimilar metals are involved. Metals can oxidize in air by reacting with oxygen and forming metal oxides. The metal becomes weaker over time, and eventually all of it may become metal oxide. Corrosion resistance refers to a metal's ability to withstand damage caused by oxidization or other chemical reactions. Both copper and aluminum 1050 used in this work have good corrosion resistance but their coupling in the presence of the brazing paste could lead to galvanic corrosion. Galvanic corrosion (also known as dissimilar metal corrosion) refers to corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte [24]. Therefore, it is crucial to assess the bond/foil interface to ensure that the composites made by CMFM can be used in moisture rich environments. This paper will investigate characteristics such as flexural strength and corrosion resistance of the two composites made by CMFM according to British standards.

2. Experimental Procedure

Manufacturing composites is a difficult endeavor and the use of numerical analysis packages is prevalent to ensure that optimal operating parameters can be selected. For this purpose, ANSYS 19.1 was utilized to carry out 3D transient thermal analysis on the composites made by CMFM. Two different composites have been numerically analyzed; layered Al and Al/Cu. The composites are 100 mm long, 25 mm wide, and 2.9 mm thick according to British and international standards [25]. Aluminum 1050 grade foils with a H14 $\frac{1}{2}$ hard temper and 99.9% pure copper foils with 500-micon thickness were utilized. The elements of the analysis for Al/Cu composite are shown in Figure 1. Experiments were also conducted (for both Al and Al/Cu composites) by placing two thermocouples on the paste-coated foils sandwiched between two heating plates to record the temperature values. This validation of the finite element model for similar (Al composite) and dissimilar (Al/Cu composite) products can serve as a useful tool for future manufacturing needs while using CMFM.

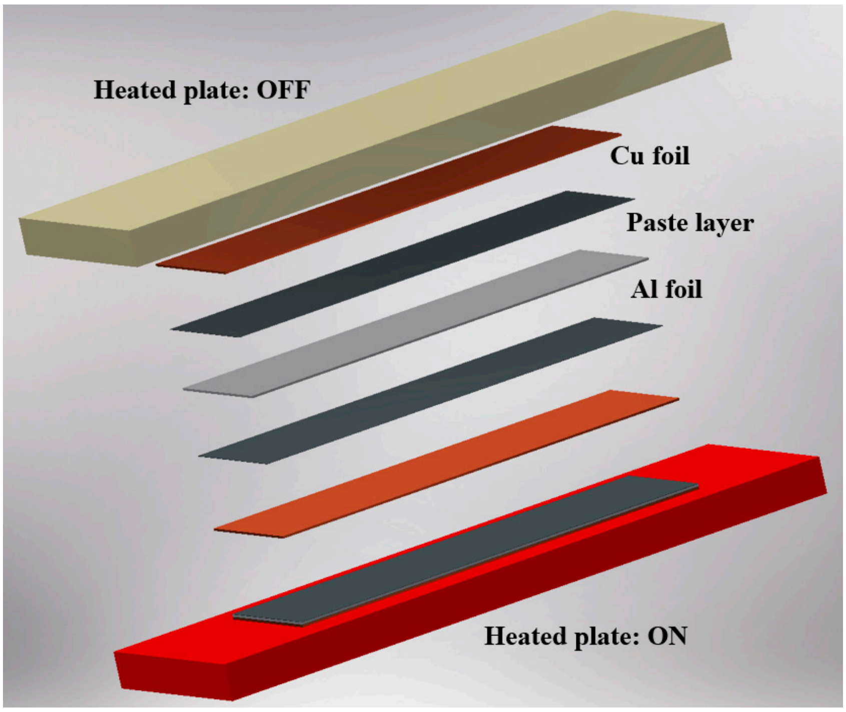

Figure 1. Elements of transient thermal analysis for Al/Cu composite.

After validation, four rectangular samples (100 mm long, 25 mm wide, and 2.9 mm thick) were produced and tested according to British and international standards [24]. Solid aluminum 1050 and 99.9% pure copper metal blocks were used to machine two samples. Two other samples were composites made from CMFM. One of them is made from 500-micon thick aluminum 1050 grade foil with a H14 $\frac{1}{2}$ hard temper and the second one is made from the same aluminum foils and 99.9% pure copper foils (500-micon thick). The foils have been bonded together with 80% zinc and 20% aluminum by weight brazing paste with non-corrosive flux. The melting point of the brazing paste ranges between 410–470 °C. The paste is deposited on the foils with a layer thickness of 100-micron to ensure consistent thickness of the resulting composites [3,14,26].

Corrosion testing was conducted on the two composites made by CMFM by immersing them in a solution of distilled water and NaCl for one week. This was done to assess whether a week-long immersion would adversely affect the bond/foil interface or not. For statistical accuracy, a total of three specimens were tested for all the different materials and testing conditions.

2.1. Finite Element Modeling

CMFM makes use of brazing paste to join the metal foils together. The operating temperature range for the paste is between 410 and 470 °C. A 3D finite element model was created in ANSYS 19.1 to carry out transient thermal analysis on the 2.9-mm-thick rectangular specimen sandwiched between two stainless steel heated plates. Each plate was 150 mm long, 40 mm wide, and 8 mm thick, and was fitted with three FIREROD cartridge heaters (Watlow, MT, USA) to allow for uniform heating of the composite. As the composites in this work are 2.9 mm thick, only one of the two plates were turned ON as shown in Figure 1. The bottom plate was set to a temperature of 470 °C, and the top plate was set at room temperature (20 °C). The reason for doing that was to allow for a gradual increase in temperature from one end of the product rather than rapid heating from both sides in a small amount of time. Large/thicker parts with a thickness over 5 mm should be processed with both plates, but for anything less than 3 mm, it is recommended to use only one plate [7,8,14,26]. Excessive heating could result in inadequate bonding due to flux being burned off quickly and pitting of the foils leading to thermal stresses or undesired change in material properties. The primary mode of heat transfer in this work is conduction. It is the transfer of heat by microscopic colliding particles that include molecules, atoms, and electrons. These particles transfer disorganized microscopic kinetic and potential energy, jointly known as internal energy, from a hotter body to a colder body. Two models were developed; one for Al composite and the other for Al/Cu composite. The simulation served as a useful tool and allowed the production of composites in a consistent manner. The properties of Al 1050 [27], 99.9% pure copper [28], stainless steel [29], and the brazing paste [30] are shown in Table 1. For the transient thermal analysis, the contacts were set as 'No Separation' in ANSYS 19.1 with an element size of 2 mm.

Table 1. Mechanical and thermal properties of materials.

Properties	Materials			
	Al 1050 H14	**Copper**	**Stainless Steel 316**	**Brazing Paste**
Yield Strength (MPa)	110	70	290	45
Tensile Strength (MPa)	120	220	580	60
Young's Modulus (GPa)	69	120	193	60
Thermal Conductivity (W/m·K)	205	401	60	130
Specific Heat (J/kg·K)	875	385	434	480

2.2. Experiment for Heating Time

Each single layer of metal foil used in this work was 500-micron-thick, with an additional layer of brazing paste that was 100-micron in thickness. The overall thickness of the specimen was 2.9 mm (according to British standards discussed in the next section). Two K-type thermocouples with an operating range of −100 °C to 500 °C were wrapped and fixed to the top of the paste-coated layers of foils using heat resistant Kapton tape, as shown in Figure 2 (for Al/Cu composite). They were connected to a data logger Datataker DT80 (Datataker Pty Ltd., Melbourne, Australia), and the run time of the experiment was the same as the simulation time for transient thermal analysis in ANSYS 19.1. Two such experiments were conducted; one for Al composite and the other for Al/Cu composite. The average temperature from the two thermocouples was compared to the temperature obtained from the numerical simulation for validation (Section 3.2).

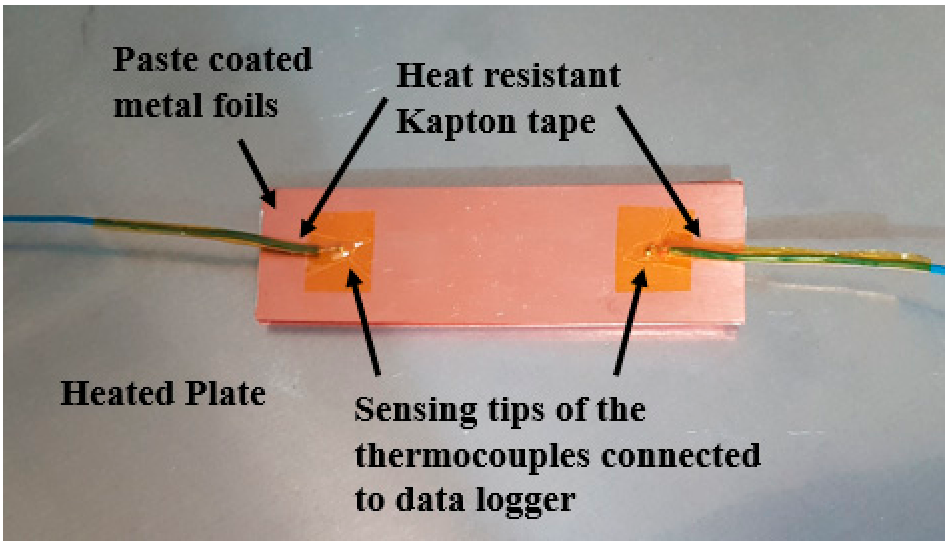

Figure 2. Experimental setup for heating time of Al/Cu composite.

2.3. Three-Point Flexural Test

Three-point flexural test samples were made by following BS EN ISO 7438-2016 [25]. This test has some distinct advantages over other tests used for the characterization of mechanical properties because of the ease of sample preparation and the test itself. This test was utilized to investigate the effect of bending loads on multi-layered Al 1050 and Al/Cu composites made by CMFM. Samples were machined out of solid metal blocks using a CNC machine. Each sample was 100 mm in length, 25 mm in width and 2.9 mm in thickness. CMFM was used to manufacture two composites; one is a layered sample made from 500-micron-thick Al foils and the other is Al/Cu composite sample made from 500-micron-thick Al 1050 and copper foils bonded together by the brazing paste. The Al composite had 5 layers of Al foils whereas the Al/Cu composite had 3 copper foils and 2 aluminum foils. Apart from the top and bottom foils, all the other foils had brazing paste on both sides. The three-point flexural test was conducted on a TIRAtest 2810 Universal Testing Machine with a speed of 2 mm/min. The former and supports are 10 mm in diameter based on the size of the tested specimens.

2.4. Corrosion Test of Composites

The corrosion test was performed in accordance with BS EN ISO 11130:2010 [31]. It was designed specifically to assess the effect of corrosion on the flexural strength of the composites made by CMFM. Corrosion, by definition, is a slow process, requiring days or years to occur to a noticeable extent, as opposed to similar electrochemical reactions such as etching, brightening, or anodizing which occur in minutes or less. To analyze this effect, the Al and Al/Cu composites were manufactured based on the validated model with a thickness of 2.9 mm. The composites were immersed in a solution of 35 g of sodium chloride dissolved in 1 L of distilled water for one week (168 h). The solution was tested for its pH using a digital pH meter (LIUMY, Shenzhen, China) every 12 h for the duration of the test. After the last pH reading on day 7, the composites were removed from the containers, dried with a clean cloth, and then air dried for 24 h. Afterwards, they were subjected to three-point flexural test on the SHT 4605 Servo Hydraulic Universal Testing Machine at a crosshead speed of 5 mm/min according to BS EN ISO 7438-2016.

3. Results and Discussions

3.1. Distribution of Temperature

Transient thermal analysis was undertaken in ANSYS 19.1 to show the heat transfer through the paste-coated metal foils. Two different 3D models were developed; one for Al composite and the other for Al/Cu composite. Regardless of the type of composite, it is essential that the heating time is controlled. The simulations could prove to be a useful tool for future product development. It can also help in removing the trial and error methodology for different geometries and product thicknesses. The numerical results for the distribution of temperature on the two different composites (Al and Al/Cu) are shown and discussed in the next two sections.

3.1.1. Temperature Distribution for Al Composite

The capacity of an object to conduct heat is termed as thermal conductivity and is given by the equation below:

$$K = \frac{QL}{A\Delta T} \tag{1}$$

In Equation (1), K is thermal conductivity (W/m·K), Q is the amount of heat transfer through the material (J/s or W), A is the area of the body (m^2), and ΔT is the difference in temperature (K). For the Al composite, aluminum and brazing paste are in contact with each other. They have different layer thickness (500-micron for Al and 100-micron for brazing paste) as well as different thermal conductivity values (205 W/m·K for Al and 130 W/m·K for brazing paste). This leads to a temperature distribution on the Al composite and the heated plates as shown in Figures 3 and 4 show the temperature distribution on the plate that was set at room temperature after 30 s.

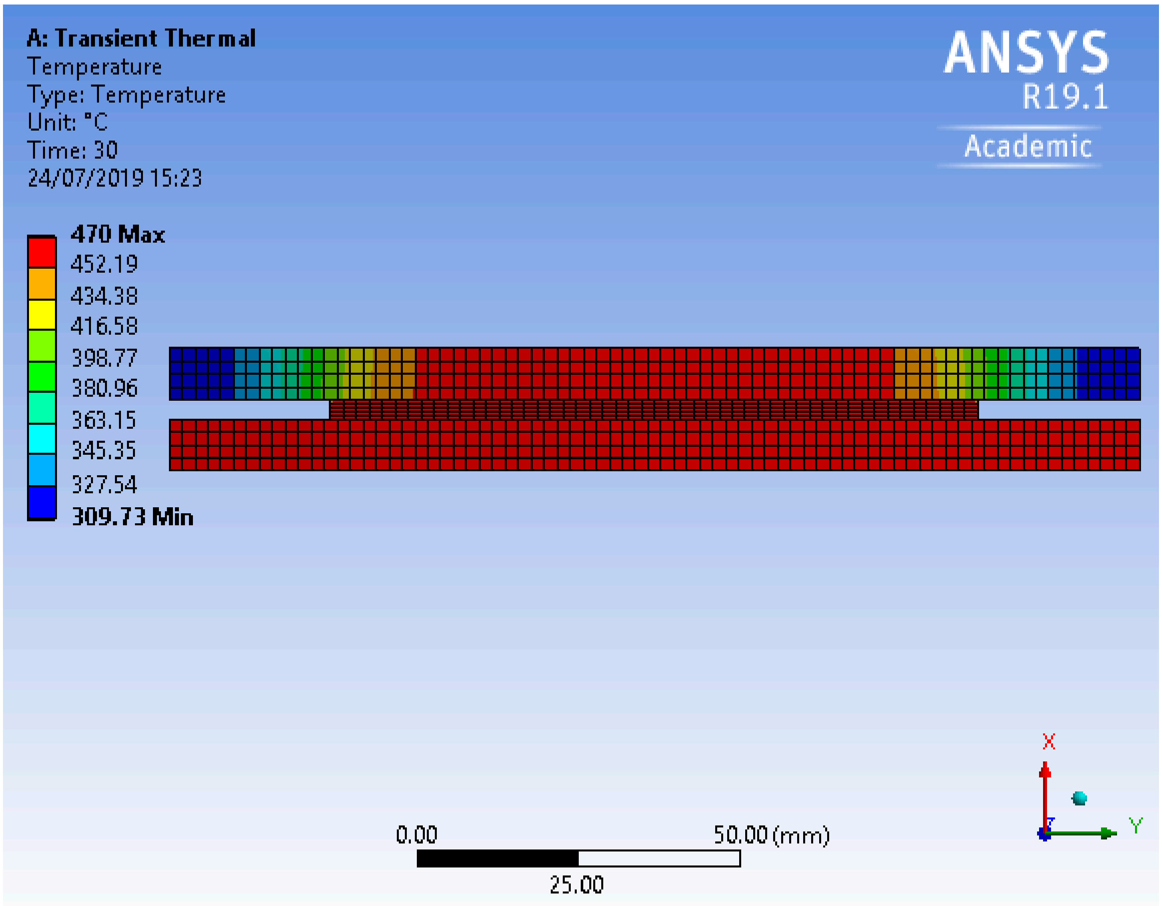

Figure 3. Temperature distribution on the plates and Al composite.

As evident from Figure 4, the temperature was higher in the middle as compared to the sides, because the specimen to be heated was placed there. The simulation was run for 30 s for this rectangular composite with 5 aluminum layers (made from 500-micron-thick foils) as compared to 40 s for a 10 aluminum layered composite (using 200-micron-thick aluminum foils) used in our previous work with a dog-bone geometry [26]. The reason is that there are less layers to braze/join in the current work (only 5 compared to 10) which has led to the top foil of aluminum (adjacent to the OFF plate) reaching 410 °C (operating range for the brazing paste is 410–470 °C) after 10 s. Since bond integrity is a function of the processing time, therefore, to ensure a strong bond, a shorter brazing cycle with fast heat-up and a very short holding time at maximum temperature was utilized [32]. Moreover, the recommendation from the manufacturer was followed that the brazing paste should not be allowed to stay more than 20 s within its operating range as after this, the flux starts to burn off leaving un-bonded areas. This is the reason for running the simulation for 30 s as after that time, simulation has shown the temperature to be 448.23 °C. This numerical simulation has been validated by an experiment that also ran for 30 s to assess whether the part could be produced in that time or not. The temperature curve (with respect to time) obtained from this simulation has been compared to the one obtained from the experiment in Section 3.2.1.

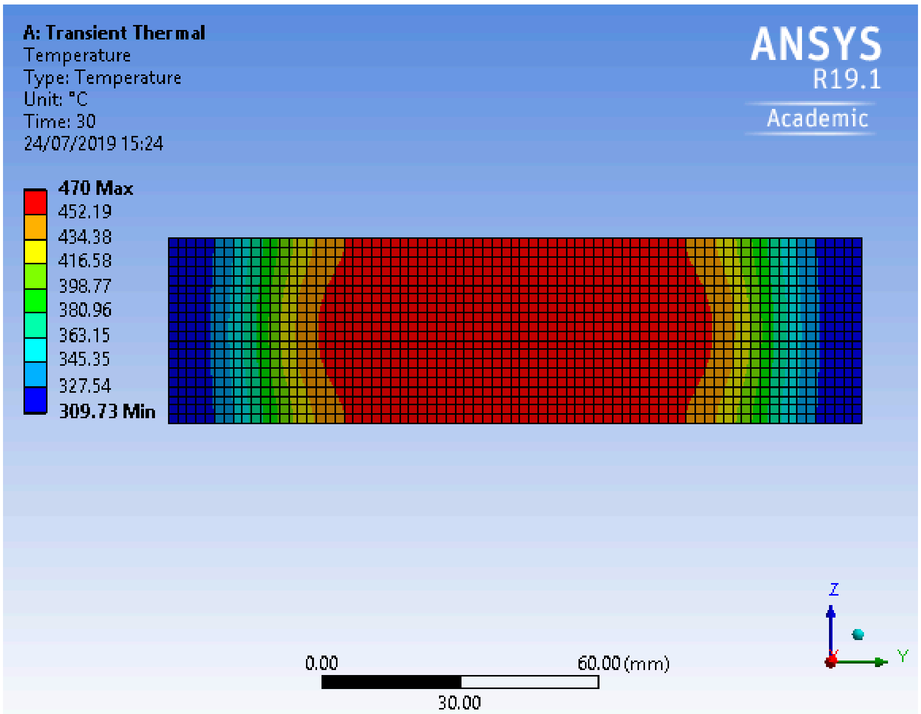

Figure 4. Temperature distribution on the OFF plate for Al composite.

3.1.2. Temperature Distribution for Al/Cu Composite

Figure 5 shows the distribution of temperature on the Al/Cu composite and the heated plates whereas Figure 6 show the temperature distribution on the plate that was set at room temperature after 30 s. In this case, a composite comprising three different materials (aluminum, brazing paste, and copper) is being heated. The minimum temperature shown for Al/Cu composite is 313.33 °C compared to 309.73 °C observed for Al composite (Figures 3 and 4). This shows a slight increase for Al/Cu composite. Generally, similar materials can conduct heat faster because their atoms are of the same size. Heat conduction in metals comes almost entirely from moving electrons. The electrons travel as waves which can slosh past many atoms without changing directions. However, if there is unevenness or irregularity in the pattern of atoms, the electron waves will bounce off those irregularities. In case of Al/Cu composite, there is clearly an uneven pattern of different types of atoms which would indicate that the thermal conductivity for this composite should be lower. However, that is not the case here. This can be attributed to the combination of the materials. Using 3 layers of copper which is an excellent conductor of heat has allowed the development of a composite that can surpass the thermal conductivity of aluminum. This combination of materials makes the product stronger and an excellent conductor of heat, thus allowing it to be used in a multitude of engineering applications. The same procedure was followed here as with the Al composite. The simulation was run for 30 s and the temperature rose to 451.34 °C compared to 448.23 °C in the case of Al composite. The numerical simulation has been validated by an experiment that also ran for 30 s to manufacture the Al/Cu composite. The temperature curve (with respect to time) obtained from this simulation has been compared to the one obtained from the experiment in Section 3.2.2.

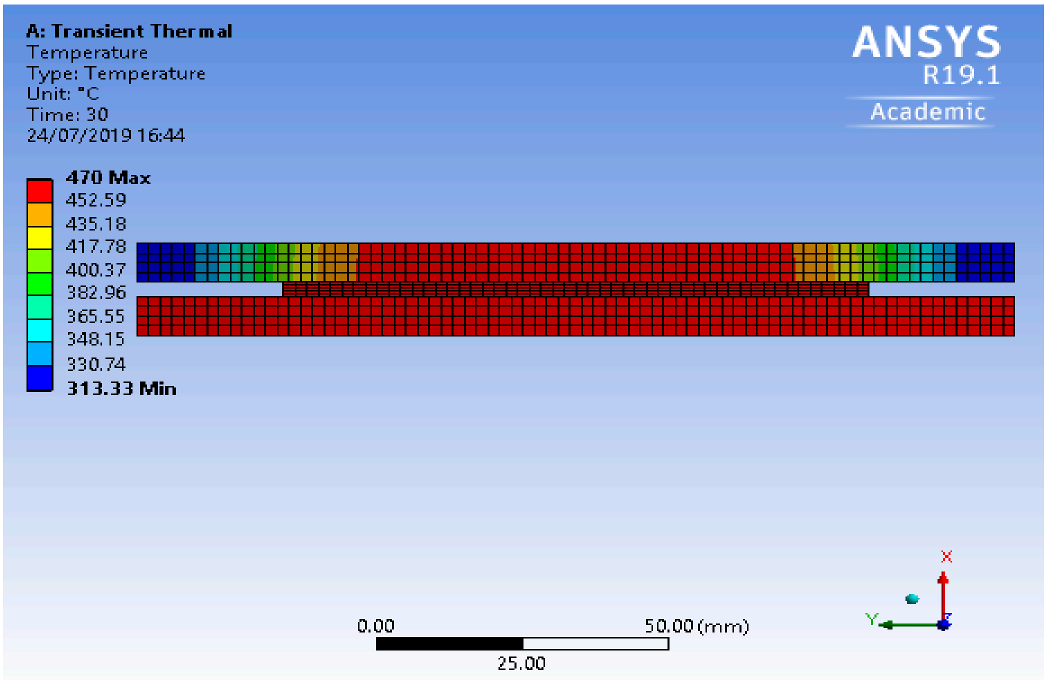

Figure 5. Temperature distribution on the plates and Al/Cu composite.

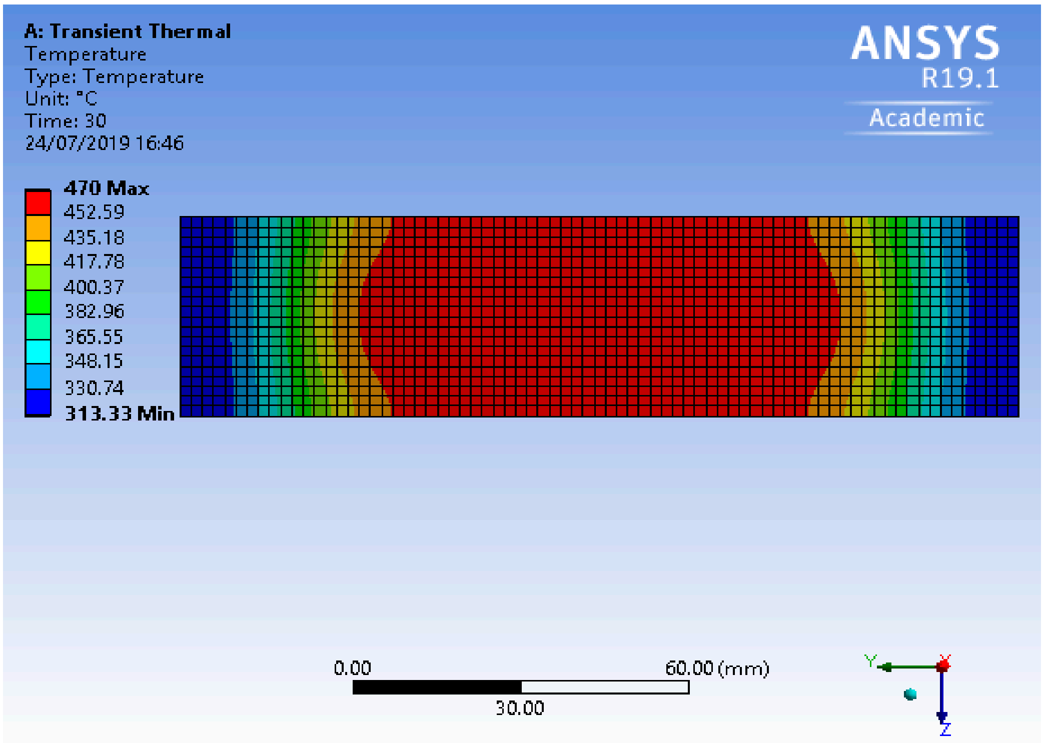

Figure 6. Temperature distribution on the OFF plate for Al/Cu composite.

3.2. Validation of Heating Time

The variation of temperature with time (transient) is governed by the following unsteady equation:

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

In Equation (2), $\alpha = \frac{k}{\rho c}$ = thermal diffusivity, and $\frac{q}{k}$ is the heat source.

In the current research, two different composites are being manufactured; one is a composite of aluminum and brazing paste whereas the second is the composite of aluminum, copper, and brazing paste. This means that even when similar material is being used, the product is still a composite as brazing paste is being used for binding purposes. Analyzing composites is extremely complex through analytical means as can be seen from Equation (2) as this equation had to be solved for each layer of the composite (whether similar or dissimilar materials) separately, and then the boundary conditions could be applied. Different materials have different rates of thermal expansion as well as different values of thermal expansion coefficients and their incorporation will result in a different set of conditions. Furthermore, thermal contact resistance of these different materials is a challenging aspect that is influenced by direction of heat flux, uneven contact pressure, relative motion or slippage between the surfaces, surface roughness, waviness or flatness, surface deformations or cracks, and surface cleanliness (presence of oxides or contaminants). Introducing all these parameters would make the analytical solution extremely complex and time-consuming. Numerical solutions could, however, be obtained in a relatively simple manner, but such simulations should be validated by experimentation. It is to be noted that the focus is not on optimizing the numerical analysis methodology but identifying an operating window in which CMFM can produce composites, thus removing trial and error for the manufacture of different geometries. This has been helped to a great extent by the large operating temperature range for the brazing paste (410–470 °C) and some useful recommendations from the paste manufacturer.

3.2.1. Validation for Al Composite

The numerical simulation for Al composite ran for 30 s in total (Section 3.1.1). This time has been used as the heating time for the experiment as well. The 2.9-mm-thick layered rectangular sample was sandwiched between two stainless steel plates. The bottom plate was set at 470 °C, and it was at the set temperature when the paste-coated foils were placed on it. Two K-type thermocouples were attached to the top of the Al composite sample with the help of heat-resistant tape. The thermocouples were connected to a data logger that collected the data for 30 s. The average temperature from the two thermocouples and the temperature taken from the simulation were plotted with respect to time and are shown in Figure 7. It is evident that there is good agreement between the finite element analysis (FEA) and experimental (Exp) results after their intersection i.e., after 19 s. The curves initially start with a significant difference until around 10 s but gradually move towards intersection. This initial difference can be explained by the materials of the brazing paste. The paste contains 80% zinc that has a melting temperature of 419.5 °C. This temperature lies within the operating range of the brazing paste (410–470 °C). The latent heat of fusion of zinc is 7.322 kJ/mol with a specific heat capacity of 25.2 J/(mol·K). This suggests the amount of heat used to melt the brazing paste can drastically reduce the temperature from rising during the experiment which is evident in the first 10 s of the experimental curve. On the other hand, the FEA model did not consider the heat consumption during the melting process for the brazing paste. The sequential melting process of discrete layers of brazing paste can also explain several 'halt' points for the EXP data in Figure 7. It is to be noted that the numerical analysis is aimed at identifying an operating window for the appropriate bonding of products made by CMFM. It is recommended to optimize the numerical simulations for factors such as air gaps, enthalpy of fusion, thermal contact resistance etc., for improved results that can also help in assessing the effects of thermal stress/strain in CMFM products. This experiment validated the applicability of numerical simulations to produce parts using CMFM. This result is in-line with the comparison done in our previous work where aluminum foils of 200-micron thickness were utilized [26]. This clearly demonstrate that numerical analysis can be utilized for producing composites using CMFM with different foil thicknesses and geometries.

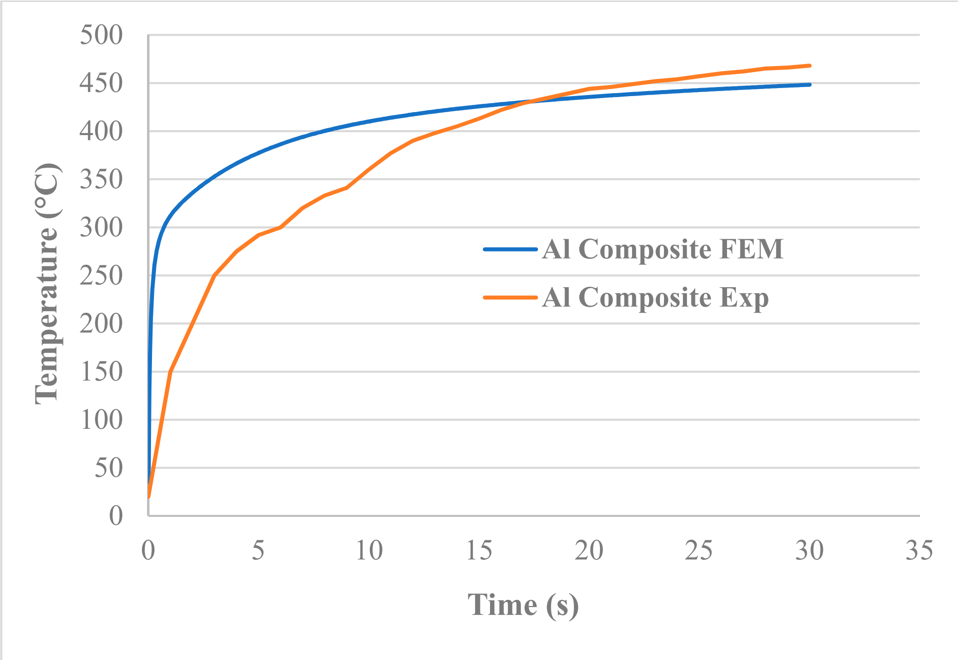

Figure 7. Comparison between finite element analysis and experimental results for Al composite.

3.2.2. Validation for Al/Cu Composite

The same procedure has been followed here as with Al composite. The experimental curve for Al/Cu composite is almost identical to the experimental curve obtained for the Al composite. Since there was little difference between the simulated results for the two composites, both the experimental curves seem to agree well with the numerical results after intersection. Much like in Figure 7, it is evident in Figure 8 that the difference is quite significant in the first 10 s but gradually becomes smaller afterwards. The reasoning is the same as with the Al composite in that the zinc's enthalpy of fusion has played a significant role in the early stages of the heating process. It is interesting to note that due to the highly conductive copper, the heat transfer has been more rapid for the Al/Cu sample compared to the Al composite. In case of Al/Cu composite, a temperature of 407 °C was reached after 13 s and the maximum temperature (470 °C) was reached after 29 s. The Al composite was at 398 °C after 13 s and entered the operating range of the brazing paste after 15 s (413 °C). The maximum temperature of the Al composted also rose to 468 °C after 30 s. The experimental curve for the Al/Cu composite also intersected the FEM curve after 16 s compared to the Al composite where the intersection occurred after 19 s. Both composites show good bonding after the 30 s heating window. There is difference between experimental and numerical results in the early stages of heating which is to be expected due to heating losses and other material related aspects (e.g., enthalpy of fusion, thermal contact resistance), but the important aspect is the reliability of this simple simulation tool that can be refined and optimized for even better results in future works. Section 3.3 will show the three-point flexural test results for the rectangular composite samples that have been manufactured with the use of these simulations.

3.3. Results from Three-Point Flexural Testing

The transient thermal analysis from ANSYS showed that 30 s are required for the manufacture of 2.9-mm-thick Al and Al/Cu composites. These times were validated by the manufacture of the rectangular layered composites to be subjected to the flexural test. These results were compared with samples made from solid Al 1050 and 99.9% pure Cu blocks using CNC machining. The Al 1050 composite is made from 5 aluminum layers whereas the Al/Cu composite is made from 3 copper layers and 2 aluminum layers. The layers were bonded together with brazing paste on both sides of the foil (apart from the top and bottom layers). Both the layered Al 1050 and Al/Cu composites behaved in the same manner as the solid Al 1050 sample (and Cu sample), in terms of bending all the way through as shown in Figure 9.

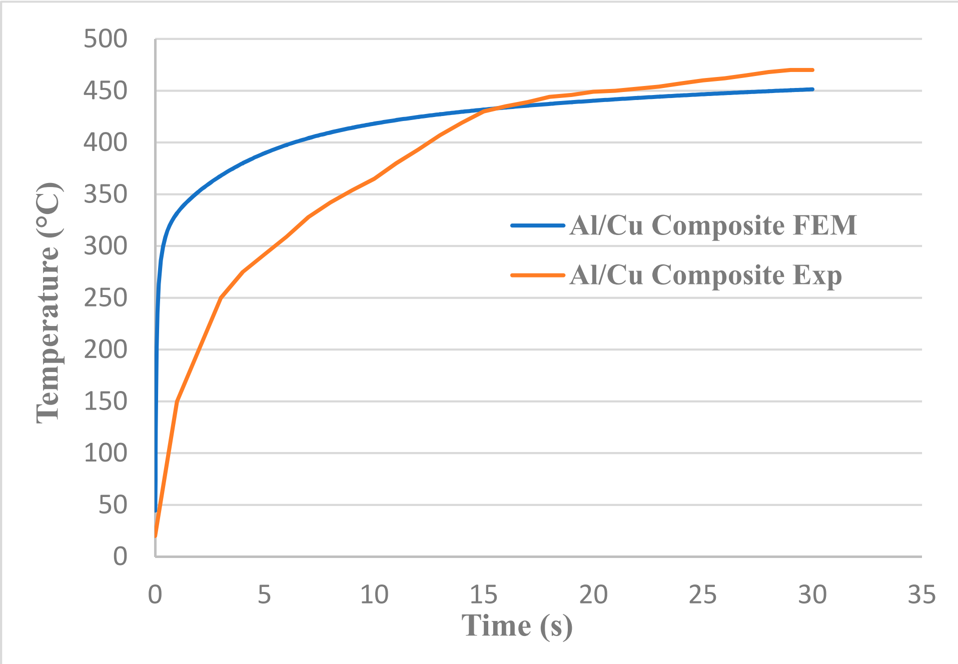

Figure 8. Comparison between finite element analysis and experimental results for Al/Cu composite.

Aluminum and copper are ductile; therefore, they show a prominent elastic as well as plastic region. The composites made by CMFM have also exhibited the characteristic curve of these ductile materials as shown in Figure 10. The maximum bending load for the solid Cu sample is 1388 N and that of solid Al 1050 is 767 N. The bending load for Al composite is 806.88 N whereas Al/Cu composite shows a bending load of 855 N. The two composites (Al and Al/Cu) have shown increased values of bending load that are 5.2% and 11.5% higher compared to solid Al 1050. It was not expected that the composites will perform better than solid Cu as it is comparatively stronger than aluminum, but the results have shown increased bending loads for the composite samples compared to the parent Al 1050. A composite tends to combine the properties of the parent materials and the Al/Cu sample made by CMFM has done the same thing. The use of copper foils has given it the capability to resist the bending load more effectively as compared to the composite made only from Al 1050 foils. The Al composite has been made from 500-micron-thick foils and shows a bending load of 806.88 N. Our previous work has shown that the bending load of Al composite made from 100-micron-thick foils to be 827.9 N which is an increase of 7.7% compared to parent Al 1050 [20]. The reason for the higher values in case of 100-micron-thick foils lies in the number of foils bonded together for the same thickness. Since the brazing paste creates an intermetallic bond with the metal foil, the yield strength of the foil and the paste add up. Increase in the number of layers leads to increase in strength [1,3,11,20] which is the reason that the composite made by 500-micron-thick foils shows lower flexural strength compared to the one made from 100-micron-thick foils.

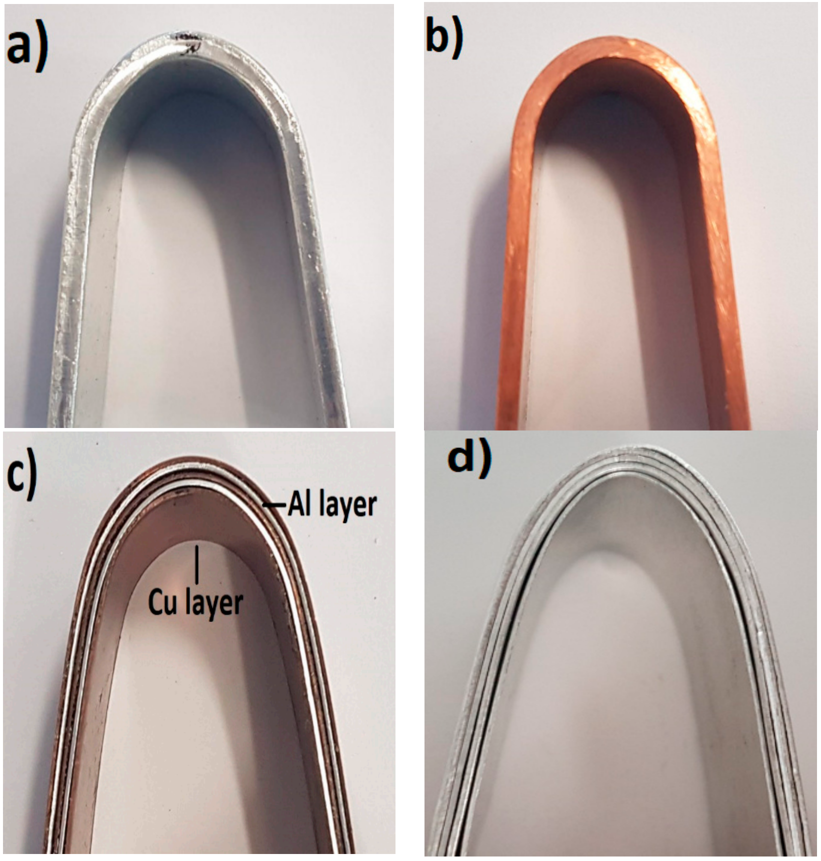

Figure 9. Bending modes; (**a**) solid Al 1050; (**b**) solid 99.9% Cu; (**c**) Al/Cu composite; and (**d**) Al composite.

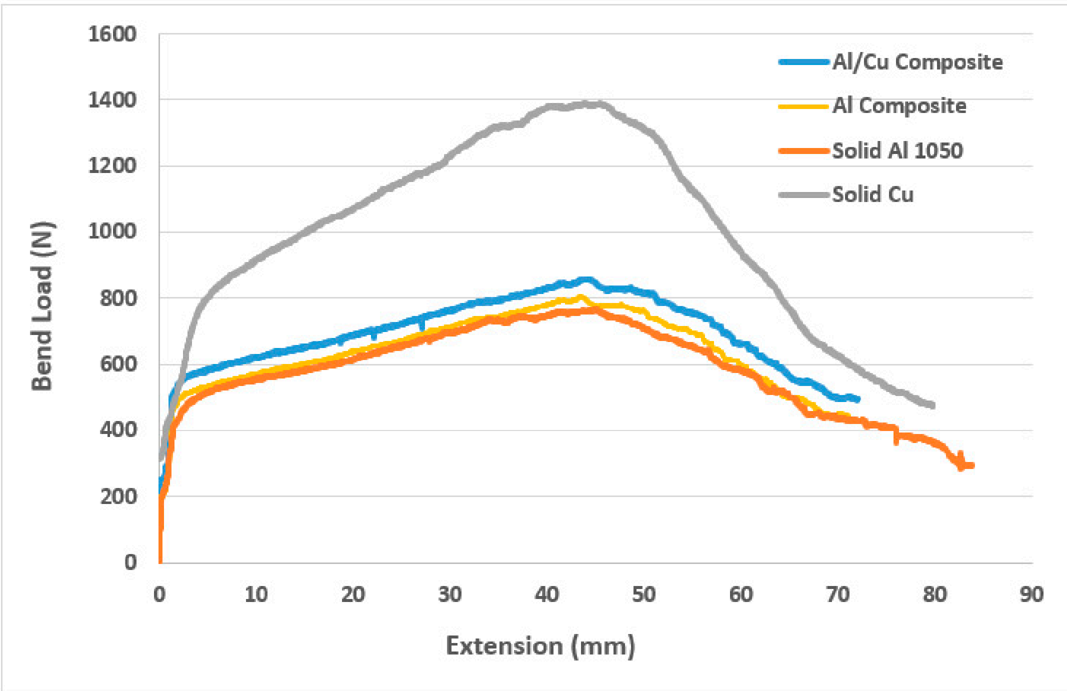

Figure 10. Comparative flexural test results.

The ease of mobility for dislocations is what makes something ductile and it is a useful quality as it allows a material to be plastically twisted with no crack and the tendency to hold the deformation that occurs in the plastic region. A ductile material can undergo significant plastic deformation before rupture, hence providing a warning that can be very helpful in engineering applications. The Al composite made from only aluminum 1050 foils shows a higher bending load (compared to parent solid aluminum 1050 sample) and ductile properties. The Al/Cu composite also exhibits ductile nature under bending load but is better in terms of resisting load compared to one of the parent metals from which it has been made from. It is the weaker of the two constituent metals from which it has been formed but stronger than the other (Al with a Young's modulus of 69 GPa whereas Cu has a value of 120 GPa) These result show the effectiveness of CMFM in terms of manufacturing resilient products suitable for bending load intensive applications and operations.

3.4. Results from Corrosion Testing

After the experimental validation of the numerical analysis, two more composites (Al and Al/Cu) were manufactured to be immersed in a solution of distilled water and NaCl. Aluminum alloys can corrode via several different pathways and recognizing the pathway, or the forms of aluminum corrosion is an important step to determine the appropriate remedy. Economically, galvanic corrosion creates the largest number of corrosion problems for aluminum alloys. Galvanic corrosion, also known as dissimilar metal corrosion, occurs when aluminum is electrically connected to a more noble metal, and both are in contact with the same electrolyte. In this work, Al 1050 has been bonded with copper which can nearly be classed as a noble metal because of this reluctance to oxidize or corrode. The corrosion could be due to a whole host of reasons, but the root cause comes down to the movement of electrons or galvanic action between the copper and its surroundings. When exposed to the atmosphere, copper oxidizes and forms copper oxide, causing bright copper surfaces to tarnish. The chemical equation for copper oxide is $4Cu + O_2 = 2Cu_2O$. When copper is exposed to air for a longer time, then copper reacts with carbon dioxide and water in the air to form a green coating of basic copper carbonate on the surface of the object. The formation of this green coating on the surface of a copper object is the cause for corrosion [33]. Green coating of basic copper carbonate is a mixture of copper carbonate and copper hydroxide, $CuCO_3$, $Cu\ (OH)_2$.

When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes faster than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone. When contact with a dissimilar metal is made, however, the self-corrosion rates will change. Corrosion of the anode will accelerate, and corrosion of the cathode will decelerate or even stop. Galvanic coupling is the foundation of many corrosion monitoring techniques. The driving force for corrosion is a potential difference between the different materials and their compatibility can be predicted by consideration of their anodic index. This parameter is a measure of the electrochemical voltage that will be developed between the metal and gold. To find the relative voltage of a pair of metals it is only required to subtract their anodic indices [34]. The anodic index for aluminum is −0.95 V and that of copper is −0.35 V which means the difference is 0.60 V which can be tolerated in controlled environments [35].

The corrosion test will investigate whether the flexural strength of the Al and Al/Cu composites has been affected by their immersion in a solution of NaCl and distilled water for one week. The composites were placed in different containers to ensure that no contamination occurs. The cylindrical containers were fitted with a lid to avoid water evaporation over time and kept in a cool/dry place away from sunlight. During the week, the pH of the solution was carefully monitored and measured every 12 h (two readings in one day) with a pH meter. A typical pH scale comprises a range from 0 to 14 with 7.0 being neutral. Values less than 7.0 are classified as acidic whereas higher values are classified as basic. Elevated acidic or basic values can cause problems which is why it is crucial to monitor the pH of the solution to ensure that a controlled environment has been provided for the test. The values for the pH measurements are shown in Figure 11. They indicate that the pH values fluctuate slightly from the first reading to the second but there is no upward trend of acidic (increase of H^+ ions concentration) or basic nature (increase of OH^- ions concentration). It is interesting to note that the first reading is always a higher value compared to the second one. This can be attributed to the time of day the reading was taken i.e., morning time compared to night (for the second reading). There are, however, no abrupt changes and the values range from 6.17 to 7.12 showing that the solution remained neutral throughout the 7-day period.

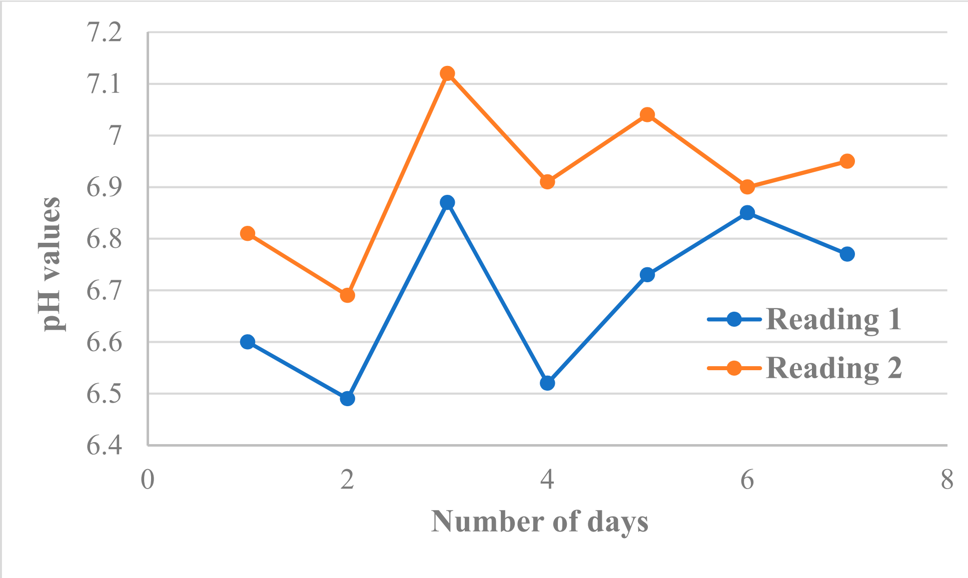

Figure 11. Measurement of pH values for 7 days.

After day 7, the composites were taken out of the containers and dried with a clean, dry cloth. They are left to be air dried for 24 h and then subjected to three-point flexural test at a speed of 2 mm/min. The resulting bending modes and bend load values are not significantly different from the ones obtained in Section 3.3. The results of the 'dry' (without immersion in the solution of NaCl and distilled water; Section 3.3) and 'wet' (after immersion in the solution of NaCl and distilled water) testing are shown in Table 2.

Table 2. Flexural strength calculations from dry and wet testing.

Test	Samples	Maximum Bending Load (N)	Difference in FS (%)
Before corrosion (dry) testing	Solid Al 1050	767	Compared to solid Al 1050
	Solid Cu	1388	
	Al Composite	806.88	5.2
	Al/Cu Composite	855	11.5
After corrosion (wet) testing	Al Composite	807.6	5.3
	Al/Cu Composite	853	11.2

The results clearly indicate that even though the difference between the anodic indexes of the two metals is 0.60 V, 7 days were not enough to observe degradation of flexural properties and there were no visible signs of color change either. The reason for no-degradation in the Al/Cu composite lies in the arrangement of its layers. Al/Cu comprise 5 foils and the order of the foils is Cu-Al-Cu-Al-Cu (every foil has a layer of brazing paste on both sides except for the top and bottom layers). Thus, both the top and bottom layers are Cu, which has the same anodic index. It is to be noted that the top and bottom layers contribute more than 90% of contacting area with the solution of NaCl and distilled water (saltwater) thus they are the major factor for the corrosion. Although there are two layers of Al within the composite, the majority of their surface is wrapped inside the composite and has very little direct contact with the saltwater. This means that the decay rate of the Cu/Al composite is close to the one of solid Cu. Therefore, more layers with a different configuration (e.g., Cu-Al-Cu-Al-Cu-Al) could help in analyzing this effect further.

The no-degradation of bend strength for the composites after a 7-day immersion in saltwater is a very promising development for composites made by CMFM because it removes the use of supplementary processes (e.g., electroplating, cathodic protection, use of antioxidant paste) to reduce galvanic corrosion. When design considerations require that dissimilar metals come in contact, the difference in anodic index is often managed by finishes and plating. The finishing and plating selected allow the dissimilar materials to be in contact, while protecting the base materials from corrosion by the nobler. It will always be the metal with the most negative anodic index which will ultimately suffer from corrosion when galvanic incompatibility is in play. The results obtained here are also in-line with our previous work with other composites made by CMFM but tested for only 24 h [19,26]. However, it is recommended that longer tests are carried out possibly spanning a month or three months to assess the integrity of the bond/foil interface as after 7 days, it has been concluded that galvanic corrosion does not adversely affect the composites made by CMFM.

4. Conclusions

This paper presented a simple 3D finite element model that shows the effect of heat supplied to the composite sample during the brazing operation of CMFM. The temperature readings from the numerical model were validated by running experiments that involved recording the average temperature values from two thermocouples attached to the samples. The two temperature curves (FEA and experimental) showed good agreement, indicating that numerical means could be utilized to assess the time required to produce composites using the process of CMFM. This approach can prove to be very helpful in producing composites with different thicknesses and geometries. Flexural testing was undertaken to assess the behavior to bending loads on the composite samples. The flexural properties of layered Al and Al/Cu composite sample made by CMFM have been investigated and compared against solid parent Al 1050 and 99.9% pure copper samples. The samples have been made and tested according to British standards. The parent metal samples were machined using a CNC machine and the composite was made from CMFM. The test results show that the composite samples can withstand higher bending load compared to parent Al 1050 sample. The Al composite is 5.2% stronger whereas the Al/Cu composite is 11.5% stronger compared to the solid Al 1050 sample. Both the composites also followed the characteristic curve for the parent metals and were completely deformed into a 'U' shape. This result shows the capability of CMFM in terms of manufacturing composite parts with superior mechanical properties.

Galvanic corrosion affects parts made with aluminum and in this work composites of aluminum and aluminum/copper have been manufactured. Therefore, it is crucial to assess the effect of corrosion on the bond/foil interface. After a 7-day immersion of the Al and Al/Cu composites in a solution of distilled water and NaCl, the rectangular parts were subjected to three-point flexural testing. The results show consistent values for both composites compared to the samples that were tested without immersion. The results indicate that galvanic corrosion does not adversely affect the parts made by CMFM after 7 days. Longer tests should be conducted to further analyze this effect.

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