EFFECTS OF INDUCTION HEATING ON THIXOFORMED MWCNT-Al ALLOY COMPOSITE

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Article History: Received 1 July 2020; Revised 12 February 2021; Accepted 24 April 2021

ABSTRACT: The aim of this paper is to investigate the effect of vertical induction heating on MWCNT-Al alloy composite during thixoforming. Several feedstocks of MWCNT-A356 alloy composite with a non-dendritic microstructure were prepared using a mechanical stirring of liquid casting. During thixoforming, the feedstocks were reheated up to the 50 % liquid fraction in the semi-solid state at 580 °C and compress into an upper mold. The heat distribution is determined by analyzing the microstructures and densities throughout the cross-sectional of the feedstock. After that, real time temperature monitoring is carried out using the EPAD-Base2 data acquisition systems, optical microscopic observations and electronic densimeter measurements were used, respectively at its surface, top, center, and bottom locations. The results show that the temperatures distribution is consistent with only ± 10 °C variation. The homogeneous heat distribution has also been observed by the similar coarsening rates of α-Al grain after thixoforming with the average grain diameter of 37.9 ± 22.8 μm and spherical factor (SF) of 0.564 ± 0.127, and the densities are almost identical of 2.675 ± 0.009 g/cm3, 2.676 ± 0.011 g/cm3 and 2.676 ± 0.007 g/cm3 at these locations. Therefore, the vertical induction heating in this study is suitable for thixoforming of the composite aluminium alloy.

KEYWORDS: *Induction Heating; Carbon Nanotube; Aluminum Alloy Composite; Thixoforming*

1.0 INTRODUCTION

A semi-solid metal processing or thixoforming has been established for quite sometimes in an automotive industry to enhance the components strength. The term thixoforming is used to describe a reheating process of alloy into its semi-solid state and after that compress it into a near net shape mold [1]. Successful thixoforming requires a non-dendritic feedstock that is thixotropic in nature [2]. The thixotropic behaviour during the semi-solid state allows the grains to expand and expel out micro-porosities that normally inherit by casting [3]. The coarsening and reduction of porosity in the matrix will eventually increase the mechanical properties of the alloy.

A356 alloy is one of the most frequently used as the thixoformed alloy due to its high fluidity that is suitable for casting. Besides, the alloy also has wider thixoforming processing windows and low sensitivity of the liquid fraction within its semi-solid state [4-5]. In addition, the feedstock must be heated uniformly over its entire cross-sectional areas to ensure homogeneous liquid-solid fraction distribution. Therefore, the reheating method shall have the capability not only to meet the requirement, but easy to control.

Induction heating method is the most frequently used semi-solid reheating process as compared with others. For instance, a conventional electrical furnace requires a long heating time and difficult to control especially for small feedstocks. The induction heating power involves Eddy currents flow inside the feedstock from the alternating electromagnetic fields of the induction coil [6]. The induced power by the current must be able to penetrate the core of the feedstock and it is called the current penetration depth. Otherwise, the power gradient will be concentrated at the surface, top or bottom of the feedstock. The non-uniformed reheating caused some issues like skin effect and elephant foot phenomena [7-9]. Therefore, an optimal heating coil design or setup is an important aspect of the uniform heating [10-11].

Although the thixoforming using induction reheating on aluminum alloy has been established, there are very limited work on the effect of induction heating subjected to multiwalled carbon nanotube (MWCNT) aluminum alloy composite. Therefore, the present study is focused on the effect of the induction heating to the heat distribution, microstructure, and densities of the feedstock in billet form. IN this experiment, a MWCNT-A356 aluminum alloy composite was prepared using a mechanical stir casting method. A wettability agent of magnesium powder was mixed with the MWCNT to enhance uniform distribution by lowered down the liquid matrix surface tension and form interfacial bonding between MWCNT and Al matrix [12-14]. The findings of this study may reveal the best homogeneous heat distribution which resulted from vertical induction heating that may contributed to the quality of the thixoformed samples.

2.0 METHODOLOGY

2.1 Materials

In this experiment, the A356 matrix chemical compositions (wt.%) of 6.5-Si, 0.2-Cu, 0.7-Mg, 0.2-Fe, 0.2-Ti, and 0.2-Cu has been reinforced by 0.5 wt.% MWCNT (>95%purity-Sigma Aldrich). The composite was prepared using a liquid casting method by mixing the MWCNT at 650 °C and stirred immediately at 500 rpm for 10 minutes before pouring into a permanent mold. The size of the billet is 25 mm and 110 mm in diameter and height, respectively. Three holes of 2.0 mm in diameter were drilled into the billet horizontally at specific heights and depths as shown in Figure 1.

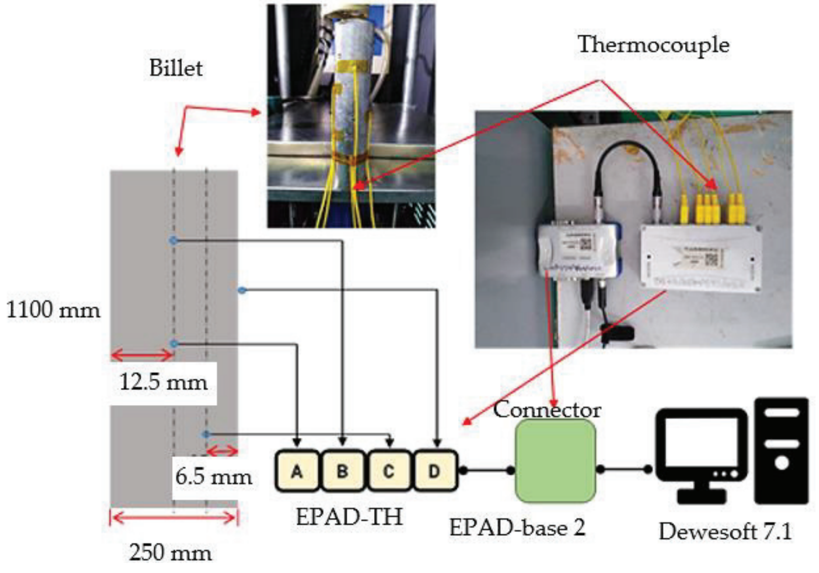

Figure 1: Schematic of data acquisition system

2.2 Experimental Setup

The K-type thermocouples were inserted into the holes and secured with a high temperature Kapton tape. An additional thermocouple was attached on to the surface of the billet to monitor skin temperature during the heating process. The thermocouples were connected to four channels of EPAD-THS and EPAD-Base2 data acquisition system. Real time temperature variations were collected and analysed using a Dewesoft 7.1 software. The induction heater specification is shown Table 1.

Table 1: Induction heating and coil specifications

Frequency	59 ± 4 kHz
Input voltage	3 phases / 415 V 50 Hz
Cycle	100 %
Maximum power	35 kW
Induction coil diameter	7 mm
Number of coil circle	10
Induction coil height	120 mm
Gap (inner coil and outer billet)	22.5 mm

The billet was placed vertically inside an induction coil of thixoforming setup as shown in Figure 2. The billet was reheating up to a semi-solid temperature of 50% solid-liquid fraction at 580 °C based on the A356 alloy differential scanning calorimetry (DSC) analysis. The isothermal heating process was hold for 5 minutes at this temperature before the billet was rammed with forging load of 5 tons into a top mold.

The effect of the induction heating on microstructures at different locations of the composite were characterized using the standard metallographic procedures and etching with Keller's solution for 10 seconds and examined through optical microscopy (OM) and I-Solution software for grain size calculation. Moreover, after the thixoforming, the top, center and bottom sections were cut into similar thickness to determine the densities at these areas using an electronic densitometer of Archimedes principle.

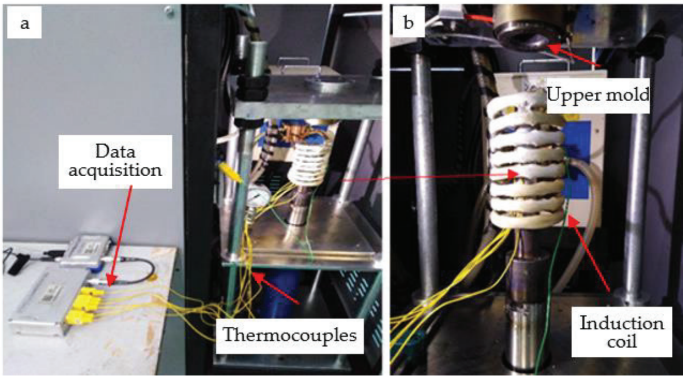

Figure 2: Schematic of the thixoforming setup:
(a) thixoforming machine and (b) thixoforming area

3.0 RESULTS AND DISCUSSION

3.1 Induction Heating Temperatures Distribution

Figure 3 shows the graphs of induction heating temperatures distribution at the composite billet. The total time taken for the reheating process was 12.3 minutes to reach the semi-solid state at 580 °C. The area of billet skin (D), half center (C) and center (A, B) can be found in Figure 1. The graphs obtained show that the temperature at the composite billet skin (D), half center (C) and center (A, B) were parallel with each other. Some variations of ± 10 °C were expected during the heating due to some movements of the thermocouples by the transformation of liquid from solid matrix during the reheating process [15-16].

Based on the calculated current penetration depth of 13.5 mm from the outer of skin of the billet to its center as compared with radius of the billet of 12.5 mm indicated that there was sufficient heat energy supplied to allow homogeneous heat distribution inside the billet. Homogenous heat distribution plays a vital role to ensure the billet is heated uniformly, so that mechanical properties enhancement could be achieved. This finding is in good agreement with Chen et al. [17] who performed an experiment using induction heating. In this experiment, they found that the SiC bricks had more excellent properties after induction heating as compared to ordinary heating. This is because the induced electric field can promote the wetting of the SiC aggregates by the Al-Si-C drops during induction heating. Surprisingly, it was also noticed that there were no signs of elephant foot and no skin effect (collapsing billet) observed during the reheating process as shown in Figure 4. The surface of the samples is very smooth indicating that the temperature is uniform throughout the sample, hence improved the mechanical properties of the thixoformed sample.

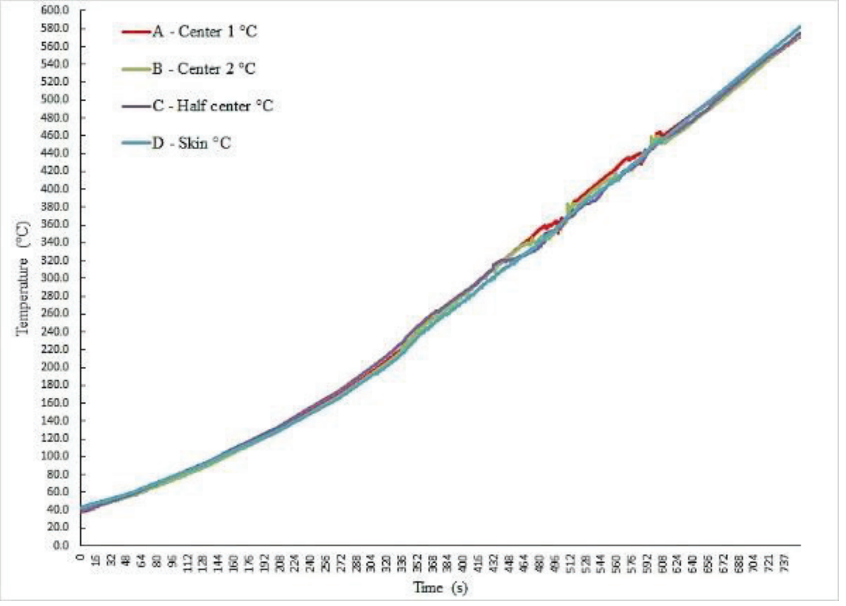

Figure 3: Graphs of the temperature during induction heating of the MWCNT-A356 composite

Figure 4: Billet of the sample after thixoforming

3.2 Microstructural Analysis

Figure 5 shows the microstructures at the cores (top, center, and bottom) of the billet before the thixoforming. There was clearly seen in the Figures 5(a)-5(c) that there is a non-dendritic structure in the sample with the same shape and size. This observation can be justified due to the uniform heat distribution throughout the sample. The microstructures of the α-Al (brighter area) mostly resembled rosette and near globular shapes. Figure 6 shows the microstructures at the cores (top, center, and bottom) of the billet after the thixoforming. Similarly, the transformation of the non-dendritic shapes (α-Al) at these locations were almost identical showing the uniform induction heating capability [14]. The α-Al grains have expanded or coarsening after thixoforming to an average grain diameter of 37.9 ± 22.8 μm with spherical factor (SF) of 0.564 ± 0.127, from 23.6 ± 11.5 μm with 0.545 ±

0.118 (before thixoforming), respectively. The increased in size by 60.6 % with slightly better SF value (perfect circle, SF=1) of the α-Al after thixoforming causing most of inherit casting defects in the matrix such as microporosity to be expelled out. Besides, the compaction of the billet at semi-solid state, resulted microporosity reduction which helps to strengthen the composite alloy [13].

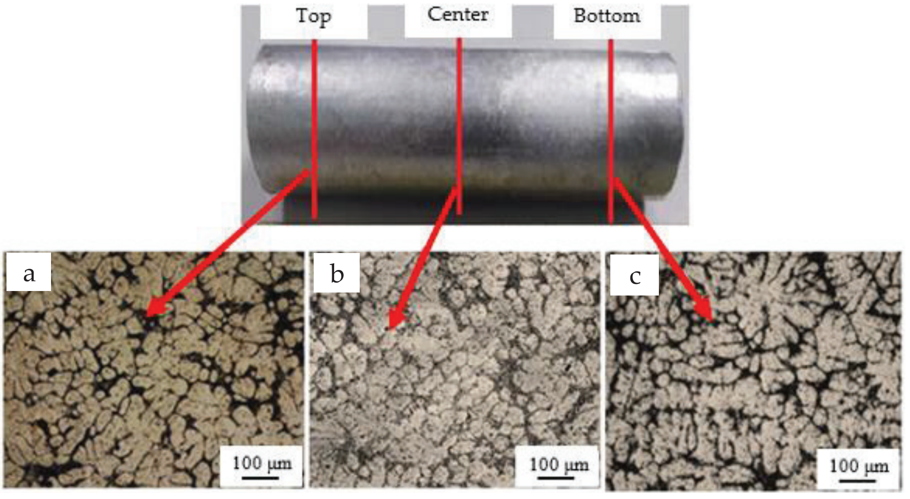

Figure 5: Non-dendritic microstructures: (a) top region, (b) center region and (c) bottom region

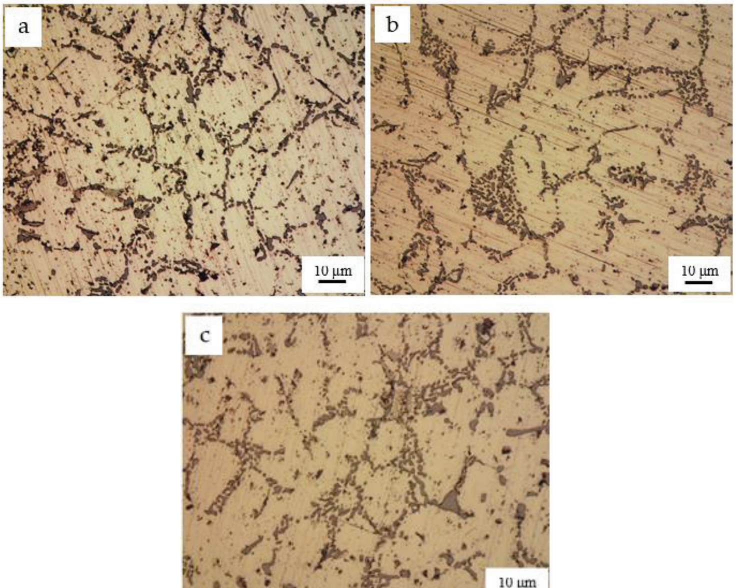

Figure 6: Microstructures at the core after thixoforming: (a) top region, (b) center region and (c) bottom region

3.2 Density

Figure 7 shows the densities of the billet composite before and after thixoforming. The average density of the composite before thixoforming is 2.636 ± 0.004 g/cm3. However, after thixoforming, the densities at the top, center and bottom sections were 2.675 ± 0.009 g/cm3, 2.676 ± 0.011 g/cm3 and 2.676 ± 0.007 g/cm3, respectively. It was clearly seen from Figure 7 that solidification with no pressure (before thixoforming) resulted with a high porosity level, whereas the density of the thixoformed composite has increased due to the thixotropic nature of the non-dendritic microstructures of the matrix [15]. It allows the reduction of porosity to take place by coarsening of α-Al and compaction [16].

In addition, the higher density of the thixoformed composite is expected to have a good mechanical property due to very minimal porosity that exist in the sample. According to Freitas et al. [18], porosity is concentrated at the rods ends; thus, this occurrence is related to liquid segregation. Normally porosity level of permanent mold cast product is around 1-2% with average size close to 70 μm [18]. In this experiment, the thixoformed sample parts are characterized by porosity levels much lower approximately 12 μm than those produced by the conventional process, therefore increased the mechanical properties of the samples.

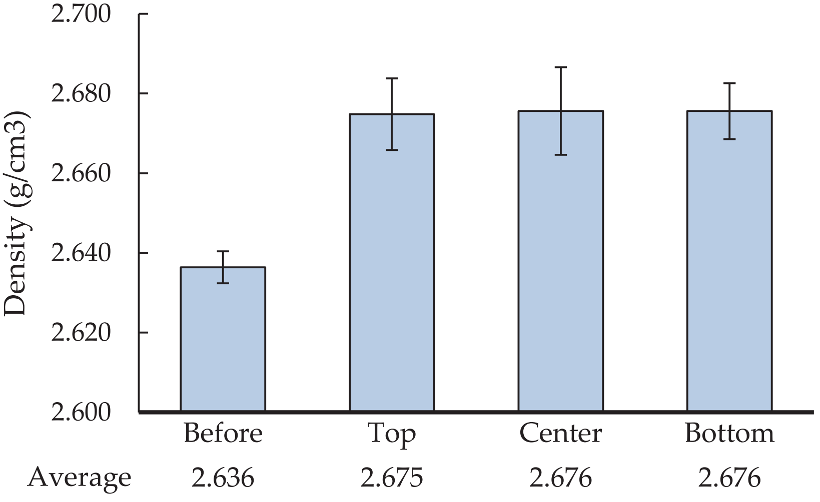

Figure 7: Densities of the composite before and after thixoforming at different locations

4.0 CONCLUSION

The results of the present investigation show that the MWCNT-A356 composite was successfully thixoformed using a vertical induction heating. The temperatures distribution at skin, core, top and bottom of the billet were consistent with only ± 10 °C variation. The consistency of the temperatures throughout the billet is very critical to ensure uniform properties of the composite, especially the mechanical strength. A homogeneous heat distribution of the induction heating can be seen by the similar coarsening rates of α-Al grain after thixoforming of the average grain diameter of 37.9 ± 22.8 μm with spherical factor (SF) of 0.564 ± 0.127 at different locations in the billet. Furthermore, the densities of 2.675 ± 0.009 g/cm3, 2.676 ± 0.011 g/cm3 and 2.676 ± 0.007 g/cm3 at these three locations also indicated uniform heat distribution. The findings revealed that the parameters of the induction heating system are suitable for the composite billet which there is no skin effect or elephant foot issues detected in the sample.

ACKNOWLEDGMENTS

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM), Universiti Kebangsaan Malaysia (UKM) and the Ministry of Higher Education Malaysia for financial support received under research grant FRGS/2018/FKP-AMC/F00379.

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