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Influence of short heat treatment on the microstructures and mechanical properties of Thixoformed aluminum alloy composite

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ABSTRACT

Typical T6 heat treatment is commonly applied to aluminum alloy to improve mechanical strength and prevent a catastrophic failure. However, previous studies of T6 have not dealt with aluminum alloy reinforced by carbon nanotubes composite in great detail. In addition, the T6 heat treatment is time-consuming and incurred a high operational cost to production. The present study was designed to determine the effect of a short T6 (ST6) on mutiwalled carbon nanotubes (MWCNT)-A356 alloy composite. The ST6 consists of 1 hour-solution treatment (ST), water quenching at room temperature, and 2 hours-artificial aging (AA). The results revealed that a total of ST and AA is enough to dissolve soluble phases and homogenize alloy elements, and MWCNT particles to be distributed uniformly in the matrix. The effectiveness of the ST6 heat treatment was also shown in the overall improvement of the alloy and composite mechanical properties against the standard T6 heat treatment. The highest values of yield strength, ultimate tensile strength, elongation to fracture, and hardness of the composite obtained were 215 MPa, 277 MPa, 6.8%, and 106.4 HV respectively.

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1.0 INTRODUCTION

The effects of heat treatment on mechanical properties enhancement of aluminum-silicon alloy have been established and well accepted. A conventional T6 heat treatment which consists of solution treatment, quenching and artificial aging is commonly used by industries like automotive and aerospace as a part of the processes (Zhu et al., 2012). Even though the ductility of the alloy is often sacrificed due to brittleness cause by the heat treatment, it is still being applied to enhance the strength and to prevent catastrophic failure (Isadare et al., 2013; Morin et al., 2016). Besides, the cost of energy is very high, the other major concerns of T6 is the time required to complete the whole processes is very long (Lu et al., 2018). According to the ASTM B917 and ASTM B91 standards, the minimum durations of T6 is 9 hours which consists of a solution treatment and artificial aging ranges between 6-12 hours at 540ºC and 3-5 hours at 155ºC, respectively (Menargues et al., 2015). The long duration not only causing delay to the production line but also increases the operation costs. Most studies in the field of short T6 heat treatment (ST6) duration have only focused on the aluminum alloy. Various approaches have been made to shorten the duration by basically looking at the purposes of each steps. For instance, the solution treatment is to dissolve soluble phases, homogenize elements and spheroidize eutectic Si particles (Bharath et al., 2020). Quenching is to suppress precipitation by soaking the treated alloy into water or other mediums at room or slightly higher temperature depending on the parts. The artificial ageing is to cause supersaturated solid solution to precipitate and distribute uniformly in the grains (Srivyas and Charoo., 2020). Zhang et al., (2002) showed that the maximum yield strength (YS) and ultimate tensile strength (UTS) of Al-7wt.%Si-0.3wt.%Mg alloy improved more that 90% and 95%, respectively, with only 30 mins of solution treatment at 540°C. Similarly, Menargues et al., (2015), also suggested of the 30 mins of solution treatment for A356 and A357 alloys for the best mechanical properties. On the other hand, Moller et al., (2008), the shortest solution treatment is 1 hour at 540°C to complete dissolution of alloying elements of semi-solid A356 alloy and the artificial aging time between 1 – 4 hrs at 180°C produced the maximum hardness.

Recently, much attention has been paid to the studies of heat treatment on aluminum alloy composites that been reinforced by hard materials such as silicon carbide (SiC) and alumina (Al_2O_3). Jiang and Wang, (2015) reported the YS, UTS and elongation to fraction percentage (ETF%) of SiC-7075 aluminum alloy composite with T6 increased to 381 MPa, 478 MPa and 8.5 % from 264 MPa, 357 MPa and 7.5 % without heat treatment, respectively. Zhang et al., (2019) compared the hardness of Al_2O_3-7075 composites with T6 improved by 52 % than the as-cast. The composites mechanical properties improvement subjected to heat treatment mainly due to the distribution of finer intermetallic compounds and high density dislocations caused by the reinforcements in the matrix alloy. Furthermore, multiwalled carbon nanotubes (MWCNT) possess an extremely high strength up to 100 GPa becoming desirable candidate as reinforcement material in aluminum matrix (Chen et al., 2016). Homogeneous distribution and good interfacial bonding of MWCNT in the matrix shall improve the overall mechanical properties of the MWCNT-aluminum alloy composite. In addition, these properties can be increased further by heat treatment and thixoforming processes. Thixoforming is compaction process at semi-solid of 30-50 % liquid fraction with non-dendritic microstructures of the matrix as prerequisite (Zoqui et al., 2014).

Although the previous research has established that the ST6 is sufficient to improve the mechanical properties of the aluminum alloy, the application on a thixoformed MWCNT-aluminum alloy composite has not been investigated in great details. Therefore, the present study was to investigate the influence of the ST6 on the composite mechanical properties.

2.0 MATERIALS AND METHODS

A 400g of commercial A356 alloy with composition of Al-6.5wt.%Si-0.2w.%Mg-0.2wt.%Cu was melted in an induction furnace. Multiwalled carbon nanotubes (MWCNT) with the dimensions of 5-10 nm, 10-40 nm and 10-30 μm in internal diameter, external diameter and length, respectively, were used as reinforcement. The melt was held at 650°C, then a mixed of MWCNT and pure magnesium (Mg) powder was injected. The Mg powder acts as wettability agent to form good interfacial bonding between carbon and Al (Hanizam et al., 2019a). The molten composite was stirred at 500 rpm for 10 minutes and poured into a permanent mold. A bilet produced was then reheated up to 580°C of it 50% liquid to solid fraction and ramped into an upper mold (Hanizam et al., 2019b). The billet was then undergone the ST6 heat treatment process of the following sequence; a solution treatment for 1 hour at 540°C, quenched at room temperature and artificial aged for 2 hours at 180°C.

The mechanical properties of MWCT-A356 alloy composite were characterized based on the tensile strength and microhardness. The ST6 billet was cut according to the ASTM E8M standard of 4 mm and 20 mm in diameter and gauge length respectively (Salleh et al., 2014), and tested using an Autograph Universal Testing machine for yield strength at 0.2% strain rate (YS) and ultimate tensile strength (UTS) and elongation to fracture (ETF). The microhardness was performed using a Vickers Hardness Matsuzawa machine (load=1 kgf and dwell time=10s). Microstructures evolution of the composite were investigated using an optical microscopy (OM). Moreover, the phases were examined using X-ray diffraction (XRD) machine of Panalytical X-Ray Diffractrometer System.

3.0 RESULTS AND DISCUSSION

3.1 Microstructures of A356 Matrix

In comparison with as-received of A356 and after mechanical stirred of MWCNT-A356 composite has shown different microstructure formations. The as-received A356 alloy demonstrated a typical dendritic arms structures Figure 1(a) and the composite has more globular or rosette shapes of α-phase surrounded by eutectic micro constituents Figure 1(b). The vortex condition in the liquid matrix during mechanical stirring managed to break and prevent the formation of dendritic arms and at the same time helps to distribute MWCNT throughout the matrix.

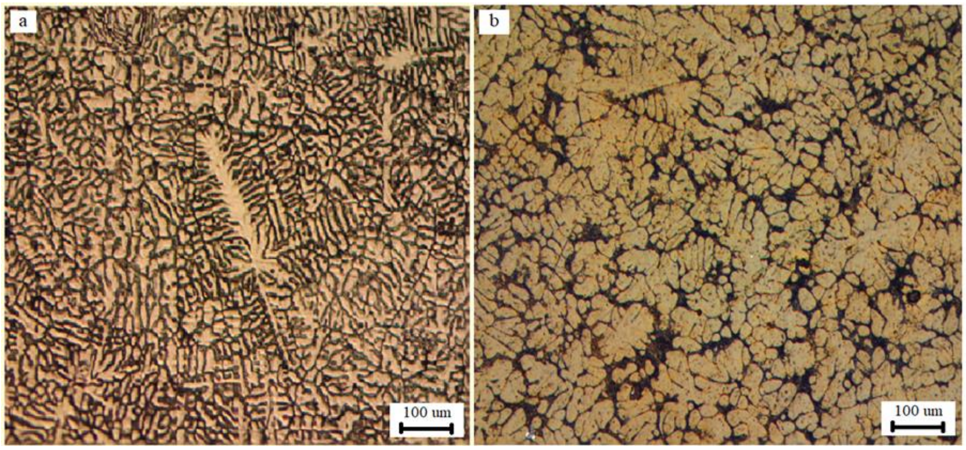

Figure 1: Microstructures of (a) as-received A356 alloy and (b) composite MWCNT-A356.

In addition, the globular shape of α-Al composite leads to more thixotropic behavior of the matrix as shown in Figure 2. The thixotropic is defined as the states of alloy behavior that remains solid when untouched and flowing like liquid when sheared. It is critical for thixoforming process which allowed the movement of α-Al matrix to move, diffuse and coalesce with one another, and coarsening during the reheating process. In addition, it also helps to push out any micro-porosity inherit from casting from the matrix. These are the major factors in thixoforming strengthening mechanisms. Furthermore, the plate-like β-Si remained unchanged after thixoforming.

On the other hand, Figure 3 shows the composite matrix microstructures after the short T6. Besides, larger and more coalescent of the α-phase, the β-Si has transformed into more spheroid shape. The spheroidization of Si from plate-like shapes is critical in strengthening and preventing propagation of micro-fracture in the composite. Moreover, it also showed that the short time of T6 is sufficient to allow the transformation of Si structure.

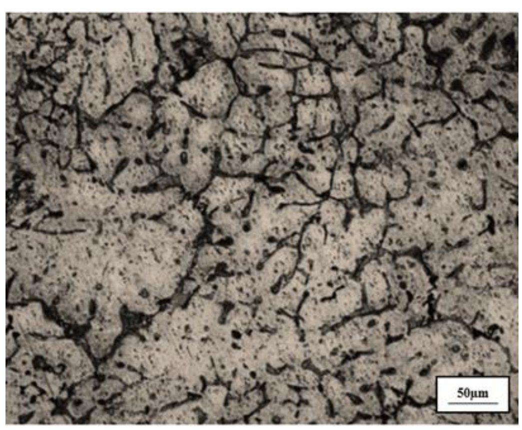

Figure 2: Microstructure of the thixoformed MWCNT-A356 composite.

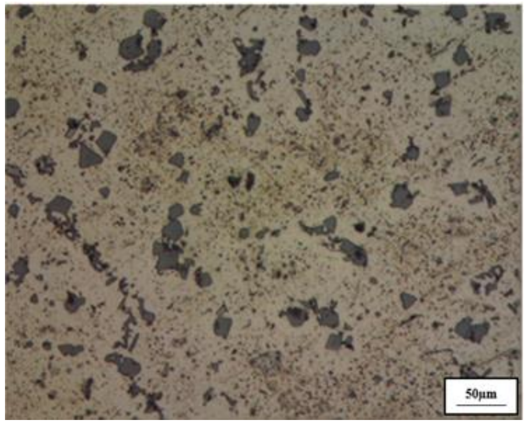

Figure 3: Microstructure of thixoformed MWCNT-A356 composite after the short T6 heat treatment.

3.2 Effect of Short Solution Heat Treatment

The diffusion of the Si-Si and inter-diffusion of Si-Al particles requires minimum activation energies of around 80 kcal/mol and 150 kcal/mol respectively (Menargues et al., 2015; Ogris et al., 2002). Therefore, the growth and evolution of Si particles is more sensitive and much faster as compared with the dissolution of Si into Al matrix (Yahaya et al., 2020). The dissolution of Si-Si particles for the A356 alloy start at 500°C after 3 min, and the total diffusion is predicted to complete below 15 min at 540°C of solution heat treatment (Ogris et al., 2002). However, the short period is not sufficient for other phases to homogenize at the grain boundaries of the matrix. In addition, the distribution of the phases, composition, size and morphology after solidification shall also influences the solution time needed (Long et al., 2013). According to Menargues et al., (2015), the safe solution time for semisolid A356 alloy is 30 min, this is to allow Mg dissolution and π-AlSiMgFe phase to transforms into β-AlFeSi. Even though, Long et al., (2013) reported similar trend on the highest hardness of 118 HV for A356 alloy obtained at higher temperature of 550°C for 30 min, there still some Si particles present in the plate-like morphology. Therefore, the 1 hour of solution treatment for the MWCNT-A356 alloy composite is to ensure most of the phases and MWCNT have enough time to dissolve and homogenize, respectively. Based on the microstructure images in Figure3, almost all eutectic Si particles have evolved into spherical shape as good indication of sufficient solution time.

3.3 Redistribution of CNT During Heat Treatment

XRD patterns acquired from the MWCNT-A356 alloy composite are presented in Figure 4. The patterns show various phases compositions were formed after the solidification including, Mg2Si, Al_4C_3, Al_8 Si_6Mg_3Fe, β-Al_5FeSi and MWCNT. The presents of MWCNT at most peaks indicate the homogeneous distribution of MWCNT in the matrix. In addition, these MWCNT are coupled with Al_4C_3 (carbide) phase show good wettability and interfacial bonding between MWCNT and Al matrix. The carbides existent is crucial to strengthening the composite by load transfer (Bakshi et al., 2009; Zhou et al., 2016). Furthermore, the formations of interfacial bonding between Al grain and MWCNT at crystal orientations / XRD °2ϴ of Al (200)/45.2° and Al (220) /65.4° indicate stable interface and appropriate amount of MWCNT in the composite (Liu et al., 2018; Hanizam et al., 2020).

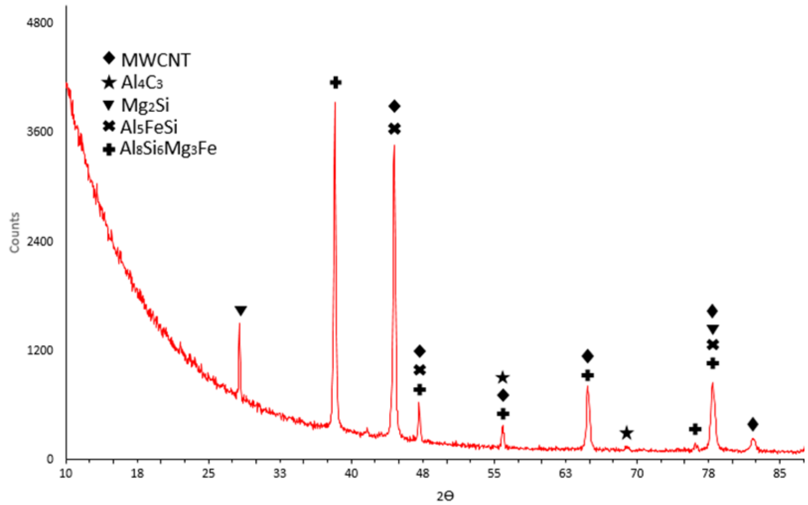

Figure 4: XRD patterns acquired from the CNT-A356 composite.

3.4 Mechanical Properties

The maximum yield strength (YS), ultimate tensile strength (UTS), elongation to fracture (ETF) and hardness of the thixoformed and short T6 heat treatment of the A356 alloy are 196 MPa, 240 MPa, 5.6% and 84.1 HV as shown in Figure 5 and Figure 6. Zhu et al., (2012) reported the A356 alloy under standard T6 state have yielded YS, UTS and ETF of 151 MPa, 250 MPa and 5.1%, respectively. Tahamtan et al., (2008) reported the highest thixoformed A356 of YS, UTS and ETF of 163 MPa, 229 MPa and 28%, respectively. These results show that comparable mechanical properties are achievable with the short heat treatment. In addition, the result also shown significant improvement of the properties with the addition of MWCNT into the alloy. The highest values of YS, UTS, ETF and hardness for the MWCNT composite obtained are 215 MPa, 277 MPa, 6.8% and 106.4HV respectively. These improvement trends validates the sufficient time of solution treatment and artificial aging of the short T6 heat treatment to allow phases dissolution and homogenization. Moreover, it also permits the further distribution of the reinforced particles within the grains matrix.

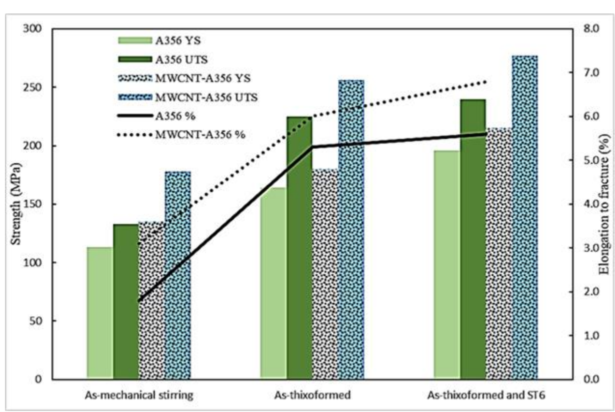

Figure 5: Comparison of mechanical properties between the alloy and alloy composite.

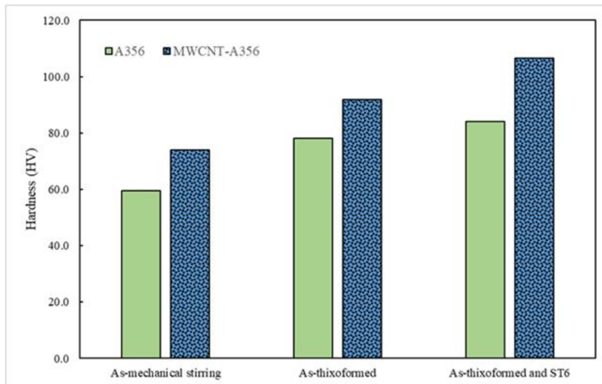

Figure 6: Comparison of microhardness between the alloy and alloy composite.

4.0 CONCLUSION

Application of the short heat treatment (solution treatment at 540 °C for 1 hr, room temperature water quenching and artificial aging at 180 °C for 2 hr) on MWCNT-A356 alloy composite has successfully improved its mechanical strength. The highest YS, UTS, ETF % and hardness of the composite obtained after ST6 are 215 MPa, 277 MPa, 6.8 % and 106.4HV, respectively. The YS, UTS and ETF % increased by 42.4 %, 10.8 % and 33.3 % as compared with the A356 with T6 as reported by Zhu *et al.,* (2012). The main contribution factors are as follows;

(a) The present of MWCNT reinforcement helps to restrict dislocations movement in the matrix by load transfer and high density of dislocation formations around themselves.
(b) Thixoforming process has improved the strength further by eliminating the micro-porosities present in the matrix through non-dendritic matrix movement during compaction.
(c) The ST6 also plays important role in elevating the strength even higher by transforming the Si plate-like into more spheroid shapes during the short solution treatment, homogenize and suppressed precipitations in the matrix uniformly during the short artificial ageing.

The improvement trend is determined by higher composite strengths over the alloy after each as-mechanical stirring casting, as-thixoformed and as-thixoformed and ST6. The mechanical properties of composite with ST6 might already suite some components requirement in automotive applications. However, further analysis shall be conducted to determine the final strength of the composite with standard T6 for comparison.

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