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Mechanical Properties of Thixoformed Al-5Si Alloy Composite Reinforced by Multiwalled Carbon Nanotubes and Alumina Powder

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ABSTRACT

Carbon nanotubes (CNT) as reinforced particles in aluminium matrix composites have been an interesting exploration in recent years. Some research combined CNT with ceramic materials as dual reinforcements in the aluminium matrix to enhance further the mechanical strength of the composite. However, the effects of some fabrication processes on the tube structural integrity of CNT are rather limited. This study is to determine the effects of single and dual reinforcements in Al5Si alloy on the mechanical properties of the composites. The reinforcement particles were pre-distributed by using a ball milling process through powder metallurgy. The mixed was green compacted into a pallet form before injected into a molten Al5Si alloy matrix. The molten composite was stirred before pouring into a permanent mould via a cooling slope. Next, the cast billet was subjected to thixoforming and T6 heat treatment processes. According to the comparison results of the pre-distributed reinforcements, the integrity of CNT structure in dual reinforcements was destroyed due to excessive milling from Al2O3 particles. There was no significant change of microstructures evolution and grain sizes of both composites after the thixoforming and T6 heat treatment. The yield strength, ultimate tensile strength and elongation to fracture of single reinforcement obtained were 316 MPa, 347 MPa, and 13.3%, respectively and much superior than the dual reinforcements. These results show that maintaining the tube structure of CNT is very critical for mechanical strength enhancement through load transfer mechanism of the CNT-Al5Si alloy composite.

Keywords:
Thixoforming, Metal matrix composite, Aluminium alloys, T6 heat treatment, Multiwall carbon nanotubes

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1. Introduction

Applications of aluminium alloy composites in the automotive industry has been well accepted because of the high strength and tough under certain conditions [1]. The composites are mostly reinforced by single reinforcement of ceramic material such as silicon carbide (SiC), alumina (Al2O3), magnesium oxide (MgO) and bismuth carbide (BiC) [2]. For instance, in the automotive sector, parts like engine, brake shoe, and train brake-lining are made of aluminium composites [3]. Moreover, dual reinforcements of SiC/Al2O3 have also been used in other parts such as camshafts, pistons and cylinder liners [4].

Recently, there has been renewed interest in developing a new aluminium composite by replacing the reinforced materials with carbon nanotubes (CNT) [5]. The excellent mechanical properties of the CNT with the Young's modulus ~1 TPa and tensile strength ~ 150 GPa are most desirable to enhance the existing composites strength further [6-7]. However, two major problems with this kind of application are poor wettability between carbon and aluminium, and difficulties of obtaining homogeneous distribution of CNT in the matrix [8]. Without good wettability or interfacial bonding, effective strengthening mechanisms, such as load transfer is not attainable [9]. Therefore, most of the studies have been focusing on powder metallurgical or solid processing route to mix CNT and aluminium matrix. Even though this process able to overcome distribution issue, parts produced are limited to light in weight and quite costly [10]. Whilst some research has been carried out on a liquid casting processing route on CNT-Al composites, there is still inadequate data to establish which the most effective casting method. Some research have also focusing on coupling the CNT with ceramic particles as dual reinforcements, before mixing into the molten matrix [11]. The ceramic particles act as additional strengthening and as carriers for the CNT to disperse into the matrix.

Although the dual or double reinforcement ideally should produce higher strength composite material, the impact of the ceramic particles on CNT is still in doubt. Especially, when dealing with the ball milling process in the powder metallurgy process route. The excessive milling by the steel balls and ceramic particles can cause serious damage to the CNT structure. Even though, some studies have shown significant increments in strength even with destroyed structure, comparison between the intacted and destroyed structure is still lacking.

Therefore, this study is comparing the effect of dual and single reinforment particles in an Al5Si matrix alloy. The overall processes involve pre-distribution of the particles using the powder metallurgy of ball milling process and composite mixing by liquid casting processing. The cast billets were also subjected to a thixoforming and T6 heat treatment processes for additional strengthening purpose. Analysis of microstructures evolution, integrity of the multiwalled CNT (MWCNT) structures and mechanical properties of the composites are determined as the outcomes of the study.

2. Methodology

The alloy used in this project is a hypoeutectic Al-Si alloy with compositions by weight percentage (wt. %) of 4.94-Si, 0.86-Cu, 0.21-Mg, 0.03-Ni, 0.02-Zn, 0.54-Fe and Al. The MWCNTs with 20–40 nm and 5–10 nm outside and inside diameters respectively as shown in Figure 1. The decomposition of the MWCNT starts at 690°C based on the thermal gravimetric analysis (TGA) using the Metter Toledo machine. A fine and extra-pure Al_2O_3 powder with average diameter of 0.3 µm was obtained from Pace Technologies. In addition, a pure aluminium powder of <5 µm in average diameter was obtained from Hmbg Chemical.

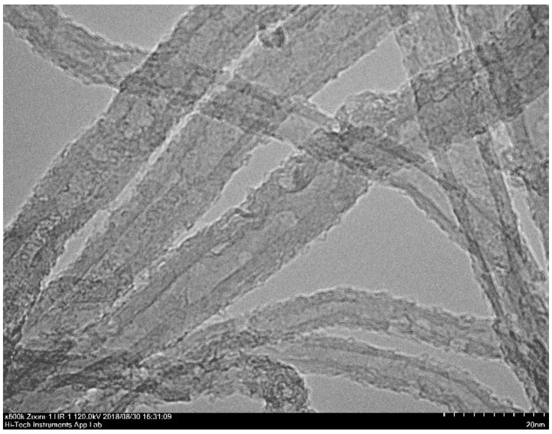

Fig. 1. TEM images of MWCNT

These materials by weight in grams (g) of 5-MWCNT, 50-Al_2O_3 and 50-Al powders were mixed by a planetary ball milling machine and compacted into pellet form as in Figure 2. A 2g of stearic acid was also put into the mixture to prevent cold welding during the ball milling process [12]. Pallets made of only MWCNT and without the Al_2O_3 were also prepared for comparison. A 400g of Al-5Si alloy was fully melted up to 700°C, brought down, and maintained at 650°C. The pellets were injected at the bottom of the crucible and stirred for 10mins at 500rpm. A cooling slope was used via a permanent mould casting, in order to have finer and more globular microstructures of the matrix composite billet [13]. The billets were subjected to a thixoforming process using a T30-80KHz Vistec machine. The thixoforming comprises of reheating process of the billet up to its semi-solid fraction of 50% liquid to solid content and then ramped into an upper mould. Finally, the billets were subjected to a standard T6 heat treatment procedures based on the ASTM B917-01 standard in a Nabertherm oven.

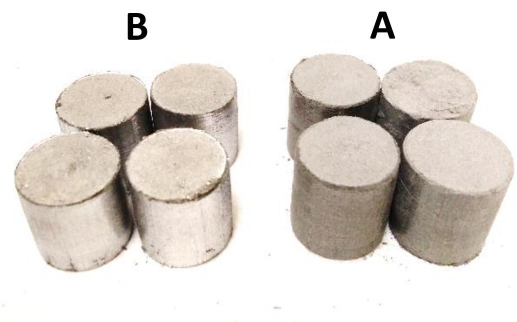

Fig. 2. The pellets (A) MWCNT and Al_2O_3 and (B) only MWCNT

The billets were machined according to ASTM E8M standard for tensile testing using the Autograph universal testing machine. Micro hardness of the composites were tested by using the Matsuzawa machine (load=1kgf; dwell time=10s). The microstructures of the composites were inspected using an optical microscope. Finally, the morphologies of the pallets and tensile fracture surfaces were analysed using field emission SEM (FESEM) and energy-dispersive X-ray spectroscopy (Hitachi-SU5000), respective.

3. Results

3.1 Microstructures evolution

Figure 3 shows both composites of similar trend microstructures evolution of α-Al after subjected to thixoforming and T6 heat treatment processes. A small rosette microstructure of α-Al were coalesced and coarsened after each process. Plate-like eutectic-Si particles were also changed into more spherical shape after T6. These transformation processes are very critical in enhancing the mechanical properties of the composites.

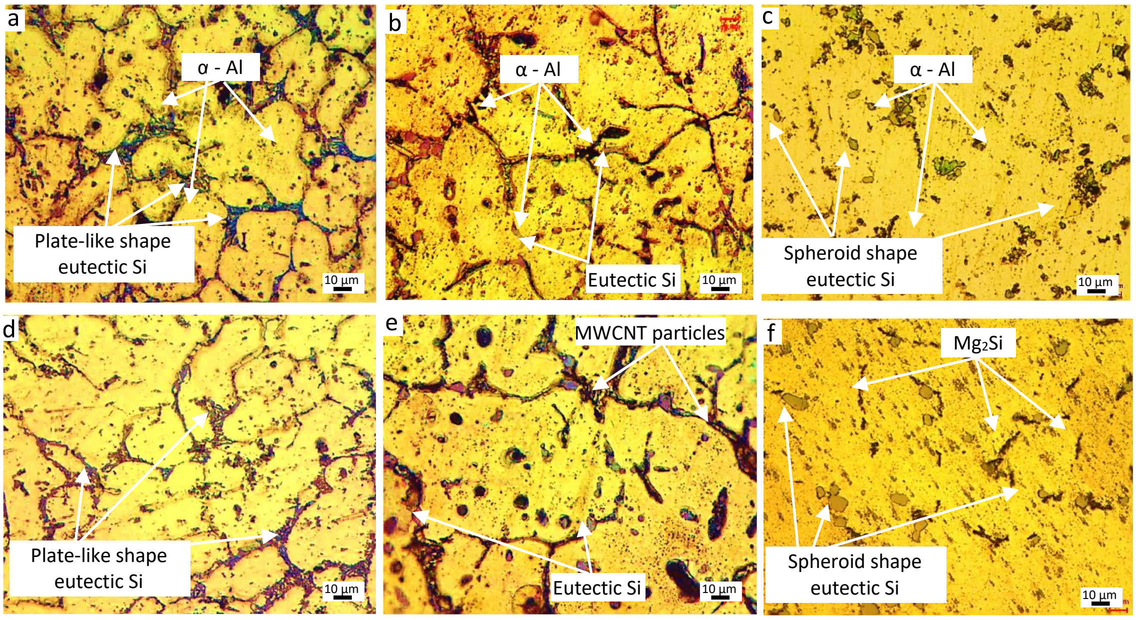

Fig. 3. Microstructures of dual reinforcements composite (a) after mechanical stirring, (b) after thixoforming, (c) after T6; single reinforcement composite (d) after mechanical stirring, (e) after thixoforming, (f) after T6

3.2 Distribution of reinforcements

The present of MWCNT was not visible in the pallet with dual reinforcements of MWCNT and Al_2O_3 as in Figure 4 (a). On the other hand, the tube structures of MWCNT were clearly observed and distributed uniformly throughout the aluminium particles surfaces for the single reinforcement of MWCNT as in Figure 4(b). Moreover, there was no agglomeration of MWCNT has been spotted in both pallets. The conditions of MWCNT in the dual reinforcement mixture might due to the excessive abrasive effects by the Al_2O_3 particles. However, according to Raju et al. [11], even though the tubes of MWCNT have been destroyed, the MWCNT still able to strengthen the matrix by their splat surface.

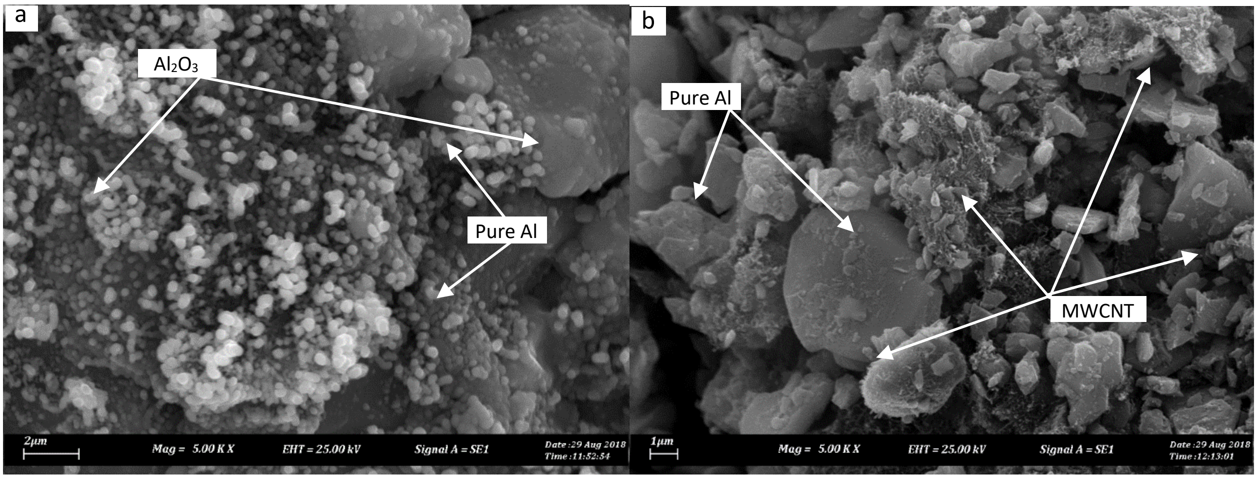

Fig. 4. SEM images of the fracture surface of green compacted pellet (a) Precursor A and (b) Precursor B

The composite with single reinforcement has shown some pulled-out and bridging structures of MWCNT in the matrix as shown in Figure 5. The pulled-out structures were the evidences of load transfer mechanism has taken placed during the tensile testing [14][15][16]. Furthermore, the bridging structures have shown good wettability and interfacial bonding between the reinforcement and matrix grains. No agglomeration of MWCNT were observed in the samples indicated homogeneous distribution of the reinforcements throughout the matrix.

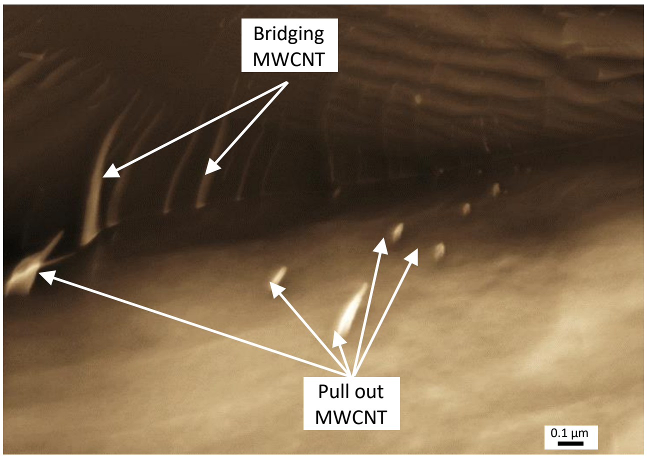

Fig. 5. FESEM images of MWCNT structures of the tensile fracture surface

3.3 Mechanical properties

The results show that the MWCNT-Al alloy composite has higher mechanical tensile strength as compared with the MWCNT-Al_2O_3-Al5Si alloy composite. The highest YS, UTS and ETF of the thixoformed-T6 MWCNT-Al5Si and MWCNT-Al_2O_3-Al alloy composites are 316 MPa, 347 MPa, 13.3% and 262 MPa, 289 MPa, 7.2%, respectively as shown in Figure 6. The composites properties improved tremendously as compared with the Al5Si alloy itself that yielded the YS, UTS and ETF of 188 MPa, 223 MPa and 4.7%, respectively.

The improvements made by the composites might be due to several factors. The presence of the reinforcements in the matrix absorbed some of the applied load or stress during the tensile testing.

The load transferred from the matrix grains to the MWCNT-Al_2O_3 or MWCNT alone and minimised the cracks propagation. Furthermore, the pulled-out and bridging structures of MWCNT as in Fig.5 and the higher tensile values as compared with the dual reinforcements, indicate that maintaining the structure integrity of the MWCNT is more critical for effective load transfer than the splat surface [17-18]. In addition, the reinforcements also help to make the matrix more ductile as compared to the alloy itself after T6. Therefore, the load transfer mechanism is the major contributor to strengthening the composite. Other mechanisms like Orowan looping system, thermal and grain refining might have minor contribution to the mechanical properties [19].

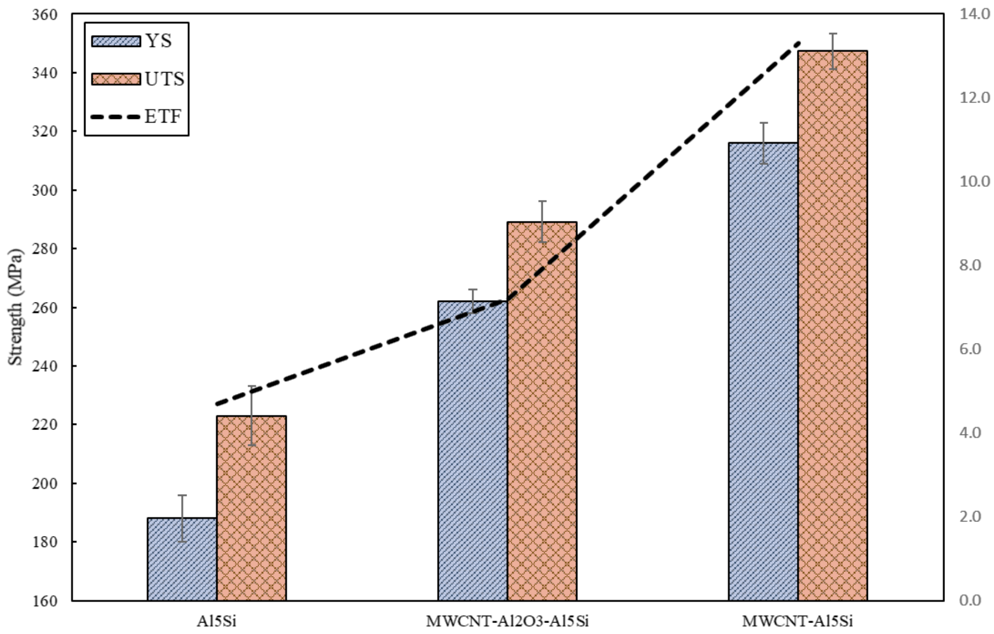

Fig. 6. Comparison of YS and UTS of the alloy, dual and single reinforcement's composites after thixoformed-T6 heat treatment

4. Conclusions

Based on the homogeneous distribution of the reinforcement particles in the matrix composite, the two steps fabrication process by pre-distributed the reinforcements using power metallurgy followed by liquid casting mixing was successful. Microstructures of the composites transformed from into small rosette α-Al grains after the cooling slope. The α-Al grains coalesced into bigger size and further coarsening after thixoforming and T6 heat treatment, respectively. Similarly, the eutectic Si particles changed from plate-like into more spherical shapes. The results showed tremendous enhancement observed on the tensile and hardness properties of the composites as compared with the alloy itself. The YS, UTS and ETF of the composites improved by (dual reinforcements) 39%, 30%, and 53% (single reinforcement) 68%, 56%, and 183%, respectively. The load transfer mechanism is the main contributor to the mechanical properties enhancement.

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