Characterization and Plastic Deformation of Aluminium Multi-Walled Carbon Nanotube Metal Matrix Composite

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Abstract: An Aluminium 6061 alloy composite reinforced with 2wt.% Multi-walled carbon nanotubes (MWCNT)particles have been fabricated by stir casting routes succeeded by T6 heat treatment and cold rolling. The microstructure and mechanical properties were compared with the 6061 Al alloy composite before and after experimentation. Microstructural characterization and mechanical property tests have been carried out in as-rolled conditions. No interfacial reactions were developed during the fabrication procedures. A vital realignment of MWCNT particles was obtained after cold rolling. The particle-free bands and porosity in as-fabricated have disappeared with further rolling passes, resulting in a more homogeneous distribution of MWCNT particles. The microhardness values of the 6061Al/MWCNT sample are much higher than those of the Al6061 sample. With increasing rolling reductions, the microhardness values of the composite and 6061Al alloy increases until reaching a limit value. Rolling of 6061Al composite significantly minimizes wear rate with accretion in the number of passes. The compressive strength of as-rolled composite has bettered the Al alloy composite by a significant amount.

IndexTerms **-** Al 6061, Multi Walled Carbon Nano Tubes, Composites, Cold Rolling, Microhardness, Wear Rate, Microstructures.

1.INTRODUCTION

During the past ten years, the evolution of metal matrix composites (MMC) has been one of the prime innovations in materials. Pioneer studies on MMCs primarily focused on the development of continuous fiber reinforced materials [1]. However, high manufacturing costs coupled with high costs of the reinforcement fibers and complex fabrication routes have limited their industrial applications and led to the evolution of particulate reinforced composites [2].
Various advanced engineering applications demand materials with great strength and stiffness as well as good elevated temperature properties. Several types of metal alloys are being fabricated to meet such demands. An alloy is different from an impure metal [3]. Alloys are made by blending two or more elements; at least one of which is a metal, a metal that is usually very soft and malleable, such as aluminium, can be reconstructed by alloying it with another soft metal. Aluminium alloy 6061 is one of the most extensively used of the 6000 series aluminium alloys whose composition is listed in table1[4]. Al alloy’s major composition other than Al is magnesium and silicon. It is a versatile heat treatable extruded alloy with medium to high strength capabilities.

Table 1. Chemical composition of Al 6061 alloy (mass fraction %)

Al 6061	Mg	Si	Cu	Fe	Mn	Cr	Zn	Ti	Al
	0.90	0.41	0.16	0.26	0.07	0.04	0.01	0.01	Bal.

Table 2. Properties: Comparison of mechanical properties of MWCNT reinforcement

Material	Young's modulus (TPa)	Tensile Strength (GPa)	Elongation at break (%)
MWCNT	0.2–0.8–0.95	11–63–150	15.4

There is continuous research for suitable reinforcement material among the scientific and engineering community’s. The research basically concentrates on recognizing reinforcement materials with excellent mechanical properties to satisfy various engineering applications [5]. Multi-Walled Carbon Nanotubes are found to be one such excellent reinforcing material which can improve properties of Al6061 Metal Matrix Composites significantly whose properties are tabulated in the table 2 [6]. MWCNT can also satisfy the requirement of lightweight with good strength. Al alloys reinforced with different wt.% MWCNT are likeable materials for automotive and aerospace applications due to their upgraded properties such as lightweight, high modulus and strength and high wear resistance [7]. Various techniques have been evolved to produce these sorts of composites. Based on the different processing temperature, the processing methods can be classified into two classes: liquid phases processing techniques (casting) and solid phase processing techniques (powder metallurgy routes). After the primitive fabrication techniques, secondary processing techniques such as extrusion, rolling or forging are essential for strengthening the composites and decreasing their porosity [8].
The current work has been carried out to improve the mechanical properties and microstructure growths of 6061 aluminium alloy reinforced with 2 wt.% Multi-Walled Carbon Nanotube after the cold rolling in the longitudinal and transverse direction. The microstructure evolutions and mechanical properties of Al6061 alloy composite were studied upon at different reduction ratios. Al6061 MMC's are commonly used the construction of aircraft structures, such as wings and fuselages, Automotive parts, such as the chassis of the Audi A8, tactical flashlights [9].

The remainder of the paper is arranged as below: The refinement process using stir casting is explained in section 2. Then the properties such as hardness, density and compression along with microstructure of composite processed by Rolling process are discussed in section 3. Finally, paper concludes with potential applications of ultrafine grained materials are discussed in section 4.

2. EXPERIMENTAL PROCEDURE

Al6061 alloy reinforced with 2wt% MWCNT Nanoparticles of particle size of 10-30 nm billets were obtained from stir casting routes. A stir casting technique has been used to develop the cast composites. The molten Al6061 alloy was stirred for a span of 10 min using a mechanical stirrer maintaining ceramic coated steel impeller. The average speed of the stirrer was kept at 450 rpm. The alloy melt at 725℃ was poured into the cast iron molds. The MMC composites and the base Al6061 alloy were constrained to solutionizing at a temperature of 555℃ for the duration of 8 h and then quenched in quenching media boiling water and air. The heat-treated strips were then cold rolled with multiple rolling passes until the reduction in thickness was achieved [10].
Plastic deformation of the Al6061 reinforced with MWCNT was carried using Multiple Rolling process in a Rolling machine with Roller diameter of 100mm, Speed- 48 rpm, Reduction gear ratio 1:30. The Experimental set-up of Rolling machine and the actual few split parts are shown in fig1.

(a)

Figure 1. Rolling Process (a) Experimental set-up of Rolling machine with inset showing the split part of actual machine showing ECAP channel.

(a) (b) (c)

Figure 2. Billet size before rolling (a) Al6061 reinforced with 2wt.% MWCNT (b) Specimens of the composite with air quenching, (c) Specimens of the composite with water quenching.

The present rolling i.e. the multi-dimensional rolling is performed for 25 cycles and Al6061 samples were cut into 48.53mm x 8.1mm with a thickness of 12mm as shown in figure 2(a), 2(c) and 2(c). These samples were rolled at 100℃ temperature. The specimens were fed through the rolls, and taken from the outlet channel, all rolling schedules were performed without lubrication and in an asymmetrical configuration, and that the friction coefficients are strictly the same on both rolls. The rolled specimens are shown in figure 3.

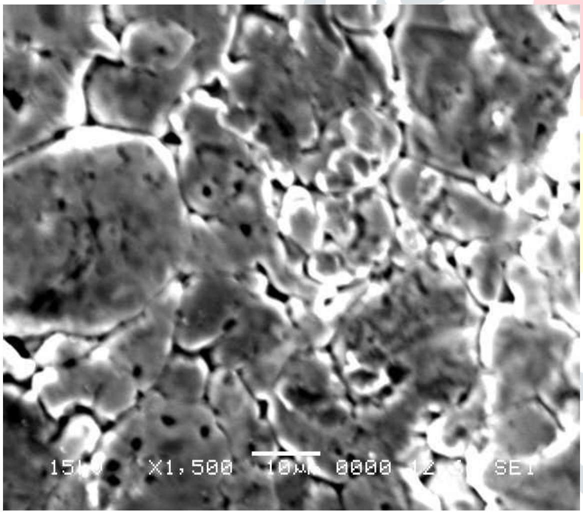
(a) (b) (c)

Figure 3. Billet size after rolling (a) Al6061 reinforced with 2wt.% MWCNT (b) Specimens of the composite with air quenching, (c) Specimens of the composite with water quenching.

3. RESULTS AND DISCUSSION

3.1Microstructure

SEM image of Al6061 MMC is shown in figure 4. (a) at different magnification. The intense observation over a wide area revealed that the MMC contained a fairly aligned array of grains and there was a higher porosity of intragranular dislocations. The achieved average grain size in this condition was ~2.8μm. Figure 4 (b), (c) and (d) shows the microstructures observed by SEM after reinforcement, water and air quenching respectively.



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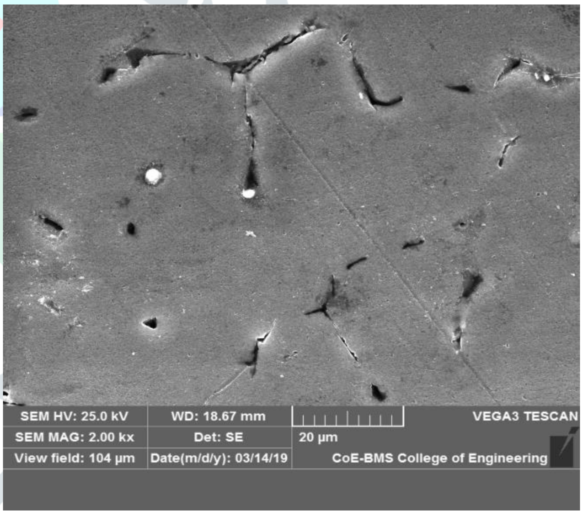

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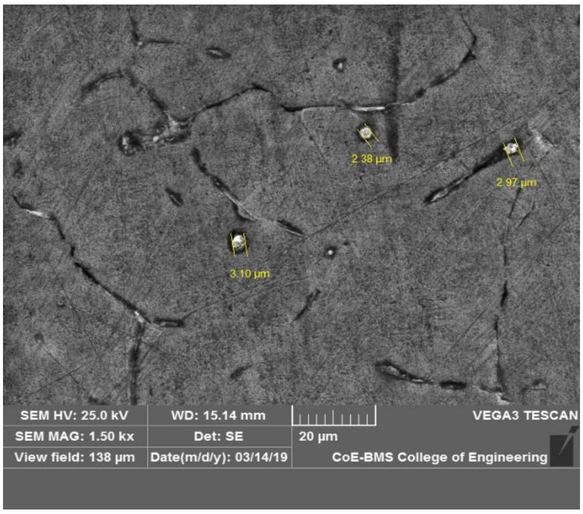

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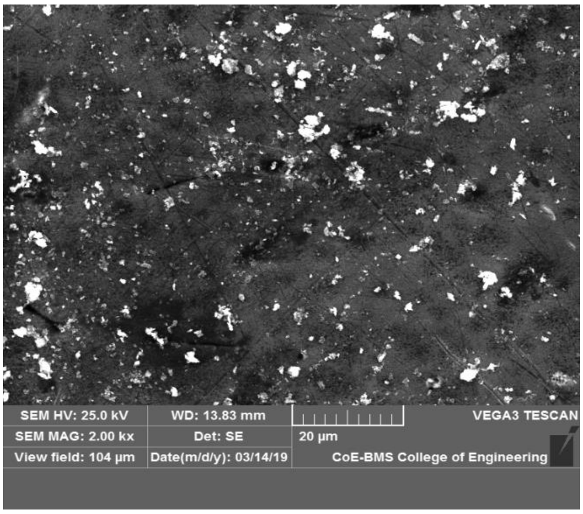
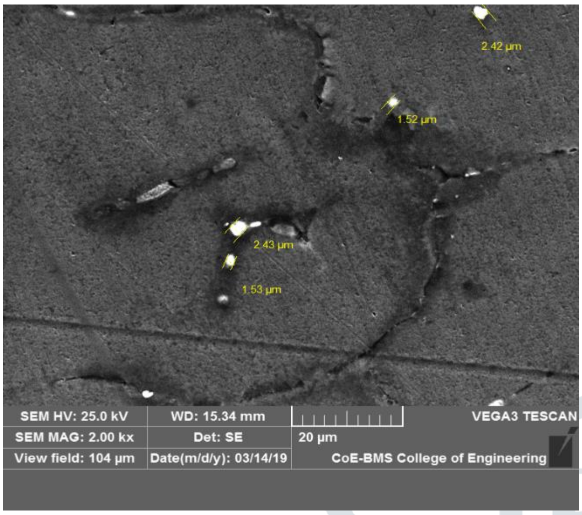


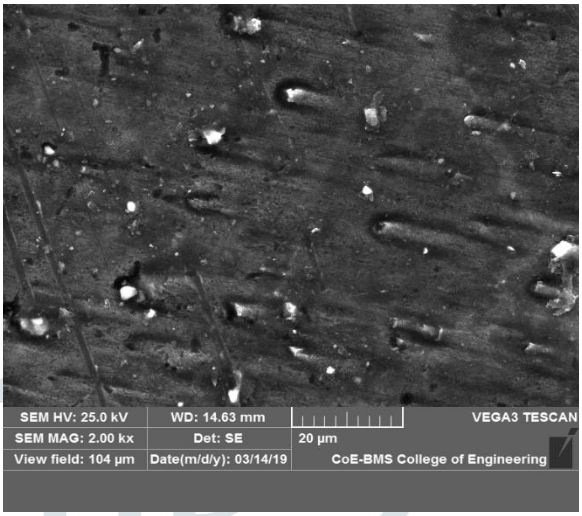
(d)

Figure 4: Scanning Electron Microscopy images before rolling of Al6061 (a) only Al6061 (before stir casting) (b) Al6061 reinforced with 2 wt.% MWCNT (c) Water quenched composite (d) Air quenched composite.

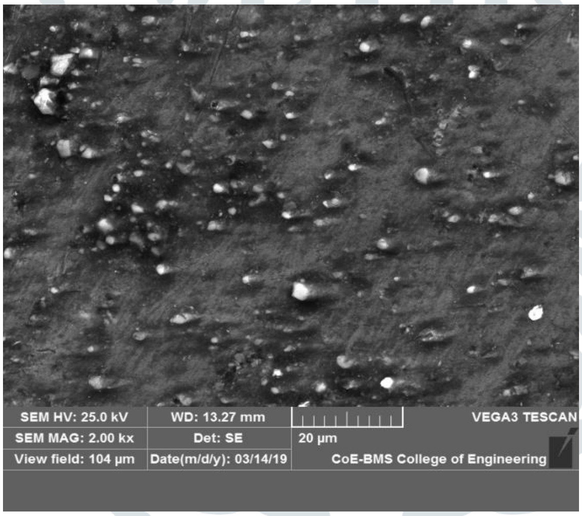
Figure 4. (b) represents Al alloy reinforced with 2 wt.% MWCNT. The SEM images have uniform black patches which show the equal distribution of carbon nanotubes and the white patches represent Al alloy elements distribution. The sudden cooling of Al alloy from high temperature around 555°C to room temperature (quenching) can be achieved by two methods. The specimen which has been quenched by immersing in boiling water (maintained at 100°C) is shown in figure 4. (c) while figure 4. (d) shows air quenched Al composite.



(a)



(b)



(c)

Figure 5. Scanning Electron Microscopy images before rolling of Al6061 (a) Al6061 reinforced with 2 wt.% MWCNT (d) Water quenched composite (c) Air quenched composite

SEM images were taken for after rolled specimens as explained above. From figure 5. (a), (b) and (c) that grain size has been considerably reduced due to the elimination of porosity along with the change in grain orientation following 25 passes of rolling process at 100°C. On measurements, it was found that the average grain size was subdued to ~1.52 µm.

3.2 Density

Density of Al 6061 MWCNT composite was measured using Archimedes' principle. Distilled water was used as immersion fluid. Theoretical density was calculated by rule of mixture and compared with measured densities. Relative density was calculated and graph was plotted for material composition and condition vs relative density for rolled samples.

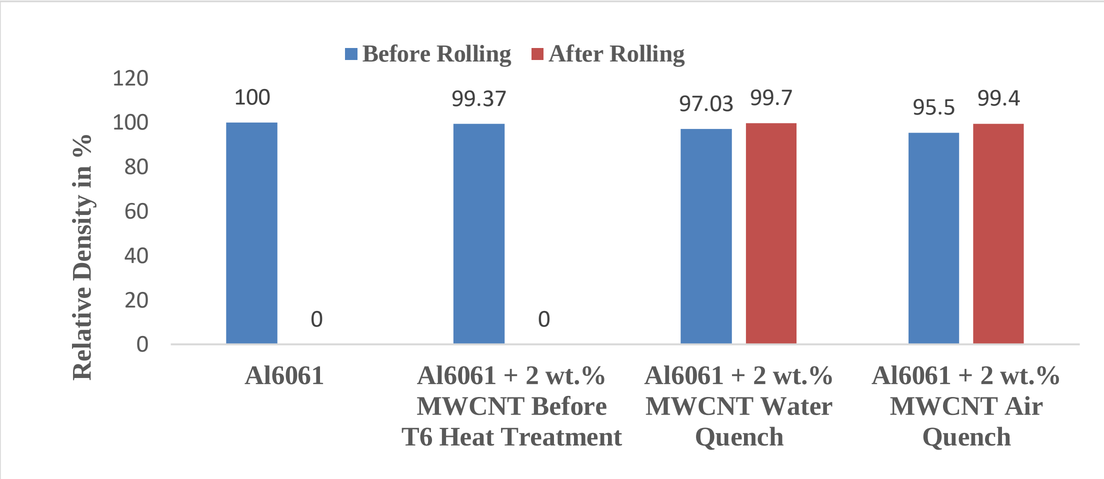


Figure 6. Relative density representation for Al6061 with 2wt. % of MWCNT before and after rolling operation.

Figure 6. shows the results of relative density measurements for rolled specimens. However, some amount of porosity was observed in the composites in cast condition. The porosity is mainly due to gas entrapment during stirring of melt in open atmosphere. Porosity in Al6061 reinforced with 2wt.% MWCNT (water quenched) was found more compared to the Al6061 reinforced with 2wt.% MWCNT (air quenched) composite. Therefore, relative density increased with the decrease in porosity.

3.3 Micro Hardness test

The Vickers hardness test process consists of indenting the test material with a diamond ball indenter subjected to a load of 1000gf. The full load is normally applied for 10 seconds. The diameter of the indentation left in the test material is measured with a low powered microscope.

The microhardness was observed for all the Al6061 alloy matrix, MWCNT reinforced composites along with water quenched and air quenched composites for rolled and unrolled conditions. The study revealed that cold rolling of Al6061 matrix alloy and its MWCNT composites for 25 cycles at a temperature of 100°C processed by quenching method results is obtaining maximum hardness of the matrix alloy and its composites. Air quenching exhibited a highest growth in hardness comparatively as shown in figure 6.

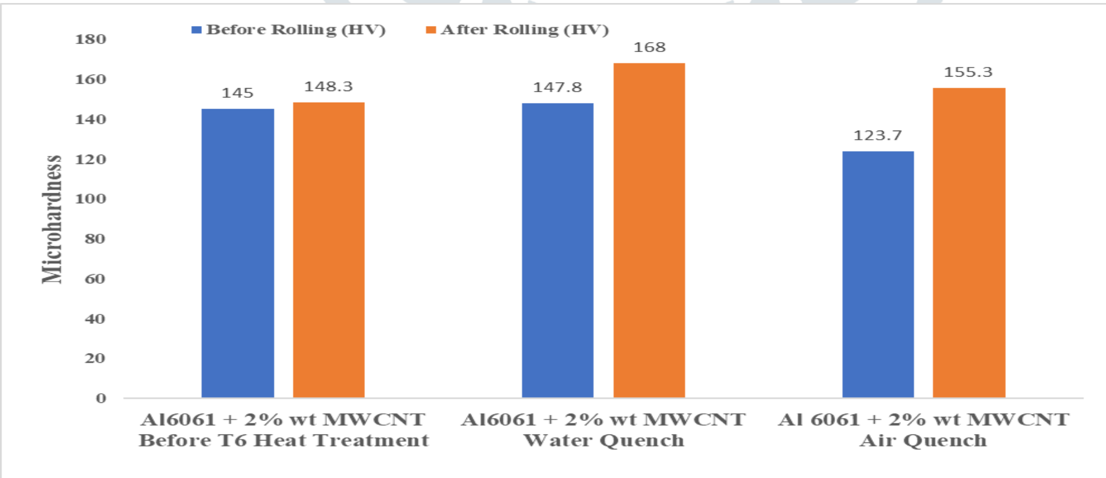


Figure 7. Microhardness representation for Al6061 with 2wt. % of MWCNT before and after rolling operation.

3.4 Wear test

The variation of abrasive wear loss of Al6061-MWCNT composites under various loads and sliding time. It is witnessed in figure 8 and 9, that the amount of MWCNT reinforcement and processing techniques for the Al6061 matrix alloy have an influence on the abrasive wear behavior of Al6061 alloy and its MWCNT composites. Load factor and sliding distance have a direct impact on wear rate, with an increase in load-wear increases and vice versa. Composite treated by Quenching technique up on rolling for Al6061 MWCNT composite enhances the abrasive wear resistance of composites which can be attributed to the fact that MWCNT itself being hard can combine the abrasion, thereby appearing in lower material removal. Higher the hardness of composites better will be its abrasion resistance.

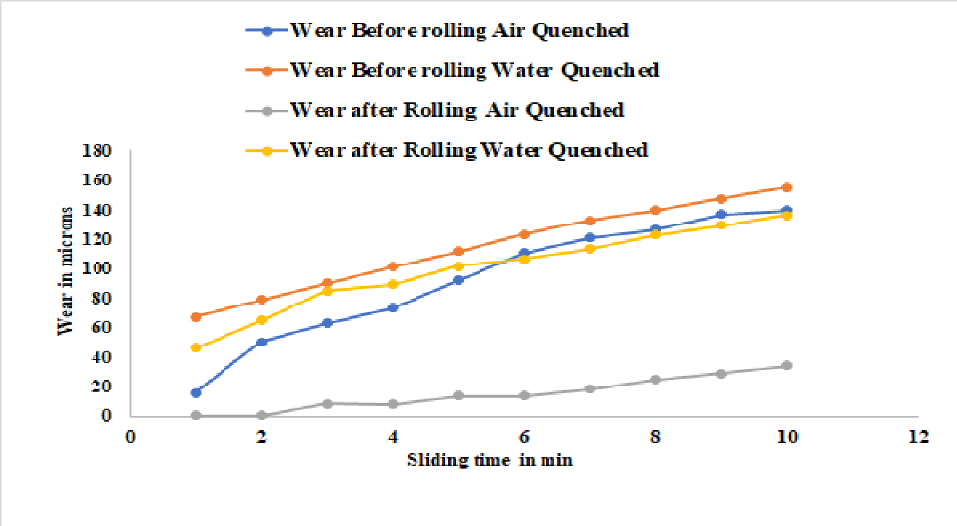


Figure 8. The variation of wear rate with varyig sliding time for Al6061 reinforced with 2wt.% MWCNT peocessed by rolling process.

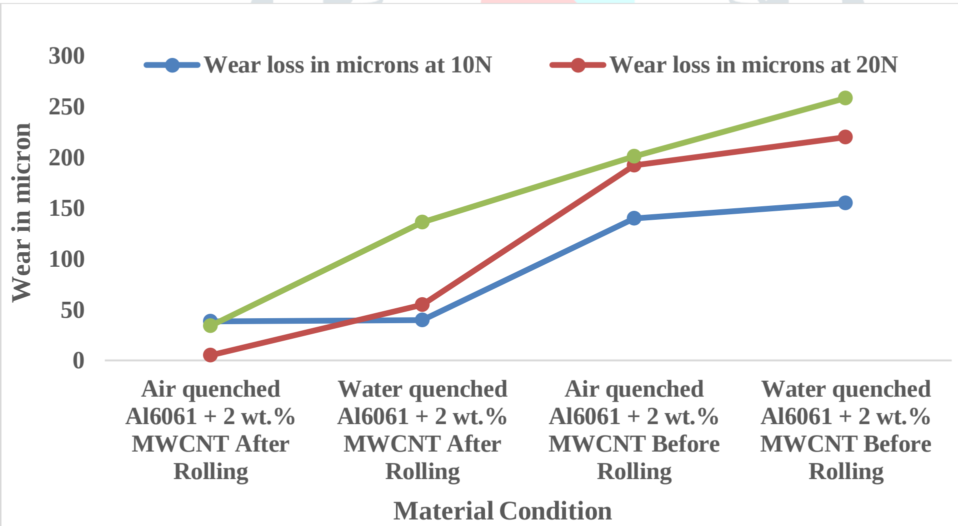


Figure 9. The variation of wear rate with load vs material condition for Al6061 reinforced with 2wt.% MWCNT peocessed by rolling process.

4. CONCLUSION

The present study shows the improvement of mechanical properties due to microstructural transformation in Al6061 after cold rolling. The results show that cold rolling generally induces a greater increase in strength. A significant redistribution of grain particles was obtained during cold rolling. Porosity was also reduced till disappeared after cold rolling.

Present work thus concludes that:

- After cold rolling, grains were broken up to fine blocks and as the number of cycles increases the grains divided into more fine blocks and evenly distributed. Apparently, the measured grain size was ~1.52 μm.
- The alloy leads to increase in hardness up to 25.5% after the succeeding reductions under cold rolling operations.
- The compression strength of the Al6061/2wt.% MWCNT composite is continuously increasing with the increase in reduction ratio.
- The density of Aluminium Al6061 MMC alloy can be increased on rolling by eliminating porosity and intragranular dislocations.
- In adhesive wear, the loss of material for Al6061-MWCNT composites is lower when compared to the Al6061 matrix alloy. Wear loss increases with increasing load and sliding distance due to the work hardening of the surface leading to abrasion wear.

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