Journal of Stress Analysis
Vol. 6, No. 1, Spring − Summer 2021, 61-66

Bu-Ali Sina University

ORIGINAL RESEARCH PAPER

The Effect of Multi-walled Carbon Nanotubes, as the Reinforcement Phase, on the Hardness and Bending Strength of Aluminum Alloy 7075

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Article info

Article history:
Received 03 April 2020
Received in revised form
15 August 2021
Accepted 21 August 2021

Keywords:
High-energy ball mill
Multi-walled carbon nanotubes
Nanocomposites
Spark-plasma sintering

Abstract

In the present investigation, to fabricate Nano-composites made of wrought aluminum alloy 7075 and multi-walled carbon nanotubes, carbon nanotubes and the alloy powders were initially dispersed in ethanol using an ultrasonic shaker to form a primary mixture. The milled powder mixture was converted into the final specimens by Spark-Plasma Sintering. To achieve a uniform distribution of carbon nanotubes in the matrix alloy, ethanol or stearic acid can be used as a Processing Control Agent (PCA). For each of the seven specimens, a series of tests were performed to study the effects of the reinforcement phase on the base alloy. As shown, the reinforced specimens were harder compared to the pure Al7075 and the sample reinforced with 1wt% of multi-walled carbon nanotubes has both the highest hardness and flexural strength among all the specimens. Additionally, when the weight fraction reached 2%, there was a noticeable drop in the mechanical properties. This novel alloy produced by powder metalurgy can be very helpul for industrial application where the increase in strength and hardness is deireable.

1. Introduction

Recently, a large number of researchers have focused on developing ultra-high-strength materials, especially in lightweight materials which can satisfy stiffer and wear-resistant engineering materials for industrial needs. Metal Matrix Composites (MMC) are considered as one of the best materials to achieve more superior properties in comparison with other materials [1].

There are four light metals in nature named as lithium, magnesium, aluminum, and titanium. Among these light metals, aluminum and its alloys have a great role in industrial applications such as aerospace applications, car factories, wire industries, etc. Aluminum with 2.7gr/cm^3 density and low melting point (below 700°C) can be a good candidate for developing the mechanical properties such as workability, high strength to weight ratio, high electrical conductivity and so on. Yet, the use of these alloys is limited due to their relatively low yield stress. Therefore, Aluminium can be considered as a main matrix part of the alloys to develop new aluminum. [2-6]. There are a large number of reinforcement elements that can be used to reinforce aluminum to improve the mechanical properties of aluminum matrix composites. Recently, the carbon-nanotubes have widely been used as the reinforcement phase due to their unique electrical, physical, chemical, thermal, and mechanical properties [7-9]. CNTs are the most promising of all nano-materials that have been studied for their potential application in composite ma-

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http://dx.doi.org/10.22084/jrstan.2021.21335.1140
ISSN: 2588-2597

terials and other electronical applications [10]. The CNTs possess relatively low density varying from 0.8 to 1.8g/cc for SWNTs and 1.4 to 1.8g/cc for MWNTs [11]. Due to high Young's modulus and tensile properties of the nano-tubes reinforcements, these materials can be considered as the possible reinforce gradient in composite materials to improve mechanical properties [12]. Powder Metallurgy (PM) techniques considered as the best technique for constructing Al-CNN alloys. This method is widely used for the production of the aluminum composite as well as the fabrication of CNT reinforced MMC. However, these attempts have not been fully successful because of the agglomeration of CNTs caused by the Van der Waals forces between CNTs [13-17]. Spark Plasma Sintering (SPS), as a well-known non-conventional sintering process, has been implicated as one of the best methods to produce nano-composite powders. The process involves the simultaneous application of pulsed DC and uniaxial pressure. With SPS, high heating rates can be achieved [18], and sintering can be performed at low temperatures for short time sintering processes. This enables the synthesis of fully dense materials [19]. There has always been a great interest in producing new materials that are heavier. This issue has provided further research, with the first use of the ultrasound casting method [24, 25]. The results of the studies have also showed the ability of the model used to predict the other notable point is when a Continuous casting process (CCCR) is used to make the plates, there is significant cost savings and production time [27]. Consideration of the effect of adhesive layer addition on the microstructure and mechanical properties of laser welded joints has also been significant in recent years [28, 29].

Two-variable sinusoidal shear deformation theory and a nonlocal elasticity theory in order to analyze the free vibration behavior of functionally graded polymer composite nanoplates reinforced with graphene nanoplatelets were studied by Arefi et al. They implicated four different kind of FG reinforcement patterns named as uniform distribution UD, and non-uniform distributions FG-O, FG-X, and FG-A. The effective elastic modulus, the Poisson's ratio, and the density of composite nanoplates were computed, and very proper results were obtained [30]. Arefi and his co-workers studied a large parametric investigation on the bending response of Functionally Graded polymer composites curved beams reinforced by graphene nanoplatelets resting on a Pasternak foundation based on the First-order Shear Deformation Theory (FSDT) and the nonlocal elasticity theory. They obtained the governing equations implicating principle of virtual works. Four different patterns were considered to describe the through-the-thickness distribution of the reinforcing phase. They presented numerical results in terms of significant parameters, such as the weight fraction and geometrical features of the graphene nanoplatelets, the total number of layers, the foundation properties, and the nonlocal parameter. They obtained effects of these quantities on the kinematic and static behavior for the nanobeam and very acceptable results were achieved [31]. The application of nano graphene and reinforced nano beams were studied precisely recently. Many other works in the literature have focused on the static, dynamic, and buckling behavior of FG-reinforced nanobeams and nanostructures due to importance of nano addition [32-34].

Altough a large number investigators have focused on nano carbon addition effects on several light alloys, it seems that there is not sufficient study in this field especially carbon nanotubes implicating spark plama sintering method. In this paper effects of nano carbon tubes addition on bending stress and hardness of Al7075 alloy were studied by implicating SPS method and very intreting results were achieved.

2. Experimental Procedure

Materials used in the present study were the multi-walled carbon nanotubes (average diameters of 10 and 65nm, Iranian nanomaterials co, Ltd), synthesized via chemical vapor deposition along with the Aluminum powder (Merck, Art. No.1056), and the main alloying elements of Aluminum alloy 7075 including Mg, Zn, and Cu. The SEM micrographs of the reinforcing nanotubes with two different mean diameters used in this research are shown in Fig. 1 and 2:

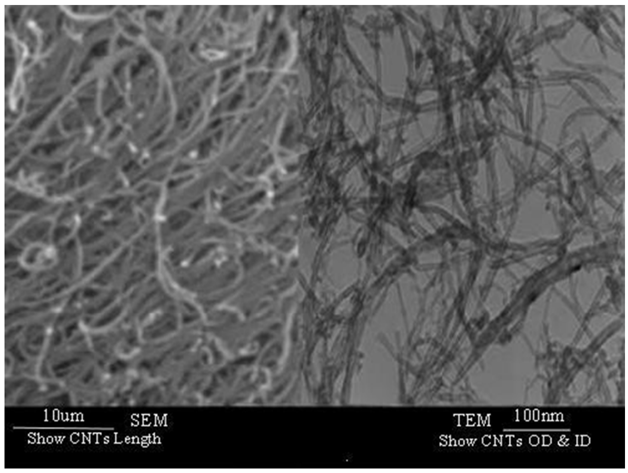

Fig. 1. SEM and TEM photos for MWCNTs (10nm).

First of all, to achieve a suitable primary mixture of carbon nanotubes and the alloy powders, they were dispersed in ethanol by using an ultrasonic shaker. For the perfect removal of ethanol and moisture, the mixture was placed in a dry oven for 12h at 60°C [20].

Then, the mechanical alloying as one of the powder metallurgy routes was applied. The mixtures with different amounts of carbon nanotubes including 0.5, 1 and 2wt% along with 1wt% of ethanol as the PCA

(Processing control agent), were placed in the stainless steel mixing jars of a planetary high-energy ball mill. the ball-to-powder mass ratio and The angular velocity at the milling process were maintained as 10:1 and 250rpm, respectively. The time duration was selected to be 24 hours as an optimum period to let the nanotubes play their important role of grinding aids to achieve fine nano-composites with a better distribution of nanotubes in the matrix alloy as the most critical challenge in nano-composites processing [21].

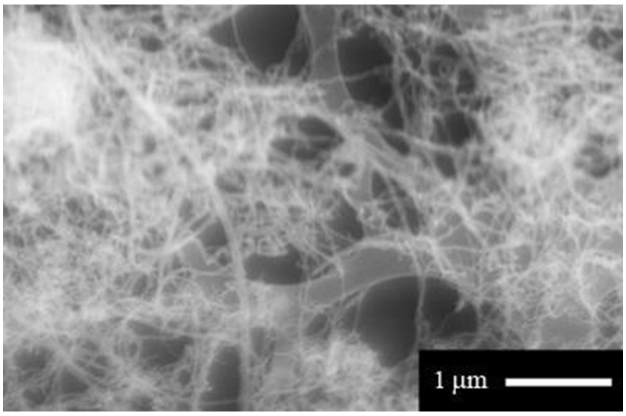

Fig. 2. SEM photo for MWCNTs (65nm).

Finally, the mechanical alloying was followed by a low-temperature compacting called spark-plasma sintering as a fast and modern sintering process that acts based on applying the heat through an electrical discharge between the alloy powders and also applies a uniaxial pressure simultaneously to sinter the specimen. The sintering temperature and pressure were respectively selected to be 395°C and 30MPa and also the time duration used was 20 minutes.

After achieving the final specimens, the microstructural analysis was carried out using a field- emission scanning electron microscopy (Fe-Sem) photo by using two samples to review the shape and morphology of the particles and nanotubes and also the distribution of nanotubes in the matrix alloy. In the final step, the 3-point flexural test and the Vickers hardness test were respectively performed for each specimen according to (ASTM C1161-02c) and (ASTM-E92) standards [22,23].

3. Results and Discussion

In this investigation, 7 specimens were made including the pure Al7075 alloy and 6 other nano-composites with the matrix phase of Al7075, reinforced respectively with 0.5, 1, and 2 weight % of multi-walled carbon nanotubes with two different mean diameters (10nm and 65nm). The wise choice of the nanotubes dimensions and weight fractions was very helpful for understanding the effect of nanotubes' existence and their size and weight fraction the flexural strength of the produced metal matrix nano-composites. The FE-SEM photos taken randomly from two of the samples are shown in Figs. 3 and 4.

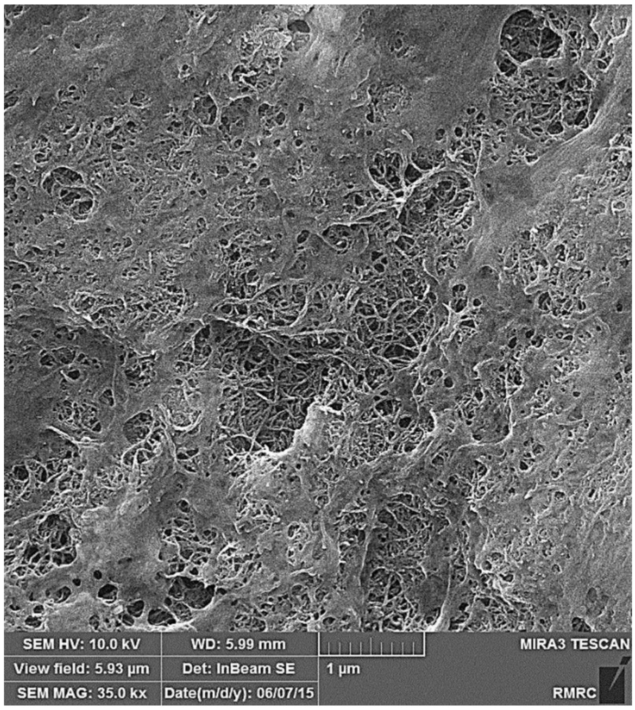

Fig. 3. FE-SEM photo with 1μm magnification for Al7075+0.5Wt% MWCNTs (10nm).

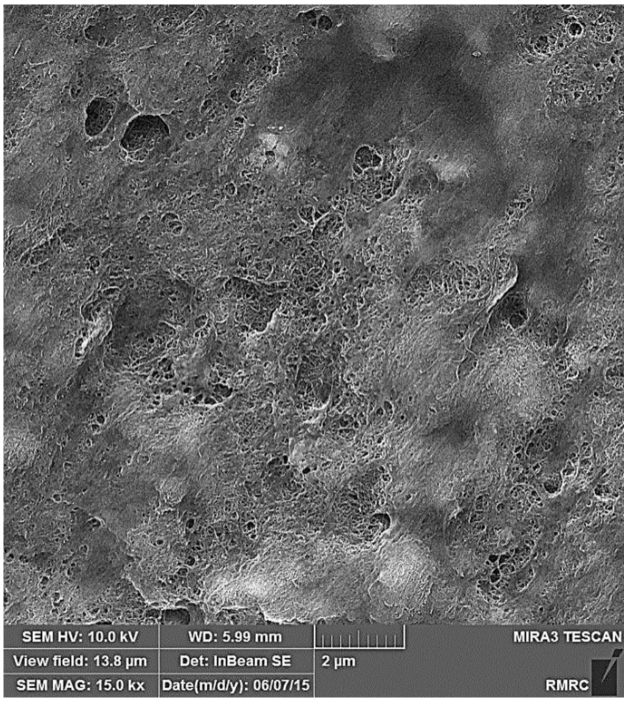

Fig. 4. FE-SEM photo with 2μm magnification for Al7075+1wt% MWCNTs (65nm).

Figs. 3 and 4 show very low porosity in both samples. These low porosities can be as a result of relatively fully dense nano-composites according to densities over 96% for all specimens. Furthermore, a suitable distribution of MWCNTs in the matrix alloy was observed which can be a result of the correct choice of the parameters in the fabrication stages, such as using the PCA in high-energy ball milling and also the importance of using an ultrasonic shaker as a pre-processing technique. Besides, it is worthy to note that carbon nanotubes nearly saved their curly-thread shape, proving that the temperature and uniaxial pressure in spark-plasma sintering could not have a major effect on nanotubes shape. From the Figs. 3 and 4 it is quite clear that in 0.5 and 1 weight% of nano addition no agglomeration were observed and the grain size reduced obviously. As a result, one can expect that both the strength and hardness should increase due to inverse relation of grain size with these two important mentioned properties. In order to imagine physical sense, it is required to consider the matrix reinforced with MWCNT with no agglomeration. The additive can place in the grain boundries and strengthen them. Therefore the magnitude of the strength and the hardness of the alloy increase as well. However, the agglomeration has detrimental effects on the strength and hardness as well due to inhomgenous media of the compoite structure of the mentioned alloy.

After reaching a homogeneous distribution of nanotubes and suitable quantities for the density, the Vickers hardness and flexural strength tests were carried out for all of the specimens. Bending strength's results are presented in Figs. 5 and 6:

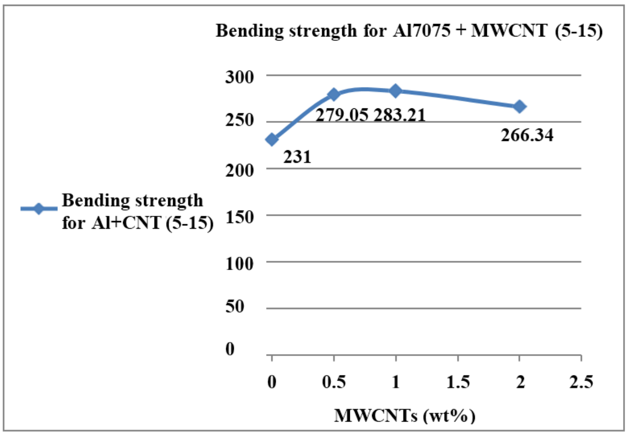

Fig. 5. Bending strength for Al7075+MWCNTs (10nm).

As it is obvious from the charts, 4 important results can be drawn which are as below:

1. The specimens reinforced with carbon nanotubes showed higher flexural strength in comparison with the pure Aluminum alloy 7075.

2. The specimen with 1wt% of multi-walled carbon nanotube, for both mean diameters (10 and 65nm), showed a higher flexural strength rather than other samples but with a slight increase in quantity from the sample reinforced with 0.5wt% of CNTs.

3. As the reinforcing phase becomes higher than 1wt% for both mean diameters (10 and 65nm) the flexural strength starts to decrease in the quantity, which can be a sign of passing the optimum weight fraction of nanotubes in the base alloy causing agglomeration of nanotubes and producing clusters of them in the microstructure of the Nano-composites and has a negative effect on the mechanical properties (bend strength).

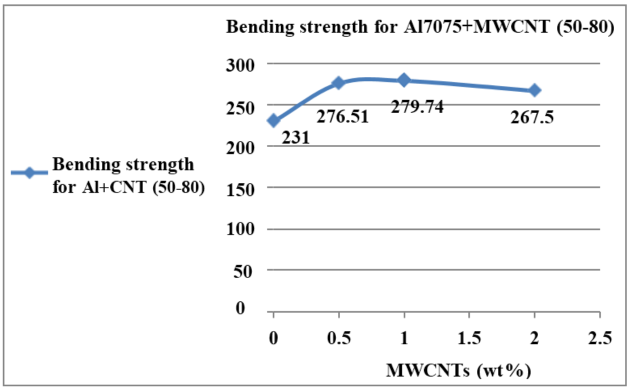

Fig. 6. Bending strength for Al7075+MWCNTs (65nm).

While reviewing the two charts, it can be understood that by using the smaller size of nanotubes, higher flexural strength can be gained for metal matrix nano-composites. Likewise, Vicker hardness test results are shown in Figs. 7 and 8:

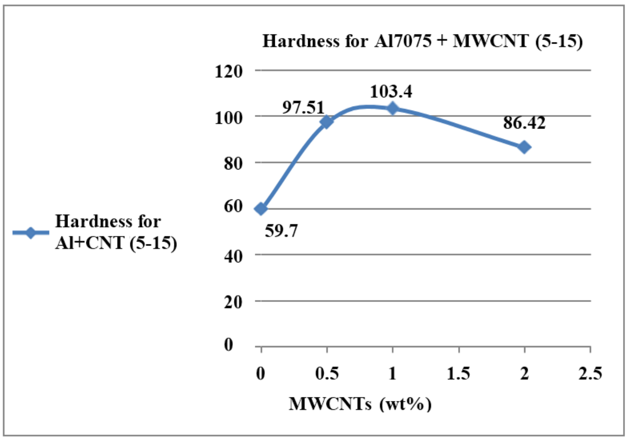

Fig. 7. Hardness for Al7075+MWCNTs (10nm).

The results achieved in the hardness test are just similar to what happened for the bending strength of the nano-composites. As shown in the Figs. 7 and 8 the magnitude of hardness increased until 1 percent nano MWCNT addition due to homogene distribution of nanao particle with no agglomeration phenomenon. This can induce physical sense that why one percent of nano addition lead to better increase in hardness and the bending strength of the pecimens. That means:

1. The specimen reinforced with 1wt% of MWCNTs (mean diameter of 10nm) was the hardest among all the specimens.

2. The reinforced samples were harder than the non-reinforced ones, proving the positive effect of nanotubes as strengthening reinforcements.

3. The specimens reinforced with lower-diameter nanotubes even with the same weight fraction showed higher hardness in comparison with other nano-composites with a larger diameter.

4. Nano-composites reinforced with 2wt% of nanotubes showed a noticeable reduction in the hardness which is probably due to cluster formation of nanotubes when agglomerating.

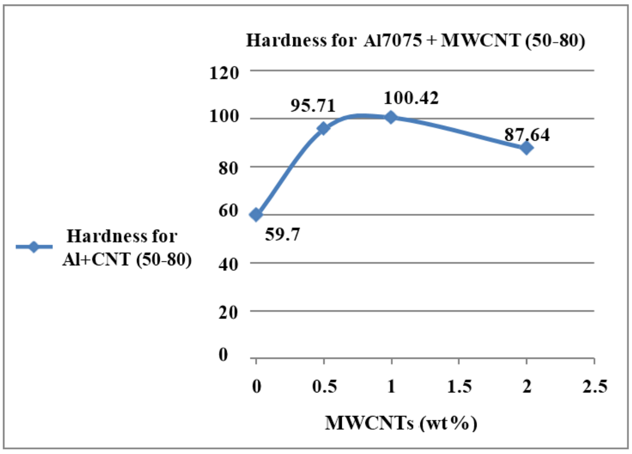

Fig. 8. Hardness for Al7075+MWCNTs (65nm).

4. Conclusions

In the present paper the effect of multi-walled carbon nanotubes, as the reinforcement phase, on the hardness and bending strength of Aluminum alloy 7075 was studied implicating novel spark plasma sintering method. Spark plasma sintering method was implicated successfully to produce the reinforced alloy implicating several percentage of multi-walled carbon nanotubes. Results showed that adding the reinforced samples were harder and had more bending strength than the non-reinforced ones. Besides, adding reinforced with 1wt% of MWCNTs (mean diameter of 10nm) was the hardest among all the specimens. The specimens reinforced with lower-diameter nanotubes even with the same weight fraction showed higher hardness in comparison with other nano-composites with a larger diameter. As the reinforcing phase became higher than 1wt% for both mean diameters (10 and 65nm), both the flexural strength and hardness decreased due to agglomeration of nanotubes and producing clusters of them in the microstructure of the Nano-composites.

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