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Ultrasonic Nano-dispersion Technique of Aluminium alloy and Carbon Nano-tubes (CNT) for Automotive Parts Applications

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ABSTRACT

The use of carbon nano-tubes (CNTs) in nanotechnology and leading industries is of extreme importance due to its various applications. One such application is producing Aluminum reinforced nano-composites which may find applications in the aerospace and automobile industries. Additions of high modulus nano particles to Aluminum alloys offer the potential to develop a lightweight composite with high mechanical properties. It is extremely difficult to disperse nano sized ceramic particles uniformly in molten metal. In order to investigate the effect of selected nano-materials (CNTs) on the microstructure and mechanical properties of composite, a new method is used to avoid agglomeration and segregation of particles. The microstructure of the composites is investigated by scanning electron microscopy (SEM). Experimental results show a nearly uniform distribution and good dispersion of the nano-particles within the Al matrix, although some of small agglomeration found. Hardness, Flexural strength and tensile strength are enhanced by incorporation of nano materials into matrix. The enhancement in values of hardness, flexural strength and tensile strength observed in this experiment is due to small particle size and good distribution of the particles, which was confirmed by SEM pictures.

Keywords: AA6061, Carbon Nano tubes (CNTs), Metal matrix nano-composites, Sonication, Ultrasonic cavitation.

I. INTRODUCTION

Metal–matrix composites MMCs have been extensively studied in the last 2 decades for many demanding applications in aerospace, automobile, and military industries, etc. However, MMCs tend to fracture easily due to their poor ductility and low fracture toughness, hindering their widespread use. Metal Matrix Nano-composites (MMNCs) are the materials in which reinforcements of nano-scale are embedded in a ductile metal or alloy matrix. Dispersion of nano-scale materials uniformly in metal matrix is a challenging task due to their poor wettability in metal matrix and their large surface to volume ratio, which easily induces agglomeration and clustering.[1]

Although MMNCs are very promising for providing superior properties, the current nano-manufacturing technologies are neither reliable nor cost effective to enable a high volume and net shape production of complex MMNC structural components with reproducible structures and properties. Traditional nano-manufactuirng methods for nano-composites, such as high energy ball milling, rapid solidification, electroplating, sputtering, etc., cannot be used for mass production and net shape fabrication of complex structural components.

Thus this calls for a new nano-manufacturing method that utilizes solidification processing and ultrasonic nano-dispersion to fabricate lightweight bulk MMNC samples, particularly the CNT nano-particle reinforced aluminum alloy AA6061. Uniform distribution and good dispersion of nano-particles in the Al matrix have been achieved. This cost effective and reliable nano-manufacturing method is very promising and can be readily scaled up for industrial scale production of complex Al MMNC structural components.

II. METHODS AND MATERIAL

1. Literature Review

CNTs are unique nano-structured material with remarkable physical and mechanical properties. Their young‘s modulus reaches 1-2 TPa and shear modulus is around 0.5 TPa. Their tensile strength, approximately 200 GPa, is about two orders of magnitude higher than that of current high-strength carbon fibers, and their density is only 1.3 g/cm3, lower than the density of commercial carbon fibers (1.8-1.9 g/cm3). These properties give an opportunity to manufacture super-strong material with extremely low mass density.

Besides the mechanical properties, carbon nano-tubes have other excellent properties, such as high thermal conductivity (~2000 W/m/K), high electric conductivity, and high chemical stability. These properties have inspired interest in using carbon nano-tubes as the ideal reinforcing materials for the next generation nano-composites. However, there are three major challenges for synthesizing the ideal nano-composite.

One of the major obstacles for using nano-tubes as metal matrix filler is the cost. However, advances in the synthesis method of CNTs continue to be rapidly improved in both quantity and quality. It is only a matter of time before high purity CNTs are massively produced at low cost. The second obstacle is dispersion. The small size and the high surface energy of CNTs make them tend to aggregate. The drawbacks of bad dispersion are bi-fold:

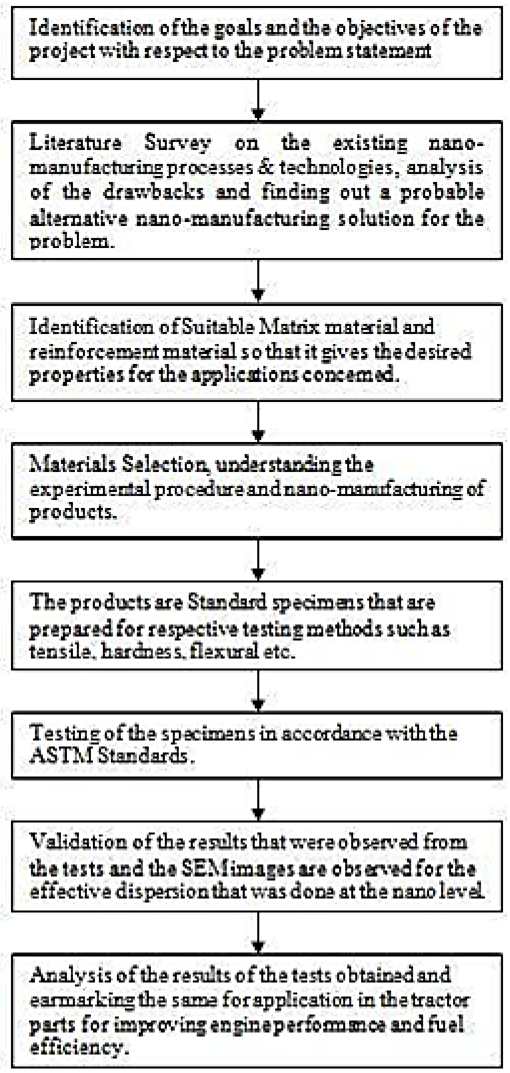
[1]. The nano-tubes can‘t be used efficiently, since the loading can‘t be transferred from matrix to individual CNT

[2]. The CNTs aggregate together and form big size clusters. This will cause serious force concentration and lower the mechanical properties of nano-composite.

The third obstacle is the adhesion between carbon nano-tubes and aluminum matrix. As CNT is a chemical inert material, good adhesion with matrix can‘t be achieved. The drawback of weak adhesion is that the load could not be transferred from the matrix to the reinforced materials efficiently. In other words, the excellent mechanical properties of carbon nano-tubes could not be fully utilized if the interfacial property between nano-tubes and matrix is too weak. Ultrasonic cavitation may help in overcoming the above obstacles if the process is undertaken properly in accordance with the optimized parameters.

In this study, the mechanical stirring and high-intensity ultrasonic processing was used to fabricate 0.5%CNTs reinforced aluminium alloy composite. The microstructures and mechanical properties of the CNTs/AA6061 composites were investigated. [2]

2. Research Work Study



3. Ultrasonic Nano-Dispersion

Ultrasonic waves are generated in a liquid suspension either by immersing an ultrasound probe or ―horn‖ into the suspension (direct sonication), or by introducing the sample container with the suspension into a bath containing a liquid through which ultrasonic waves are propagated (indirect sonication). In a sonication bath (indirect sonication), the ultrasonic waves must traverse the bath liquid and then pass through the wall of the sample container before reaching the suspension. In direct sonication, the probe is immersed directly into the suspension, reducing the physical barriers to delivering the power to the dispersion.

Direct sonication is recommended over indirect sonication for the purpose of dispersing dry powders, as it yields a higher effective energy output into the suspension. Indirect sonication can be used to re-suspend ENMs which have been pre-processed via direct sonication, or for ENMs that may be subject to unintended modifications or damage under direct sonication. Sonication is a highly system-specific dispersion procedure, involving a variety of concomitant complex physicochemical interactions that can result in either cluster breakdown or further agglomeration, as well as other effects including chemical reactions.

For a given system, optimal sonication conditions must be determined by assessing the effect of a variety of sonication parameters on the dispersion state of the suspension under a broad range of relevant conditions. The various parameters concerned with sonication are Temperature, Sonication time and operation mode, Sample volume and concentration, Sonicator probe, container geometry and tip immersion, medium properties. The typical parts of a Ultrasonic Cavitation machine are described in Fig. 1.

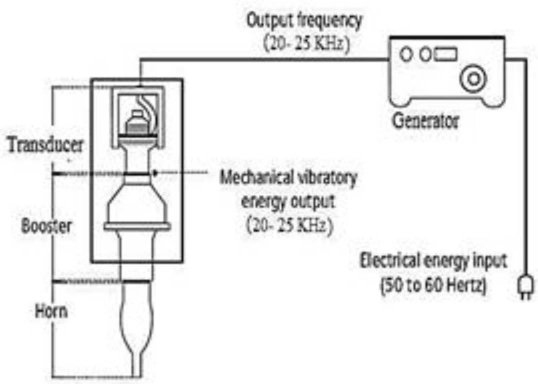


Figure 1. Typical Parts of a Ultrasonic Cavitation Machine

4. Principle

Ultrasonic waves are the waves of frequency above 17~20 kHz and generated by mechanical vibrations of frequencies higher than 18 kHz. When these waves propagate into liquid media, alternating compression and expansion cycles are produced. During the expansion (rare fraction) cycle, high intensity ultrasonic waves make small bubbles grow in the liquid. When they attain a volume at which they can no longer absorb enough energy, they implode violently. This phenomenon is known as cavitation. During implosion, very high temperatures and pressures are reached inside these bubbles.[2]

Cavitation is the formation of vapor or gas bubbles in a liquid caused by reduction in pressure at constant temperature. This is in contrast to the nucleation of bubbles due to an increase in temperature above the saturated vapor/liquid temperature, which is called boiling. The dynamic pressure reduction can be achieved in many ways, of which ultrasonic waves is one. Hence it is termed as ultrasonic cavitation.

After cavitation, bubbles are formed by a dynamic pressure reduction, which are subjected to a pressure increase. As the growth of the bubbles stops, the bubbles begin to collapse. If only vapor is present in the bubbles, the collapse becomes more severe. This is represented in Fig.2 which is concerned with the cavitation bubbles preventing the formation of clusters of nano-particles in the melt.

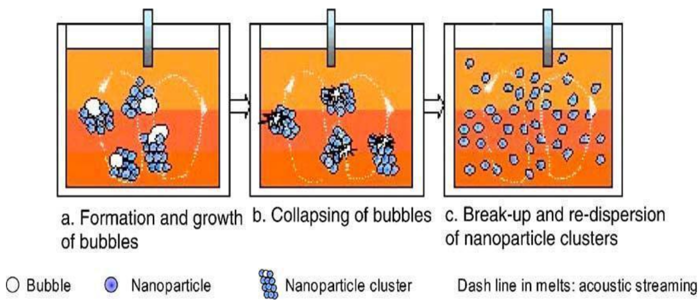


Figure 2. Ultrasonic Cavitation/Nano-dispersion Principle

A. Material Selection

Aluminum alloy AA6061 was selected as a matrix material since it is a versatile heat treatable alloy with medium to high strength properties. The chemical composition of the AA6061 alloy is shown in Table 1. The nano-sized particles used in this study were Multi-walled Carbon Nano-tubes,

spherical shape, average diameter of 20 - 45 nm, Colour – Black, CN purity > 95%, Length – Several Microns, Surface
Area > 500m^2/gm, Impurity < 2-3%.

Table 1 – Typical Composition of Aluminium alloy 6061

COMPONENT	AMOUNT (wt.%)
Aluminium	Balance
Magnesium	0.8-1.2
Silicon	0.4-0.8
Iron	Max. 0.7
Copper	0.15-0.40
Zinc	Max. 0.25
Titanium	Max. 0.15
Manganese	Max. 0.15
Chromium	0.04-0.35
Others	0.05

The experimental nano-manufacturing setup is shown in Fig. 3, including furnace, ultrasonic probe, temperature controller, and inert gas protection nozzles. In this process, an electric resistance heating unit was used to melt the AA6061 in a graphite crucible with a 1.2 kg capacity. Nano sized CNT particles were fed into melts during the ultrasonic processing. The aluminum melt pool was protected by argon gas.

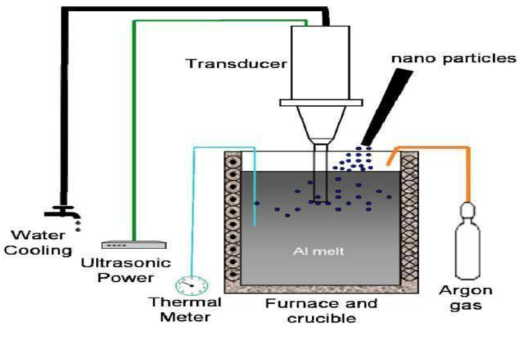


Figure 3. Nano Manufacturing setup

The processing temperature was controlled at approximately 150°C above the alloy melting point 650°C. The ultrasonic probe is made of niobium (Nb), which can withstand high processing temperature with minimum ultrasonic cavitation induced erosion. The parameters that were employed in ultrasonic nano-dispersion is given below.

- Matrix material : AA 6061
- Reinforcement : CNT
- Size of CNT particle : 20 – 45 nm
- Melting Temp : 820^o C
- Power rating : 2 kW
- Flow rate of Argon gas: 6Lit / min at 140Kg / cm^2
- Die Preheating temp : 500^{o}C
- Operating temp of furnace - 900^{o}C
- Power of Furnace = 5 kW

When nano-sized CNT particles were added in the Al alloy melts, the viscosity of the molten Al alloy significantly increased. Thus, after efficient ultrasonic processing, a higher melt temperature of 820°C was used to ensure the flowability of the nano-composite melt inside a mold. The geometry of the casting mold was designed according to the ASTM standard given in figure and the cast plates are of dimensions 110mm*110mm*10mm which is in Fig. 4.The weight percentages of 0.5 wt.% nano-sized CNT in aluminum melts were processed for microstructure study and for testing of mechanical properties of the composite.[3]

For metallographic examination, specimen (fig.4) was prepared by grinding through 1×0, 2× 0, 3× 0, 4× 0 quality emery papers followed by polishing with 6 micro meter diamond paste. The microstructures were obtained by viewing the samples at different magnification levels on SEM (Model: HITACHI make with field emission gun).the Nano-particles were well dispersed in the AA6061 matrix, although some micro clusters remained in the matrix. It is believed that high intensity ultrasonic waves generated strong cavitation and acoustic streaming effects.

Figure 4. Microstructure Specimen

The SEM images (Fig.5 and Fig.6) show the presence of CNT in trace quantities in the AA6061 matrix. This shows that the dispersion has been quite uniform which was achieved by mechanical stirring followed by ultrasonic cavitation.

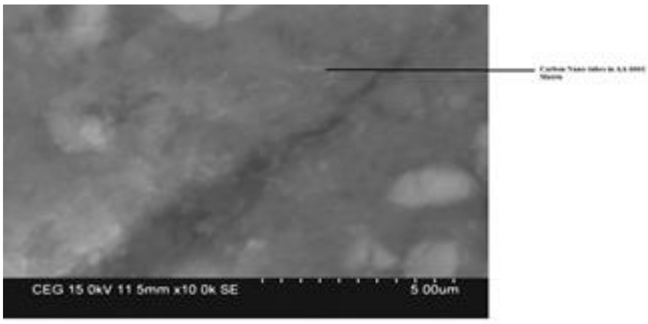


Figure 5. Fibers of carbon nano-tubes in AA6061 matrix

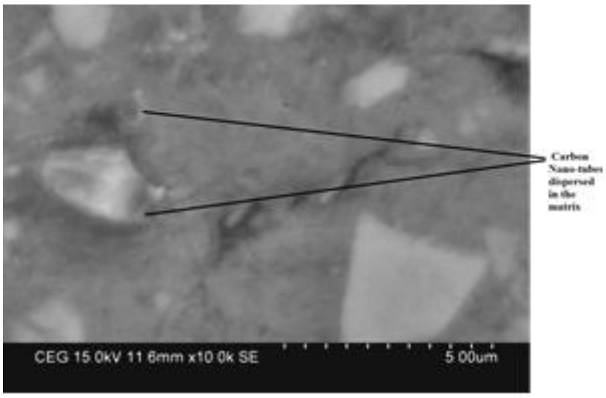


Figure 6

5. Mechanical Properties

FLEXURAL TEST (THREE POINT BEND TEST)

The three point bending flexural test provides values for

$$\sigma_f = \frac{3PL}{2bd^2} \qquad E_f = \frac{L^3 m}{4bd^3}$$

$$\epsilon_f = \frac{6Dd}{L^2}$$

d= Depth of tested beam, (mm)
D = maximum deflection of the center of the beam, (mm)
m= The gradient (i.e., slope) of the initial straight-line portion of the load deflection curve,(P/D), (N/mm)
R= The radius of the beam, (mm)
σ_f = Strain in the outer surface, (mm/mm)
E_f = flexural Modulus of elasticity, (MPa)
P = load at a given point on the load deflection curve, (N)
L = Support span, (mm)
b = Width of test beam, (mm)

Thus based on the above formula the theoretical and practical flexural stress values are observed and it is then compared with the value of standard alloy. The flexural test is carried out in Tinius Olsen Horizon UTM (H100KN) in accordance with the ASTM Standards. The specimen is of the dimension 100mm*40mm*10mm.

The modulus of elasticity in bending E_f, flexural stress ,flexural strain ϵ_f and the flexural stress-strain response of the material. The main advantage of a three point flexural test is the ease of the specimen preparation and testing.

Table 2 Stress and Strain

Force	Position	Time	Stress(MAa)	Th.Strain
3.83	0.00531	0.787	0.122152	0.019305
42.5	0.0274	1.44	1.35547	0.099616
247	0.0677	2.66	7.877673	0.246132
712	0.127	4.44	22.70811	0.461724
1670	0.25	8.13	53.262	0.908906
2170	0.335	10.7	69.2087	1.217934
2680	0.44	13.9	85.47434	1.599675
3180	0.57	17.8	101.421	2.072306
3600	0.707	21.9	114.8163	2.570387
3930	0.836	25.8	125.3411	3.039383
4270	0.991	30.4	136.1849	3.602904
4830	1.32	40.2	154.0452	4.799025
4930	1.39	42.5	157.2345	5.053519
4980	1.43	43.6	158.8292	5.198944
5020	1.49	45.4	160.1049	5.417081
5020	1.5	45.6	**160.1049**	5.453438

The tensile test results are shown in Table 3, where the tensile strength and yield strength are normalized with those of as-cast pure A6061 alloy. It can be found that with only 0.5 wt.% nano-sized CNT, the ultimate tensile strength (UTS) of the nano-composites were improved more than 11.82% respectively. The improvement in mechanical properties is significantly better than that of the AA6061 composite with the same percentages that micro particle reinforcement can offer, but there has been a decrease in ductility and it is within the permissible levels of 4-6% decrease.

It is expected that if the processing parameters and casting process are customized and optimized, the mechanical properties of MMNCs will be further improved with further increasing wt% of CNTs in AA6061 matrix.[4]

Thus from the above table, it is found that the maximum flexural stress obtained was 160.1 Mpa which gives a 28% increase in the value of that of the alloy.[4]

The tensile properties of the nano-composite specimens (Fig. 7) were tested with a Tinius Olsen Horizon (H100KN) UTM according to the standard of ASTM E8.The theoretical

Stress and strain for the composite may be calculated by the following formulas:

Stress (ρ) = P/ A

Strain (Ɛ) = ΔL/L

P = Applied Load (in N)

L = Elongation (in cm/m)

A = Area of Cross-section (in cm^2/m^2)
The ASTM E8 Standard Tensile test specimen is given in

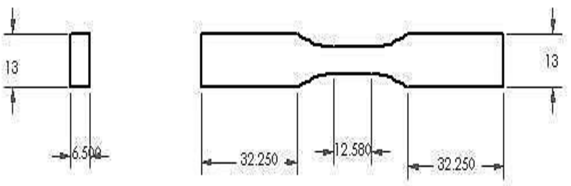


Figure 7

Table 3 Tensile test results

Force	Position	Stress	Strain	Time
34.3	0.0432	0.54	0.216	0.0278
203	0.312	3.2	1.56	0.162
381	0.422	6	2.11	0.217
1010	0.81	16	4.05	0.412
1270	0.94	20	4.7	0.476
1590	1.09	25	5.45	0.552
1910	1.23	30	6.13	0.62
2220	1.35	35	6.76	0.683
2480	1.45	39	7.24	0.731
3050	1.65	48	8.24	0.831
3750	1.87	59	9.34	0.942
4760	2.17	75	10.8	1.09
5460	2.36	86	11.8	1.19
6160	2.56	97	12.8	1.29
6980	2.79	110	13.9	1.4
7460	2.93	117	14.7	1.47
7600	2.97	120	14.9	1.5

(All dimensions are in mm)

The hardness of the samples was measured using a Rockwell hardness testing machine by applying a load of 150N. The load was applied for 20 seconds. In order to eliminate possible segregation effect a minimum of three hardness readings were taken for each specimen at different locations of the test samples.[5]

III. RESULTS AND DISCUSSION

The results augment the fact of replacing the conventional materials by Nano-composite which has higher mechanical properties when miniaturization is taken into account at the nano-level. The values are listed in Table 4 which gives an insight into the properties of the nano-manufactured product.

Table 4 – Comparison of AA6061 Alloy vs 0.5 wt% CNT reinforced AA6061

MATERIAL	HARDNESS (ROCKWELL 'B' SCALE)	TENSILE STRENGTH (MPa)	FLEXURAL STRESS (MPa)
AA6061	**90**	**110**	**125**
AA6061 + 0.5 wt% CNT	**114**	**123**	**160**
% Increase	**26.67**	**11.82**	**28**

Thus the composite can find its applications in pulling parts; lever arms of a tractor so that the products are light weight with high strength properties. It can also be extended to other structural and engine parts as well.

IV. CONCLUSION

In this study, hardness, tensile strength of AA6061 reinforced with 0.5wt% of CNT nano-particles was examined and compared with pure alloy. With the addition of reinforcement, tensile strength, hardness of nano CNT reinforced composites were increased with no significant change in ductility. By SEM Microstructures, it can be observed that reinforcements are well dispersed in AA6061 matrix.

More specifically, the rate of increase in yield strength is not in proportionate with that of ultimate tensile strength and hardness. Decrease in ductility and non uniformity in increase of tensile properties in the former case may be due to uneven size of particles and contamination. The microstructure study shows that high-power ultrasonic is effective to disperse Nano size CNT particles in aluminum alloy AA6061 and enhances the wettability between the particles and Al matrix. However, it is typical that a small amount of micro clusters remained in the matrix. The superior nano-particle dispersion resulted in significantly improved mechanical properties.

Thus with better mechanical properties than that of the pure AA6061 alloy, with better and proper Nano-manufacturing technologies/techniques, CNT reinforced AA 6061 alloy can be employed for manufacturing of typical structural and automobile components like Crank Shaft, Cam Shaft etc. The reinforced composite may also be used in the manufacture of any tractor components, with its light weight, but high strength increases the engine performance as well as the fuel efficiency.

V. SCOPE FOR FUTURE WORK

Nano-particles by inventing good feeding techniques. Tribological behaviour, machinability, Thermo-mechanical behavior, Impact strength and fatigue strength of nano composites is untouched in this work. If the observed properties were better than the pure alloy, then based on the properties the composite can be selected for different applications by optimizing the various parameters concerned like wt%, Sonication time etc. and by employing sound casting technology.

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