Aluminum Nanocomposite based on Ensemble of Carbon Materials for Enhanced Vibration Damping

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Abstract: - Many aluminum nanocomposites consisting of a single particulate phase have been synthesized and tested in the past. However, vibration damping characteristics of aluminum nanocomposite based on ensemble or combination of two morphologically different carbon-based materials have not been reported. Therefore, in this work the focus is to synthesize an aluminum nanocomposite based on the combination of two different carbon-based particulate phases namely graphite flake and carbon fiber in order to identify any improvement in the damping ability of the as-synthesized aluminum nanocomposite material. Aluminum nanocomposite was prepared using stir casting method. The particulate phases of carbon were used in varying weight compositions but were always in an equal ratio relative to each other. The material was casted in form of thin rectangular bars using metallic dies and tested in a cantilever beam configuration. MEMS based accelerometer via Arduino microcontroller was used to collect the time dependent response at the free end of the beams. The damping constant ζ was estimated from the response curves. Experiments indicate that compared to the pristine aluminum bars, the damping ability of the as-synthesized aluminum nanocomposite increases by almost 117 % at 3 wt% of the particulate phase. The increase in damping is mainly attributed to the trans-granular frictional effects and weak interfacial bonding between the metal matrix and the particulate phases. Aluminum nanocomposite is successfully prepared using combination of two morphologically different carbon-based particulate phases. The as-synthesized material shows favorable damping performance that can be exploited in structural, automotive, marine and aerospace applications.

Keywords: - Aluminum nanocomposite, graphite powder, carbon fiber, free vibrations, damping ratio

1. INTRODUCTION

Aluminum and its nanocomposites are getting exceedingly popular in areas like automotive, aerospace, aircraft and construction industry [1]. According to the Aluminum Association, automobile manufacturers have shown interest in aluminum and its nanocomposites for automotive industry. Aluminum in the automotive industry could become an alternate material to steel thereby saving the overall cost, fuel, environment and also increasing the opportunity of dent resistance [2]. Due to this reason there have been many researches on the dynamic analysis of automotive chassis investigating the opportunity of using aluminum-based alloys and nanocomposite materials for its construction [3, 4]. Aluminum nanocomposites are also widely used in aircraft and aerospace applications which demands high temperature resistance [5].

Aluminum has also shown remarkable utility in construction industry for instance aluminum and its alloys have been used in the construction of bridge decks, roof structures, antenna towers and building structures such as columns [6 - 8]. Due to its high strength to weight ratio and low corrosion rate aluminum is also being utilized in marine and ship building industry [9]. However, it is to be noted that all these applications demand high structural integrity, safety and robustness against adverse dynamic conditions like mechanical vibrations. The ability of a material to resist mechanical vibrations is known as the material damping and is due to the microstructure effects of the material which can result in energy loss. Damping remains the essential component for efficient vibration isolation or suppression specially if the structure is to operate near resonance. Therefore, in the field of mechanical vibrations significant amount of research work is devoted towards the investigation of damping ability of a design which can include various types of dampers, foundations and frames [10 - 14]. These researches are of prime importance in order to design stable, noiseless and vibration resistant structures.

It has been known that dispersing different nanostructured materials in aluminum metal matrix can give rise to a new class of materials the so-called aluminum nanocomposites which shows superior mechanical properties [15 - 17]. Aluminum nanocomposites can be synthesized using techniques like metal casting and powder metallurgy with some inherent variations and complexities. It has been found that fabrication technique, particulate material phase, its morphology and its amount can affect the mechanical properties of the nanocomposite material. Several research works have shown this behavior for instance, El-Kady et al. [18] have shown that damping constant of rheocasted and squeeze casted A356 aluminum alloy nanocomposite using aluminum oxide nanoparticles increases by an order of magnitude compared to pristine A356 aluminum.

Deng et al. [19] have shown that damping constant of 2024 aluminum and multi walled carbon nano tubes nanocomposite fabricated through powder metallurgy process and hot extrusion can reach high values at elevated temperatures. Reddy et al. [20] have prepared pure aluminum and boron nitride nanocomposite material using powder metallurgy and hot extrusion process. They showed that damping constant of the as-fabricated nanocomposite increases by almost 27 % compared to the pure aluminum. These researches have indeed shown that adding particulate phase to aluminum can make it resistant against mechanical vibrations.

The above-mentioned researches successfully synthesized vibration resistant aluminum nanocomposites, however these studies have used one single particulate phase in the aluminum metal matrix. On the other hand, these techniques have utilized technologically advanced fabrication methods and materials like carbon nano tubes which can be costly. Therefore, in this paper mainly our goal is to study the effect of two morphologically different particulate phases of carbon on vibration damping ability of the as-synthesized aluminum nanocomposite material. The as-synthesized aluminum nanocomposite material is based on the ensemble of two morphologically different particulate phases of carbon namely the graphite flakes and the carbon fibers. The aluminum nanocomposite is prepared using a simple and cost-effective method of stir casting [21, 22]. Particulate phases of carbon were added in amounts of 1, 2 and 3 wt% in pure molten aluminum with continuous mechanical stirring and finally casted in form of thin rectangular bars using metallic dies. The different sections of this paper outline the complete experimental route for the fabrication and testing of the as-fabricated aluminum nanocomposite material.

2. EXPERIMENTAL

2.1. Materials

Aluminum 6061 ingots were purchased form a local supplier and was further examined using x-ray fluorescence (XRF) technique that confirms 99.23% aluminum. Milled carbon fibers of average dimensions' length (44 μm) × diameter (7 μm) and graphite flakes of average planar dimension 73 μm were imported from China. Methanol and graphite paste as die lubricants were purchased from the local chemical market (Pakistan). Carbon fibers, graphite flakes and die lubricants were used as received.

2.2. Synthesis of aluminum nanocomposite

In order to have a fair basis of comparison pristine aluminum bars were initially casted in this work. Firstly, 1 kg of aluminum ingots was placed in a steel crucible having proper clamping fixtures and a pouring notch. The crucible with its contents was placed inside a gas fired furnace that was having a cover lid with a center hole. Aluminum ingots were melted at 660^{o}C and 30 min with continuous stirring at 600 rpm. The stirring was done using a hand held drill machine and a stainless steel four-blade stirrer welded at the end of a solid rod also made of stainless steel. The other end of the rod was securely held within the chuck of the drill machine. The temperature of the melt was recorded using a laser temperature gun. Molten aluminum was poured into two-piece metallic dies having proper gating system and lubrication using the paste of ethanol and graphite. Prior to pouring, the dies were pre-heated in a furnace till red hot. The molten aluminum was found to solidify within 4 to 5 min at atmospheric conditions, after which the casted bars were smoothly taken out by opening the dies. Machining procedures were performed to give finish size of length 250 mm, width 20 mm and thickness 4 mm. In case of synthesis of aluminum nanocomposite all steps till melting of the aluminum ingots remains the same. However, after the melting of aluminum ingots the particulate phases in 1:1 ratio of weight relative to each and concentrations of 1, 2 and 3 wt% in totality were carefully measured using an electronic balance with an accuracy of 0.1 mg. The particulate phase was pre-heated in stainless steel bowl by placing it on the lid of the furnace for 10 to 15 minutes and was loaded at a constant rate using a hollow tube equipped with a funnel at one end and continuous stirring. After complete loading of the particulate phase stirring was continued for 2 h. The molten aluminum containing the particulate phase was poured into metallic dies and was allowed to solidify for 4 to 5 min. Finally, the casted bars of aluminum nanocomposite were machined to the same final size as mentioned previously. Fig. 1 depicts the complete schematic diagram of the stir casting process used in this work.

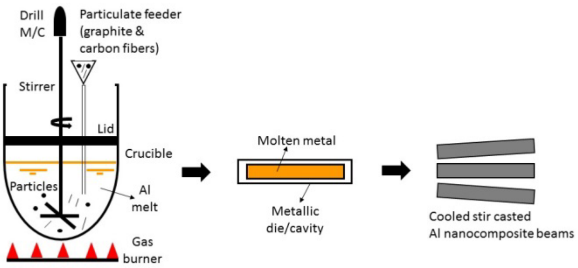

Figure 1. (color online) Schematic diagram of the stir casting process.

2.3. Damping characterizations

In this work the damping was defined and measured as the damping ratio more commonly known as the zeta ζ. It is widely accepted that ζ represents the ratio of actual damping to that of critical damping present in the system of interest (in this case the stir casted beams). As mentioned previously, in order to have a fair basis of comparison pristine aluminum beams were tested first in this work. It is to be noted that free vibration testing or the time domain approach is a simple and cost-effective method highlighting the fact that faster decay of vibration in time corresponds to the presence of high damping ability in the structure. Therefore, all beams in this work were tested under cantilever configuration and free vibration conditions i.e. the time domain approach. Each beam was tested twice by altering the fixed and free end of the beam. The ends were altered in order to have complete idea about the homogeneous dispersion of the particulate phase present in the beams. Beams with free length of 176 mm were securely clamped in a vice that was mounted on a rigid and balanced metallic table with welded joints. A small displacement of 1 mm was applied manually at the free end of the beams. A micro-electro-mechanical accelerometer ADXL345 was attached at the free end of the beams using a scotch tape. The accelerometer was connected to Arduino UNO microcontroller for programming and data logging. An open ware Telemetry Viewer version 05 was used to visualize the vibratory motion on real time basis on a personal computer. Curve fitting of the data sets were performed using freeware Matlab code that provided the values for natural frequency f_n, damping ratio ζ, amplitude *A* and phase angle ϕ according to Eq. (1) [23]. The Matlab code was capable of handling the input data in form of experimentally measured acceleration-time history while fitting Eq. (1) to output the required damping ratio and the frequency. The basic schematic of the experimental setup used to measure the vibratory response is shown in Fig. 2.

$$x(t) = Ae^{-2\pi\zeta f_n t}\sin\left(\sqrt{1-\zeta^2}f_n t - \phi\right) \quad (1)$$

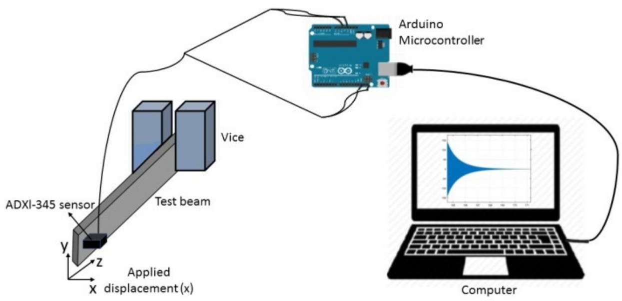

Figure 2. (color online) Schematic diagram of the vibration testing set up.

3. RESULTS AND DISCUSSION

Figures 3a-d depicts the typical response of the stir casted pristine aluminum beam and also the nanocomposite beams at 1%, 2% and 3% concentrations of the particulate phase. Curve fitting of the experimentally measured response was performed using Eq. (1) as stated above.

The percentage of error between the fitted equation and the experimental data sets was found to be less than 1% in all cases. It can be noticed from Figs. 3a-d that the response envelop continuously converges with increasing concentration of the particulate phase which indicates faster decay. Only a small portion of the response curve was fitted as shown in Figs. 3.a-d.

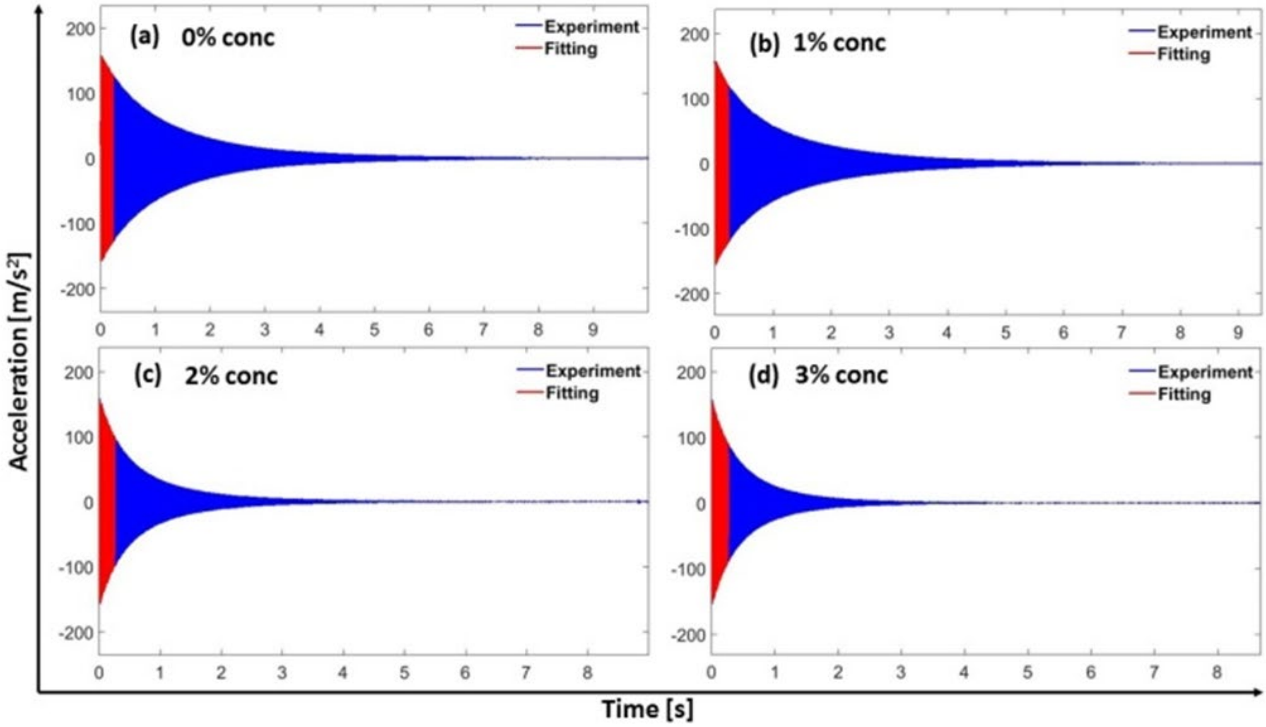

Figure 3. (color online) Measured vibration response (a) 0% (b) 1% (c) 2% and (d) 3% concentration.

Table 1 indicates the values of the natural frequencies and the damping ratios for various beams obtained in this manner.

Table 1. Frequency and damping ratio at various concentration of the particulate phase.

Concentration (%)	Frequency (Hz)	Damping ratio (ζ)
0 (pristine Al)	91.07	0.0018
1	85.84	0.0024
2	79.06	0.0036
3	79.39	0.0039

It can be noticed from Table 1 that damping ratio increases with increasing concentration of the particulate phase. The maximum damping ratio achieved at 3% concentration was about 117% higher than the damping ratio of pristine aluminum used in this work which indicates large increase in the damping ability of the as-synthesized nanocomposite material.

This increasing trend of the damping ratio with concentration is also shown in Fig. 4. It can be seen that this trend can be modeled with a simple linear fit of the form shown in Eq. (2):

$$\zeta = \frac{15c+36}{20000} \tag{2}$$

Where, *c* is the concentration in percent. The linear model can predict the values of the damping ratio.

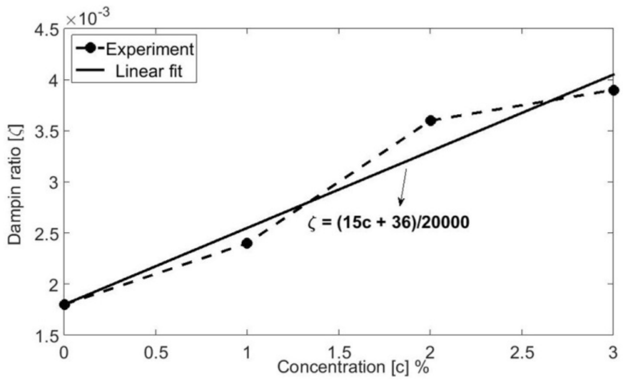

Figure 4. Variation of damping ratio as a linear fit.

The linear model can predict the values of the damping ratio with less than 10% error within the experimental regime. Figs. 5a and b shows typical scanning electron micrographs of the cross section of the nanocomposite material.

From Fig 5 it can be clearly seen that the particulate phases are morphologically different from each other and are randomly distributed within the metal matrix. According to the past research works, there can be several reasons for increasing damping effect in the metal matrix particulate nanocomposites [24]. However, from Fig. 5a it can be noticed that the average size of the graphite flakes used in this work remains 73 µm which is larger than the grain size of the cast aluminums [25], [26].

From Fig. 5a it can also be noticed that the average length of the carbon fibers is around 44 µm. Since, the size of both the particulate phases used in this work remains larger than the grain size of cast aluminum, the possibility of inter-granular as well as grain boundary damping mechanisms are excluded. Therefore, the increase in damping of the as-synthesized aluminum nanocomposite is mainly due to the trans-granular frictional effects.

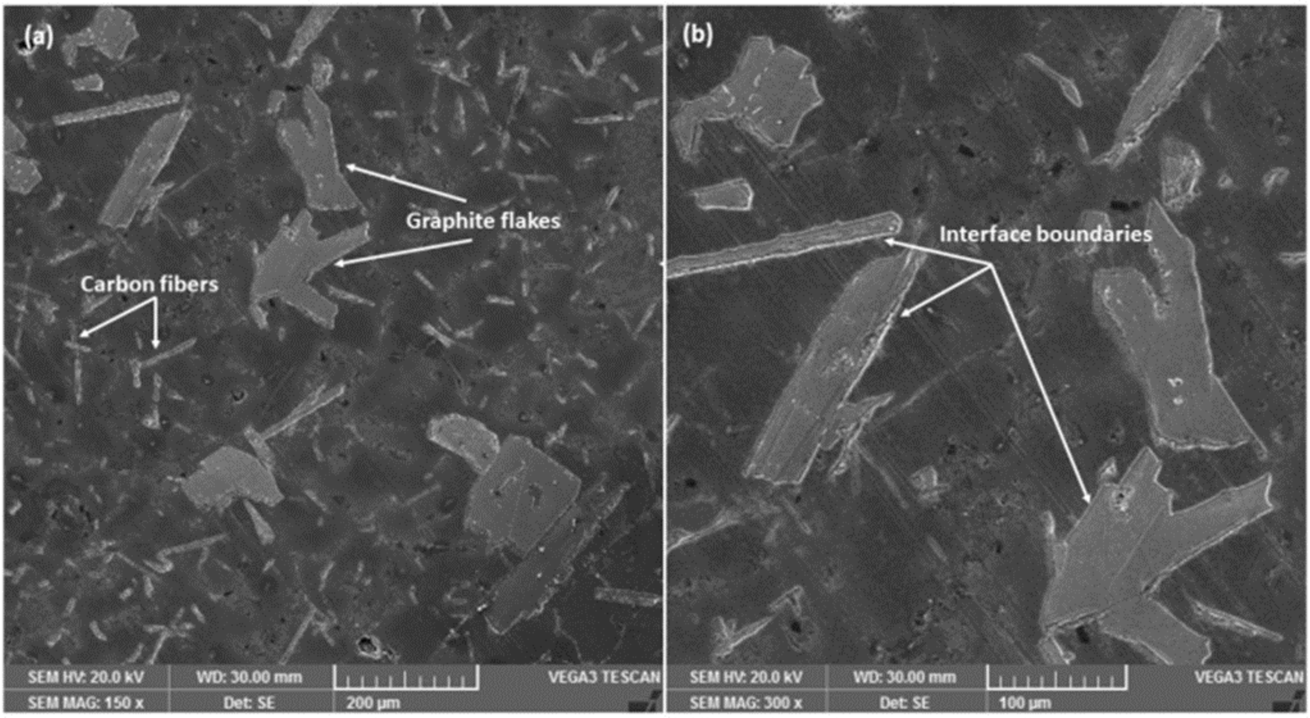

Figure 5. SEM micrographs showing typical dispersion of the particulate phases (a) 150× (b) 300×

As the concentration of the particulate phase in the metal matrix increases, the friction sites also increase in number and ultimately the damping ratio increases. Also, from Fig. 5b it can be anticipated that due to the large size of the particulate phase they are not very strongly bonded with the metal matrix. This is also evident from the values of the natural frequencies calculated at 2% and 3% concentration in this work (see Table 1).

The drop in natural frequency at higher concentrations can be attributed to large particulate size and their weak interfacial bonding with the metal matrix. This effect can also cause increase in the damping ability of the material. As shown in the schematic diagram (see Fig. 6) during the applied vibrations the loosely bonded particulate phases (i.e. graphite flakes and carbon fibers) can slip and slide linearly as well in angular manner and starts to rub against the background metal matrix grains and possibly grain boundaries and/or dendrite structures present in cast aluminums [27] which can increase the dissipation effects, ultimately causing the damping ability of the nanocomposite to increase.

Therefore, it can be claimed that large size particulate phase can cause increase in damping due to weak interfacial bonding and trans-granular frictional effect with the background metal matrix.

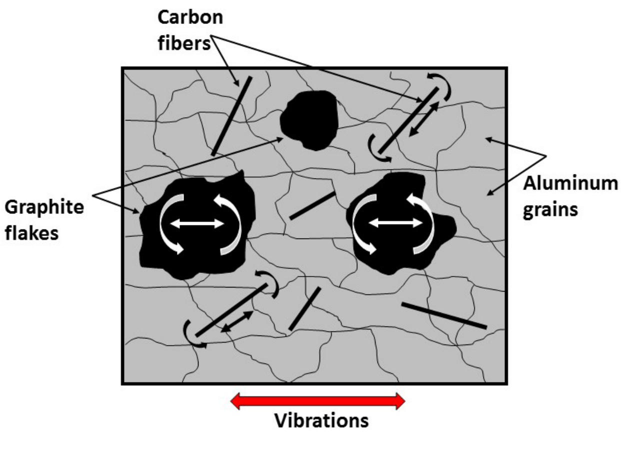

Figure 6. (color online) Schematic of the damping mechanism taking place in the aluminum matrix. Curved arrows indicate angular slip/slide while straight arrows indicate linear slip/slide of the particulate phase over the aluminum grains during applied external excitation.

This increase in damping is therefore accompanied by the drop in the natural frequency of the tested samples. However, it can be noticed from

Table 1 that the drop in the natural frequency is only 13% as compared to 117% increase in the damping ratio of the as-synthesized nanocomposite material.

4. CONCLUSIONS

Aluminum nanocomposite using ensemble of two morphologically different carbon particulate phases was successfully synthesized using cost effective and scalable process of stir casting for enhancing the damping ability of the material. The increase in damping of aluminum nanocomposite material using two morphologically different particulate phases was achieved and studied for the first time. The damping ratio was predicted by conducting simple set of experiments based on the concept of unidirectional free vibrations. The damping ratio of the as-synthesized nanocomposite material was found to increase linearly with the concentration of the particulate phase. Precisely, the largest value of the damping ratio in this work was found to be 0.0039 at 3% concentration of the particulate phase. This value of damping ratio was 117% higher than the damping ratio of the pristine aluminum used in this work. Also, if compared with the damping ratio of pure aluminum this indicates an increase of almost 732%. The mechanism of increase damping is attributed to the trans-granular frictional effect and weak interfacial bonding of particulate phase with the metal matrix. The as-synthesized aluminum nanocomposite shows favorable damping characteristics which can be potentially utilized in light weight automobiles, aerospace and marine applications.

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