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Short Communication

Evaluation of the damping behaviour of Al-Mg-Si alloy based composites reinforced with steel, steel and graphite, and silicon carbide particulates

Kenneth Kanayo Alaneme [a,b,*], Adetomilola Victoria Fajemisin [a,b]

[a] Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure PMB 704, Nigeria

[b] African Materials Science and Engineering Network (AMSEN) – A Carnegie- IAS Regional Initiative in Science and Education Network, South Africa

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ABSTRACT

Metallic materials known for their good toughness and ductility are now contemplated as replacements to the inherently brittle ceramics which are typically used as reinforcements in aluminium based composites (AMCs), because of the growing structural applications of AMCs. However, the good damping properties offered by the ceramic reinforced AMCs have not been well studied in their metallic reinforced counterparts. The present study investigates and compares the damping behaviour of Al-Mg-Si alloy based composites reinforced with 6 and 8 wt% steel particles to that reinforced with a hybrid mix of 6 wt% steel and 2 wt% graphite, and 8 wt% SiC particles. The aluminium based composites were produced using stir casting process and the microstructures characterised with backscattered electron mode imaging. A dynamic mechanical analyser was used to evaluate the damping properties of the composites produced. The results show that the storage modulus of the composites containing 8 and 6 wt% steel particles were higher than that of the other composite grades with the 8 wt% SiC reinforced composite composition recording the lowest value. The Aluminium based composite containing 8 wt% steel particles also had the highest loss modulus over the test temperature range (70–250 °C) but because of its relatively higher storage modulus, it did not record the best damping capacity which was obtained with the 8 wt% SiC reinforced composite. The effect of the test frequencies 5 Hz and 10 Hz on the damping properties was on the average marginal, while significant variation in damping properties with test temperature were observed in the study.

1. Introduction

Aluminium based composites (AMCs) reinforced with metallic materials have recently being the subject of interest in the composites community because of the increasing use of AMCs as structural materials in several applications [1,10]. In most load and stress bearing applications, a good combination of strength, low density and high toughness are required for effective service reliability. Ceramic reinforced AMCs which are commercially the most available AMCs, have limited toughness and ductility to adequately meet the expected functionality and safety requirements for some applications. This is on account of the inherent brittle nature of ceramic reinforcements [11]; and the relatively low wettability between ceramics and metallic melts, which results in poor interface bonding and strength [2]. Consequently, metals which are intrinsically tough and possess good wettability with aluminium, have been subject of investigations as potential replacement for ceramic based reinforcements in AMCs [17,21].

Presently, Ni and Fe based alloys are the most researched metallic reinforcements for AMCs [12,15], and Fe based alloys curiously has been of interest particularly, because of the relatively low cost of procurement and ready availability [17]. Viala et al. [23] reported that the metallurgical bonding between Al-Si alloy inserted with cast iron is continuous; consequently, the composite possesses good thermal conductivity and mechanical properties. Fathy et al. (2015) established that improved compressive strength and hardness are obtained in AMCs reinforced with Fe powder, due to the grain refinement engendered by the Fe powder on the composite. This is coupled with the formation of $Al_{13}Fe_4$ intermetallic compound which contributes to the strengthening of the composite. Selvakumar et al. [17] reported that when stainless steel particles are incorporated in AA 6082 via friction stir processing, the tensile strength of the composites are enhanced without sacrificing ductility. This was reflected in the fracture surface topography which consisted primarily of a network of well developed dimples.

* Corresponding author at: Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure PMB 704, Nigeria.

E-mail address: kalanemek@yahoo.co.uk (K.K. Alaneme).

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Several other studies have also considered the mechanical properties – fracture toughness and ductility, and wear behaviour of AMCs reinforced with steel chips/particles and the performance have also been reported to be superior to that of SiC reinforced AMCs [8,29].

Despite the promise which these Fe based alloy/steel reinforced AMCs hold for improved mechanical and structural performance, there have been very few investigations on their damping properties. It is common in most structural applications for materials to be subjected to structural or mechanical vibrations. Proper function of the material will be partly dependent on its ability to absorb and dissipate vibration energies, which is a function of the materials damping capacity [22]. Strengthening and damping capacity is reported to be hardly compatible in conventional monolithic alloys, as both require structural defects for activation and enhancement. Studies are available which have reported on the damping behaviour of AMCs reinforced with ceramic materials. Lavernia et al. [13] reported that significant improvement in specific strength and stiffness was achieved with the addition of SiC or Al_2O_3 to AMCs, but no consistency was observed with respect to damping capacity improvement or impoverishment. [24–25] reported that graphite addition improves the damping capacity of AMCs, and this can be increased further with increase in the volume fraction of the graphite reinforcement; however, a corresponding decrease in storage modulus with increase in the volume fraction was observed. Rohatgi et al. [26] also reported improved damping capacity in Al alloy composites reinforced graphite with increase in the volume percent of graphite within the range studied. However, the same trend was not observed in SiC reinforced Al alloy composite which did not show any noticeable improvements in damping capacity. Fly ash reinforced AMCs in independent studies, have been observed to exhibit improved damping capacity compared to the monolithic Al alloy [27,28]. Silva Prasad et al. [19] studied the damping behaviour of selected AMC reinforcement powders, namely: rice husk ash (RHA), fly ash, Fe powder and SiC. It was observed that RHA had the lowest damping capacity of all the reinforcement powders studied, and the damping properties of all the powders were influenced by test frequency and temperature.

It can be inferred from the above literature surveyed that the damping behaviour of AMCs reinforced with metallic materials is yet to receive much attention from researchers. In the present study, steel particles reinforced solely with Al, and in combination with graphite is assessed with that reinforced with SiC to ascertain their damping properties. The steel reinforced-, and steel+ graphite reinforced- composites have been reported in a recent study to possess superior combination of strength, toughness and wear resistance compared to the composite reinforced with SiC [29]. But their damping behaviour which will be instructive for their selection as structural material has not been considered.

2. Materials and methods

2.1. Materials

Al-Mg-Si alloy was utilised as metal matrix for the development of the Al based composites; while steel, graphite and silicon carbide were selected as reinforcements. The chemical composition of the Aluminium alloy matrix used in the research is presented in Table 1. The steel particles were derived from ball milling of steel chips obtained from boring of medium carbon steel. The steel particles obtained were of size 100 μm passing, while the graphite and silicon carbide were analytical pure grades of average particles size of 30 μm, sourced from licenced local vendors of chemicals and industrial materials.

Table 1
Chemical Composition of Aluminium based Alloy.

Element	Al	Si	Fe	Mn	Mg	Zn	Cr	Ti
Composition	98.7	0.45	0.10	0.02	0.48	0.02	0.01	0.01

2.2. Composite production

The Al-Mg-Si alloy based composites were produced using double stir casting procedure in accordance with Alaneme and Aluko [4]. Four different compositions of the composites were processed – two compositions having 6 and 8 wt% steel particles as reinforcement; and the other two compositions, consisting of 6 wt% steel + 2 wt% graphite particles, and 8 wt% SiC particles. Before the melting process, the reinforcements were preheated separately at 250 °C for 15–20 min to eliminate dampness and reduce potential temperature gradient which arise when a cold material is added to the melt. The preheating also helps improve wettability between the melt and the reinforcements. The al-mg-Si alloy was charged into a crucible furnace and melted completely at a temperature of 750 °C ± 30 °C. Thereafter, the melt was cooled to a semi-solid state maintained at 600 °C. The reinforcements were added at this stage, and manual stirring was performed for 5–10 min. The melt – reinforcement mix were superheated to 780 °C ± 30 °C, afterwards and mechanical stirring was then performed using a mechanical stirrer operated at a stirring speed of 400 rpm for 10 min. The molten composites were then cast into metallic moulds to facilitate fast cooling rates, which help in grain refinement. The composite compositions produced and the sample designations are presented in Table 2.

2.3. Structural characterization

A Carl Zeiss Sigma field emission scanning electron microscope (FE-SEM) was used the microstructural characterization of the Al-Mg-Si alloy based composites. Back scattered electron (BSE) mode imaging was used for the microstructural analysis of the composites. The samples for the examination were metallographically prepared following standard procedures. The samples were etched using Keller's reagent (5 ml – nitric acid, 3 ml – hydrochloric acid, 2 ml – hydrofluoric acid, 190 ml – distilled water), swabbing for 10–20 s, after which microstructural analysis was performed.

2.4. Damping behaviour

The damping capacity measurements were performed on a Dynamic Mechanical Analyzer, using three-point bending mode in accordance with ASTME756-05 (2010) [5] standard. Rectangular bar samples with dimensions of 40 mm × 5 mm × 0.9 mm^3 were prepared for the damping capacity test. For the assessment of temperature dependent damping behaviour of the composites, the test was performed using a strain amplitude (ε) of 15 μm, vibration frequencies (f) of 5 and 10 Hz, temperature range (t) 30 °C to 250 °C, and heating rate (T′) of 5 °C/min. The storage modulus (dynamic modulus) (E') and loss modulus (E'')were determined from the test,

Table 2
Sample Designation and Composite Compositions.

Sample designation	Composite composition
AA/6Sp	Al-Mg-Si alloy + 6 wt% steel particles
AA/8Sp	Al-Mg-Si alloy + 8 wt% steel particles
AA/6Sp + 2Cg	Al-Mg-Si alloy + 6 wt% steel + 2 wt% graphite particles
AA/8SiC	Al-Mg-Si alloy + 8 wt% SiC

Fig. 1. The Dynamic Mechanical Analyzer and Testing Set up.

and the damping capacity measured from the loss tangent (tan δ), using the relation [19]:

$$tan\delta = \frac{E''}{E'} \quad (2.1)$$

The Dynamic Mechanical Analyzer and the entire test set up used for the damping test is presented in Fig. 1.

3. Results and discussion

3.1. Microstructures

Representative micrographs of the composites produced are presented in Fig. 2. The microstructures show evidence of particles

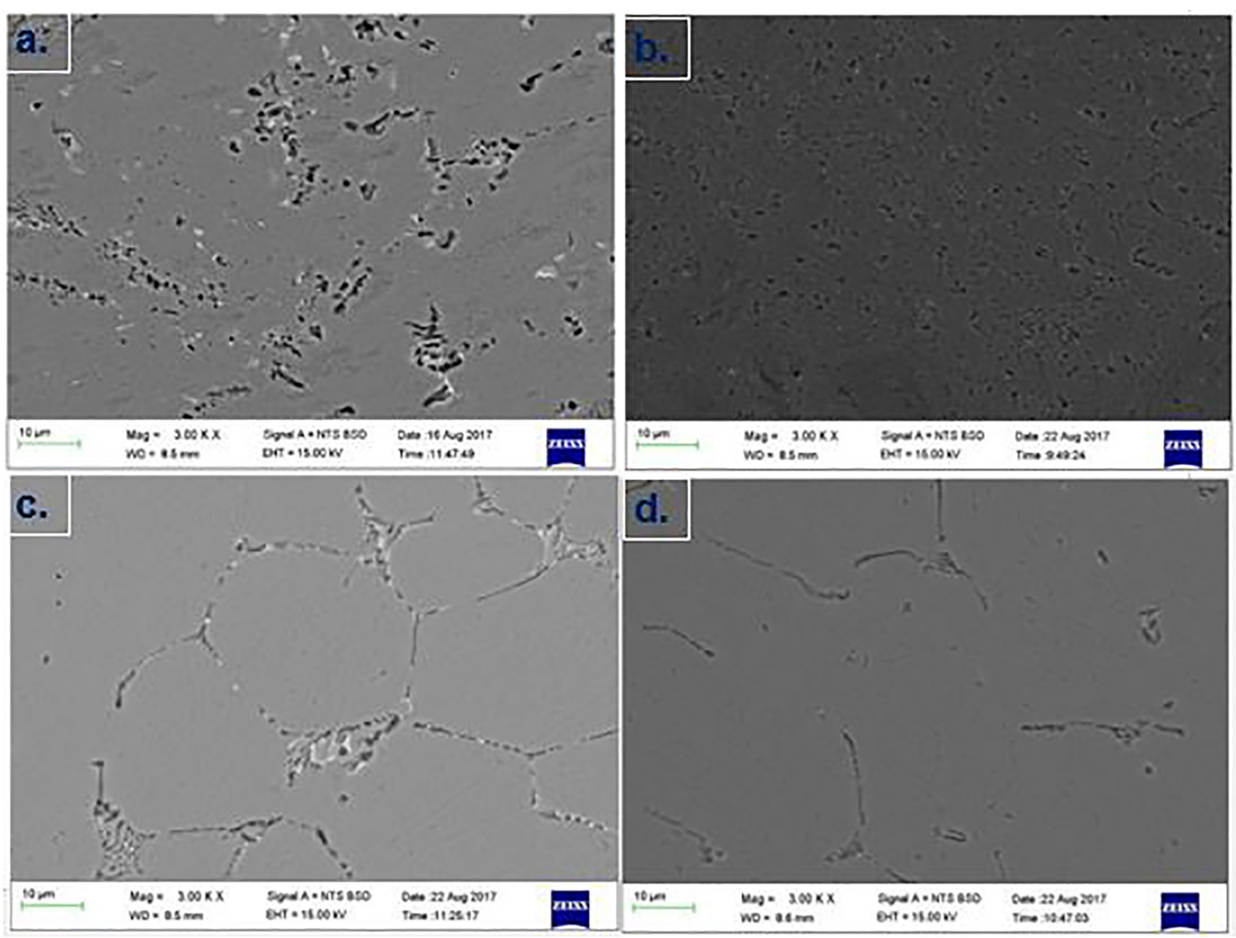

Fig. 2. Representative SEM micrographs of the Al-Mg-Si based composites reinforced with (a) 6 wt% steel particles, (b) 8 wt% steel particles, (c) 6 wt% steel and 2 wt% graphite particles, and (d) 8 wt% SiC particles.

dispersion in the Al-Mg-Si alloy matrix. The 8 wt% steel particles reinforced Al-Mg-Si alloy based composite (Fig. 2b), is observed to have the best dispersion of the reinforcement particles of all the composites studied. The grain boundaries of all the composites with the exception of the Al-Mg-Si alloy based composition reinforced with 6 wt% steel + 2 wt% graphite (Fig. 2c) were not well delineated, which makes grain size estimation a bit difficult. This is however a feature observed in several other Al based composites reported in literature [3,10,16].

3.2. Damping behaviour

The results of the damping test carried out on the composites are presented in Figs. 3–5 and Tables 3–5.

Fig. 3 shows the storage modulus of the composites produced. It is observed that the test frequencies of 5 and 10 Hz had little effect on the storage modulus of the composites. This clearly analysed in Table 3, where it is observed that not more than 200 MPa difference in storage modulus was recorded for any of the composite compositions tested at 5 and 10 Hz frequency both at 30 °C and 250 °C. For both test frequencies (5 and 10 Hz), it is observed that the Al based composite containing 8 wt% steel particles had the highest storage modulus over the temperature range of 30–250 °C, while the 8 wt% SiC reinforced Al based composite had the least storage modulus. For both test frequencies, and the temperature range of 30–250 °C, the storage modulus of the 8 wt% reinforced Al based composite was averagely 15, 36, and 58% higher than that of the 6 wt% steel particles reinforced-, 6 wt% steel particles + 2 wt % graphite reinforced-, and 8 wt% SiC reinforced- Al based composites, respectively. The implication is that the steel particles containing composite compositions have higher energy absorption capacity compared to that containing 8 wt% SiC. It is also observed that for all the composite compositions and test frequencies, the storage modulus decreases with increase in temperature. The decrease in storage modulus with increase in temperature is attributed to the decrease in the dynamic stiffness of the composites with temperature [19]. The storage modulus is a measure of the ability of a material to store deformation or mechanical energy in an elastic manner when subjected to a cyclic load. The elastic properties of a material are strongly linked to the bond strength in the material [7]. At higher temperatures, there is generally lower bond strength in materials due to the weakening of the bonding between atoms in solids. In the present case, the decrease in the storage modulus with temperature may be linked to the weakening of the matrix/reinforcement bonding which contributes to lower stiffness of the composites.

The loss modulus of the composites are presented in Fig. 4. It is observed that the same trend of variation of loss modulus with temperature is followed by the composites both at 5 Hz and 10 Hz test frequencies. Table 4 shows that at 30 °C, the loss modulus was slightly higher for all composite compositions tested at 10 Hz in comparison to those tested at 5 Hz, with the only exception being the composite composition containing 6 wt% steel particles. The reverse trend is observed at 250 °C, where it is noticed that all the composite compositions had slightly lower loss modulus at test frequency of 10 Hz compared to 5 Hz, again the exception was the composite composition containing 6 wt% steel particles. The effect of composite composition and test temperature on the loss modulus was however more distinct and consistent than that of test frequency. It is observed from Fig. 4 that for both test frequencies,

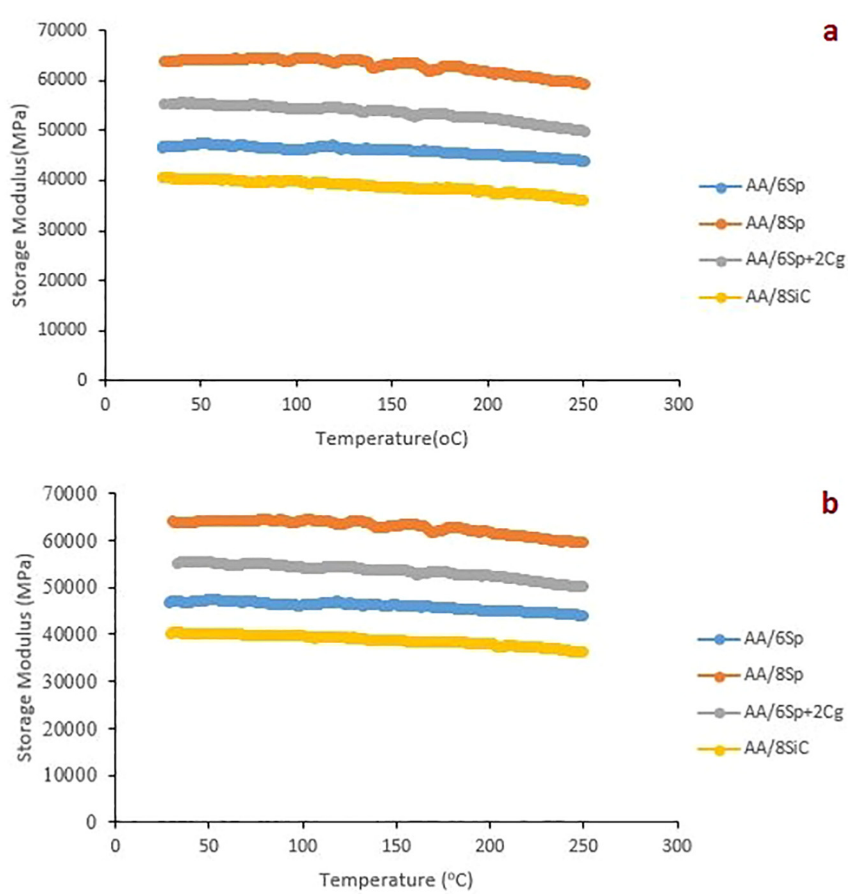

Fig. 3. Storage modulus as function of temperature for composites tested at (a) 5 Hz, and (b) 10 Hz.

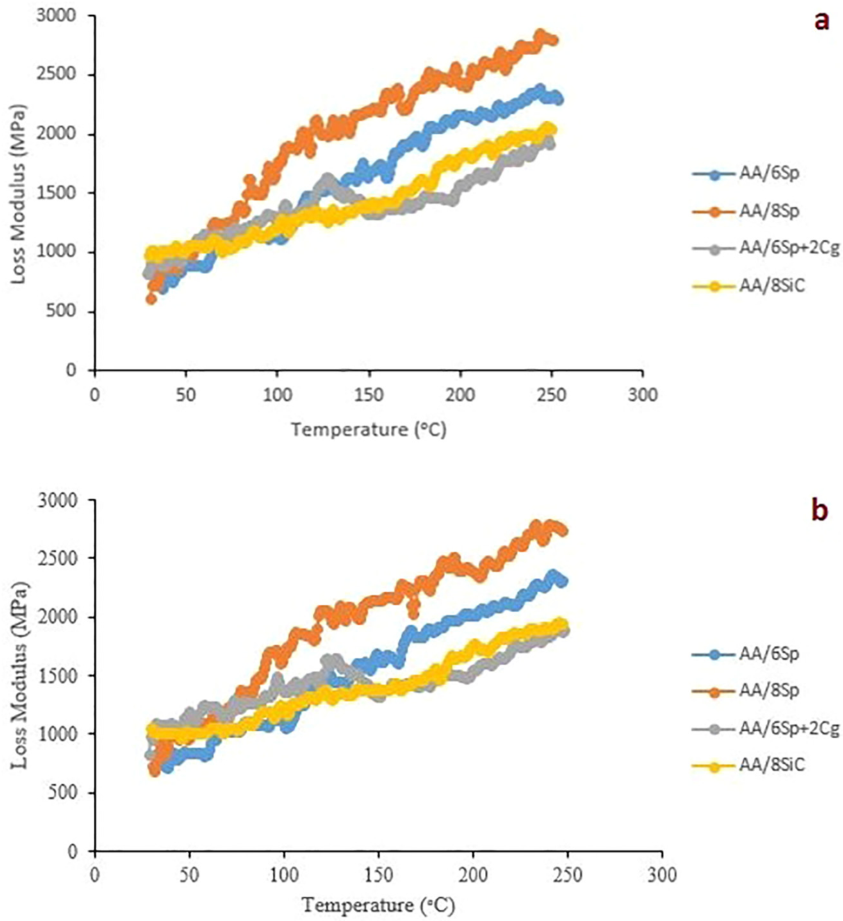

Fig. 4. Loss modulus as function of temperature for composites tested (a) 5 Hz, and (b) 10 Hz.

there is a significant increase in loss modulus with increase in test temperature. Percent increase of between 200 and 465% was observed for 5 Hz while between 190 and 400% increases observed for 10 Hz test frequency, when the test temperature was increased from 30 °C to 250 °C. The highest loss modulus was observed in the composite composition containing 8 wt% steel particles, followed by the composition with 6 wt% steel particles. The general increase in loss modulus with increase in temperature can be linked to the greater capacity for particle movement and particle/grain boundary sliding at higher temperatures, which is reported to facilitate greater energy dissipation in AMCs [18].

The damping capacity of the composites are presented in Fig. 5. As with the case of the loss modulus (Fig. 4, it is observed that similar variation in damping capacity with temperature is observed to be exhibited by the composites irrespective of the test frequency. Table 5 show that at 30 °C the damping capacity of all the composites tested at 10 Hz were slightly higher than that for 5 Hz, but when tested at 250 °C, the reverse effect is observed as the damping capacity values at 5 Hz were slightly higher than that at 10 Hz. The damping capacity of the composites are generally observed to increase with increase in temperature – damping capacity increase of over 4 times that observed at 30 °C, is obtained when the composites are tested at 250 °C. This significant increase in damping capacity with increase in temperature, is ascribed to the relatively improved particle movement with temperature, and higher capacity for boundary and interface sliding with increased temperature [14].

Furthermore, it is observed from Table 5 that at room temperature the 8 wt% SiC reinforced composite had the highest damping capacity compared to the other composite compositions. This may be attributed to two principal factors: the intrinsic damping properties of the matrix and reinforcements, and dislocation damping which is facilitated by a greater difference in the coefficient of thermal expansion (CTE) of the matrix and the reinforcement. Silva Prasad et al. [19] has reported that the damping capacity of SiC powder is higher than that of Fe, so based on the rule of mixture, it is expected that the damping capacity of the SiC reinforced Al based composite will be higher than that containing steel, as long as the same weight fraction of the reinforcement is maintained. Silva Prasad and Shoba [18] reported that a greater amount of dislocations are generated when there is a significant difference in the coefficient of thermal expansion between the matrix and the reinforcement. This is also dependent on the volume fraction of the reinforcement. In the present case, the CTE difference between Al-Mg-Si alloy (21.4×10^{-6}/°C) and the steel particles (11.7×10^{-6}/°C) (~2:1) is not as large as that of Al-Mg-Si alloy (21.4×10^{-6}/°C) and SiC (4.3×10^{-6}/°C) (~5:1). Thus for the same volume fraction of reinforcement, there are likely more thermal stresses generated at the matrix/SiC particle interfaces (which facilitates more dislocations generation) compared to the case of the matrix/steel particles interfaces. Table 6 presents the CTE and dislocation densities generated for the composites studied, computed using the relation:

$$\alpha_c = \alpha_r V_r + \alpha_m V_m \tag{3.1}$$

$$\alpha_c = (\alpha_{steel} V_{steel} + \alpha_{graphite} V_{graphite}) + \alpha_m V_m (\text{for the hybrid composite}) \tag{3.2}$$

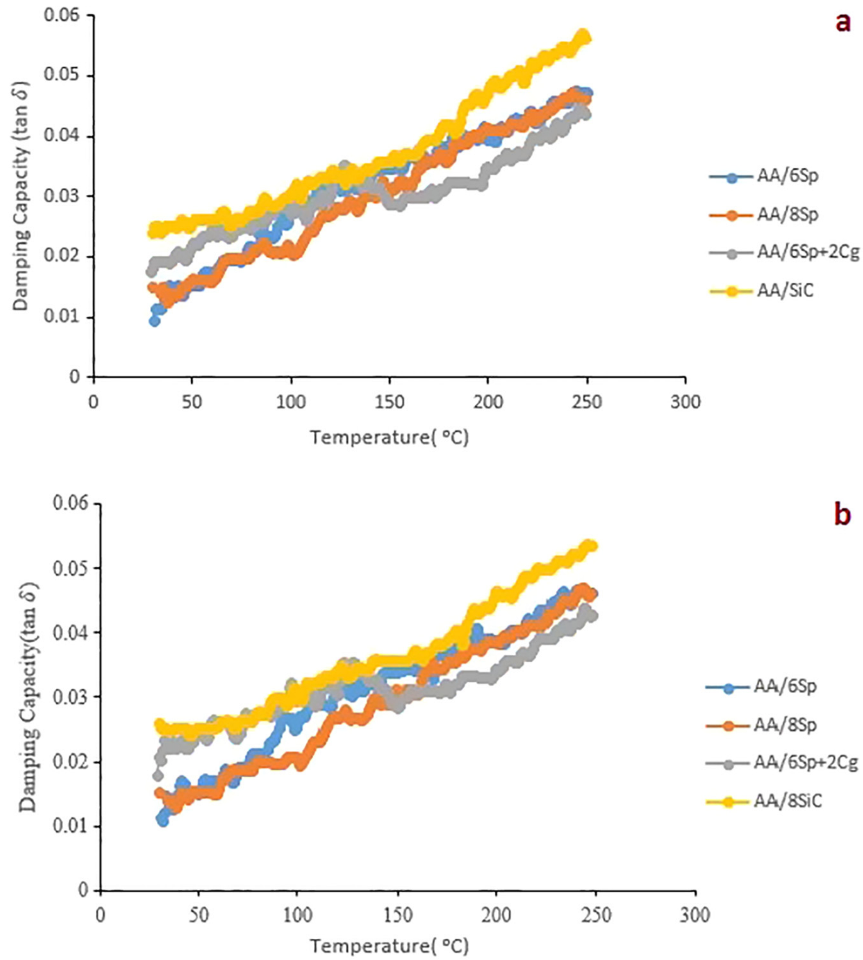

Fig. 5. Damping Capacity as function of temperature for composites tested at (a) 5 Hz, and (b) 10 Hz.

Table 3
Storage Modulus of the Al-Mg-Si Based Composites at 30 °C and 250 °C for Test Frequencies of 5 and 10 Hz.

Composite Composition	Storage modulus (MPa) @ 30 °C		Storage modulus (MPa) @ 250 °C	
	5 Hz	10 Hz	5 Hz	10 Hz
AA/6 Sp	46618.91	46635.63	43934.31	43975.85
AA/8 Sp	63901.76	64073.53	59410.10	59535.49
AA/6Sp + 2Cg	55291.52	55242.87	49913.41	50095.46
AA/ 8SiC	40483.66	40298.98	36118.84	36186.12

Table 4
Loss Modulus of the Al-Mg-Si Based Composites at 30 °C and 250 °C for Test Frequencies of 5 and 10 Hz.

Composite composition	Loss Modulus (MPa) @ 30 °C		Loss modulus (MPa) @ 250 °C	
	5 Hz	10 Hz	5 Hz	10 Hz
AA/6Sp	818.69	762.11	2285.38	2308.84
AAi/8Sp	602.08	687.75	2796.65	2740.05
AA/6Sp + 2Cg	818.57	827.06	1913.18	1905.82
AA/8SiC	972.35	1018.70	2029.48	1938.39

Table 5
Damping Capacity of the Al-Mg-Si Based Composites at 30 °C and 250 °C for Test Frequencies of 5 and 10 Hz.

Composite Composition	Damping capacity (tan δ) @ 30 °C		Damping capacity (tan δ) @ 250 °C	
	5 Hz	10 Hz	5 Hz	10 Hz
AA/6Sp	0.0094	0.0108	0.0473	0.0471
AA/8Sp	0.0148	0.0150	0.0460	0.0455
AA/6Sp + 2Cg	0.0176	0.0177	0.0442	0.0427
AA/8SiC	0.0240	0.0251	0.0562	0.0534

Table 6
Estimated Dislocation Density and Coefficient of Thermal Expansion of the Al-Mg-Si Composites.

Composite composition	Estimated dislocation density, ρ(m^{-2})	CTE, α(/°C)
AA/6Sp	1.75×10^{11}	20.82×10^{-6}
AA/8Sp	2.38×10^{11}	20.62×10^{-6}
AA/6Sp + 2Cg	3.7×10^{11}	20.40×10^{-6}
AA/8SiC	13.9×10^{11}	20.03×10^{-6}

$$\rho = \frac{B\varepsilon V_r}{bd(1-V_r)} \text{(Shoba etal.., 2016)} \quad (3.3)$$

$$\rho = \frac{B\varepsilon(V_{steel} + V_{graphite})}{bd(1-(V_{steel+V_{graphite}})} \text{(for the hybrid composite)} \quad (3.4)$$

$$\text{and} \epsilon = (\alpha_m - \alpha_r)\Delta T \quad (3.5)$$

where α_c is the thermal coefficient of expansion of the composite, α_r is the thermal coefficient of expansion of the reinforcement, α_m is the thermal coefficient of expansion of the matrix, V_r is the volume fraction of the reinforcement, V_m is the volume fraction of the matrix, α_{steel} is the thermal coefficient of expansion of the steel particles, $\alpha_{graphite}$ is the thermal coefficient of expansion of the graphite particles, V_{steel} is the volume fraction of the steel particles, V_{steel} is the volume fraction of the steel particles, d is the reinforcement particle size, ε is the thermal mismatch strain, b is the burgers vector of Al = 0.32 nm [20], B is a constant of magnitude 12 [6], while ΔT is temperature difference.

It is noted that there is an inverse relation between the dislocation density generated in the composites and the CTE values; and can be confirmed that the 8 wt% SiC reinforced Al-Mg-Si alloy based composite had the highest dislocation density of all the composites produced. Silva Prasad and Shoba [18] reported that large difference in CTE between a metal matrix and the reinforcement can result in temperature gradients which can induce thermal stresses in the metal matrix (Al-Mg-Si alloy in the present case). The thermal stresses can be partially released by the generation of dislocations, mostly at the particle/matrix interface. The dislocations based on the Granato-Lucke mechanism [9], can behave like an elastic string when pinned by particles (Fig. 6). The string – type vibrations of the dislocations when a cyclic load is applied on them is accompanied with the dissipation of energy to the environment. Thus the mechanism of energy dissipation is by the string-like vibration of the dislocations pinned by particles under the influence of cyclic/sinusoidal loading. If the applied load is increased, there is a likelihood for the pinned dislocations to meander away (bow out) at some weak pinning sites, and consequently, facilitate the motion of the dislocations which contributes to increase in the materials energy dissipation capacity.

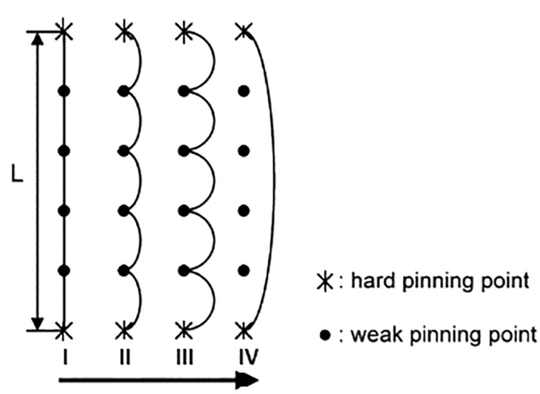

Fig. 6. Idealized schematic model of Granato-Lucke mechanism of dislocation damping.

4. Conclusion

The damping behaviour of Aluminium based composites reinforced with 6 and 8 wt% steel particles has been compared with that reinforced with a hybrid mix of 6 wt% steel and 2 wt% graphite, and 8 wt% SiC particles. The results show that:

- the storage modulus of the composites containing 8 and 6 wt% steel particles were higher than that of the other composite grades with the 8 wt% SiC reinforced composite composition recording the least value. Also the storage modulus decreased generally with temperature, and was marginally influenced by the test frequencies of 5 and 10 Hz.
- The Aluminium based composite containing 8 wt% steel particles had the highest loss modulus over the test temperature range (70–250 °C). Also there was significant increase in the loss modulus with increase in test temperature.
- The inherent damping capacity of SiC, and a greater difference in coefficient of thermal expansion between the Al alloy matrix and the 8 wt% SiC particles; were found to contribute to the higher damping capacity exhibited by this composite in comparison to steel reinforced composite compositions produced. The damping capacity of the composites, as with loss modulus, generally increased with increase in the test temperature.
- effect of the test frequencies 5 Hz and 10 Hz on the damping properties was on the average marginal, while significant variation in damping properties with test temperature were observed in the study.

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