1. Introduction

Even though bulk metals and alloys are economically high-performance materials in general, new types of metallic materials have been actively investigated to go beyond boundaries of science for more optimized applications. It is known that metals and alloys lose their stiffness at high temperatures due to increased atomic movements. More sustainable metallic materials are desirable to be employed in harsh environments. This unique demand could be solved by using the nature of composite materials. The resulting materials after metals and alloys are combined with another material are called metal matrix composites (MMC), which are attractive metallic materials due to their advantages over conventional metals and alloys [1]. These advantages include high specific modulus, better heat conductivity owing to ceramic particles and being the only way to introduce carbide and oxide into some metals where useful [2]. Thus, MMCs have found numerous applications in industries, such as marine, defense, automobile and aerospace [1,3].

On the other hand, drawbacks such as failures due to high-stress concentration at sharp transitions of matrix/reinforcement interfaces limit their potentials in broader practical applications. A solution proposed to this problem is the concept of functionally graded materials (FGMs). FGMs were initially invented to be used in heat-resistant applications [4]. But, they have been attracted by many industries due to their unusual changing and alterable properties, such as elastic modulus, strength and ductility by location owing to their continuously changing chemical composition profiles [5,6].

Among MMCs and FGMs, Al/SiC metal matrix composites are attractive materials considering their low cost and high specific strength [1,7]. It is known that Al/SiC MMCs suffer from low fracture resistance [7]. One of the most powerful tools to achieve better fracture resistance is fabricating them in an FGM form. It was reported that Al/SiC FGMs are more resistant to fracture compared to their MMC counterparts [8]. On the other hand, FGMs have attractive mechanical and thermal strength, which make them promising in structural applications.

Mechanical properties of Al/SiC MMCs and FGMs have been intensively investigated until now [1,7,9]. One of the underrated properties of MMCs and FGMs is the damping capacity. This property is useful in practical applications such as semiconductor equipment, shock waving in seismic structures in addition to vibration and noise reduction in aerospace structures [2], since structures might experience high vibration and consequently high noise under dynamic loading. On the other hand, the use of damper materials might eliminate the need of complicated systems for energy absorbing. Thus, low-density composites that have high damping capacity would be of interest for the aforementioned industrial needs. Al alloys have low density and low damping capacity [10]. Thus, Al-matrix composites might be promising candidates for lightweight damping materials. Al alloys reinforced by ceramic particles have shown acceptable damping capacities [11,12]. SiC has been one of the most widely used reinforcement in addition to Al2O3 [10]. Damping capacities of Al/SiC composites generally increased with vibrating frequency and particle size [13] due to increased plastic damping. On the other hand, it was reported that the dynamic modulus was inversely proportional to SiC particle size [13] owing to reduced dislocation density. General damping mechanisms for
MMC are proposed to be summation of intrinsic damping contributions of metal matrix and reinforcing particles in addition to damping of matrix/particle interfaces [2]. The damping mechanisms of 6061 Al/SiC MMCs were revealed to be dislocation damping and interface damping at low temperatures. On the other hand, damping mechanisms were grain boundary damping in addition to interface damping at high sample temperatures [2].

Damping capacity is directly related to internal friction of a material. In MMCs, the internal friction might stem from many factors including dislocations generated due to thermal mismatch between matrix and reinforcements, friction at interface of matrix and reinforcements in addition to friction due to interactions of the reinforcements and obstacles, such as second phases, grain boundaries, dislocations, etc., in the microstructure [14–16].

Studies investigating and comparing damping behavior of both MMCs and FGMs are limited. Thus, in this work, damping capacity and storage moduli of Al/SiC MMCs and FGMs were investigated through a dynamic mechanical analyzer at various loading frequencies ranging 1 to 30 Hz. Damping capacities and storage moduli were compared as functions of composite type and loading frequencies.

2. Experimental procedure

The MMC composites were produced by a powder stacking-hot pressing method using Al6061 and SiC powders in nominal compositions of 70% Al and 30% SiC. The chemical composition of the starting Al6061 (Alfa Aesar product number: 43,332) powders is shown in Table 1. Average particle diameter of Al spherical powders was 10μm, where the average powder diameter of spherical SiC powders was 44μm. The metal and ceramic powders were mechanically blended for 3 hours to obtain a homogeneous mixture followed by pouring the mixture into a sintering mold. The sintering process was conducted at 600°C under 100 MPa for 90 min. A vacuum and argon atmosphere were used to prevent oxidation during sintering. Figure 1 shows the production process of the Al/SiC metal-matrix and functionally graded composites by powder stacking hot pressing technique.

An optical microscopy was used to investigate the distribution of Al and SiC powders through the

Table 1. Chemical composition of Al6061.

|   | Si   | Fe   | Cu   | Mn   | Mg   | Cr   | Zn   | Ti   | Al   |
|---|------|------|------|------|------|------|------|------|------|
| Al6061 | 0.4–0.8% | 0.7% | 0.15–0.4% | 0.15% | 0.8–1.2% | 0.04–0.35% | 0.25% | 0.15% | Balance |

![Figure 1](image-url). The production process of functionally graded composite by powder stacking hot pressing technique [17] (reprinted with kind permission of The EPJ Plus).
functional graded layers. The micro images were taken at 10x magnification.

Functionally graded materials were processed by using Al6061 metal and SiC ceramic powders in various compositions by a powder stacking-hot pressing method similar to MMCs. A layer-wise form used in processing is as follows:

\[
V_m = \left( \frac{k - 1}{nol - 1} \right)^n \quad \text{and} \quad V_{e} = V_{f}(1 - V_m)
\]

where nol is total layer number of related specimens, k is layer number (from 1 to 20), n is exponent value controlling the composition variation and Vf is volume fraction of ceramic constituent of the top layer.

Figure 2 shows the structure of FGMs used in this study. The top layer of FGMs had 40% Al-60% SiC while the bottom layer had 100%Al. The volume fraction of Al and SiC through the thickness of the manufactured specimen gradually changed as shown. Aydin et al. investigated ballistic deformation behavior of Al/SiC FGMs in metal-rich (n = 0,1), linear (n = 1) and ceramic-rich (n = 10) compositions and they found that FGMs in linear compositions showed improved mechanical responses [18]. Thus, FGMs in the linear compositions were selected to characterize in this study.

Curricular dies in diameter of 90 mm and in height of 16 mm were used in the sintering process. An electro discharge machine (EDM) was used to cut test samples in dimensions of 16 mm x 5 mm x 4 mm.

A Perkin Elmer Dynamic Mechanical Analyzer (DMA)-8000 was used to investigate the internal friction of the MMCs and FGMs with selected frequencies of 1, 10 and 30 Hz and 10°C/min heating-cooling rates. The materials are held in the DMA analyzer until starting (room temperature-RT) and end temperatures (400°C) are stabilized. The dynamic range of the analyzer is 0–600 Hz while the temperature range is 0–400°C. DMA is a technique where small deformation is applied to a material through cyclic forces. This way, it is possible to collect materials’ responses to any changes in temperature, stress and frequency. Oscillatory force applied to a sample at a certain frequency makes it possible to measure elastic properties and damping properties. In DMA analysis, stress or strain can be kept constant. In our experiments, displacement was kept constant and the samples were deformed via sinusoidal force generated by force motor. In the strain controlled tests, the analyzer moves the probe to reach the selected displacement while measuring the necessary stress. The forces required to deform materials with the certain amount are related to stiffness of materials. Displacement used in the single cantilever bending tests was 0,05 mm. Temperature of the materials was measured by thermocouples gently attached to the samples during experiments. The experimental measurements of the damping properties of the composites were conducted in accordance with ASTM D4065-12 [19].

3. Results and discussions

Figure 3 shows optical images of each FGM layers through the thickness of the material. The distribution of Al and SiC powders can be easily tracked on the images. Dark areas on the images show SiC particles, while white areas show Al matrix.

It is clear that the microstructures of each layer show uniform distribution of SiC ceramic particles. The bright matrix phase is a strong sign of nonporous microstructure. This shows an effective bonding between ceramic particles and Al matrix. On the other hand, in some images such as 20 and 21, there exist dark pits in some regions. These pits can be linked to ceramic particle pull-outs during the polishing process.

It is known that damping capacity is a sign of internal friction in a material’s microstructure. These internal frictions might stem from atomic level factors including vacancy diffusion, grain boundary motion, etc. In metal matrix composites, these frictions can be divided into internal frictions of matrix material, reinforcing particles and matrix/particle interfaces [2,12,13]. For quasi-static deformation, Hooke’s law assumes that the stress-strain graph follows the same path without delay (time-independent). But in case of high-frequency loadings, this is not the case and a hysteresis is observed between loading and unloading curves in mechanical tests (time-dependent) as shown in figure 4a. This hysteresis represents the dissipated energy/damping capacity during a loading cycle for materials [2]. In sinusoidal loading, this behavior is observed as an offset between stress and strain path as shown in figure 4b.

The two main properties extracted from DMA experiments are dynamic modulus (e.g. storage modulus) E’ and dynamic loss modulus (e.g. loss modulus) E”. The
storage modulus is closely related to material stiffness, which is often expressed as dynamic Young’s modulus. Thus, the storage modulus determines the stiffness of the material. It is also related to energy storage of a material upon application of a load. On the other hand, loss modulus is regarded as the tendency of a material to dissipate energy. Thus, the loss modulus is linked to internal friction in a microstructure due to relaxation processes such as friction between in heterogeneities. Tan δ represents a relationship between $E'\delta$ and $E''\delta$ such as $\frac{E'}{E''}\delta$ [13] as shown in figure 4c. Thus, Tan δ is a factor that represents dissipated energy in DMA analysis.

Figure 5 shows Tan δ values of MMCs and FGMs as a function of temperature at various vibrating frequencies. Figure 5a shows the responses at 1 Hz. Tan δ reached to $30.4\times10^{-3}$ and $21.2\times10^{-3}$ in FGM and MMC, respectively. Figure 5b and 5c show the Tan δ values at 10 Hz and 30 Hz, respectively. Tan δ values of FGMs were $25.6\times10^{-3}$ and $18.8\times10^{-3}$ at vibrating frequencies of 10 and 30 Hz, respectively. On the other hand, Tan δ values of MMCs were $15.5\times10^{-3}$ and $10.4\times10^{-3}$ at frequencies of 10 and 30 Hz, respectively.

As stated above, the offset between stress and strain in sinusoidal loading is the sign of dissipated energy and is linked to the fact that localized arrangements of atoms and deformation process take time at dynamic loading. These atomic level frictions are small at low temperatures, while they are larger at high temperatures due to increased mobility [13]. Thus, Tan δ values in figure 5 increased with increasing sample temperatures, which is in good agreement with literature [2,13,20].

It is also clear that damping capacities of FGMs are larger compared to MMCs. This means that internal frictions in FGMs are larger compared to MMCs.

Table 2 shows the Tan δ values for MMCs and FGMs at vibrating frequencies of 1, 10 and 30 Hz. Comparing the two types of materials; the Tan δ values of FGMs were higher than MMCs. The Tan δ values were $30.4\times10^{-3}$ and $21.2\times10^{-3}$ at vibrating frequency of 1 Hz for FGM and MMC, respectively. Possible reasons for the difference
between the two materials could be the different microstructures and related frictions during testing.

Higher Tan δ in FGMs could be related to higher interface density compared to MMCs. Since Tan δ is an expression of internal friction in materials, if there are more interfaces in a microstructure, it is not surprising to observe more friction due to these interfaces and consequently higher Tan δ in FGMs.

On the other hand, it is evident that the Tan δ values of the two materials decreased with
Table 2. Tan δ values of MMC and FGM materials as a function of temperature at vibrating frequencies of 1, 10 and 30 Hz.

| Material type | Frequency (Hz) | MMC | FGM | MMC | FGM | MMC | FGM |
|---------------|---------------|-----|-----|-----|-----|-----|-----|
|                | 1 Hz           | 10 Hz | 30 Hz |     |     |     |     |
| Tan δ (x10⁻³) | 21.2           | 30.4 | 15.5 | 23.4| 9.8 | 19.2 |

Increasing frequencies. This result is in good agreement with the current literature on the damping energy dependence on vibrating frequency. The damping capacity decreases with increasing vibrating frequency in metallic materials such as monolithic alloys [20], MMCs [2] and shape memory alloys [21]. It is known that the damping capacity of a metallic material is directly related to the constituents of MMCs. Thus, as the amount of particulates in an MMC increases, the overall damping capacity is expected to increase. In MMCs, the addition of particulates into matrix material causes stress intensity and related plastic zones at the matrix/reinforcement interface in the microstructure. Based on the description of damping capacity, the plastic deformation is one of the main sources in increasing dissipated energy and consequently damping energy in metallic materials. Thus, the increase in the volume fraction of the plastic zone at the matrix/reinforcement interface is a strong sign of increased energy dissipation. The dissipated energy due to plastic zone is expressed as [22]:

\[ \tan \delta \approx \frac{f_{vp}G_\varepsilon f^{out}}{\pi \sigma_0^2} \]  

(2)

where \( f_{vp} \) is the volume fraction of plastic zone, \( G_\varepsilon \) is shear modulus of composite, \( \sigma_0 \) is alternating shear stress and \( \varepsilon \) is the corresponding strain. Based on the equation, it is clear that the dissipated energy is a direct function of volume fraction of plastic zone and strain.

The relation of frequency and strain can be expressed with the following equation, where strain rate is formulated as [23]:

\[ \varepsilon = 4\varepsilon_a \omega \]  

(3)

In the equation above, \( \varepsilon \) is strain rate, \( \varepsilon_a \) is strain amplitude and \( \omega \) is vibration frequency. So, the strain rate is directly related to vibrating frequency. On the other hand, in strain hardenable materials (e.g. Al), strain rate could be linked to flow stress such as [24]:

\[ \sigma_0 = K(\varepsilon)^\beta \]  

(4)

where \( K \) and \( \beta \) are material constants. Thus, an increase in frequency results in an increase in strain rate and consequently in flow stress. Based on the equation above, an increase in flow stress decreases dissipated energy. Then, this argument explains the decrease in the Tan \( \delta \) with increasing vibrating frequency as shown in Table 2.

However, there are studies, where Tan \( \delta \) increases with vibrating frequency such as in SiC and Al₂O₃ reinforced Al alloys [2] and RHA particles reinforced A356.2 alloy [25]. The main reason for the behavior was generally explained by the thermoelastic damping property of materials [2]. Based on Zener thermoelasticity theory, damping increases with increasing frequency if the frequencies are smaller than Zener relaxation frequency [26].

Figure 6 shows storage moduli of MMCs and FGMs as a function of temperature at various vibrating frequencies. Figures 6a, 6b and 6c show the relationships between storage moduli and temperature of MMCs and FGMs at vibrating frequencies of 1, 10 and 30 Hz, respectively. The storage modulus of FGMs at 1 Hz was 172 GPa at RT and decreased to 115 GPa as the temperature increased to 400°C. On the other hand, the storage modulus of MMCs at 1 Hz was 144 GPa at RT and decreased to 100 GPa as the sample temperature increased to 400°C. Similar tendencies were observed at other test frequencies of 10 and 30 Hz.

It is clear that the storage moduli of FGMs were higher compared to MMCs. Storage modulus is a sign of deformation energy that the material stores during loading. This means that storage modulus can be linked to elastic behavior (e.g. elastic modulus) of materials. Thus, higher storage modulus signifies stiffer behavior in materials. Since the FGMs have higher strength and stiffness compared to MMCs, higher storage modulus in FGMs compared to MMCs is an expected result.

On the other hand, storage moduli decreased with increasing temperature for both materials as in alloys [20,27] and metal matrix composites [13]. Since the storage modulus is closely related to elastic modulus, it is not surprising that the storage modulus decreased with increasing sample temperature. Due to increase in mobility of atoms, particles and interfaces in the microstructure with increasing temperature, a relaxation is observed. This makes the FGMs and MMCs softer at high temperatures. This fact is shown as decreased storage moduli in Figure 6.

Figure 7a shows the storage moduli for MMCs while Figure 7b shows the storage moduli for FGMs at vibrating frequencies of 1, 10 and 30 Hz.

It is clear that the storage modulus decreased with vibrating frequency for both materials. The storage modulus is almost not sensitive to vibrating frequency at low temperatures and the relationship is more sensible at high temperatures. It appears to be the effect of vibrating frequency on the storage modulus is less at lower temperatures.

Thus, the decrease in the storage modulus with frequency is larger at low frequency compared to higher frequencies, being independent of material type. More specifically, the decrease in the storage modulus of FGMs at 1 Hz as the temperature increased...
from RT to 400°C is 45 GPa. On the other hand, the decrease at 30 Hz is 35 GPa. This means that the materials are stiffer at higher frequencies as predicted [28]. This behavior can be explained by Arrhenius-type relaxation rate [28–30], such as:

$$V_r = V_{ro} \exp \left( -\frac{E_A}{KT} \right)$$  \hspace{1cm} (5)

where $V_r$ is relaxation rate, $V_{ro}$ is frequency factor, $E_A$ is the energy of activation, $K$ is Boltzmann constant, $T$ is temperature. Based on the equation, as the temperature increases, the relaxation rate $V_r$ increases and consequently relaxation time decreases. Shorter relaxation times result in larger phase lags and higher decrease in storage modulus at high temperatures. Thus, storage modulus of FGMs and MMCs are more sensitive to vibrating frequencies at high temperatures. On the other hand, since the storage modulus is closely related to stiffness of a material, it is not surprising that storage modulus decreases with increasing sample temperatures due to thermally activated relaxation mechanisms.

4. Conclusions

In this study, Al/SiC functionally graded and metal-matrix composites were investigated through dynamic
mechanical analyzer as a function of vibrating frequencies. Internal frictions were strongly dependent on material type and vibrating frequency. It was found that Tan δ reached to 30.4 × 10⁻³ and 21.2 × 10⁻³ in FGM and MMC, respectively, at vibrating frequency of 1 Hz. The damping capacity decreased as the frequency increased to 10 Hz and 30 Hz. Storage moduli were 172 GPa and 144 GPa for FGMs and MMCs, respectively, at 1 Hz. Similar to Tan δ, storage moduli of both materials were more sensitive to frequency change at higher temperatures. Storage moduli and damping capacities were observed to be higher in FGMs compared to MMCs.

Data availability
The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Disclosure statement
No potential conflict of interest was reported by the authors.

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