DYNAMIC MECHANICAL PROPERTIES OF PARTICULATE REINFORCED METAL-MATRIX COMPOSITES AT LOW TEMPERATURES

X. Jiang, L. Ouellet and D. Nikanpour

Advanced Materials and Thermal Group, Space Technologies,
Canadian Space Agency
6767 route de L'Aeroport, St-Hubert, Quebec J3Y 8Y9, Canada

SUMMARY: Dynamic mechanical properties, particularly the damping capacity, of the material are important parameters that the engineers need to consider when they select materials for space structure application. The materials studied in this paper are two SiC particulate reinforced aluminum composites, which have the same volume fraction of ceramic particulate and same type of matrix, but are fabricated by different processing techniques - one by powder metallurgy and another by squeeze casting. Microstructures of two composites were studied using optical and scanning electron microscopes. Changes in damping capacity of the composites at sub-ambient temperature region were studied using Dynamic Mechanical Analyzer (DMA). The result shows that sub-ambient temperature has little effect on the damping characteristics of squeeze cast processed composite, but significantly influence the damping capacity of samples processed by powder metallurgy. Analysis shows that such difference in damping behavior of two composites at sub-ambient temperature is due to the significant difference in their microstructures.

KEYWORDS: MMC, Dynamic mechanical property, damping capacity, low temperature, thermal stress.

1. INTRODUCTION

Ceramic particulate reinforced aluminum matrix composites (Al-MMC) as an advanced composite material emerged almost two decades ago [1]. The primary advantages of Al-MMCs over conventional aluminum alloy are that the materials offer much higher specific stiffness and yield strength. Compared to the continuous fiber reinforced composites, the particulate reinforced composites also have advantages, such as being isotropic in properties and offer ease in fabrication and secondary processing (forging, extrusion, rolling and drilling etc). Consequently, they have been increasingly used as structure material for aerospace applications, in which a structure or a component is required to have low mass.

In practice, however, when engineers design a lightweight aerospace structure or component from Al-MMCs, they have also to consider dynamic mechanical properties of the material, particularly the damping capacity. A material of high damping capacity has the potential to greatly reduce vibration of a structure. This is also of great importance for space structures because the vibration, caused during launch or by the maneuver of the spacecraft or its on-board instrument, needs to be under control as quickly as possible. On-orbit the precision of spacecraft positioning system can also be adversly affected. The difficulties in controlling the vibration of a structure in space come from the facts that there are no air resistance and gravity to help the attenuation of the vibration like on ground. Dealing with the vibration control from the aspect of pure structure design (so-called active vibration damping control) can hardly be satisfied because the structure design of a space structure can be subjected to a number of constraints. A solution normally comes from a combined consideration of both active vibration damping and intrinsic (passive) damping of the materials. In terms of this requirement, materials to be used for space structure should have high damping capacity.

A number of papers have been concerned with the design of space structure or components [2, 3]. Studies conducted by Ashley [4, 5] on the interaction between passive damping and active structural damping have concluded that it would be desirable if passive damping ratios of the structures are greater than 0.01 for control system stability. Polymer material is well known to have high damping capacity, but does not have the required specific stiffness and strength for the space structure applications. Carbon fiber reinforced polymer matrix composite has sufficiently high specific stiffness and strength and also has relatively high damping capacity [6]. However, several problems, such as outgassing of the material in the vacuum of space and rapid degradation under ultraviolet radiation prevent it from being used in space structures directly exposed to the space environment. The search for composite materials with high specific stiffness and sufficiently high damping capacity has thus focused on various types of metal matrix composites, particularly the ceramic particulate reinforced composites as it can also meet other requirements mentioned earlier.

A number of studies on the damping property of Al-MMC have been published over last 10 years, notably the works by Hang et al [7] and Shamsul et al [8], in which the Al-MMCs were found to have higher damping capacity (0.05 to 0.01) than aluminum alloys (0.02 to 0.05) in ambient temperatures. With the increase of the temperature at above $150^\circ C$, the increase in damping capacity of the Al-MMC becomes much more pronounced than that of the aluminum alloys. The underlined explanations were that the particulate/matrix interface slide/friction when there is a weak bonding between matrix and reinforcement with grain boundary relaxation and energy dissipation through the dislocation occurring in the matrix near the particulate/matrix interface. High density of dislocation in the matrix, which is caused by buildup of the thermal stress at the interface due to the large thermal expansion mismatch between ceramic particulate and matrix, was considered to be a factor in giving the composite a high damping capacity[8, 9]. Further study by Wong et al [7] showed that the damping mechanisms were also frequency dependent. High frequency leads to short relaxation time and thus decrease the damping factor of the composites. Unfortunately a common point of all those studies is that they only concerned the damping characteristics of the Al-MMCs at the temperatures above the ambient temperature. At sub-ambient temperature region, however, because there is a large difference in coefficients of thermal expansion (CTE) between ceramic particulate and aluminum matrix, thermal stress in the Al-MMCs, particularly around the particulate/matrix interface, could be very high, which has also been confirmed in previous study [10]. In some circumstances, thermal stress can even exceed the yield strength of matrix and cause matrix plastic flow. When the thermal stress reaches this level, it could create de-bonding at particulate/matrix interface, giving rise to grain boundary relaxation and significantly increase the density of dislocation in the matrix. How is the damping characteristic of a metal matrix composite affected in this case has thus become an interesting question. The goal of this study is to provide answers to this question.

2. EXPERIMENTAL PROCEDURES

2.1 Composite materials

Two ceramic particulate reinforced aluminium metal matrix composites were investigated in this study. Sample A is a commercially available 35%SiC particulate reinforced Al 7075*, produced by powder metallurgy process and heat-treated into T6 form. Sample B is also a 35%SiC reinforced Al 7075, but produced by high-pressure squeeze casting process** and is also heat-treated to T6 form. Because of the difference in processing routes, two samples could be expected to have different microstructural characteristics and consequently give different dynamic mechanical behaviours. To perform dynamic mechanical property test, small samples were cut off from large samples using the EDM (Electric Discharge Machine) technique, and were subsequently machined into $1\times 10\times 50\,mm^3$ with a good surface finish.

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* Composite was provided by Alyn Inc., California, USA

** Material Technology Laboratory of CANMET, Ottawa, Canada

2.2 Microstructure study
Microstructures of the composites were studied using both optical and scanning electron microscope to understand the general microstructure features within the composites, which may support the explanation of microstructure-related dynamic mechanical property.

2.3 Dynamic mechanical property test
Dynamic mechanical properties of the composites, mainly the change in damping capacity of composites with the temperature and vibration frequency, were studied using Dynamic Mechanical analyzer (DMA, model 2980, manufactured by T. A. Instrument). Tests are done in three points bending mode with a driving shaft in the middle to apply a sinusoidal force. Both heating and cooling rate were 5° C/minute. Fig.1 shows the testing fixture for the DMA tests.

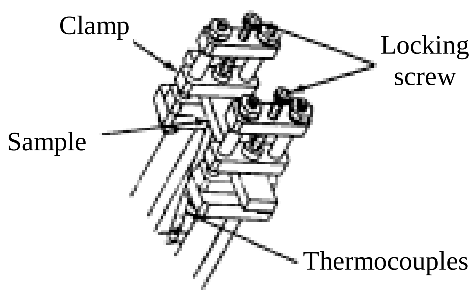

Fig.1 DMA testing fixture

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Microstructures of composites
Fig.2 shows the microstructures of two composites observed by optical microscope at high magnification. In general, particulate distributions in both samples are uniform without evidence of large voids and big clusters of particulate. Composite A, produced by powder metallurgy, has smaller reinforcing particulate and better distribution uniformity than composite B, produced by squeeze casting. Fig. 3 shows the SEM photographs of these two samples, clearly revealing the difference in microstructure between two samples. While the powder metallurgy processed sample has little porosity (fully densified), the composite (sample B) produced by squeeze casting shows the existence of pores of size up to ~ 10 microns. Whether these differences in microstructural characteristics between two samples would result in difference in dynamic mechanical properties seems to be an interesting question to be answered.

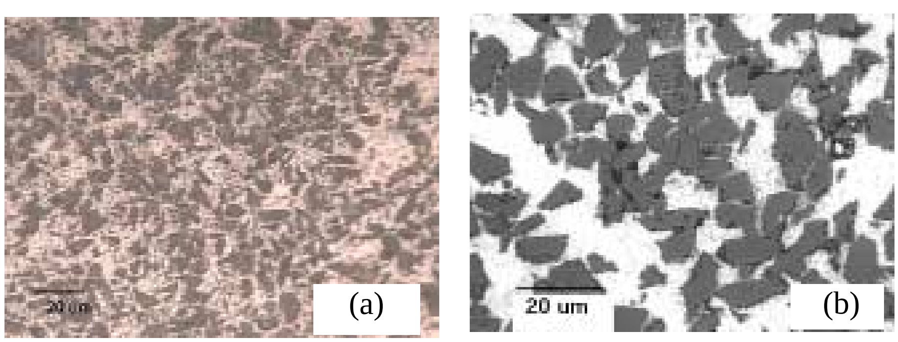

Fig.2 Optical microscope observation of polished surfaces of (a) powder metallurgy processed 35%SiC particulate reinforced Al 7075 composite (b) squeeze casting processed 35%SiC particulate reinforced Al 7075 composite.

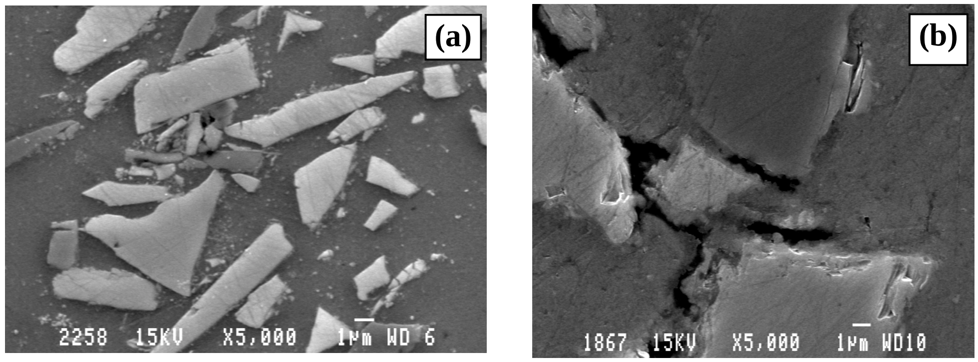

Fig.3 SEM photographs of polished surfaces of (a) powder metallurgy processed 35%SiC particulate reinforced Al 7075 composite and (b) squeeze casting processed 35%SiC particulate reinforced Al 7075 composite.

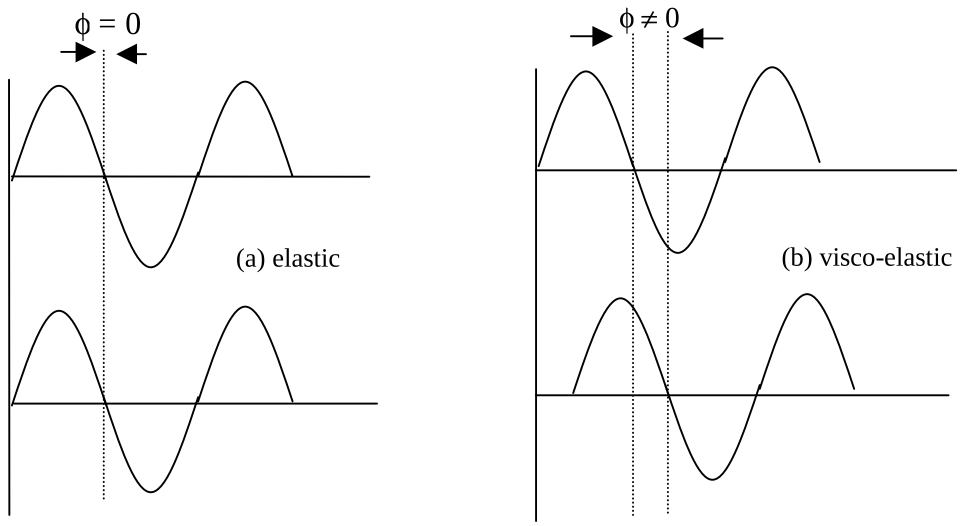

Fig.4 Schematic illustration of strain-load responses of elastic material and visco-elastic materials.

3.2 Damping of ceramic particulate reinforced metal-matrix composites.

Damping capacity is the material's capability to dissipate elastic strain energy during mechanical vibration, which is associated with the visco-elastic characteristic of material. For an ideal elastic material, there would be no damping or energy loss during vibration process. Reflected in a mechanical vibration system, there would be no phase difference between load (σ_0) and deformation of material (ε_0) and Hooke's law ($E = \sigma_0/\varepsilon_0$, where is the Young's modulus of the material) is applied. Strictly speaking an ideal elastic material does not exist. Materials show visco-elastic behavior more or less, which can be reflected by a phase difference, ϕ, between the load and deformation (Fig.4b). For material of high stiffness, the value of ϕ is generally very small and can be neglected in practice. However, for polymer material, it is relatively large. To consider the visco-elastic behavior of a material, the Hooke's law is revised [11]:

$$E^* = \frac{c_0}{\varepsilon_0}(\cos\phi + \sin\phi) \tag{1}$$

Where E* is defined as the complex modulus, and following E' and E'' are defined as storage modulus and loss modulus respectively.

$$E' = \frac{\varsigma_0}{\varepsilon_0} \cos\phi \qquad (2)$$

$$E' = \frac{\varsigma_0}{\varepsilon_0} \sin\phi \qquad (3)$$

The so-called damping capacity is defined as the ratio of loss modulus to storage modulus and equals to tan ϕ.

$$\frac{E^{''}}{E^{'}} = \frac{\sin\phi}{\cos\phi} = \tan\phi \qquad (4)$$

Damping characteristics of aluminum alloy was firstly characterized in this study. Fig.5 shows the change in damping capacity (tan ϕ) of aluminum ally 7075 with temperatures from –100° C to 150° C. Essentially the damping capacity of Al 7075 is very small and changes only a little with the temperatures up to 150° C, similar to what was reported by Wong et al [7] on damping behavior of Al 6061 alloy. Vibration frequency also seems to have very little affect on damping capacity of Al 7075 alloy.

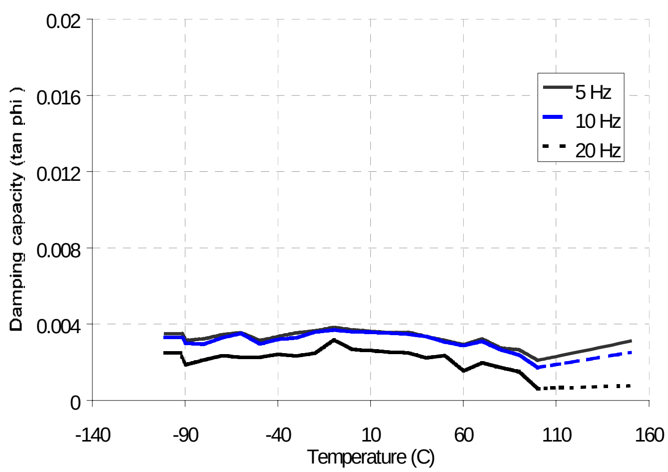

Fig.5 The change in damping capacity of Al 7075 (T6) alloy with the temperature.

Fig.6 shows the change in damping capacity of sample B (squeeze casting processed MMC) with the temperature at 3 vibration frequencies. At the temperature range between -100° C and 50° C, the damping capacity of the composite is very small, similar to what has been shown by the Al 7075 alloy, and changes little with temperature. Even cooling down to -100° C seems to have little effect on damping capacity of the composite. However, at the temperatures above 50° C, the damping capacity of the composite increases rapidly with the increase of the temperature. Study by Shamsul et al [8] on similar type of particulate reinforced aluminum metal-matrix composite showed that the damping capacity of the composite would not be significantly higher than that of aluminum alloy until ~ 180° C, at which point the matrix begins to soften. The rapid increase in damping capacity which begins at ~50° C may suggest a different damping mechanism involved. Fig.7 shows the change in damping capacity of sample A (powder metallurgy processed MMC) with the temperature. Overall the damping capacity of the composite is significantly higher than that of Al 7075 alloy and also sample B. Of particular interesting is the profile of damping capacity with the temperature, in which there are two valleys and a strong peak. At the temperature above ~ 120° C, the damping capacity of the composite increases with the increase of the temperature, very similar to the result reported by Shamsul et al [8]. However, at the temperature below 120° C, damping capacity of the composite increases initially as the temperature drops. When the temperature enters the sub-ambient region, it drops again back to the level where it is at the temperature of ~120° C. Tests at three vibration frequencies (5 Hz, 10 Hz and 20 Hz) showed almost identical results. This is a sharp contrast to the result obtained from sample B.

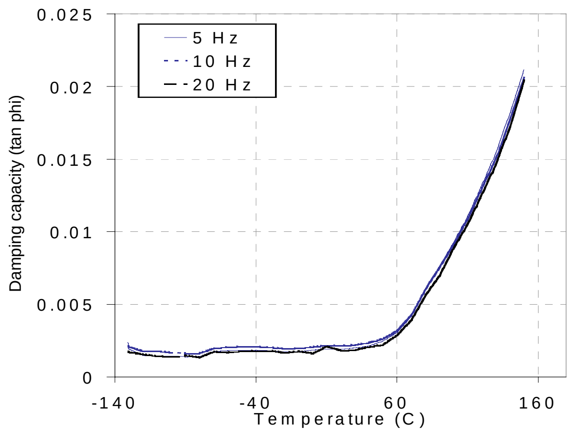

Fig.6 The change in damping capacity of squeeze casting processed 35%SiC-Al 7075 composite

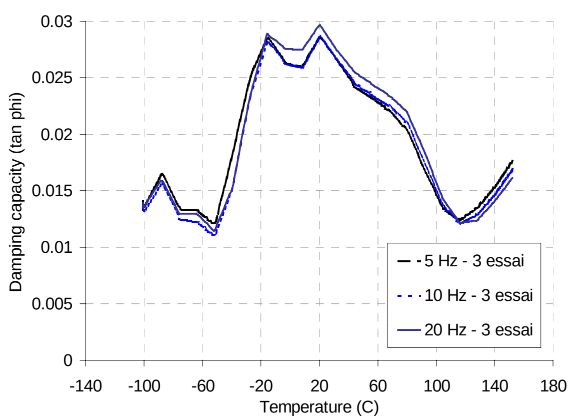

Fig.7 The change in damping capacity of powder metallurgy processed 35%SiC/Al 7075 composite

It is well established that damping capacity of a composite is strongly influenced by its microstructural characteristics [8]. There are several damping mechanisms that could be present in the particulate reinforced metal matrix composites [1, 6], such as the dislocation unpinning and plastic relaxation, local dissipative interfacial processes, particulate/matrix interface frictional sliding, grain boundary sliding and interfacial diffusion. The contribution from dislocation unpinning and relaxation is determined by the density of dislocation in the metal matrix of the composite. Whereas the rest of mechanisms are either determined by the particulate/matrix bonding strength or if there exists a interfacial layer (a reaction product between matrix and reinforcement) at the particulate/matrix interface. In the composite fabricated by the squeeze casting, ceramic particulate is interconnected, forming a particulate network, because the process requires the preform to have certain strength to maintain the its porous structure upon infiltration of molten aluminum under high pressure. Essentially it is the aluminum matrix which fills the pores of porous SiC preform. When the composite is cooled from the processing temperature, there is tendency that matrix shrink away from the encompassing SiC particulate network except at the points where matrix and particulate network lock each other. This is because the CTE of the matrix is much larger than that of SiC particulate. As a result of the matrix shrinking away from the particulate network, there will be limited interactions between SiC particulate and matrix. All those damping mechanisms mentioned earlier will not be effective and thus the damping capacity of the composite is low, similar to damping characteristics of either aluminum alloy or porous SiC ceramic. When temperature further drops into sub-ambient temperature region, the tendency of separation between particulate and matrix is further enhanced. It is likely that the lack of extensive interaction between particulate and matrix keeps the damping capacity of the composite at a low level, similar to aluminum alloy. Reversibly, when the composite is heated up, the larger expansion of the aluminum matrix relative to the SiC particulate will result in extensive mechanical interaction between particulate and matrix, and thus the interfacial friction sliding during vibration, which contributes to the damping capacity. Because the expansion of the matrix is constrained by the SiC particulate network, the thermal stress within the composite builds up, which subsequently induces local deformation of the matrix and dislocation in the matrix. When the dislocation in the matrix increases substantially and there is also extensive interaction between particulate and matrix, damping mechanisms related to dislocation and interfacial friction sliding will take place. This is probably why a rapid increase in damping capacity of the composite appears at the temperature of ~50° C and above.

In contrast to the damping characteristics of sample B, sample A (processed by powder metallurgy) had higher damping capacity and an interesting change in damping capacity with the temperature. The main reason may be attributed to the different in microstructures between the two composites. The distribution of SiC particulate in the matrix in sample A is very uniform and the SiC particulate is well separated by the matrix rather than the existence of extensive particulate network (sintered porous SiC preform). Instead of the matrix being encompassed by the SiC particulate network as in sample B, the SiC particulate is completely encompassed by the matrix in sample A. When the composite is cooled down from the processing temperature (sintering: probably 400° C ~ 500° C in this case), the thermal mismatch caused stress build up around the SiC particulate. The aluminum matrix around the particulate is in tension while the particulate is under compression. The compression strength of the SiC particulate is generally very high compared to the yield strength of the matrix. So the chance for SiC particulate being broken by thermal stress would be very low. It is well demonstrated that ceramic particulate reinforced aluminum metal matrix composite has significantly increased damping capacity at the temperature above 150° C because of so-called visco-elastic behavior of matrix at those temperatures [8]. So when the temperature drops from that temperature, it can be expected that damping capacity of the composite drops due to the gradual disappearing of vico-elastic behavior of the matrix. But at the same time, the thermal stresses builds up and dislocation in the matrix is generated. At a certain point, the damping mechanisms associated with the dislocation begin to pick up. This is probably why the damping capacity of the composite begins to increases as the temperature drops below 120° C. The damping capacity of the composite reaches a peak at ~ 0° and then begins to decline. A possible explanation may be that density of dislocation in the matrix has reached its maximum point at that point and at same time, the thermal stress has exceeded the yield strength of the matrix, causing matrix plastic flow. The matrix plastic flow relieves the thermal stress to some extent and also enables the escape of dislocations at either grain boundary or particulate/matrix interface. As long as the matrix plastic flow continues, the density of dislocation gradually decreases and thus the damping capacity of the composite decreases. At temperature below -50° C, another increase in damping capacity is seen, which is probably due to the re-building up of thermal stress and re-increase in dislocation density as the temperature drops further in sub-ambient temperature region.

4. CONCLUSIONS

This study has shown that SiC particulate reinforced aluminum metal matrix composites, in general, have higher damping capacity than its matrix material – aluminum alloy. Composites processed by different routes were found to have significantly different microstructure characteristics, which in turn strongly influence the damping behavior of the composites, particularly at sub-ambient temperature. For squeeze casting processed composite, its damping capacity is not significantly affected by sub-ambient temperatures even at -100° C. At sub-ambient temperatures, there is a significant effect on damping capacity of the composite processed by powder metallurgy. A significant peak in damping capacity appears in the region around the breakeven point of ambient and sub-ambient temperatures. A conclusive explanation is still under investigation. A possible explanation is that this is due to the increase and decrease in dislocation density in the matrix, associated with the thermal stress buildup upon cooling and subsequently thermal stress relief when matrix plastic flow occurs.

5. REFERENCES

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