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A study on the damping capacity of $BaTiO_3$-reinforced Al-matrix composites

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Abstract. To study the damping capacity of $BaTiO_3$/Al composites, Al composites reinforced with $BaTiO_3$ powder (average grain sizes: 100 and 1000 nm) were fabricated by the hot-pressing sintering method. The damping properties of pure Al and $BaTiO_3$/Al composites were investigated and compared based on the dynamic mechanical analysis over a wide range of temperatures (50–285°C). Compared with pure Al matrix, 1000 nm $BaTiO_3$/Al composites with 5 and 10% mass fractions of $BaTiO_3$ exhibited better damping capacity. For 100 nm $BaTiO_3$/Al composite, its damping capacity is slightly higher than that of pure Al below 145°C, while it becomes lower above this degree. The damping capacity enhancement of $BaTiO_3$/Al composites can be explained by the ferroelastic domain damping. Furthermore, 5 and 10% $BaTiO_3$/Al composites have higher bending strength and hardness than pure Al sample.

Keywords. $BaTiO_3$; Al-matrix composites; damping capacity; ferroelastic domain damping; mechanical property.

1. Introduction

Damping capacity is a physical property that measures the ability of a material to convert mechanical energy of vibrations to heat which is dissipated through the volume of the material. Damping decreases the amplitude of mechanical vibrations which helps to reduce the harmful effects of noise and mechanical vibrations. A material that combines good mechanical properties and a high vibration damping ability is therefore highly desirable for structural applications, where the effect of noise and vibrations is intolerable. Unfortunately, materials that possess high damping abilities usually exhibit poor mechanical properties, thus, a material that combines good mechanical properties and a high vibration damping ability is therefore extremely desirable for structural applications, where the effect of noise and vibrations are intolerable, especially in military submarine propellers and aerospace structures. Consequently, searching for a material with both good mechanical performance and high damping properties is a critical issue.

Owing to low density, good ductility, easy fabricability and superior strength through alloying and heat treatment, Al-matrix composites are a unique class of materials consisting of a reinforcing phase embedded in an alloy or a metal matrix [1,2], thus Al alloys and Al-matrix composites are one kind of the most important and widely used engineering materials, especially in the field of aerospace. Additionally, for Al-matrix composites, damping capacity also plays a fundamental role and attracts a lot of interest. Some valuable and exploratory works have already been reported to reinforce Al with superior intrinsic damping performance materials, and the results showed that the damping capacity of Al-matrix composites can increase greatly [3–5]. Therefore, reinforcing Al alloy matrix with higher damping particles could be an efficient way to obtain Al-matrix composites with both high strength and high damping capacity.

Ferroelectric and piezoelectric ceramics can exhibit considerable high vibration damping capacity due to the anelastic response of ferroelastic domains to an external applied stress. Some piezoelectric materials such as $BaTiO_3$ PZT ($Pb(ZrTi)O_3$) and $LiNbO_3$ have been focussed and considered as the new reinforcements for developing high-damping composites. The piezoelectric powder has been successfully added to fabricate Al-matrix composites as the reinforcement, realizing the high-damping capacities [6–9]. Besides, based on the experimental and theoretical studies, some novel properties of piezoelectric materials could also be observed with decreasing grain size, and there existed the decrease of dielectric constant and the multiphase coexistence in fine-grained $BaTiO_3$ powder [10,11].

In this study, $BaTiO_3$ powders (average grain sizes: 100 and 1000 nm) were added into Al powder to fabricate $BaTiO_3$/Al composites by the hot-pressing sintering method. The damping capacity and mechanical properties of pure Al sample and prepared $BaTiO_3$/Al composites were carefully investigated.

2. Experimental

To fabricate $BaTiO_3$/Al composites, firstly, $BaTiO_3$ raw powders (purity of 99.5%, average grain sizes of 100 and 1000 nm) were respectively mixed with Al powder (average diameter of 50 μm) in a planetary miller at a speed of

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200 r min^{-1} for 1 h. The mass fractions of $BaTiO_3$ powders are controlled to be 5 and 10%, respectively. Secondly, the mixture powders were poured into the graphite dices and sintered in a graphite furnace by a uniaxial hot pressing at 560°C for 15 min with a pressure of 30 MPa. Finally, the bulk specimens were ground and polished. As a comparison, pure Al sample was prepared with the same process.

X-ray diffraction (XRD) was conducted to check the crystal structure of $BaTiO_3$/Al composites by using a D8 Advance instrument (Cu Kα). Scanning electron microscope (SEM, Philip XL-30FEG) with an energy dispersive X-ray analyser (EDX) was used to examine the morphology and component of pure Al and $BaTiO_3$/Al composites. The damping capacity measurements were performed on dynamic mechanical analysis (DMA Q800, TA Instruments Inc. USA) using three-point bending testing method in single cantilever mode at the constrained frequency of 15 Hz. The temperature was set to continuously increase from 50 to 285°C with a heating rate of 3°C min^{-1}. The bending strength was measured by the three-point bending method and the hardness was evaluated by the Rockwell hardness tester (HRA) at room temperature.

3. Results and discussion

Figure 1 shows the XRD patterns of 100 and 1000 nm $BaTiO_3$/Al composites tested at room temperature. In the XRD patterns, the (111), (200), (220) peaks of pure Al with face-centered-cubic structure are overlapped the peaks of (111), (200) and (002), (202) and (220) of 1000 nm $BaTiO_3$ with tetragonal phase at around 38, 45 and 66°, so the XRD patterns $BaTiO_3$/Al composites are similar to that of 1000 nm $BaTiO_3$. Additionally, the crystal structure of 100 nm $BaTiO_3$ powder has been proved to be multiphase coexistence of cubic and tetragonal phases at room temperature, and their mass fractions were respectively 82.0 and 18.0% [10], while the phase of 1000 nm $BaTiO_3$ is a tetragonal structure, therefore the XRD patterns of 1000 and 100 nm $BaTiO_3$/Al composites are similar. Besides, no other peaks appear in XRD patterns, which indicate that there are no impurities in $BaTiO_3$/Al composites.

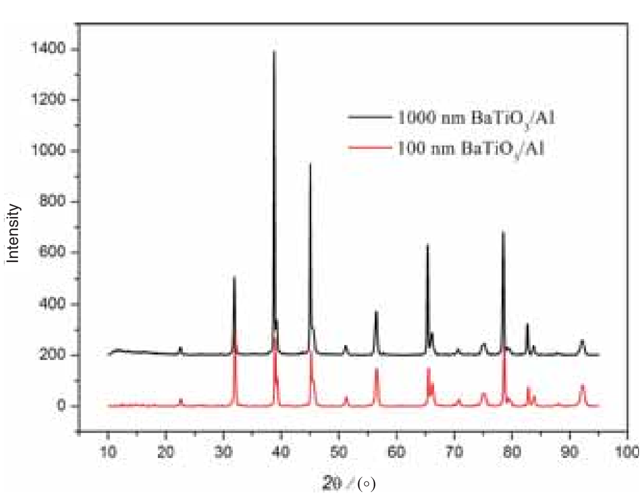

Figure 1. The XRD patterns for 1000 nm $BaTiO_3$/Al composites.

Their morphologies of pure Al and $BaTiO_3$/Al composites were characterized by the scanning electron microscope.

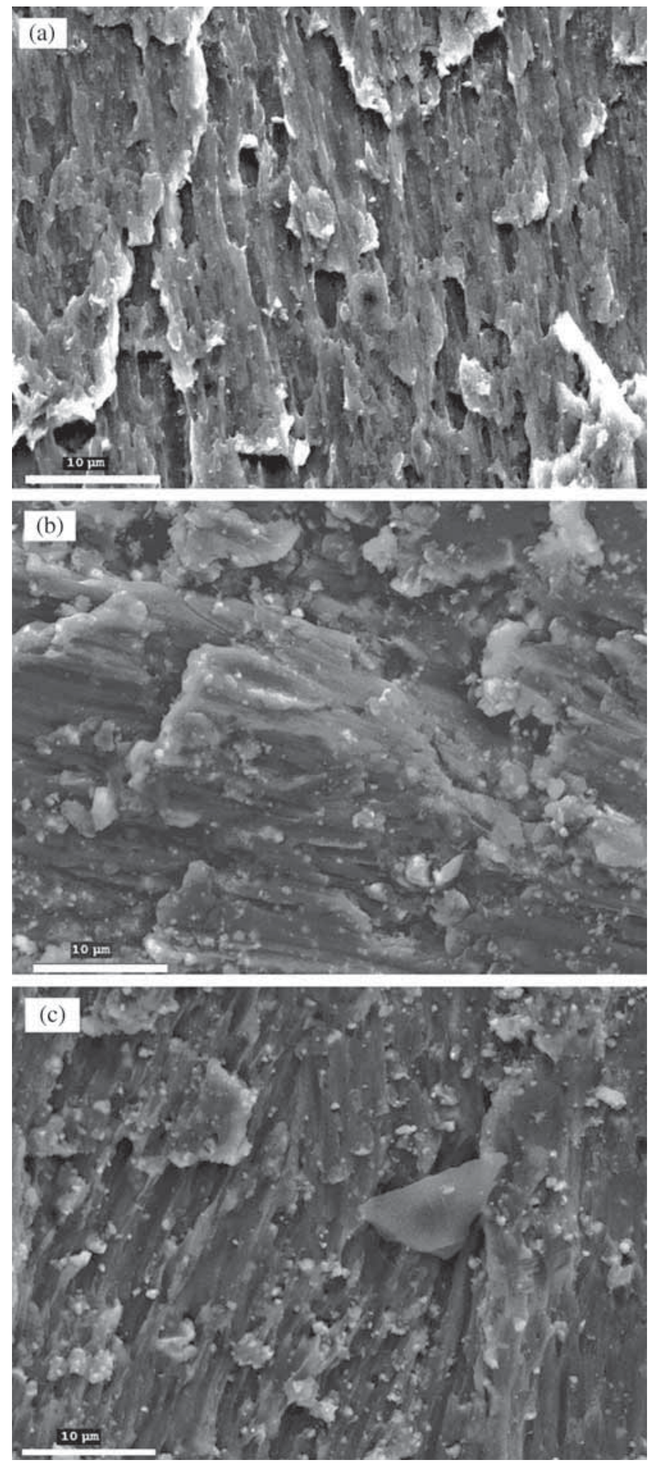

Figure 2. SEM images of the fracture surfaces of Al-matrix sample and 1000 nm $BaTiO_3$/Al composites. (**a**) Pure Al-matrix sample, (**b**) 5%$BaTiO_3$/95% Al composite and (**c**) 10% $BaTiO_3$/90% Al composite.

Taking 1000 nm $BaTiO_3$/Al composites as an example, figure 2a–c shows the fractured surfaces of pure Al sample, 5% $BaTiO_3$/95% Al and 10% $BaTiO_3$/90% Al composites, respectively. From figure 2, it can be observed that all sintered samples are dense, moreover uniformly distributed $BaTiO_3$ particles (white areas) in Al-matrix would be found with increasing $BaTiO_3$ content. EDXs of the fractured surfaces of above samples were also shown in figure 3a–c, respectively. Figure 3a shows that only Al element exists in pure Al sample, while Al, Ti and O could be detected in 5% $BaTiO_3$/95% Al composite in figure 3b. When the mass fraction of $BaTiO_3$ increased to 10%, Ba as well as Al, Ti and O would all be found in figure 3c. The EDX analyses also show that no impurity has been observed in these samples. For the samples of 100 nm $BaTiO_3$ group, similar results of SEM images and EDX analysis could be obtained.

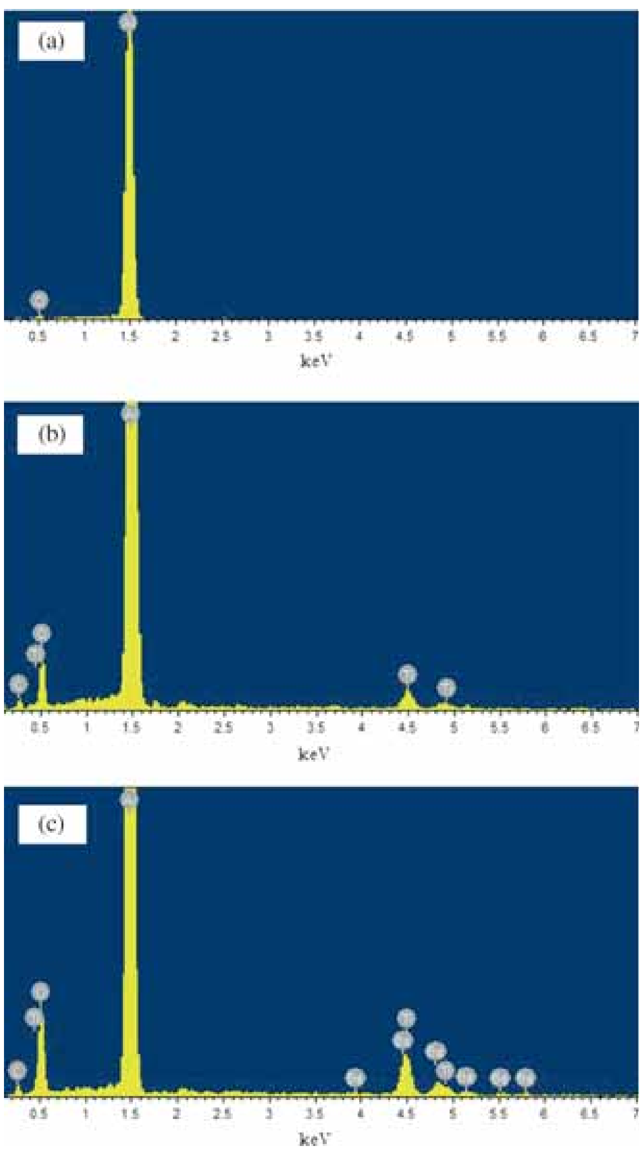

Figure 3. EDS of fracture surfaces of Al-matrix sample and 1000 nm $BaTiO_3$/Al composites. (**a**) Pure Al-matrix sample, (**b**) 5%$BaTiO_3$/95% Al composite and (**c**) 10% $BaTiO_3$/90% Al composite.

Figure 4 shows the damping capacities and storage moduli of pure Al sample and 1000 nm $BaTiO_3$/Al composites as a function of temperature at a frequency of 15 Hz. The damping capacities of all three samples gradually enhanced, whereas their storage moduli slowly decreased from 50 to 285°C. Compared with pure Al sample, both tan-δ values of 1000 nm $BaTiO_3$/Al composites (5 and 10% $BaTiO_3$) are higher in figure 4a, furthermore, the tan-δ value of the composites increased with the higher $BaTiO_3$ content. Contrastingly, storage moduli slowly decreased with increasing temperature and $BaTiO_3$ content in figure 4b, and the values of $BaTiO_3$/Al composites are always lower than that of pure Al sample. Therefore, it can be inferred that the damping capacities of $BaTiO_3$/Al composites are better than that of pure Al-matrix based on the above results.

The damping capacities and storage moduli of 100 nm $BaTiO_3$/Al composites are also shown in figure 5. When temperature gradually rise from 50 to 285°C, on one hand, the change tendencies are similar with 1000 nm $BaTiO_3$/Al composites, their tan δ values all increased with increasing temperature; on other hand, the increasing rates of pure Al

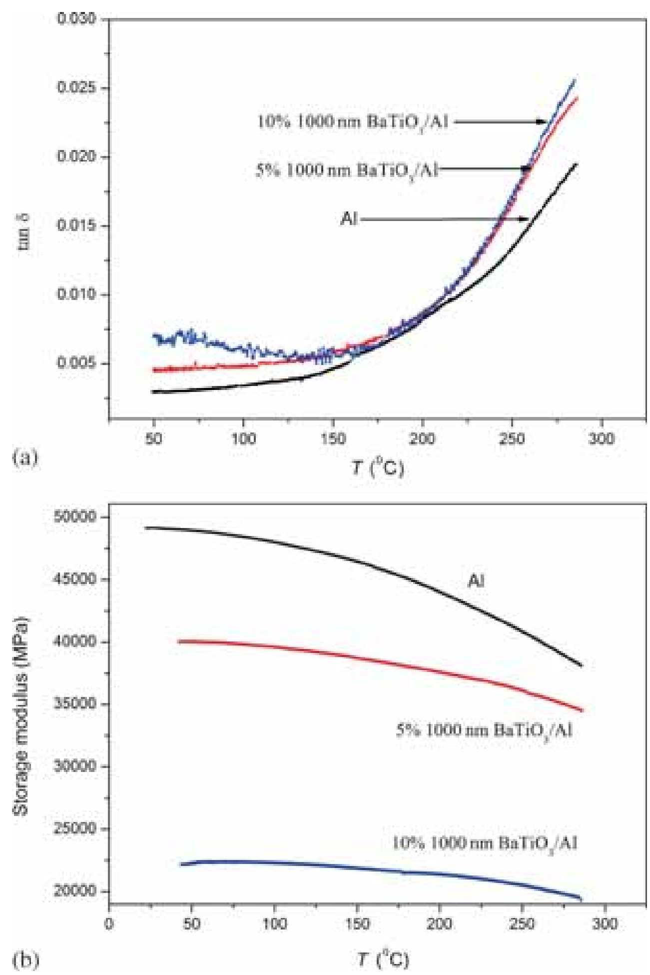

Figure 4. Damping capacity (tan δ) and storage modulus as function of temperature for pure Al sample and 1000 nm $BaTiO_3$/Al composite.

sample and 10% $BaTiO_3$/90% Al composites are faster than that of 5% $BaTiO_3$/95% Al composites. Below 145°C, the tan δ values of 10% $BaTiO_3$/90% Al composites and pure Al sample are basically equal, and they are higher than that of 5% $BaTiO_3$/95% Al composites. However, along with increasing temperature, both damping capacities of $BaTiO_3$/Al composites (5 and 10% $BaTiO_3$) become even lower than that of pure Al sample. Figure 5b shows that the storage moduli gradually decreased from 50 to 285°C, and the values of 5% $BaTiO_3$/95% Al composites are far lower than those of pure Al sample and 10% $BaTiO_3$/90% Al composite. Below 205°C, storage moduli of 10% $BaTiO_3$/90% Al composites are lower than that of pure Al sample, but it becomes higher above this degree. Based on these damping capacity results of $BaTiO_3$/Al composites with different grain sizes and mass fractions, higher mass fraction and larger particle size of $BaTiO_3$ are favourable to achieve the higher damping of $BaTiO_3$/Al composite.

The dependence of damping capacity of Al-matrix on temperature has been extensively studied. Usually, the damping capacity is low at room temperature, and will increase with increasing temperature. The damping mechanisms are ascribed to the dislocation damping, interface damping and intrinsic damping of second phases at low testing temperature, and to dislocation damping, grain boundary damping and interface damping at high testing temperature [5].

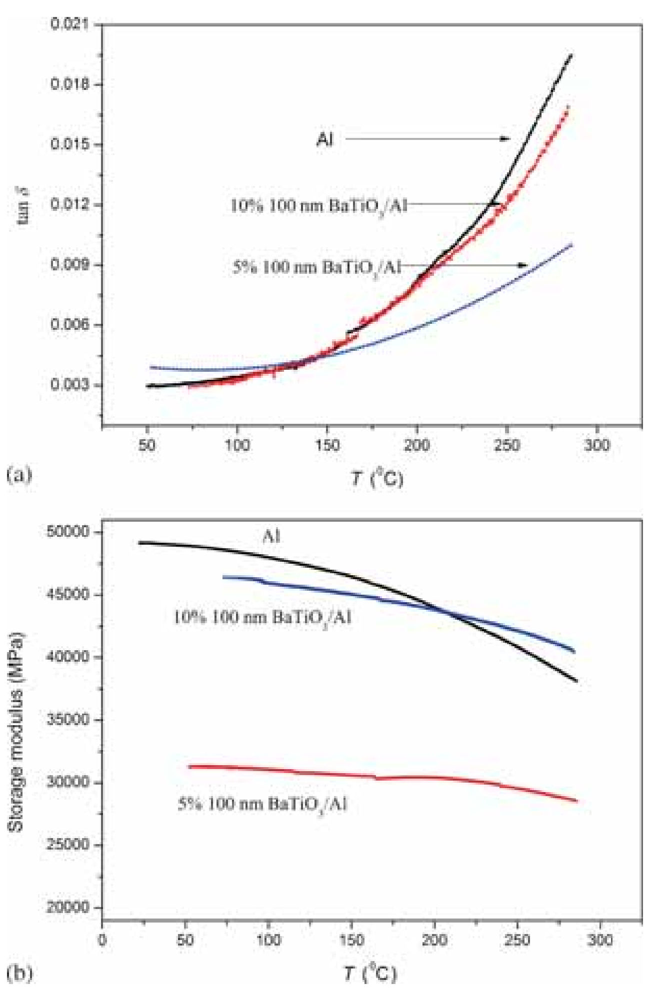

Figure 5. Damping capacity (tan δ) and storage modulus as function of temperature for pure Al sample and 100 nm $BaTiO_3$/Al composite.

With a decreasing temperature, $BaTiO_3$ crystal undergoes three successive phase transitions from a cubic phase to a tetragonal phase at 130°C, then to an orthorhombic phase at 5°C, finally to a rhombohedral phase at −90°C. The stable phase at room temperature is the ferroelectric tetragonal phase. The tetragonal microstructure consists of both 180 and 90° domains, of which the 90° domains are ferroelastic. The high damping in the tetragonal phase is due to the 90° domain wall motion caused by ferroelastic domain switching. Moreover, these domain walls can move under external stress or electric fields [12]. So, in $BaTiO_3$/Al composite, besides the mechanisms as described above, the ferroelastic domain damping must be considered. The motion of domain walls and its interaction with point defect (oxygen vacancies) result in energy dissipation, so the damping capacity increases. Of course, when $BaTiO_3$ particles as the second phase were added into Al-matrix, the effect of $BaTiO_3$ particles on the damping capacity of $BaTiO_3$/Al composites also were attributed to the dislocation damping, grain boundary damping and interface damping between $BaTiO_3$ particles and Al-matrix. Different effect of 100 and 1000 nm $BaTiO_3$ on Al-matrix composites are possibly attribute to the size effect and the crystal structure. As the crystallite size of $BaTiO_3$ powder reduced to the nanoscale, multiphase coexistence will occur. For example, the cubic phase was observed and there is even a coexistence of hexagonal and tetragonal phases in $BaTiO_3$ nanoparticle with a size of 40 nm at room temperature [10,11,13]. Owing to the piezoelectric effect of the piezo-damping, the reinforcement results on the damping capacities of 1000 nm $BaTiO_3$ is more favourable. For 100 nm $BaTiO_3$, its failure of exerting the intrinsic damping is probably caused by the insufficient $BaTiO_3$ content,

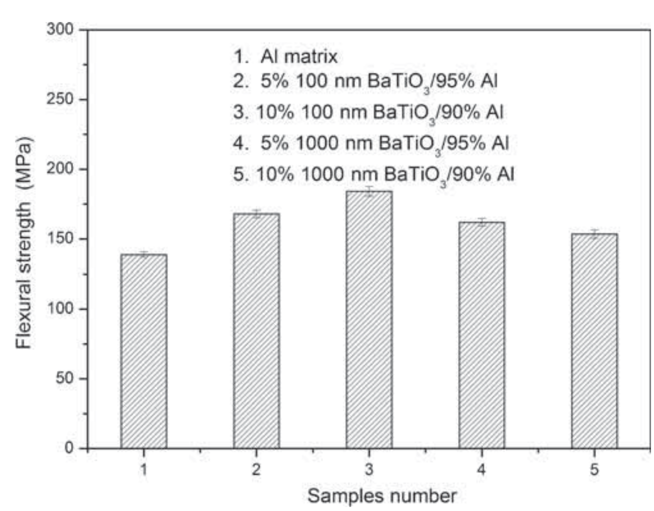

Figure 6. Flexural strengths of Al-matrix and $BaTiO_3$/Al composites.

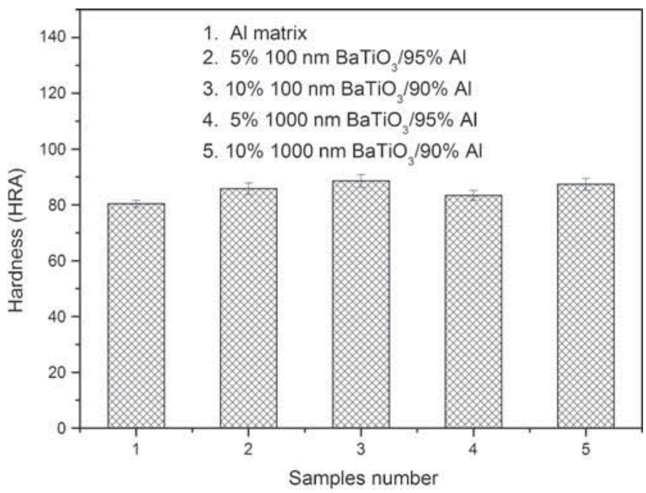

Figure 7. Hardness of Al-matrix and $BaTiO_3$/Al composites.

more likely by its poor interface bonding in the composites and less tetragonal ferroelectric phase content in 100 $BaTiO_3$ particle [4]. Furthermore, detailed investigations are necessary to understand the damping mechanism of $BaTiO_3$/Al composite.

The effects of $BaTiO_3$ piezoelectric phase on the fracture toughness and tensile strength of $BaTiO_3/Al_2O_3$ and $BaTiO_3$/Al composites have been studied in previous works. It is reported that the fracture toughness of $BaTiO_3/Al_2O_3$ could be improved [13,14] and the tensile strength of $BaTiO_3$/Al composite is 42% higher than that of Al-matrix [4]. In this study, the effect of $BaTiO_3$ particles on the mechanical properties was also investigated. The flexural strength and hardness test results of Al-matrix and $BaTiO_3$/Al composite are shown in figures 6 and 7, respectively. It can be seen that the flexural strength and hardness both increase with the addition of $BaTiO_3$. For 100 nm $BaTiO_3$, the flexural strength values of Al-matrix, 5 and 10% $BaTiO_3$/%Al composite are 138.7, 167.9 and 184.1 MPa respectively, and the hardness (HRA) values are 80.4, 85.8 and 88.6, sequentially. When the grain size of $BaTiO_3$ particles is 1000 nm, the values of flexural strength and hardness slightly decreased, the flexural strength values of 5 and 10% $BaTiO_3$/%Al composite are 162.8 and 153.4 MPa, and the hardness values are 83.4 and 87.4, respectively. The results illustrate that the bending strength and hardness values of all composites are higher than that of Al-matrix, especially for 100 nm $BaTiO_3$, whose reinforcing effect is more obvious. The maximum values of bending strength and hardness of $BaTiO_3$/Al composite are 33 and 10% higher than those of Al, respectively. This improvement is possibly attributed to the extraordinary effect of nanosize materials. A lot of research results show that when the second phase particle size is less than 100 nm and will produce the dispersion strengthening effect [15,16]. Additionally, the interfaces and nanosize particles in composites can prevent the crack extension and heighten the mechanical property, so the interface effect may also play an important role [4].

4. Conclusions

In conclusion, the damping and mechanical properties of pure Al sample and $BaTiO_3$/Al composites have been investigated in this study. Compared with pure Al sample, 1000 nm $BaTiO_3$/Al composite always exhibits superior damping capacity under our experimental conditions. For 100 nm $BaTiO_3$/Al composite, its damping capacity is slightly higher than that of pure Al sample below 145°C, while it becomes even lower than that of pure Al sample above this degree. Both the bending strength and hardness of $BaTiO_3$/Al composite are enhanced in comparison with pure Al sample.

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