Original Article

Mechanical behaviour and damping properties of Ni modified Cu–Zn–Al shape memory alloys

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1. Introduction

There is a growing attention to the problems created by mechanical, structural and noise vibrations in the environment on the account of industrial processes, seismic events, excavation, construction, mining, and exploration activities [1–3]. These vibration sources can generate diverse effects ranging from mild discomfort and general machinery inefficiencies to collapse of structures, loss of investments, lives and properties [3,4]. In order to mitigate the potential hazards which could arise from such vibrations, there is growing interest in the development of damping materials for vibration control in engineering structures and systems [4–6]. Damping materials possess the inherent capacity of attenuating vibrations by dissipating the energy absorbed during the vibration to a safe mode such as heat, usually by hysteretic actions [7]. There is a wide range of engineering materials with damping ability among which shape memory alloys (SMAs) have been found extremely useful [8,9].

Shape memory alloys are known principally for their shape memory effect and pseudoelastic properties, but have also been observed to possess high damping capacity — which makes them attractive for the design of vibration control devices [10,11]. The high damping capacity observed in SMAs has been attributed to the high internal friction occurring during martensitic transformation, which manifests in the loss of energy by the movement between the martensite variant interfaces and the parent martensite habit planes [12,13]. These remarkable damping properties have been observed principally in NiTi and Cu based SMAs. CuZnAl based SMAs are however the focus of this research because of its relatively cheaper processing cost and its relatively superior strain recovery compared to other Cu based SMAs [14].

The damping properties of CuZnAl based SMAs have been the subject of several investigations [15,16]. Nai-chao [17] showed that the damping performance of CuZnAl SMAs is dependent on whether it is in martensitic or austenitic state. The area enclosed by the hysteretic loop — which is a measure of the damping capacity — was observed to be larger in the martensite state than in the...
austenitic state. The former was thus better suited for vibration control application. Wu et al. [18], studied the damping characteristics of the inherent and intrinsic internal friction of CuZnAl SMAs containing varied Zn content. It was reported that the damping capacity was sensitive to the Zn composition of the alloys. Compositions containing 7.5–8.5 wt.% Zn were found to have higher damping capacities compared to compositions containing 7 wt.% Zn (Cu7Zn11Al), because the γ’3 martensite phase they are characterized which possesses a 2H type structure with abundant movable twin boundaries. Cimpoesu et al. [19] studied the effect of stress on damping capacity of CuZnAl SMAs. It was observed that the internal friction peak in these SMAs, is influenced by the temperature and deformation. Also lean amounts of elements like iron, lead, and nickel present in the CuZnAl alloy, helped improve the damping capacity of the alloy. The role of these elements (iron, lead and nickel) when used independently as additions to the CuZnAl alloy was however not covered by the study.

It is recalled that the use of elements such as Fe, B, Ni, Ti, among others as micro-alloying additions in Cu based SMAs, have been reported to modify the grain structure; and consequently, improve the toughness and the overall mechanical performance of the SMAs [14]. Ni in particular, has been reported to help raise the transformation temperature of Cu based alloys, but its impact on mechanical and damping behaviour when used as micro-alloying addition in CuZnAl alloys has not received comprehensive reportage in literature. This happens to be the focus of the present study, which aims at assessing the potentials of Ni modified CuZnAl SMAs for structural and damping applications where there is a growing quest for functional and cheap alternatives to NiTi based SMAs.

2. Experimental

2.1. Materials preparation

Conventional liquid metallurgy route was utilized for the production of the Ni modified CuZnAl alloys following procedures in accordance with Alaneme [20]. Five compositions of the alloys were produced containing: Cu18Zn7Al as base alloy composition, 0.1, 0.2, 0.3 and 0.4 wt.% Ni additions to four different heats of the Cu18Zn7Al alloy — for the production of the four Ni modified alloy compositions. A crucible furnace was used for the melting operation, and the melts cast into cast iron metallic moulds. The chemical compositions of the five CuZnAl based alloys produced were determined by SEM-EDS analysis, and are presented with their respective sample designations in Table 1. A homogenization treatment performed at 800 °C for 4 h followed with air cooling, was undertaken to improve the chemical and microstructural homogeneity in the alloys produced. They were subsequently cold deformed to 10% reduction of the original thickness, using a miniature cold rolling machine; and thereafter, annealed at 450 °C for 1 h followed by air cooling to eliminate cold deformation induced internal stresses developed in the samples. The samples for mechanical and damping tests, microstructural and phase analysis, were then machined to standard specifications before a final annealing at 400 °C for 2 h followed by water quenching at room temperature, was performed to eliminate machining stresses on the samples.

2.2. Microstructure and phase characterization

The structures of the produced alloys were characterized using optical microscopy (OM), scanning electron microscopy (SEM), and X-ray diffractometry (XRD) in accordance with Alaneme et al. [21]. The microstructures of the CuZnAl alloys produced were studied using a Zeiss optical microscope. The samples were prepared to metallographic finish using a series of grinding and polishing processes. The mirror finish surface produced on each sample was etched by swabbing for 10–20 s using a solution containing 5 g ferric chloride, 10 ml HCl, and 95 ml ethanol, after which microstructural analysis was performed on the samples. The optical microscopy analysis was complemented with detailed microstructural and compositional studies using a TESCAN VEGA3 thermionic emission scanning electron microscope system with accessories for energy dispersive spectroscopy (EDS). The SEM analysis entailed the use of back scattered electron (BSE) and secondary electron (SE) modes imaging for assessing the phase and the grain distribution, while SEM-EDS analysis was used for the determination of the chemical compositions of the CuZnAl alloys. XRD analysis was finally utilized for the phase characterization of the CuZnAl alloys produced. The samples for the analysis were prepared following standard procedures. The crystalline phases present and their peak intensities were determined using a PANanalytical Empyrean diffractometer with PIXCEL detector and Fe filtered Co-Kz radiation source was used for the analysis. The analysis was performed from diffraction 2θ angle spectral range of 0° to 120° while the phases were identified using the XPert Highscore plus software. The crystal structures of the phases identified were determined by analyzing the pattern of the diffracting crystal planes (hkl) for the entire range of the 2θ diffraction angles [22].

2.3. Mechanical testing

A Vickers hardness scale was used for the evaluation of the hardness of the alloys, using a hardness testing machine. The samples were prepared with fine finished plane parallel surface, while the testing procedure was in accordance with the ASTM E92-17 standard [23]. The hardness test was performed using a 30 kgf load for a dwell time of 10 s. The hardness indentation was repeated for a minimum of five times and readings within the margin of 2% were taken for the determination of the average hardness values.

The tensile testing was performed on the as-produced CuZnAl alloys using a universal testing machine. The samples for the test were machined to tensile test specification of 5 mm diameter and 30 mm gauge length. The test samples were mounted on the testing platform and pulled in tension to fracture at a strain rate of 10−3/s. The samples preparation, testing procedure and data analysis were performed following the recommendations of ASTM E8/E8M-15a [24] standard. Three repeated tests were performed for each CuZnAl alloy composition produced to guarantee the reliability and to assure the reproducibility of the test results. The ultimate tensile strength and strain to fracture were evaluated from the stress–strain curves developed from the test conducted.

The fracture toughness values of the CuZnAl alloys were evaluated using the circumferential notch tensile (CNT) testing approach in accordance with Alaneme [25]. The CuZnAl alloy samples were machined to the test specifications: gauge length of 27 mm, gauge diameter of 6 mm (D), notch diameter of 4.2 mm (d),

<table>
<thead>
<tr>
<th>Sample</th>
<th>Approximate composition</th>
<th>Cu</th>
<th>Zn</th>
<th>Al</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cu–18Zn–7Al</td>
<td>74.77</td>
<td>18.15</td>
<td>7.08</td>
<td>–</td>
</tr>
<tr>
<td>B</td>
<td>Cu–18Zn–7Al–0.1Ni</td>
<td>74.75</td>
<td>18.20</td>
<td>6.95</td>
<td>0.1</td>
</tr>
<tr>
<td>C</td>
<td>Cu–18Zn–7Al–0.2Ni</td>
<td>74.64</td>
<td>18.06</td>
<td>7.10</td>
<td>0.2</td>
</tr>
<tr>
<td>D</td>
<td>Cu–18Zn–7Al–0.3Ni</td>
<td>74.59</td>
<td>18.03</td>
<td>7.12</td>
<td>0.3</td>
</tr>
<tr>
<td>E</td>
<td>Cu–18Zn–7Al–0.4Ni</td>
<td>74.56</td>
<td>18.08</td>
<td>6.96</td>
<td>0.4</td>
</tr>
</tbody>
</table>
and notch angle of 60°. The samples were mounted on the testing stage and subjected to tensile loading to fracture using a universal testing machine operated at a strain rate of $10^{-3}$/s. The fracture loads ($P_f$) obtained from the CNT samples' load-extension plots were used to evaluate the fracture toughness of the alloys based on the relation [26]:

$$K_{IC} = \frac{P_f}{D^{3/2}} \left[1.72 \left(\frac{D}{d}\right) - 1.27\right]$$  \hspace{1cm} (1)$$

where $D$ and $d$ are the specimen diameter and the diameter of the notched section, respectively. The results were validated for plane strain condition required for valid fracture toughness determination using the relations in accordance with Nath and Das [27]:

$$D \geq \left(\frac{K_{IC}}{\sigma_y}\right)^2$$  \hspace{1cm} (2)$$

Three repeated tests were performed for each Cu–Zn–Al alloy composition to ensure that generated results are consistent and hence reliable.

2.4. Damping behaviour

The temperature dependence of the damping properties of the CuZnAl alloys were assessed on a dynamic mechanical analyzer, using the three-point bending deformation mode in accordance with the ASTM E756-05 [28] standard. Rectangular bar samples with dimensions of 40 mm $\times$ 5 mm $\times$ 0.9 mm, were prepared for the damping tests. For the measurements of the temperature dependent damping properties, the test conditions were set to strain amplitude ($\varepsilon$) of 10 μm, vibration frequency ($f$) of 1 and 2 Hz, temperature range ($T$) from room temperature to 250 °C and heating rate ($T'$) of 5 °C/min. The loss modulus ($E''$) and the storage modulus ($E'$) were determined from the test, and the damping capacity measured from the loss tangent ($\tan \delta$), using the relation [29]:

$$\tan \delta = \frac{E''}{E'}$$  \hspace{1cm} (3)$$

3. Results and discussion

3.1. Microstructure and phase analysis of the Cu–Zn–Al alloys

3.1.1. Optical microscopy

The optical micrographs of the unmodified and Ni modified CuZnAl alloys are presented in Fig. 1. Fig. 1a shows the optical micrograph of the unmodified CuZnAl alloy, which is observed to contain sharp edged directionally solidified grains. The elongated grain feature is very common in CuZnAl shape memory alloys (although less than 2°) which is a common feature in alloys with essentially varied grain morphology. This sort of influence of Ni as micro-alloy addition, has been repeatedly reported in several reports [14,33,34]. Fig. 3 with representative EDS spectra confirms the presence of Cu, Zn, Al and Cu, Zn, Al, Ni for the unmodified and the 0.4% Ni modified CuZnAl alloy, respectively.

3.1.2. SEM observations

Representative secondary electron mode images of the unmodified and selected modified Cu–Zn–Al alloys are presented in Fig. 2. They all demonstrate profoundly identical structure features as observed in the corresponding optical micrographs of the investigated alloys (Fig. 1). As it is seen in Fig. 2a, the unmodified alloy microstructure consists of predominantly elongated grains with sharp edges. In Fig. 2b, the micrograph of the 0.2% Ni modified CuZnAl alloy shows predominantly a finer structure with a few needle-like precipitated features, while in Fig. 2c the 0.4% Ni modified CuZnAl alloy is seen to consist of slightly elongated larger size grains compared to the unmodified one. These results confirm the observations from the optical microscopy investigation that the presence of Ni in the CuZnAl alloys significantly alters their solidification patterns with essentially varied grain morphology. The analyses from Fig. 1 and Table 2 show that the amount of Ni used as micro-alloying addition in CuZnAl alloy significantly affects its solidification patterns. Grain modification was more pronounced and distinct for the 0.1% Ni modified CuZnAl alloy where a dramatic transformation from sharp edged elongated grain structure to a predominantly granular structure was observed. The 0.2% Ni addition resulted in the finest size and least predominant presence of the needle-like structures and the 0.3% Ni addition only induces slight changes in the grain edge morphology, while the 0.4% Ni modified CuZnAl alloy composition shows changes in both grain growth and in grain edge morphology.

3.1.3. Analysis of X-ray diffraction

The X-ray diffraction analysis of the unmodified and selected modified CuZnAl alloys is presented in Fig. 4. As it is observed from the patterns, all samples consist essentially of CuZn phase despite the differences in grain morphology (see Figs. 1 and 2). There are slight shifts in the peak positions for each of the alloy compositions (although less than 2°) which is a common feature in alloys with slightly altered alloying composition (due to the difference in lattice parameters). The analysis of the pattern of the diffracting crystal planes for the entire 2θ diffraction angles and the lattice parameters confirm the CuZn phase to be the β-phase, which from studies has been shown to be martensitic and displays shape memory capacity [35]. There are very small peaks of CuAl and NiAl phases observed from the XRD scan for the Ni modified compositions. These peaks are, however, not well resolved in the plots because of the small intensities. The predominance of the Cu–Zn peaks in the diffractograms as analyzed is in agreement with the EDS results presented in Fig. 3.
Fig. 1. Optical micrographs of (a) unmodified Cu–Zn–Al alloy, and (b) 0.1 wt.% Ni-, (c) 0.2 wt.% Ni-, (d) 0.3 wt.% Ni-, and (e) 0.4 wt.% Ni-modified Cu–Zn–Al alloys.

Table 2
Average lath martensite transverse axis thickness in the CuZnAl alloys produced.

<table>
<thead>
<tr>
<th>Sample designation</th>
<th>Composition</th>
<th>Average lath martensite thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cu–18Zn–7Al</td>
<td>7.9 ± 0.04</td>
</tr>
<tr>
<td>B</td>
<td>Cu–18Zn–7Al–0.1Ni</td>
<td>7.0 ± 0.02</td>
</tr>
<tr>
<td>C</td>
<td>Cu–18Zn–7Al–0.2Ni</td>
<td>3.8 ± 0.02</td>
</tr>
<tr>
<td>D</td>
<td>Cu–18Zn–7Al–0.3Ni</td>
<td>7.1 ± 0.02</td>
</tr>
<tr>
<td>E</td>
<td>Cu–18Zn–7Al–0.4Ni</td>
<td>9.7 ± 0.04</td>
</tr>
</tbody>
</table>
3.2. Mechanical behaviour

3.2.1. Hardness

The hardness values of the unmodified and Ni modified CuZnAl alloys are presented in Fig. 5. It is observed that the hardness values of the CuZnAl alloys with Ni addition, are basically greater than that of the unmodified CuZnAl alloy. The maximum increase is obtained in the 0.2% Ni modified CuZnAl alloy, which corresponds to a 38.4% increase in hardness. The hardness, however, is found decreased with the further increase of the Ni addition, albeit not congruently with Ni concentration. The improved hardness observed in the Ni modified CuZnAl alloys, is attributed to the presence of Ni as micro-alloying addition, which resulted in the reduction of the elongated grain width (i.e. grain thickness) and the modification of grain edge morphology. The 0.2% Ni modified CuZnAl alloy has the highest hardness value, as it is seen in Fig. 1 and Table 2, this sample also contains the finest size grain structure with the smallest grain width, respectively. This improved resistance to indentation with the decreased grain size is in agreement with the Hall–Petch relation [36].

3.2.2. Tensile properties

The stress–strain plots of the unmodified and Ni modified CuZnAl alloys are presented in Fig. 6, while the ultimate tensile strength and percentage elongation plots are presented in Figs. 7 and 8, respectively.

As it can be seen in Fig. 7, the ultimate tensile strength (UTS) of the unmodified and the 0.4% Ni modified CuZnAl alloys show values of 450.85 MPa and 452.62 MPa, respectively; which are lower than the UTS values of the other Ni modified CuZnAl alloys. Compared to the unmodified CuZnAl alloy, tensile strength increases of 9.8, 12.1, 13.7, and 0.4% were obtained with the use of 0.1, 0.2, 0.3, and 0.4 wt.% Ni, respectively. The low tensile strength of the unmodified and 0.4 wt.% Ni modified CuZnAl alloys can be linked to the relatively larger width of the elongated grains in these samples. Also the sharp edges of the grain structure for both samples is another important factor. Sharp tip grain edges usually serve as stress concentration sites which would suggest that the nominal stress acting on the material is considerably amplified to values exceeding its maximum stress bearing capacity at the grain tips [37]. Accordingly, the improved tensile strength of the 0.1, 0.2, and 0.3 wt.% Ni modified CuZnAl alloys, is linked to the finer elongated grain width coupled with the change in the grain morphology to the granular structure (for the 0.1% Ni modified alloy), and the round/elliptical grain edges (for the 0.3% Ni modified alloy). The finer grain structure, round/elliptical grain edges and granular structures observed in these Ni modified CuZnAl alloys, reduce the
tendency of the grain edges to serve as stress concentration sites. Consequently, the nominal applied stress on the alloys must be high to attain the maximum stress bearing capacity values for the process of micro-crack formation and fracture to be heralded in the alloys. The significance of the results is that the addition of between 0.1 and 0.3 wt.% Ni to CuZnAl alloy can enhance the stress transmission/bearing capacity of the alloy.

The percentage elongation of the unmodified and Ni modified CuZnAl alloys are presented in Fig. 8. It is observed that the elongation values of the unmodified and 0.4 wt.% Ni modified CuZnAl

Fig. 3. Representative SE mode images and EDS profiles of (a) unmodified Cu–Zn–Al alloy, and (b) 0.4 wt.% Ni modified Cu–Zn–Al alloy.

Fig. 4. X-ray diffractograms of the unmodified and Ni modified Cu–Zn–Al alloys.
Alloys are almost at the same level (8.5–8.6%). But there is an improvement in the elongation values for the other Ni modified CuZnAl alloys ranging between 10.7–14.3%. The CuZnAl alloy modified with 0.3 wt.% Ni shows the highest elongation value of 14.3%. This implies that the addition of 0.1–0.3 wt.% Ni can result in improved ductility in CuZnAl alloys and hence enhanced plastic workability of these. The reasons for the lower percentage elongation of the unmodified and 0.4% Ni modified CuZnAl alloys, is tied to the sharp tip grain edges, which can restrain plastic deformation due to the triaxial stress state created at such sites. The plasticity restraint makes the alloys more resistant to yielding and hence exhibit less ductility [36]. In the case of the 0.1, 0.2 and 0.3 wt.% Ni modified CuZnAl alloys, the development of a granular structure, fewer sharp edged grains, and curved/elliptical grain edges, respectively; are responsible for the high plastic strain sustaining capacity of these alloys.

3.2.3. Fracture toughness

The fracture toughness of the unmodified and the Ni modified CuZnAl alloys are presented in Fig. 9. It is clearly seen that all the Ni modified CuZnAl alloys except the 0.4% Ni modified composition, show fracture toughness values that are higher than that of the unmodified one. The fracture toughness increase of 13.4, 28, and 12% are obtained for the 0.1, 0.2 and 0.3% Ni modified CuZnAl alloys, respectively, while a 4% decrease in fracture toughness is observed for the 0.4% Ni modified one. These observations imply that the 0.1–0.3% Ni microalloying addition in the CuZnAl alloy improves its resistance to crack propagation, while the 0.4% Ni microalloying addition, is detrimental to the toughness of the CuZnAl alloys. The same reasons attributed to the improved ductility are valid for the improvement in the fracture toughness — that is, the change in the grain edge shape from sharp edged to round/elliptical shape for the 0.1 and 0.3 Ni modified CuZnAl alloys and to the fewer elongated grain structure in the 0.2% Ni modified one. A preponderance of sharp edge grains is known to facilitate the triaxial stress state at the grain tip which suppresses yielding and accentuates brittle fracture susceptibility [21].
3.3. Damping properties

Fig 10 shows the damping capacity, storage modulus, and loss modulus of the unmodified and Ni modified CuZnAl alloys. As it is seen in Fig. 10a, at 1 Hz test frequency only the 0.2% Ni modified CuZnAl alloy shows higher damping capacity values than the unmodified one for the test temperature range of 25 °C–250 °C. The 0.4% Ni modified CuZnAl alloy exhibits the least damping capacity of all the alloys under investigation. The Peak internal friction of 0.43 was obtained at 75 °C for the 0.2% Ni modified CuZnAl alloy, while the unmodified, the 0.1 and 0.3% Ni modified CuZnAl alloys show less obvious damping peaks. A peak internal friction of 0.026 was observed for the 0.4% Ni modified CuZnAl alloy at 225 °C; but this alloy maintains a constant low value of 0.001 from room temperature to about 200 °C.

The same trend is observed for 2 Hz frequency (Fig. 10b) where also the 0.2% Ni modified CuZnAl alloy shows the highest damping capacity for the test temperature range of 25 °C–250 °C. However, a peak internal friction of 0.034, which is lower than 0.043 at 1 Hz is obtained at 50 °C for this 0.2% Ni modified CuZnAl composition. The unmodified alloy exhibits the next highest damping capacity among other alloy compositions, while the 0.4% Ni sample again exhibits the least damping capacity. Damping capacity is associated with the movement and reorientation of martensite variants and

![Graphs showing damping properties](https://example.com/graphs)

Fig. 10. (a) Damping capacity of the unmodified and Ni modified Cu–Zn–Al alloys at 1 Hz test frequency; (b) Damping capacity of the unmodified and Ni modified Cu–Zn–Al alloys at 2 Hz test frequency; (c) Storage modulus of the unmodified and Ni modified Cu–Zn–Al alloys at 1 Hz test frequency; (d) Storage modulus of the unmodified and Ni modified Cu–Zn–Al alloys at 2 Hz test frequency; (e) Loss modulus of the unmodified and Ni modified Cu–Zn–Al alloys at 1 Hz test frequency; and (f) Loss modulus of the unmodified and Ni modified Cu–Zn–Al alloys at 2 Hz test frequency.
interfaces [14]. The results described above, thus, imply that such movement and orientation of the martensite variants are better facilitated in the 0.2% Ni modified CuZnAl alloy than in others. The low damping capacity of the 0.4% Ni modified CuZnAl alloy will accordingly be linked to the restriction of the movement of the parent phase/martensite interfaces and the martensite variants [18]. This may be on the account of the population of the Ni solute atoms which can wield a pinning effect on the boundaries and interfaces. This is why smaller internal friction peaks are observed for the 0.2% Ni modified alloys show peak internal frictions of about 0.015 and 0.013, respectively, at 225 °C.

The E* “storage modulus” (see Fig. 10c and d) as a measure of the capacity of a material to absorb and to store energy induced by vibrations [29] is observed to be stable for the temperature range of 25 °C–250 °C for all alloy compositions, with the exception of the 0.4% Ni modified one, which is observed to exhibit a drastic drop in storage modulus (energy absorption capacity) at about 200 °C. The 0.1% Ni modified CuZnAl alloy shows the highest storage modulus of 130,300 MPa, while the 0.2% modified one has the least storage modulus of averagely 4500 MPa. It is noted that the storage modulus was not affected by the frequency (either 1 or 2 Hz).

The “E*” loss modulus (see Fig. 10e and f) meaning the energy dissipation capacity in form of heat of the material [29] shows an intermittent variable in the temperature range of 25 °C–200 °C, but beyond this temperature, there is continuous increase in the loss modulus with the increase in temperature. The 0.1 and 0.2% Ni modified compositions exhibit higher loss modulus values compared with the others above 200 °C. It is noted that at about 200 °C, there is a dramatic and significant drop in the loss modulus of the 0.4% Ni modified CuZnAl alloy. This suggests that this composition may not be suitable for damping applications.

4. Conclusion

The microstructure, mechanical behaviour and damping properties of unmodified and 0.1–0.4% Ni modified Cu–18Zn–7Al alloys were investigated. Sharp edged elongated grain structures synonymous with the directional solidifications were observed in the unmodified and the 0.4% Ni modified CuZnAl alloys. The grain structure was, however, significantly altered in the 0.1, 0.2 and 0.3% Ni modified CuZnAl alloys, where granular structure, small grain width with fewer sharp edge grains, and curved/round grain edges, respectively, were observed. The mechanical properties of the unmodified and the 0.4% Ni modified CuZnAl alloys were generally lower than those of the 0.1 and 0.3% Ni modified ones. The 0.4% modified CuZnAl alloy showing the lowest damping capacity, does not seem, thus, suitable to serve as a damping material, while the 0.2% Ni modified one exhibits the highest damping capacity among all the CuZnAl alloy compositions.

References