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Development and Characterization of Pseudo-Elastic Ternary Cu-Al-Be Shape Memory Alloy and Its Scope as Shape Memory Hybrid Composites

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Abstract

This research investigated the potential of the Cu-11.95Al-0.51Be shape memory alloy (SMA) for vibration damping applications. This specific composition of the alloy was selected to ensure the presence of the austenite phase (ß-phase) and to evaluate the pseudo-elastic (SE) behavior. This research explores the design, fabrication, and characterization of a pseudo-elastic ternary alloy. The key parameters examined in this study were the alloy phase and pseudo-elastic behavior. Other important factors, such as microstructure, transformation temperatures, and mechanical properties, were also thoroughly analyzed. Characterization techniques employed in this research include X-ray diffraction (XRD), optical microscopy (OM), differential scanning calorimetry (DSC), hardness test (VHN), uniaxial tensile test (UTM), and cyclic tensile tests. This research provides important insights into the potential of this SMA as a hybrid composite, contributing to the improved performance of composite materials. The composites that are embedded with SMAs can possess superior vibration damping capabilities. Results revealed that the ternary Cu-11.95Al-0.51Be SMA exhibits a pure austenite phase at room temperature, which is essential for pseudo-elastic behavior. The results also confirmed a good reversible martensitic transformation and pseudo-elastic behavior of the developed alloy, making it a promising candidate for vibration damping applications.

Keywords: Alloys, Cu-Al-Be SMAs, microstructural properties, mechanical properties, pseudo-elasticity, vibration damping, hybrid composites

INTRODUCTION

Shape memory alloys (SMAs) are a special class of smart materials. These materials exhibit two functional characteristics: the 'shape memory effect (SME)' and 'pseudo-elasticity (SE).' These are unique metallic materials that can regain their original shape or recover large deformations by undergoing a reversible thermo-elastic martensitic transformation. SMAs can regain their original or predefined shape by either changing the temperature or unloading. The ability to regain its original shape by increasing the temperature is known as the 'shape memory effect,' and the ability to recover from a large deformation upon unloading is known as 'pseudo-elasticity' or 'super-elasticity' (SE). These unique features make them attractive for various applications such as actuators, sensors, and vibration damping systems [1].

Microscopically, phase transformation can be defined as the transition from a crystallographic

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phase (martensite) that is stable at low temperatures to a different crystallographic phase (austenite) that is stable at high temperatures. These phase transformations can be characterized by four transformation temperatures, such as A_s (austenite phase start temperature), A_f (austenite phase finish temperature), M_s (martensite phase start temperature), and M_f (martensite phase finish temperature). Crystallographic recoverability or reversibility is characteristic of thermo-elastic martensitic transformation (TMT), which is characterized by thermal hysteresis ($A_f – M_s$).

When SMAs are incorporated into composites, they can offer a wide variety of advantages over existing composites, such as improved mechanical properties, superior energy dissipation capacity, crack healing, and residual strength. Shape memory hybrid composites, or hybrid composites, have emerged as an innovative solution to dampen vibrations in various engineering applications such as aerospace, structural, and automotive sectors, where high specific strength and superior vibration damping capabilities are of utmost importance.

By utilizing the solid-to-solid phase transformation capabilities, composites embedded with SMAs can achieve superior vibration damping capabilities. By mitigating undesired vibrations, these shape memory hybrid composite materials exhibit enhanced performance.

When pseudo-elastic Cu-Al-Be SMAs are integrated into composite materials for vibration damping applications, these shape memory hybrid composite materials exhibit unique energy dissipation mechanisms that enhance the damping capacity of the composite material. This behavior emerges from the special properties of SMAs, such as martensitic phase transformation and super-elasticity.

In this shape memory hybrid composite material, SMAs can undergo stress-induced martensitic transformations under loading, which helps provide damping by the conversion of mechanical energy into thermal energy. Hysteresis in the phase change results in energy dissipation and vibration damping without any external devices or systems. This improves the damping capacity of the composite material. This is a major phenomenon that adds advantages to shape memory hybrid composites over conventional composites. Furthermore, the interfacial friction between SMAs and composites improves energy dissipation. In addition, cracking or permanent deformation under loading in composites can be prevented because SMAs have the ability to undergo large deformation and full recoverability upon unloading.

Naresh et al. [2] demonstrated that the integration of SMA fibers into aluminum metal composites can enhance their energy absorption capacity, ability to heal cracks, and residual strength. In this study, a wire with 0.8 mm diameter wire was reinforced with an aluminum matrix.

From the literature, it is identified that the inclusion of SMA fibers into the Al matrix can be achieved by two methods: adding these SMA fibers to molten aluminum or incorporating them into the mold during casting. Controlled cooling and post-casting heat treatment are important factors that minimize thermal stresses and optimize the mechanical properties, respectively.

Branco et al. [3] developed a promising method to strengthen the walls of old buildings using the hysteretic behavior of wires to reinforce a composite wall.

Shahverdi et al. [4] reported the potential of SMAs for strengthening reinforced concrete structures in cement-based members and investigated their performance using iron-based SMA strips.

Abdulridha and Palermo [5] examined the implementation of a thin shear wall made of SMA steel-reinforced concrete, which showed notable displacement recovery following severe drifts.

Lester et al. [6] presented an extensive review of SMA composite systems that covered metal matrix and ceramic matrix composites and the inclusion of SMAs in polymer composites.

Superelastic SMAs in polymer composites offer a unique and novel solution for vibration damping applications, leveraging the distinctive mechanical properties of SMAs to enhance energy dissipation. SMAs can undergo reversible phase transformations that provide high flexibility, allowing them to absorb and release energy cyclically, which is ideal for mitigating vibration. When embedded in polymer matrices, these materials benefit from the polymer's light weight and flexibility, while gaining the SMAs resilience and adaptive mechanical response. This synergy makes SMA-polymer composites attractive for engineering applications requiring enhanced vibration control, particularly in the aerospace, automotive, and civil engineering fields, where lightweight, durable damping solutions are essential.

Cohade [7] reviewed the applications of SMA wires when incorporated into high-performance fiber-reinforced polymer composite materials (FRPs) and highlighted the critical parameters for the successful integration of SMAs into FRPs.

Although NiTi-based shape memory alloys are the most widely used SMAs, the demand for Cu-based shape memory alloys is growing mainly because of their low cost and ease of processing relative to NiTi SMAs [8]. The first successful applications of SMAs based on the SME were coupled, which were developed for hydraulic systems of F-14 jet fighters by Raychem Corp. The first application of SMAs based on pseudo-elasticity was an orthodontic arch wire [9].

However, the inherent brittleness of binary Cu-Al SMAs limits their application. To overcome this, researchers have explored adding alloying elements, such as Ni, Zn, Be, and Mn, to improve their properties [10]. Among the possible ternary additions to these Cu-based binary SMAs, Cu-Al-Be ternary alloys have gained significant attention because of their attractive properties, such as low and intermediate transformation temperatures, good pseudo-elastic and damping properties, and good corrosion resistance.

The addition of beryllium to Cu-Al SMAs has been reported to enhance their mechanical properties, including strength and ductility, without significantly compromising their shape memory characteristics. This makes Cu-Al-Be ternary alloys particularly attractive for applications requiring both high damping capacity and good mechanical strength, such as vibration damping in aerospace, automotive, and structural engineering.

Higuchi et al. [11] investigated the behavior of martensitic transformation in Cu-Al-Be ternary alloys with a composition range of Al-9.0 to 11.46 and Be-0.77 to 0.59, compared with Cu-Al-Ni and Cu-Zn-Al SMAs, and reported that TMT also appeared in Cu-Al-Be alloys. The results revealed that the Cu-11.46A-l0.59Be SMA exhibited better functional characteristics (shape memory properties) than other SMAs in the selected range of composition.

Montecinos et al. [12] investigated the grain size dependence of the DO_3-18R martensitic transformation start temperature (M_s) and start stress (σ_s) in a Cu-22.66Al-2.98Be (atomic %) alloy and reported that M_s decreases and σ_s increases as the grain size decreases. Nespoli et al. [13] reported that the martensitic transformation temperature of an alloy was significantly lowered by the addition of beryllium. Belkahla et al. [14] reported that the addition of small concentrations of beryllium to Cu-Al alloys close to the eutectoid composition leads to a sharp decrease in the martensitic transformation temperature. Balo et al. [15] characterized two compositions of Cu-Al-Be SMAs and reported that the alloy Cu-11.8Al-0.5Be SMA exhibited superelastic behavior that has the potential for application in seismic-energy control. Araya et al. [16] evaluated the properties of a superelastic Cu-Al-Be SMA under cyclic loading to ensure its potential for applications in seismic control. The results show that nearly ideal superelastic properties can be obtained with an axial strain of up to 3%. Overall, the damping potential of the alloy was moderate, typically less than 5%.

Medina et al. [17] discussed the optimal thermal treatment to improve the mechanical properties of Cu-Al-Be SMA wires for seismic control applications. Four different thermal treatments were applied to four batches of wire specimens. The four specimens were subjected to both cyclic and monotonic axial tests at different ambient temperatures. The test results revealed that a minimum heat treatment time of 25 min at 750 °C was essential for obtaining pseudo-elasticity at ambient temperature. Prashantha [18] investigated the shape memory properties of Cu-Al-Be SMAs in the composition range of 11–14 wt.% of aluminum and 0.4–0.5 wt.% of beryllium. The results revealed that the addition of small amounts of beryllium to the Cu-Al alloy enhanced the corrosion resistance, and the hardness could be improved by decreasing the grain size. The ternary Cu-Al-Be SMAs exhibited good SME (up to 100%), which varied with the variation in the chemical composition of the alloys.

Guniputi (2021) and Narasimha (2022) [19, 20] investigated the properties of Cu-Al-Be SMAs with compositions ranging from Al-11 to 11.85, Be-0.40 to 0.44. Alloys in the hypoeutectoid region (that is, <11.8 wt.% of Al) exhibit a mixture of 'α' and $\beta 1'$ phases, and the eutectoid and hypereutectoid alloys (i.e., ≥11.8 wt.% of Al) form complete $\beta 1'$ martensite. It was also reported that an increase in the weight % of Be forms coexistence of martensite variants ($\beta 1' + \gamma 1'$) in the alloy. $\beta 1'$ martensite has an orthorhombic crystal structure (18R layered configuration), $\gamma 1'$ martensite has monoclinic structure (2H configuration), whereas α is FCC structure. Kalinga [21] reported that the addition of Al ≥ 11.5 wt.% and Be ≥ 0.57 wt.% forms a complete austenite phase ($\beta 1$ phase). The ternary base alloy Cu-11.5Al-0.57Be exhibited a tensile strength of 216.39 ± 30.17 MPa and a ductility of 9.24 ± 0.66%, with intergranular brittle failure. Pseudo-elastic behavior was observed for the composition range Al-11.98 to 12.23, Be-0.55 to 0.57, whereas the martensite phase was observed for the composition range Al-11.08 to 11.98 and Be-0.45 to 0.49.

From the literature, it is identified that there is a gap in evaluating the pseudo-elastic behavior for the composition range of Be-0.50 to 0.55. Therefore, there is scope to investigate the pseudo-elastic behavior of Cu-11.95Al-0.51Be ternary SMA.

Pseudo-elastic Cu-Al-Be ternary SMAs have the scope for vibration damping applications owing to their ability to exhibit pseudo-elastic behavior. Pseudo-elasticity allows for the recovery of large, reversible strains upon unloading, which is crucial for effective damping vibrations. To fully appreciate the potential of this alloy, it is crucial to understand its phase transitions, microstructural evolution, and corresponding thermomechanical properties [22].

The microstructural, thermal, and mechanical properties of the alloys were thoroughly examined to determine their suitability for this purpose. This study focuses on the fabrication and characterization of a novel Cu-11.95Al-0.51Be SMA for vibration damping applications and presents insights for utilizing this alloy as a hybrid composite material. The microstructure, thermal properties, mechanical properties, and functional characteristics of the alloy were investigated using X-ray diffractometer, optical microscope, differential scanning calorimeter, universal testing machine and hardness testing machine The findings of this research confirm the potential of the Cu-11.95Al-0.51Be SMA for vibration damping applications.

MATERIALS AND METHODOLOGY

Materials

Pieces of copper, aluminum, and beryllium copper master alloy (CuBe4) with a purity of 99.9% are shown in Figures 1, 2, and 3, respectively, and were taken in the quantities listed in Table 1.

Table 1. Types of metals and their purity.

S.N.	Metals	Purity (%)
1	Copper (Cu)	99.9
2	Aluminum (Al)	99.9
3	Copper beryllium ($CuBe_4$)	99.9

Figure 1. Copper

Figure 2. Aluminum pellets.

Figure 3. $CuBe_4$ master alloy.

Figure 4. Induction melting furnace with inert gas setup.

Methodology

Sample Preparation

A pseudo-elastic ternary SMA was prepared by vacuum induction melting (VIM).

The mixture of the raw materials was melted in a graphite crucible, which was placed in an induction furnace heating coil chamber under an inert (argon) atmosphere, as shown in Figure 4. The molten alloy was cast into a plate of dimensions 100 mm × 100 mm × 3 mm. To ensure better homogeneity, the cast alloys were re-melted twice. The cast alloys were then subjected to homogenization at 850°C for 4 h in a muffle furnace to ensure a homogeneous distribution of alloying elements and were subsequently air-cooled to room temperature to prevent cracking (Figure 5).


Figure 5. Alloy plate.

Specimen Preparation

Alloy specimens were extracted from homogenized cast plates using a wire electrical discharge machine (WEDM) for microstructural, tensile, and cyclic tensile tests, and a low-speed diamond cutting machine for differential scanning calorimetry (DSC) tests to determine the phase transformation temperatures of the alloys in this study.

Betatization and Quenching

From the literature, it was observed that the transformation temperature and grain size increased with increasing betatization temperature and duration. Among different betatization treatments, such as 850°C/15 min, 850°C/30 min, 900°C/15 min, and 900°C/30 min, it was observed that the betatization treatment at 850°C for 15 min resulted in good recovery of the SMAs [19].

The rapid quenching of Cu-Al-X (where, X = Ni, Be, and Mn) SMAs from the high-temperature phase to room temperature forms metastable phase austenite or martensite variants, depending on the wt.% of Al and the ternary element.

In this study, flat dog-bone-shaped specimens were prepared for uniaxial tensile and cyclic tensile 7tests on a cast alloy plate. The specimens were betatized/annealed at 850°C for 15 min in a muffle furnace and then rapidly quenched in water at room temperature.

Characterization

The following characterization techniques were employed to investigate the properties of the Cu-11.95Al-0.51Be alloy:

- *Compositional analysis:* The elemental composition of the homogenized SMAs was determined using an optical emission spectrometer (OES). The spark ignited at different locations on the plate, and the average of the readings was the final value of the composition.
- *Phase identification:* The phases existing in the SMAs after performing the betatization and quenching processes, and their crystal structures, were determined using an X-ray diffractometer. The phases that existed in the evaluated alloys were identified by X-ray diffractometer and X'Pert HighScore software. From the literature, it is known that depending on the wt.% of Al and ternary element, the rapid quenching of Cu-Al-X (X =Be, Mn, and Ni) SMAs from high-temperature ‘β’ (A2) phase to room temperature forms metastable phase ‘β_1’ (DO_3) austenite or ‘β'_1’ (18R) and Υ'_1 (2H) martensite.
- *Microstructural analysis:* The microstructure of the prepared alloy was examined using optical microscopy (OM). The samples for microscopy were prepared using fine polishing. Subsequently, the specimens were etched using an etchant. Acetone was used to clean the etched samples properly, and their microstructures were examined using OM.
- *Thermal analysis:* DSC was used to determine the transformation temperatures of the alloys. The SMA specimens were extracted from the alloys using a low-speed diamond cutter. The martensite phase and austenite phase transformation temperatures were determined from the first cooling and second heating cycles, respectively, with a heating/cooling rate of 10°C/min.

The martensite phase transformation temperatures (M_s, M_f) and austenite phase transformation temperatures (A_s, A_f) are determined from the thermograms by adopting the baseline tangent method. From the area under the phase transformation cycles of the DSC curve, the enthalpy change (ΔH) was measured. Enthalpy is defined as the chemical energy needed for phase transformations (Figure 6).

As the name suggests, '$\Delta H_{M \to A}$' takes place when heat energy is added for the reverse martensitic transformation and is preceded by a positive sign, indicating an endothermic reaction, whereas '$\Delta H_{A \to M}$' occurs when heat energy is removed for the forward martensitic transformation and is preceded by a negative sign, indicating an exothermic reaction.

- *Mechanical properties:* The mechanical properties of the alloys were determined by uniaxial tensile tests using a universal testing machine (UTM). The tensile tests were conducted at a strain rate of 1 mm/min. Hardness tests were performed using a Vickers hardness testing machine.
- *Functional characterization:* Pseudo-elasticity (SE) is defined as an unloading-based shape recovery. This parameter can be determined through cyclic tensile tests using universal testing machines. The cyclic tensile tests were performed at a crosshead speed of 0.5 mm/min.

The data obtained from these characterization techniques were analyzed to evaluate the suitability of the Cu-11.95Al-0.51Be alloy for vibration damping applications.

RESULTS AND DISCUSSIONS

Phase Identification

The prepared ternary Cu-Al-Be SMA samples were betatized at 850°C for approximately 15 min and then rapidly quenched in water at room temperature.

The phases present in the evaluated alloys were analyzed by X-ray diffractometer using X'Pert HighScore software and are presented in Figure 7. The existence of a pure austenite phase was identified from the diffractogram. It was further revealed that Cu-Al-Be SMAs with a composition range between the hypoeutectoid and hypereutectoid regions exhibit a pure austenite phase.

Microstructure

Optical micrographs were captured from the ternary SMA samples, and the microstructure is shown in Figure 8. It can be observed from this Figure that the ternary alloy consisted of coarse grains.

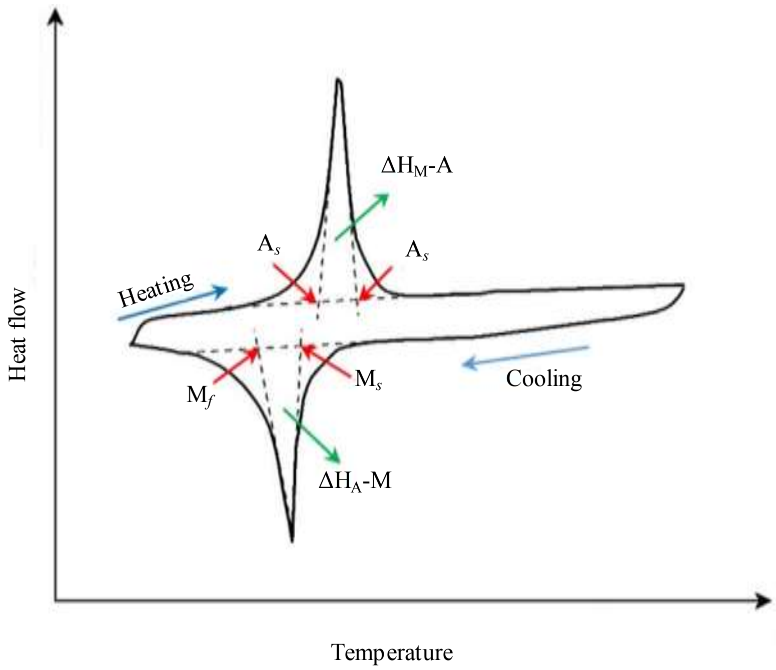

Figure 6. Schematic of the measurement for phase transformation temperatures from DSC curves.

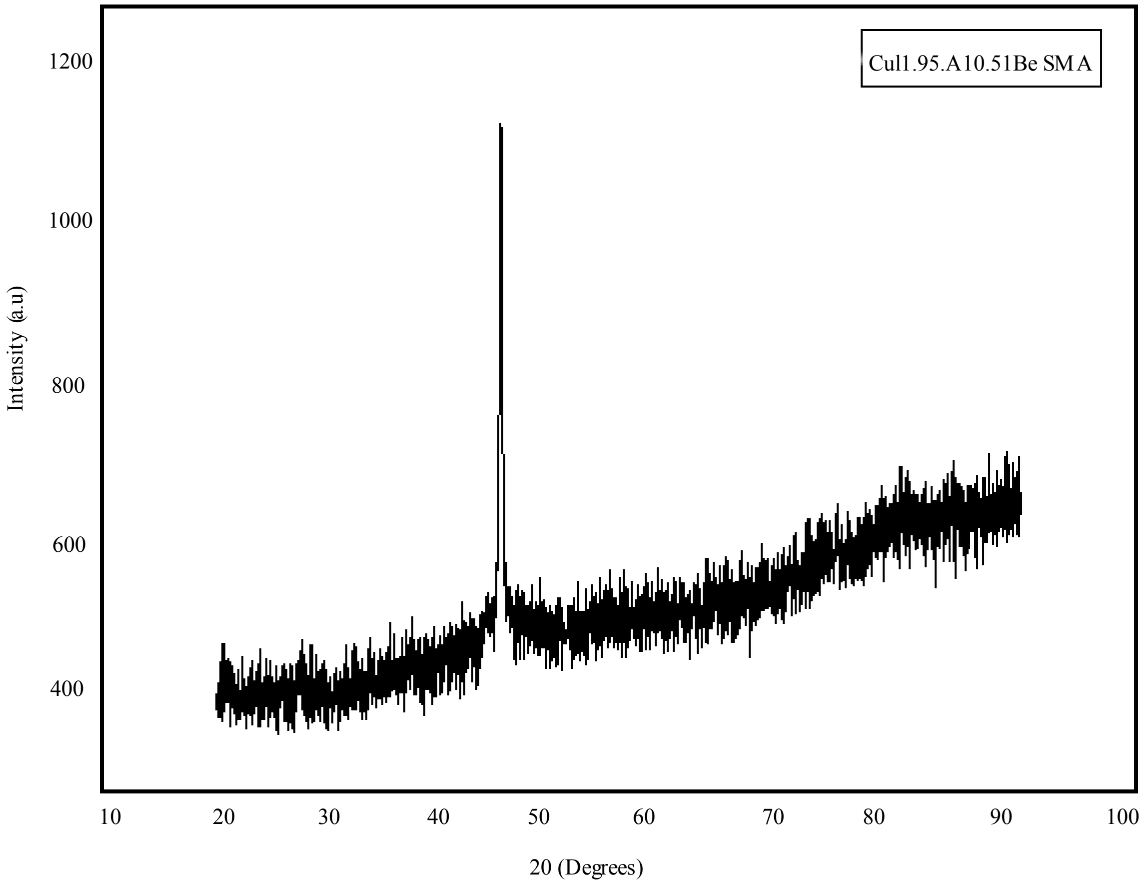

Figure 7. X-ray diffractogram of ternary shape memory alloy (Cu-Al-Be).

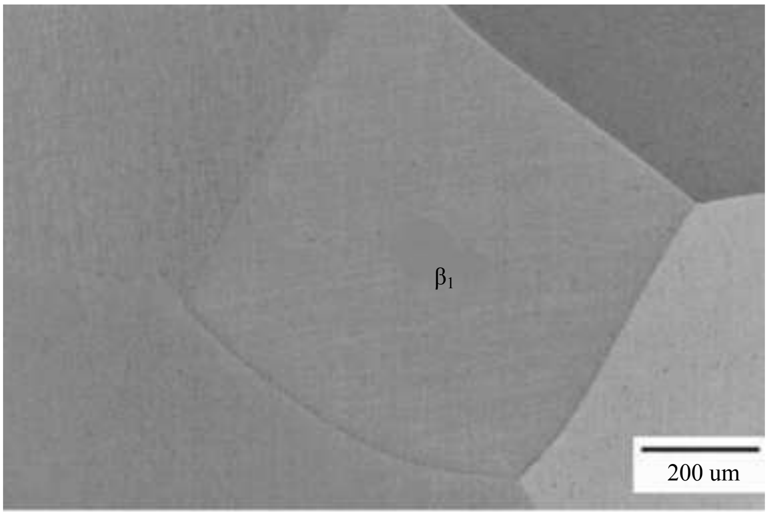

Figure 8. Microstructure of a ternary alloy.

Figure 8 depicts that ternary SMA possesses a complete austenite ($\beta 1$) phase. It was also confirmed with an X-ray diffractogram.

Transformation Temperatures

The transformation temperatures, enthalpies, and hysteresis of the betatized and quenched Cu-Al-Be SMAs were measured using DSC and enthalpy (ΔH) from the area under the curve, and the results are depicted in Figure 9.

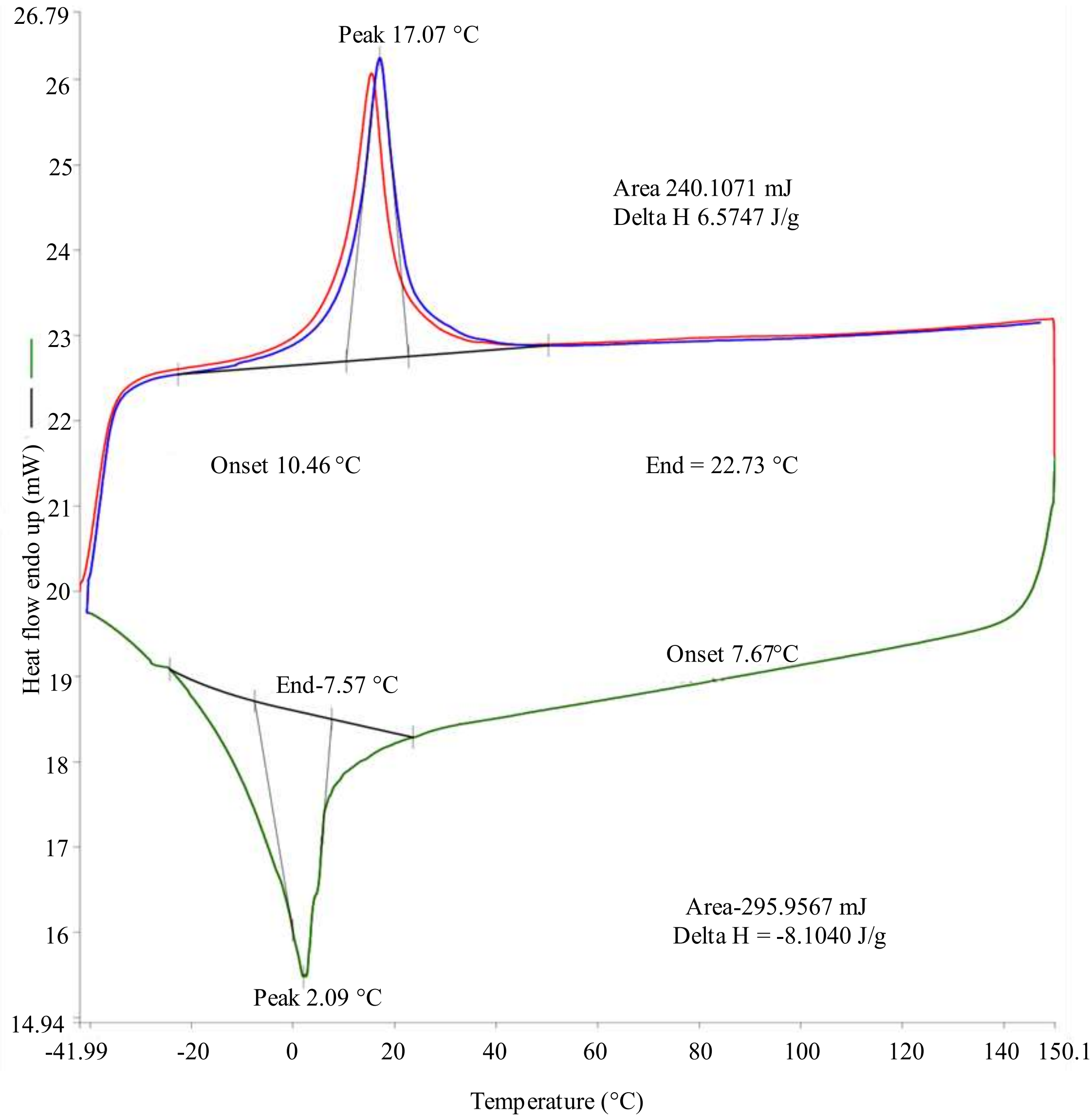

Figure 9. Thermogram of ternary SMA.

Table 2. Transformation temperatures, enthalpies, and hysteresis of ternary alloys.

Transformation temperatures (°C)		**Hysteresis (A_f – M_s) (°C)**	**ΔH$_{M\rightarrow A}$(J/g)**	**ΔH$_{A\rightarrow M}$(J/g)**
M_s	7.67	15.06	6.57	-8.10
M_f	-7.57			
A_s	10.46			
A_f	22.73			

The obtained phase transformation temperatures of the martensite (M_s, M_f) and austenite (A_s, A_f) phases of Cu-Al-Be ternary alloy are represented in Table 2.

From the obtained results, it can be reported that the Cu-11.95Al-0.51Be SMA has potential for room temperature applications, as it exhibits phase transformation near ambient temperature. The hysteresis, defined as the difference between the austenite finish temperature and martensite start temperature (A_f – M_s), is 15.06°C. A larger thermal hysteresis results in greater energy dissipation; hence, this alloy, with a hysteresis of 15.06°C, is well suited for vibration damping applications.

Mechanical Properties

The tensile strength can be analyzed by the results of the tensile tests, and the maximum tensile stress up to which the material can withstand the load without fracture can be determined.

The mechanical properties, that is, the ultimate tensile strength and ultimate tensile strain, of the alloys were determined by uniaxial tensile tests. The mechanical properties of the SMAs that exhibited the austenite phase at room temperature were evaluated.

Figure 10 shows the stress versus strain graph, which depicts the yield point and ultimate tensile strength. The results of the tensile tests are listed in Table 3.

From the results obtained from the uniaxial tensile test, it was observed that this alloy possesses good mechanical properties and can be reported that this alloy can sustain heavy loads and can be deformed before fracture.

The hardness of the ternary alloys was determined using a Vickers hardness testing machine, as shown in Figure 11. The hardness values obtained from the tests are presented in Table 4.

Table 3. Mechanical properties of a ternary alloy from uniaxial tensile test.

S.N.	Mechanical properties	
1.	Ultimate tensile strength (MPa)	339.9
2.	Ultimate tensile strain (%)	14.64

Table 4. Hardness of ternary shape memory alloy.

S.N.	Material	Vickers' hardness number (VHN)
1	Cu-11.95Al-0.51Be SMA	292.2

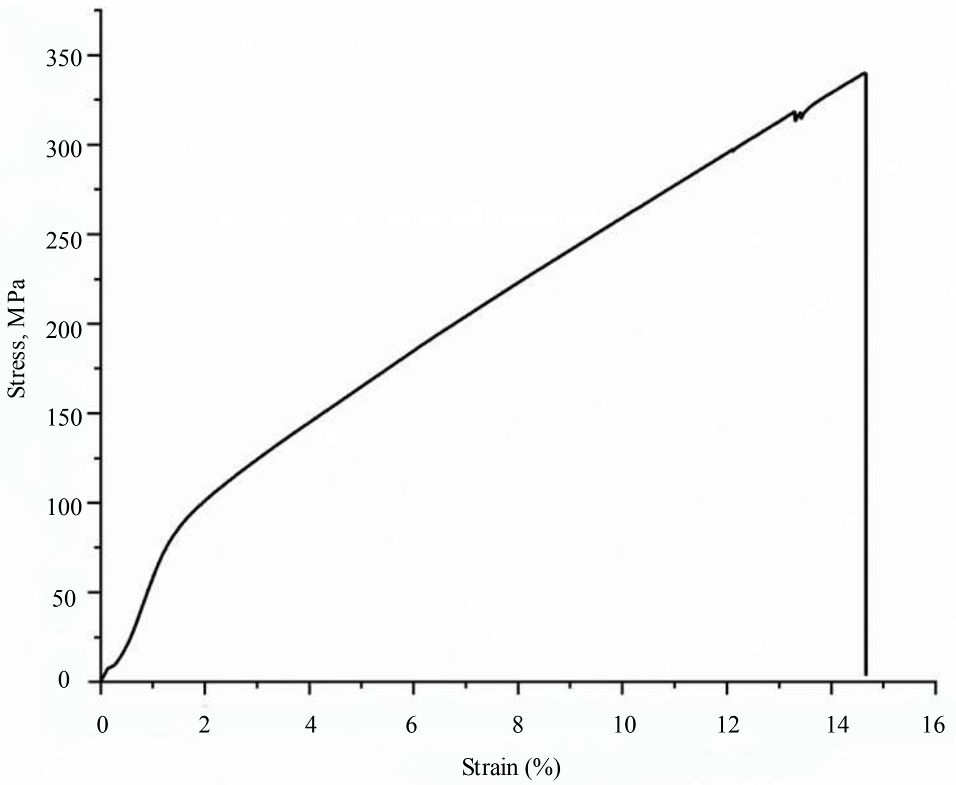

Figure 10. Stress–strain curve of ternary SMA.

Pseudo-Elastic Behavior

The pseudo-elastic behavior of the alloy was assessed through cyclic tensile tests, that is, cyclic loading-unloading tensile tests at room temperature using a UTM. The pin-loaded flat dog-bone specimens, shown in Figure 12, were prepared for the cyclic tensile test with the dimensions listed in Table 5. The effects of cyclic loading and unloading were investigated to evaluate pseudo-elastic behavior. Figure 13 shows the stress–strain hysteresis curve of the cyclic tensile tests on the Cu11.95Al0.51Be ternary alloy for deformation strains of 2–6%.

Figure 11. Vickers hardness testing machine.

Figure 12. Flat dog-bone shape specimen prepared for cyclic tensile tests.

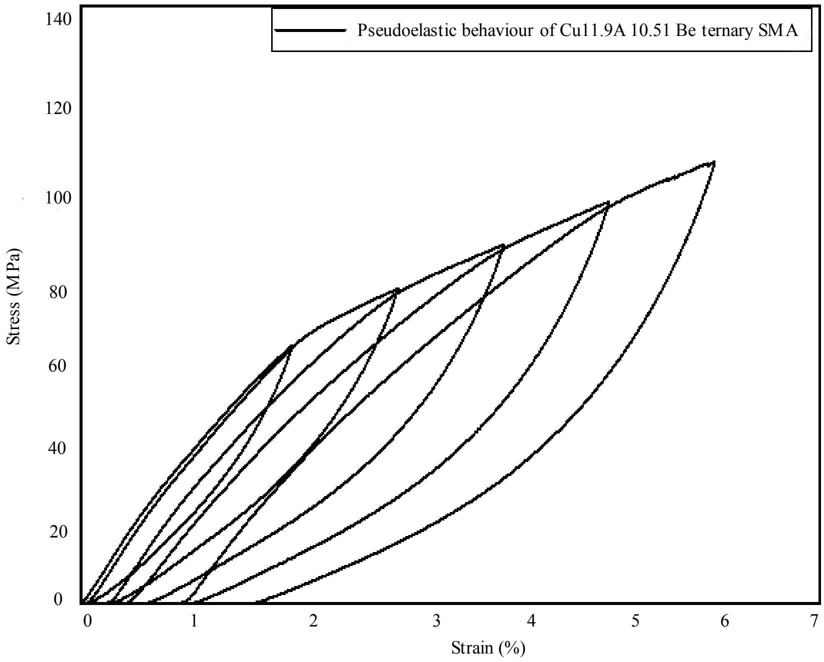

Figure 13. Stress–strain curve of cyclic tensile tests.

Table 5. Dimensions of a flat dog-bone shape specimen prepared for cyclic tensile tests.

S.N.	Specimen dimension (unit)	Value
1.	Total length (mm)	60
2.	Gauge length (mm)	25
3.	Gauge width (mm)	6
4	Thickness (mm)	3
5	Gripping length (mm)	15
6.	Gripping width (mm)	10
7	Hole diameter (mm)	6

From the obtained plot, the critical stress required to induce martensitic transformation and recoverable strain were evaluated. The critical stress was evaluated as the stress corresponding to the deviation from the initial linear elastic behavior of the stress–strain curve.

From the obtained results, it is noted that the values of the critical stress (σ_{cs}) of stress-induced transformation during loading and reverse transformation during unloading are not the same, which indicates hysteresis in the stress–strain curve. This hysteresis represents a dissipation of energy during a loading-unloading process that represents its potential for vibration damping applications. The cyclic tensile tests have been performed on the alloy in the range of 2–6% of deformation strain, and results revealed that it exhibits a significant pseudo-elastic behavior up to the strain of around 4% with a small residual strain (Figure 14).

Cyclic loading with the increasing deformation strain beyond 4% leads to a decrease in σ_{cs} and an increase in the strain retained upon unloading. The presence of residual strain upon unloading indicates the existence of martensite in the material.

Scope of Applications

The Cu-11.95Al-0.51Be SMA is a pseudo-elastic shape memory alloy that can undergo large, reversible deformation under loading through stress-induced martensitic transformation. Therefore, it exhibits potential in vibration damping applications. It has the potential to emerge in the aerospace, automotive, and structural engineering fields, but its use in the biomedical field is limited owing to the toxic nature of beryllium. Some important applications of this method are described below.

- Vibration dampers in aircraft panels and frames (passive vibration control).
- Smart morphing structures (shape changes with reversible deformation under aerodynamic loads).
- Actuation-enabled fasteners or connectors (shape-changing couplings with respect to external stimuli).
- Crash-energy absorbers (integrated into bumpers for energy dissipation).
- Vibration control in engine mounts or suspension systems (reduces vibrations induced by engine/road).
- Smart adaptive body panels (deformation under minor collisions can be recovered).
- Seismic dampers in civil structures (energy dissipation in bridges, buildings, and towers during earthquakes).

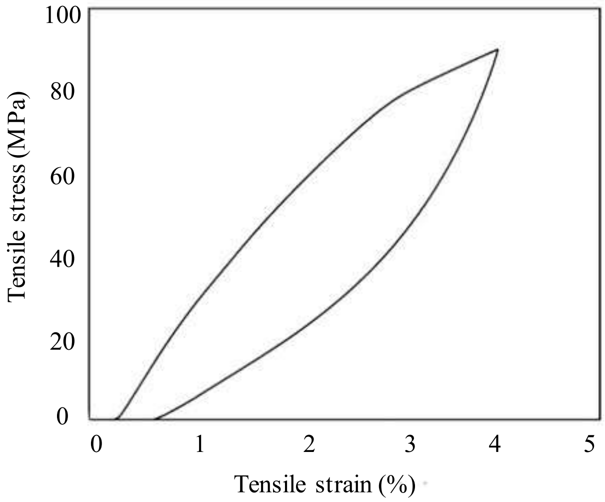

Figure 14. Stress–strain hysteresis curve of the ternary alloy for the deformation strain of 4%.

Advantages of Cu-11.95Al-0.51Be Over the Other Cu-Al-Be SMAs

The Cu-11.95Al-0.51Be pseudo-elastic SMA is advantageous compared with other Cu-Al-Be alloys because of its optimized superelastic behavior at ambient temperature, high recoverable strain and vibration damping, enhanced cyclic fatigue resistance, and better thermal stability.

These important characteristics of Cu-11.95Al-0.51Be SMAs make them suitable for vibration damping systems to absorb and dissipate mechanical energy during vibrational loading. It can provide high performance and serve as an economical alternative to NiTi SMAs.

Cu-Al-Be SMAs with a compositional range of 11.08 to 11.98 wt.% and Be 0.45 to 0.49 wt.% exhibits martensite phase, and beyond this range exhibits austenite phase. However, this research reported that within the compositional range of Al (i.e., 11.08 to 11.98 wt.%), the alloy can exhibit pure austenite by adding 0.02 wt.% of Be, which is a very slight increase.

Table 6 shows that the alloys with aluminum near and more than 11.90 wt.% and beryllium near to and more than 0.50 wt.% exhibit pure austenite phase, which is responsible for pseudo-elasticity.

Table 7 compares the phase transformation behavior of the developed pseudo-elastic Cu-11.95Al-0.51Be SMA with other pseudo-elastic Cu-Al-Be SMA, which have a near compositional range.

From Table 7, observed that the Cu-11.98Al-0.55Be SMA has a lower transformation enthalpy (ΔH), whereas the Cu-11.95Al-0.51-Be SMA has a higher transformation enthalpy (ΔH), which indicates that the Cu-11.95Al-0.51-Be SMA is more suitable for vibration damping applications. The phase transformation in the Cu-11.95Al-0.51Be SMA occurred near room temperature, which makes it more practical.

Table 6. Examination and comparison of phases present in Cu-11.95Al-0.51Be SMA and other Cu-Al-Be SMAs have a near compositional range.

S.N.	Cu-Al-Be SMAs with compositional range (wt.%)		Phases present in the alloy
1.	Cu-11.95Al-0.51Be SMA		Austenite phase (SE)
2	Cu-Al-Be SMAs (Al=11.08 to 12.23, Be=0.45to 0.57)	Al=11.08 to11.98, Be=0.45 to 0.49	Martensite phase
		Al-11.98 to12.23, Be-0.55 to 0.57	Austenite phase (pseudo-elastic behavior)
3	Cu-Al-Be SMAs (Al-11.0 to11.85, Be-0.40 to 0.44)	Region of hypoeutectoid (i.e., <11.8 wt.% of Al)	Exhibit a mixture of ‘α’ and $\beta 1'$ phases
		The eutectoid and hyper-eutectoid alloys	Complete $\beta 1'$ martensite.
4	Cu-11.53Al-0.49Be SMA	Mixture of both austenite and martensite phases	
5	Cu-11.8Al-0.5Be SMA	β′ martensite phase (18R structure)	
6	Cu-11.98Al-0.55Be SMA	Pure austenite phase of cubic ($\beta 1 - DO3$) structure	

Table 7. Comparison of phase transformation behavior of Cu-11.95Al-0.51Be SMA with other near pseudo-elastic SMAs.

S.N.	Pseudo-elastic Cu-Al-Be SMA	Transformation temperatures (°C)			Hysteresis (°C)		$\Delta H_{M \rightarrow A}$(J/g)	$\Delta H_{A \rightarrow M}$(J/g)
		M_s	M_f	A_s	A_f	$(A_f - M_s)$		
1.	Cu-11.95Al-0.51Be SMA (wt.%)	7.67	-7.57	10.46	22.73	15.06	6.57	-8.10
2.	Cu-11,98Al-0.55Be SMA (wt.%)	-25.13	-27.96	-18.95	-10.40	14.73	6.01	-1.45

Table 8. Comparison of the mechanical properties of Cu-11.95Al-0.51Be SMA with other near pseudo-elastic SMAs.

S.N.	Pseudo-elastic Cu-Al-Be SMA	Ultimate tensile strength (MPa)	Ultimate tensile strain (%)
1.	Cu-11.95Al-0.51Be SMA (wt.%)	339.9	14.64
2.	Cu-11.98Al-0.55Be SMA (wt.%)	216.39	9.24

A wide hysteresis denotes the capacity to absorb more vibrational energy. From Table 7, the Cu-11.95Al-0.51Be SMA has slightly more hysteresis, with a difference of 0.33. Thus, it can be reported that the Cu-11.95Al-0.51Be SMA is well suited for vibrational damping applications.

Table 8 compares the mechanical properties of the pseudo-elastic Cu-11.95Al-0.51Be SMA with other pseudo-elastic Cu-Al-Be SMA, which have a near compositional range.

From Table 8, it can be observed that the Cu-11.95Al-0.51Be SMA has a higher strength and ductility than the Cu-11.98Al-0.55Be SMA, with a difference of 123.51 MPa in strength and 5.4% in ductility.

Owing to its superior thermal and mechanical performance, the Cu-11.95Al-0.51Be SMA is a good option for vibration damping applications in aerospace, automotive, and civil structures.

CONCLUSIONS

This study explored the potential of a Cu-Al-Be SMA for vibration damping applications, focusing on its design, development, and characterization. The key conclusions drawn from the present investigation are as follows.

1. Cu-11.95Al-0.51Be wt.% SMA was prepared using the induction melting technique, and that exhibited pure austenite phase at room temperature, which is an essential characteristic of the alloy to possess pseudo-elastic behavior.
2. The microstructure was observed using an optical microscope, which revealed that the ternary alloy consisted of coarse grains and exhibited a complete austenite phase, which was confirmed by X-ray diffractometer.
3. The transformation temperatures of the martensite (M_s, M_f) and austenite (A_s, A_f) phases of Cu-11.95Al-0.51Be ternary alloy were 7.67°C, -7.57°C, 10.46°C, and 22.73°C, respectively. The thermogram of the ternary SMA exhibits a sharp endothermic peak that indicates the rapid transformation of martensite to austenite owing to the composition of Al near the eutectoid.
4. The ultimate tensile strength and tensile strain were determined using uniaxial tensile tests, and the obtained values were 339.9 MPa, 14.64%, respectively. The hardness of the ternary alloy was determined by using a Vickers hardness test, and the obtained value was 292.2 VHN. These test results indicated an improvement in the mechanical properties of the Cu-11.95Al-0.51Be ternary alloy.
5. Pin-loaded flat dog-bone specimens were prepared for cyclic tensile tests. A cyclic tensile test was performed, and the reverse martensitic transformation was observed up to a deformation strain of approximately 4%. Cyclic loading with the increasing deformation strain beyond 4% leads to a decrease in σ_{cs} and an increase in the strain retained upon unloading.

These ternary Cu-11.95Al-0.51Be SMAs exhibit good reverse martensitic transformation with good mechanical properties; hence, these findings suggest that this alloy has potential for vibration damping applications, and the integration of this alloy can improve the properties of conventional composites. Furthermore, the properties of the composites infused with these SMAs can be investigated by varying the volume percentage of the fibers. Further, there is scope to improve the functional properties of Cu-Al-Be ternary alloys by the addition of quaternary alloying elements, manganese, and incorporation into polymer composites for superior performance in vibration damping applications, where the specific strength is the most important.

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