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Improving Thermal and Mechanical Properties of Cu-Al Based Alloy Used for High-Temperature Applications (A Review)

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Abstract:- Despite the increased usage of composite materials, high-strength aluminum alloys maintain significance in airframe construction. Aluminum's attributes of being lightweight, relatively low-cost, heat-treatable, and capable of withstanding high-stress levels contribute to its continued importance. These properties also reduce manufacturing and maintenance costs compared to other high-performance materials. Recent advancements in aluminum aircraft alloys have enabled them to compete effectively with modern composite materials. This study delves into the latest developments, focusing on improving the mechanical properties of aluminum alloys and utilizing high-performance joining techniques. Cu-Al-based alloys represent a new class of functional materials. Due to their unique thermoelastic martensite structure, their exceptional damping performance has garnered attention in materials science and engineering. However, challenges such as elastic anisotropy and larger grain sizes can lead to brittle fractures, impacting the material's mechanical properties. It is widely acknowledged that achieving a finer grain size is pivotal when creating Copper Aluminum alloys with exceptional mechanical attributes and effective damping characteristics. Smaller grain sizes allow for the combined use of fine grain strengthening and interfacial damping, resulting in alloys demonstrating exceptional overall characteristics. This paper presents several standard approaches for preparing Copper Aluminum alloys, subsequently examining research efforts dedicated to enhancing grain size through alloying and heat treatment. Moreover, nanomaterials are being investigated as potential agents for reinforcing Cu–Al-based alloys, leading to substantial improvements in their mechanical characteristics and damping capacities. The study aims to serve as a valuable reference for future research in developing structure-function integrated materials capable of simultaneously offering high strength and high damping characteristics.

***Keywords**:- Cu-Al Alloy, Damping Alloys, Strengthening Elements, Heat Treatments.*

I. INTRODUCTION

Altering the microstructure by applying heat or using alloys can enhance mechanical and damping qualities. The characteristics of copper-aluminum-based alloys are mainly affected by the β-phase at elevated temperatures and are strongly associated with the composition and amount of alloying elements present. Modifying the size of the grains, enhancing the dispersion strengthening, and inducing the martensitic transformation (MT) behavior are the key elements that will improve the damping and mechanical characteristics through alloying [1], [2].

Damping alloys are broadly employed in various industries, including automotive, optical instruments, and military sectors, due to their exceptional capacity to diminish vibrations and noise efficiently [2], [3]. Conventional damping alloys, like Fe-based alloys, Mn–Cu alloys, and Ti–Ni alloys, possess several drawbacks, including costly raw materials, challenging manufacturing processes, or a heavy dependence on magnetic fields. These constraints constrain its utilization in specific applications [4], [5]. Copper-aluminum damping alloys have attracted considerable attention and can overcome the problems. Due to their distinctive thermoelastic martensitic structure, they possess remarkable damping properties, rendering these alloys extremely useful [6]. The impressive capability to damp vibrations is attributed to various mechanisms, including the following: the movement of defect pairs, dislocation relaxation, dislocation-point defect interaction, and the Planar interface motion, including that of phase interfaces grain boundaries and twins [6], [7]. Despite the favorable damping properties of the Copper Aluminum-based alloy, it exhibits strong elastic anisotropy, high order, relatively low fatigue strength, a propensity for cracking along the crystal plane, and large grain sizes. These characteristics do not enhance its mechanical properties [8], [9]. Generally, there is an inverse correlation between mechanical properties and damping performances [10], [11]. However, it is crucial to guarantee desirable mechanical and damping characteristics to apply damping alloys effectively in practical situations. Presently, researchers have diligently sought the advancement of Copper Aluminum alloys that exhibit exceptional damping capabilities and desirable mechanical traits by the incorporation of alloying elements or the refinement of grain size via heat treatment [12].

➢ *Copper - Aluminum Binary Phase Diagram*

Comprehensive knowledge of the crystal structure and phase diagram is crucial for improving the performance of the desired metal. Figure 1 displays the Copper Aluminum phase diagram, which indicates that the Copper-Aluminum alloy exhibits a solitary β phase, which has a body-centered cubic structure at temperatures over 565°C, provided that the atomic concentration of the Al element falls within the range of 20 to 30% [13], [14]. Throughout the cooling process, the high-temperature β phase undergoes orderly transitions to the β2 phase and then to the β1 phase as the temperature decreases. Ordered transitions can still occur despite rapid cooling. The phases characterized by higher Al content, β2 (CuAl: B2) and β1 (Cu3Al: DO3), exhibit highly ordered structures [14]. At a state of equilibrium, phase β will undergo a eutectoid reaction at a temperature of 565°C, resulting in its breakdown into the phases α and γ2 [15]. The α phase is created when aluminum dissolves into Copper, resulting in a solid solution with a face-centered cubic structure (FCC) and a comparatively low hardness level.

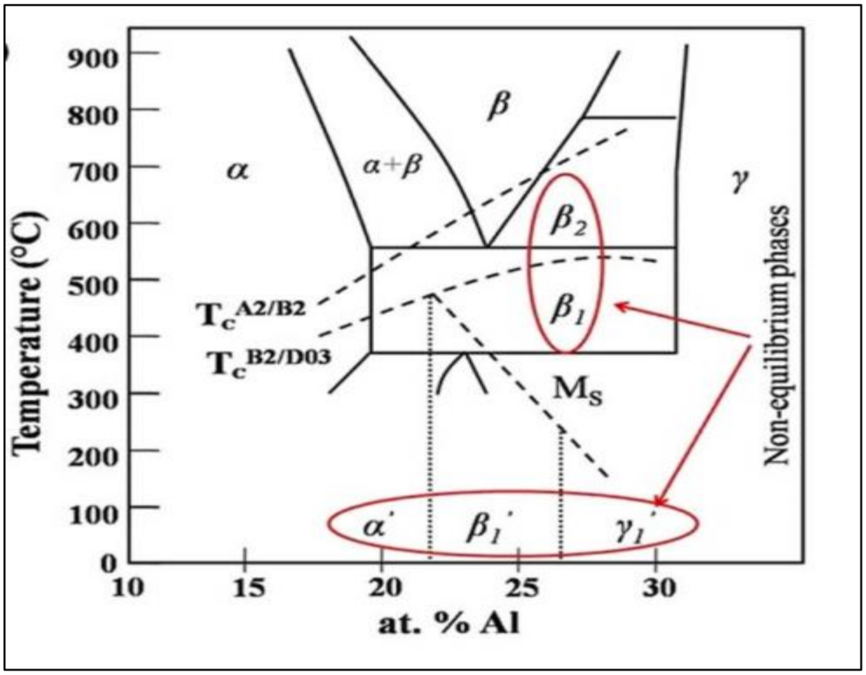

Fig 1: Copper-Aluminum Binary Phase Diagram.

II. FABRICATION OF COPPER-ALUMINUM BASED ALLOY

The preparation process of a material is widely recognized as a critical factor in determining its microstructure, which in turn has a significant impact on its qualities. Hence, it is imperative to employ appropriate preparation techniques to achieve the necessary characteristics. The following text will concisely overview several techniques for preparing Copper-aluminum based alloys. It mainly includes traditional casting methods that are well-established and straightforward, in addition to the more modern mechanical alloys and powder metallurgy techniques that have developed in recent years.

There has been a significant growth in the use of Aluminum castings in the automobile sector, transitioning from non-structural implementations, such as cylinder heads and engine blocks, to encompassing structural elements like suspension struts. This shift is attributed to the advantageous outcomes achieved by combining the benefits of lightweight construction with desirable mechanical qualities [16], [17]. Aluminum and copper alloys are widely regarded as highly viable substitutes for structural components due to their inherent internal soundness, structural integrity, exceptional strength, and remarkable toughness. Nevertheless, the constraints of casting alone are inadequate for enhancing the grain size. Consequently, incorporating alloying components into the casting process is an efficient approach to diminishing the grain size. Scientific investigations have shown that adding elements belonging to category IV, including Zr, Ti, Cr, B, and V, to the Copper Aluminum Nickel alloy significantly improves its mechanical properties [18].

Al-Cu can be produced with a functional gradient utilizing powder metallurgy technology, which allows for examining the material's composition, microstructure analysis, and mechanical properties. A novel methodology was discovered. The solution-precipitation method successfully produces graded materials with a dispersed and homogeneous microstructure in the matrix material preparation process [19].

Subham Kundu et al. [20] employed the powder metallurgy technique to produce an Aluminum metal matrix composite comprising varying weight percentages of Copper, specifically 10%, 20%, and 30%. The powder metallurgy methodology is utilized to attain the efficient dispersion of copper powder via the ball milling procedure. The provided SEM image depicts the spatial arrangement of copper particles in conjunction with Aluminum powder. Copper is used as a binding agent to enhance hardness during testing using a Rockwell hardness tester.

Mechanical alloying (MA) is a method employed to process powders, utilizing mechanical forces to induce alloy formation in which powder particles are repeatedly welded, fractured, and re-welded within a high-energy ball mill. Its research aimed to produce oxide-dispersion strengthened (ODS) superalloys, mainly composed of nickel and iron, designed explicitly for use in the aerospace industry [21]. Various techniques have been proposed to prevent or reduce it. The current comprehension of the modeling of the MA process has also been deliberated. This text describes the current and future applications of MA. Whenever feasible, the product phases achieved using MA have been compared with those acquired through rapid solidification processing, which is another non-equilibrium processing technique. Figure 2 depicts the microstructures of the original elemental powders. Copper powders exhibit an agglomeration morphology, whereas Aluminum and nickel powders possess spherical and very homogeneous morphologies. Figure 3(a–d) depicts the changes in the shape and structure of the milled powders during different milling durations. The MA technique comprises cold welding and fracturing as its primary stages. During the initial phase of the MA method, the powders undergo a micro-forging process that results in their flattening into platelet shapes. Subsequently, the powders transform their microstructure, resulting in a lamellar structure because of recurrent cold welding caused by high-energy impacts. Additionally, it is worth mentioning that the layers that have been created are characterized by their substantial thickness and lack of structural uniformity. As the milling process continues, the thickness of the layers diminishes, and the laminated structure becomes discontinuous [22].

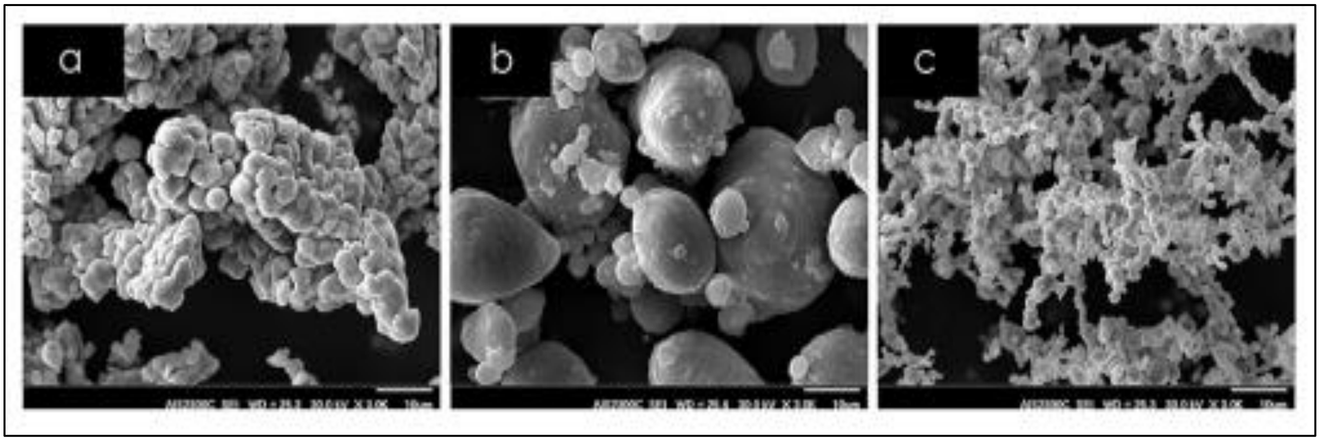

Fig 2. Initial Elemental Powder SEM pictures (a) Copper, (b) Aluminum, and (c) Nickel [22].

The hot pressing (HP) manufacturing technique creates dense alloys with minimal waste [23]. Additionally, this strategy offers the benefits of increased manufacturing efficiency and consistent product organization. The alloy is composed of Cu, 14.2 Al, and 4.2 Ni and was fabricated by Rodríguez et al. [24] with favorable malleability by subjecting it to hot pressing at a temperature of 900°C for 1 hour. Evidence demonstrates that employing the suggested powder metallurgy technique and high-temperature hot-rolling generates a distinct microstructure that can potentially optimize the ductility and thermo-mechanical properties of Copper, aluminum, and nickel alloys. The primary feature of this microstructure is the abundance of low-angle sub-grains, resulting in an efficient distribution of stress along the borders between grains. Sub-boundaries consist of super dislocations and can absorb dislocations in motion. Vajpai et al. [25] improved the qualities of Cu-Al-Ni alloy by using this approach; these included a smaller grain size and higher fracture strength. The shape memory alloy (SMA) strips made of Copper, Aluminum, and nickel, with an average grain size of around 27 µm, were effectively manufactured via hot densification rolling of unsheathed sintered powder preforms. These preforms were created from pre-alloyed Copper Aluminum Nickel powder atomized with argon. A negligible rise in grain size was observed after subjecting the hot rolled and completed Copper Aluminum Nickel strips to a heat treatment at a temperature of 950 °C for 4 hours. The minimal increase in grain size seen during the heat-treatment process was caused by the restraining influence of nano-sized alumina particles that accumulated along the borders between the grains.

Furthermore, the choice of hot-pressing temperature significantly impacts the characteristics of the alloy [26]. Utilizing HIP is a significant technique for acquiring compact materials with exceptional performance. The technique involves subjecting the product to uniform pressure and high temperature in all directions, resulting in high-density products with increased internal density under high temperature and pressure conditions [27], [28].

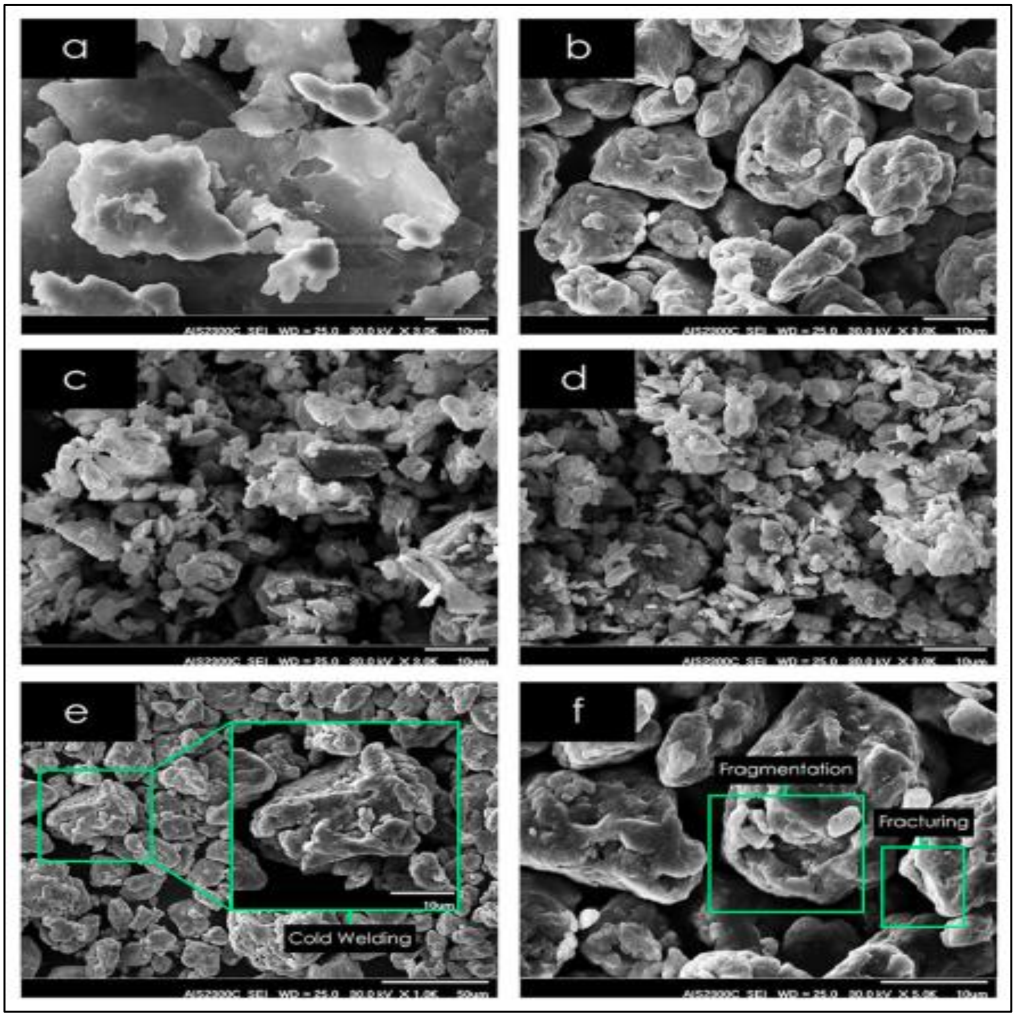

Fig 3. The Scanning Electron Microscopy (SEM) Images Illustrate the Microstructural Changes During Milling [22].

Spark Plasma Sintering (SPS) has several advantages, including rapid heating, reduced sintering duration, adjustable structure, energy efficiency, and environmental friendliness. Due to these characteristics, it is well-suited for the manufacturing of metal materials, composite materials, and ceramic materials [29], [30]. The technology influences the holding duration, pressure, current, and sintering temperature. By using suitable process parameters, the powder can be efficiently transformed into compact blocks [31]. Richard and his colleagues Richard et al. [32] successfully manufactured alloys that consist of Copper, 13.01 Aluminum, 3.91 Nickel, 0.37 Titanium, and 0.24 Carbon using Spark Plasma Sintering (SPS) technology, which exhibited outstanding properties. This technique involves rapid powder heating by passing an electric current through a graphite mold using alternating current while subjecting the sample to a maximum uniaxial pressure of 99.5 MPa.

To summarize, Powder metallurgy and casting are two separate procedures. Casting is a process that involves the transformation of a liquid material into a solid form through molding. However, this process is susceptible to imperfections such as porosity and shrinkage, which can be challenging to rectify. PM utilizes the amalgamation of low-melting-point substances among particles for molding, typically resulting in a more homogeneous and refined microstructure. Therefore, powder metallurgy techniques are widely used in applying Copper Aluminum based alloys to provide a more uniform and finer grain structure.

III. IMPACT OF THE ADDITION OF ALLOYING ELEMENTS

An alloy's addition of suitable components can enhance its mechanical properties and suspension capabilities by affecting dispersion strengthening, grain refinement, phase martensite behavior, and transition behavior [33]. The efficacy of alloying as a method for modifying the microstructure of alloys has been established by numerous studies. The addition of manganese, titanium, Cobalt to the Cu-11.9Al-4Ni alloy by Saud et al. [34] led to precipitate and accumulation phases at the grain boundaries, which impeded the grains' growth and reduced their diameters to 450, 650, and 320 µm, respectively.

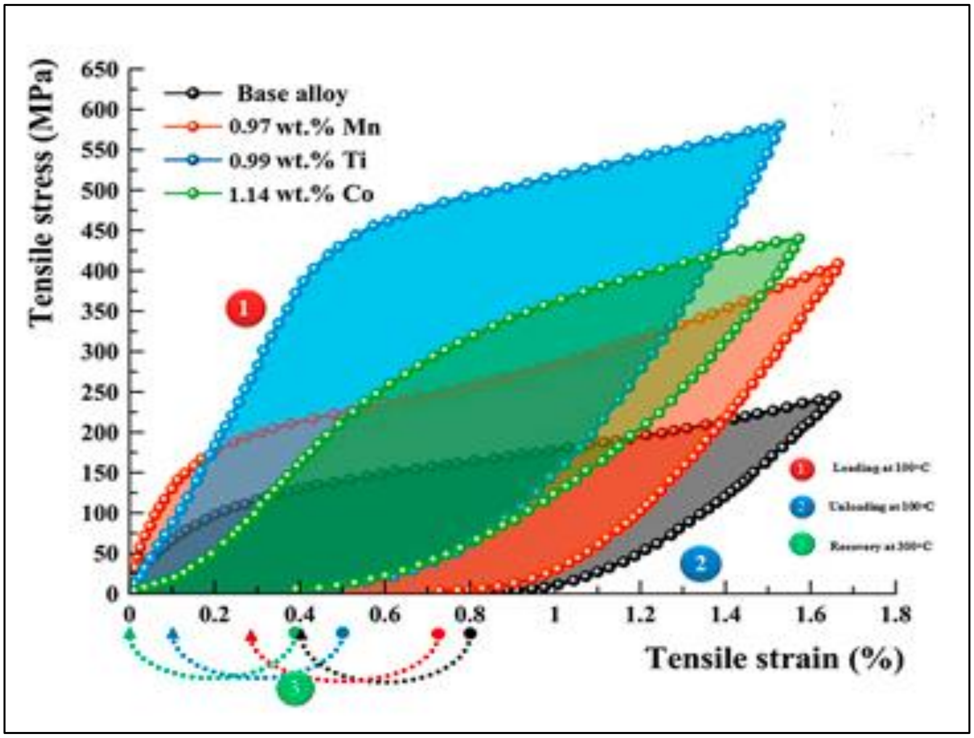

Fig 4. The Impact of Alloying Elements on the Mechanical Properties of Copper Aluminum Alloy [34].

The specific alloying element primarily determined the characteristics of the precipitates. The study revealed that an alloy containing 1.14 wt% of Cobalt (Co), as depicted in Figure 6, demonstrated the most substantial improvement in the recovery of shape memory, ductility, and transformation temperatures. The significant enhancements can be mainly attributed to the remarkably abundant occurrence of the γ2 phase in the microstructures of the improved alloy.

Similarly, Sampath [35] introduced titanium (Ti) and zirconium (Zr) into the copper-aluminum nickel alloy. Small particles with high concentrations of Titanium and Zirconium elements hindered the formation and enlargement of grains by acting as obstacles. The results suggest that alloying significantly influences microstructural correction. The study demonstrates that the inclusion of grain-refining substances leads to a significant decrease in the grain size of the alloys. Furthermore, grain refining and introducing alloying elements lead to a rise in the transition temperatures.

Dalvand et al. [36] incorporated a 0.04% concentration of rare-earth elements (Ce and La) into the Copper,12 Aluminum, 3Nickel, and 0.6Titanium alloy. The addition resulted in a substantial decrease of approximately 30% in the average grain size. The observed decrease is responsible for the production of precipitated phases rich in rare-earth elements. Optical micrographs of the Copper, 12Aluminum, 3Nickel, 0.6 Titanium and Copper, 12Aluminum, 3Nickel, 0.6 Titanium, and RE samples are depicted in Figure 5 (a, b). Under typical temperatures, both alloys display a complete martensitic state with X-phase precipitates spread randomly, measuring several micrometers in cross-sectional area. Through analysis of the chemical composition of the alloys listed in Table 1, it can be deduced that the inclusion of rare earth (RE) elements in the quaternary Cu-Al-Ni-Ti (or Cu-Al-Ni-X) alloys leads to more refinement of the grain structure Zhang et al. [37]. They have introduced varying amounts of Niobium into the Copper, 13Aluminum, and 4Nickel alloy. As a result, A novel phase, known as (Al, Ni) Cu4Nd, has emerged in the substrate material alongside the pre-existing 18R structure and 2H structure martensite. This study aimed to evaluate the impact of introducing Nd on the mechanical characteristics, transformation, and corrosion performance of Copper, Aluminum, and Nickel shape memory alloys (SMAs). This research represents a pioneering effort in this field. The main findings can be succinctly summarized as follows:

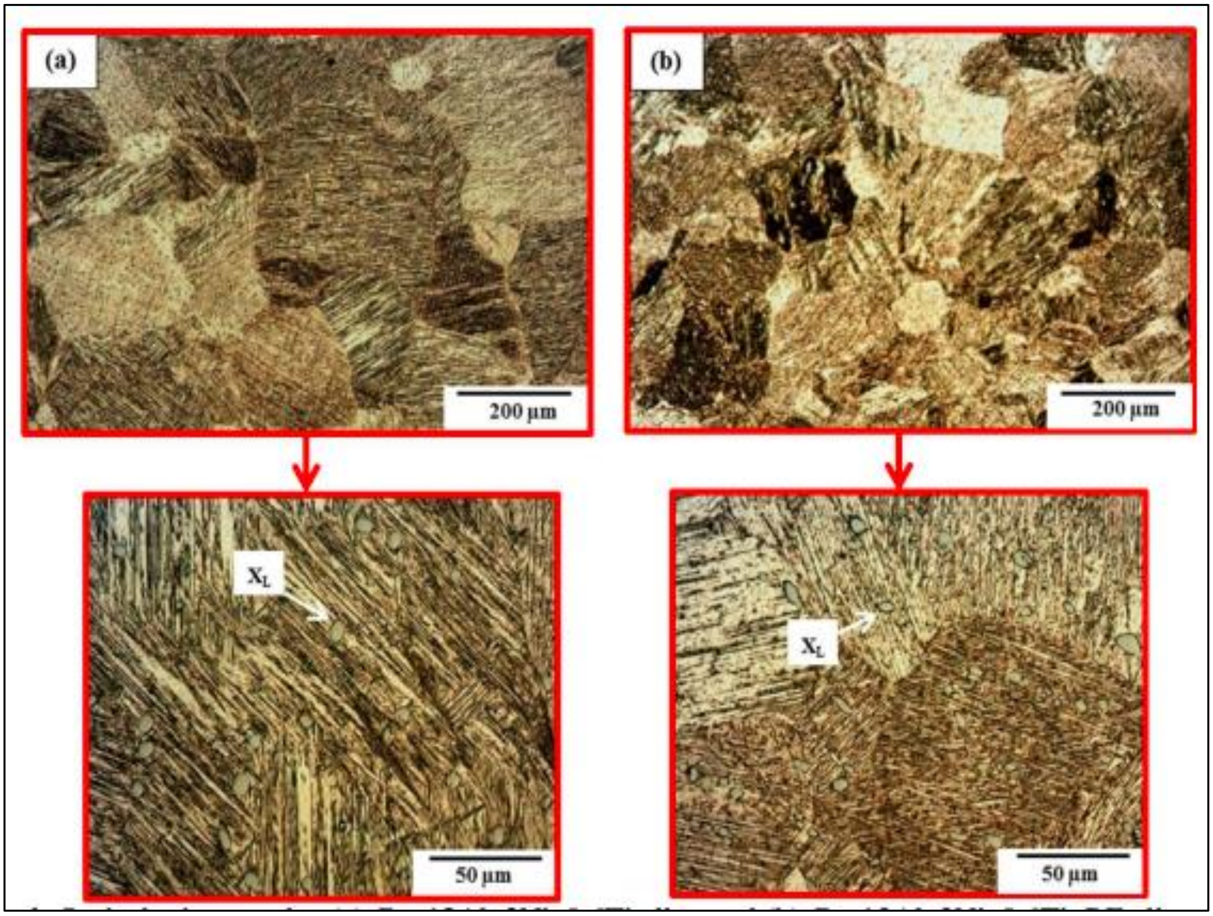

Fig 5. Optical Micrographs of Two Alloys are Shown: (a) Cu–12Al–3Ni–0.6Ti alloy and (b) Cu–12Al–3Ni–0.6Ti–RE alloy [36].

Table 1. An investigation of Optical Micrographs was Conducted to Determine the Microstructural Properties of Cu–12Al–3Ni–0.6Ti and Cu–12Al–3Ni–0.6Ti–RE alloys [36].

Alloy	**Average diameter of grains (µm)**	**ASTM Grain Size Number (G)**	**Area fraction of X_L precipitations**
Cu-12Al-3Ni-0.6Ti	211±7	1.57	3.12±0.08
Cu-12Al-3Ni-0.6Ti-RE	154±3	2.45	3.04±0.1

The inclusion of Nd reduced grain size in the Cu-Al-Ni alloy to around 200 µm. Additionally, the presence of (Al, Ni)Cu4Nd phase with a size of roughly 100-200 nm was discovered within the matrix.

- Multiple factors, including grain boundaries, grain size, phase sequence, vacancies, precipitation, structural morphology, and dislocations, typically influence the mechanical characteristics of alloys. Copper-based alloys that exhibit notable differences in elasticity in different directions are frequently prone to stress concentration, disrupting the continuity of strain [38]. Additionally, the alloy's susceptibility to brittle fracture is attributed to the presence of impurity elements that segregate along the grain boundaries and the relatively large grain size. In order to objectively assess the relative significance of nucleation and growth in fine and coarser wires, it has been conducted measurements of the linear plate number density, as seen in Figure 6, plotted against the transformed fraction. The transformed fraction refers to the instantaneous strain normalized by the maximum strain at the end of the transformation. During the test, two plates are generated around the delicate wire within the visual range. A lengthy, level ledge in the diagram denotes the expansion of one of these plates. In contrast, the evolution of the coarser wire follows a distinct pattern, where strain is predominantly. The continuous formation of new phase domains predominantly accumulates them. Coalescence initiates at modest strains and gradually becomes dominant after reaching the peak in Figure 6.

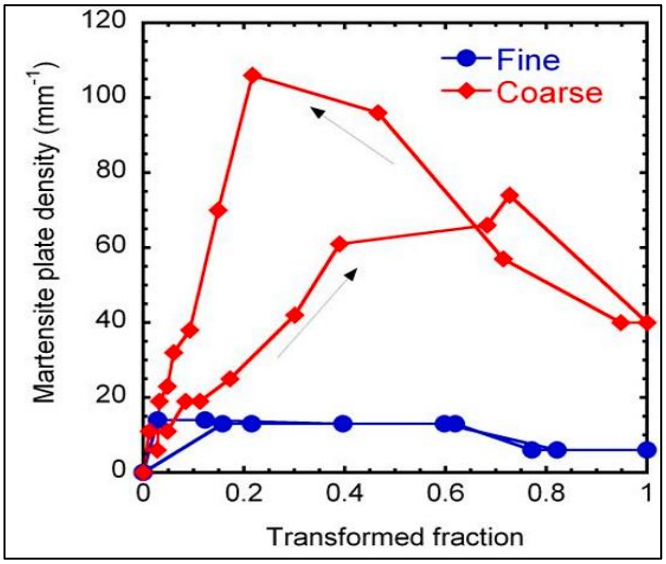

Fig 6. Martensite Plate Density for the Fine and Coarse Wire [38]**.**

Moreover, it has been observed that incorporating appropriate alloying elements can augment the material's malleability by strengthening the boundaries between grains, all while avoiding the creation of barriers in the γ-phase [39]. In addition, other researchers have achieved significant advancements in this subject. Incorporating various Gd elements into the Cu–13.0Al–4.0Ni alloy resulted in the formation of AlCu4Gd, which effectively impeded the enlargement of grains and enhanced grain refinement. It ultimately enhanced the mechanical characteristics of the material [40]. The fracture strength of the alloy had a substantial rise, rising from 580 MPa to 1,200 MPa. The inclusion of the hard material Ce.

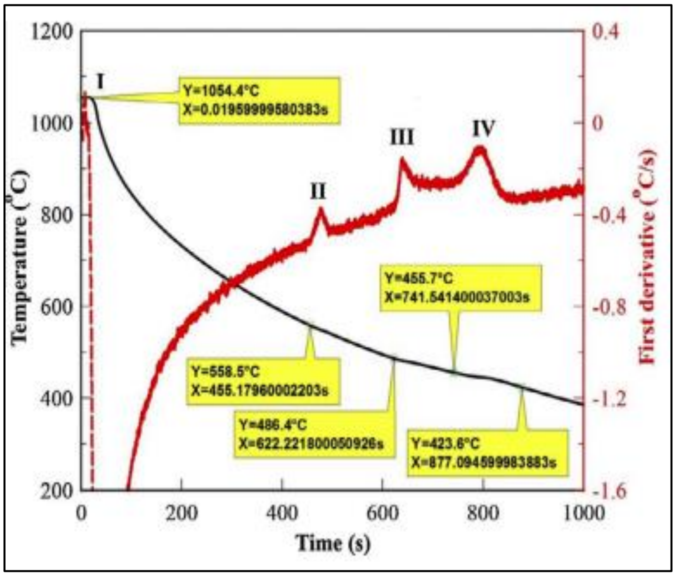

Fig 7. The Cooling Curve of the Central Thermocouple, Together with its Associated Derivative Curve, Illustrates the Characteristic Temperatures and Timings of the Cu-Al-Ni-Ag Shape Memory Alloy [41]**.**

T0o the Cu–14Al–4.5Ni alloy boosts its hardness. Ce is challenging to dissolve in the matrix, but it helps accomplish grain refinement, resulting in improved alloy strength [42]. Grain refinement is achieved by incorporating 2.5-weight percent manganese into the Cu–11.9Al–3.8Ni alloy, increasing fracture strength and strain [43]. Similarly, incorporating Ag in Cu-Al-Ni alloy enhances its fracture strength and shifts the fracture mode from brittle to mixed. The presence of Ag precipitation at the grain boundary has two effects: it hinders the mobility of dislocations and reduces stress concentration, enhancing the material's mechanical characteristics [41].

Figure 7 displays a cooling curve acquired while the Cu–Al–Ni–Ag SMA was solidifying, along with the accompanying first derivative curve. Derivative cooling curves offer additional insights into each process that are not readily observable on the cooling curve [41].

The changes in the microstructure of Cu–Al–Ni SMA and Cu–Al–Ni–Ag have a notable impact on the stress-strain curve, as depicted in Figure 8. The fracture stress-strain values are provided in Table 2.

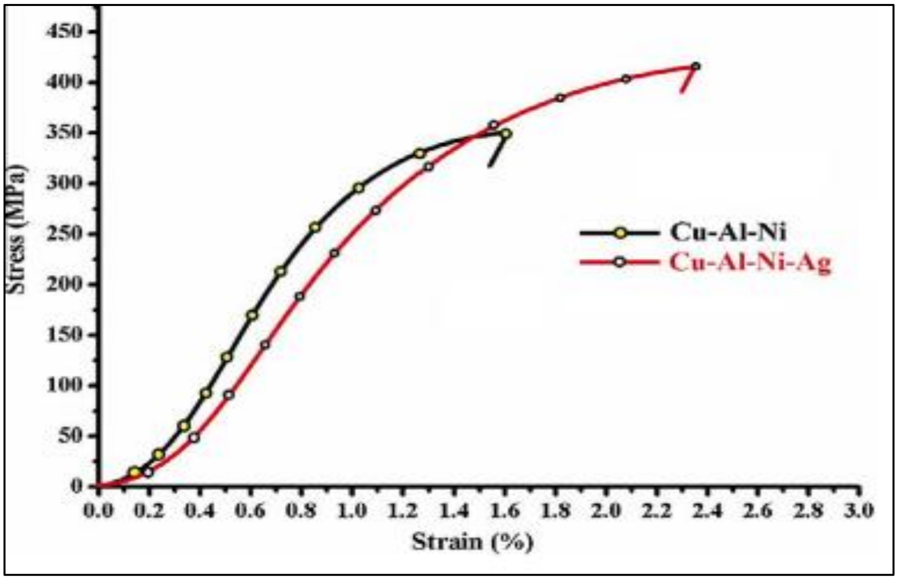

Fig 8. The Stress-Strain Curves were Obtained from the Tensile Tests Conducted on Cu-Al-Ni and Cu-Al-Ni-Ag Shape Memory Alloys (SMAs).

Table 2. Results Obtained from the Tensile Test for Cu–Al–Ni and Cu–Al–Ni–Ag SMAs [41].

Alloy	Fracture Stress (MPa)	Fracture Strain (%)	Shape Recovery (%)
Cu-Al-Ni	350	1.65	50
Cu-Al-Ni-Ag	420	2.35	80

The cu-based alloy has gained significant attention as a novel functional material because of its exceptional damping capabilities. Aside from the energy wasted by the hysteresis of defects and dislocations, the high damping capacity of the material is also attributed to the frictional energy dissipated at various interfaces, such as martensite/martensite, parent/martensite, and twin interfaces [44].

The Cu–XAl–4Ni shape memory alloys (SMAs) undergo martensitic transformation across a wide temperature range by precisely adjusting their chemical composition within the X = 13.0 to 14.5 range. Moreover, the variations in chemical composition significantly affect the internal friction qualities of Cu–XAl–4Ni shape memory alloys. Shape memory alloys (SMAs) with a higher concentration of Aluminum (Al), such as Cu–XAl–4Ni SMAs, have decreased internal friction peaks, which can be attributable to a reduction in the amount of transformed martensite and the existence of γ2 phase precipitates [45]. Researchers have conducted extensive studies on refining the grain size and martensite to increase the interfacial density.

Lu et al. [46] demonstrated that the optimal concentration of Ce elements exhibits a substantial enhancement in the damping capabilities of the alloy. The findings demonstrated that the alloy achieved optimal damping performance at a Ce concentration of 0.05 wt%. As the Ce content increases, the size of the Ce-rich phase expands, and the volume fraction gradually increases.

Alloying is essential for modifying the microstructure, which is directly linked to the qualities of the alloy. Alloying components, such as common or rare earth elements, are added to the Cu-Al-based alloy to decrease its massive grain structure and enhance its overall qualities.

IV. IMPACTS OF HEAT TREATMENT

Heat treatment is a crucial procedure in mechanical manufacturing. By altering the interior microstructure or chemical composition of the surface through manipulation, it enhances the performance of the workpiece [47]. Heat treatment technology is often necessary in practical applications to enhance the mechanical properties of metal materials, in addition to the careful selection of materials and processing techniques.

Yildiz [48] examined Cu-Al-Ti-Ta alloy microstructure under varying cooling conditions. According to the data, water and air cooling mostly create 18R martensite with a small amount of 2H martensite, whereas furnace cooling significantly increases the amount of 2H martensite. A study investigated the influence of cooling rate on the microstructural, structural, transformation, and shape recovery properties of a heat-treated Cu-12.4Al-1.2Ti-1.2Ta (wt.%) alloy. Decreasing the cooling rate of the alloy leads to significant changes in the phase components and transformation behavior, resulting in a drop in the shape recovery ratio of the alloy.

Ren et al. [49] achieved the formation of Cu–Al alloys with varying grain sizes by manipulating the temperature throughout the heat treatment process. It has been observed that the alloy's grain size increases as the temperature rises, particularly between 600 and 800°C.

Hence, the unique microstructure of Cu-based alloys, including grain size, martensite type, and the presence of second-phase particles, confers outstanding mechanical properties and better damping capabilities. To get excellent mechanical qualities, it is necessary to choose the optimum settings for the heat treatment process carefully. Qader et al. [50] examined the alteration in the mechanical characteristics of Cu–13Al–3Ni-4Hf alloy during the aging process. They discovered that the formation of β-phase (Cu3Al) occurred when the alloy was aged at temperatures over 973 K. This phase transformation increased its brittleness.

A notable shear stress concentration arises from the combination of elevated elastic anisotropy and incongruous deformation of adjacent grains. When cooled appropriately, the copper-based alloy develops two layers of columnar grains. When the cooling rate is high enough, a monolayer of columnar grains will form., as seen in Figure 9 [51].

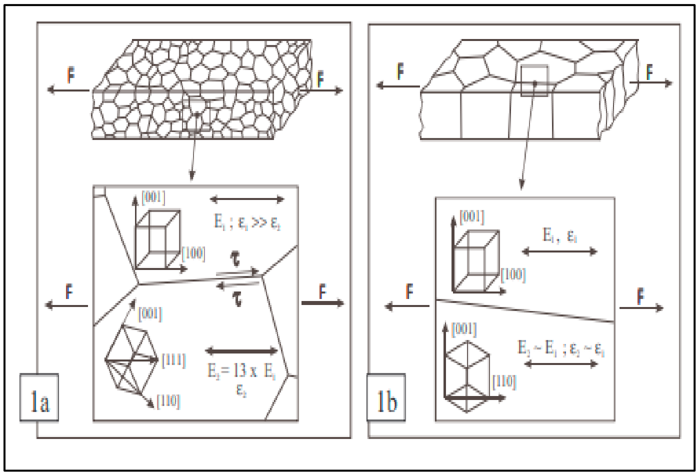

Fig 9. a) The Stochastic Grain Orientation Leads to Substantial Disparities in attributes Across Neighboring Grains in the Direction of the Load. Conversely, the Presence of a Single-Layer Columnar Fiber Textured Structure Guarantees that the Mechanical Characteristics of Neighboring Grains in the Direction of the Load are Comparable [51]**.**

The ribbons have the correct chemical compositions, are mainly martensitic, and demonstrate a form memory effect, even when spun at moderate wheel speeds, without additional treatment. Due to the limited thermal ductility of Cu-Al-Ni alloys, it is challenging to manufacture wide ribbons with a fully martensitic single-layer columnar structure using a free jet melt spinner. Consequently, heat treatment is necessary even for materials spun from a molten state. Boron enhances the material's malleability but does not impede the creation of a single-layer columnar structure when added in tiny quantities, provided the cooling rates are sufficiently rapid.

The primary objective of both solid solution and aging treatments is to enhance the damping performance by manipulating the energy-absorbing mobile interfaces and flaws. Earlier, the text also discussed the dual impact of grain refinement on damping qualities. Therefore, carefully selecting the appropriate heat treatment technique for optimal enhancement is necessary.

Consequently, academics have extensively researched the correlation between temperature and damping. Research demonstrated that the damping initially increased with an elevation in the surrounding temperature, primarily due to the reduction in martensite quantity. This allowed for increased mobility of twin boundaries and phase interfaces at elevated temperatures, leading to more significant energy expenditure. Liu et al. [52] investigated the impact of aging treatment within the temperature range of 250–400°C on the damping characteristics of columnar Cu–Al–Mn shape memory alloys and their underlying mechanism. The findings indicated that the highest point of damping is 0.11. As the aging temperature and time rose, the amount of bainite precipitates in the columnar Cu-Al-Mn shape memory alloy initially increased, then reduced, and ultimately increased again. However, the damping capacity of the alloy followed a different trend, decreasing initially, then increasing, and finally decreasing again.

The quenching voids in the quenched samples exhibited a high concentration and random distribution. During the aging process in the martensite phase, vacancies will gradually build up around the dislocation or interface, hindering the movement of dislocations and interfaces, which leads to decreased internal friction associated with the movement of dislocations and interfaces. Furthermore, the reverse magnetostriction (MT) will also be impeded, resulting in an elevation of the MT temperature and a reduction in the maximum intensity of phase change damping generated by the reverse MT [53].

Hence, a successful combination of heat treatment and alloying can lead to additional enhancement of alloy characteristics. Alloying has the potential to enhance the mechanical and damping qualities by precisely regulating the size of the grains, resulting in strengthened fine-grained structures and increased opportunities for energy dissipation through movable surfaces. Typically, combining solid solution treatment with alloying enhances the production of martensite, which positively affects the damping qualities of the alloy.

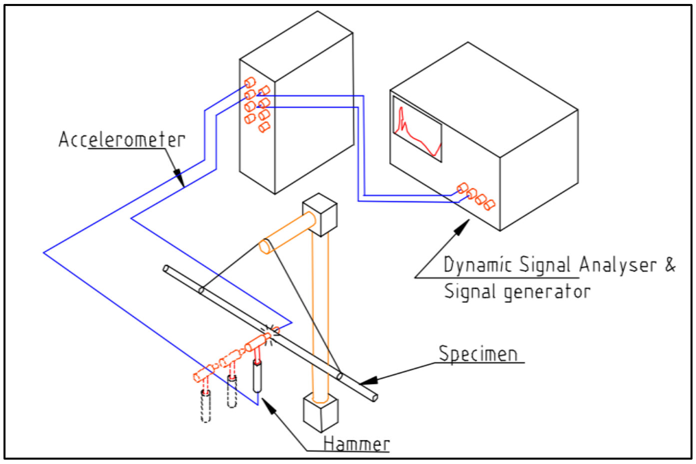

Fig 10. The Diagram Illustrates the Experimental Arrangement of the Suspended Beam Technique [54]**.**

Currently, in addition to alloying and heat treatment, which are crucial for enhancing the overall performance of alloys, researchers are increasingly focusing on nanotechnology—the distinctive nanoscale structure of nanomaterials results in increased strength and diffusivity. Therefore, nano reinforcement is an efficient approach to achieving high-performance alloys [54]. The ASTM C1259-98 standard performed the impact-based "free-free" or "suspended" beam method. The experimental setup, depicted in Figure 10, is described below.

Figure 11 displays a standard circular diagram from which points a and b are chosen to calculate the damping loss factor. These points correspond to frequencies ωa and ωb, respectively. The process of obtaining FRF data was discovered to be highly consistent, and the technology used is non-destructive. It utilizes inexpensive equipment and can accept diverse specimen formats and sizes.

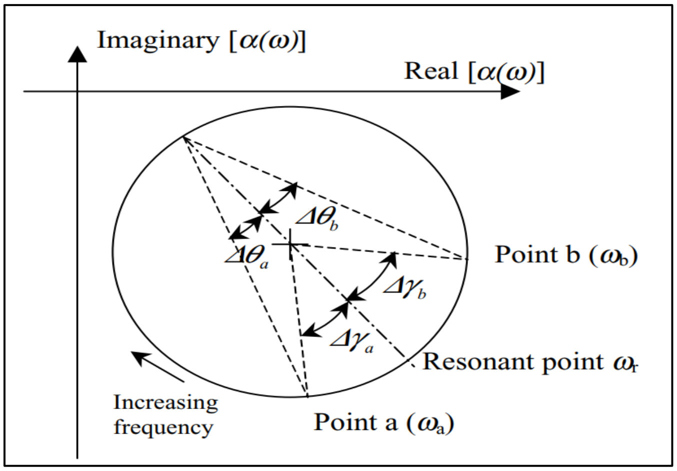

Fig 11. A Standard Acceptance Frequency Response Function (FRF) Illustrates the Inherent Frequency and Two Selected Data Points used to Calculate the Damping Coefficient [54]**.**

V. CONCLUSIONS

This article primarily discusses the impact of four distinct aspects on the mechanical characteristics of nanomaterials: nanoparticle selection, production technique, grain size, and grain boundary structure. Individually, these parameters do not influence the mechanical properties of nanomaterials. However, they interact and rely on one another. Employing diverse materials and processing processes enables the acquisition of nanostructures exhibiting distinct microstructures and mechanical properties. The divergence in mechanical characteristics among nanomaterials arises from the aggregation of multiple variables. Furthermore, building upon prior research, it has been also presented the latest advancements in the mechanical characteristics and potential applications of nanomaterials.

Several investigations on nanomaterials have yielded significant outcomes. Nanomaterials have been utilized in industrial manufacturing. Nevertheless, there is a need for more research on the molding mechanism and reinforcement process of the microstructure of nanomaterials, leaving numerous topics yet to be investigated. Nanomaterials possess distinct characteristics that confer them extensive possibilities for application and significant potential value in the future. Hence, it is imperative to persist in exploring nanomaterials and enhance our comprehension of their molding mechanism, strengthening process, and modification techniques to enhance their qualities.

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