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Enhancing Mechanical Performance of NiTi Shape Memory Alloys via Niobium and Copper Additions

Yasaman Ghasemi [1], Hosein Mahbadi[1*], Fariborz Heidary[1]
[1] Department of Mechanical Engineering, CT.C., Islamic Azad University, Tehran, Iran.
*h_mahbadi@iau.ac.ir

Abstract

Nickel-titanium alloys are used in industrial and medical applications due to their outstanding properties such as high corrosion resistance, biocompatibility and superelastic behavior, which can withstand large reversible deformations without permanent deformation. This study investigates the improvement of mechanical properties and structural behavior of nickel-titanium alloys by adding different concentrations of copper and niobium. The addition of copper has a significant effect on the density of the alloy, which leads to an increase in shape memory properties, and the tensile strength and hardness are slightly affected, indicating good structural stability, and the Young's modulus and shear modulus also decrease with increasing weight percentage of copper. The addition of niobium modifies the phase structures in the alloy. Also, the optimized hysteresis loop shows a significant increase in the mechanical strength and yield stress and deformation range of the alloy compared to the reference sample, such that the accumulation of plastic strain in one cycle is reduced compared to the pure nitinol alloy and the elastic deformation capacity is increased. Cyclic loading of improved nitinol compared to pure nitinol reduces ratcheting effects and leads to greater cyclic stability, which ultimately leads to improved vibration behavior of the structure. The best alloy composition contains 2.5%copper and 6%niobium, which shows better mechanical properties than pure nitinol, making it a promising candidate for medical and automotive applications where high performance and reliability are essential.

Keywords: Ni-40Ti-xCu-yNb, Mechanical Properties, Simulation, Nickel Superalloys

1. Introduction

Shape memory alloys (SMAs) are alloys that, after plastic deformation, recover their original shape upon application of heat[1]. This rare property is attributed to a reversible phase transformation from martensite to austenite and vice versa[2]. SMAs exhibit their performance by means of two main effects. The first is the shape memory property (SME) where defrmation is reversed by heating above a critical temperature and superelasticity (SE), which enables recovery of large strains through mechanical unloading at temperatures above the transformation thereshold [3-6]. During SME, the material is typically in the martensitic transforms into detwinned martensite. After unloading, the detwinned structur remains until heating avove the austenite finish temperature triggers the reverse transformation, restoring the original shape. When we apply an external force, the martensite transforms to non-twinned martensite [7, 8].

NiTi-based SMAs are widely used due to their excellent mechanical properties, biocompatibility and robust SME and SE behavior. Their performance is highly sensitive to nickel (Ni) content, thermomechanical treatment, and alloying addistions, which influence transformation temperatures and mechanical stability [10 ,9]. These properties have enabled NiTi alloys to find applications in automotive systems, biomedical devices, civil infrastructure, robotics, and microelectromechanical systems (MEMS) [11, 12]. For example, 60NiTi alloys exhebit high harenablity, low apparent elastic modulus, and large elastic strain limits exceeding 3% [13].

Previous stuedies have explored the effects of alloying NiTi with elements such as niobium (Nb) and copper (Cu). Medeiros and Araújo, synthesized TiNiNb alloys via plasma arc melting and found that Nb addisions had minimal impact on transformation temperature but reduced hardness and had limited influenc on leastic modulus [14]. Copper on the other hand, has gained attention for its ability to reduce thermal hysteresis and enhance stability during cycling. Cu-based SMAs offer easier processing and lower cost, though their ductility remains a challenge [15, 16]. Studies have been shown that Cu additions can improve SME, fatigue life, and martensite yield strength, while also reducing the martensite start temperature [17-20]. However, excessive Cu content may negatively affect ductility and fatigue performance [21]. Alnomani et al. reported that 2.5 wt% Cu yielded optimal hardness, while higher Cu levels led to a decline[22].

Niobium (Nb), with its body-centered cubic (bcc) structure and limited solubility in the NiTi, is a promissing ternary addition due to its low toxicity and corrosion resitance. Nb can reduce transformation temperatures and increase thermal hysteresis by forming Nb-rich phase that enhance hardness and strength [23]. Most studies focus on Nb concentrations between 3-9 wt%, though some explore up to 30 wt% with limited analysis [24-28]. Horiuchi et al. examined Cu additions to Ti-18 mol% Nb alloys and found that Cu reduced lattice parameters and enables SE at 4 mol%, while SME was suppressed at higher Cu levels [29]. Other studies confirm that Nb additions can improve martensitic transformation stresses, hardness and radiopacity in NiTi alloys [30]. Ashkani et al. investigated Ti-9Mo alloys alloyed with Cu and Al, noting that Cu reduced elastic modulus (desireable for biomedical use), while Al increased it. [31].

Bulding on previous research, this study investiages the combined effects of copper (Cu) and niobium (Nb) additions on NiTi shape memory allooys using computational simulation. NiTi alloys were modified with Cu additions of 0.5, 1.5, 2.5, and 3.5 wt%, and Nb additions of 3.6, and 9 wt%. representing a systematic exploration of ternancy compositions. The alloys were subjected to heat treatement simulations to evaluate changes in microstructure, phase transformation behavior, and mechanical peoperties. A comprehensive dataset was generated and anlyzed, aiming to what has been reported for binary and isngly modified NiTi systems.

2. Materials & Methods

In this study, the addition of copper (Cu) and niobiom (Nb) elements on the Nickel-titanium (Ni-Ti) alloy composition was performed using computational simulation. The JMatPro software was employed for this purpose[32]. Cu and Nb were selected based on their complementary mechanical properties. Cu reduces the thermal hysteresis and stabilizes the martesitic phase, while Nb enhances the strength and mitigrates fracture and cracking tendencies in the alloy. In the simulation environment, NiTi-based alloyes modified with Cu and and Nb were analyzed. The chemical compositen used in the simulation are presented in Table 1.

Table 1. Chemical compositions used in the simulation environment

Composition(wt.)	Ni	Ti	Cu	Nb
Ni-40Ti	Base	40	0	0
			0.5	3
			0.5	6
			0.5	9
			1.5	3
			1.5	6
			1.5	9
			2.5	3
			2.5	6
			2.5	9
			3.5	3
			3.5	6
			3.5	9

Table 2 summerizes the baseline mechanical properties of the pure NiTi alloy used for comparison.

Table 2. Mechanical properties of pure NiTi alloy[13]

Composition	Mechanical Properties in Environment Temperature							
Ni-40Ti	Poisson's ratio	Strength (MPa)	Hardness (HRC)	Young's Modulus (GPa)	Density (g/cc)	Electrical resistivity (10^-6 Ω.cm)	Thermal expansion (10^-6/°C)	Thermal conductivity (W/m-°K)
	0.34	1000	56-62	95	6.7	80	12.4	18

In this simulation, a range of mechanical properties and thermophisical properties of the modified alloys were evaluated and presented through comparitive graphs. Simulations of elastic modulus, shear modulus, density, and Poisson's ratio were conducted using a liquid fraction thereshold of 0.01% and at a temperature of 37 ºC, reperesnting physiological conditions. Mechanical property analysis was performed after simulating heat treatment at 500 °C, assuming an average grain size of 100 µm. Additionally, outputs for electrical resistivity, enthalpy, and other mechanical parameters were obtained by introducing Nb into Cu-reinforced NiTi alloys.

3. Result and Discussion

To validate the accuracy of the simulation, the density of NiTi (nitinol) obtained from the software was compared with a published reference. The simulated density was 6.48 g/cm³, while the literature reports a value of 6.45 g/cm³. The difference of 0.03 g/cm³ falls within the expected range of measurement uncertainty and minor compositional variations in NiTi alloys, and is therefore considered negligible.

3.1. Physical and phase properties

The results in Figure 1 show that with increasing copper (Cu) content, the density of the alloy decreases. Similarly, the addition of 3, 6, and 9 wt% niobium (Nb) results in a downward trend in the density curve. It is important to note that at 3.5 wt% Cu, the density drops significantly, which is attributed to structural changes in the alloy. At this concentration, the alloy largely loses its shape memory behavior, and the formation of brittle phases leads to cracking and incomplete recovery.

Although pure Cu and Nb have relatively high densities (8.96 g/cm³ and 8.57 g/cm³, respectively), they are not responsible for the observed decrease in overall alloy density. The slight reduction in density up to 2.5 wt% Cu is primarily due to changes in crystal structure and the emergence of new phases.

Nb-containing alloys often exhibit lower densities compared to other metallic systems due to several intrinsic factors:

- Atomic mass effect: Nb has a lower atomic mass than many transition metals. When it replaces heavier atoms in the alloy, the overall density decreases.
- Solid solution behavior: Nb can form solid solutions with NiTi, altering atomic arrangements and potentially leading to less densely packed crystal structures.
- Phase transformation influence: Nb promotes the formation of secondary phases that may be less dense than the base NiTi matrix, especially during heat treatment or alloying.

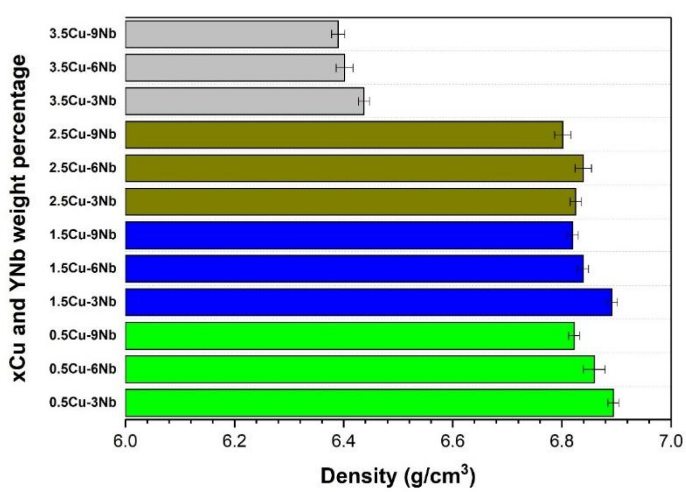


Figure 1. The effect of changes in the weight percentage of Cu and Nb on the density of various alloys.

The results indicate that Ni, Cu, and Nb have similar elemental densities, so the observed changes in the alloy density curves primarily reflect structural transformations rather than differences in elemental mass. In general, reducing alloy density is beneficial for biomedical applications, as it lowers the weight of implanted components and improves patient comfort. The addition of Cu reduces thermal hysteresis, enabling more precise control of phase transformation behavior, while Nb enhances biocompatibility and mitigates cracking in the final alloy. These properties also make Cu–Nb-modified NiTi alloys suitable for heavy-duty automotive and rail components, where weight reduction and mechanical resilience are essential[33, 34]. To clarify the relationship between atomic structure and density, we refer to the standard formula:

$$\rho = \frac{\mathrm{n.M}}{\mathrm{V_{unit.cell}\,N_a}} \quad (1)$$

In equation (1), ρ represents the density of the material, n is the number of atoms contained within a unit cell, M is the atomic weight of the element or alloy component, $V_{unit.cell}$ denotes the volume of the unit cell, and N_a is Avogadro's number, which relates atomic-scale quantities to macroscopic measurements. This formula illustrates how changes in atomic arrangement, atomic mass, and unit cell geometry directly influence the overall density of an alloy.

Figure 2 presents the molar volume values for different alloy compositions. The results clearly show that with increasing alloying content, molar volume increases significantly. When Cu is added to NiTi, it tends to substitute for Ni atoms. Due to the larger atomic radius of Cu, this substitution leads to an increase in lattice parameters, thereby expanding the molar volume. At 3.5 wt% Cu, the alloy reaches a structural saturation threshold, where intermetallic phases begin to form. Up to this concentration, Cu contributes to lattice stress absorption, but beyond this point, the alloy experiences structural distortion and a decline in shape memory performance. Similarly, increasing Nb content also leads to a rise in molar volume, despite Nb and Ti having comparable atomic radii. This increase is attributed to the formation of secondary phases and the distinct electronic behavior of Nb, which alters bonding characteristics. Nb also increases interatomic spacing within the matrix, resulting in redistribution of lattice stresses and further influencing phase stability.

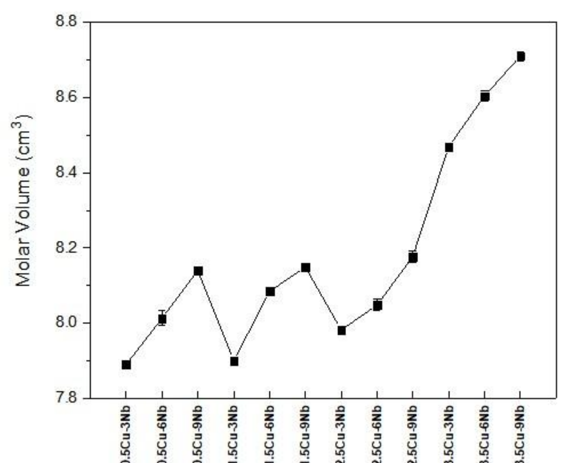
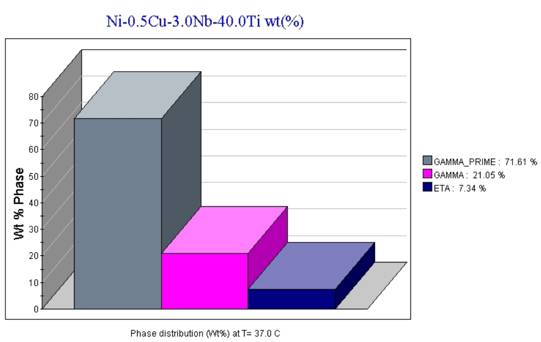


Figure 2. The effect of changes in the weight percentage of Cu and Nb on the Molar Volume of various alloys.

Nitinol is a Ni–Ti–based superalloy that is known for its unique functional properties such as the shape memory effect and super-elasticity. The microstructural stability and performance of this alloy can be optimized through the addition of alloying elements and the formation of strengthening phases. In Ni-based superalloys, the γ phase (Ni-rich matrix) acts as a continuous background phase with an FCC structure, providing a relatively tough framework for the alloy. In contrast, the γ′ phase (ordered precipitates of $Ni_3(Al, Ti)$) is a coherent phase with an FCC structure that forms as fine precipitates within the γ matrix and plays the main strengthening role by impeding dislocation motion. Although Nitinol is primarily strengthened through martensitic transformation rather than γ/γ′ precipitation, understanding these two classical phases in Ni-based superalloys is important, especially when alloying elements such as Nb or Cu promote the formation of secondary phases and influence the mechanical behavior. The γ matrix provides a stable framework that supports complete martensitic transformation, while the γ′ precipitates help control grain growth and stabilize the microstructure, indirectly enhancing shape memory performance.

The addition of Cu and Nb also leads to serious phase changes. By adding 0.5% Cu and 3, 6, and 9 wt.% Nb, as can be seen in Figure 3, the γ' phase decreases and the γ phase increases. Also, the η phase reaches from about 7% to 4% in the range of 6% Nb and again increases in the η phase at 9% Nb. The γ' phase is a phase that is formed for the precipitation of reinforcement in superalloys and has an FCC structure. Also, the γ phase, which is increased with the percentage of Nb, is the background phase for superalloys, and this phase also has an FCC structure. This phase formation can change the mechanical properties mentioned in the next section.



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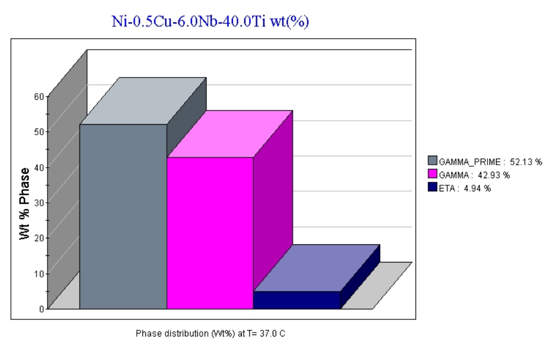

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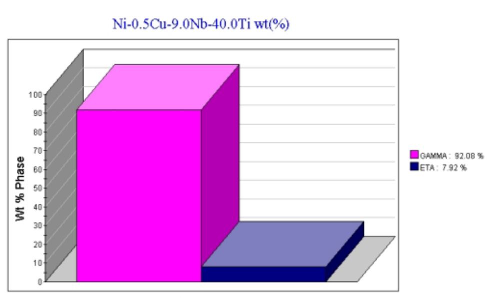
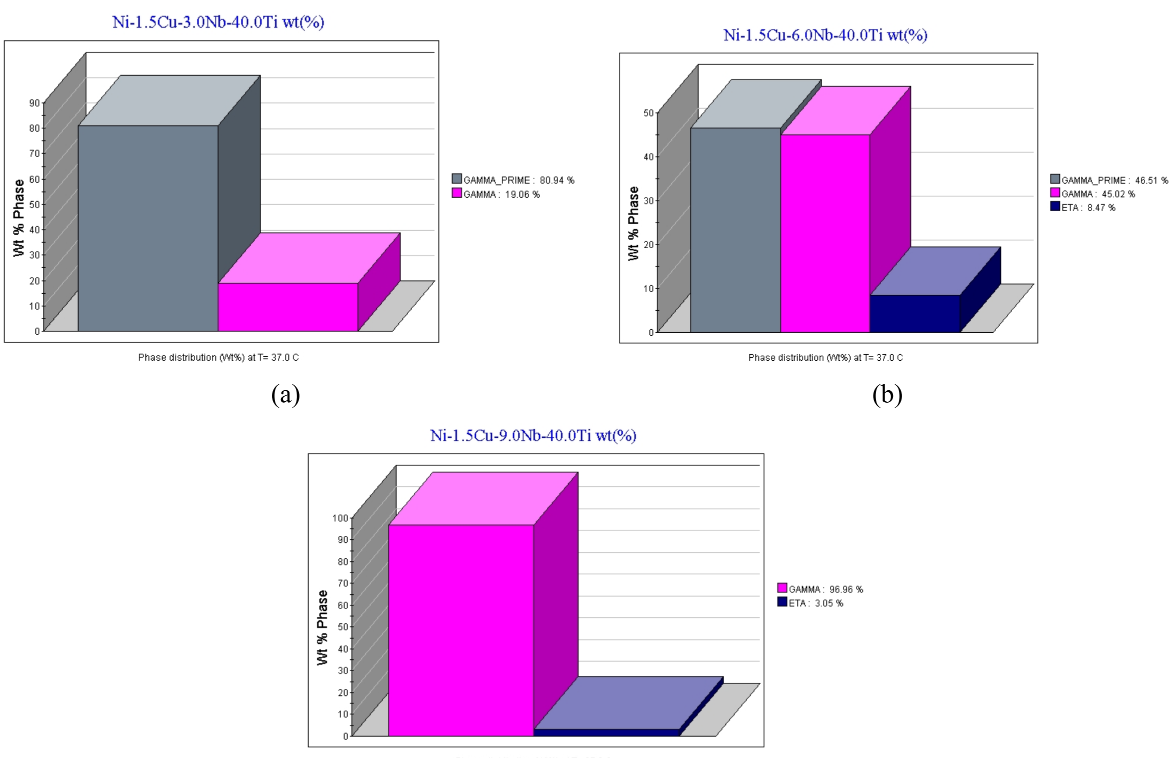


(c)

Figure 3. Phase formation for different alloys, a) Ni-40Ti-0.5Cu-3Nb, b) Ni-40Ti-0.5Cu-6Nb , c) Ni-40Ti-0.5Cu-9Nb.

The η phase is a Ni–Ti–rich intermetallic compound with a hexagonal crystal structure that typically forms at grain boundaries or within the matrix during prolonged heat treatment or high levels of alloying. Unlike the coherent γ′ phase, the η phase is often semi-coherent or incoherent with the γ matrix, which can lead to reduced ductility; however, when present in limited amounts, it may contribute to strengthening by hindering dislocation motion and stabilizing grain boundaries. Nevertheless, excessive formation of the η phase can cause embrittlement and deteriorate the shape memory performance. Specifically, uncontrolled η phase formation can increase brittleness and disrupt martensitic transformation, reducing shape recovery, while a limited and well-distributed amount can help maintain shape memory performance.

Figure 4 shows the phases formed in Ni-40Ti-1.5Cu-xNb alloys. As the Cu content increases up to 1.5 wt%, the γ' phase gradually decreases and eventually disappears, while the η phase emerges in small quantities. Notably, when 6 wt% Nb is added, the η phase increases to 8.47 wt%, which contributes to increased brittleness and incomplete shape memory behavior. When 2.5 wt% Cu is introduced, the γ phase becomes dominant, and with 6 wt% Nb, the alloy transitions into a single-phase γ structure. In contrast, when Nb is added at lower Cu levels, both γ' and η phases are present, but the η phase content remains below 3 wt% in the 6 wt% Nb alloy. This lower η content is associated with reduced brittleness and improved shape memory performance. The phase evolution trends observed in Figure 5 further support these findings, confirming the structural transitions and phase stability across different Cu–Nb combinations.



(a) (b)

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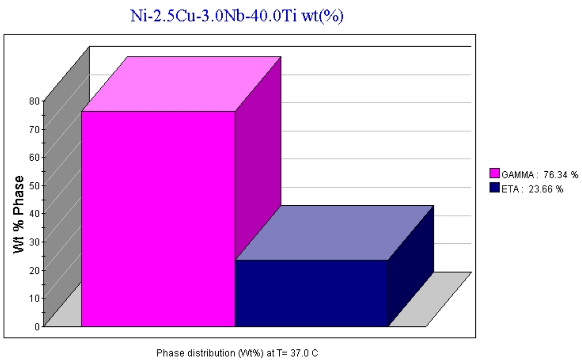
Figure 4. Phase formation for different alloys, a) Ni-40Ti-1.5Cu-3N b) Ni-40Ti-1.5Cu-6Nb , c) Ni-40Ti-1.5Cu-9Nb.



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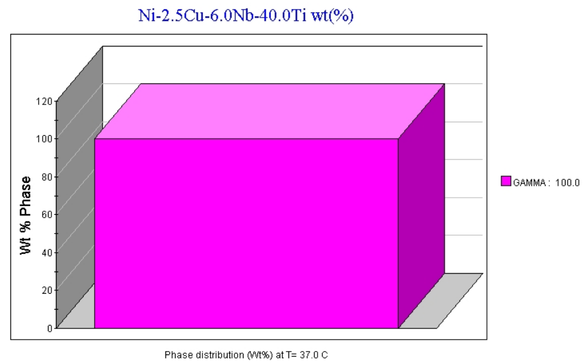

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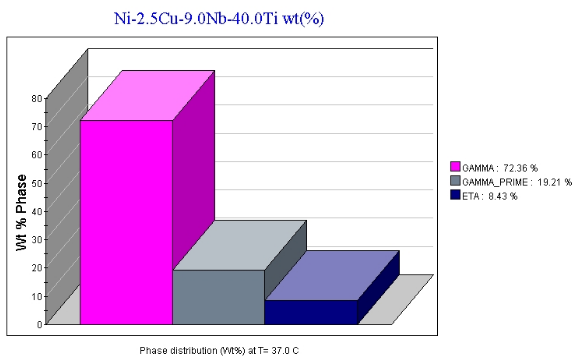
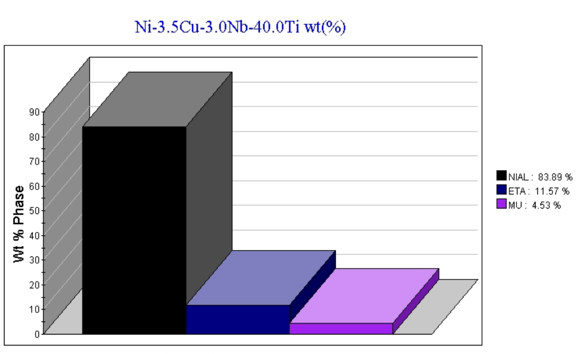


(c)

Figure 5. Phase formation for different alloys, a) Ni-40Ti-2.5Cu-3Nb, b) Ni-40Ti-2.5Cu6Nb , c) Ni-40Ti-2.5Cu-9Nb.

Figure 6 illustrates the phase evolution in NiTi alloys with increasing Cu content. When the Cu concentration reaches 3.5 wt%, the dominant phase transitions to NiAl, a highly ordered intermetallic compound with a simple cubic structure. This phase is known for its high hardness, but it is also prone to premature cracking and mechanical failure, which significantly reduces the alloy's cyclic life. The formation of the NiAl phase has a direct impact on the shape memory behavior of the alloy. As NiAl becomes dominant, it consumes part of the parent phase responsible for shape memory, thereby weakening the alloy's ability to recover its original shape. This structural shift marks a critical threshold where Cu-induced reinforcement begins to compromise functional performance.



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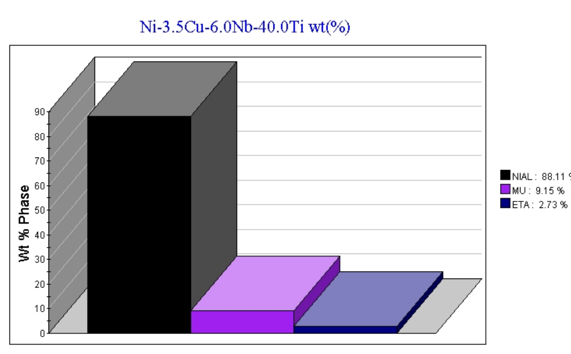

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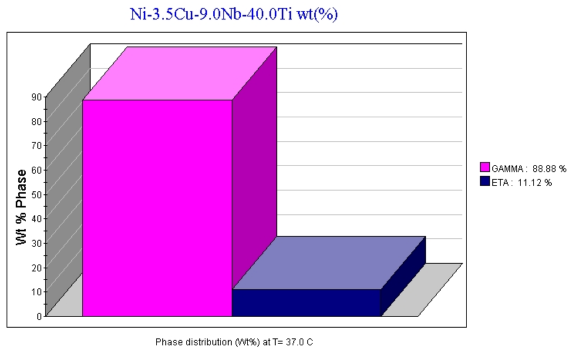


(c)

Figure 6. Phase formation for different alloys, a) Ni-40Ti-3.5Cu-3Nb, b) Ni-40Ti-3.5Cu-6Nb , c) Ni-40Ti-3.5-Cu9Nb.

3.2. Mechanical Properties

The mechanical behavior of the simulated alloys was evaluated based on yield stress, tensile strength, and hardness, as shown in the graphs below. All simulations were conducted assuming an average grain size of 100 µm and a heat treatment temperature of 500 °C, applied uniformly across the alloy structures.

3.2.1. Tensile properties

Figure 7 presents the yield strength values for different alloy compositions. Yield strength corresponds to the minimum stress level at which the material undergoes 0.2% permanent deformation, marking the onset of plasticity. With increasing Cu content (as shown in Figure 3), the alloy exhibits network softening, resulting in a gradual decrease in yield stress. However, Cu additions up to 3.5 wt% are considered optimal, as they help reduce stress concentrations and regulate internal stresses. In this range, the addition of Nb promotes the formation of secondary phases, such as eta and intermetallic compounds, which contribute to resistance against initial yielding. These optimized compositions demonstrate adequate resistance to transient mechanical loads, making them suitable for medical applications and potentially more demanding environments[34]. For example, the alloy containing 0.5 wt% Cu and increasing Nb content up to 9 wt% shows a yield strength reduction from approximately 716 to 710 MPa. Similarly, the alloy with 2.5 wt% Cu exhibits a decrease from 709 to 706 MPa, indicating a modest reduction in principal stress while maintaining structural integrity.

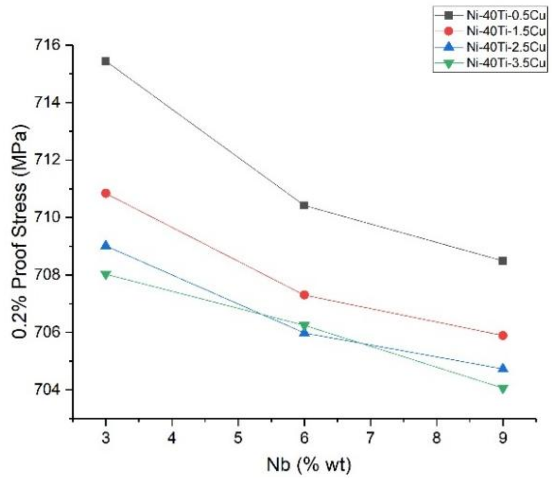


Figure 7. Principal stress results due to the addition of 3, 6, and 9 wt.% Nb to nickel alloys reinforced with 0.5, 1.5, 2.5, and 3.5 wt.% Cu

Figure 8 illustrates the tensile strength variations across different alloy compositions following simulation. Tensile strength is a key mechanical property that defines the maximum stress a material can endure before failure, representing its ultimate resistance to tensile loading.

As the Cu content increases, the tensile strength of the alloy gradually decreases, and a similar downward trend is observed with increasing Nb content. Despite this reduction, the combined addition of Cu and Nb refines the microstructure, enhancing fracture resistance mechanisms. Specifically, Nb promotes grain boundary adhesion, which helps inhibit crack propagation and contributes to structural stability. It is noteworthy that at 2.5 wt% Cu, the tensile strength curve exhibits a gentler slope across varying Nb levels, indicating a more stable mechanical response. One contributing factor to the observed strength reduction with increasing Nb is the growth in grain size. In many NiTi–Nb alloys, higher Nb concentrations can lead to grain coarsening, which in turn lowers tensile strength. This grain size effect also influences hardness, producing a parallel trend in mechanical behavior.

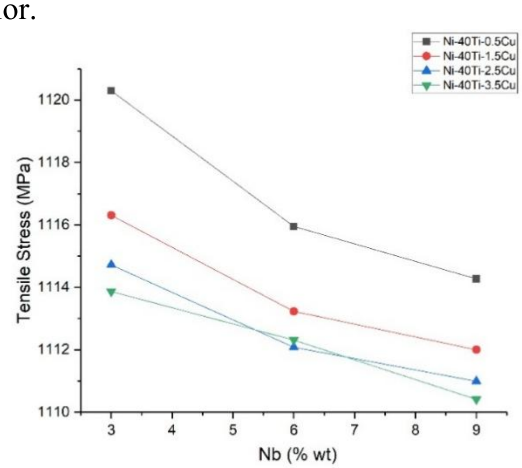


Figure 8. Strength results due to the addition of 3, 6, and 9 wt.% Nb to nickel alloys reinforced with 0.5, 1.5, 2.5, and 3.5 wt.% Cu.

3.2.2. Hardness

Figure 8 illustrates the tensile strength variations across different alloy compositions following simulation. Tensile strength represents the maximum stress a material can withstand before failure and serves as a key indicator of its ultimate resistance to tensile loading. As the Cu content increases, the tensile strength of the alloy gradually declines, and a similar downward trend is observed with increasing Nb content. Despite this reduction, the combined addition of Cu and Nb contributes to microstructural refinement, which enhances fracture resistance mechanisms. Nb, in particular, promotes grain boundary cohesion, helping to inhibit crack propagation and improve overall structural stability. At 2.5 wt% Cu, the tensile strength curve displays a gentler slope across varying Nb levels, suggesting a more stable mechanical response. One contributing factor to the observed strength reduction with increasing Nb is the tendency toward grain growth. In many NiTi–Nb alloys, higher Nb concentrations can lead to grain coarsening, which in turn diminishes tensile strength. This grain size effect also influences hardness, producing a parallel trend in mechanical behavior.

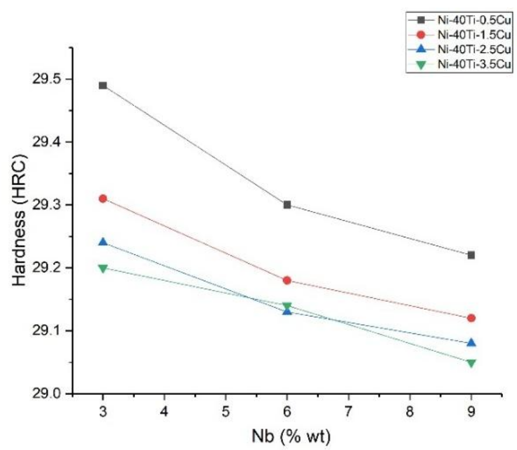


Figure 9. Hardness results due to the addition of 3, 6, and 9 wt.% Nb to nickel alloys reinforced with 0.5, 1.5, 2.5, and 3.5 wt.% Cu.

3.2.3. Shear and Young's Modulus

Young's modulus is a fundamental mechanical parameter that reflects the stiffness of a material and its ability to resist elastic deformation under applied stress. As shown in Figure 10, increasing the content of copper (Cu) and niobium (Nb) generally leads to a reduction in Young's modulus across the alloy compositions.

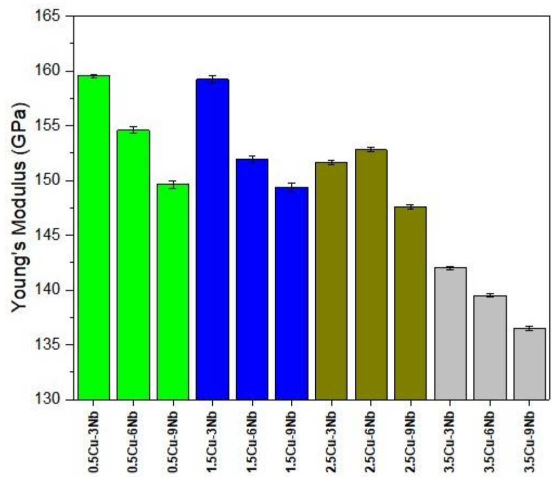


Figure 10. Young's modulus results due to the addition of 3, 6, and 9 wt.% Nb to nickel alloys reinforced with 0.5, 1.5, 2.5, and 3.5 wt.% Cu.

At 0.5 wt% and 1.5 wt% Cu, the addition of Nb results in a consistent decrease in Young's modulus, indicating similar mechanical behavior across these compositions. In contrast, at 2.5 wt% Cu, Young's modulus initially increases with Nb addition, but then follows a downward trend from 6 to 9 wt% Nb, resembling the behavior observed in the lower Cu content alloys. When 3.5 wt% Cu is introduced, the decrease in Young's modulus becomes more pronounced with increasing Nb, suggesting significant structural softening and reduced stiffness. This trend implies that lower Cu concentrations, particularly up to 2.5 wt%, help preserve the shape memory characteristics of the alloy, while Nb additions up to 6 wt% appear to support structural stability without excessive formation of secondary phases. The alloy composition of 2.5 wt% Cu and 6 wt% Nb emerges as a promising candidate for optimal performance, maintaining mechanical integrity and minimizing phase-induced distortion. The reduction in Young's modulus with Nb addition can be attributed to several intrinsic factors. First, Nb possesses relatively flexible atomic bonding characteristics, which reduce the stiffness of individual atomic interactions and lower the overall modulus. Second, Nb tends to form solid solutions with other metals, disrupting the orderly atomic arrangement and diminishing the efficiency of stress transfer through the lattice. Third, Nb promotes the formation of secondary phases that inherently possess lower elastic moduli, further contributing to the softening of the alloy. These effects make Nb-containing alloys particularly attractive for applications requiring lower hardness and higher ductility, such as in aerospace and automotive components[35-37].

Another important mechanical parameter is the shear modulus, which quantifies the material's resistance to angular deformation and is typically correlated with Young's modulus. As shown in Figure 11, the shear modulus decreases with increasing Cu and Nb content. This reduction is primarily due to lattice softening and the formation of softer secondary phases, mirroring the behavior observed in Young's modulus. In particular, alloys with 0.5 wt% and 1.5 wt% Cu exhibit similar shear modulus trends, while the alloy with 3.5 wt% Cu shows a significant decline, indicating excessive phase formation and structural instability. The composition of 2.5 wt% Cu and 6 wt% Nb again demonstrates balanced mechanical behavior, with minimal phase growth and stable modulus values, making it a strong candidate for biomedical and structural applications.

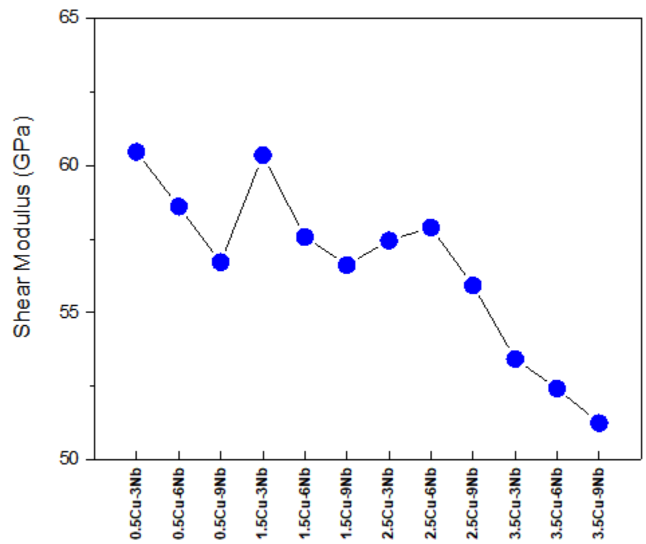
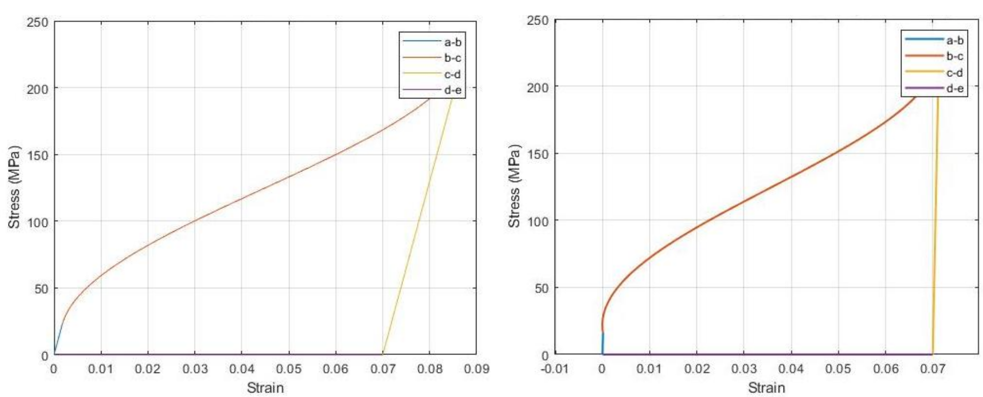


Figure 11. Shear modulus results due to the addition of 3, 6, and 9 wt.% Nb to nickel alloys reinforced with 0.5, 1.5, 2.5, and 3.5 wt.% Cu.

3.2.4. Hystersis loop

The cyclic plastic behavior of the alloy can be evaluated by comparing the stress–strain diagrams of the original loop and the optimized loop, as shown in Figure 12. In the original loop, the alloy exhibits limited elastic deformation. In contrast, the optimized loop demonstrates improved mechanical performance, characterized by higher proof stress, greater ultimate tensile strength, enhanced Young's modulus, and an expanded strain deformation range.



(a) (b)

Figure 12. Hysteresis loop results of a) pure Ni-Ti, b) Ni-40Ti-2.5Cu-6Nb

These improvements enable the alloy to withstand higher cyclic loads, while the cumulative plastic deformation per cycle (i.e. ratchetting behavior) is significantly reduced. This behavior indicates a stronger tendency toward shakedown, where the alloy stabilizes after several stress cycles and reaches a steady-state stress–strain response without further plastic strain accumulation. Such stabilization is critical for long-term durability under cyclic loading. Overall, the modification of mechanical properties not only enhances the ultimate strength of the alloy but also improves its cyclic stability, thereby reducing the risk of ratcheting-induced damage and extending the functional lifespan of the material.

4. Conclusion

The density of NiTi alloy decreases slightly with the addition of Cu, but at 3.5 wt% Cu, this reduction becomes significant due to structural changes. Similarly, the addition of 3, 6, and 9 wt% Nb to Cu-reinforced NiTi alloys results in a downward trend in density. It is important to note that the molar volume increases continuously with Cu and Nb additions, with 3.5 wt% Cu showing a marked increase due to the onset of structural saturation and the formation of intermetallic phases, which induce lattice distortion. Phase analysis reveals that with Nb additions to alloys containing 0.5, 1.5, and 2.5 wt% Cu, the γ phase increases, the γ' phase decreases, and a small amount of η phase is formed. The presence of the η phase at these compositions contributes to structural brittleness and incomplete shape memory behavior. At 3.5 wt% Cu, the alloy exhibits a dominant NiAl intermetallic phase, which is conductive but brittle, and likely lacks shape memory capability, leading to cracking and reduced functional recovery. In contrast, the alloy with 2.5 wt% Cu and 6 wt% Nb maintains a dominant γ phase, and based on the overall mechanical and structural properties, it can be considered an optimal alternative to pure NiTi.

The formation of the η phase due to impurity additions remains negligible up to ~2 wt%, where it may even contribute to structural stability. However, when the η phase exceeds 5 wt%, it negatively affects the alloy by reducing superelasticity, compromising shape recovery, and increasing brittleness. Mechanical analysis shows that with increasing Cu and Nb content, the strength, hardness, and principal stress decrease slightly, indicating crack resistance, adequate load-bearing capacity, and structural stability. In terms of Young’s modulus and shear modulus, the alloys exhibit similar trends, with lower values reported at 3.5 wt% Cu, suggesting that the optimal Cu range lies between 0.5 and 2.5 wt%. Alloys with low Cu content and up to 6 wt% Nb preserve the shape memory effect, as the structure remains stable and secondary phase formation is minimal or negligible. Comparison of stress-strain curves between the original and optimized rings confirms that the mechanical optimization—including increased yield stress, ultimate tensile strength, and Young’s modulus—enhances the elastic deformation capacity within a cycle and reduces plastic strain accumulation. These improvements improve vibration behavior. It is further expected that cyclic loading of the improved Nitinol will reduce ratcheting effects compared to pure Nitinol, leading to greater cyclic stability along with improved strength.

Based on the findings, the Ni-40Ti-2.5Cu-6Nb alloy is proposed as an optimal candidate for medical and automotive applications. This composition retains shape memory properties, exhibits Young’s modulus comparable to pure NiTi, and offers lower density, making it suitable for lightweight implants such as stents and components requiring weight reduction. Additionally, Nb contributes to biocompatibility and corrosion resistance. Future research could explore the mechanical behavior of reinforced shape memory alloy-based sandwich beams. Incorporating this optimized alloy into the core layers of sandwich structures, as opposed to using pure NiTi, is expected to significantly enhance strength, stiffness, fatigue resistance, and deformation recovery capacity. Investigating the type and amount of reinforcement, microstructural characteristics, and phase distribution within sandwich layers could provide valuable insights for advancing the mechanical design of these systems and achieving optimal performance in high-demand applications.

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