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ARTICLE

Evaluation of Low-Damping Properties Induced by Plastic Deformation and Heat Treatment in Co-Ni-Cr-Mo-Based Alloy

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Abstract: The strength and damping properties of Co-Ni-Cr-Mo-based alloys with 0.5wt% Nb addition after various plastic deformation and heat treatment processes were investigated. Through Vickers hardness tests, free resonance Young's modulus measurements, and microstructure analysis, the effects of dislocation density, vacancy formation, and recrystallization on the alloy performance were clarified. Results indicate that increasing the rolling reduction enhances damping property due to higher dislocation density, whereas aging below the recrystallization temperature reduces damping property via dislocation pinning by the Suzuki effect. Recrystallization heat treatment restores the original structure and damping level. This alloy possesses tensile strength of approximately 1500 MPa and logarithmic decrement value δ^{-1} in the range of $2\times10^{-4}-3\times10^{-4}$, demonstrating superior mechanical properties compared with the Ti-based alloys, which makes it an excellent candidate material for ultrasonic tools and medical applications.

Key words: Co-Ni-Cr-Mo-based alloy; low-damping properties; Suzuki effect; plastic deformation

1 Introduction

The damping properties of metallic materials, representing their ability to absorb energy under vibration or impact, play a crucial role in aerospace, automobile, and electronics industries[1–4]. Materials with low damping properties are particularly in demand for applications requiring vibration attenuation, and their broader utilization is anticipated. Ultrasonic damping is primarily caused by energy dissipation or absorption within the material during ultrasonic wave propagation, serving as a measure of energy reduction. Key contribution factors include internal friction, density, elasticity, and temperature dependence of the material[5–7]. Ultrasonics are pivotal as wave energy for transmitting power in various devices, ranging from ultrasonic cutters and welders to endoscopic surgical instruments and ultrasonic trocars[8–11]. Currently, aluminum alloys are known for their lightweight and heat dissipation, tool steels are known for their excellent wear resistance, and titanium alloys with high strength and hardness are widely used in various fields[12–15].

The resonance frequency (f) of the sample can be determined using the free resonance method, as follows:

$$f = 1.028\frac{h}{L^2}\sqrt{\frac{E}{\rho}} \tag{1}$$

where h and L are the thickness and length of Co-Ni-Cr-Mo (CNCM) alloy plates, respectively; E and ρ are the Young's modulus and density of CNCM alloy, respectively. Apply an electrical current on the plate through wires attached to both ends, and the vibration amplitude can be measured at the center. Under the free resonance measurement setup, the resonance frequency is predominantly influenced by bending vibrations along the length direction, whereas the effects of width are considered negligible or integrated into the density and elasticity parameters. The assumption of negligible width

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influence is based on the thin-plate condition, which ensures that the dominant mode of vibration is governed by length and thickness. The logarithmic decrement (δ^{-1}) is determined using the half-width method, as follows:

$$\delta^{-1} = \frac{f_u - f_l}{\sqrt{8}\, f} \tag{2}$$

where f_u and f_l are the upper and lower limits of the resonance peak frequency, respectively. This method provides a reliable evaluation of damping properties of metallic materials. The experiment setup and method are designed to analyze the effects of plastic deformation and heat treatment on damping properties. The results obtained from these measurements can be used to evaluate the relationship between microstructure evolution and the damping behavior of the alloy.

CNCM-based alloys have drawn attention for applications in medical implants and energy sector due to their excellent combination of strength and Young's modulus[16–22]. Recent studies have highlighted the significant influence of defect control, such as dislocations and vacancies, during plastic deformation or heat treatment on the vibration-damping properties of these alloys[16–17,23]. Particularly, significant work-hardening behavior and the formation of deformation twins at high temperatures have been noticed in Co-Ni superalloys[24]. It is found that the dislocation pinning based on the Suzuki effect is an important factor governing the dislocation mobility and dynamic strain aging[25]. Elucidating the mechanism of such defect control process is also of great significance to efficiently transmit and control vibrational energy. The damping ratio strongly depends on factors, such as crystal structure, defect density, and heat treatment temperature, which govern energy dissipation mechanisms within the material[26–30].

Ref. [16 – 17] reported that CNCM alloys maintain high levels of strength (1400 – 1500 MPa) and Young's modulus (220 – 230 GPa) while exhibiting exceptionally low damping property under specific heat treatment conditions. However, the effect of microstructure changes caused by cold plastic deformation (e.g., increased dislocation density, formation of extended dislocations, and recrystallization behavior) on the internal friction is obscure.

This study investigated a CNCM alloy with 0.5wt% Nb addition, focusing on the effects of cold plastic deformation at various rolling reductions (50%, 70%, and 86%), aging heat treatments at 637–873 K, and recrystallization heat treatment around 1323 K on the evolution of damping properties. A comprehensive evaluation was conducted, which combined microstructure observation via optical microscope (OM) and X-ray diffractometer (XRD), Vickers hardness tests, and damping property measurements by free resonance Young's modulus equipment. This study also investigated the effect mechanism of Nb addition on dislocation pinning via the Suzuki effect and damping properties. These findings are expected to provide valuable insights for designing components for CNCM alloys in ultrasonic applications, such as cutters, endoscopic surgical instruments, and ultrasonic welding tools.

2 Experiment

The composition of CNCM alloy used in this research is shown in Table 1. Based on the results in Ref. [16 – 17], the alloy includes 0.5wt% Nb, which enhances its mechanical properties. The alloy was prepared by vacuum melting, followed by forging and thick-plate rolling.

The CNCM alloy plates were solution-treated at 1573 K for 3.6 ks, followed by cold rolling with reductions of approximately 50%, 70%, and 86%, separately. Subsequently, the rolled samples underwent aging heat treatments at 637, 723, 773, 823, and 873 K for 1.8 – 7.2 ks, or recrystallization heat treatment at 1323 K for 14.4 ks.

Phase identification was conducted using XRD (PANalytical X'Pert MPD, Netherlands) with Cu-Kα radiation. For OM observations, the sample surfaces were polished with emery paper (3000#), etched using a solution of HCl, HNO_3, acetone, and H_2O with the volumetric ratio of 4: 1: 1: 1, and heated to 313 K for 0.18 – 0.3 ks. Microstructure observations were conducted using scanning electron microscope (SEM, JEOL Inc., Japan) at an accelerating voltage of 20 kV and transmission electron microscope (TEM). Vickers hardness was measured using a hardness tester. Damping property measurements were performed at room temperature using a free resonance Young's modulus measurement system (EG-HT, Nihon Techno Plus Co., Ltd, Japan). The dimension of samples for damping property measurement was 60 mm× 7.8 mm×2 mm, and δ^{-1} values were recorded within the frequency range of 6–20 kHz.

3 Results and Discussion

3.1 Microstructure of CNCM alloy after cold rolling and heat treatment

Fig. 1 shows SEM images of the CNCM alloy after solution treatment at 1573 K for 3.6 ks and subsequent cold rolling at different reductions. Annealing twins can be observed in the solution-treated sample, as shown in Fig. 1a. However, cold plastic deformation blurs the twin boundaries, leading to an increased density of dislocations and vacancies within the microstructure. Furthermore, as the rolling reduction increases from 50% to 86%, the fibrous microstructure becomes more refined. However, at cold rolling reduction of 50%, the microstructure is not yet fully streamlined, and some regions still retain a partially deformed structure, as shown in Fig. 1b.

Fig. 2 shows XRD patterns of CNCM alloys after solution treatment at 1573 K for 3.6 ks and subsequent cold rolling at different reductions. These results confirm that all samples exhibit a γ-face centered cubic (fcc) single-phase structure.

Fig. 3 shows XRD patterns of CNCM alloys processed by solution treatment and cold rolling with reduction of 86% before and after aging heat treatment at various temperatures

Table 1 Composition of CNCM alloy

Ni	Cr	Mo	Nb	Fe	Ti	Co
31.8	20.2	9.0	0.5	1.7	0.5	Bal.

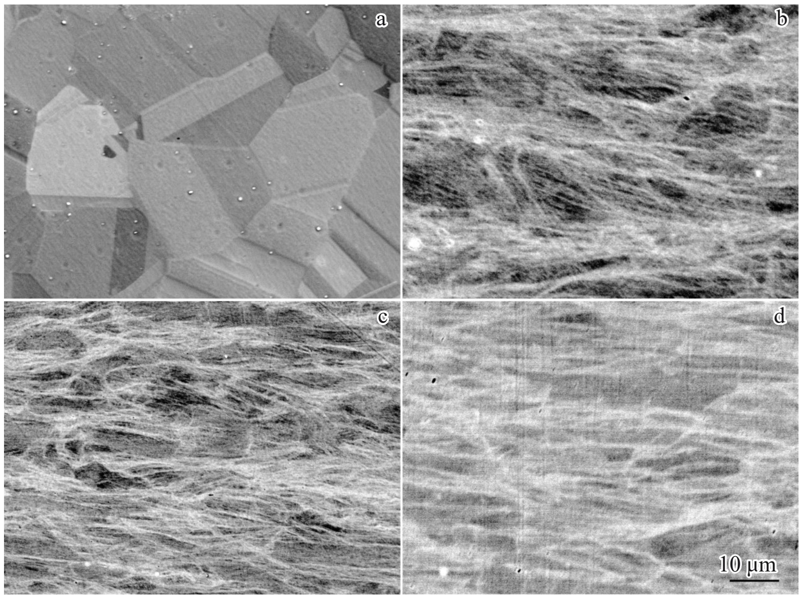

Fig.1 SEM images of CNCM alloys after solution treatment at 1573 K for 3.6 ks (a) and subsequent cold rolling at reductions of 50% (b), 70% (c), and 86% (d)

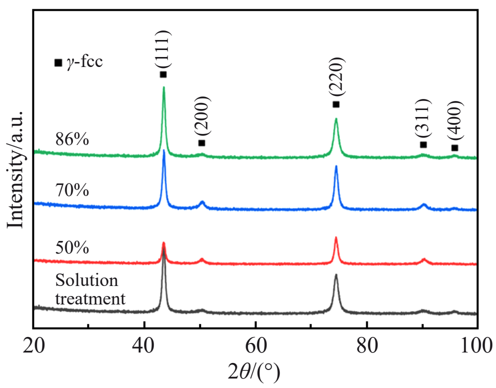

Fig.2 XRD patterns of CNCM alloys after solution treatment at 1573 K for 3.6 ks and subsequent cold rolling at different reductions

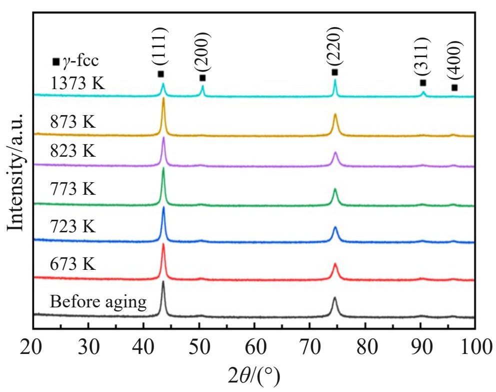

Fig.3 XRD patterns of CNCM alloys processed by solution treatment and cold rolling with reduction of 86% before and after aging heat treatment at various temperatures for 3.6 ks

for 3.6 ks. After aging heat treatment at 637, 723, 773, 823, 873, and 1373 K for 3.6 ks, all samples consistently exhibit a γ-fcc single-phase structure. Based on Ref. [16 – 17], recrystallization does not occur during heat treatments below 1073 K.

Fig.4 shows TEM images of the samples after cold rolling at different reductions[25], which illustrates the progressive microstructure refinement with the increase in plastic deformation. These reductions significantly influence the dislocation density, grain boundary evolution, and strain hardening, ultimately affecting the mechanical properties, such as strength and ductility. Deformation band and deformation twin with plate-like structure can be observed in Fig. 4a, which indicates the strain localization within the microstructure. Fig. 4b shows the presence of twins. Fig. 4c shows the nanoscale twinning (marked by dotted circles), suggesting the nucleation of deformation twins as a direct consequence of the applied rolling strain. With the increase in rolling reduction to 70% (Fig.4d), the microstructure evolves into a distinctive reticular pattern composed of twinning and deformation bands. The transformation of the diffraction pattern from discrete spots to a continuous ring structure suggests the initiation of strain-induced grain subdivision, which is a phenomenon commonly observed in severely deformed metals. However, in this research, the distinct reticular pattern observed in the microstructure provides additional insight into the specific grain refinement mechanisms occurring in the CNCM alloy under high rolling reductions. The dark-field image (Fig. 4e), extracted from a specific region of the diffraction ring, further corroborates the spatial correlation between the reticular deformation bands and grain refinement. Under reduction of 90% (Fig. 4f), the reticular deformation bands remain well-defined, accompanied by extensive twinning. The ring-shaped diffraction pattern provides further evidence of strain-induced grain subdivision, reinforcing that significant microstructure refinement occurs during cold rolling with reduction beyond

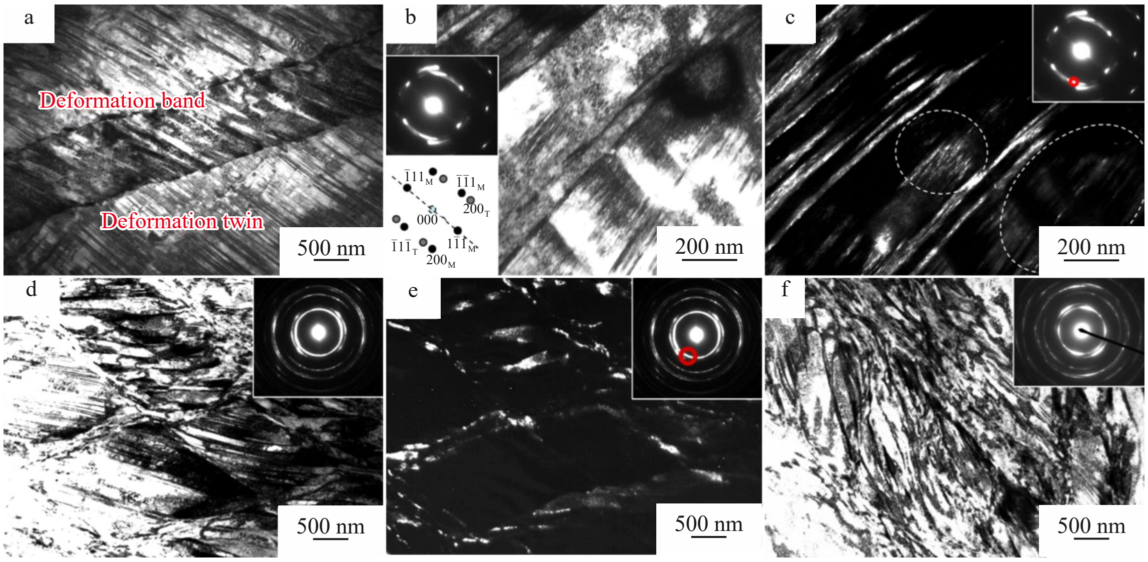

Fig.4 TEM images of CNCM alloys after cold rolling[25]: (a) 50% reduction; (b) magnified image of Fig. 4a; (c) dark-field image of Fig. 4b; (d) 70% reduction; (e) dark-field image of Fig.4d; (f) 90% reduction

70%. At this level of deformation, the accumulation of dislocations reaches a critical point, promoting dynamic recovery and the onset of continuous dynamic recrystallization. This transition leads to the progressive refinement of grain structures and the formation of ultrafine grains, further enhancing the mechanical stability and strain accommodation capacity of alloys. These observations confirm the progressive refinement of the grain structure and the transition towards ultrafine-grained morphology under severe plastic deformation.

Fig. 5 shows the microstructures and grain boundary maps of CNCM alloys during annealing at 1073 K for different durations[25]. The grain boundary maps depict the high-angle grain boundaries (HAGBs) in black and Σ3 coincident site lattice (CSL) boundaries in red. The proportion of Σ3 boundaries in the recrystallized regions is quantified. After 120 s of heat treatment, small recrystallized grains emerge sporadically, as shown in Fig. 5a. At 210 s, the overall microstructure is basically unchanged, as shown in Fig. 5c. However, after 270 s, a substantial increase in fine recrystallized grains is observed, as shown in Fig. 5e, suggesting an accelerated nucleation and growth process. Grain boundary analysis indicates a continuous rise in the fraction of Σ3 boundaries with the heat treatment proceeding. Notably, the formation of Σ3 boundaries occurs even in the absence of immediate grain growth, suggesting their role in suppressing grain coarsening and stabilizing grain boundaries during recrystallization.

3.2 Hardness and damping properties of CNCM alloy after cold rolling and heat treatment

Fig. 6 presents the hardness evolution of CNCM alloys subjected to cold rolling with reductions of 50%, 70%, and

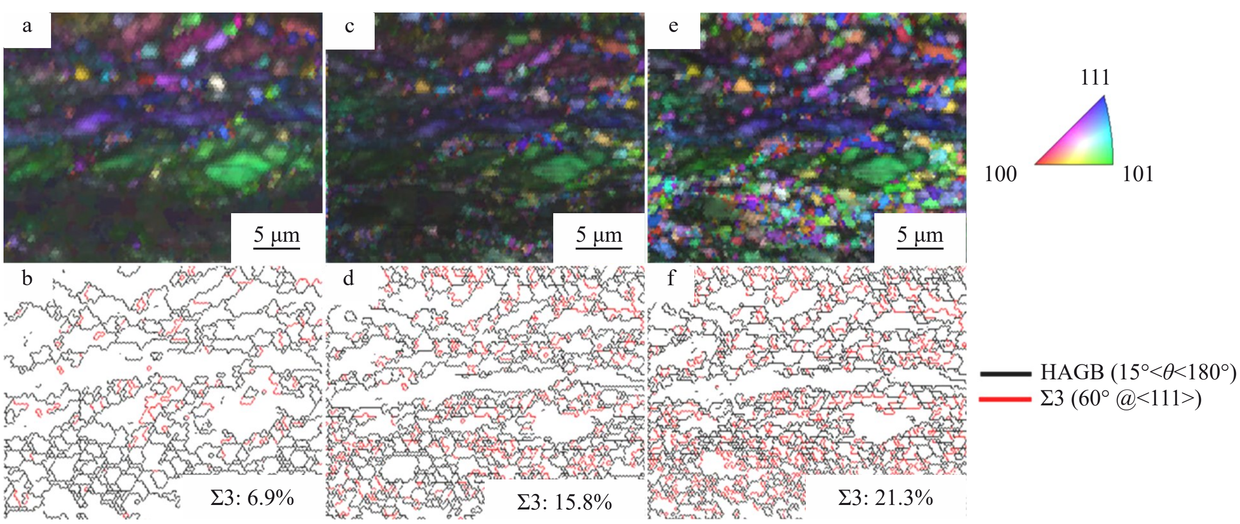

Fig.5 Microstructures (a, c, e) and grain boundary maps (b, d, f) of CNCM alloys during annealing at 1073 K for different durations[25]: (a–b) 120 s, (c–d) 210 s, and (e–f) 270 s

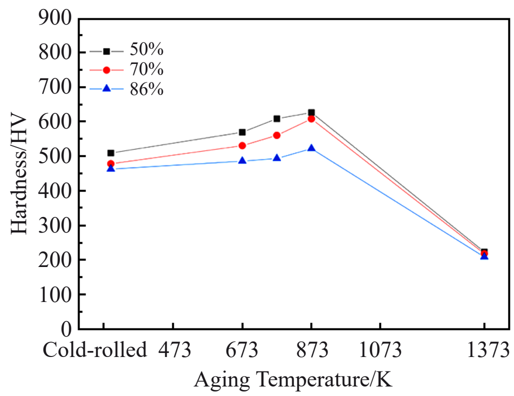

Fig.6 Hardness of cold-rolled CNCM alloys before and after aging heat treatment at various temperatures for 3.6 ks

86% followed by aging heat treatment at various temperatures for 3.6 ks. Hardness exhibits a correlation with rolling reduction due to the increasing dislocation density and strain hardening. Under the same rolling reduction, the hardness reaches the peak value at 873 K. Beyond this temperature, a substantial decline in hardness is observed, particularly at 1373 K, where recrystallization and grain growth dominate, leading to microstructure recovery and softening. The hardness range (600±50 HV) aligns with the tensile strength values (1400–1500 MPa)[16–17].

Fig. 7 illustrates the damping behavior of CNCM alloy at different processing stages, i.e., logarithmic decrement δ^{-1} of cold-rolled CNCM alloys before and after aging at various temperatures for 3.6 ks. δ^{-1} for the original alloy is 3.2×10^{-4}, and it significantly increases to about 10^{-3} after cold rolling, which is attributed to the increased dislocation density and corresponding internal friction. A marginal rise in δ^{-1} with the increase in rolling reduction from 50% to 86% is attributed to the further accumulation of dislocations. After aging heat treatment (673 – 873 K), δ^{-1} remains relatively stable in the range of 2×10^{-4} – 3×10^{-4} with only minor fluctuations. The decline in δ^{-1} with the increase in plastic deformation suggests the pinning of dislocations by solute segregation, which is likely due to the Suzuki effect, therefore restricting the

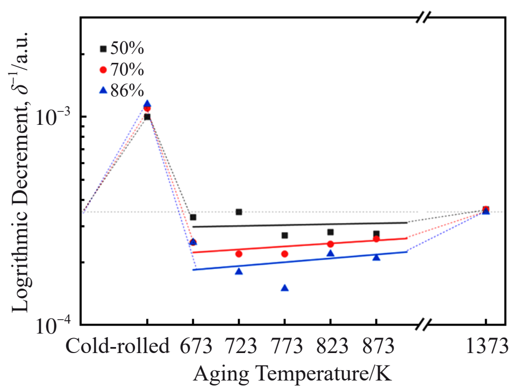

Fig.7 Logarithmic decrement δ^{-1} of cold-rolled CNCM alloys before and after aging at various temperatures for 3.6 ks

dynamic internal friction. After aging heat treatment at 1373 K, δ^{-1} reverts to the value at the solution-treated state, indicating substantial microstructure recovery via recrystallization and grain coarsening, effectively eliminating the dislocation-induced damping contributions.

4 Discussion

4.1 Mechanism of logarithmic decrement changes induced by cold plastic deformation and recrystallization heat treatment

This study aims to elucidate the mechanism by how plastic deformation and variations in heat treatment temperature influence δ^{-1}. Conventionally, vibration-damping materials dissipate vibrational energy by increasing the dislocation density or enhancing the twin formation within the crystal grains. However, this study attempts to reduce internal friction and suppress energy loss to achieve a lower δ^{-1}.

Two primary mechanisms are proposed to explain the changes in δ^{-1} observed in CNCM alloys:

(1) Cold plastic deformation increases dislocation density, lattice distortion, and atomic vacancies, all of which contribute to the increased internal friction and energy dissipation. As a result, δ^{-1} rises. (2) Recrystallization heat treatment mitigates dislocations, lattice distortions, and atomic vacancies, generally leading to a lower δ^{-1}. However, the formation of alloy-specific twins during recrystallization may increase internal friction, promoting energy dissipation and causing a subsequent rise in δ^{-1}.

Meanwhile, when the recrystallization heat treatment is performed after plastic deformation, the fibrous microstructure formed during cold rolling rapidly recovers and it is recrystallized, activating atomic diffusion. This process promotes recovery of lattice defects, elimination of dislocations and vacancies, and rearrangement of atoms, significantly reducing the residual stress and ultimately lowering the damping ratio to near-minimum values. At higher temperatures (above the recrystallization temperature), dislocations and vacancies are further diminished, and δ^{-1} further decreases, eventually approaching the value at the solution-treated state.

The observed trends in hardness changes induced by cold deformation and aging heat treatment in this study are consistent with the results in Ref. [25]. It was previously reported that hardness is increased with the increase in rolling reduction from 50% to 86% (or even 90%), and it may decrease or become stable depending on the annealing or aging heat treatment conditions.

Moreover, Ref. [25] showed that the dislocation density measured by the modified Warren-Averbach method was 8.9×10^{15}, 2.5×10^{16}, and 4.5×10^{16} m^{-2} at the reduction of 50%, 70%, and 90%, respectively. The high dislocation densities can be implied by the elevated hardness and microstructure. This phenomenon indicates that the increase in dislocation density due to cold deformation enhances the hardness, whereas partial recovery and rearrangement of dislocations during aging heat treatment lead to slight decrease or stabilization in hardness.

4.2 Positioning of CNCM alloy with low δ^{-1}

Fig. 8 illustrates the relationship between δ^{-1} and tensile strength for various materials[30], including CNCM alloy in this research. At the tensile strength of approximately 1500 MPa, the CNCM alloy exhibits δ^{-1} of 2×10^{-4} – 3×10^{-4}, surpassing those of the previously known high-strength low-damping materials. The δ^{-1} value and strength of this alloy is approximately 1.7 times lower and 1.5 times higher than those of the Ti alloys, respectively, showing promising application as ultrasonic wave transmission materials. Generally, the materials with a high Young's modulus have lower internal vibration friction. The Ti6Al4V alloys exhibit a Young's modulus of around 110 GPa, and the Young's modulus of CNCM alloy achieves approximately 230 GPa, which is way more than that of Ti6Al4V alloys. This result explains the significantly lower δ^{-1} of CNCM alloy. Additionally, the internal friction is thought to be absorbed and relaxed at viscoelastic phase boundaries. XRD analyses (Fig. 2 – Fig. 3) confirm that the CNCM alloy retains a γ-fcc single-phase structure before and after heat treatment, contributing to its low damping properties.

4.3 Damping characteristics of CNCM alloy based on Suzuki effect, texture formation, and recrystallization behavior

4.3.1 Dislocation structures and textures formed by cold rolling

In this study, cold rolling significantly increases the dislocation density in the CNCM alloy, resulting in a rise in both the hardness and δ^{-1} (Fig. 4 – Fig. 5). According to Ref. [25], CNCM alloys subjected to cold rolling are known to form characteristic fcc metal rolling textures, such as {110} <001> Goss and {110} <112> Brass textures. The formation of these textures involves the refinement of dislocation cell structures and the generation of deformation twins (Fig. 1b – 1d). Consequently, the pronounced increase in dislocation density aligns with the results in Ref. [25]. The findings in this study demonstrate a clear correlation: increased rolling reduction→increased dislocation density→increased hardness→increased internal friction (δ^{-1}). These results are consistent with the features of cold-rolled structures (Goss and Brass textures) and high-density dislocation structures[25].

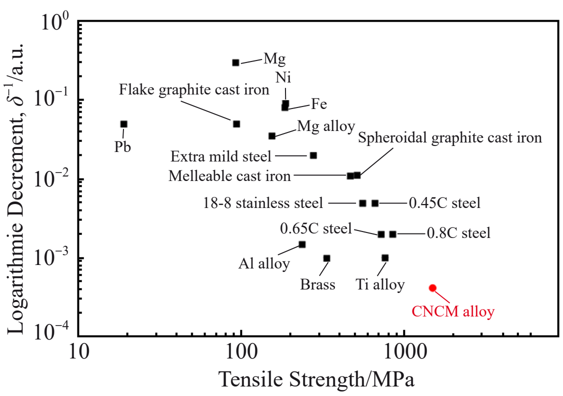

Fig.8 Relationships between logarithmic decrement δ^{-1} and tensile strength of various materials

4.3.2 Dislocation pinning and Suzuki effect during heat treatment below recrystallization temperature

This study proposes a mechanism for the reduction in δ^{-1} during aging heat treatments below the recrystallization temperature (approximately 873 K). According to Ref. [25], heat treatment of CNCM alloys around 973 K results in the transformation of dislocations into a stacking fault network accompanied by Shockley partial dislocations. This process induces segregation of alloying elements due to the Suzuki effect.

The Suzuki effect involves the accumulation of solute elements at stacking fault planes or dislocation cores, significantly reducing the mobility of dislocations. As a result, dislocations become immobilized, suppressing their elimination and vibration, which leads to a substantial decrease in internal friction (δ^{-1}). In this study, the fact that the aged samples exhibit hardness of around 600 HV while maintaining low δ^{-1} value suggests that continuous locking of dislocations via Suzuki segregation plays a critical role. These results strongly correspond to the Suzuki effect[25] at approximately 973 K[25].

4.3.3 Microstructure changes and recovery of damping properties during heat treatment above recrystallization temperature

The results of this study indicate that heat treatment at approximately 1373 K, which is above the recrystallization temperature, significantly reduces dislocation density and restores the microstructures of CNCM alloy to the initial ones. Consequently, δ^{-1} returns to the value at solution-treated state immediately (3.2×10^{-4}). It is reported that significant recrystallization occurs around 1073 K, transforming the microstructure into fine grains with few residual dislocations.

This behavior can be attributed to the extensive dislocation networks formed during cold rolling being eliminated or reduced to isolated dislocations within recrystallized grains. As a result, internal friction caused by dislocation vibration markedly diminishes. However, Ref. [25] suggests that an increase in grain boundaries may increase the internal friction. Thus, the final δ^{-1} appears to be determined by a balance between lower δ^{-1} due to dislocation elimination and energy dissipation at grain boundaries. In this study, grain growth is inferred to occur concurrently with heat treatment at 1373 K, which contributes to the overall enhancement in damping properties. These findings imply that high-temperature heat treatment not only promotes recrystallization but also facilitates grain growth, leading to improved damping characteristics by minimizing structural defects.

4.3.4 Mechanical anisotropy and directional dependence of damping

Ref. [25] reported that the Young's modulus and tensile strength of CNCM alloys exhibit significant anisotropy dependency on the direction, such as the rolling direction, transverse direction, or intermediate direction (e.g., 60°). This anisotropy is primarily attributed to the orientation distribution of Goss and Brass textures formed during cold rolling. In this study, δ^{-1} is measured in a single longitudinal direction, and its directional dependence has not been explicitly investigated. However, considering the bow-out behavior of dislocations and the variation in elastic constants based on crystallographic orientation, it is highly probable that the damping ratio will exhibit some degree of anisotropy during the application of tools or components.

As reported in Ref. [25], the Goss and Brass textures developed during deformation and heat treatment processes significantly influence the elastic constants and dislocation mobility in specific crystallographic directions. For practical applications, it is desirable to conduct directional damping ratio evaluations along rolling direction, transverse direction, or intermediate direction to account for the potential anisotropy in the material performance.

In conclusion, due to the Suzuki effect, texture formation, recrystallization behavior, and mechanical anisotropy[25], the sequential behavior can be observed: high-density dislocation introduction by plastic deformation→dislocation pinning (substantial δ^{-1} reduction) →dislocation elimination and structure recovery by high-temperature recrystallization.

CNCM alloys, classified as high-entropy alloys, are characterized by high configurational entropy and severe lattice distortion effects, which strongly promote dislocation locking and recrystallization mechanisms within specific temperature ranges. The phenomena of dislocation pinning around 973 – 1073 K and recrystallization initiation above 1073 K align well with the microstructure control mechanisms reported in Ref.[28].

5 Conclusions

1) Rolling reduction leads to a significant increase in dislocation density, resulting in increased internal friction and a rise in δ^{-1} value. The formation of characteristic rolling textures, such as {110}<001> Goss and {110}<112> Brass textures, and the accompanying high-density dislocation structures in CNCM alloys are direct reasons accounting for these phenomena.

2) Aging heat treatment below the recrystallization temperature (approximately 873 K) facilitates the element segregation near dislocation cores due to the Suzuki effect, leading to continuous locking of dislocations. This phenomenon significantly reduces δ^{-1} value to 2×10^{-4}–3×10^{-4}, achieving ultra-low damping level while maintaining high hardness (about 600 HV). The Suzuki effect is of great significance in achieving this low damping value.

3) Heat treatment at approximately 1373 K, which is above the recrystallization temperature, eliminates most of the dislocations introduced during cold rolling, allowing the grain structure to recover to the original state. Consequently, δ^{-1} returns to its original value of about 3.2×10^{-4}. While the increase in grain boundaries may increase the internal friction, the grain growth during high-temperature treatment contributes to the overall reduction in damping value.

4) The CNCM alloy achieves a tensile strength of approximately 1500 MPa with an ultra-low logarithmic decrement of 2×10^{-4} – 3×10^{-4}. The δ^{-1} value and strength of CNCM alloy is approximately 1.7 times lower and 1.5 times higher than those of the Ti alloys, respectively, making it one of the most promising materials for ultrasonic applications, such as surgical instruments and ultrasonic cutters.

5) The Goss and Brass textures formed through repeated cold rolling and annealing processes are expected to influence not only Young's modulus and strength but also the damping ratio, depending on the direction. For practical application and component design, optimizing processing conditions while considering the directional dependence of texture is critical.

6) CNCM alloy has high strength and ultra-low damping properties, offering high performance as ultrasonic wave transmission materials, and surpassing the conventional materials, such as Ti alloys. Intentional control of dislocation pinning and recrystallization behavior provides a unique opportunity to achieve desired mechanical properties and low damping properties simultaneously. This research provides valuable guidance for the development of high-performance materials for ultrasonic surgical devices, industrial ultrasonic tools, and a wide range of other applications.

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塑性变形与热处理对Co-Ni-Cr-Mo基合金低阻尼性能的影响

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摘 要：研究了添加0.5wt% Nb的Co-Ni-Cr-Mo基合金在不同塑性变形和热处理条件下的强度和阻尼性能。通过维氏硬度测试、自由共振杨氏模量测量和微观组织分析，阐明了位错密度、空位形成和再结晶对该合金性能的影响。结果表明，随着轧制变形程度的增加，位错密度升高，阻尼性能得到增强，而在再结晶温度以下的时效处理通过Suzuki效应导致的位错钉扎作用降低了阻尼性能。再结晶热处理可恢复材料的原始组织结构和阻尼水平。该合金的抗拉伸强度约为1500 MPa，对数衰减值δ^{-1}处于2×10^{-4}~3×10^{-4}之间，表现出优异的力学性能，相较于Ti基合金更具优势，使其成为超声波工具和医疗应用的理想材料。

关键词：Co-Ni-Cr-Mo基合金；低阻尼性能；Suzuki效应；塑性变形

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