

# Effect of Magnesium Microalloying on Microstructural Strengthening and Mechanical Properties of Beryllium Bronze

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## Abstract

To address the critical bottlenecks of traditional beryllium bronze, such as poor strength-ductility synergy and susceptibility to high-temperature softening caused by its reliance on a single precipitation strengthening mechanism, a 0.08% Mg micro-alloying modification strategy is proposed in this study. By systematically investigating the effects of aging treatments on the microstructure, as well as the room-temperature and medium-to-high-temperature mechanical properties of the Mg-containing beryllium bronze, the strengthening role of Mg and the underlying mechanisms for microstructural stabilization are thoroughly revealed. The results indicate that the introduction of trace amounts of Mg yields a significant grain refinement effect, reducing the average grain size of the alloy from 25~40  $\mu\text{m}$  to 15~25  $\mu\text{m}$ . The Mg atoms exhibit a globally uniform solid solution state without grain boundary segregation. Without interfering with the normal nucleation of the  $\gamma'$ -Be<sub>2</sub>Cu precipitates, a ternary synergistic strengthening system comprising "grain refinement, solid solution, and precipitation" is successfully established. Regarding the room-temperature mechanical properties, after a peak aging treatment at 330 °C for 2 h, the tensile strength of the alloy reaches 1211 MPa, while the elongation is robustly maintained at 8.98%. This strength-ductility synergy is significantly superior to that of traditional Mg-free beryllium bronzes. In terms of medium-to-high-temperature performance, tests demonstrate that after holding at 300 °C for 15 min, the tensile strength remains as high as 1119 MPa with an outstanding strength retention rate of 92.4%, exhibiting exceptional high-temperature thermal stability. Notably, when benchmarking the high-temperature performance against the commercial C17200 alloy, it is found that the uniformly dissolved Mg atoms kinetically suppress the coarsening rate of the strengthening precipitates through a strong "solute drag" effect. Within the core service temperature range of  $\leq 300$  °C, the microstructural stabilization efficacy provided by merely 0.08% of inexpensive Mg perfectly achieves functional equivalence to that of 0.2%~0.4% of costly and scarce strategic cobalt (Co). While significantly enhancing the comprehensive performance of beryllium bronze, this study provides a novel pathway to overcome the limitations of high-cost cobalt resources and to develop highly cost-effective, heat-resistant copper-beryllium alloys.

## Keywords

**Beryllium Bronze; Magnesium Microalloying; Aging Process; Microstructure; Mechanical Properties; Strength-Plasticity Matching; High-Temperature Stability.**

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## 1. Introduction

Beryllium bronze, widely acclaimed as the "King of Elasticity" among non-ferrous metals, occupies an irreplaceable position in critical sectors such as aerospace, precision electronics, and high-end

tooling[1][2][3]. These superior capabilities-including an exceptional elastic limit, robust fatigue resistance, and significant precipitation hardening characteristics-are primarily derived from its core strengthening mechanism: the precipitation of coherent, ordered  $\gamma'$ -Be<sub>2</sub>Cu nanophases during post-solution aging treatment[4][5][6].

Despite these advantages, traditional beryllium bronze alloys rely on a single precipitation strengthening mechanism, which inherently leads to critical bottlenecks such as insufficient strength-ductility synergy and poor thermal stability at elevated temperatures. These intrinsic deficiencies significantly restrict the application of the material under high-precision and high-load operating conditions.

Magnesium (Mg) is a common alloying element utilized in copper alloys to enhance the matrix through lattice distortion induced by solid solution. Furthermore, Mg addition typically facilitates grain refinement. However, a persistent challenge in copper alloy design is the tendency of Mg to segregate at grain boundaries, which often precludes the achievement of a uniform solid solution state necessary for optimal strengthening.

In this study, a micro-alloying strategy using trace amounts of magnesium was implemented to investigate its influence on the microstructural evolution and mechanical properties of beryllium bronze. The objective of this research is to elucidate the strengthening role of Mg and provide a viable pathway for addressing the performance limitations of traditional beryllium bronze alloys[7][8].

## 2. Experimental Materials and Methods

### 2.1 Material Preparation

The magnesium-containing beryllium bronze was fabricated via vacuum induction melting (VIM). High-purity electrolytic copper, Cu-2Be master alloy, and Cu-10Mg master alloy were utilized as the primary raw materials. The precise chemical composition of the alloy was determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), with the results summarized in Table 1. The resulting ingots were subjected to homogenization annealing, followed by hot rolling and solution treatment (780 °C for 30 min). Subsequently, the materials underwent cold drawing to produce semi-hard rods with a final diameter of 6 mm.

**Table 1.** Chemical Composition of the Material (wt.%)

Element	Be	Mg	Ni	Cu
W <sub>B</sub> /%	2.04	0.08	0.26	Bal.

### 2.2 Aging Process

Aging treatments were performed at various temperatures, specifically 310 °C, 320 °C, 330 °C, 340 °C, and 350 °C, with holding durations set at multiple gradients ranging from 0.25 h to 4 h. The heat treatment was conducted in a box-type resistance furnace. To ensure precise temperature control, a thermocouple was placed in direct contact with the specimen surface. The heating rate was maintained at 10 °C/min, and the specimens were air-cooled to room temperature upon completion of the aging process[9][10][11][12].

### 2.3 Mechanical Property Testing

Standard tensile specimens were prepared in accordance with GBT 34505-2017 (*Test Method for Tensile Testing of Copper and Copper Alloys at Room Temperature*), with specific dimensions illustrated in Figure 1. Room-temperature tensile tests were executed using a universal testing machine to determine the tensile strength and elongation. For each experimental group, three replicate specimens were tested, and the average values were recorded as the final results.

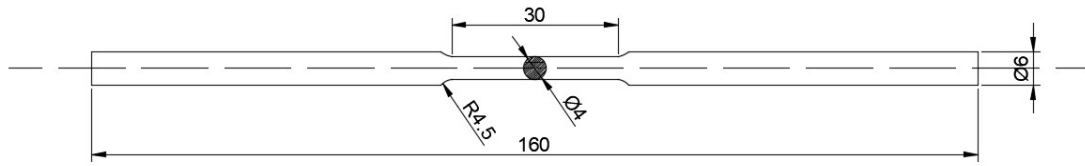


Figure 1. Schematic Diagram of the Tensile Specimen

Previous studies have indicated that conventional beryllium bronze begins to exhibit a decrease in strength at 150 °C, with softening significantly accelerating beyond 350 °C [13][14][15]. In this study, to evaluate the enhancement of high-temperature thermal stability provided by magnesium microalloying, peak-aged specimens were selected for high-temperature tensile testing. These specimens were held at temperatures of 250 °C, 300 °C, and 350 °C for 15 min prior to stretching. The tensile strength and the corresponding strength retention rates were subsequently calculated [16]. For hardness measurements, specimens were machined into standard dimensions of  $\phi 6 \text{ mm} \times 10 \text{ mm}$ . Following a sequential grinding and polishing process (rough grinding, fine grinding, and final polishing), Vickers hardness was measured using a universal hardness tester. A load of 10 kgf was applied for a duration of 10 s. To ensure statistical accuracy, five different positions were tested on each specimen, and the average value was recorded.

### 2.4 Microstructural Characterization

Specimens for microstructural analysis were mounted, ground, and polished according to standard metallographic procedures. The polished surfaces were etched for 5–10 s using a chemical solution composed of 8 g  $\text{CuCl}_2$  and 92 mL ammonia. After etching, the samples were rinsed with absolute ethanol and blow-dried. Grain morphology was observed via optical microscopy (OM), and the average grain size was statistically determined [17].

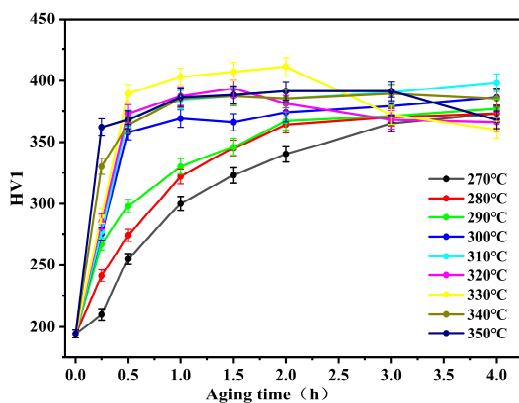
The microstructure and grain boundary morphology were further examined using scanning electron microscopy (SEM). This was coupled with energy-dispersive X-ray spectroscopy (EDS) to analyze the distribution variance of magnesium between the grain interiors and grain boundaries.

For advanced analysis, transmission electron microscopy (TEM) specimens were prepared using twin-jet electropolishing and focused ion beam (FIB) techniques. High-resolution observations and precise micro-area compositional analyses were performed to characterize the solid solution features of Mg and to identify the morphology and distribution of the  $\gamma'$ - $\text{Be}_2\text{Cu}$  precipitates.

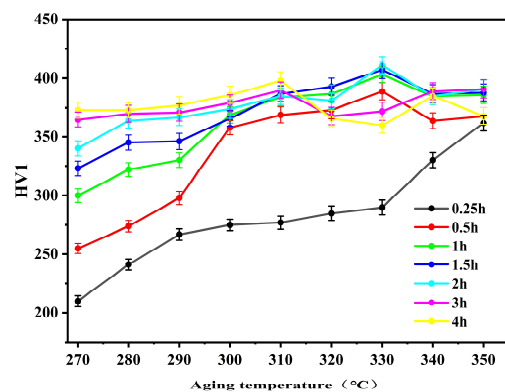
## 3. Results

### 3.1 Effect of Mg Microalloying on the Mechanical Properties of Beryllium Bronze

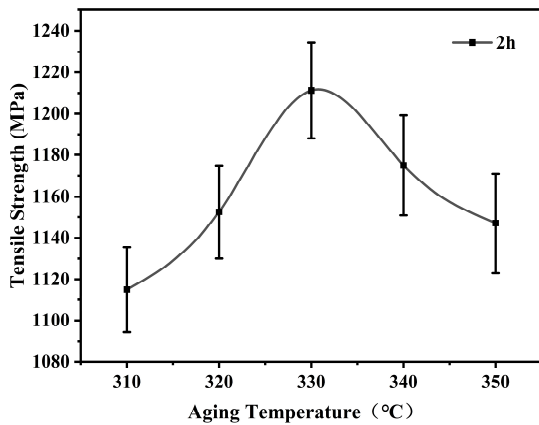
#### 3.1.1 Room-Temperature Mechanical Properties



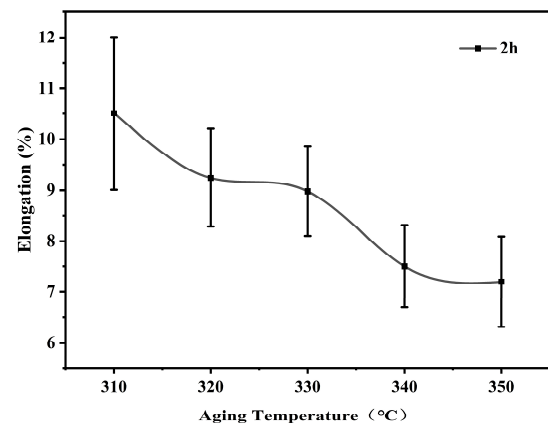
(a) Vickers Hardness vs. Aging Time



(b) Vickers Hardness vs. Aging Temperature



(c) Tensile Strength (MPa)



(d) Elongation (%)

**Figure 2.** Room-Temperature Mechanical Properties of 0.08% Mg-doped Beryllium Bronze

The aging hardening curves of the microalloyed beryllium bronze are presented in Figure 2(a). The results demonstrate that the hardness follows a typical precipitation hardening behavior. Specifically, when the aging time is less than 0.5 h or the temperature is below 300 °C, the alloy remains in the under-aged stage, where hardness increases rapidly with increasing time or temperature. Peak aging is achieved at 330 °C for 2 h, yielding the maximum hardness across the tested range. As the aging time exceeds 3 h or the temperature surpasses 340 °C, the alloy enters the over-aged stage, characterized by a gradual decline in hardness.

Based on the hardening response, the aging temperature range for room-temperature tensile testing was narrowed down to 310–350 °C for a constant duration of 2 h, with results shown in Figures 2(c) and 2(d). The tensile strength exhibits a "first increase then decrease" trend as the aging temperature rises, reaching a peak value of 1211 MPa at 330 °C, which corresponds to the peak-aged state. Conversely, the elongation consistently decreases with increasing temperature, dropping from 10.5% at 310 °C to 7.2% at 350 °C.

The aging process is a critical stage for regulating the microstructure and mechanical properties of beryllium bronze. Variations in temperature and time directly influence the size, quantity, distribution, and interfacial matching of the precipitates, which in turn determine the strength, hardness, and plasticity synergy of the alloy. Experimental results indicate that as the aging temperature rises from 310 °C to 350 °C, both hardness and tensile strength follow the typical aging hardening law, peaking at 330 °C after 2 h. Under this optimal condition, the alloy achieves a tensile strength of 1211 MPa, a hardness of 411 HV, and an elongation of 8.9%, representing the optimal comprehensive synergy between strength and plasticity.

As the aging temperature increases, the decomposition rate of the supersaturated solid solution accelerates, leading to the continuous nucleation and dispersed precipitation of the  $\gamma'$  strengthening phases. This significantly enhances the resistance to dislocation motion, thereby continuously increasing strength and hardness. At 330 °C, the precipitates are fine and uniformly distributed, maintaining a coherent relationship with the matrix. At this stage, the precipitation strengthening effect is maximized, resulting in the peak strength and hardness of the alloy. This behavior is highly consistent with the aging precipitation patterns observed in traditional beryllium bronze.[18] Related studies also confirm that the early stages of aging in beryllium bronze are dominated by the nucleation and growth of high-density nanophases, with performance improving progressively alongside the precipitation process.

When the aging temperature is further increased to 350 °C, the strength and hardness of the alloy begin to decline, while the elongation shows a slight recovery. This is attributed to excessive temperatures promoting the rapid coarsening of precipitates, which causes some  $\gamma'$  phases to lose their

coherency. Consequently, the dispersion strengthening effect is significantly reduced. Furthermore, increased precipitation at the grain boundaries leads to a reduction in the load-bearing capacity of the alloy. This phenomenon aligns with the general law of high-temperature aging coarsening observed in copper alloys.

**Table 2.** Comparison of Room-Temperature Mechanical Properties between Mg-microalloyed and Traditional Mg-free Beryllium Bronze[19]

Material Type	Aging Process	Tensile Strength (MPa)	Vickers Hardness (HV)	Elongation (%)
Traditional Mg-free QBe2.0	As-received (Untreated)	787	240	2.4
	240°C×2h	934	294	11.6
	260°C×2h	1194	378	3.6
	320°C×2h	1349	434	2.1
	370°C×2h	1102	359	4.1
0.08%Mg Microalloyed	310°C×2h	1115	385	10.5
	320°C×2h	1152	389	9.2
	330°C×2h	1211	411	8.9
	340°C×2h	1175	391	7.5
	350°C×2h	1147	385	7.2

As indicated in Table 2, compared with the traditional Mg-free QBe2.0 alloy, the peak aging process of the 0.08% Mg microalloyed beryllium bronze shifts to 330 °C for 2 h. At this condition, the peak tensile strength reaches 1211 MPa and the Vickers hardness is 411 HV. Although the strength is slightly lower than that of the traditional alloy, the peak aging elongation reaches 8.9%, which is approximately 4.3 times the peak plasticity of the traditional alloy. Furthermore, the elongation remains stable between 7.2% and 10.5% throughout the entire aging range of 310–350 °C, successfully achieving a synergistic optimization of high strength and high ductility.

### 3.1.2 Medium-to-High-Temperature Mechanical Properties

Figure 3 and Table 3 provide a detailed comparison of the tensile strength evolution at different temperatures between the 0.08% Mg microalloyed beryllium bronze and the C17200 alloy (2.0%Be-0.4%Co-0.1%Ni). The data indicates that within the core industrial service temperature range of ≤300 °C, the performance of the 0.08% Mg experimental alloy is comprehensively and significantly superior to that of the cobalt-containing C17200.

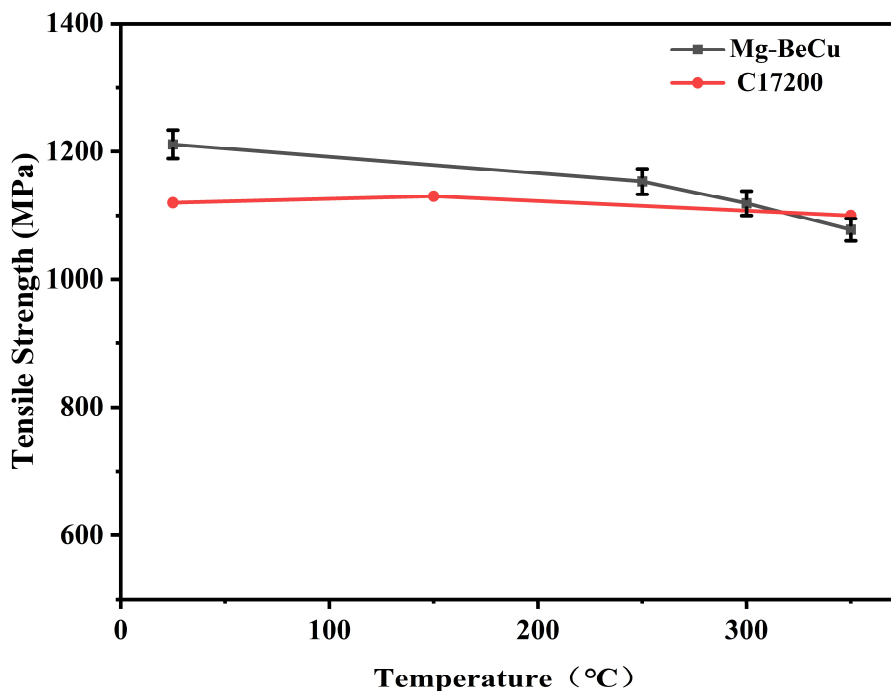
The room-temperature (25 °C) strength of the experimental alloy is as high as 1211 MPa, which is an increase of nearly 100 MPa compared to C17200. Upon entering the medium-to-high temperature range, the experimental alloy exhibits exceptional thermal stability: At 250 °C, the tensile strength is

robustly maintained at 1152 MPa. At 300 °C, the tensile strength remains steady at 1119 MPa, representing an outstanding strength retention rate of 92.4%.

Throughout this range, the absolute strength values consistently remain above those of C17200. Although the curves intersect at 350 °C, where the cobalt-containing system exhibits a slightly higher ultimate resistance, the introduction of trace magnesium significantly enhances the service strength within the mainstream operating conditions of  $\leq 300$  °C. Moreover, this modification substantially reduces raw material costs. In summary, 0.08% Mg microalloying is a highly strategic and cost-effective means of enhancing the medium-to-low temperature service capabilities of beryllium bronze.

**Table 3.** High-Temperature Tensile Strength of 0.08% Mg Alloy vs. C17200 Alloy at Various Holding Temperatures[20]

Aging Temp. (°C)	Mg-BeCu Tensile Strength (MPa)	Strength Retention Rate	Aging Temp. (°C)	C17200 Tensile Strength (MPa)
25	1211	100%	25	1120
250	1152	95.1%	150	1130
300	1119	92.4%	350	1110
350	1078	89.8%		

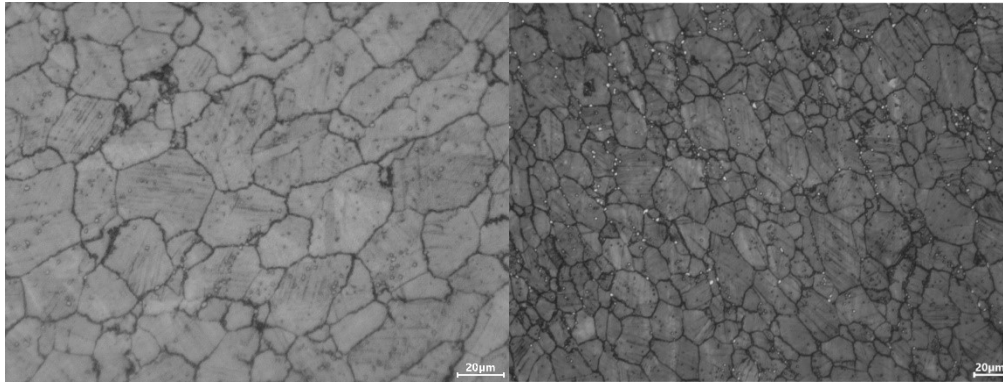


**Figure 3.** Comparison of Tensile Strength between 0.08% Mg Beryllium Bronze and C17200 at Elevated Temperatures

### 3.2 Effect of Magnesium Microalloying on the Microstructure of Beryllium Bronze

#### 3.2.1 Grain Morphology and Size Characteristics

Figure 4 illustrates a comparison of the metallographic structures of the beryllium bronze alloy before and after the addition of 0.08% Mg. Compared with traditional magnesium-free beryllium bronze, the grains of the alloy with the addition of 0.08% Mg are significantly refined, and the microstructure becomes more uniform. The grains of traditional beryllium bronze are relatively large and unevenly distributed, with a grain size ranging from 25 to 40  $\mu\text{m}$  [21]. After magnesium microalloying, the grain size of the alloy is reduced to 15–25  $\mu\text{m}$ , with an average grain size of approximately 20  $\mu\text{m}$ . The grain morphology appears more regular with distinct grain boundaries, and the overall microstructural uniformity is markedly improved.

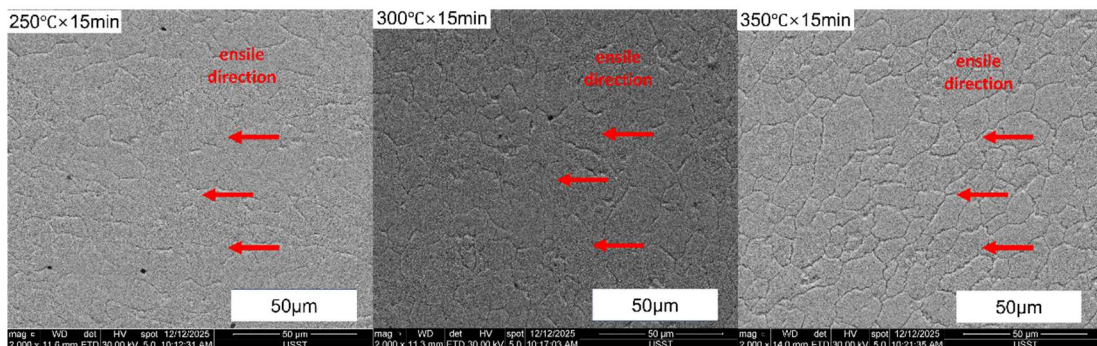


(a) Traditional Beryllium Bronze (b) 0.08% Mg Beryllium Bronze

**Figure 4.** Comparison of Metallographic Microstructure Before and After 0.08% Mg Addition

The longitudinal section microstructures of specimens subjected to high-temperature tensile testing at **250 °C/15 min**, **300 °C/15 min**, and **350 °C/15 min**-conditions where the alloy demonstrated superior performance stability-were observed. The results, illustrated in **Figure 5**, indicate that no significant grain growth, deformation, or recrystallization occurred under these high-temperature conditions. The alloy effectively maintained its fine-grained characteristics, with grain sizes remaining within the **15–25 µm** range.

This demonstrates that the addition of magnesium effectively inhibits grain boundary migration and grain coarsening at elevated temperatures. Consequently, the fine-grained microstructure remains stable within high-temperature service environments.



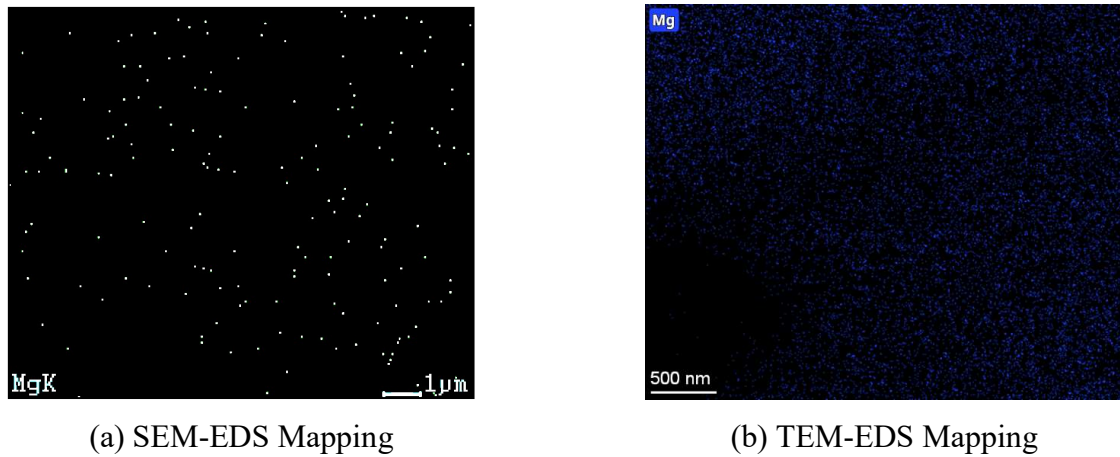
(a) 250°C/15min; (b) 300°C/15min; (c) 350°C/15min

**Figure 5.** Longitudinal Section Grain Morphology of Microalloyed Beryllium Bronze after 300°C × 2h Heat Treatment followed by High-Temperature Tensile Testing

### 3.2.2 Distribution Characteristics of Magnesium

The distribution of magnesium within the alloy is illustrated in **Figure 6**. It can be observed that the Mg element is distributed continuously and uniformly throughout the entire observation area, with no evidence of localized enrichment or increased concentration at the grain boundaries.

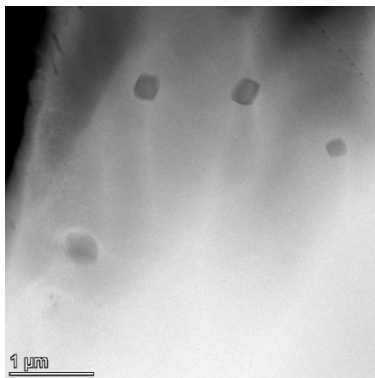
When integrated with the grain size data, it is noted that the observation scales for **SEM-EDS** and **TEM-EDS** are **1 µm** and **500 nm**, respectively. Given that these scales are significantly smaller than the average grain size of **20 µm**, it clearly demonstrates that magnesium is distributed within the copper matrix in the grain interior rather than at the grain boundary positions. The micro-area compositional analysis results from both SEM-EDS and TEM-EDS further confirm the uniform solid solution characteristics of magnesium within the copper matrix.



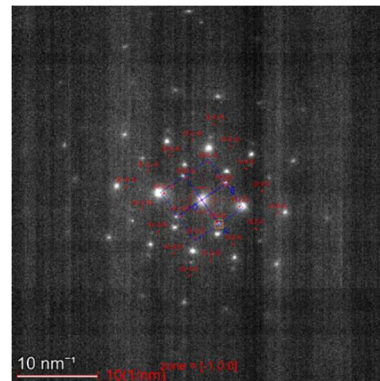
**Figure 6.** Magnesium Distribution Characteristics

### 3.2.3 Characteristics of Precipitates

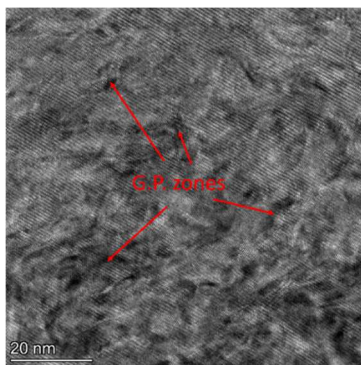
As shown in the high-resolution TEM observations in Figure 7, nano-scale  $\gamma'$ -Be<sub>2</sub>Cu precipitates remain present within the matrix of the magnesium-microalloyed beryllium bronze. These precipitates maintain a strong coherent relationship with the copper matrix and are uniformly distributed. The uniform solid solution of magnesium does not exert any adverse effects on the formation or distribution of the  $\gamma'$ -Be<sub>2</sub>Cu precipitates. Ultimately, a superior composite microstructure is established, characterized by a "fine-grained structure + magnesium-solid-solution matrix + dispersed  $\gamma'$ -Be<sub>2</sub>Cu precipitates". This architecture provides the structural guarantee for the synergistic enhancement of the alloy's mechanical properties.



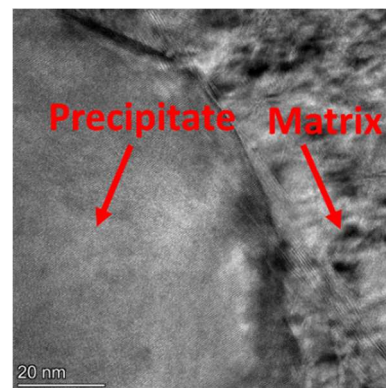
(a)  $\gamma'$ -Be<sub>2</sub>Cu Precipitates ( $\times 22,000$ )



(b) SAED Indexing of  $\gamma'$ -Be<sub>2</sub>Cu Precipitates



(c) High-Resolution image of  $\gamma'$ -Be<sub>2</sub>Cu Precipitates ( $\times 630,000$ )



(d) High-Resolution image of  $\gamma'$ -Be<sub>2</sub>Cu Precipitates ( $\times 630,000$ )

**Figure 7.** TEM Morphology and Precipitate Characteristics

## 4. Results Analysis and Discussion

### 4.1 Impact of Mg Microalloying on the Mechanical Properties of Beryllium Bronze

Comparing this study with similar research on beryllium bronze, it is evident that conventional QBe2.0 alloys, while possessing high strength in the peak-aged state, typically exhibit elongations below 3%. This leads to a severe imbalance between strength and ductility. In contrast, the Mg-containing alloy prepared in this experiment achieves an ultra-high tensile strength of 1211 MPa while robustly maintaining an elongation of approximately 9%. This significant data contrast indicates that the strategic regulation of aging processes combined with Mg microalloying modification can achieve a synergistic enhancement of both strength and ductility, breaking the "high strength but brittleness" performance bottleneck inherent in traditional alloys. The essence of this performance improvement lies in the introduction of magnesium, which optimizes the strengthening architecture of the alloy across multiple scales, as analyzed below:

Metallographic and SEM observations reveal that the addition of trace Mg significantly refines the average grain size of beryllium bronze from 25–40  $\mu\text{m}$  to approximately 20  $\mu\text{m}$ . This grain refinement contributes twofold: first, according to the Hall-Petch relationship, the significantly increased number of grain boundaries strengthens the resistance to dislocation motion, directly enhancing yield strength. Second, the regular and uniform fine-grained structure more effectively alleviates stress concentration during plastic deformation, thereby preserving a good plasticity reserve while increasing strength, which optimizes the strength-ductility matching[22].

EDS mapping confirms that Mg exists as a uniform solid solution within the copper matrix. Since the atomic radius of Mg (1.60 Å) is significantly larger than that of Cu (1.28 Å), this substitutional solid solution induces intense lattice distortion, creating an effective stress field that obstructs dislocation glide. This not only substantially improves the intrinsic base strength of the matrix and overall load-bearing capacity but also provides a more stable matrix environment for subsequent nanophase precipitation, forming the foundational support for the alloy's high performance[23][24].

TEM observations demonstrate that during the 330 °C peak aging stage, the  $\gamma'$ -Be<sub>2</sub>Cu precipitates reach an ideal nucleation density and dispersed distribution while maintaining a coherent relationship with the matrix. This optimal microstructural state provides the strongest pinning and blocking effects against dislocation movement, serving as the core contributor to the alloy's peak tensile strength and hardness[25][26].

### 4.2 Mechanism of Enhanced Stability in Medium-to-High Temperature Performance

The strengthening mechanism of conventional beryllium bronze highly depends on the dispersed distribution of precipitates. At excessive service temperatures, the precipitates undergo rapid coarsening via the Ostwald Ripening mechanism, leading to the severe destruction of the coherent strain field and a subsequent rapid softening and degradation of mechanical properties[27]. In the commercial C17200 alloy, a relatively high content of cobalt (0.2%–0.4%) is added to inhibit the unstable coarsening of the strengthening phases. This study introduces a minute amount of magnesium (0.08% by mass) to successfully construct a "triad" synergistic architecture of "precipitation strengthening, solid solution strengthening, and grain refinement strengthening". Within the service window of  $\leq 300$  °C, the performance of the 0.08% Mg experimental alloy comprehensively exceeds that of C17200.

From a micro-physical perspective, Mg atoms are distributed throughout the matrix as a uniform solid solution. The intense lattice distortion caused by the larger Mg atomic radius effectively enhances the high-temperature deformation resistance of the matrix. Simultaneously, the micro-addition of Mg exerts a significant grain refinement effect (refining grains from 25–40  $\mu\text{m}$  to 15–25  $\mu\text{m}$ ). The vastly increased number of effective grain boundaries plays a critical role in hindering dislocation motion and suppressing grain boundary sliding at high temperatures, thereby delaying microstructural softening at the mesoscopic scale.

In the core service temperature range ( $\leq 300$  °C), trace amounts of inexpensive Mg exhibit a dynamic locking efficacy comparable to high-cost Cobalt. Although  $\gamma'$ -Be<sub>2</sub>Cu precipitates inevitably undergo some growth due to thermal activation, the uniformly distributed Mg atoms significantly increase the long-range diffusion barrier through a strong "solute drag" effect, kinetically locking the coarsening rate of the strengthening phases[28]. During this process, the persistent solid solution and grain refinement strengthening compensate for the strength loss caused by the weakening of precipitation strengthening. This synergistic mechanism based on trace Mg atoms accurately replicates the microstructural locking function of high-content cobalt in C17200 alloys.

## 5. Conclusion

- (1) After aging at 330 °C for 2 h, the alloy achieves a tensile strength of 1211 MPa and an elongation of 8.98%, realizing an excellent synergy between high strength and high ductility.
- (2) At medium-to-high temperatures ( $\leq 300$  °C), the alloy maintains a tensile strength above 1119 MPa with a strength retention rate exceeding 92.4%. This demonstrates that micro-magnesium addition provides a cost-effective alternative to expensive cobalt while maintaining superior high-temperature performance.
- (3) Microalloying with 0.08% Mg significantly refines the beryllium bronze microstructure, reducing grain size from 25–40  $\mu\text{m}$  to 15–25  $\mu\text{m}$  and improving organizational uniformity. Mg atoms exist as a uniform solid solution within the copper matrix without grain boundary segregation and do not interfere with the formation of  $\gamma'$ -Be<sub>2</sub>Cu precipitates. This establishes a stable microstructural framework comprising fine grains, a solid-solution matrix, and dispersed precipitates.

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