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Effect of Rolling and Heat Treatment Parameters on Anisotropy of High-Purity Copper Plates

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High-purity copper plates (5N, 99.999 %) are critical materials in automotive, consumer-electronics, and defense applications due to their excellent formability. Their performance strongly depends on in-plane anisotropy and crystallographic texture. This study examines the texture evolution of high-purity copper plates under varied rolling and annealing conditions to clarify how processing affects mechanical properties, anisotropy (IPA %), and forming behavior. Results indicate that adjusting hot- and cold-rolling reductions and annealing parameters allows control of deformation (Brass, Copper) and recrystallization (Cube) textures. An optimal balance minimizes anisotropy, lowering IPA and Δr, thereby reducing earing and improving yield in deep-drawing. Conversely, for explosive-formed tail-fin projectiles requiring directional anisotropy, cold rolling is omitted and higher-temperature hot rolling plus annealing is used to promote Cube textures that induce controlled ears for functional shaping.

Keywords: High-purity copper plate, Anisotropic, Texture, *r*-value

1. INTRODUCTION

High-purity copper plates (99.999%) are extensively employed in consumer products, automotive components, industrial hardware, and select military-grade weapon systems. Owing to their exceptional formability, these materials are frequently subjected to demanding forming techniques such as deep drawing and, in more extreme cases, explosive forming. The success of such processes is closely linked to the copper plate's formability and in-plane anisotropy.

Deep drawability refers to the material's capacity to sustain deformation during stamping operations. Two key indicators that govern this property are the plastic strain ratio (r) and the planar anisotropy coefficient (Δr). The average plastic strain ratio is calculated as $\bar{r} = (r_0 + 2r_{45} + r_{90}) / 4$, which reflects the material's resistance to thickness reduction during deformation. A higher $\bar{r}$ value indicates superior thinning resistance and improved deep-drawing behavior. Conversely, the planar anisotropy coefficient, defined as $\Delta r = (r_0 - 2r_{45} + r_{90}) / 2$, quantifies the directional variation in plastic strain ratios. A larger Δr denotes greater anisotropy, which increases the risk of ear formation during deep drawing, thereby deteriorating the overall formability.

In addition, in-plane anisotropy (IPA) serves as a practical index to evaluate directional differences in mechanical behavior. It is defined as IPA = (2X_{max} – X_{mid} – X_{min}) / 2X_{max}, where X_{max}, X_{mid}, and X_{min} represent the maximum, intermediate, and minimum values, respectively, of a selected mechanical property such as yield strength, tensile strength, or elongation. A lower IPA indicates a more isotropic plate, which is favorable for consistent forming performance.

This study investigates the evolution of crystallographic texture in high-purity copper plates (99.999%) subjected to different rolling and annealing conditions. The objective is to clarify the correlations among processing parameters, mechanical properties, IPA%, $\bar{r}$, Δr, and their influence on forming behavior, particularly in the context of deep drawing and explosive forming techniques.

2. EXPERIMENTAL METHOD

To investigate the effects of hot rolling, cold rolling, and annealing treatments on the mechanical behavior, in-plane anisotropy (IPA%), plastic strain ratio (r), planar anisotropy coefficient (Δr), crystallographic texture, and forming performance of high-purity copper plates (99.999%), a series of systematic processing conditions was designed and implemented.

The copper plates were first hot-rolled at two temperatures (500°C and 700°C), followed by cold rolling with two thickness reductions (30% and 60%), and subsequently annealed at two temperatures (350°C and 500°C), as schematically illustrated in Figure 1 and summarized in Table 1.

Post-processing characterization included tensile testing to determine mechanical properties, optical microscopy for microstructural analysis, and X-ray diffraction (XRD) for crystallographic texture evaluation. Furthermore, both deep drawing and explosive forming tests were conducted to assess the influence of processing-induced texture and anisotropy on the forming performance under different loading conditions.

3. RESULTS AND DISCUSSION

3.1 Influence of Rolling and Heat Treatment on the Microstructure and Mechanical Properties of High-Purity Copper Plates

Figure 2 presents the optical microstructures of high-purity copper plates processed via three distinct routes. In Processes A and B, the plates underwent hot rolling followed by 30% and 60% cold rolling, respectively, and were subsequently annealed at a relatively low temperature. As a result, the microstructures exhibited equiaxed grains interspersed with partially fragmented and unrecrystallized regions. The corresponding average grain sizes were approximately 40 μm and 36 μm, respectively. Notably, increasing the cold rolling

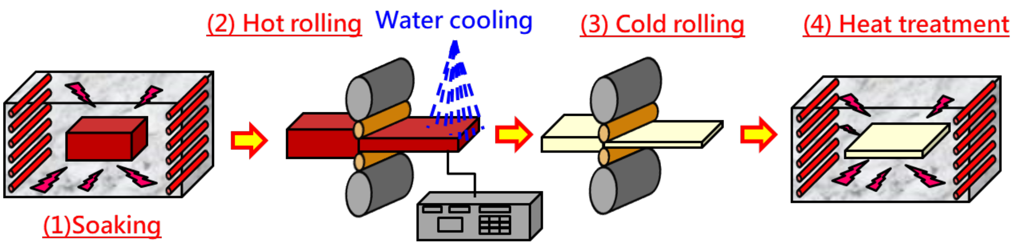

Fig.1. Process flow diagram for the production of high-purity copper plates in this study.

Table 1 Hot rolling, cold rolling, and heat treatment parameters of copper plates in three processes.

	Hot rolling Temperature (°C)	Hot rolling Reduction (%)	Cold rolling Reduction (%)	Heat treatment Temperature (°C)
Process A	500	60	30	350
Process B	500	60	30	350
Process C	700	60	0	500

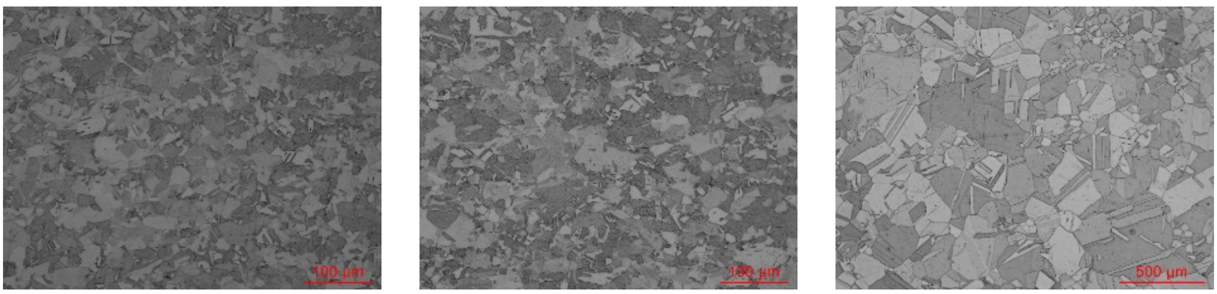

Fig.2. The microstructure of copper plates produced using different processes in this study.
(a) 600 °C hot rolling + 30% cold rolling + 350 °C annealing,
(b) 600 °C hot rolling + 60% cold rolling + 350 °C annealing,
(c) 700 °C hot rolling + 500 °C annealing.

reduction from 30% to 60% did not yield significant grain refinement.

In contrast, Process C involved hot rolling at a higher temperature without subsequent cold rolling, followed by high-temperature annealing. This approach led to a fully recrystallized microstructure characterized by coarse equiaxed grains and well-defined annealing twins. The average grain size observed in Process C was markedly larger, reaching approximately 132 μm.

Table 2 summarizes the mechanical properties and in-plane anisotropy index (IPA%) of the high-purity copper plates produced through the three processing routes. A comparison between Processes A and B indicates that subsequent cold deformation following hot rolling results in increased yield strength (YS) and decreased elongation (EL). This trend is primarily attributed to the residual deformation substructures generated during cold rolling, which are not fully eliminated by low-temperature annealing.

Figures 3 through 5 present EBSD-based texture analysis results for high-purity copper plates processed

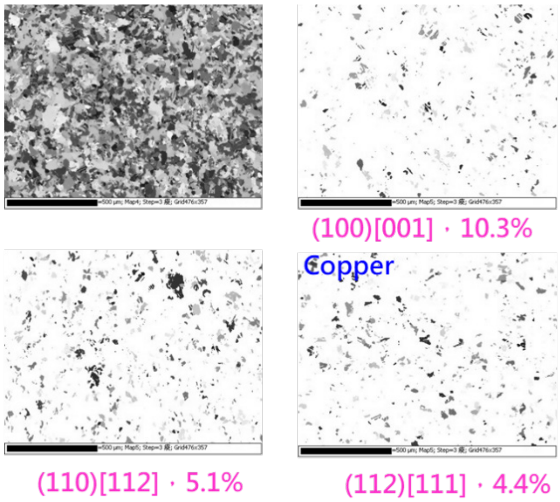

Fig.3. Distribution of Cube, Brass, and Copper texture components of high-purity copper plate produced in Process A (600°C hot rolling + 30% cold rolling + 350°C annealing).
Cube: (Brass + Copper) = 1:0.9

Table 2 Mechanical properties and IPA% of copper plates produced in different processes in this study.

(a) 600 °C hot rolling + 30% cold rolling + 350 °C annealing

Process A	YS (MPa)	TS (MPa)	EL%
0 °	67.4	233.7	60.5
45 °	68.5	224.1	60.2
90 °	69.9	224.1	61.3
IPA%	2.8	0.09	1.5

(b) 600 °C hot rolling + 60% cold rolling + 350 °C annealing

Process B	YS (MPa)	TS (MPa)	EL%
0 °	75.3	231	54.1
45 °	71.2	229	56.3
90 °	70.6	230	57.4
IPA%	5.8	0.15	3.8

(c) 700 °C hot rolling + 500 °C annealing.

Process C	YS (MPa)	TS (MPa)	EL%
0 °	61.2	217.3	67.3
45 °	55.2	220	72.1
90 °	56.3	219.5	69.3
IPA%	8.9	0.7	5.2

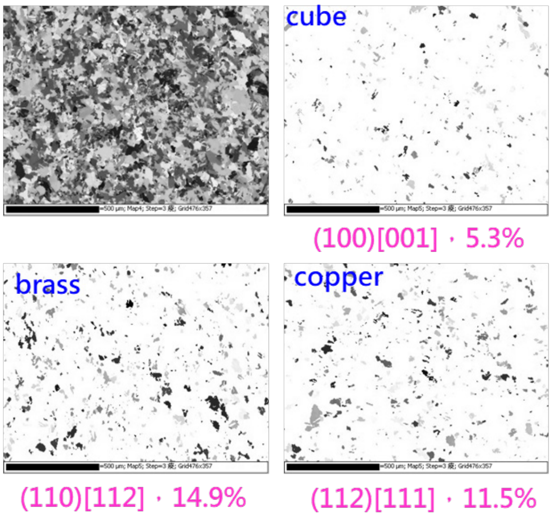

Fig.4. Distribution of Cube, Brass, and Copper texture components of high-purity copper plate produced in Process A (600°C hot rolling + 50% cold rolling + 350°C annealing).
Cube: (Brass + Copper) = 1:5

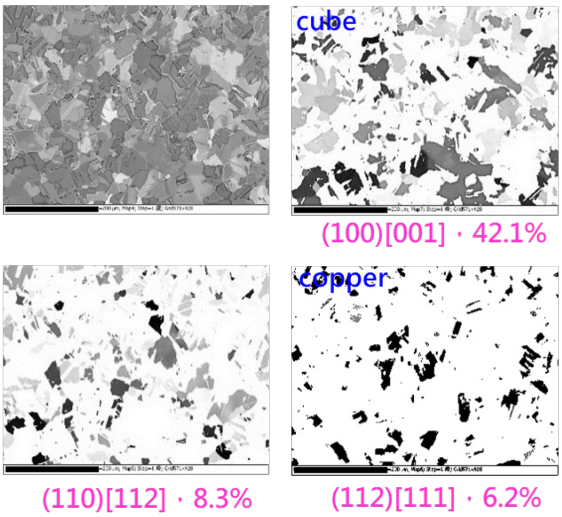

Fig.5. Distribution of Cube, Brass, and Copper texture components of high-purity copper plate produced in Process C.
Cube: (Brass + Copper) = 2.9:1

via Routes A, B, and C, respectively. The volume fractions of key crystallographic components—Cube {100}<001>, Brass {110}<211>, and Copper {112}<111>—were quantified to evaluate texture evolution.

In Process A, the plate exhibited 10.3% Cube, 5.1% Brass, and 4.4% Copper textures. The recrystallization-induced Cube {100}<001> component was nearly balanced with the deformation-induced Brass and Copper textures, yielding a volume ratio of approximately 1:0.92. This directional equilibrium, involving Cube orientations at 0° and 90°, and Brass/Copper components around 45°, effectively suppressed in-plane anisotropy.

Process C, utilizing elevated hot rolling and annealing temperatures, produced a significantly higher Cube content of 42.1%, compared to 8.3% Brass and 4.1% Copper. The Cube-to-deformation texture ratio reached 2.9:1, resulting in greater crystallographic alignment. This led to pronounced directional dependence, as evidenced by elevated in-plane anisotropy indices (IPA%) in both yield strength and elongation.

In contrast, Process B, with a 60% cold rolling reduction, exhibited enhanced Brass (11.6%) and Copper (8.4%) components, but only 8.3% Cube texture. The recrystallization-to-deformation texture ratio declined to 1:5, indicating insufficient recovery during low-temperature annealing. Consequently, Process B demonstrated the highest IPA% values among all three processes, reflecting strong mechanical anisotropy.

These findings confirm that extensive cold rolling promotes deformation textures, while annealing encourages Cube recrystallization. An optimal balance between these texture types effectively mitigates anisotropy in high-purity copper plates, thereby improving formability in multi-directional forming processes.

3.2 Effect of Rolling and Heat Treatment on the Stamping and Explosive Forming Characteristics of High-Purity Copper Plates

The rolling and heat treatment processes applied to high-purity copper plates critically shape their crystallographic textures, which in turn govern the degree and nature of mechanical anisotropy. The effect of this anisotropy—whether beneficial or detrimental—depends on the intended forming method. In deep drawing operations, for instance, pronounced anisotropy may lead to irregular plastic flow, resulting in undesirable edge earing or even cracking, thereby reducing material yield.

Specific textures are associated with distinct earing behaviors: Cube {100}<100> textures tend to produce ears along the 0° and 90° directions, while Brass {011}<211> and Copper {112}<111> textures promote earing near 45°. Texture analysis revealed that Process A achieved a near-equilibrium texture state, with a Cube:(Brass + Copper) ratio of approximately 1:0.9. This balance facilitated mutual cancellation between the 0°/90° and 45° earing tendencies, yielding the lowest earing rate (1.5%) among the three processes.

By contrast, Process B—with a higher cold rolling reduction of 60%—exhibited dominant deformation textures, causing the Cube:(Brass + Copper) ratio to drop to 1:5. The predominance of 45°-oriented textures resulted in a more pronounced earing pattern, with the earing rate increasing to 4.9%. In Process C, recrystallization was extensive, leading to a texture dominated by Cube orientations and minimal deformation textures. This imbalance favored earing at 0° and 90°, resulting in the highest earing rate (8.3%).

As summarized in Table 3, Process B and C showed elevated *r*-values along 0° and 90°, indicative of greater contraction in the length and width directions during drawing—commonly resulting in a four-ear configuration. In contrast, Process A demonstrated a relatively higher r_{45} value, which is typically associated with a two-ear pattern. Moreover, the higher average *r*-value of Process A reflects superior resistance to thinning and fracture, implying enhanced drawability under stamping conditions.

The planar anisotropy coefficient (Δr) serves as a quantitative indicator of directional variation in plastic strain ratios. A higher Δr reflects more severe anisotropy, which in turn enhances the likelihood of earing during deep drawing. As presented in Table 3, Process C exhibited the highest Δr value (0.27), which corresponds directly to the highest observed earing rate of 8.3%.

Beyond conventional stamping, high-purity copper plates are also extensively employed in the fabrication of explosively formed projectiles (EFPs) for military-grade applications. In this context, forming a sufficiently elongated and symmetric tail fin is critical to ensuring aerodynamic stability and long-range precision, as illustrated in Figures 6 and 7.

In Process A, the near-equilibrium coexistence of Cube textures at 0°/90° and Brass/Copper textures at 45° effectively suppresses directional anisotropy. This suppression minimizes earing, which, although favorable for deep drawing, hinders the formation of distinct tail fins during explosive forming. As a result, the copper plate fails to produce the aerodynamic morphology required for sustained flight, leading to premature descent and inaccurate targeting.

Conversely, the copper plate from Process C—processed via high-temperature hot rolling followed by high-temperature annealing—exhibits a fully recrystallized structure dominated by Cube {100}<100> textures. This pronounced texture orientation promotes significant earing along the principal directions, facilitating the formation of a well-defined and elongated tail fin during explosive forming. Consequently, projectiles formed from Process C plates demonstrate stable ballistic flight, with verified effective targeting at ranges exceeding 100 meters.

Table 3 Measurement results of *r*, Δ*r*, and lug ratio of copper plates with different processes in this study

	r0	r45	r90	r	Δr	Earing rate%
Process A	0.793	0.961	0.733	0.86	-0.19	1.5
Process B	0.812	0.712	0.834	0.77	0.11	4.9
Process C	0.912	0.625	0.872	0.76	0.27	8.3

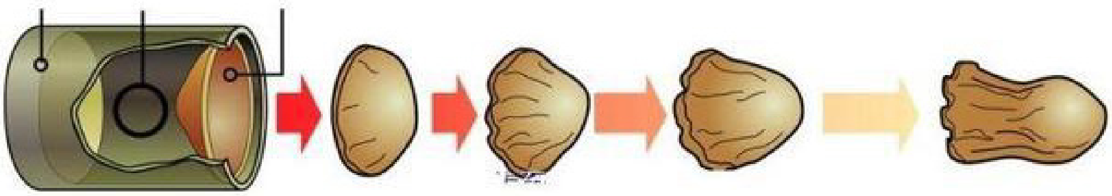

Fig.6. Schematic diagram of EFP [7].

Fig.7. Explosively Formed Projectile (EFP) [8] .

4. CONCLUSIONS

(1) Excessive cold rolling promotes the development of deformation textures, particularly Brass {011}<211> and Copper {112}<111>, whereas subsequent annealing facilitates the formation of recrystallized Cube {100}<100> textures. When these textures coexist in an optimal ratio, directional mechanical property differences are minimized, thereby reducing anisotropy in high-purity copper plates.

(2) The copper plate processed via Process C underwent high-temperature hot rolling followed by high-temperature annealing, resulting in full recrystallization. The resulting Cube texture content significantly exceeded the combined Brass and Copper texture components, with a Cube:(Brass + Copper) ratio of 2.9:1. Consequently, this led to higher mechanical anisotropy and elevated IPA% values for both yield strength (YS) and elongation (EL) compared to Process A.

(3) During deep drawing, the near-equal presence of Cube textures along the 0°/90° directions and Brass/Copper textures at 45° in Process A effectively cancels out directional anisotropy. This texture compensation results in a significantly reduced earing rate of only 1.5%.

(4) The predominance of Cube texture in the Process C copper plate enhances earing behavior, promoting the formation of an elongated tail fin during explosive forming. This enables the projectile to maintain aerodynamic stability and accurately strike targets at distances exceeding 100 meters.

REFERENCES

1. Tao Meng, Ling Gao, "Microstructures and Thermal Conductivity Anisotropy of Hot-Rolled Cu/Kovar Composite Plates," *Journal of Materials Research and Technology*, Vol. 35, March-April 2025, pp. 1741-1751.

2. Solouki H., Jamaati R., Jamshidi Aval H., "High-Temperature Annealing Behavior of Cold-Rolled Electrolytic Tough-Pitch Copper," *Heliyon*, 2024, Vol. 10(12), Article e33276. DOI: 10.1016/j.heliyon.2024.e33276

3. Jing Qin, Chen Zhou, Dongsheng Wang, Xun Li, Yujun Hu, Jingwen Wang, Youwen Yang, "Effects of Microstructure and Texture on the Deep Drawability of C10200 Copper Sheets," *Journal of Materials Research and Technology*, 2023, Vol. 25, pp. 773-785. DOI: 10.1016/j.jmrt.2023.05.273

4. Gerber, P., Tarasiuk, J., Chauveau, Th., & Bacroix, B., "A Quantitative Analysis of the Evolution of Texture and Stored Energy During Annealing of Cold-Rolled Copper," *Acta Materialia*, 2003, Vol. 51 (20), pp. 6359-6371. DOI: 10.1016/j.actamat. 2003. 08.039.

5. Guo J., Nielsen S. F., & Bøtticher C., "Texture in Cold-Rolled and High-Temperature Annealed Cu Foils," *IOP Conf. Ser.: Mater. Sci. Eng.* 1249 (2022) 012052.

6. Y. C. Liu and W. R. Hibbard Jr., "Recrystallization of a Cold-Rolled Copper Single Crystal: In Situ XRD Dynamics," *JOM*, vol. 5, pp. 672-679, 1953.