Materials Science

AIMS Materials Science, 13(3): 502–517.
DOI: 10.3934/matersci.2026024
Received: 28 March 2026
Revised: 06 May 2026
Accepted: 18 May 2026
Published: 02 June 2026

https://www.aimspress.com/journal/Materials

Research article

Experimental investigation on longitudinal-bending composite ultrasonic vibration-assisted milling of C194 copper alloy

Wenxin Zhang, Zhewen Cao and Junjie Zhang*

Center for Precision Engineering, Harbin Institute of Technology, Harbin 150001, China

* **Correspondence:** Email: zhjj505@gmail.com.

Abstract: Copper is an important engineering material for precision micro-devices, due to its superior electrical/thermal conductivity and ductility. However, its high plasticity and toughness introduce significant challenges in traditional milling, including work hardening, tool adhesion, burr accumulation, and poor surface finish, which limit further improvement of machined surface quality. Ultrasonic vibration-assisted machining (UVAM) can improve surface integrity of difficult-to-machine materials by introducing high-frequency intermittent cutting, which reduces cutting force, heat accumulation, and tool wear. Compared with one-dimensional longitudinal or two-dimensional longitudinal-torsional vibration, the longitudinal-bending composite vibration enables independent adjustment of amplitude and phase via two separate ultrasonic signals, thus offering greater flexibility under varying machining conditions. Nevertheless, the research on longitudinal-bending UVAM of copper remains scarce. In this study, we experimentally investigated longitudinal-bending composite vibration-assisted milling (LBVAM) of copper. Burr morphology, surface roughness, and microstructure were systematically compared among conventional milling, longitudinal vibration-assisted milling, and LBVAM. The influences of vibration amplitude and spindle speed on surface quality were also examined. Experiments were conducted using a 1 mm diameter four-edge tungsten steel micro-milling cutter, with amplitudes ranging from 1 to 5 μm and spindle speeds of 1000–3000 r/min. Our results showed that longitudinal-bending composite vibration significantly suppresses burr formation and reduces surface roughness by 40.27% compared to conventional milling, and by 23.44% compared to single longitudinal vibration-assisted milling. Furthermore, surface roughness further decreases with increased amplitude, reaching a minimum of 129 nm at 5 μm, accompanied by a uniform "fish-scale" microstructure. The best surface quality was achieved at 2000 r/min, whereas speeds that were too high or too low caused disordered surface texture or secondary damage. This work confirms the

feasibility and advantages of longitudinal-bending UVAM in enhancing machined surface quality of copper, thus providing valuable processing support for the microfabrication of high-precision copper components in precision electronic applications.

Keywords: copper; longitudinal-bending composite vibration; ultrasonic vibration-assisted milling; surface quality; burr suppression

1. Introduction

Copper exhibits exceptional electrical conductivity, thermal conductivity, machinability, and ductility. The micro components made from copper, such as the cavity of speed control tubes, anode blocks for magnetrons, high-energy lasers, microwave accelerators, miniature direct current (DC) commutators, and electronic packaging housings, are extensively utilized in industries such as electronic communications, defense, and aerospace. The surface quality of these micro components critically impacts equipment performance, thus demanding stringent requirements for their machined surface quality. Micro-milling stands as an efficient and adaptable mechanical processing method for manufacturing components from materials. However, due to copper's high plasticity and toughness, common issues during milling include severe work hardening, tool adhesion, excessive burr formation, and poor surface roughness, making it challenging to achieve high-quality machined surfaces [1]. Therefore, developing technologies to enhance copper's milling performance is urgent.

During copper milling, the material's high plastic deformation, adhesive properties, and surface susceptibility to scratches significantly increase surface defects, compromising workpiece quality-a major challenge in precision copper machining. Extensive research demonstrates that ultrasonic vibration-assisted techniques can markedly improve milling performance of difficult-to-machine materials. This method employs high-frequency, low-amplitude vibrations to achieve intermittent cutting. The resulting tool-chip separation effectively reduces cutting forces, heat generation, and tool wear, thereby enhancing surface finish [2].

Commonly used ultrasonic vibration-assisted milling processes are categorized into unidirectional vibration of tools or workpieces, and longitudinal-torsional composite vibration of tools [3]. Niu discovered that applying longitudinal vibration to tools can effectively increase the probability of local fracture in carbon fibers, thereby improving the surface machining quality of 60% silicon carbide particle (SiCp)/Al composites [4]. Sun et al. conducted experimental research on one-dimensional longitudinal vibration assisted milling (LVAM) of C/SiC composites, finding that the average cutting force was reduced by 43.7% compared to conventional milling (CM) while improving groove edge quality and surface roughness [5]. Rinck et al. discovered that ultrasonic vibration-assisted milling effectively reduces cutting force and surface roughness in TC4 titanium alloy machining. They further compared the effects of one-dimensional longitudinal vibration and two-dimensional longitudinal-torsional composite vibration on TC4 titanium alloy milling, finding that longitudinal-torsional composite vibration not only further reduces cutting force and roughness but also decreases tool wear compared to LVAM [6]. Liu et al. found that applying axial vibration-assisted milling to tools reduces surface roughness by 44% compared to conventional aluminum-based composite milling, with surface roughness increasing rapidly with vibration frequency [7]. Chang et al. discovered that the surface micro-texture produced by vibration-assisted milling significantly improves the surface morphology of groove bottoms in TC4 titanium alloy groove milling. Furthermore, ultrasonic vibration assistance reduces the detachment and edge fracture of the milling groove sidewall, thereby ensuring a smooth surface and regular shape of the sidewall [8]. The aforementioned studies indicate that two-dimensional longitudinal torsional vibration is more effective than one-dimensional longitudinal vibration in improving the milling performance of difficult-to-machine materials [9].

Longitudinal-torsional composite vibration systems can achieve only single-phase signal excitation, lacking the capability to independently adjust amplitude and phase in both vibration directions, which limits their processing conditions. In contrast, longitudinal-bending composite vibration-assisted systems (LBVA) enable independent adjustment of amplitude and phase through two-phase independent ultrasonic signals with adjustable phase differences, offering greater flexibility in adapting to diverse processing conditions. Comprehensive reviews have systematically evaluated the application of ultrasonic vibration assisted machining (UVAM) in processing difficult-to-machine materials. Yuan et al. reviewed special machining technologies for SiCp/Al composites and concluded that UVAM, through its high-frequency intermittent cutting mechanism, effectively improves surface integrity while reducing cutting forces and tool wear [10]. The review further identified multi-dimensional composite vibration modes, particularly those with independently controllable amplitude and phase in multiple directions, as a critical future research direction. Furthermore, Yuan et al. systematically analyzed the influence of different ultrasonic vibration forms, ranging from one-dimensional longitudinal to two-dimensional elliptical and longitudinal-torsional vibration, on machining performance, demonstrating that two-dimensional composite vibration consistently yields superior results in terms of force reduction and surface quality improvement [11]. Nevertheless, both reviews noted that longitudinal-bending composite vibration, despite its unique advantage of independent dual-direction amplitude adjustment, has been scarcely studied, and its application to highly ductile materials such as copper has not been reported. These identified gaps provide a rationale for this experimental investigation. Du et al. designed and developed an ultrasonic vibration device with longitudinal-bending composite vibration, conducting experimental trials on a TC4 titanium alloy using longitudinal-bending vibration assisted milling (LBVAM). The results demonstrated that this assisted milling method reduces cutting forces by 39.3% and 27.2% compared to CM and LVAM, respectively, while decreasing workpiece surface roughness by 85.2% and 54.4%, respectively, significantly improving surface quality [12]. Moreover, Hu found that introducing longitudinal-bending ultrasonic vibration effectively reduces noticeable chip adhesion during TC4 titanium alloy milling, enhancing dry machining capability and surface integrity. They discovered that the tool tip trajectory during LBVAM follows a uniform spiral curve, creating periodic separation and contact between the tool and workpiece material to achieve optimal intermittent cutting effects. Compared to conventional TC4 milling, this assisted milling reduces surface roughness by 54.2% and shows significant improvements in cutting force reduction and tool wear mitigation [13]. However, there are few studies on the longitudinal-bending compound vibration-assisted milling of TC4, and no research on the longitudinal-bending compound vibration-assisted milling of copper.

Furthermore, ultrasonic vibration-assisted milling is significantly influenced by amplitude and rotational speed. Regarding amplitude effects, Zhang et al. conducted experiments on longitudinal ultrasonic vibration-assisted milling of the TC4 titanium alloy at varying amplitudes. The study revealed that as the amplitude increases, the cutting force and heat generation decrease correspondingly, with the workpiece surface roughness reduced. Larger amplitudes improve the machinability and surface quality of TC4 titanium alloy [14]. Li et al. compared the machining performance of longitudinal ultrasonic vibration-assisted milling on TC18 titanium alloy at different rotational speeds, finding that cutting force and surface roughness increase with spindle speed [15]. Li et al. discovered that increasing the feed rate per tooth significantly reduces surface defects in nickel-based superalloys. However, when the feed rate exceeds 4 μm, the beneficial effect of ultrasonic vibration-assisted milling on surface quality diminishes. [16]. Gao et al. conducted experimental research on ultrasonic vibration-assisted milling of the TC4 titanium alloy, revealing that under low-amplitude conditions, increased spindle speed reduces surface roughness while enhancing the regularity of micro-texture. Under identical rotational speeds, the regularity of micro-texture exhibits a trend of first increasing then decreasing with rising ultrasonic amplitude [17]. However, research on the coupling effects of amplitude and rotational speed on longitudinal-bending compound ultrasonic vibration micro-milling remains scarce.

In precision electronic applications, such as lead frames and micro-connectors, copper components are often required to achieve surface roughness values below 150 nm to ensure reliable electrical contact and thermal management. Conventional milling processes, hampered by severe burr formation and tool adhesion, consistently fail to meet these stringent surface quality demands. Consequently, there is a pressing industrial need to develop novel processing technologies capable of enhancing the machinability of this alloy. The longitudinal-bending composite vibration-assisted approach, with its independently tunable dual-direction amplitudes, presents a promising but unexplored solution to this challenge.

Therefore, we carried out a longitudinal-bending composite vibration-assisted milling experiment and compared the micro morphology, surface machining quality, and burr morphology of the longitudinal-bending composite vibration-assisted milling with that of ordinary milling. The influence of different vibration amplitude and vibration shaft speed on the longitudinal-bending composite vibration-assisted milling was studied, and the feasibility of improving the milling performance of the material by the longitudinal-bending composite vibration-assisted milling was proved.

2. Materials and methods

The experimental study on ultrasonic vibration-assisted milling of copper longitudinal-bending was conducted on a self-developed milling machine, as shown in Figure 1. The schematic diagram of longitudinal-bending milling is illustrated in Figure 2. The self-developed milling machine features a three-axis coordinated motion control system comprising a Z-axis displacement platform, X-Y two-dimensional moving platform, multi-axis motion controller, electronic handwheel, and PC host computer. The motion controller selected was the Taida IMAC-FX motion controller, which was developed based on the Turbo PMAC2 core. This controller supported up to 2-axis analog and 4-axis pulse motion control, with an expandable two-channel handwheel interface. The Z-axis displacement platform and X-Y two-dimensional displacement platform had stroke lengths of 150 mm and 100 × 100 mm respectively, with repeat positioning accuracies of 1 and 2 μm. The longitudinal-bending composite ultrasonic vibration shaft was connected to the high-speed spindle via a tapered mandrel and secured by bolts on both flange sides. The vibration shaft internally contained two sets of lead zirconate titanate (PZT) ceramic elements, an amplitude rod, end covers, as well as circuit connection accessories, including collector rings, brushes, and electrodes. When an alternating current (AC) voltage was applied, the longitudinal vibration ceramic underwent high-frequency stretching and contraction along the Z-axis direction, exciting the longitudinal vibration mode. Moreover, the X+ and X– regions of the bending vibration ceramic thickened and thinned, respectively, thereby activating the bending vibration mode.

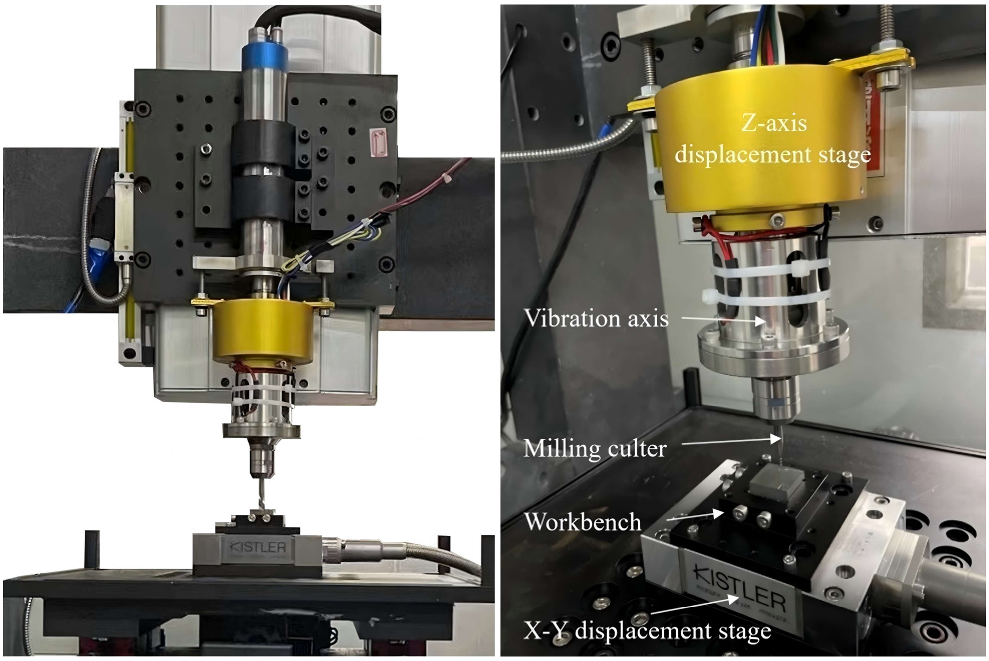

Figure 1. Auxiliary milling device for longitudinal-bending compound vibration.

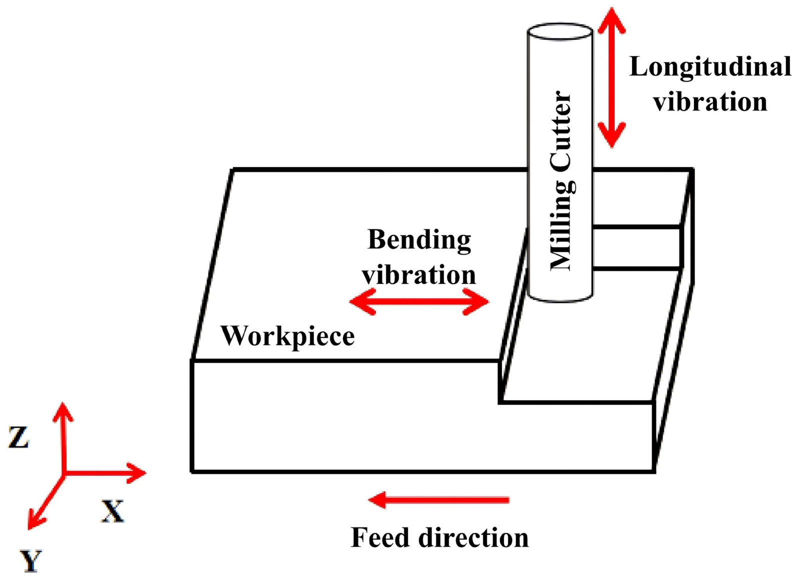

Figure 2. Schematic diagram of longitudinal-bending compound vibration-assisted milling.

The spindle speed range of 1000–3000 r/min was selected based on two major considerations. First, the upper limit was constrained by the operational lifespan of the collector ring in the self-developed ultrasonic vibration spindle system, which was rated for a maximum continuous speed of 3000 r/min. Second, this range encompassed the typical cutting speeds (approximately 3–9 m/min for a 1 mm tool) recommended for micro-milling of copper to balance tool deflection limitations with machining efficiency. Furthermore, this range enabled a clear investigation of the transition from vibration-dominated (lower speeds) to kinematics-dominated (higher speeds) material removal regimes in LBVAM.

The workpiece was fabricated from copper with dimensions of 20 × 10 × 5 mm. A 1 mm diameter four-edge tungsten steel micro-milling cutter was employed, featuring a 55° helix angle, 3° rake angle, 8° flank angle, and 3 mm blade length. Given the cutter's low bending stiffness, the feed rate was significantly reduced compared to CM, with the maximum feed rate capped at 5 μm/z. The spindle's maximum speed was limited to 3000 rpm due to the collector ring's lifespan constraints in the ultrasonic auxiliary system, while the maximum ultrasonic amplitude was restricted to 5 μm by the power supply voltage. To evaluate the combined effects of longitudinal-bending and ultrasonic vibration on machining, vibration-free CM and single longitudinal ultrasonic-assisted milling experiments with identical amplitudes were conducted, followed by comparative analysis. The final experimental parameters are detailed in Table 1. Surface burr formation was observed using a DinoLite AF451 digital microscope, while the milling surface morphology and roughness were analyzed via JSM7800F scanning electron microscopy and Zygo Newview 8200 white light interferometer.

Each milling experiment was repeated three times under the same conditions. For each machined groove, surface roughness was measured at three equally spaced positions along the groove bottom, and the mean value with standard deviation (mean ± SD) was reported.

Table 1. Experimental processing parameters.

No.	Depth of cut (μm)	Longitudinal vibration amplitude (μm)	Bending vibration amplitude (μm)	Spindle speed (r/min)	Vibration frequency (kHz)	Feed rate (mm/s)
1		0	0	1000/2000/3000		
2		1	0	1000/2000/3000		
3		3	0	1000/2000/3000		
4	200	5	0	1000/2000/3000	18.41	0.33/0.67/1.00
5		1	1	1000/2000/3000		
6		3	3	1000/2000/3000		
7		5	5	1000/2000/3000		

Note: All experiments were performed under dry milling conditions using a 1 mm diameter four-edge tungsten steel micro-milling cutter.

3. Results

3.1. Effect of longitudinal-bending composite vibration on machinability of copper

To investigate the impact of combined longitudinal-bending vibration on milling performance, three experimental conditions were conducted: CM, LVAM, and LBVAM, all performed at 1000 rpm spindle speed with 1 μm amplitude for longitudinal vibration and combined vibration. Figure 3 displays the burr morphology of grooves from each process. Figure 3a reveals that CM produced significant burr accumulation on groove sidewalls, particularly severe on the end milling side. This occurred due to the high plasticity of copper, which generates continuous chips during CM that hinder removal and cause tool-chip adhesion. Such adhesion disrupts tool-workpiece contact, leading to continuous material compression on the end milling side and excessive burr formation. Figure 3b shows reduced burr formation after LVAM, as the impact load from longitudinal vibration shifted material removal mode from shear to impact-shear, accelerating chip fracture and minimizing burr generation. The LBVAM (Figure 3c) eliminated burr formation on both groove sides. This improvement resulted from combined effects: While longitudinal vibration provides impact force, the intermittent cutting action of bending vibration reduces cutting force and compressive effects, enabling faster chip removal. Therefore, LBVAM effectively suppresses burr formation in copper, improving machining quality.

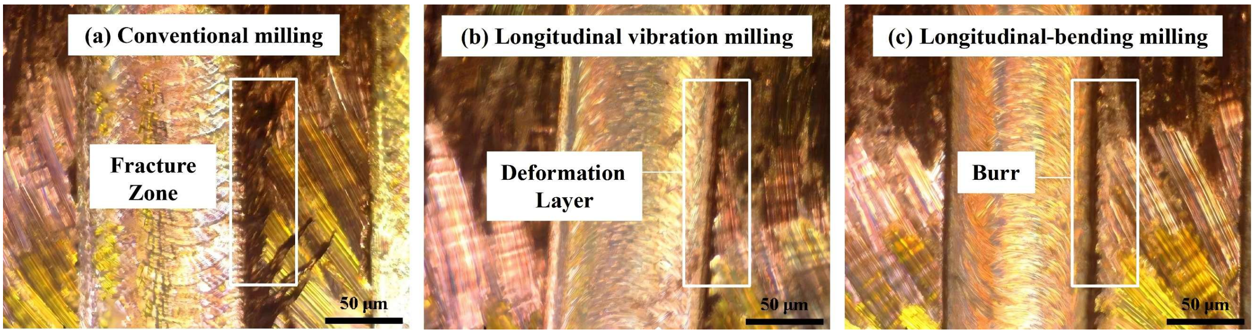

Figure 3. Comparison of burr morphology between (a) CM, (b) LVAM, and (c) LBVAM.

Figure 4 presents the quantitative statistical results of surface roughness (Ra) of grooves machined by the three methods. Each bar represents the mean Ra value from three independent repeated experiments, with error bars indicating ± one standard deviation. The CM sample achieved a surface roughness of 514 ± 19 nm. After applying LVAM, the Ra value decreased to 401 ± 10 nm. For LBVAM, the surface roughness was further reduced to 307 ± 10 nm, corresponding to a 40.27% reduction compared with CM and a 23.44% reduction compared with LVAM, respectively.

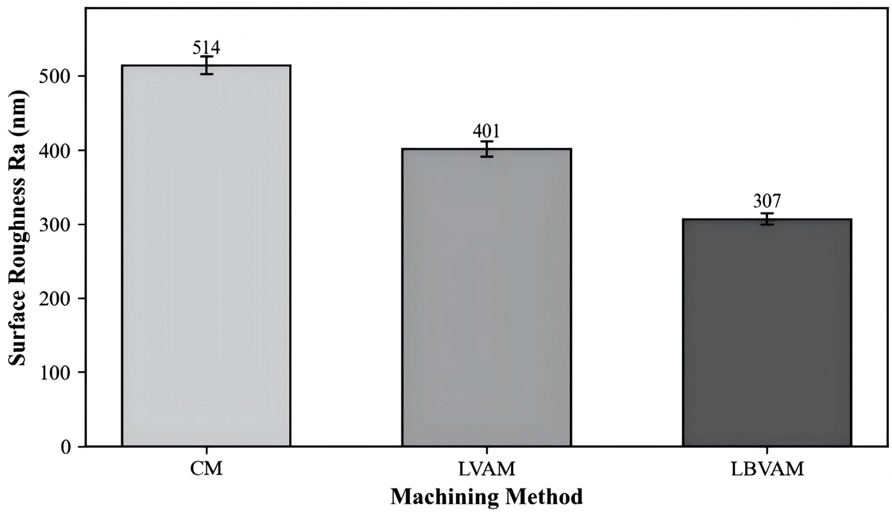

Figure 4. Comparison of surface roughness Ra for CM, LVAM, and LBVAM at 1 μm amplitude and 1000 r/min. Error bars represent ± one standard deviation (n = 3).

Figure 5 demonstrates the surface roughness and morphology of grooves machined using CM, LVAM, and LBVAM at 1 μm amplitude. The CM groove, as observed in Figure 5a, featured irregular scratches and significant feed marks on the machined surface. This phenomenon primarily resulted from continuous tool-workpiece contact during machining, where compression and friction between the tool and workpiece compromised the integrity of the machined surface. Figure 5b shows that the application of vibration assistance reduced the surface roughness of the LVAM groove. Under high-frequency ultrasonic vibration, the material removal mechanism transitions from shear fracture to impact-shear fracture, decreasing cutting force and chip length. However, irregular scratches persisted, hindering further surface roughness improvement. This was mainly due to continuous tool-workpiece contact during single longitudinal vibration milling, which maintains material compression and friction. Figure 5c shows the longitudinal-bending composite vibration-assisted milling groove achieving a further reduction in surface roughness. The additional reduction in surface roughness was attributed to the effective suppression of material adhesion effects by the composite vibration, which generated smaller chips and facilitated chip removal while preventing secondary damage to precision surfaces. In conclusion, compared with CM and LVAM, the longitudinal-bending composite vibration-assisted milling achieved the most prominent reduction in groove surface roughness, demonstrating the significant advantage of longitudinal-bending composite vibration in reducing surface roughness.

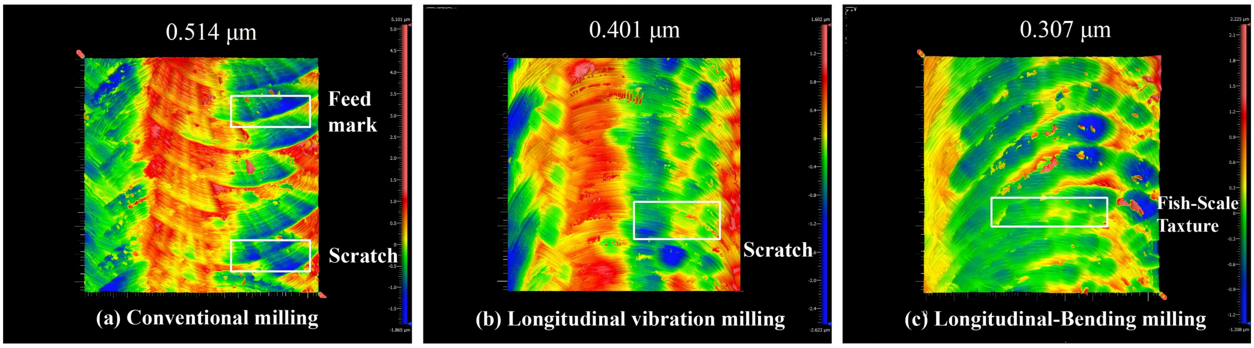

Figure 5. Surface roughness measurement of groove bottom using white light interferometer: (a) CM, (b) LVAM, and (c) LBVAM.

Figure 6 presents microscopic images of copper surface morphology processed under 1 μm amplitude conditions using CM, LVAM, and LBVAM, further elucidating the evolution of surface morphology during ultrasonic vibration-assisted milling. In CM (Figure 6a), the surface displays continuous, parallel, and unidirectional micro-grooves with a scratch width of 1.2 μm and a depth of 0.3–0.5 μm, representing the regular feed marks left by conventional milling. These distinct groove defects arose primarily from the superior toughness of copper, resulting in strong chip-material adhesion and subsequent material delamination during continuous tool-workpiece contact. Under LVAM (Figure 6b), applying longitudinal vibration to the tool transformed these marks into wave-like periodic macro-grooves with a period width of 2.8 μm and a deeper undulation of 1.0–1.5 μm, flattening the layered ridges and reducing feed marks while yielding a denser and more undulating texture.

In LBVAM (Figure 6c), the coupling of longitudinal and bending vibrations broke the unidirectional scratch pattern, effectively suppressing material adhesion and facilitating rapid chip removal. This process produced a uniform fish-scale texture, with each periodic unit measuring 3.0 μm laterally and 2.2 μm longitudinally, exhibiting a texture relief of approximately 0.8 μm, accompanied with the formation of an isotropic surface topography and a substantial reduction in surface roughness. The residual unevenness observed in the groove surface was attributed to the micro-milling cutter's runout error and flutter. Although runout affected the actual separation cutting efficiency, the ultrasonic frequency significantly exceeded the rotational speed, thus enabling intermittent cutting to achieve satisfactory results.

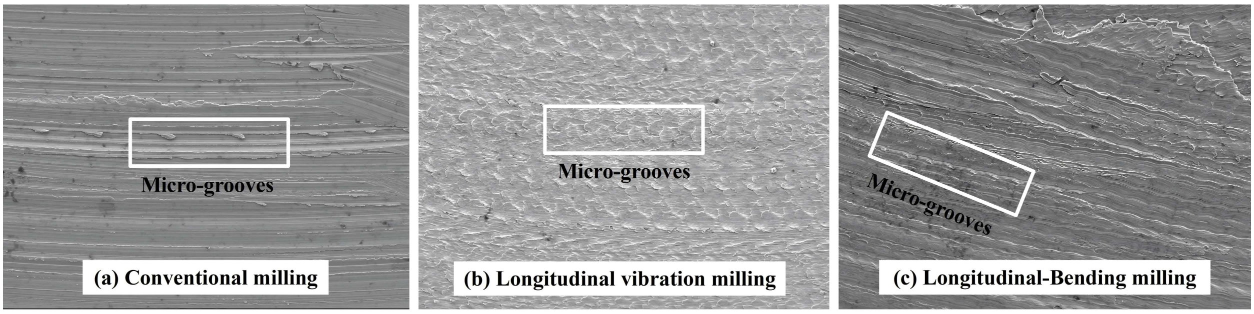

Figure 6. Comparison of surface morphology of copper after (a) CM, (b) LVAM, (c) LBVAM.

3.2. Influence of amplitude on machining performance

To investigate the impact of ultrasonic amplitude on workpiece surface morphology, a white light interferometer was employed to measure surface morphology at 2000 rpm under varying ultrasonic amplitudes, as shown in Figure 7. After CM, the machined surface exhibited distinct tool feed marks with a surface roughness of 333 nm. As the ultrasonic amplitude increased, the surface roughness of the sample continued to decrease. At an amplitude of 5 μm, the surface roughness was reduced to 129 nm, representing decreases of 51.1% and 31.7% compared to 1 and 3 μm amplitudes, respectively. Under higher ultrasonic amplitudes, the impact-shear effect caused by tool vibration became more pronounced, further flattening the layered micro-peak structures on the machined surface. Additionally, the increased separation distance between the tool and workpiece further reduced cutting force and heat generation. The lower cutting force and reduced cutting temperature minimized elastic deformation of the machined surface, improving the surface roughness in the machining area.

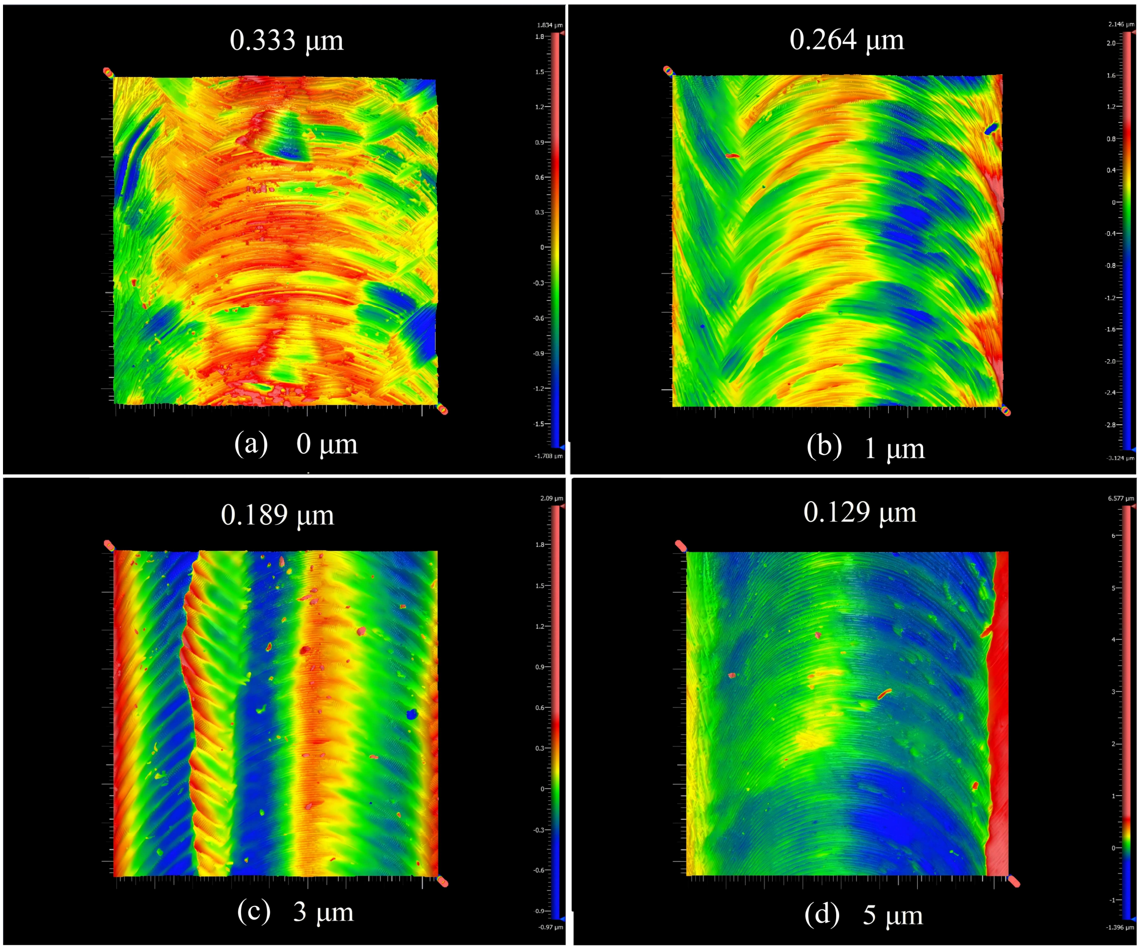

Figure 7. Surface roughness of longitudinal-bending composite vibration-assisted milling under different amplitudes for copper: (a) 0 µm, (b) 1 µm, (c) 3 µm, and (d) 5 µm.

To further investigate the impact of vibration amplitude on workpiece surface morphology, microscopic observations were conducted on the machined grooves, as illustrated in Figure 8. As shown in Figure 8a, CM produced grooves and ridges without additional deformation, with distinct cutting marks on the machined surface. When the vibration amplitude reached 1 µm, the longitudinal ultrasonic vibration flattened the layered ridges, resulting in a "fish-scale" micro-texture on the machined surface. As the ultrasonic amplitude increased, the impact effect caused by tool vibration became more pronounced, and the micro-texture gradually became more apparent. At an amplitude of 5 µm, the surface micro-texture exhibited optimal regularity, as depicted in Figure 8d, with "fish-scale" micro-textures uniformly distributed across the surface. The uniform micro-texture generated under high-amplitude conditions was also a key factor contributing to a significant decrease in surface roughness.

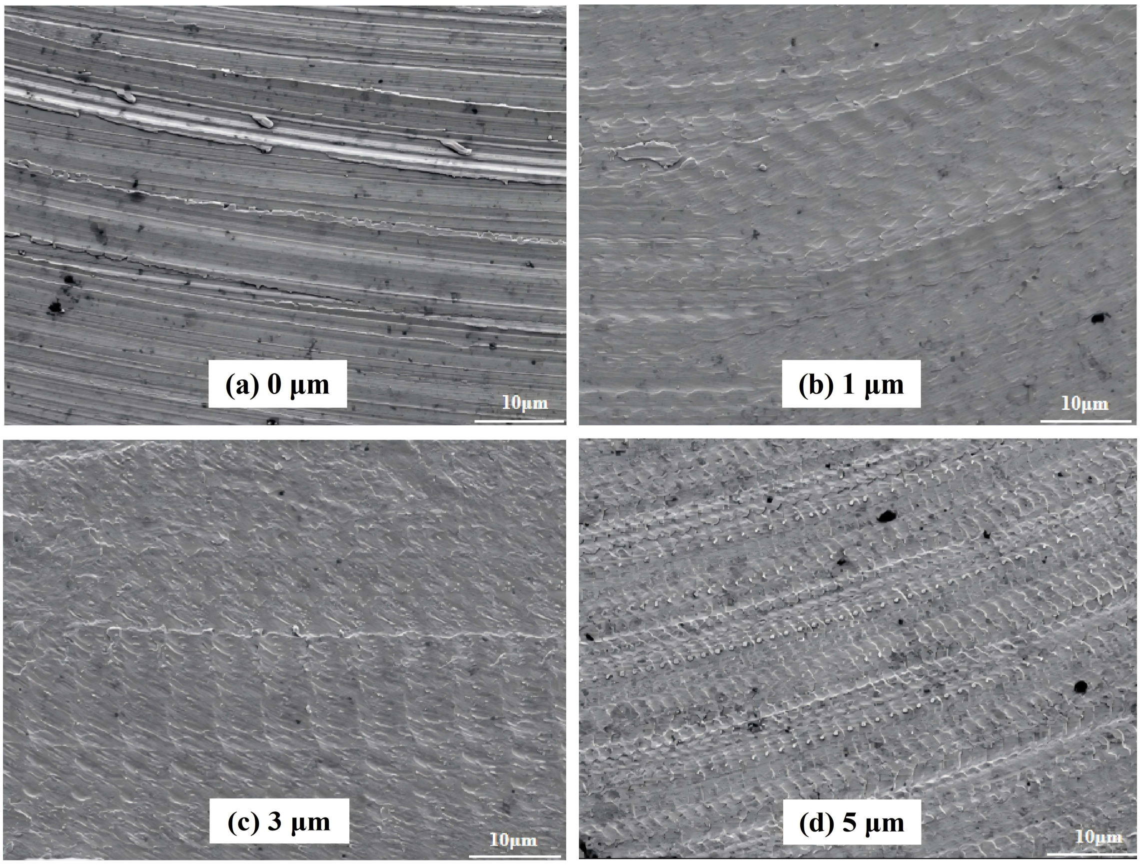

Figure 8. Surface morphology of longitudinally bent copper under different vibration amplitudes: (a) 0 μm, (b) 1 μm, (c) 3 μm, and (d) 5 μm.

3.3. Effect of spindle speed on machining performance

In subsequent research, we investigated the effects of spindle speed on surface finish at identical vibration amplitudes, with surface roughness measurements shown in Figure 9. At 1000 rpm, ultrasonic vibrations dominated through high-frequency impacts, producing distinct micro-pits and corrugated macro-textures, achieving a surface roughness of 214 nm. As rotational speed increased, the ironing effect became more pronounced, resulting in more regular micro-textures and further surface refinement, with roughness decreasing to 129 nm. However, when spindle speed exceeded this range, un-flattened ridges were cut by high-speed rotating tools, causing secondary damage that degraded surface quality. The roughness then increased to 258 nm. Experimental results demonstrated that moderate increases in spindle speed enhanced surface finish quality, forming uniform “fish-scale” microstructures that positively improved material adhesion and lubrication performance.

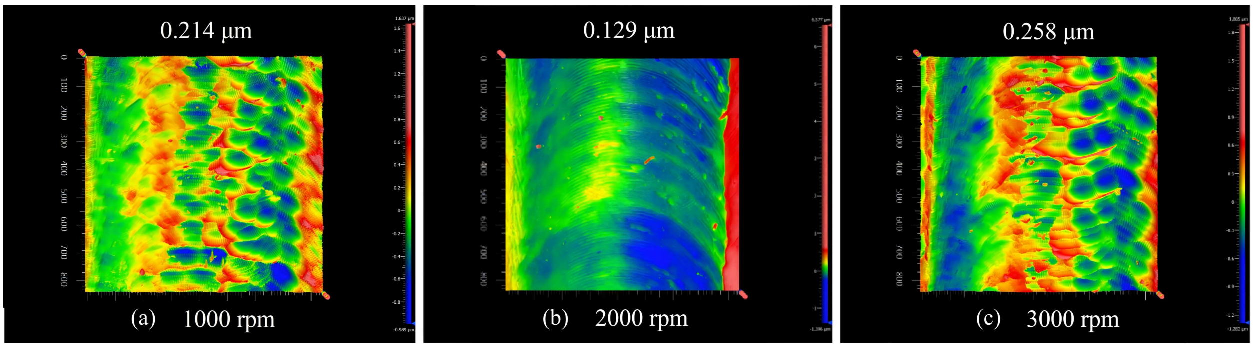

Figure 9. Surface roughness of longitudinal-bending composite vibration-assisted milling under different rotational speeds of copper: (a) 1000 rpm (b) 2000 rpm (c) 3000 rpm.

We further examined the influence of rotational speed on workpiece surface machining. Microscopic morphology observations of the machined grooves are presented in Figure 10. Figure 10a displays the surface microstructure at 1000 rpm. At lower speeds, the tool's elliptical motion under high-frequency impact created distinct micro-pits on the machined surface. When the spindle speed reached 2000 rpm, the ironing effect became more pronounced, with the surface micro-texture evolving into a uniformly arranged "fish-scale" pattern, thereby improving surface quality. However, further speed increases induced secondary damage through material compression and friction caused by the elliptical tool movement. Figure 10c shows scratches resulting from this, which disrupted the uniform "fish-scale" micro-texture and degraded surface machining quality.

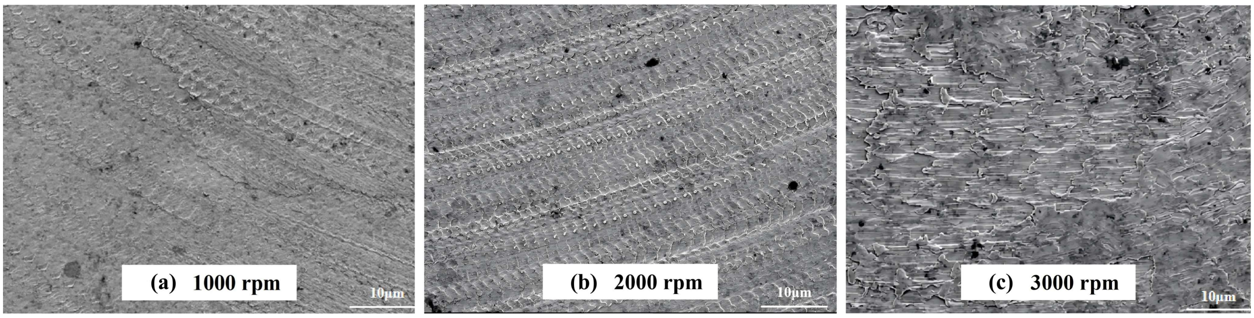

Figure 10. Surface morphology of longitudinal-bending composite vibration-assisted milling under different rotational speeds of copper.

4. Discussion

In this study, we systematically investigate the impact of longitudinal-bending ultrasonic vibration-assisted milling on the machinability of copper alloy through experimental research, with comparative analysis against conventional milling and single longitudinal vibration-assisted milling. The results demonstrated that longitudinal-bending composite vibration-assisted milling effectively addresses issues such as severe burr formation, high surface roughness, and chip adhesion caused by the high plasticity and toughness of copper during milling. Under identical processing parameters, this method significantly reduces burr formation on groove sidewalls, achieving a surface roughness of 307 nm, representing 40.27% and 23.44% improvements over conventional and single longitudinal vibration milling, respectively. The microstructure exhibits a more uniform "fish-scale" texture, indicating that the combined effects of longitudinal impact and intermittent cutting from bending vibration not only enhance chip fracture and removal but also reduce tool-workpiece compression and friction, thereby improving surface integrity. Regarding amplitude effects, surface roughness progressively decreases with increasing ultrasonic amplitude, reaching a minimum of 129 nm at 5 μm amplitude, accompanied by significantly enhanced regularity in surface micro-texture. This suggests that higher amplitudes amplify impact-shear effects, further flattening surface micro-ridges and improving surface quality. For spindle speed, optimal surface quality is achieved at 2000 r/min, where roughness is minimized and texture is uniform. Lower speeds dominate micro-pitting due to high-frequency impact, while excessively high speeds cause secondary surface damage from tool compression and flutter. To clarify the mechanism underlying the optimal spindle speed, a kinematic analysis based on the tool-tip trajectory model established by Du et al. [12] and Hu et al. [13] is performed. In LBVAM, the number of vibration cycles per spindle revolution, $N = 60f/n$, determines the degree of trajectory overlap between consecutive cutting paths. At 1000 r/min ($N \approx 1105$), the excessively dense trajectory overlap causes the tool to repeatedly impact the same surface region, producing a dominant ironing effect and irregular micro-pits, as similarly observed by Hu et al. [13]. At 3000 r/min ($N \approx 368$), the insufficient vibration cycles per revolution result in incomplete trajectory overlap, causing the tool to plow through uncut ridges and generate secondary surface damage. At 2000 r/min ($N \approx 552$), the trajectory overlap achieves an optimal balance: as demonstrated by Du et al. [12], the critical condition for effective intermittent cutting, where the bending amplitude exceeds 0.5 times the feed per tooth, is well satisfied (amplitude = 5 μm, feed per tooth ≈ 1.5 μm/z). Under this condition, the longitudinal vibration uniformly irons the surface ridges while the bending vibration maintains discrete periodic separation, leading to the most uniform fish-scale texture and the lowest surface roughness (129 nm). This mechanistic explanation confirms that 2000 r/min represents the optimal balance between excessive overlap and insufficient cutting coverage.

In conclusion, longitudinal-bending composite ultrasonic vibration-assisted milling demonstrates significant advantages in improving surface quality of copper metal. By optimally matching vibration amplitude and spindle speed, the microstructure and surface roughness can be further refined, providing an effective process reference for precision microfabrication applications of such materials. This study has certain limitations, such as not entailing the coupling effects of variables like vibration frequency and feed rate across a wider parameter range. Future research will be performed to extend this work by systematically investigating the coupling effects between vibration frequency and feed rate on chip morphology and tool wear. Specifically, a full-factorial experimental design is planned, encompassing frequency ranges up to 40 kHz and feed rate ranges up to 5 μm/z to establish a process window suitable for industrial application. Furthermore, the long-term influence of longitudinal-bending vibration on tool life and the evolution of subsurface residual stress will be examined in depth, thereby facilitating the practical deployment of this technology in precision manufacturing.

5. Conclusions

In this study, we experimentally investigated the LBVAM of C194 copper alloy. Systematic comparisons among CM, LVAM, and LBVAM were conducted, and the effects of vibration amplitude and spindle speed on surface quality were examined. The major conclusions are as follows:

(1) LBVAM effectively suppresses burr formation on groove sidewalls. Under 1 μm amplitude and 1000 r/min, LBVAM reduces surface roughness to 307 nm, representing a 40.27% reduction compared with CM (514 nm) and a 23.44% reduction compared with LVAM (401 nm).

(2) Surface roughness decreases progressively with increasing ultrasonic amplitude, reaching a minimum of 129 nm at 5 μm (2000 r/min), accompanied by a uniform fish-scale micro-texture.

(3) An optimal spindle speed of 2000 r/min yields the best surface quality. Lower speeds (1000 r/min) cause excessive vibration impact overlap and micro-pits, while higher speeds (3000 r/min) induce secondary damage from insufficient trajectory overlap.

(4) LBVAM, by optimally matching vibration amplitude and spindle speed, significantly enhances the machined surface quality of copper alloys, providing an effective process reference for precision microfabrication of copper components.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The authors greatly acknowledge support from the National Natural Science Foundation of China (52275416 and 52305497).

Author contributions

Wenxin Zhang: investigation, methodology, validation, visualization, writing–original draft; Zhewen Cao: visualization, investigation, writing–review & editing; Junjie Zhang: review & editing, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

Junjie Zhang is an editorial board member for *AIMS Materials Science* and was not involved in the editorial review or the decision to publish this article. The authors declare no conflict of interest.

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