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ORIGINAL ARTICLE

Surface integrity optimization in milling of aluminum 1100: effects of supercritical CO_2 + MQL and emulsion cooling with various milling strategies

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Abstract
Aluminum alloys, widely utilized for their superior thermal and electrical conductivity, excellent corrosion resistance, and high machinability, often encounter critical challenges during milling, particularly the formation of built-up edges (BUE) and surface integrity degradation. Effective cooling and lubrication strategies are essential to mitigate thermal effects, reduce tool wear, and improve surface quality. While supercritical CO_2 ($scCO_2$) combined with minimum quantity lubrication (MQL) has shown promise as a cooling and lubrication method in the milling of materials like titanium and Inconel, its effectiveness in aluminum milling remains unexplored. This study investigates the effects of different process fluids and milling strategies on the surface integrity of aluminum alloys. Three cooling methods—dry, emulsion, $scCO_2$ combined with MQL—were assessed across four milling strategies: unidirectional, bidirectional, contour, and trochoidal milling. Surface topography, roughness, and waviness were analyzed to evaluate milled surface quality. Additionally, variations in feed rate and cutting speed were explored to understand their influence on surface integrity. The results indicate that $scCO_2$ + MQL improves surface roughness by up to 15% and waviness by 35% compared to emulsion cooling, particularly when combined with trochoidal milling, which exhibited the best surface integrity. However, the extended machining time associated with trochoidal milling limits its practicality, making unidirectional milling a viable alternative for balancing surface quality and productivity. Adjustments in feed rate and cutting speed also influenced surface integrity, with lower feed rates and higher cutting speeds generally yielding better surface roughness. Overall, the findings show the potential of sustainable process fluids, particularly $scCO_2$ + MQL, for enhancing aluminum milling processes in precision manufacturing applications.

Keywords Supercritical CO_2 · Minimum quantity lubrication · Aluminum milling · Surface integrity · Machining strategy · Sustainable manufacturing

1 Introduction

Aluminum is widely used across industries due to its properties, such as a good strength-to-weight ratio, corrosion resistance, weldability, machinability, and formability [1, 2]. Despite these advantages, machining aluminum presents several challenges, such as the formation of BUE, and adhesion of chips on the surface, which can negatively impact surface finish [3–5]. To overcome these challenges and achieve desired surface qualities, effective thermal management is required, along with careful control of cutting parameters, milling strategies, and cooling methods [6–9].

Various process fluids are employed in milling operations, including emulsion, MQL and cryogenic cooling [10]. Emulsion cooling remains the most commonly used

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technique due to its high effectiveness in heat dissipation and broad industrial application. However, environmentally friendly alternatives such as MQL and $scCO_2$ have gained attention for their ability to reduce lubricant consumption, reducing the need to clean parts after machining, minimize pollution, and enhance workplace safety, aligning with green manufacturing principles [11–13]. While dry machining offers environmental benefits, it presents challenges in managing heat and maintaining tool life, especially in the case of aluminum [14]. Combining MQL with $scCO_2$ provides precise, minimal lubricant delivery to the cutting zone, achieving superior cooling and lubrication, reducing thermal effects, and improving surface finish, which optimizes both tool life and part quality [15, 16].

Additionally, selecting an optimal milling strategy is essential for managing thermal effects, minimizing tool wear, and achieving high surface quality, especially in machining aluminum components [17]. Various strategies, including unidirectional, bidirectional, trochoidal, and contour milling, offer specific advantages depending on the desired outcome [18, 19]. For example, trochoidal milling is particularly effective at reducing cutting forces and heat generation, which minimizes tool wear and enhances surface quality [20, 21]. Investigating these strategies enables the understanding the limits between process kinematic and workpiece quality, improving energy efficiency, and ensuring consistent surface finishes.

Several studies have examined the effects of different milling strategies and parameters on the surface roughness and overall part quality of aluminum alloys. Kiswanto et al. [22] demonstrated that machining parameters, such as cutting speed and feed rate, significantly influence surface roughness and burr formation in Al1100, with lower feed rates contributing to improved surface finishes. Vakondios et al. [23] investigated ball-end milling of Al7075-T6 and showed that strategies like vertical, pull, push, and oblique cutting significantly influenced surface quality. All these studies were conducted using emulsion coolants. However, Jebaraj and Kumar [24] explored cryogenic cooling methods, specifically cryogenic CO_2 and LN_2. Their results indicated that cryogenic LN_2 cooling achieved the lowest cutting temperatures, reducing tool wear and enhancing surface finish at higher cutting speeds. Cryogenic CO_2, while also reducing cutting temperatures compared to conventional coolants, showed slightly lower performance compared to LN_2 in terms of surface roughness at higher feed rates but still exceeded traditional cooling methods.

MQL has also emerged as an efficient cooling method in aluminum milling. Khettabi et al. [25] found that MQL cooling effectively reduces cutting forces, friction, and wear compared to dry processes in high-speed milling of aluminum alloys like 7075, 6061, and 2024. Yazid et al. [26] highlighted that optimizing feed rates and cutting speeds under MQL not only improves surface quality but also prolongs tool life, making MQL a viable eco-friendly alternative to traditional cooling methods. Garcia et al. [27] also demonstrated that MQL was superior to dry machining for Al6082-T6, achieving improvements in both surface finish and tool wear reduction. Duan et al. found that optimizing the nozzle position for nanofluid MQL in milling 7050 aluminum alloy led to a 30.4% reduction in surface roughness [28]. Some other studies shows that electrostatic atomization MQL (EMQL) outperforms conventional MQL with finer droplet atomization, a 42.4% reduction in tool wear, and a 47% improvement in surface roughness [29, 30].

While the application of $scCO_2$ combined with MQL has been studied for materials such as titanium, steel, and Inconel alloys, its use in aluminum alloys remains limited. Zhang et al. [31] investigated milling of SiCp/Al composites using $scCO_2$ + MQL with ultrasonic vibration, finding significant reductions in surface roughness and work hardening, particularly at higher milling speeds. Another study by Yu et al. [32] on 50% SiCp/Al composites reported that $scCO_2$-based MQL led to a 36% reduction in bonding layer thickness and a significant decrease in subsurface damage compared to dry cutting, while minimizing surface defects like pits.

The advantages of $scCO_2$ + MQL have also been well-documented for other materials. Gao et al. [33] demonstrated that $scCO_2$ significantly reduced milling forces, tool wear, and surface roughness in the milling of Inconel 718. Similarly, Khosravi et al. [34] studied $scCO_2$ + MQL in high-speed milling of Ti- 6 Al- 4 V, noting substantial reductions in cutting forces, surface roughness, and improved tool life compared to emulsion-based cooling, which shows the effectiveness of $scCO_2$ + MQL in managing thermal effects and improving machining performance in challenging materials.

Despite promising results for materials like titanium, Inconel, and SiCp-Al composites, the application of $scCO_2$ + MQL to aluminum alloys remains uninvestigated. Existing research suggests that $scCO_2$ + MQL could significantly reduce tool wear, cutting forces, and enhance surface finish in milling of different materials. Further experimental research is needed to validate these hypotheses and explore its full potential in milling of aluminum.

This research aims to evaluate the interplay between milling strategies and process fluids to identify the optimal combination for enhancing aluminum component performance. Specifically, four machining strategies—unidirectional, bidirectional, contour, and trochoidal—are evaluated under three lubrication methods: dry, emulsion, and $scCO_2$ + MQL, considering various cutting speeds and feed rates. Additionally, this study analyzes surface waviness to

understand its impact on the quality of milled components. Alongside these objectives, the research emphasizes the importance of achieving clean workpiece surfaces post-milling and explores approaches to minimize or eliminate the need for subsequent cleaning, addressing a critical aspect of industrial applicability. The goal is to bridge the gap in understanding $scCO_2$ + MQL's effectiveness in aluminum milling compared to traditional process fluids.

2 Material and method

In this study, commercially pure aluminum with dimensions of 70 × 70 × 8 mm was selected as the workpiece material. The milling experiments were conducted using a 5-axis GF Mikron MILL S 400 U machine, equipped with the Fusion Coolant Systems Pure-Cut + ®. This process fluid utilizes a mixture of $scCO_2$ and MQL as the cooling and lubrication medium, as shown in Fig. 1. Three kinds of process fluids were assessed in this study: dry, emulsion, and a combined $scCO_2$ + MQL system. The MQL system employed a blend of light hydrocarbons, primarily C10-C13 alkanes and isoalkanes, with minimal cyclic and aromatic compounds, to ensure effective lubrication. In the $scCO_2$ setup, high-purity carbon dioxide (99.995%) was applied in its supercritical state for enhanced cooling performance. For emulsion cooling, Aquatec 7560 served as both a coolant and lubricant throughout the milling process. Dry milling conditions were also included as a baseline for comparative analysis.

The $scCO_2$ + MQL coolant was delivered through the internal channels of the milling tool, as illustrated in Fig. 1, with the $scCO_2$ pressure maintained at 118 bar and MQL oil supplied at a flow rate of 6 ml/min. For all experiments, solid carbide end mills with integrated internal cooling channels were used, specifically uncoated, three-flute tools with a 12-mm diameter, as shown in Fig. 2. Uncoated tools were selected due to their sharper cutting edges, which result in lower friction and reduced plastic deformation during the milling of pure aluminum.

Four milling strategies were examined: unidirectional, bidirectional, contour, and trochoidal milling. Preliminary tests were performed at two different cutting speeds and two feed rates to assess the effects of milling parameters on surface quality and determine optimal conditions. Table 1 presents an overview of the process fluids, milling strategies, and cutting speeds and feed rates tested.

Unidirectional milling, shown in Fig. 3a, involves the cutting tool moving in a single direction along the workpiece for each pass. In this method, the tool cuts as it moves from one end of the workpiece to the other, then lifts off and returns to the next position without cutting. This approach is commonly used to achieve high precision and a superior surface finish; for this study, all tests for unidirectional milling employed climb milling. Conversely, bidirectional milling, illustrated in Fig. 3b, involves the cutting tool moving in alternating directions along the workpiece, cutting in both forward and reverse directions without lifting off between passes. This continuous movement allows for faster material removal. Trochoidal milling, illustrated in Fig. 3c, enhances milling efficiency by control of the chip thickness, reducing cutting forces and extending tool life. The tool moves in a circular or trochoidal motion, engaging the material at a consistent depth while maintaining lower radial engagement.

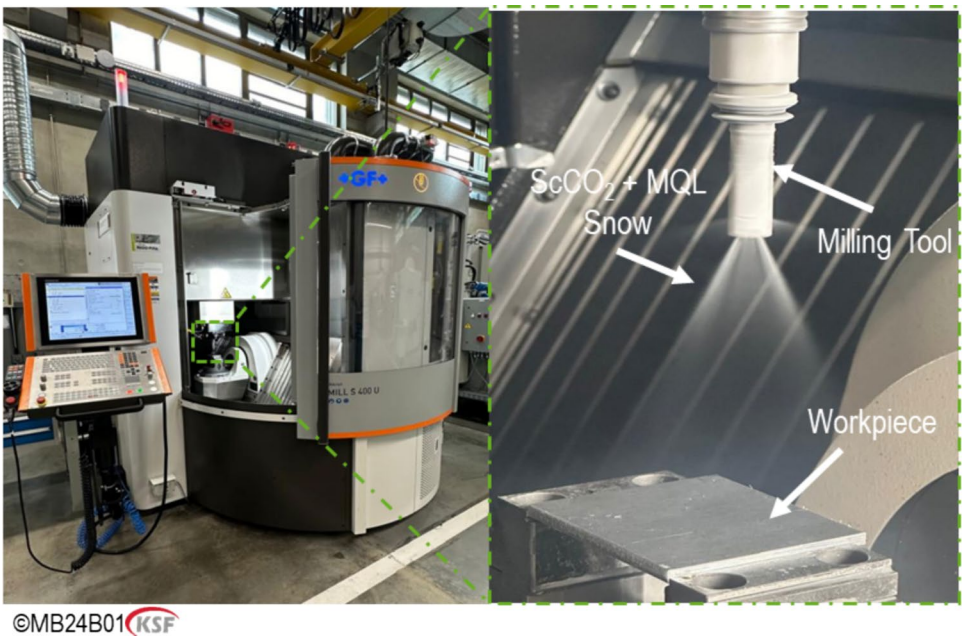

Fig. 1 Experimental setup and preparation

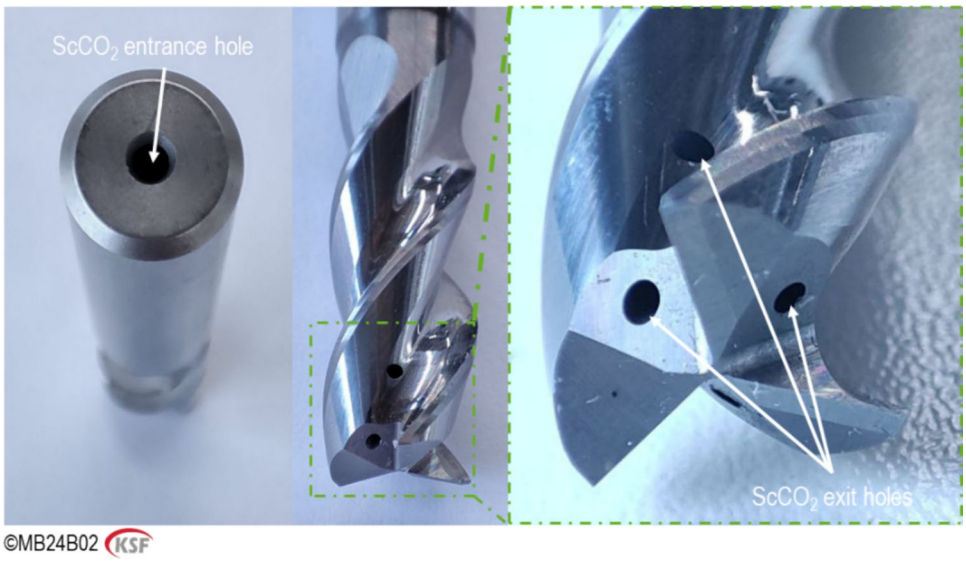

Fig. 2 Images of special end mill used in experimental tests

Table 1 Investigated parameter ranges and their corresponding levels in this study

Cooling method	Milling strategy	Cutting speed (m/min)	Axial depth of cut (mm)	Feed rate (mm/min)
Dry	Unidirectional			
Emulsion	Bidirectional	150		300
$scCO_2$ + MQL	Contour		0.3	
	Trochoidal	188		375

This approach allows gradual material removal, reduces heat buildup, and improves chip evacuation, which is particularly beneficial for aluminum machining [35]. Contour milling, as shown in Fig. 3d, follows the contours of surface, with the toolpath offset by a specified distance to maintain constant tool engagement.

Moreover, a confocal microscope (Nanofocus Mobile µsurf) was used to evaluate the surface integrity of the milled workpieces. Surface roughness was measured at three different areas of the workpiece to ensure reliability and minimize randomness in the experimental data.

3 Results and discussion

3.1 Surface topography and roughness

The confocal microscopy of the milled surface for unidirectional and bidirectional milling under dry conditions are illustrated in Fig. 4 a, b, while the corresponding surface roughness parameters Sa, Sk, Spk, and Svk are presented in Fig. 4 c. These experiments were conducted with a depth of cut of 0.3 mm, a feed rate of 300 mm/min, and a cutting speed of 150 m/min. The surface topography images indicate that the bidirectional milling strategy results in a rougher surface compared to unidirectional milling. The surface of bidirectional milling shows a more uneven profile, characterized by larger peaks and valleys, which can be attributed to the worse thermal conditions experienced in dry bidirectional milling. Specifically, the alternating milling directions in bidirectional milling led to increased thermal fluctuations, elevated friction, and greater force variation, all of which contributed to poorer surface integrity. These trends are confirmed by the surface roughness parameters presented in Fig. 4 c. When comparing roughness parameters, bidirectional milling showed significantly higher values: a 43%

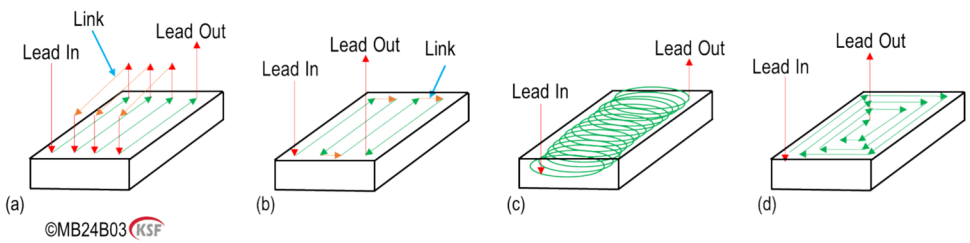

Fig. 3 Schematic illustration of different milling strategies used in the experiments: **a** unidirectional, **b** bidirectional, **c** trochoidal, and **d** contour

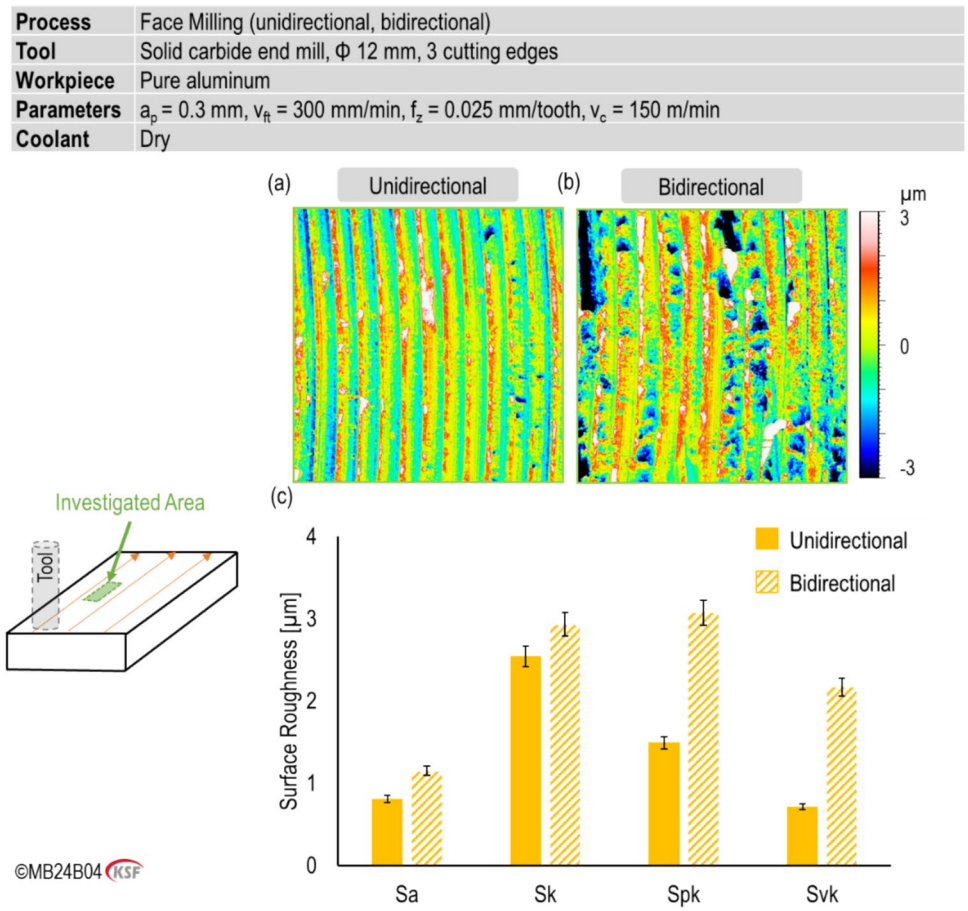

Fig. 4 Surface topography of milled aluminum under dry conditions: comparison of **a** unidirectional and **b** bidirectional milling strategies, and **c** corresponding roughness parameters (Sa, Sk, Spk, Svk)

increase in Sa, 15% in Sk, 106% in Spk, and 200% in Svk, compared to unidirectional milling. The lower Sa and Sk values in unidirectional milling indicate a smoother surface and a more uniform load-bearing area, beneficial for applications requiring high durability. In contrast, the increased Spk and Svk in bidirectional milling reveal more pronounced peaks and deeper valleys, which contribute to higher roughness and may reduce performance quality in precision-critical applications. Thus, while bidirectional milling is faster, unidirectional milling offers better surface integrity.

The lack of cooling under dry milling conditions worsened these issues. Without a coolant, the heat generated during milling led to increased thermal expansion of the tool and workpiece, accelerating tool wear and promoting BUE formation. These thermal effects were significantly more pronounced in bidirectional milling, which had a lower effective cooling time due to the continuously alternating tool path, leading to less favorable thermal dissipation. Consequently, these factors contributed to the poorer overall surface finishes observed.

Based on the unsatisfactory results observed under dry milling conditions, particularly in bidirectional milling, we decided to exclude the dry cooling method from subsequent experiments. The surface roughness values, especially for the unidirectional milling strategy, were still higher than expected for high-precision applications, necessitating further exploration with alternative cooling strategies to achieve acceptable surface quality in face milling of aluminum.

The effects of milling parameters, specifically feed rate and cutting speed, on surface integrity were investigated to determine optimal conditions for face milling of aluminum. Figure 5 a presents confocal microscopy images for face milling of pure aluminum at feed rates of 300 mm/min and 375 mm/min under two process fluids of emulsion and $scCO_2$ + MQL, while Fig. 5 b shows the corresponding surface roughness parameters: Sa, Sk, Spk, and Svk. Increasing the feed rate leads to a relative degradation in surface quality under both cooling conditions. Specifically, confocal images reveal that surfaces milled at higher feed rates (e.g., 375 mm/min) exhibit more pronounced peaks and valleys, indicating increased surface roughness. This observation is further verified by surface roughness measurements, where Sa, Sk, Spk, and Svk all show increases as the feed rate is raised. While the increase in Sa is relatively low, the more substantial rises in Sk, Spk, and Svk indicate that the core roughness, as well as the heights of surface peaks and depths of valleys, become more pronounced at higher feed rates. The difference between the

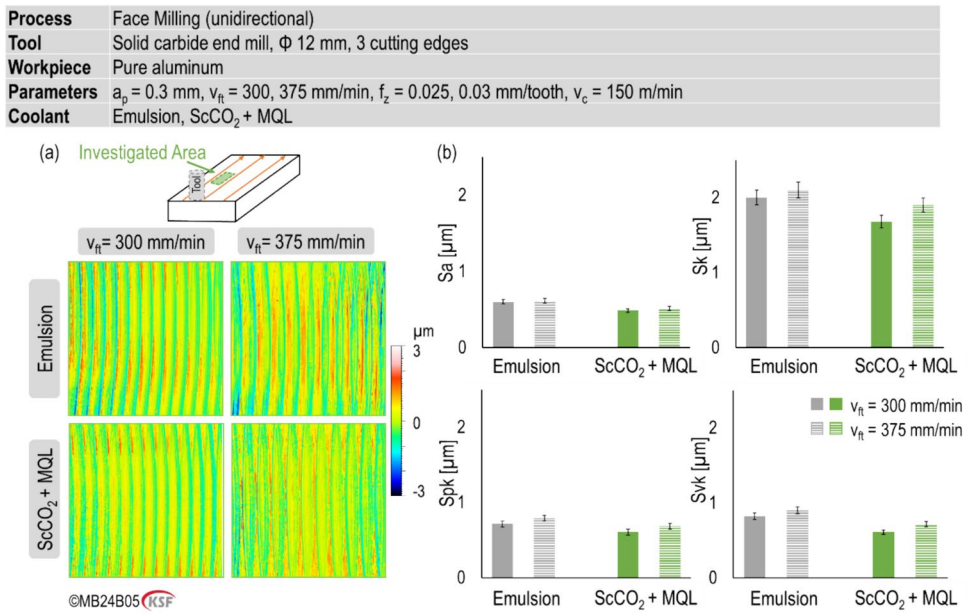

Fig. 5 **a** Surface topography images and **b** surface roughness parameters (Sa, Sk, Spk, Svk) in unidirectional milling at different feed rates under emulsion and $scCO_2$ + MQL cooling

increase in Sa and the more marked rises in Sk, Spk, and Svk can be explained by the averaging nature of Sa. Sa tends to smooth out extreme surface features across the entire area, thereby masking localized variations. On the other hand, parameters like Sk, Spk, and Svk are more sensitive to localized peaks and valleys, effectively capturing the roughness features that become more pronounced with an increase in feed rate. Higher feed rates lead to deeper grooves, sharper peaks, and more distinct valleys due to increased material removal per pass and less overlap between each tooth. However, since Sa averages these variations across the surface, it results in only a slight overall increase, whereas Sk, Spk, and Svk better reflect the localized roughness changes.

When comparing the two cooling methods, $scCO_2$ + MQL demonstrates an advantage over emulsion in terms of surface quality. The confocal images from the milled surfaces for $scCO_2$ + MQL reveal a smoother surface compared to those produced under emulsion cooling at both feed rates. This is quantitatively reflected in the surface roughness parameters, where surfaces milled under $scCO_2$ + MQL consistently show lower Sa, Sk, Spk, and Svk values than those milled with emulsion.

The superior performance of $scCO_2$ + MQL is attributed to its enhanced cooling and lubrication capabilities, which reduce BUE formation, friction, and thermal softening during milling, resulting in an improved surface finish [22, 36]. $scCO_2$ acts as a carrier and diluent with good solubility in oils, reducing the lubricant's viscosity and refining oil droplets into smaller particles. This facilitates finer mist distribution, improving dispersion and penetration into the tool-workpiece interface, which enhances lubrication efficiency, lowers friction, and promotes effective chip evacuation.

Importantly, $scCO_2$ remains in its supercritical state without chemically degrading the lubricant or altering the material properties of aluminum [37]. Instead, it significantly improves thermal management and lubrication, indirectly enhancing surface roughness. By maintaining consistent cutting condition and preventing BUE, $scCO_2$ + MQL promotes a uniform surface finish. Ultimately, $scCO_2$ enhances surface roughness through process stability and effective lubrication rather than by altering the workpiece's inherent mechanical properties.

Figure 6 a presents confocal images at cutting speed of 150 and 188 m/min, while Fig. 6b shows the corresponding surface roughness parameters: Sa, Sk, Spk, and Svk. The confocal images demonstrate that increasing cutting speed from 150 to 188 m/min results in a notable improvement in surface quality. This enhancement is consistent in both cooling conditions- emulsion and $ScCO_2$ + MQL. The surface texture becomes smoother at higher cutting speed, with fewer and less pronounced peaks and valleys. The roughness parameters shown in Fig. 6b confirm this trend, with all key values—Sa, Sk, Spk, and Svk—decreasing as the cutting speed increases. This indicates that higher cutting speeds contribute to a reduction in surface roughness, likely due to more efficient material removal and reduced tool-workpiece friction, which minimizes surface deformation and reduce the risk of BUE formation. The same trends are shown in face milling of aluminum plates in other researches [38, 39].

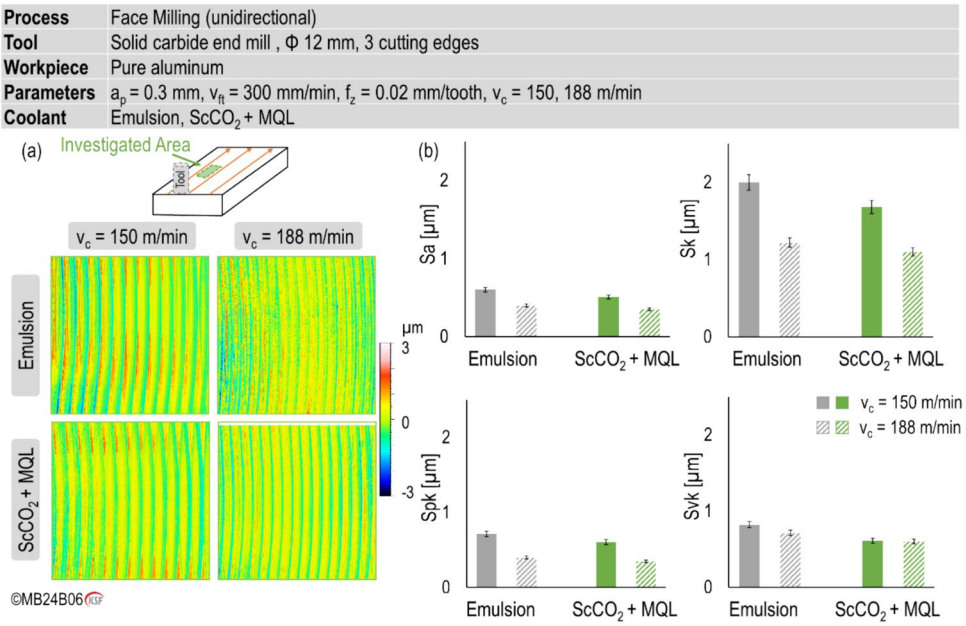

Fig. 6 **a** Surface topography images and **b** surface roughness parameters (Sa, Sk, Spk, Svk) in unidirectional milling at different cutting speeds under emulsion and $scCO_2$ + MQL cooling

When comparing the two process fluids, it is evident that $ScCO_2$ + MQL produces relatively better surface finishes than emulsion at both cutting speeds, which is further supported by lower Sa, Sk, Spk, and Svk values in Fig. 6b. The enhanced cooling and lubrication provided by $ScCO_2$ + MQL appears to decrease the thermal and mechanical stresses typically encountered in the milling process, leading to smoother surfaces. Specifically, at a cutting speed of 150 m/min, the reduction in surface roughness parameters is between 16 and 25%, while at a cutting speed of 180 m/min, these reductions range between 10 and 15%.

The results indicate that a lower feed rate of 300 mm/min and feed per tooth of 0.02 mm/tooth combined with a cutting speed of 188 m/min yields better surface roughness. The surface topography and roughness parameters consistently show enhanced surface quality under these conditions. Therefore, subsequent investigations in this paper employ these optimal parameters—300 mm/min feed rate and 188 m/min cutting speed—to explore the effects of different milling strategies on surface integrity.

Figure 7 illustrates the effects of different milling strategies, unidirectional, bidirectional, contour, and trochoidal, on the surface quality of pure aluminum under emulsion and $ScCO_2$ + MQL process fluids. Confocal microscopy images for each strategy are shown in Fig. 7a), while corresponding surface roughness parameters, including Sa, Sk, Spk, and Svk, are presented in Fig. 7b. The results indicate that trochoidal milling produces the best surface quality among the four strategies, as reflected in both confocal images and roughness measurements. The continuous circular tool path in trochoidal milling minimizes cutting forces, reduces heat generation, and improves chip evacuation, leading to lower tool wear and more consistent cutting conditions [40]. These advantages contribute to a smoother, more uniform surface with significantly lower Sa, Sk, Spk, and Svk values. Specifically, the Sa for trochoidal milling with $ScCO_2$ + MQL cooling is approximately 0.56 of the Sa value observed in contour milling under the same cooling condition. In contrast, contour milling demonstrates the poorest surface quality, with pronounced peaks and valleys visible in the confocal images and elevated roughness values across all parameters. Frequent changes in tool engagement and direction during contour milling lead to uneven force distribution, increasing tool wear and the potential for vibrations—challenges that are particularly pronounced in softer, thermally sensitive materials like aluminum. Furthermore, the kinematics of this strategy results in a deterioration of surface quality and the formation of regions with plastic deformation. Unidirectional milling yields the second-best surface quality, followed by bidirectional milling. Although previous dry milling results in Fig. 4 indicate that bidirectional milling significantly degrades surface quality compared to unidirectional milling, the differences observed here are smaller, likely due to the cooling benefits provided by emulsion and $ScCO_2$ + MQL. Under $ScCO_2$ + MQL cooling, the Sa values for unidirectional and bidirectional milling differ by approximately 20%, with unidirectional milling achieving smoother surfaces due to the stability and consistency of force distribution along a single cutting direction.

A detailed investigation of surface roughness parameters in Fig. 7b reveals that $ScCO_2$ + MQL cooling generally leads to a reduction of about 10–15% in surface roughness across all measured parameters compared to emulsion cooling. This indicates that $ScCO_2$ + MQL is effective in

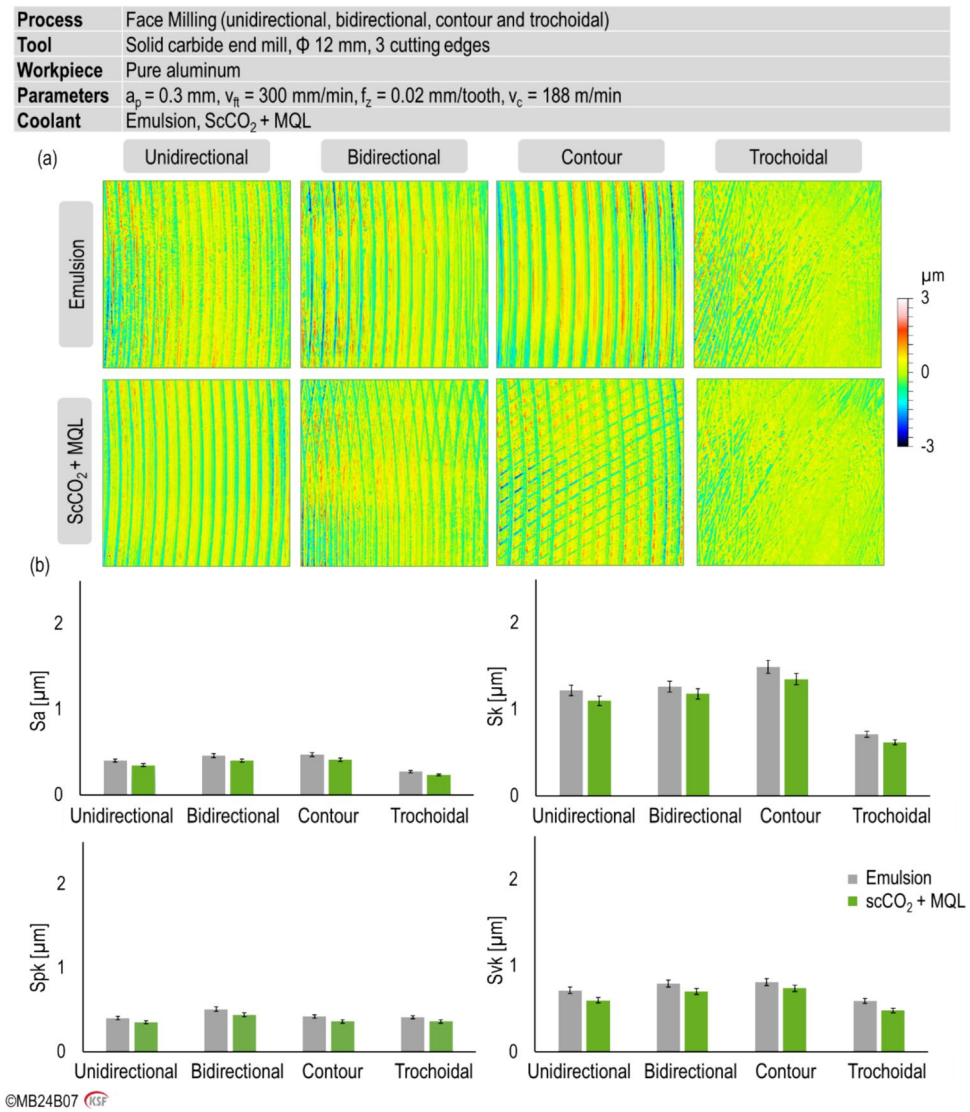

Fig. 7 **a** Confocal images and **b** surface roughness parameters (Sa, Sk, Spk, Svk) in unidirectional, bidirectional, contour, and trochoidal face milling of aluminum plates under emulsion and $scCO_2$ + MQL cooling

improving surface quality, offering a steady and reliable advantage over emulsion cooling across various milling strategies. Emulsion cooling primarily dissipates heat but provides limited lubrication, leading to higher friction, increased tool wear, and BUE formation, all of which negatively impact surface roughness. In contrast, $scCO_2$ + MQL enhances both cooling and lubrication, reducing friction, adhesion, and chip stagnation, which leads to improved surface integrity. The superior lubrication of $scCO_2$ + MQL minimizes direct tool-workpiece contact, decreasing tool wear, ultimately resulting in a smoother surface finish compared to emulsion cooling.

In summary, trochoidal milling combined with $ScCO_2$ + MQL cooling yields the best surface quality under the tested conditions. Contour milling produces the highest surface roughness, while unidirectional and bidirectional milling yield intermediate performance, with bidirectional milling exhibiting slightly poorer surface quality.

Moreover, a comprehensive multi-factor analysis was conducted to evaluate the effects of cutting speed v_c, feed rate v_f, cooling method, and machining strategy on surface roughness (Sa), including their interactions. The analysis revealed that cutting speed, cooling method, and machining strategy had significant effects on Sa, while feed rate was not statistically significant. Among these factors, the cooling method showed the strongest influence on surface roughness, as indicated by its notably high F-value, demonstrating the critical role of lubrication and cooling in achieving better surface quality. Significant two-way interactions were also observed, particularly between cutting speed and cooling method, indicating that the effect of cutting speed on surface roughness is highly dependent on the cooling conditions applied. Similarly, the interaction between cutting speed and machining strategy revealed the importance of tool path combined with cutting speed in determining surface quality. These results clearly show the

Table 2 Summary of variance analysis (ANOVA) results for factors affecting surface roughness (Sa) in milling of aluminum plates

Factor	*p*-value	*F*-value	Effect
Cutting speed	0.019	14.46	Significant
Feed rate	0.755	0.30	Not significant
Cooling method	0.000	166.89	Highly significant
Machining strategy	0.039	8.06	Significant
Cutting speed: cooling method	0.035	8.61	Significant
Cutting speed: machining strategy	0.030	8.91	Significant
Feed rate: cooling method	0.117	3.82	Not significant
Feed rate: machining strategy	0.186	2.63	Not significant
Cooling method: machining strategy	0.033	7.83	Significant

complex interplay between process parameters and their combined impact on surface roughness. The corresponding *p*-values and *F*-values for each factor and interaction are summarized in Table 2.

3.2 Surface waviness

Figure 8 a presents the effects of various milling strategies, unidirectional, bidirectional, contour, and trochoidal, and process fluids on the surface waviness of face-milled aluminum plates. Waviness measurements were taken along two consecutive milling passes, showing also the influence of overlapping of the passes on surface quality. For all milling strategies, cooling with $ScCO_2$ + MQL significantly reduces surface waviness compared to emulsion cooling, achieving reductions of approximately 35%. This substantial reduction is attributed to the enhanced lubrication and cooling properties of $ScCO_2$ + MQL, which lower tool wear and plastic deformation during milling, stabilize temperatures, and support consistent cutting conditions. Together, these factors reduce tool deflection and vibration, both essential for minimizing waviness [41].

Comparing the waviness across different milling strategies in the diagram in Fig. 8a and the waviness profile for different milling strategies under $ScCO_2$ + MQL in Fig. 8b), bidirectional milling produces the highest waviness, while trochoidal milling achieves the best results, showing a 45% reduction in waviness compared to bidirectional milling. Contour milling yields relatively poor results, with waviness values approximately 10% lower than those of bidirectional milling. Unidirectional milling ranks second in waviness performance.

Trochoidal milling's continuous cutting path with lower radial engagement helps maintain consistent cutting forces, thereby minimizing tool deflection and vibration. This stability allows for smoother transitions between passes, effectively reducing the impact of any misalignment or variations in tool path overlap, resulting in a more uniform surface. Bidirectional milling, despite its practicality in terms of tool path efficiency, produces

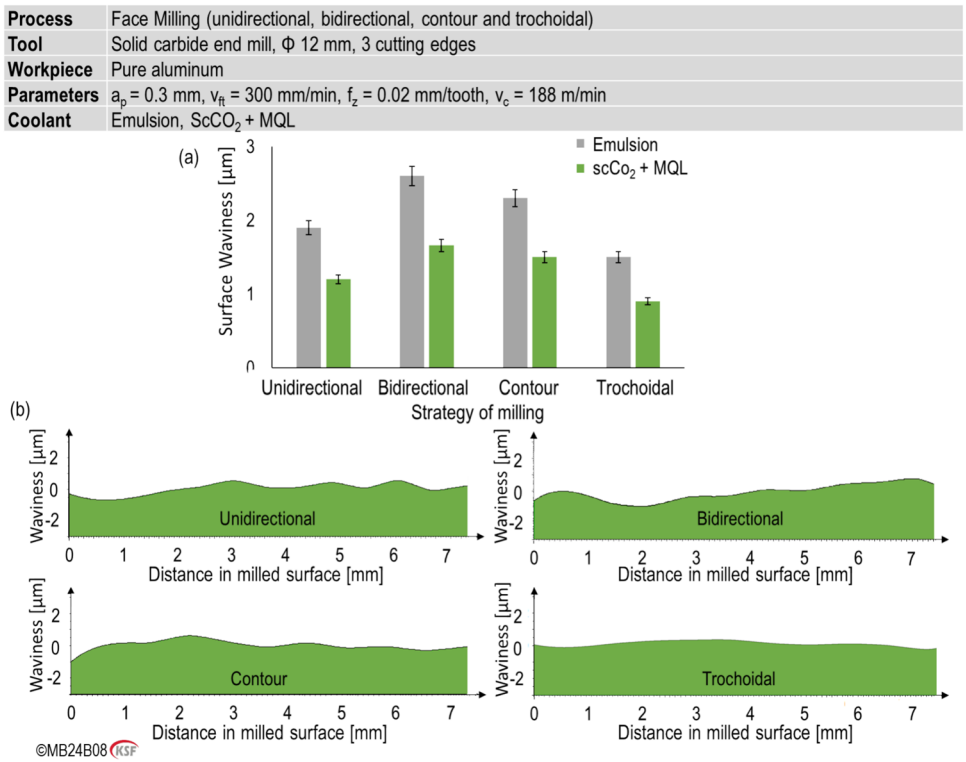

Fig. 8 **a** Comparison of surface waviness across three passes of milling using different strategies: unidirectional, bidirectional, contour, and trochoidal milling of aluminum plates, evaluated under emulsion and $ScCO_2$ + MQL process fluids. **b** Correspondence surface waviness profiles for milling strategies using $ScCO_2$ + MQL cooling

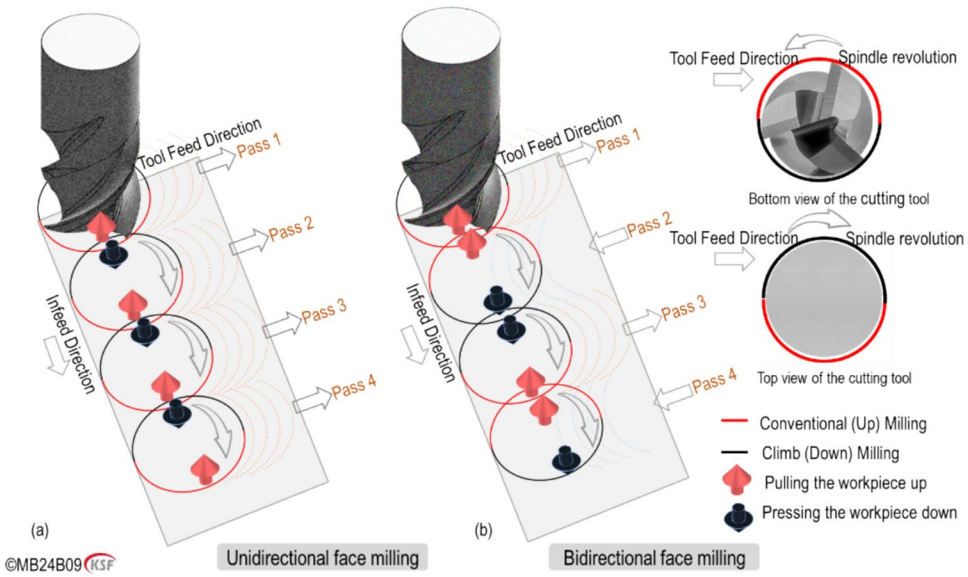

Fig. 9 Schematic illustration of **a** unidirectional and **b** bidirectional milling strategies, showing tool feed direction, spindle revolution, and successive passes in the milling process

the highest surface waviness among the tested strategies. This can be attributed to the alternating direction of each pass, which introduces periodic shifts in cutting forces as the tool reverses direction. Figure 9 provides a schematic representation of unidirectional and bidirectional milling strategies, illustrating four passes of face milling. This diagram helps explaining why bidirectional milling often results in greater surface waviness compared to unidirectional milling. In unidirectional milling, the tool consistently moves in the same direction for each pass. As a result, half of the area under tool is subjected to an up milling (pulling) effect, while the other half experiences down milling (pushing) toward the fixture. This pattern repeats across all passes, causing each side of the milled surface to undergo alternating pulling and pushing forces. This alternation results in a more balanced force distribution throughout the milling process, which contributes to a more uniform surface finish.

In contrast, bidirectional milling involves the tool changing direction after each pass, which leads to an imbalance in the forces exerted on the milled surface. Specifically, one side of the surface may be pulled in consecutive passes, while the other side is consistently pushed. This inconsistency in force application leads to a less uniform surface finish. Considering that, in this study, the "a_e" value is 75% of the tool diameter, unidirectional face milling maintains a consistent engagement profile—comprising 25% up milling and 50% down milling—for each pass, thereby ensuring a more uniform effect on the workpiece. However, in bidirectional face milling, the tool engagement alternates between 25% up milling and 50% down milling in one pass, followed by 25% down milling and 50% up milling in the subsequent pass. This alternating engagement leads to an uneven force distribution between consecutive passes, introducing non-uniform forces and additional vibrations, which contribute to increased surface waviness. Therefore, the consistent tool direction in unidirectional milling helps mitigate these variations, resulting in a smoother surface compared to the bidirectional approach.

In the case of contour milling, as like as bidirectional milling, the variability in tool engagement along the workpiece edge often leads to inconsistent cutting forces and increased tool and workpiece deflection, which can cause periodic waviness patterns to develop on the surface.

The variation in force distribution between unidirectional and bidirectional milling also leads to different burr formations in their overlap interactions, as shown in the optical microscopy images in Fig. 10. In this figure, the optical microscopy images of three successive passes are shown for both unidirectional and bidirectional milling, with the overlap interaction depicted at higher magnification to highlight differences in burr formation. As shown in Fig. 10 a, for unidirectional milling, the interactions are consistent, and the burr formation remains uniform across two passes. In contrast, in bidirectional milling, as shown in Fig. 10 b, the burr formation is more pronounced in one of the interactions compared to the others. This difference is due to the varying forces applied to the surface during unidirectional and bidirectional milling, as previously described in Fig. 9.

The more pronounced reduction in surface waviness compared to surface roughness when switching from emulsion to $ScCO_2$ + MQL in face milling can be attributed to the stabilization of macro-scale factors such as tool deflection, vibrations, plastic deformation, and cutting forces. The $ScCO_2$ + MQL combination provides superior cooling and lubrication, reducing cutting forces significantly and minimizing dynamic instabilities that contribute to waviness. Moreover, the enhanced thermal control achieved by $ScCO_2$ reduces

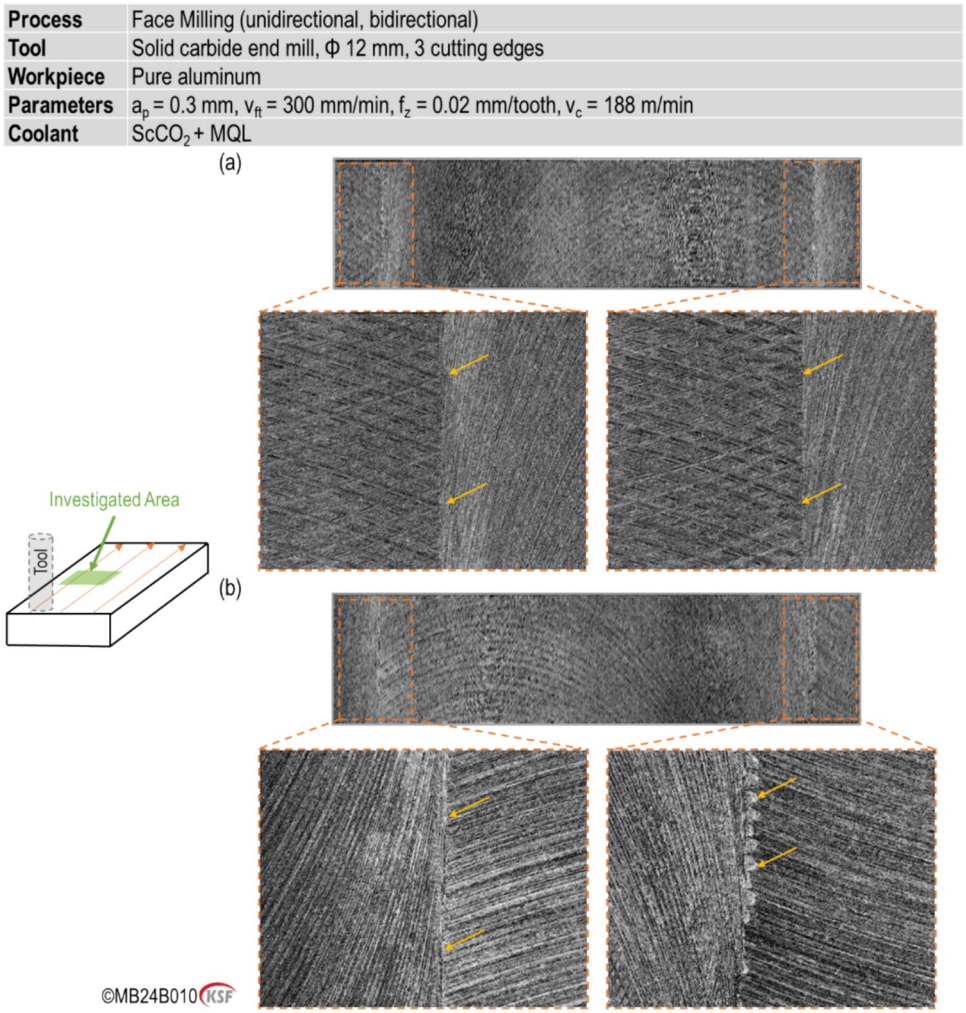

Fig. 10 Overlapping interaction between successive passes in **a** unidirectional and **b** bidirectional milling strategies, illustrated with optical microscopy images (300 × magnification)

thermal gradients during milling, leading to decreased tool deviations and contributing to a more consistent tool path, which is particularly beneficial in reducing waviness. Efficient chip evacuation further prevents re-cutting and chip accumulation, which are major contributors to larger surface deviations, thereby further reducing waviness. In contrast, surface roughness is primarily influenced by localized tool-material interactions, tool sharpness, and micro-scale surface characteristics, which are inherently less affected by changes in cooling method compared to the factors affecting waviness. Therefore, while both roughness and waviness benefit from $ScCO_2$ + MQL, the impact on waviness is more significant due to the reduction in macro-level dynamic disturbances and improved overall cutting stability.

3.3 Machining time in different milling strategies

The process time for milling a plate with the dimensions of 70 × 70 mm using defined cutting parameters but different milling strategies is shown in Fig. 11. Investigation of the results in the diagram reveals that unidirectional, bidirectional, and contour milling all exhibit machining times ranging between 2 and 3 min, making them relatively efficient in terms of processing speed. In contrast, trochoidal milling, when applied under the same cutting parameters, requires approximately 25 min, which is substantially longer than the other techniques. Notably, the relatively small milled area in our study (70 × 70 mm) results in unidirectional and bidirectional milling times being quite close, with unidirectional taking approximately 180 s and bidirectional about 154 s. However, for larger milled areas, this difference becomes significantly more pronounced due to the nature of these milling strategies. Moreover, it is important to note that the purpose of this study was to compare different milling strategies under identical machining conditions to isolate the influence of toolpath strategy on surface integrity and process efficiency. Although all strategies used the same nominal axial depth of cut, trochoidal milling exhibited significantly longer machining time due to its circular toolpath and low radial engagement, which result in a higher number of tool entry and exit events and an extended toolpath length. While this strategy is commonly employed

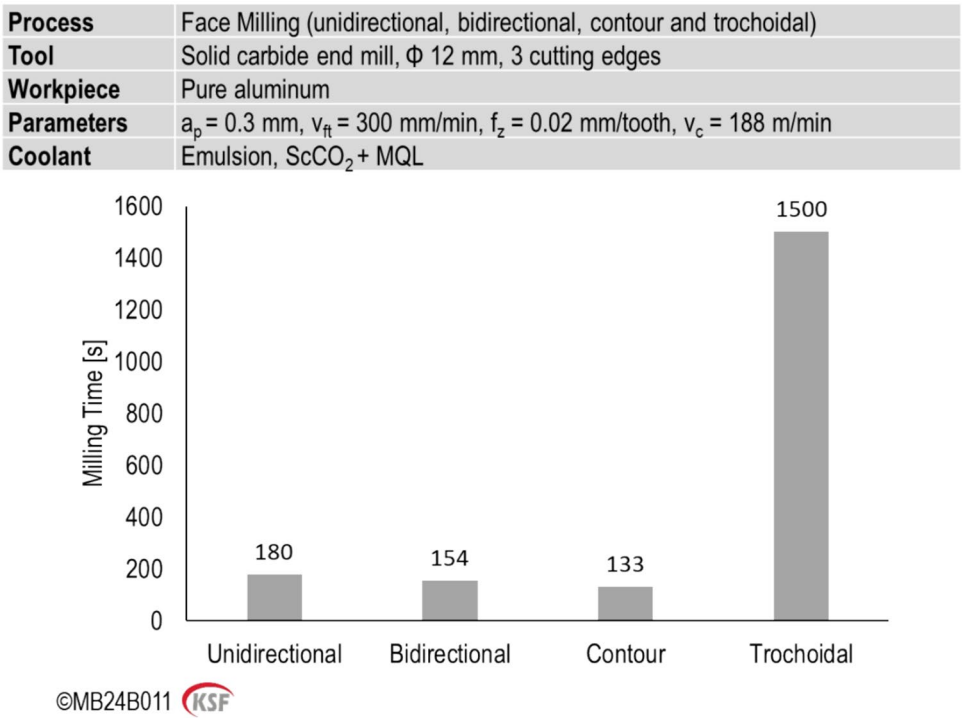

Fig. 11 Face milling duration for a 70 × 70 mm aluminum plate

in roughing operations with deeper axial depths to improve productivity, such an adjustment was not feasible here due to its adverse effect on surface roughness. Thus, in the context of this comparison, trochoidal milling's advantage in surface quality comes at the cost of prolonged machining time, showing the practical trade-offs between quality and efficiency when selecting a suitable strategy under fixed process parameters.

When balancing machining time with acceptable surface quality, unidirectional face milling emerges as the optimal choice. It offers a practical compromise, delivering reasonable surface roughness and waviness within a short processing period. Thus, for applications where a combination of lower milling time and acceptable surface finish is required, unidirectional face milling is recommended as the most effective technique.

4 Conclusion

In this paper, the effects of cooling methods, milling strategies, and milling parameters on the surface quality of aluminum 1100 in face milling operations are investigated. The study evaluates various cooling approaches, including dry, emulsion, and $scCO_2$ + MQL, alongside milling strategies such as unidirectional, bidirectional, contour, and trochoidal, to determine optimal conditions for achieving superior surface integrity. The main conclusions are summarized as follows:

1. $ScCO_2$ + MQL demonstrated superior performance over emulsion cooling in enhancing both surface roughness and waviness. Notably, the surface waviness of specimens milled using $scCO_2$ + MQL was reduced by nearly 35% compared to those produced with emulsion cooling.
2. Trochoidal milling with $scCO_2$ + MQL consistently delivered the best surface quality, achieving the lowest values in surface roughness parameters (Sa, Sk, Spk, Svk) and minimal waviness. The general surface roughness of the trochoidal-milled surface was 40% lower than that of the contour-milled surface, which exhibited the poorest surface quality. Additionally, the waviness of the trochoidal-milled surface was 45% lower than that of the bidirectional-milled surface, which showed the highest waviness among the strategies tested. However, trochoidal milling has a considerably higher machining time compared to other strategies, making it less practical for applications where time efficiency is essential.
3. Unidirectional milling produced better surface quality than bidirectional milling due to more stable force and thermal distribution. For applications requiring a balance between shorter machining time and acceptable surface quality, unidirectional milling is the optimal strategy, providing an efficient compromise.
4. It was demonstrated that machining parameters significantly affect surface quality, with higher cutting speeds improving surface finish, especially under $scCO_2$ + MQL. Conversely, higher feed rates led to increased surface roughness.

In conclusion, although trochoidal milling with $scCO_2$ + MQL delivers the highest surface quality, its prolonged machining time limits its practicality for industrial applications. In contrast, unidirectional milling with $scCO_2$ + MQL offers the best balance between surface quality, machining efficiency, and sustainability. These results confirm the potential of $scCO_2$ + MQL as a viable alternative to conventional cooling methods, making it particularly suitable for precision manufacturing in the aerospace, automotive, and sustainable machining industries. To further validate its industrial application, future research should focus on long-term tool wear, economic feasibility, and a comprehensive investigation of machining parameters to determine the optimal conditions for milling aluminum alloys using $scCO_2$ + MQL cooling.

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Author contribution The conception and design of the study were undertaken by Bahman Azarhoushang and Amir Alinaghizadeh. Material preparation, data collection, and analysis were performed by Armin Siahsarani, Amir Alinaghizadeh, Masoud Bayat, and Robert Bösinger. The first draft of the manuscript was written by Armin Siahsarani and Masoud Bayat, with Bahman Azarhoushang and Saeed Amini reviewing and editing versions. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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