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Study on Surface Characteristics and Work Hardening of SiCp/Al Composites by $SCCO_2$-MQL Combined with Ultrasonic Vibration Milling

Huiping Zhang [1,*], Yihan Tao [1], Yanlin Wu [1] and Yongxin Li [2]

[1] School of Mechanical Engineering, Harbin University of Science and Technology, Harbin 150080, China; 2220110109@stu.hrbust.edu.cn (Y.T.); 2020110203@stu.hrbust.edu.cn (Y.W.)
[2] School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China; 2021217016@mail.hfut.edu.cn
* Correspondence: zhping302@hrbust.edu.cn

Abstract: This study investigated the milling of SiCp/Al composite materials using Polycrystalline Diamond (PCD) tools under various machining conditions, including dry cutting conditions, supercritical carbon dioxide ($SCCO_2$) conditions, supercritical carbon dioxide cooling with minimum quantity lubrication ($SCCO_2$-MQL) conditions, ultrasonic vibration conditions, and supercritical carbon dioxide cooling with minimum quantity lubrication combined with ultrasonic vibration conditions. The objective was to compare the surface roughness and morphology of the materials under different machining conditions. Furthermore, under dry cutting conditions and $SCCO_2$-MQL combined with ultrasonic vibration, the effects of different milling parameters on the surface roughness and morphology of SiCp/Al composite materials were investigated through a univariate experiment. Microhardness tests were carried out on the machined workpieces to explore the influence of process conditions and milling parameters on work hardening. The experimental results indicate that among all the tested machining conditions, the $SCCO_2$-MQL in combination with the ultrasonic vibration process significantly reduced the surface roughness of the material. When the milling speed was increased from 40 m/min to 120 m/min, both the surface roughness and the degree of work hardening first increased and then decreased. As the feed rate or cutting depth increased, the degree of work hardening also increased. Therefore, under $SCCO_2$-MQL combined with ultrasonic vibration conditions, it is recommended to use a milling speed of more than 60 m/min and avoid using high feed rates and cutting depths in order to optimize the machining performance.

Keywords: SiCp/Al composites; $SCCO_2$-MQL ultrasonic vibration; surface features; work hardening

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1. Introduction

Metal matrix composites (MMCs) are composite materials that are prepared by incorporating ceramic materials as the reinforcing phase and metals such as aluminum, titanium, magnesium, copper, and nickel as the matrix. Metal matrix composites (MMCs) have attracted significant attention in recent years due to their versatile processing capabilities and tailored properties for various practical requirements [1]. SiCp/Al composite material is a new type of multiphase material that is prepared by incorporating SiC particles as the reinforcing phase and combining them with ductile aluminum material through complex preparation processes. One of the commonly used methods for preparing SiCp/Al composites is powder metallurgy. The process is that the mixed powder is cold-pressed and then sintered to achieve the composite [2]. Due to its lightweight and high specific strength, SiCp/Al composite material has been widely used in the aerospace field [3,4]. In the field of optical precision instrument manufacturing, SiCp/Al composite material is also considered a preferred choice [5]. Its low thermal expansion coefficient is highly favored, and it has extensive applications in electronic packaging and thermal control components [6,7]. However, while enhancing the overall performance of the material, this composite material also poses significant challenges to its processing. During the machining process, the high-speed rotation of the tool generates a large amount of cutting heat, which not only can alter the microstructural properties of the material but also lead to significant tool wear [8,9]. Conventional flood cooling lubrication strategies are inefficient in this process and environmentally unfriendly, especially considering the requirements for green and efficient production within the framework of "Made in China 2025". In response to these issues, the concept of composite ultrasonic vibration-assisted machining under supercritical carbon dioxide cooling with minimum quantity lubrication ($SCCO_2$-MQL) conditions has been proposed [10]. The unique properties provided by SiC particles in SiCp/Al composite materials have sparked great interest in their machining characteristics among researchers worldwide. Swastik Pradhan et al. used multi-layer coated hard alloy inserts to machine SiCp/Al MMC with a volume fraction of 10%. The study found that feed rate was the most important factor, followed by cutting speed and cutting depth [11]. Xingwen Wang studied ultrasonic vibration-assisted machining of SiCp/Al composite materials and found that ultrasonic vibration resulted in high subsurface density and good surface finish of the workpiece [12]. Mengfei Li et al. conducted end milling experiments on SiCp/A356Al and found that under dry cutting conditions, fractured SiC particles caused severe scratching on the surface, forming protrusions that were unfavorable for obtaining a smooth surface [13]. Muthukrishnan used PCD tools to machine SiCp/Al composite materials and investigated the generation of irregular-shaped built-up edges on the tool surface when the cutting speed varied between 200 and 400 m/min; at higher cutting speeds, the increase in tool wear on the rake face had a smaller impact on surface roughness [14].

Some scholars have studied surface defects and surface morphology [15–17], and the research shows that the interaction between particles and tools has great impact on the machined surface morphology. Some brittle particles fracture in the cutting path, and the residual part on the workpiece surface causes the surrounding matrix to produce work hardening, reducing the surface integrity. Some particles are completely removed from the surface of the workpiece, leaving holes and greatly reducing the surface quality. These residues and voids are characterized by the formation of peaks and troughs on the surface, resulting in obvious microscopic surface defects and surface damage. Ruxin Shi from the Harbin University of Technology conducted end milling experiments on SiCp/6063Al under both low-temperature minimum quantity lubrication and dry conditions, and the results show that low-temperature minimum quantity lubrication had good lubrication effects and significantly reduced the strengthening effect of work hardening [18]. Chongyan Cai et al. found that in supercritical CO_2-based minimum quantity lubrication with oil-on-water droplet cutting fluid ($SCCO_2$-OoWMQL) conditions, due to better cooling, lubrication, and chip evacuation performance, the cutting forces, temperature, and surface roughness were all minimized [19]. Chunzheng Duan of Dalian University of Technology found that when milling SiCp/Al composites under $SCCO_2$ conditions, the shed SiC particles did not stay in the cutting zone, which reduced the friction between SiC particles, the tool, and the machined surface. This is suitable as the preferred cooling lubrication method for cutting SiCP/Al composites [20]. Quan et al. conducted turning experiments on SiCp/Al composite materials under dry cutting conditions and found that the maximum microhardness value was often not obtained on the surface of the specimen, but on the subsurface. Additionally, the experimental data indicated that as the cutting speed increased, the surface roughness of the specimen decreased [21].

It can be seen from the above that $SCCO_2$ has an excellent cooling effect, MQL has an excellent fluid flushing effect, and the cutting force is greatly reduced when milling materials under ultrasonic vibration conditions. Therefore, on this basis, this paper will mill SiCp/Al composite materials under dry cutting conditions, $SCCO_2$, $SCCO_2$-MQL, ultrasonic vibration, and $SCCO_2$-MQL combined with ultrasonic vibration conditions, compare and analyze the results, and then conduct single-factor experiments under $SCCO_2$-

MQL composite ultrasonic vibration and dry cutting conditions. The effects of process conditions and cutting factors on roughness and surface morphology were investigated. On this basis, according to the microhardness of the machined workpiece, the influence of process conditions and milling parameters on the work hardening of the material was investigated. The purpose of this paper is to provide some reference for the subsequent research on milling SiCp/Al composites under $SCCO_2$-MQL composite ultrasonic vibration.

2. Experimental Equipment and Materials

2.1. Experimental Equipment

Milling experiments of SiCp/Al composite materials were all carried out on a VDL-1000 three-axis vertical machining center, as shown in Figure 1. During the experiments, supercritical carbon dioxide equipment was connected to the machine tool. The supercritical carbon dioxide micro-lubrication equipment used Cry0lube-i0oW equipment produced by Dongguan Anlin Machinery Manufacturing Technology Co., Ltd. (Dongguan, China) The ultrasonic vibration system was produced by Kunshan Hengyou Yinda Machinery Technology Co., Ltd. (Kunshan, China). Its cutting tool was the integral PCD micro-edge flat end milling cutter produced by Huizhuan. The model number was $\varphi 8 \times 2.5 \times 45L \times \varphi 8$-30F. The ultrasonic vibration frequency used in the experiment was 27 khz, the amplitude was 7 μm, and the cutting oil content in $SCCO_2$-MQL was 20 mL/h. The $SCCO_2$ flow rate was 4 L/h. The MQL injection angle was 30°. For the measurement of cutting force, we choose the Kistier9253B23 model three-way piezoelectric dynamometer, a Kistier5070A charge amplifier, and a PCIMDAS1602/16 data acquisition card.

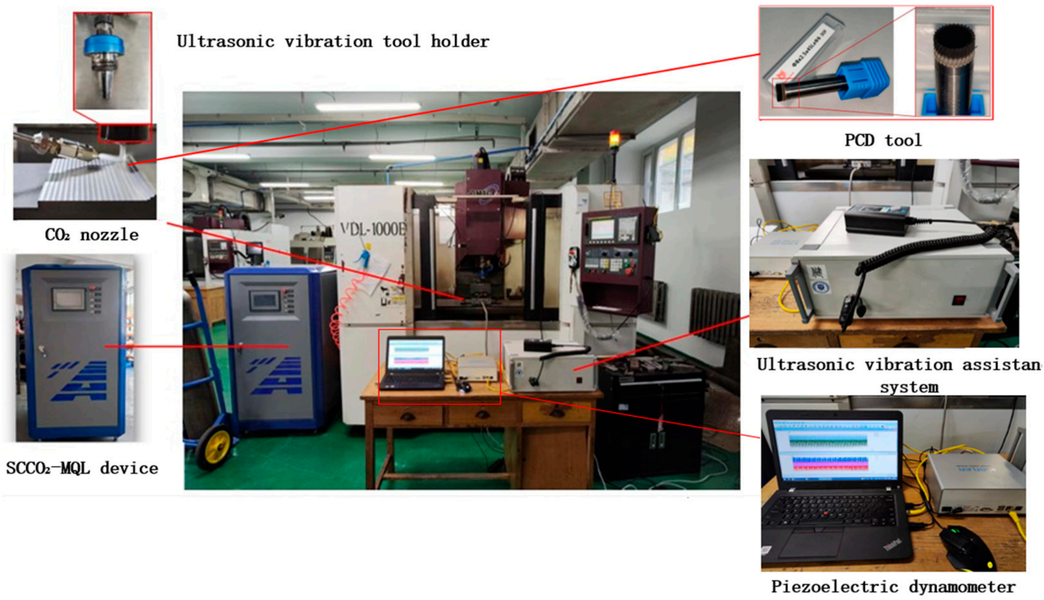

Figure 1. VDL-1000 three-axis vertical machining center.

2.2. Experimental Material

The volume fraction of SiC in the SiCp/Al composite material selected in this paper was about 45%, the matrix was 6063DL31 forged aluminum alloy cuboid material, and the diameter of the silicon carbide particle was about 5–10 μm. In order to facilitate the experimental research of cutting, it was designed as a cuboid. The specific dimensions of the material were 200 mm × 150 mm × 90 mm. Its microstructure is shown in Figure 2. The composite material mainly consisted of the following elements: C, Mg, Al, Si, and Cu. The chemical composition and content of these elements are shown in Table 1.

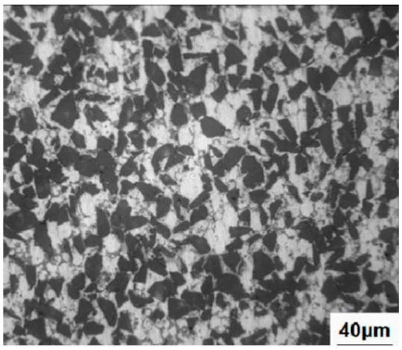

Figure 2. Microstructure of SiCp/Al composites.

Table 1. Chemical compositions of SiCp/Al composite material.

Element Type	C	Mg	Al	Si	Cu
Weight ratio (%)	9.43	0.51	43.13	45.13	1.80
Atomic ratio (%)	19.59	0.47	34.7	44.34	0.9

3. Influence of Process Conditions on Geometric Characteristics of Milling Surfaces of SiCp/Al Composites

3.1. Experimental Planning

The effects of dry cutting conditions, $SCCO_2$, $SCCO_2$-MQL, ultrasonic vibration, and $SCCO_2$-MQL combined with ultrasonic vibration on the surface roughness and surface topography of SiCp/Al composites were investigated, and a single-factor comparison experiment was designed. The milling parameters were set as follows: feed rate f was 0.06 (mm/r), milling width a_e was 8 (mm), and milling depth a_p was 0.15 (mm). Based on the above experimental conditions, the milling speed v_c was used as the processing variable, and five different parameter levels (40, 60, 80, 100, 120) m/min were established, comprising a total of 25 experimental groups.

In the process of the cutting experiment, the TR-200 roughness instrument was used to measure roughness, and 5 surface roughness parameters Ra at different positions on the sample surface were taken. The average value was taken to calculate the surface roughness value, as shown in Figure 3a. After the milling experiment was completed, the workpiece was removed, and the surface roughness was accurately measured using a SuperView W1 white light interferometer to obtain the surface topography. The white light interferometer is shown in Figure 3b.

(**a**) (**b**)

Figure 3. Testing instrument. (**a**) TR-200 roughness meter; (**b**) white light interferometer.

3.2. Analysis of the Influence of Process Conditions on Milling

3.2.1. The Effect of Process Conditions on the Surface Roughness of SiCp/Al Composite Material Milling

Figure 4 illustrates the trend of the influence of different process conditions on the surface roughness (*Ra*). The experimental results indicate that as the milling speed (v_c) increases, the surface roughness generally tends to decrease under all five different process conditions. Specifically, under dry cutting conditions, the surface roughness of the workpiece is the highest. Compared with dry cutting, the addition of supercritical carbon dioxide reduces the surface roughness. This is because when CO_2 is sprayed on the cutting area through the nozzle at high pressure, the high-pressure CO_2 will blow the chips away, and the cutting area will cool down quickly and take away a lot of cutting heat so as to further ensure the quality of the processed surface. Ultrasonic vibration is of great help to the removal, pressing, and ejecting of SiC particles during material processing. Notably, the lowest surface roughness values of the machined material were achieved under the combined condition of $SCCO_2$-MQL and ultrasonic vibration.

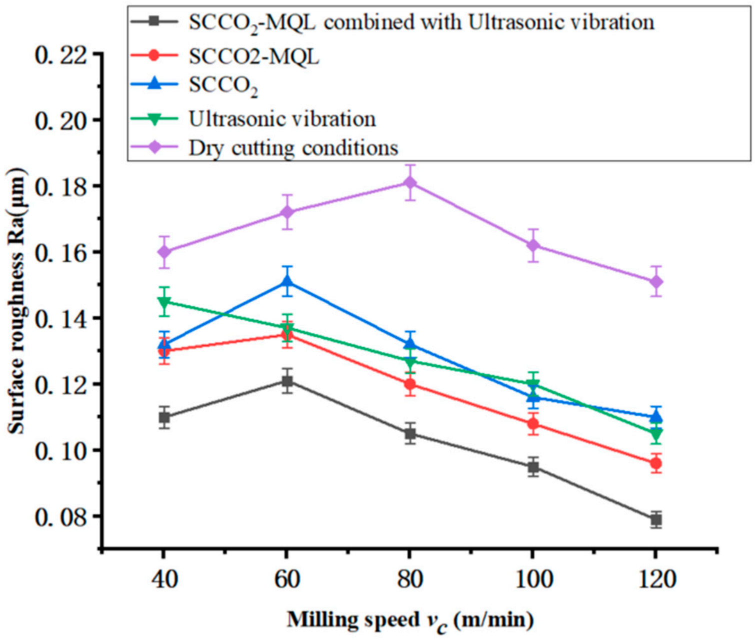

Figure 4. Comparison curve of the influence of process condition on surface roughness with cutting speed.

3.2.2. The Influence of Process Conditions on the Surface Morphology of Milled SiCp/Al Composite Materials

Figure 5 presents a comparative analysis of the surface micromorphology under five different processing conditions at milling speeds (v_c) of 40 m/min, 80 m/min, and 120 m/min. Through comparison, it can be found that under ultrasonic vibration, due to good chip removal and effective removal of SiC particles, the surface topography becomes better and better as the cutting speed continues to increase. Moreover, surface defects are mainly caused by particle pulling out, extrusion, and scratching, so there are fewer surface defects under ultrasonic vibration. With $SCCO_2$ alone, the lack of lubrication results in more surface defects. Wang et al. obtained a similar situation by simulating the milling process where the SiC particles broke and rotated within the matrix, resulting in single small voids and large discontinuous voids on the machined surface [22]. Under the simultaneous action of $SCCO_2$-MQL and ultrasonic vibration, it is obvious that the surface morphology is greatly improved, the surface roughness is improved, and the peak valley distance is reduced.

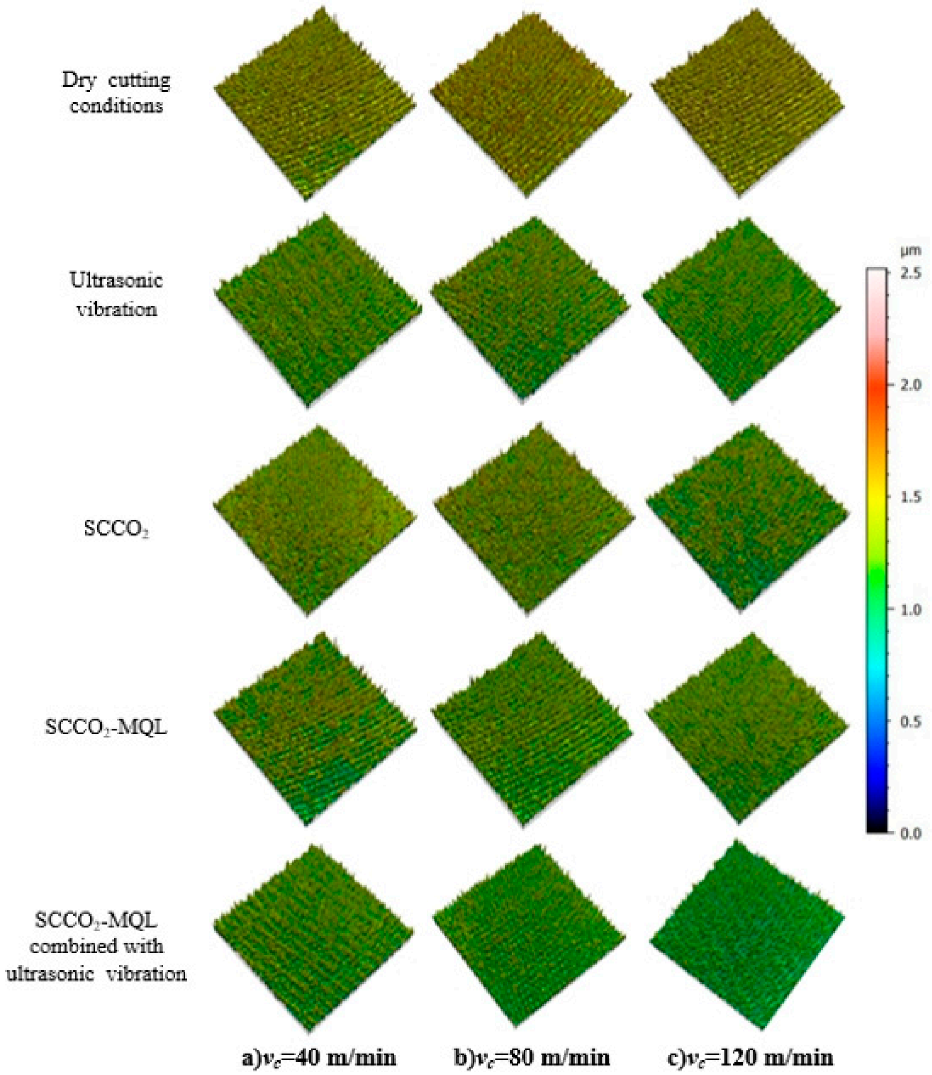

Figure 5. Comparison of surface micromorphology.

4. Effects of Milling Parameters on SiCp/Al Composite Materials under Different Process Conditions

4.1. Experimental Planning

To investigate the effects of $SCCO_2$-MQL combined with ultrasonic vibration conditions and dry cutting conditions on the surface geometric characteristics of milled SiCp/Al composite materials, single-factor experiments were designed for milling speed (v_c), feed rate (f), and milling depth (a_p) [23] to compare the differences in surface roughness (Ra) and surface morphology after machining. At the same time, the cutting force (F) in the milling process was measured. The experimental scheme is shown in Table 2.

Table 2. Test factors and level.

Factor	Level Parameter	Manufacturing Environment
Milling speed v_c (m/min)	40, 60, 80, 100, 120	Dry cutting conditions, $SCCO_2$-MQL combined with ultrasonic vibration
Feed rate f (mm/r)	0.02, 0.04, 0.06, 0.08, 0.1	
Milling depth a_p (mm)	0.2, 0.4, 0.6, 0.8, 1	

4.2. Comparative Analysis of the Impact of Milling Parameters on Surface Roughness

4.2.1. The Influence of Milling Speed on Surface Roughness

Figure 6 shows the contrast curve of workpiece surface roughness (*Ra*) and cutting force (*F*) under dry cutting and $SCCO_2$-MQL combined with ultrasonic vibration when the milling speed (v_c) changes in the range of 40~120 m/min. As shown in Figure 6b, under $SCCO_2$-MQL combined with ultrasonic vibration conditions, the surface roughness peaks when v_c is 60 m/min. Niu Qiulin et al. also found this trend in milling experiments on SiCp/Al composites [23]. The main reason is that under the displacement–particle interaction, the number of silicon carbide hard particles in SiCp/Al composite material that are crushing, breaking, and pressing into the ejection increases, which increases the cutting force. Due to surface defects such as micro-cracks, large pits, and low milling speed, it is easy for the tool tip to form chip nodules, resulting in increased machining surface roughness. As the milling speed increases from 60 m/min to 120 m/min, the surface roughness shows a decreasing trend, with the magnitude of decrease growing larger, reaching a lowest surface roughness of 0.081 µm when v_c is 120 m/min. This is mainly because the milling speed increases the temperature of the cutting area; the higher temperature makes the aluminum matrix soften and flow, fills the defects left after the removal of the particles, and makes the SiC particles easier to cut off. The chip tumor is reduced or even disappears, and finally, the surface roughness of the material is reduced.

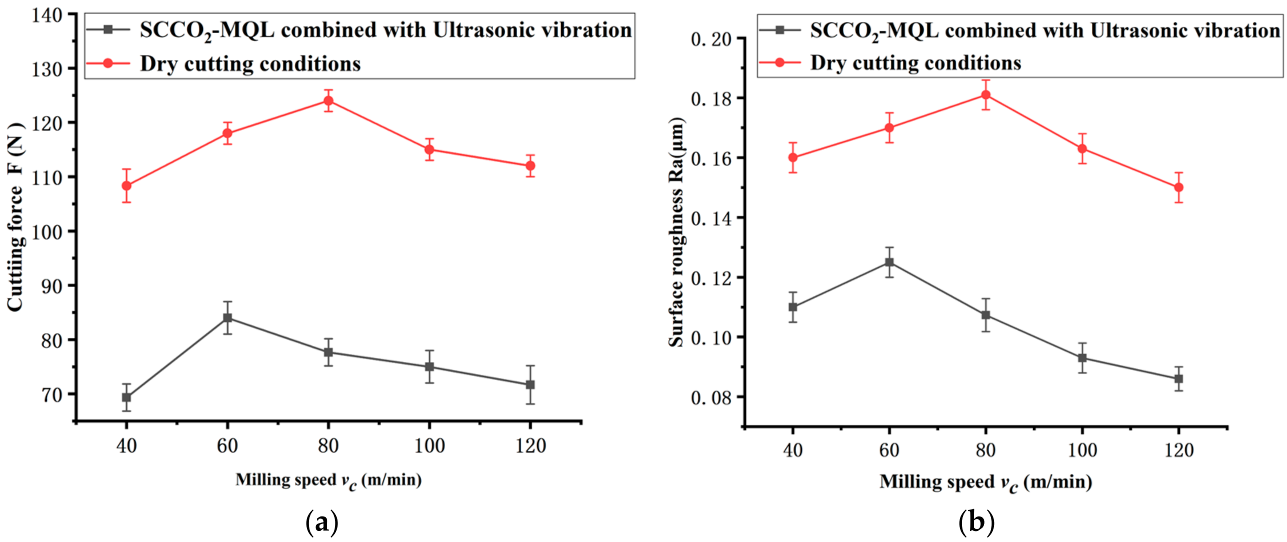

Figure 6. Variation in surface roughness with milling speed (f = 0.06 mm/r, a_p = 0.6 mm). (**a**) Effect of milling speed on cutting force; (**b**) effect of milling speed on surface roughness.

As can be seen from the results in Figure 6, the surface roughness obtained via $SCCO_2$-MQL ultrasonic vibration under the same milling parameters is 37.42% lower than that obtained via dry cutting. High-pressure CO_2 takes away the chips produced by cutting, which greatly reduces the friction generated by the tool-piece chips. The addition of ultrasonic vibration causes a certain increase in the diffusion rate of oil mist molecules and the removal of hard SiC particles and cutting force; the reduction has a good effect, so the surface roughness can be reduced.

4.2.2. The Influence of Feed Rate on Surface Roughness

Figure 7 shows the comparative curve of the influence of surface roughness (*Ra*) and cutting force (*F*) under dry cutting and $SCCO_2$-MQL combined with ultrasonic vibration when the feed velocity F varies within the range of 0.02~0.1 mm /r. Based on the analysis of the Figure 7b, it is known that as the feed rate (f) increases from 0.02 to 0.1 mm/r, the surface roughness (*Ra*) also increases under both dry cutting conditions and $SCCO_2$-MQL combined with ultrasonic vibration conditions.

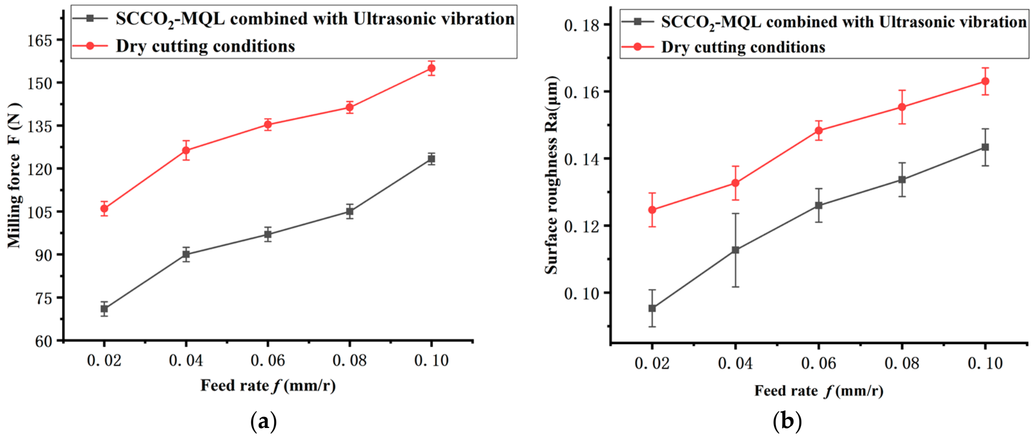

Figure 7. Variation in surface roughness with feed rate (v_c = 80 m/min, a_p = 0.6 mm). (**a**) Effect of feed rate on cutting force; (**b**) effect of feed rate on surface roughness.

$SCCO_2$-MQL combined with ultrasonic vibration conditions has a certain amount of improvement compared with dry cutting under the feed factor, but the improvement effect is not large. Firstly, $SCCO_2$-MQL combined with ultrasonic vibration has the effect of cooling, reducing wear, and reducing cutting force, which is conducive to the removal of SiC particles and can effectively inhibit the vibration generated during the cutting process. This is very beneficial for the reduction in surface roughness. $SCCO_2$-MQL combined with ultrasonic vibration does not have much influence on the cutting geometry theory from the point of view of the feed rate, so $SCCO_2$-MQL combined with ultrasonic vibration conditions has a limited effect on the cutting feed rate factor.

4.2.3. Influence of Milling Depth on Surface Roughness

Figure 8 shows the contrast curve of the influence of surface roughness (*Ra*) and cutting force (*F*) on dry cutting and $SCCO_2$-MQL combined with ultrasonic vibration when milling depth (a_p) varies between 0.05 and 0.25 mm. According to the analysis of the results, it is evident that under both dry cutting conditions and $SCCO_2$-MQL combined with ultrasonic vibration, the rate of increase in surface roughness accelerates as the milling depth (a_p) ranges from 0.05 to 0.25 mm.

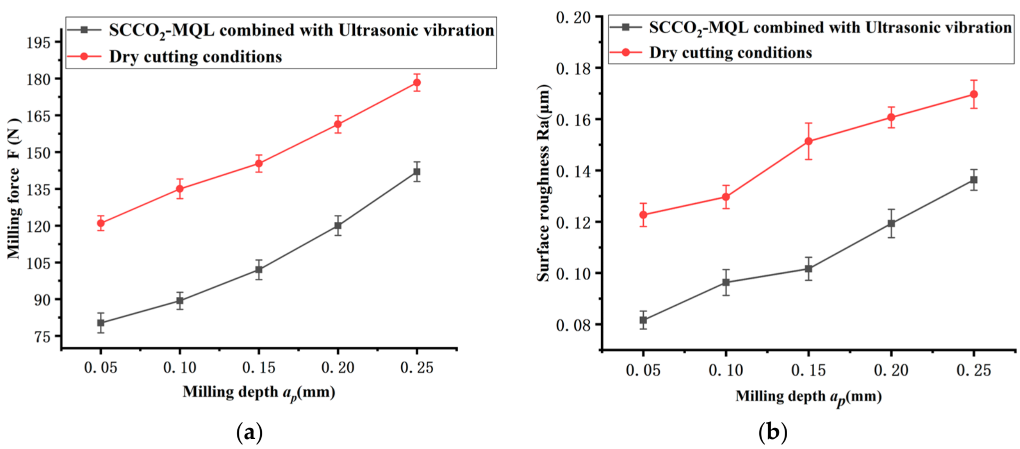

Figure 8. Variation in surface roughness with milling depths (v_c = 80 m/min, f = 0.06 mm/r). (**a**) Effect of milling depths on cutting force; (**b**) effect of milling depths on surface roughness.

At 0.05~0.15 mm, the effect of vibration reduction, lubrication, and force reduction in $SCCO_2$-MQL combined with ultrasonic vibration assisted cutting is maximized, but at 0.20 mm and 0.25 mm back cutting quantity, the excessive amount of removed material causes great damage to the tool, making the machining surface roughness difficult to ensure and unstable. According to the observation in Figure 8b, when compared with dry cutting, the addition of ultrasonic vibration has a good control effect on the cutting force, is very beneficial to the removal of materials, and reduces the surface roughness value accordingly. Therefore, the PCD micro-edge milling cutter should not choose a too-large cutting amount in the cutting process.

4.2.4. Influence of Milling Parameters on Surface Topography

Figure 9 shows a comparative diagram of the surface morphology under $SCCO_2$-MQL combined with ultrasonic vibration and dry cutting conditions as the milling speed (v_c) varies. It was observed that under $SCCO_2$-MQL combined with ultrasonic vibration conditions, when v_c increased in the range of 40~60 m/min, the peak and valley drop of the processed surface was obvious and the spacing was slightly reduced, which was due to the improvement of milling speed, which shortened the cutting time of the tool so that the spacing of the tool marks decreased but the number of broken SiC hard particles increased. The plastic flow of the aluminum matrix makes the distance between peaks and valleys larger. With the increase in cutting speed v_c from 60 m/min, the machining surface tends to be smooth, and the gap between the tool marks is further reduced. The dry cutting condition also has a similar rule, but due to the lack of cooling and lubrication conditions, the surface pits increase, and scratches and knife marks are more obvious. $SCCO_2$-MQL combined with ultrasonic vibration under the condition of cooling lubrication and chip removal greatly enhanced the surface morphology when compared to the dry cutting condition.

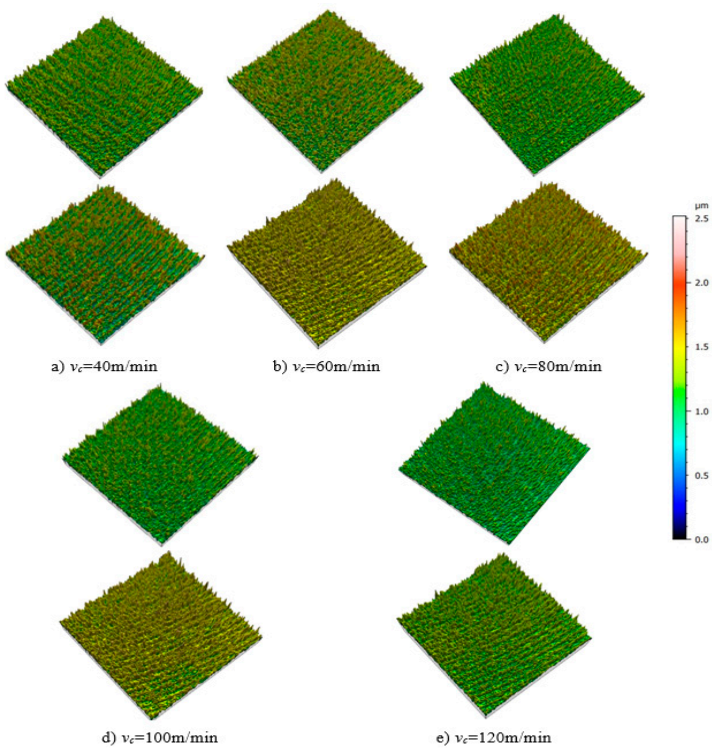

Figure 9. Comparison of surface topography of $SCCO_2$-MQL combined with ultrasonic vibration (**top**) and dry cutting condition (**bottom**) with cutting speed (f = 0.06 mm/r, a_p = 0.6 mm).

Figure 10 presents a comparison diagram of surface morphology changes with the feed rate (f) under $SCCO_2$-MQL combined with ultrasonic vibration and dry cutting conditions. With the change in feed rate from 0.02 to 0.08 mm/r in the two process environments, the surface topography of the workpiece gradually deteriorated, the peak–valley spacing increased, the tool mark spacing became larger, and the surface defects increased. Meanwhile, the excessive feed rate caused the tooltip failure and the tool mark spacing to become less obvious, but the surface pits and the peak and valley drop were very large, resulting in extremely poor surface topography.

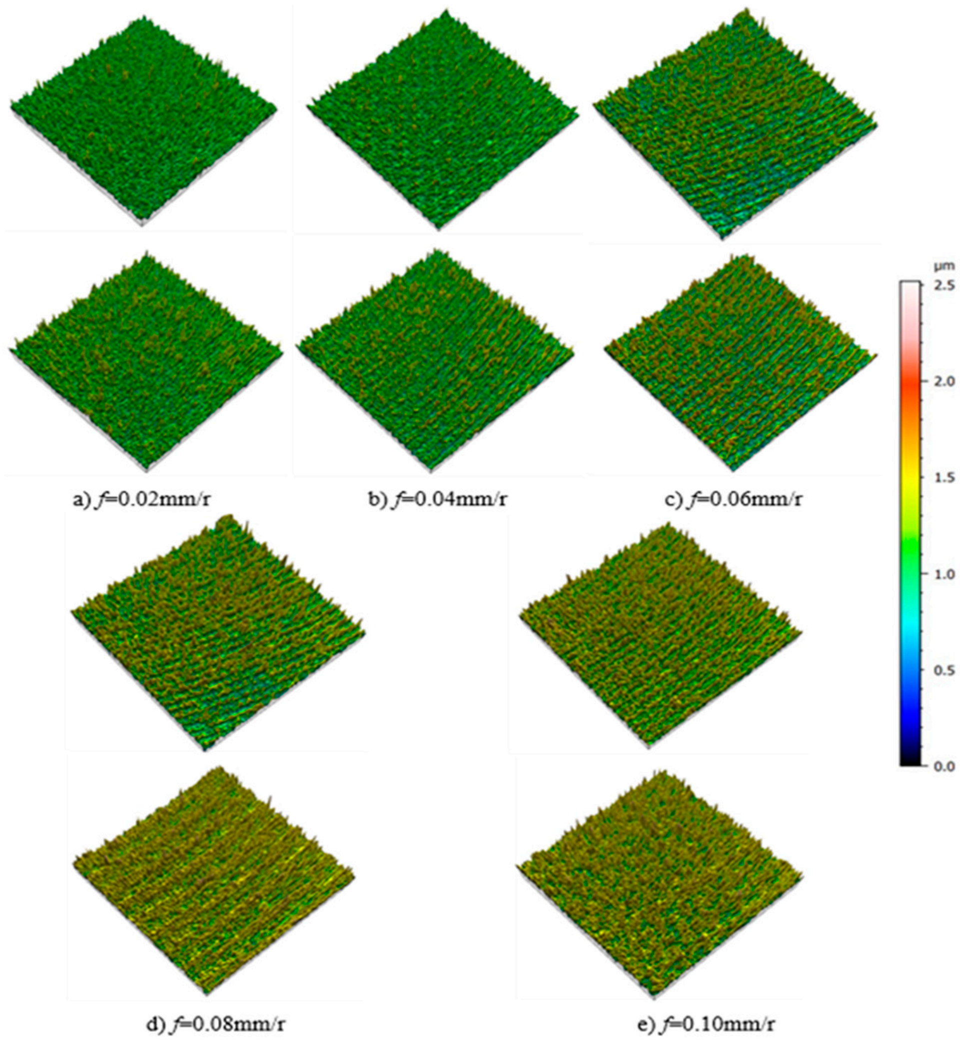

Figure 10. Comparison of the surface morphology of $SCCO_2$-MQL combined with ultrasonic vibration (**top**) and dry cutting condition (**bottom**) with the change in feed rate (v_c = 80 m/min, a_p = 0.6 mm).

By comparing the surface morphology of the two environments, it can be seen that $SCCO_2$-MQL combined with ultrasonic vibration conditions can greatly improve the surface defects caused by a large feed rate. It can be seen by f = 0.08 mm/r and 0.10 mm/r that due to its cooling and lubrication effect and the auxiliary removal of SiC particles via ultrasonic vibration, it not only reduces the wear of the tool but also prolongs the failure time. Moreover, the formation of surface defects is reduced, and the deterioration of surface morphology is delayed under a large feeding rate. Scholar Yanling Tang [24] also found a similar phenomenon.

Figure 11 provides a comparison diagram of surface morphology changes with the milling depth (a_p) under $SCCO_2$-MQL combined with ultrasonic vibration and dry cutting conditions. As can be seen from the figure, when the milling depth a_p increases in the range of 0.05~0.15 mm, the surface morphology under the two process conditions is good and there is no significant difference, which is due to the low material removal rate. The small defects formed by the removal of SiC particles can be covered by the plastic flow of the aluminum matrix. However, when the milling depth a_p is 0.20 mm and 0.25 mm, due to the influence of the excessive material removal rate, the surface topography under the two process conditions deteriorates greatly, especially in the dry cutting condition. Here, the increase in cutting heat and cutting force in the cutting process of the tool aggravates e tool wear and even the edge breaks, thus affecting the machining surface topography. The zigzag appearance in the figure is the result of increased tool boundary wear, which leads to the deterioration in the surface topography.

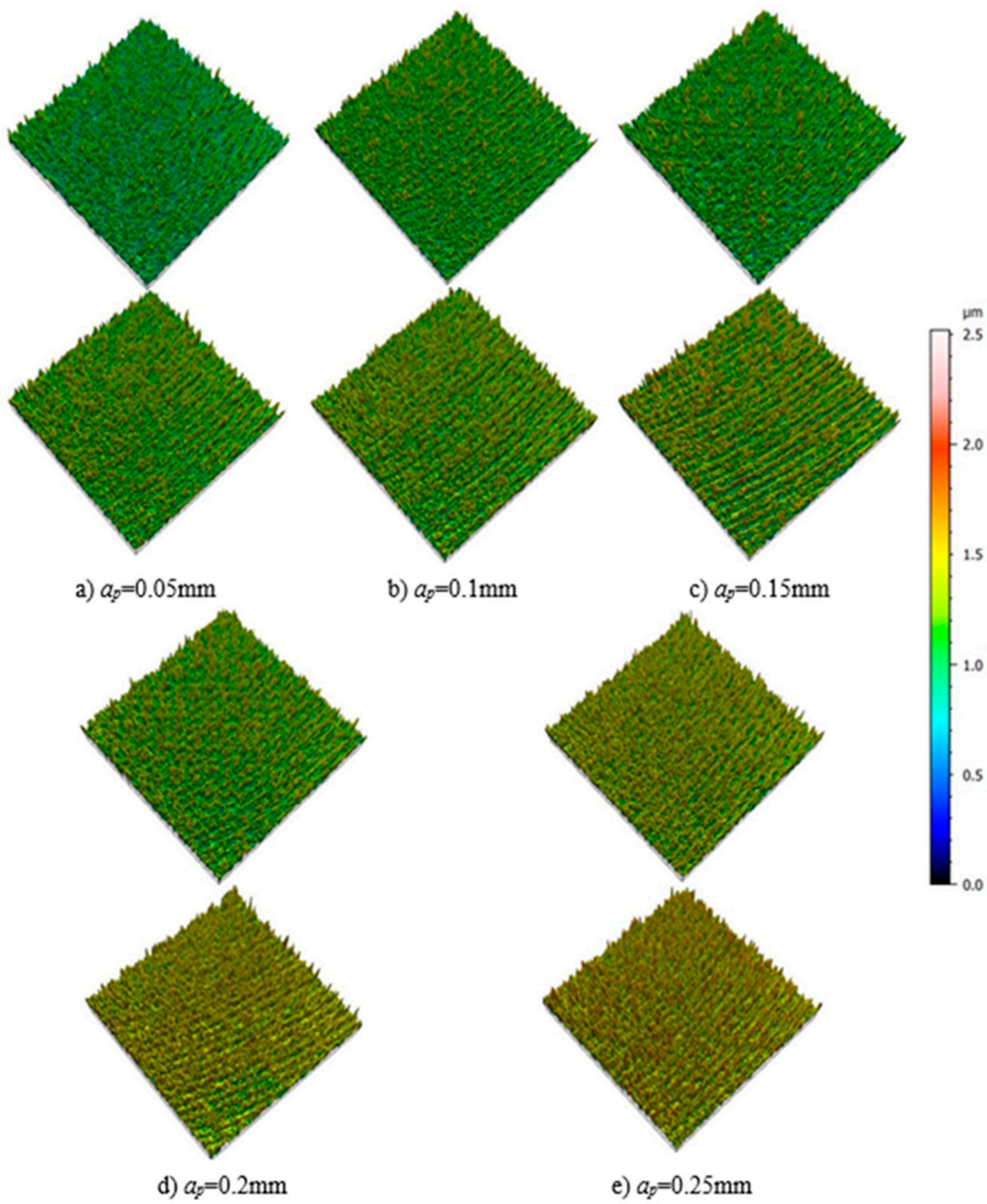

Figure 11. Comparison of surface topography of $SCCO_2$-MQL combined with ultrasonic vibration (**top**) and dry cutting condition (**bottom**) with cutting depth (v_c = 80 m/min, f = 0.06 mm/r).

5. Study on Work Hardening of SiCp/Al Composites via $SCCO_2$-MQL Ultrasonic Vibration Milling

5.1. Work Hardening Experiment Planning

5.1.1. Experimental Planning

Firstly, experimental parameters were selected under five different machining conditions (dry cutting conditions, $SCCO_2$, $SCCO_2$-MQL, ultrasonic vibration, $SCCO_2$-MQL combined with ultrasonic vibration): the feed rate f was 0.06 (mm/z), the milling width a_e was 8 (mm), and the milling depth a_p was 0.15 (mm) for the experiments. The work hardening of the machined surface was then tested after machining. Subsequently, experiments were conducted with milling speed (v_c), feed rate (f), and milling depth (a_p) as variables, while other parameters were held constant to determine the effect of cutting parameters on work hardening under different machining conditions. This explores the specific improvement effects of $SCCO_2$-MQL combined with ultrasonic vibration conditions on the workpiece work hardening during machining. Table 3 lists the experimental parameters.

Table 3. The single-factor contrast test.

Factor	Experimental Parameters	Experimental Environment
Milling speed v_c (m/min)	40, 60, 80, 100, 120	Dry cutting conditions
Feed rate f (mm/r)	0.04, 0.06, 0.08, 0.1, 0.12	$SCCO_2$-MQL combined with
Axial cutting depth a_p (mm)	0.2, 0.4, 0.6, 0.8, 1	ultrasonic vibration

5.1.2. Measurement Method

After the completion of the milling experiment, the workpiece milling experiment area was divided into 6 mm × 8 mm × 10 mm samples through wire cutting. A DHV-1000 digital microhardness tester was used to perform indentation detection experiments for work hardening of samples, as shown in Figure 12. Since a large number of SiC particles are dispersed in the material, if the surface of the wire-cut specimen is ground and polished, the plastic phase will be removed, resulting in the exposure of the reinforced phase particles and an overall high measurement value [25]. Therefore, we chose to directly measure the microhardness of the wire-cut specimen.

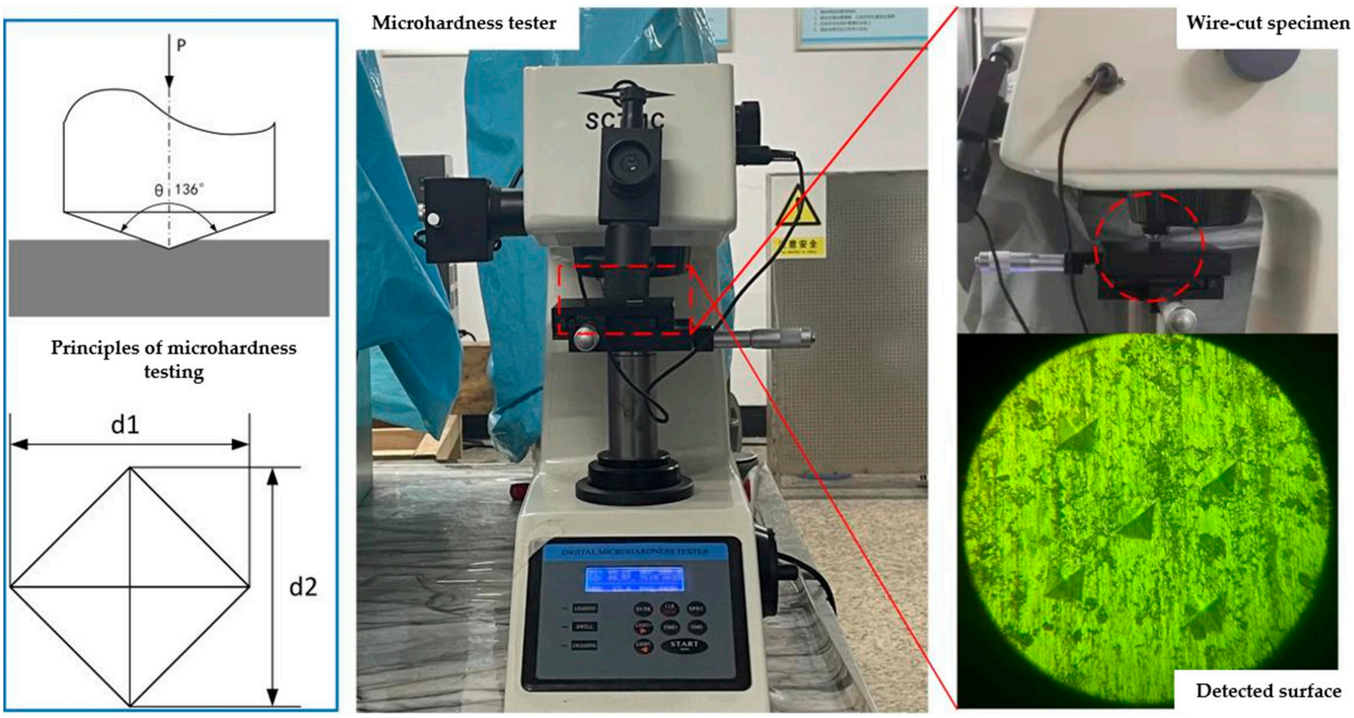

Figure 12. Microhardness test.

5.2. Influence of Process Conditions and Processing Parameters on Work Hardening

5.2.1. Influence of Different Process Conditions on Work Hardening of SiCp/Al Composites in Milling

Figure 13 shows the microhardness curves under different process conditions. The comparative analysis of the experimental results indicates that as the milling speed (v_c) increases, the microhardness *HV* generally shows a trend of first increasing and then decreasing.

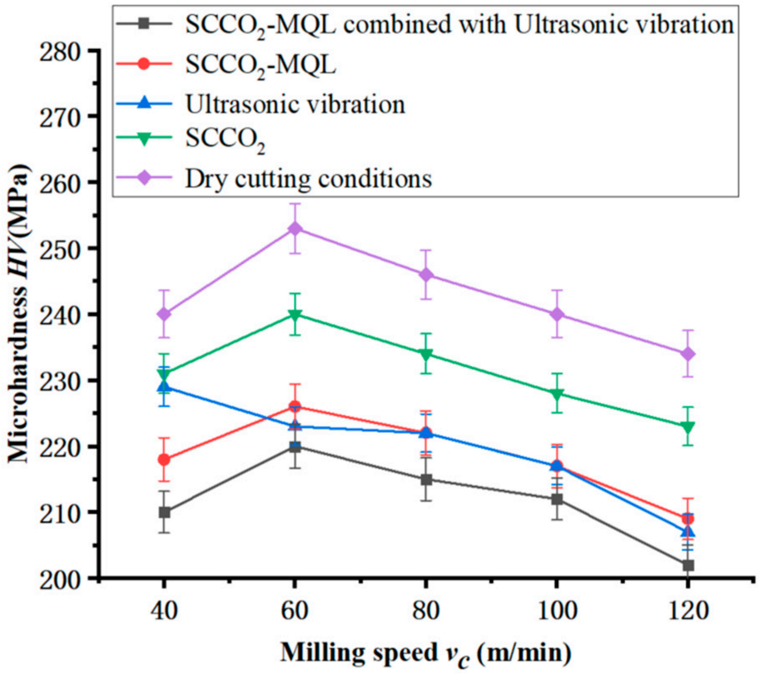

Figure 13. Microhardness curves under different lubrication conditions.

Work hardening is the result of plastic deformation of the surface layer of the workpiece and the joint action of cutting heat. Because the tool is not sharp, after the tool surface produces a certain extrusion of the machined surface, the machined surface metal will produce a certain elastoplastic deformation under the joint action of cutting heat. In the process of grain refinement, hardness is improved to a certain extent [26]. Under the conditions of standalone CO_2 cooling and dry cutting, the degree of hardening is relatively high. This is primarily because standalone cooling effectively reduces the cutting temperature, preventing softening of the workpiece during the milling process. In the case of dry cutting conditions, the intense squeezing, friction, and plastic deformation during the cutting process leads to a higher degree of work hardening.

Therefore, under the condition of $SCCO_2$-MQL composite ultrasonic vibration, the cutting force and friction are reduced, the damage to the surface structure of the processed material is small, and the dislocation deformation of the grains is small. This leads to a minimum degree of work hardening.

5.2.2. Influence of Milling Speed on Work Hardening of SiCp/Al Composites

Figure 14 presents the comparison curves of microhardness *HV* of SiCp/Al composite material machined under dry cutting conditions and $SCCO_2$-MQL combined with ultrasonic vibration conditions as a function of different milling speeds (v_c). The graph shows that as the milling speed (v_c) increases from 40 m/min to 60 m/min, the microhardness of the material under both processing conditions increases. However, as the milling speed continues to increase to 120 m/min, the microhardness consistently decreases.

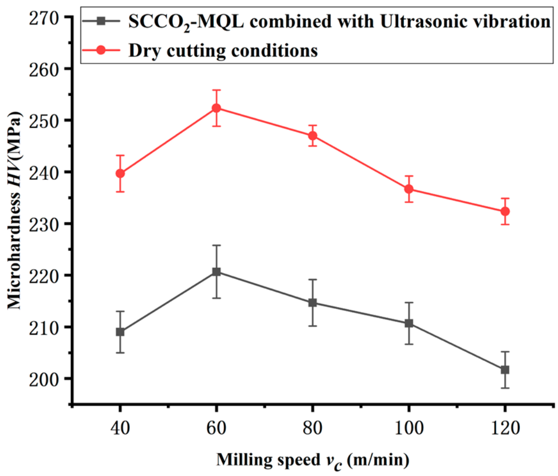

Figure 14. The variation curve of microhardness values with milling speed.

The microhardness of the material under SCCO$_2$-MQL combined with ultrasonic vibration is significantly lower than that under dry cutting conditions, which is mainly affected by the difference in cutting force, cutting temperature, and friction during cutting. With the increase in milling speed, the cutting force increases. The surface grain dislocation and entanglement are serious, which makes the microhardness increase to a certain extent, but with the continuous improvement in the milling speed, the cutting temperature increases, which has a softening effect on the material surface, especially the aluminum matrix. In addition, the continuous increase in the milling speed makes the tool contact time shorter and shorter, and the plastic deformation decreases. Therefore, the microhardness gradually decreases when the milling speed is greater than 60 m/min.

5.2.3. Influence of Feed Rate on Work Hardening of SiCp/Al Composites in Milling

Figure 15 is the plotted comparison curves of microhardness *HV* of SiCp/Al composite material machined under dry cutting conditions and SCCO$_2$-MQL combined with ultrasonic vibration conditions as a function of different feed rates (f). The microhardness under both conditions tends to increase with an increase in feed rate. The primary factor is the increase in plastic deformation; as the feed rate increases, the material removal rate continuously improves, resulting in severe plastic deformation on the surface layer of the material, and thus, the work hardening becomes progressively more severe.

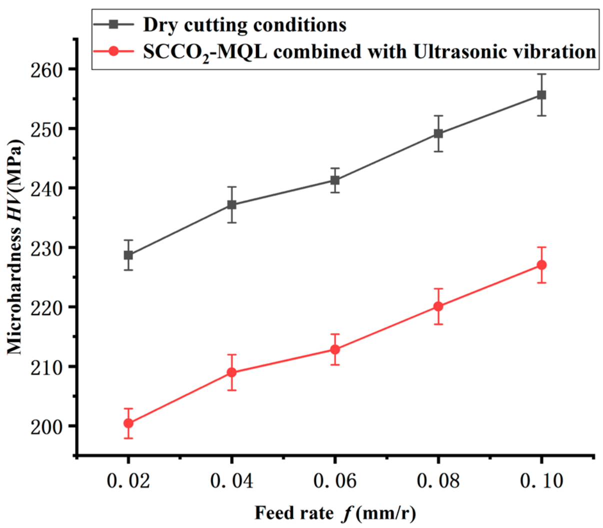

Figure 15. The variation curve of microhardness values with feed.

5.2.4. Influence of Milling Depth on Work Hardening of SiCp/Al Composites

Figure 16 represents the comparison curves of the microhardness *HV* of SiCp/Al composite material machined under dry cutting conditions and $SCCO_2$-MQL combined with ultrasonic vibration conditions for varying milling depths (a_p). Under both conditions, the microhardness consistently increases as the milling depth increases. The effect of milling depth is significant, and the work hardening becomes more severe with an increase in the milling depth. This is because the greater the milling depth, the more serious the tool wear. As a result, there is increased fracturing and reorganization of the grains on the material surface, as well as more severe dislocation, which contributes to the continuous increase in microhardness.

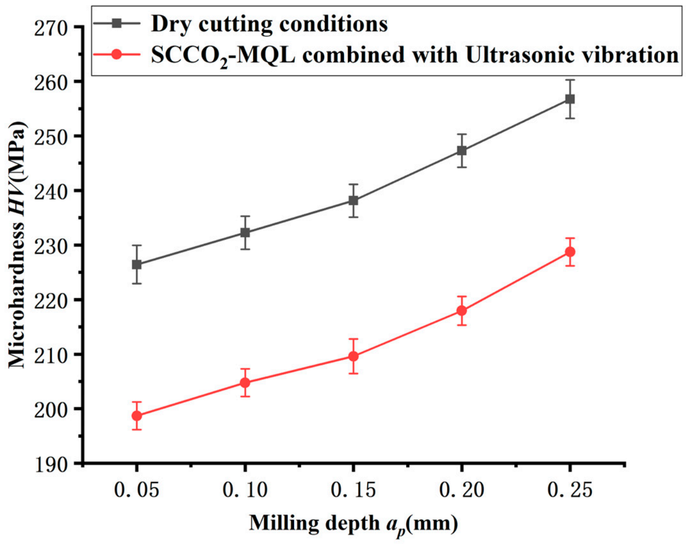

Figure 16. The variation curve of microhardness values with milling depth.

6. Conclusions

Firstly, under the condition of dry cutting and $SCCO_2$-MQL ultrasonic vibration, when the milling speed v_c increases from 40 m/min to 120 m/min, the surface roughness increases first and then decreases, and the minimum surface roughness reaches 0.081µm at 120 m/min. When the feed f is 0.02~0.1 mm/r or the cutting depth a_p is 0.05~0.25 mm, the surface roughness increases continuously, and it has a great influence on the surface roughness. In addition, from the microscopic morphology, the cooling, lubrication, and chip removal effects of $SCCO_2$-MQL ultrasonic vibration are remarkable, which can inhibit the generation of surface defects such as holes, pits, scratches, and cracks. Secondly, the experimental analysis shows that the inhibition of $SCCO_2$-MQL ultrasonic vibration on work hardening is the best under all processing conditions. The overall work hardening degree of $SCCO_2$-MQL under ultrasonic vibration is 125.9%, while the hardening degrees under the $SCCO_2$-MQL, ultrasonic vibration, $SCCO_2$, and dry cutting conditions are 129.4%, 130.2%, 136.9%, and 143.7%, respectively. In this study, it was found through milling experiments that compared with other processing conditions, $SCCO_2$-MQL ultrasonic vibration conditions have better improvements to the reduction in surface roughness of the processed material, the improvement in surface morphology, and the suppression of material work hardening.

Microhardness can reflect the hardness and strength changes of the material, and the surface roughness affects the appearance and function of the workpiece. When selecting the best milling scheme, the changes in surface roughness and microhardness should be considered comprehensively to ensure the quality and performance of the workpiece while improving the machining efficiency. This comprehensive analysis method will help us to develop more effective processing strategies to meet the needs of different application scenarios and provide a useful reference for further research and optimization of composite material processing.

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References

1. Ouyang, L.; Luo, C. Application and Progress of Composite Materials. *Automot. Technol. Mater.* **2000**, 28–31.
2. Tang, S. Preparation and Properties of SiCp/Al Composites. *Mech. Des. Manuf. Eng.* **2019**, *48*, 110–113.
3. Liu, J.; Cheng, K.; Ding, H.; Chen, S.; Zhao, L. An Investigation of Surface Defect Formation in Micro Milling the 45% SiCp/Al Composite. *Procedia CIRP* **2016**, *45*, 211–214. [CrossRef]
4. Li, M.; Wang, A.; Xie, Z.; Sun, Y.; Zhang, H. Research status and progress of SiC particle reinforced Al matrix composites. *Powder Metall. Ind.* **2015**, *25*, 55–60. [CrossRef]
5. Yu, H.; Zhou, X.; Zhang, C.; Cao, Y.; Liu, R.; Zhang, Y. Research progress of SiC mirror and its preparation technology. *New Technol. Technol.* **2006**, *5*, 26–30. [CrossRef]
6. Zhou, Y.; Zhang, D.; Wang, W.; Li, L. Research status and Aerospace application of silicon carbide particle reinforced aluminum matrix composites by selective laser melting forming. *Aeronaut. Manuf. Technol.* **2018**, *61*, 68–73. [CrossRef]
7. Zhang, Q.; Jiang, L.; Wu, G. Microstructure and thermo-physical properties of a SiC/pure-Al composite for electronic packaging. *J. Mater. Sci. Mater. Electron.* **2014**, *25*, 604–608. [CrossRef]
8. Wang, T.; Xie, L.; Wang, X.; Jiao, L.; Shen, J.; Xu, H.; Nie, F. Surface Integrity of High Speed Milling of Al/SiC/65p Aluminum Matrix Composites. *Procedia CIRP* **2013**, *8*, 475–480. [CrossRef]
9. Wang, T.; Xie, L.; Wang, X.; Ding, Z. PCD tool performance in high-speed milling of high volume fraction SiCp/Al composites. *Int. J. Adv. Manuf. Technol.* **2015**, *78*, 1445–1453. [CrossRef]
10. Guo, S.; Li, C.; Zhang, Y.; Yang, M.; Jia, D.; Zhang, X.; Liu, G.; Li, R.; Bing, Z.; Ji, H. Analysis of volume ratio of castor/soybean oil mixture on minimum quantity lubrication grinding performance and microstructure evaluation by fractal dimension. *Ind. Crop. Prod.* **2018**, *111*, 494–505. [CrossRef]
11. Pradhan, S.; Singh, G.; Bhagi, L.K. Study on surface roughness in machining of Al/SiCp metal matrix composite using desirability function analysis approach. *Mater. Today Proc.* **2018**, *5*, 28108–28116. [CrossRef]
12. Wang, X. Research on SiCp/AL Milling Mechanism and Surface Quality under Ultrasonic Excitation. Ph.D. Thesis, North University of China, Taiyuan, China, 2018.
13. Li, M. Study on Surface Quality of SiCp/Al Composites by High Speed Milling. Master's Thesis, Harbin Institute of Technology, Heilongjiang, China, 2020; pp. 39–46. [CrossRef]
14. Muthukrishnan, N.; Murugan, M.; Rao, K.P. Machinability issues in turning of Al-SiC (10p) metal matrix composites. *Int. J. Adv. Manuf. Technol.* **2008**, *39*, 211–218. [CrossRef]
15. Zhang, X.; Zhou, H.; Zhou, B.; Wang, R.; Han, H.; Jiang, X.; Li, M. Surface Morphology and Kerf Quality During Fiber Laser Cutting of High Volume Fraction SiC Particles-Reinforced Aluminum Matrix Composites. *J. Mater. Eng. Perform.* **2022**, *32*, 5906–5918. [CrossRef]
16. Zhang, P.; Yue, X.; Zhang, Q.; Zong, C.; Lu, W.; Fang, Y. Investigation on the influence of SiC particle parameters on the machinability of SiCp/Al composite. *Vacuum* **2021**, *191*, 110340. [CrossRef]
17. Zheng, W.; Zhou, M.; Zhou, L. Influence of process parameters on surface topography in ultrasonic vibration-assisted end grinding of SiCp/Al composites. *Int. J. Adv. Manuf. Technol.* **2017**, *91*, 2347–2358. [CrossRef]
18. Shi, R. Study on Surface Characteristics of SiCp/Al Composites Processed by Low-Temperature Micro-Lubrication and High-Speed Milling. Master's Thesis, Harbin University of Science and Technology, Heilongjiang, China, 2020; pp. 35–39. [CrossRef]
19. Cai, C.; Liang, X.; An, Q.; Tao, Z.; Ming, W.; Chen, M. Cooling/Lubrication Performance of Dry and Supercritical CO_2-Based Minimum Quantity Lubrication in Peripheral Milling Ti-6Al-4V. *Int. J. Precis. Eng. Manuf. Technol.* **2021**, *8*, 405–421. [CrossRef]
20. Duan, C.; Che, M.; Sun, W.; Wei, B.; Liu, Y. Effect of Different cooling and lubrication Methods on Tool wear in Cutting SiC_P/Al Composites. *J. Compos. Mater.* **2019**, *4*, 1244–1253. [CrossRef]
21. Quan, Y.; Ye, B. The effect of machining on the surface properties of SiC/Al composites. *J. Mater. Process. Technol.* **2003**, *138*, 464–467. [CrossRef]
22. Wang, T.; Xie, L.; Wang, X. Simulation study on defect formation mechanism of the machined surface in milling of high volume fraction SiCp/Al composite. *Int. J. Adv. Manuf. Technol.* **2015**, *79*, 1185–1194. [CrossRef]

23. Niu, Q.; Gao, H.; Zhang, S. Experimental Study on Surface quality and Chip Morphology of SiCp/Al Composites by Ultrasonic vibration assisted milling. *Tool Technol.* **2012**, *56*, 12–17.
24. Tang, L. Study on the Surface Quality and Tool Wear of SiCp/Al Composites for Milling. Master's Thesis, Hunan University of Science and Technology, Xiangtan, China, 2017; pp. 35–41.
25. Wang, X. Research on Simulation Method and Surface Integrity of Aluminum Based Silicon Carbide Micro-Cutting. Master's Thesis, Changchun Institute of Science and Technology University, Changchun, China, 2019; pp. 34–35.
26. Fang, Y.; Wang, Y.; Zhang, P. Study on Removal Mechanism and Surface Quality of SiCp/Al Composites by high-speed cutting. *Ploidy Surf. Technol.* **2022**, *51*, 293–300.