

Article

Surface Quality of High-Concentration SiC/Al Grinding with Electroassisted Biolubricant MQL

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Abstract: SiC/Al composites are widely used in aerospace and other fields due to their excellent mechanical properties. For large-concentration composites, due to the extremely high proportion of SiC and the unstable interface between the two phases, the SiC particles are broken and detached during the processing, which makes the surface quality of the workpiece insufficient to meet the service requirements. Electrically assisted cutting technology is expected to break through this technical bottleneck. This paper investigates the surface quality of high-concentration SiC/Al grinding with electroassisted biolubricant MQL. The surface morphology after processing is observed. Firstly, by comparing the traditional grinding and electrically assisted grinding conditions, it is found that the fundamental reason for the improvement in the grinding surface quality using a pulse current is the improvement in the Al plasticity. Secondly, based on the thermal effect and non-thermal effect of the pulse current, the influence of the electrical parameters (current, duty cycle and frequency) on the machining indication quality is discussed. It is found that when the current and duty cycle increase, the machining surface quality will also increase, while the frequency change has little effect on the surface quality. Finally, friction and wear experiments are carried out on the grinding surface under different working conditions to explore the friction and wear characteristics of the surface of the workpiece. The results show that the pulse current can significantly improve the wear resistance of the grinding surface.

Keywords: pulse current; grinding process; SiC/Al composites; biolubricant MQL



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1. Introduction

SiC/Al composite materials find wide application in aerospace, deep-sea engineering, electronic packaging, automotives, and other industries due to their excellent characteristics, including high hardness, stiffness, wear resistance, and thermal conductivity [1–3]. SiC, known for its hardness and brittleness, exhibits strong abrasiveness, while Al alloy, a ductile material, is susceptible to external strains. These materials have distinct material removal mechanisms [1,4]. SiC is prone to surface damage, cracks, and defects during processing due to its hard and brittle nature, while Al tends to form built-up edges that can compromise the surface quality due to its higher toughness [5–7]. Particle debonding and fragmentation can occur in SiC/Al processing, leading to the formation of pits and grooves on the workpiece surface, significantly affecting its performance and service behavior [2]. The volumetric ratio of SiC to Al in composites affects their machinability, with higher SiC volume fractions resulting in increased surface roughness and a higher likelihood of brittle removal during machining, leading to more pits and grooves. The depth and

width of these grooves also increase significantly, posing risks of workpiece fracture and safety hazards [8,9]. Therefore, a new cutting approach is urgently needed to enable the low-damage machining of high-volume SiC/Al composites. Since Machlin's discovery of the influence of the current on material deformation, extensive research has been conducted on this phenomenon, termed the electric–plastic effect, which describes the impact of the current on material plasticity [10]. Scholars have investigated the application of the electric–plastic effect in various cold deformation processes, such as tension, drawing, and rolling, focusing on materials like magnesium alloys, aluminum alloys, and Al_{0.6}CoCrFeNiMn high-entropy alloys. The findings have shown that the pulse current can significantly enhance the material plasticity, formability, and elongation and reduce material flow stress [11–15]. Moreover, researchers have introduced a pulse current during heat treatment processes for materials such as 20CrMnTiH, Ti–6Al–4V, and Cu–15Ni–8Sn, revealing that the pulse current can effectively improve the elongation, tensile strength, fatigue life, and corrosion resistance [16–19]. Initially, researchers believed that the reduction in material deformation resistance caused by the pulse current was mainly due to Joule heating [20]. Comparative tensile experiments conducted by Goldman et al. on superconducting lead crystals at 4.2 K with an electrical current supported this view and attributed the influence of the electric–plastic effect to Joule heating [21]. Additionally, Magargee et al. [22] conducted electric-assisted tensile experiments on commercially pure titanium, focusing solely on the thermal effect, and established an electroplasticity model. However, some researchers have argued that the electric–plastic effect resulting from the pulse current involves not only thermal effects but also non-thermal effects. Scholars have decoupled the influence of Joule heat on the electrically assisted machining process during an electrically assisted tensile test and found that there are not only thermal effects but also non-thermal effects involved in the electroplastic effect [23,24]. Subsequently, extensive investigations into the non-thermal effects, including the electron wind effect, dislocation depinning, and magneto-plastic effects, were conducted [25–28]. However, a unified theoretical understanding of the specific application of the electric–plastic effect has not yet been achieved [29].

The current research has extensively explored the application of electric-assisted cold deformation processes, aiming to utilize electroplasticity concepts in the field of cutting processing. However, there are differences between cutting and cold deformation processes. Cold deformation involves material flow and deformation, while cutting includes material fracture and removal, resulting in higher forces and heat generation [30–32]. Turning and drilling experiments have been conducted on materials such as SAE1020 steel, 7075 aluminum alloy, and 1045 carbon steel. The results have shown that the application of a pulse current reduces the cutting forces and increases the cutting speed [33,34]. The electron wind effect and Joule heating effect are believed to be the underlying causes of these phenomena. Similar experiments on materials like SAE1020 steel and TC27 have demonstrated that the pulse current not only reduces the cutting forces but also improves the surface quality and reduces tool wear [35–37]. The decrease in cutting forces indicates the presence of the electric–plastic effect during the machining process. Additionally, the presence of cracks during machining increases the resistance in the crack region, leading to increased Joule heating in this area [38,39]. Thermal expansion, in turn, reduces the compressive stress and decreases the likelihood of crack formation [40]. Most of the current research focuses on conventional materials. However, brittle materials possess characteristics such as easy fracturing, a limited electric–plastic effect, high electrical resistance, or non-conductivity, which limit the significant effects of the electric–plastic effect during their machining processes [41]. Therefore, the application of the electroplastic effect in the processing of brittle materials is limited, and there is no research value in this field. The electroplastic effect in composite materials composed of brittle and ductile phases has certain research value. The current research shows limited consideration of the electroplastic effect in composites, especially in high-concentration ceramic composites. Most of the research on ceramic composites has focused on the grinding process, which involves harsh conditions such as high pressure, high temperatures, and high speeds, resulting in a large number

of processing defects. Therefore, there is no report on the application of electro-assisted machining in the high-concentration ceramic composite grinding process [42–44]. In the process of electrical machining, the current through the workpiece will produce very high heat. In addition, the grinding process itself has the characteristics of a high speed and high heat, so it is necessary to adopt appropriate lubrication methods [45]. Traditional water-based lubrication methods, such as pouring lubrication, will lead to safety hazards such as short circuits during processing, so they cannot be used. Vegetable oil is commonly used in micro-lubrication methods because of its advantages of renewability, low toxicity, and easy degradation [46–48]. Because of its certain insulation characteristics, the addition of an insulating medium in the grinding process can avoid short circuits and other conditions and can show better lubrication and cooling effects. Based on the aforementioned objective realities, this study aims to investigate the surface quality of high-concentration SiC/Al composite materials using electric-assisted grinding.

2. Experimental Scheme

2.1. Experimental Materials

SiC/Al composites with a SiC volume fraction of 70% were selected as the research objects. High-concentration SiC/Al composites exhibit high brittleness, making them prone to brittle removal during the machining process. The physical properties of the SiC/Al composites are presented in Table 1. The composite material was prepared into experimental specimens measuring 45 mm × 10 mm × 10 mm.

Table 1. Physical properties of experimental materials.

Material	Component	Density (g/cm ³)	Thermal Expansion Coefficient (10 ^{−6} /K)	Thermal Conductivity W/(m·K)
SiC/Al	Al + 70%SiC	2.9–3.3	6.5–9.5	180–240

Because synthetic lipids have the characteristics of a high biodegradation rate, a negligible threat to human beings, and no pollution to the environment, they follow the principle of green environmental protection. Therefore, during the experiment, KS-1040 synthetic grease was used as a cutting fluid to lubricate the grinding process. The physical properties of the cutting fluid are shown in Table 2.

Table 2. Physical properties of cutting fluid.

Fluid	Kinematic Viscosity @40 °C (mm ² /s)	Open Cup Flash Point (°C)	Pour Point (°C)	Density @20 °C (g/cm ³)
KS-1040 synthetic grease	68	198	−15	0.835

2.2. Experimental Device

Traditional grinding was set as the control condition in the experiment, and the machining performance of electric-assisted grinding was compared and studied. To further investigate the influence law of the pulse current size, duty ratio, and frequency on the surface quality of the grinding process, we designed 9 groups of single-factor experiments. The specific parameter settings are presented in Table 3. During the experiment, firstly, comparative experiments were conducted under various working conditions to elucidate the mechanism of the pulse current in the grinding process of high-concentration SiC/Al composites. Secondly, grinding experiments were performed under different electrical parameter conditions, and surface roughness and morphology measurements were taken to further examine the influence of the electrical parameters on the surface quality. Lastly, considering the non-uniformity of high-concentration SiC/Al composites, the frictional wear mechanism of the newly generated surface during electric-assisted grinding was analyzed, and the characteristics of the frictional wear on the machined surface were investigated.

Table 3. Experimental parameter settings.

Serial Number	Pulse Current Size (A)	Frequency (Hz)	Duty Ratio (%)
Control group	0	0	0
1	250	200	50
	500	200	50
	750	200	50
	500	200	25
2	500	200	50
	500	200	75
	500	100	50
	500	200	50
3	500	400	50

The processing and testing equipment used in the experiment is shown in Figure 1. The DC pulse power supply, as depicted in Figure 1a, was capable of output square wave pulses ranging from 0 to 1000 A, with an adjustable duty ratio of 0–100%. The grinding of the workpiece was performed by a plane grinding machine, as shown in Figure 1b. A resin-bonded CBN grinding wheel with a diameter of 180 mm, width of 13 mm, and grit size of 120# was employed. The specific grinding parameters were as follows: wheel speed of 30 m/s, grinding depth of 10 μm , and feed rate of 1 m/min. An pneumatic micro-lubrication device, depicted in Figure 1c, was utilized during the experiment, with KS-1040 synthetic grease serving as the coolant. The flow rate was 60 mL/hour. The friction and wear testing machine, shown in Figure 1d, employed a GCr15 ball with a diameter of $\Phi = 9.525$ mm to implement a single case of reciprocating friction on the machined surface. The friction time was 15 min, with an applied load of 5 N and a linear speed of 2 mm/s. The machined surface was observed using an OLS5000 confocal laser scanning microscope (CLSM) (Japan) and a Sigma300 field emission scanning electron microscope (SEM) (Sigma, Taufkirchen, Germany), represented in Figure 1e,f, respectively. To ensure an effective power supply to the workpiece, the experiment used two copper plates to connect the workpiece and the power supply, as illustrated in Figure 1g.

In consideration of the large transient current passing through the workpiece during electro-assisted grinding, which can potentially have a significant impact on the machining equipment, insulation treatment was implemented between the grinding wheel and the machine tool, as well as between the workpiece and the machine tool. In this experiment, a nylon material was used for the chuck of the grinding machine, and a silicone rubber sheet was employed for insulation at the connection between the worktable and the machine tool. Ceramic fixtures were utilized for clamping. Once the pulse current stabilized at the set value, the grinding experiment commenced.



Figure 1. Laboratory equipment. (a) Pulsed power supply, (b) grinder, (c) minimal quantity lubrication device, (d) friction and wear tester, (e) OLS5000 confocal laser scanning microscope (Japan), (f) Sigma300 field emission scanning electron microscope, (Sigma, Taufkirchen, Germany), (g) power-up method.

3. Results and Discussion

The main objective of this study was to investigate the influence of the pulse current parameters on the surface quality of SiC/Al composites during grinding. Firstly, a comparative experiment between conventional grinding and electro-assisted grinding was conducted to validate the effectiveness of the pulse current in improving the surface quality. Secondly, a single-factor experiment on the pulse current, frequency, and duty ratio was carried out. Through roughness and microscopic morphology analyses, the impact of these electrical parameters on the surface quality of the grinding process was determined. Finally,

friction and wear experiments were carried out on the grinding surface to analyze the wear resistance of the new surface.

3.1. Grinding

3.1.1. Comparative Experiment

First, a comparative experiment was conducted between conventional grinding and electro-assisted grinding. The conventional grinding experiment served as the control, while electro-assisted grinding was performed under the condition of a pulse current magnitude of 500 A, frequency of 200 Hz, and duty ratio of 50%. The experimental results of both methods were compared and analyzed to evaluate the influence of applying a pulse current on the surface quality of grinding. Under the two working conditions, five surface roughness values (S_a) on the grinding surface were measured, and the average surface roughness value was calculated, as shown in Figure 2. The average surface roughness values for conventional grinding and electro-assisted grinding were $1.416 \mu\text{m}$ and $1.053 \mu\text{m}$, respectively. It is evident that the application of a pulse current can significantly reduce the surface roughness of the workpiece, resulting in a 25.6% reduction compared to conventional grinding. The subsequent average surface roughness values were calculated using the same method. The reduction in the roughness of the machined surface reduces the friction and energy loss during frictional force and wear applications. At the same time, lower roughness can prevent the faster wear of the workpiece and improve its service life. In applications such as sealing, lower roughness can also improve the sealing performance and improve the reliability of the workpiece.

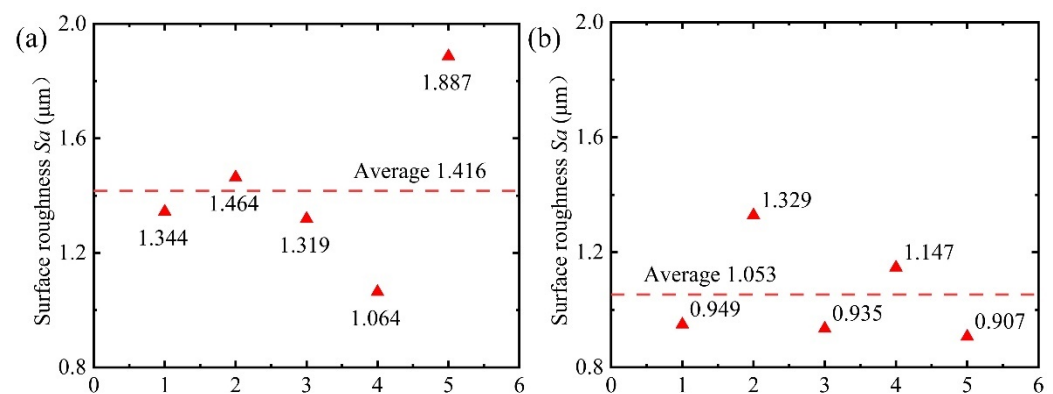


Figure 2. Grinding surface roughness of workpiece. (a) Conventional grinding surface, (b) electrically assisted grinding surface.

The surface microstructures under the two conditions, conventional grinding and electro-assisted grinding, are depicted in Figure 3. By comparing Figure 3a,c, it can be observed that after applying the pulse current, the proportion of Al on the machined surface increased, and the proportion of bare SiC particles decreased accordingly. The analysis suggests that the pulse current promotes dislocation movement, thereby enhancing the plasticity of the aluminum (Al). This phenomenon has been demonstrated in a study by Xiao et al. [49] within the context of electro-assisted cold deformation. The increased plasticity of Al leads to improved flowability during grinding, facilitating its spread and distribution on the workpiece surface. Consequently, there is a higher proportion of Al on the surface. Figure 3b illustrates the SEM microstructure of the conventional grinding surface, revealing the presence of long and continuous grooves. In contrast, Figure 3d shows the SEM microstructure of the electro-assisted grinding surface, where no similar grooves are observed. This clearly indicates that the application of a pulse current can effectively suppress the formation of surface grooves during grinding.

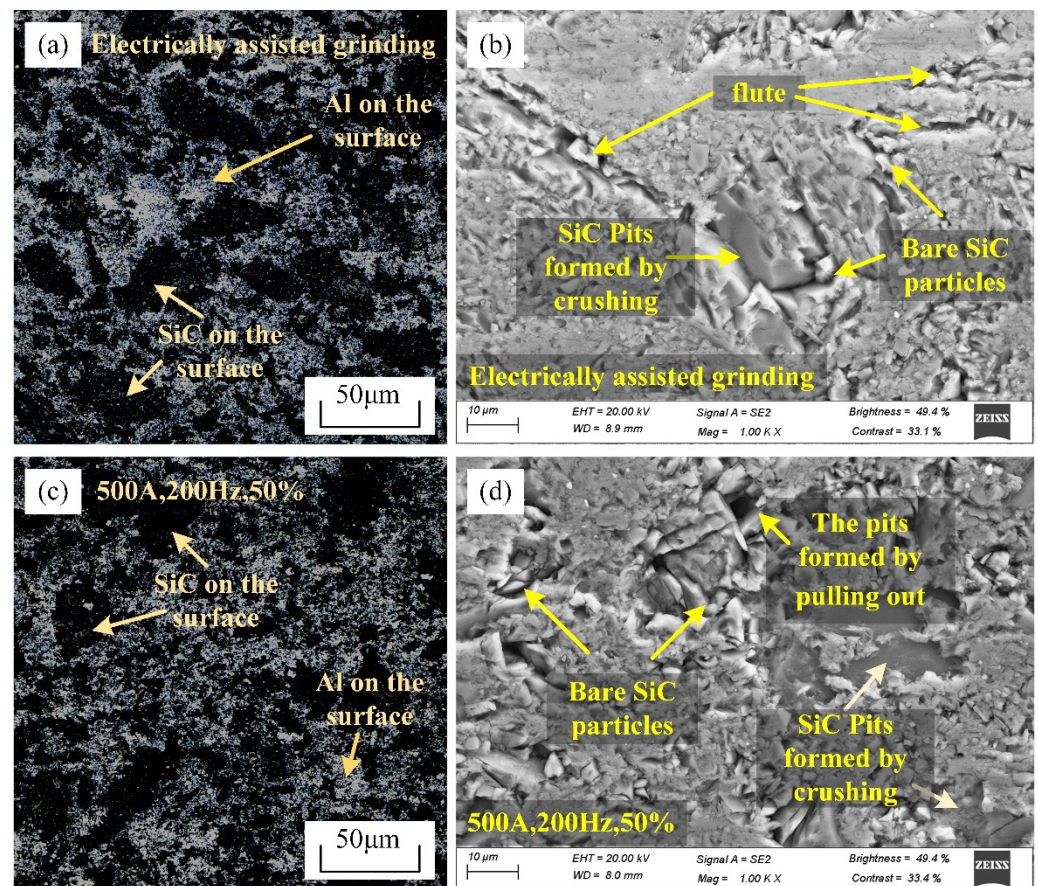


Figure 3. Grinding surface microstructure. (a,c) Surface CLSM images, (b,d) surface SEM images.

The analysis shows that, under the conditions of conventional grinding, SiC particles are prone to fracture and removal due to the grinding forces. As shown in Figure 4a, due to the low content of Al and its limited ability to expand and distribute on the surface, the broken SiC particles are not wrapped by the Al, so they are exposed on the machined surface. Consequently, these exposed SiC particles are susceptible to detachment under external forces, leading to the formation of localized grooves, as depicted in Figure 4b. Since the experimental material used is a high-concentration SiC/Al composite, the Al content between the SiC particles is relatively low, and continuous SiC particles may even appear, resulting in insufficient force buffering between the SiC particles under external forces. Moreover, due to the high cutting forces during grinding, continuous crushing occurs in one direction on the machined surface. At this point, the fragmented Al debris formed has difficulty in effectively filling the gaps, resulting in the groove microstructure shown in Figure 3b. Figure 4c displays the microstructure of the electro-assisted grinding surface. The introduction of an external electric field is observed to enhance the flowability of the aluminum (Al). As a result, the filling of the machined surface transitions from fragmented debris in conventional grinding to a flocculent filling pattern. This enhanced flowability enables the Al to penetrate small gaps, improves its ability to fill and heal grooves, and effectively prevents the formation of continuous pits. The flocculent Al filling in the pits provides robust cushioning against forces during the workpiece machining process, thereby reducing the occurrence of continuous SiC particle crushing. Moreover, the flocculent Al exhibits stronger adherence to SiC, preventing SiC detachment. Consequently, under the conditions of electro-assisted grinding, the likelihood of forming elongated grooves on the machined surface is significantly reduced.

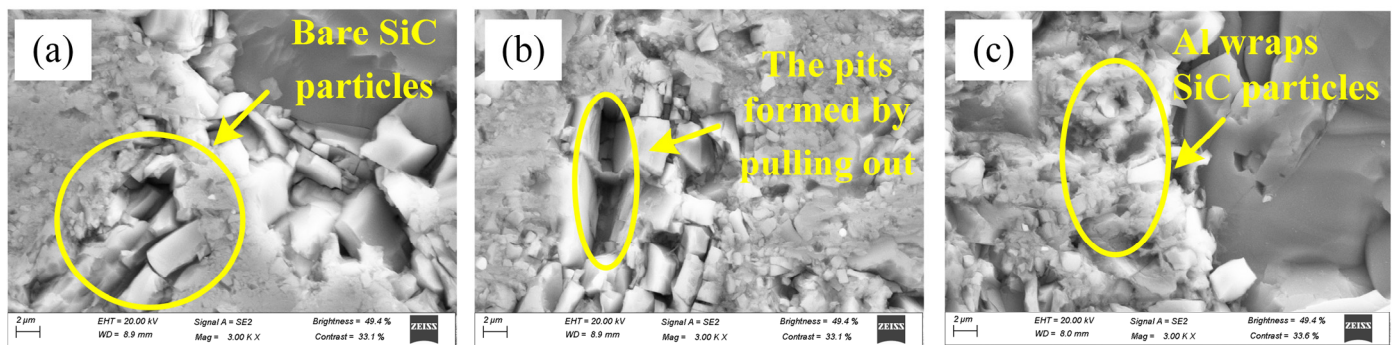


Figure 4. Grinding surface SEM microstructure. (a,b) Traditional grinding, (c) electrically assisted grinding.

In conclusion, the conventional grinding process results in a relatively low proportion of Al on the surface, as most of the Al is removed by the grinding wheel. Only fragmented Al debris remains, and its limited expansion ability under the external force makes it difficult to effectively fill the pits. Consequently, the grinding surface exhibits a large number of pits and grooves, leading to increased surface roughness. However, when a pulse current is applied, the proportion of Al on the workpiece surface increases, appearing in a flocculent form. In this state, Al demonstrates an improved spreading ability under external forces and enhanced adherence to the exposed SiC particles. As a result, it effectively prevents the formation of numerous pits and grooves on the surface, thereby reducing the surface roughness of the workpiece.

At the same time, due to the existence of grinding wheel pores, the difference in the protrusion height between different abrasive grains, and the micro-cracks of the abrasive grains themselves, it is possible to observe capillary microchannels in the grinding zone, as shown in Figure 5a [50]. After applying the pulse current, the surface of the workpiece always has a certain charge, and the liquid produces an electrowetting effect in the channel under the driving force of the capillary force [48]. As shown in Figure 5b, due to the electric double layer generated at the microchannel wall and the liquid interface, the charge on the microchannel wall generates an upward electrodynamic component for the polarized fluid, which drives the fluid to migrate to the gas phase side. Because the grinding zone is arc-shaped, the lubricant entering from the grinding zone laterally is difficult to lift longitudinally under conventional gas pressure, but the electrowetting effect provides additional power for the wetting of the lubricant in the vertical direction, so the effective wetting length of the micro-lubricant can be increased, thereby enhancing the lubrication capacity of the grinding zone [51,52]. In summary, it can be seen that the cutting fluid can more easily penetrate into the cutting space during the electrically assisted grinding process, resulting in a better lubrication effect and improving the surface quality after grinding.

3.1.2. Effect of Pulse Current on Grinding Surface

Experimental investigations were conducted with fixed grinding parameters in terms of the frequency (200 Hz) and duty ratio (50%) under different pulse currents (250 A, 500 A, 750 A). Figure 6 illustrates the influence of the pulse current on the surface roughness; the univariate function image $y = 1.3903 + (-0.0007088x)$ is obtained by fitting the data. The image shows that there is a significant negative correlation between the average surface roughness and the current amplitude. As the pulse current increased, the average surface roughness decreased, and the rate of decrease became more pronounced. Compared to conventional grinding, increasing the pulse current from 250 A to 750 A resulted in a 26% reduction in the average surface roughness. The minimum surface roughness value of 0.863 μm was achieved at a pulse current of 750 A.

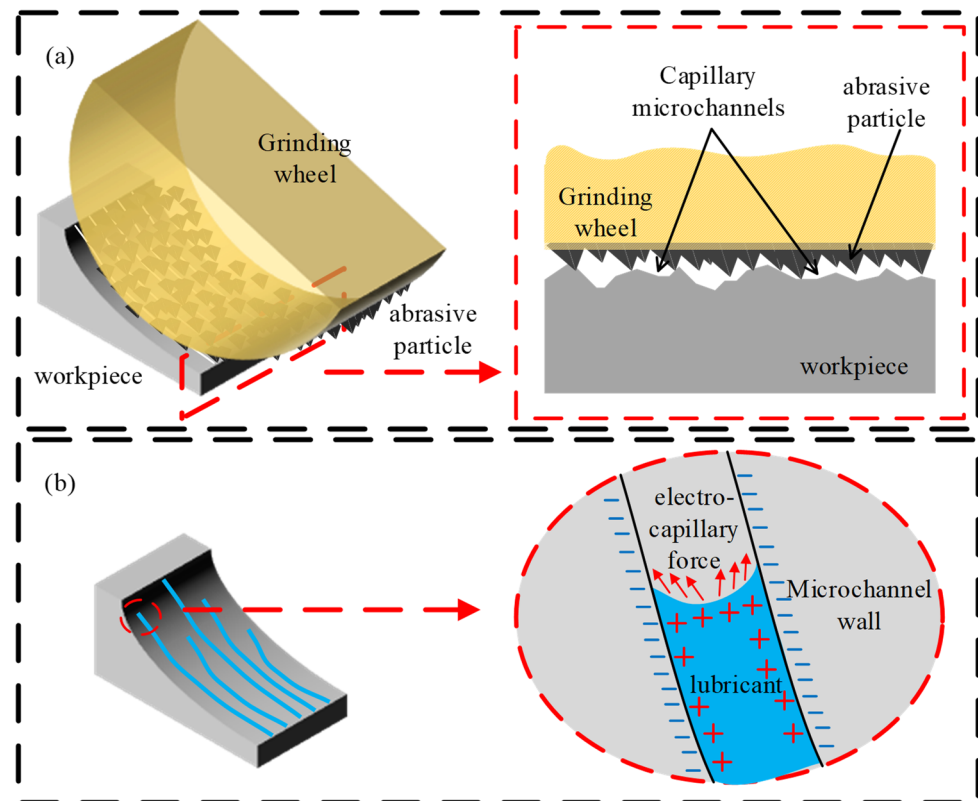


Figure 5. (a) Microchannel of grinding wheel workpiece interface, (b) electrowetting effect in microchannel of grinding zone.

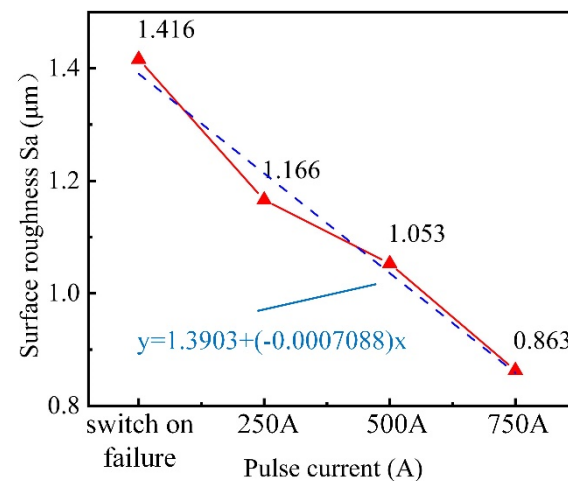


Figure 6. Effect of pulse current on surface roughness.

Figure 7 illustrates the microstructures of the workpiece surface under the operating conditions of 250 A, 500 A, and 750 A. As shown in Figure 7a,c,e, with the increasing pulse current, the proportion of Al on the workpiece surface gradually increases, while the exposed area of SiC correspondingly decreases. This is because, with the increase in the pulse current, the intensity of the thermal effect and non-thermal effect is enhanced, leading to the increased plasticity of the Al. As depicted in Figure 7b,d,f, with the increasing pulse current, the flocculent nature of the surface Al becomes more pronounced, the probability of the occurrence of grooves formed by continuous crushing is reduced, and the number of exposed SiC particles decreases continually. At the same time, the depth of the SiC particle crushing pits decreases, resulting in finer SiC particles on the workpiece surface. Figure 7b shows the SEM image of the grinding surface under the 250 A condition, where grooves

are still present but with a reduced length compared to conventional grinding. Figure 7d displays the SEM image of the grinding surface under the 500 A condition, where the grooves formed by continuous crushing are almost eliminated, and the fractured pits of multiple SiC particles exhibit a dispersed distribution with a reduced depth. Additionally, a small amount of flocculent Al fills the gaps between the SiC particles. Figure 7f presents the SEM image of the grinding surface under the 750 A condition, where Al is uniformly present in a flocculent form. The depth of the SiC particle crushing pit decreases, the SiC particle size on the surface is smaller, and the flocculent Al filling between the SiC particles increases.

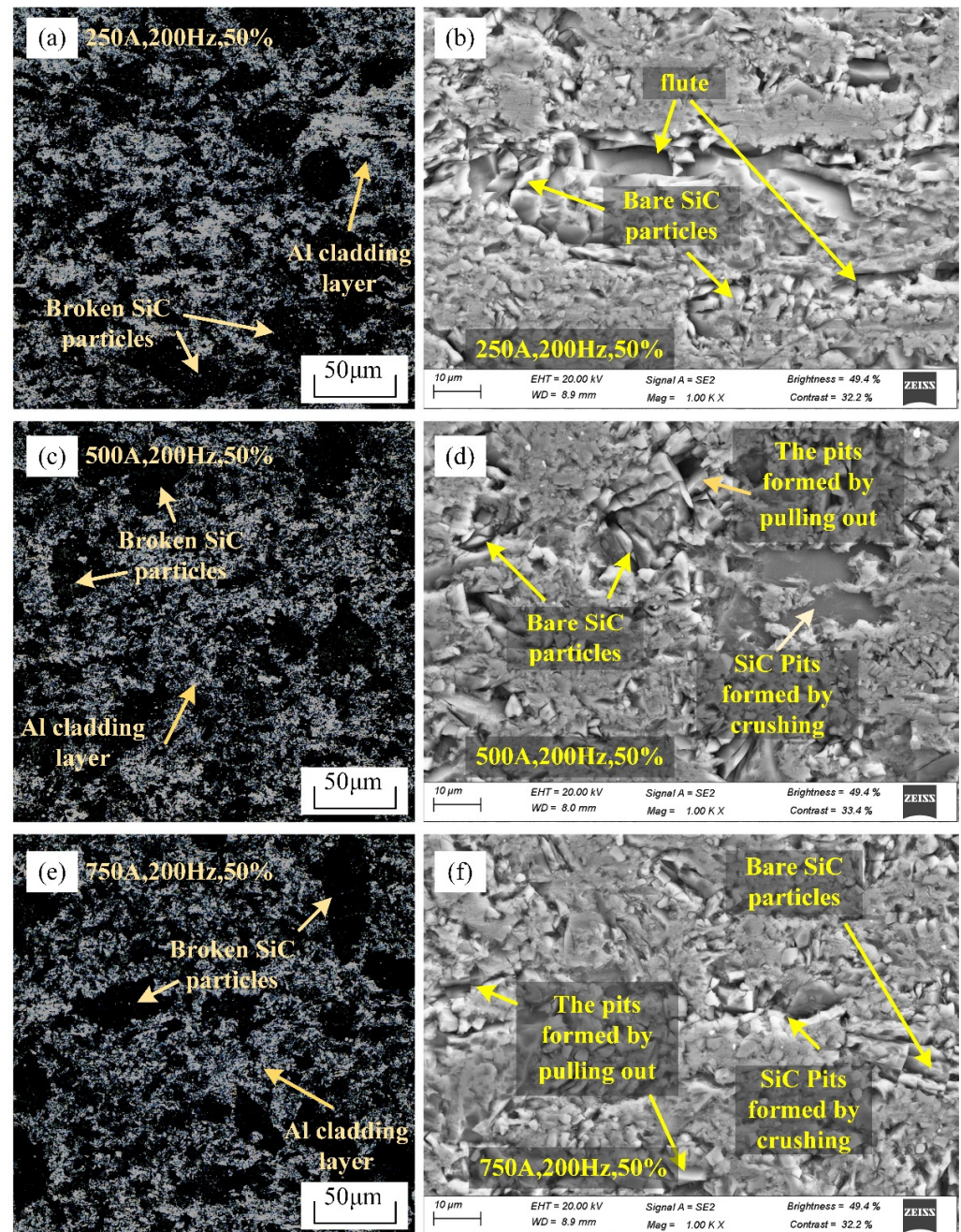


Figure 7. Effect of pulse current on surface morphology. (a,c,e) Grinding surface CLSM images, (b,d,f) grinding surface SEM images.

As the pulse current increases, the plasticity of aluminum (Al) gradually improves, leading to increased holding power on the silicon carbide (SiC) particles. This change in

holding power has a significant influence on the crushing behavior of the SiC particles. When the holding power is high, the cutting forces acting on the SiC particles strongly compete with the holding power of the matrix material, resulting in the easy crushing of the SiC particles into smaller fragments. Conversely, when the holding power is low, the competition between the cutting forces and holding power is relatively weak, and the SiC particles tend to fracture as a whole. Furthermore, the increased plasticity of Al enhances its flowability, enabling it to better penetrate into small gaps. Consequently, under the holding action of flocculent Al after crushing, the post-fracture SiC particles are less prone to debonding and the formation of pull-out pits. Only when the local concentration of SiC is high can the pull-out pits formed by the crushing of multiple closely adjacent SiC particles be retained. Figure 8 demonstrates that applying a pulse current to the workpiece results in the increased plasticity of Al, causing noticeable deformability in the SiC particles. During the machining process, Al experiences extrusion and an increased holding force due to the rotation and sinking of the external forces. This leads to a decrease in the interaction area between the abrasive grains and SiC particles, while the holding area of Al correspondingly increases, resulting in a reduced effective volume of crushing. Additionally, the rebound effect after being subjected to forces contributes to the reduction in the crushing pit depth.

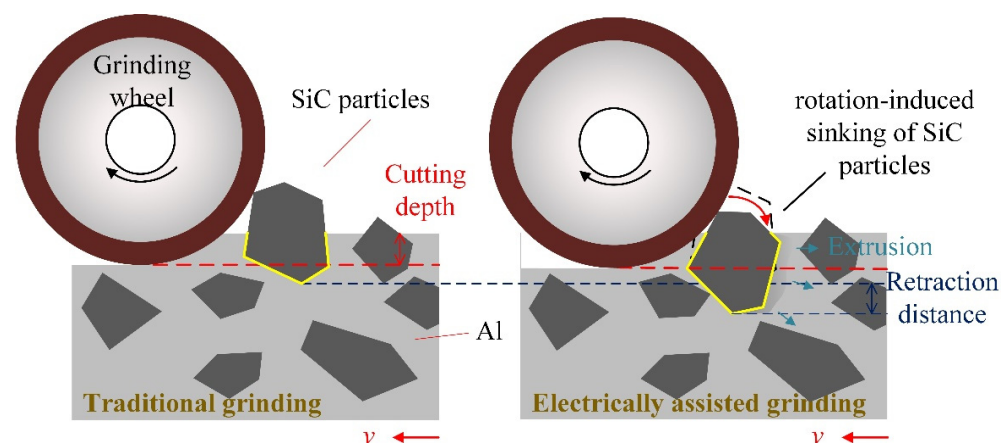


Figure 8. A schematic diagram of SiC particle reducibility.

In conclusion, increasing the pulse current results in the enhanced plasticity of the aluminum (Al) on the workpiece surface, leading to a more pronounced flocculent morphology. This, in turn, improves the expansion and penetration ability of Al under external forces and increases its holding power on the silicon carbide (SiC) particles. As a result, the size of the fractured pits on the surfaces of the SiC particles is effectively reduced, resulting in an improved crushing morphology. Overall, as the pulse current increases, the proportion of Al on the surface increases, gradually reducing the surface roughness of the workpiece. However, it is important to note that when the pulse current reaches 750 A, surface burn occurs due to the Joule heating effect. At the same time, with the increase in the pulse current, the influence of the electrocapillary phenomenon gradually increases, and the liquid is more likely to penetrate into the cutting space, which increases the lubrication effect and the surface quality of the machined surface.

3.1.3. Effect of Duty Ratio on Grinding Surface

Experimental investigations were conducted with fixed grinding parameters in terms of the current (500 A) and frequency (200 Hz) under different duty ratio conditions (25%, 50%, 75%). Figure 9 illustrates the influence of the duty ratio on the surface roughness; the unitary function image $y = 1.3809 + (-0.006384)x$ is obtained by fitting the data. It shows that there is a significant negative correlation between the duty cycle and the average surface roughness value. Compared to conventional grinding conditions, increasing the

duty ratio from 25% to 75% resulted in a 21.3% reduction in the average surface roughness. The minimum surface roughness value of 0.924 μm was obtained at a duty ratio of 75%.

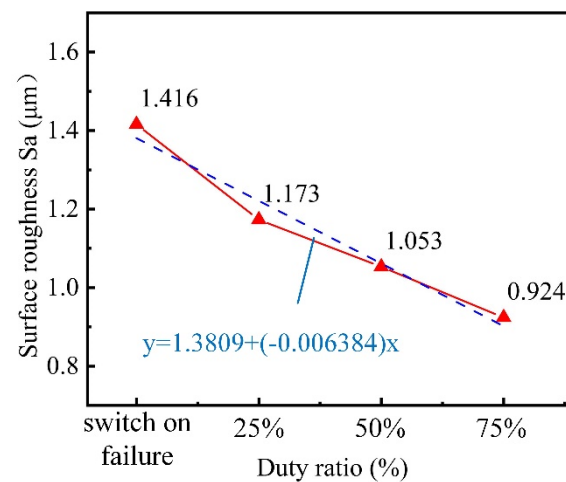


Figure 9. Effect of duty ratio on surface roughness.

Figure 10 depicts the surface microstructures under different duty ratios of 25%, 50%, and 75%. Upon comparing Figure 10a,c,e, it is observed that the proportion of Al on the workpiece surface gradually increases with an increase in the duty ratio. Furthermore, comparing Figure 10b,d,f, it is evident that as the duty ratio increases, the flocculent morphology of Al on the surface becomes more prominent, and the number of exposed SiC particles gradually decreases. Figure 10b shows the SEM image of the grinding surface under a 25% duty ratio, where a certain number of exposed SiC particles are present on the workpiece surface, along with grooves formed by continuous crushing, resulting in deeper pits from SiC particle fractures. Figure 10d displays the SEM image of the grinding surface under a 50% duty ratio, where no grooves are observed and the number of exposed SiC particles is reduced. Figure 10f presents the SEM image of the grinding surface under a 75% duty ratio, where Al is predominantly present in a flocculent form on the surface, and the fractured SiC particles are smaller in size. This phenomenon can be attributed to the increased duty ratio, which results in a longer energization time and enhances the electroplasticity effect, thereby increasing the plasticity of the aluminum (Al). Consequently, the surface morphology and roughness exhibit a similar trend regarding the variations in the duty ratio as for changes in the pulse current. When the duty ratio reaches 100%, the pulse current transforms into a direct current, and the current primarily exerts a thermal effect on the workpiece. Consequently, the influence of the electroplasticity effect on the workpiece is weakened [22].

3.1.4. Influence of Frequency on Grinding Surface

Experimental investigations were conducted with fixed grinding parameters in terms of the pulse current magnitude (500 A) and duty ratio (50%) under different frequencies (100 Hz, 200 Hz, 400 Hz). Figure 11 illustrates the influence of the frequency on the surface roughness, showing minimal variations in the average surface roughness with an increasing pulse current frequency. Compared to conventional grinding, an approximately 2.4% reduction in surface roughness was observed when the frequency increased from 100 Hz to 400 Hz. Similar conclusions were also reported by Zhao et al. [53] in their experimental study on the pulse-current-assisted dry cutting of W93NiFe.

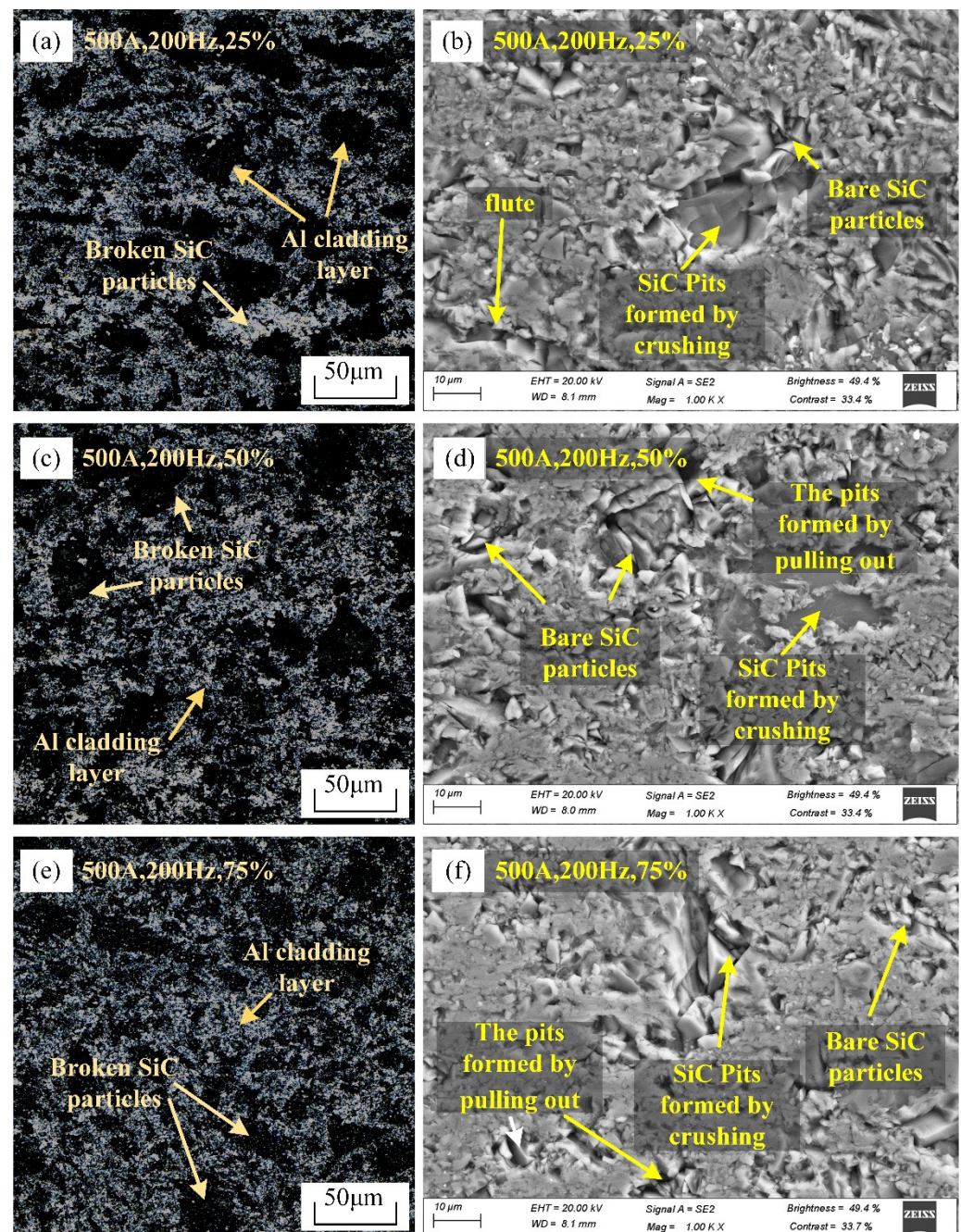


Figure 10. Effect of pulse current duty ratio on surface morphology. (a,c,e) Grinding surface CLSM images, (b,d,f) grinding surface SEM images.

Figure 12 displays the surface microstructures of the workpiece under different frequencies of 100 Hz, 200 Hz, and 400 Hz. Upon comparing Figure 12a,c,e, it is evident that there is no significant change in the proportion of Al on the workpiece surface with the increasing pulse current frequency. Additionally, comparing Figure 12b,d,f, it can be observed that although the magnitude of the pulse current increases, there are no noticeable changes in the morphology of the fractured SiC particle pits on the workpiece surface or in the morphology of Al. According to the analysis, the change in the pulse current does not increase the energization time, and the impact strength of the current on the material is not improved—only the impact frequency is changed. Therefore, at different frequencies, the surface quality of the workpiece is similar, which is also verified by the roughness results.

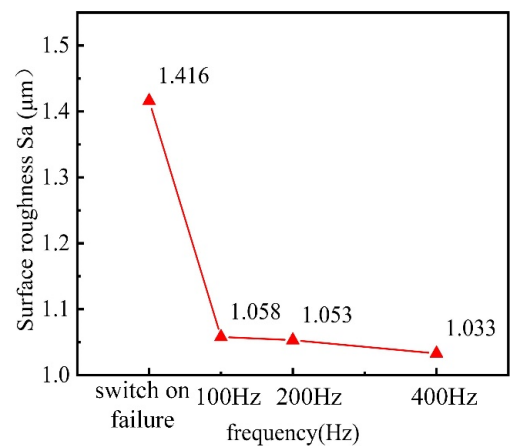


Figure 11. Effect of frequency on surface roughness.

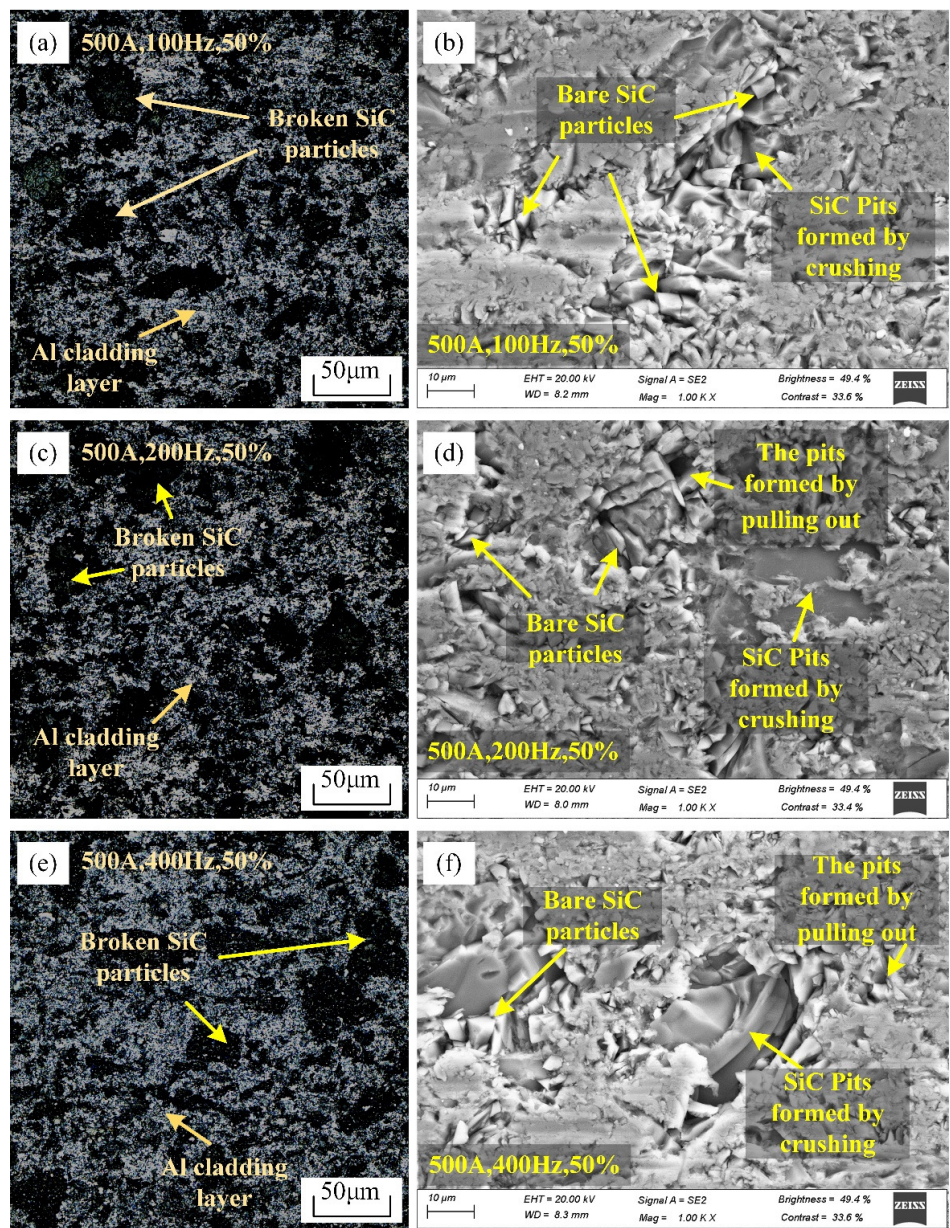


Figure 12. Effect of pulse current frequency on surface morphology. (a,c,e) Grinding surface CLSM images, (b,d,f) grinding surface SEM image.

In conclusion, during the pulse-current-assisted grinding of SiC/Al composites, the magnitude and duty ratio of the pulse current significantly affect the surface quality of the grinding process. However, the frequency has a minimal influence on the workpiece surface quality. The improved surface quality achieved through electro-assisted grinding is primarily attributed to the enhanced flowability of Al, facilitated by the pulse current. This increased flowability allows for better penetration during the machining process and enhances the healing capacity of Al regarding pits and grooves on the surface. Moreover, the pulse current enhances the holding power of Al towards SiC particles, preventing the detachment of fractured SiC particles and the formation of pits. To further investigate the wear resistance of the workpiece surface obtained through electrical-assisted grinding, friction and wear experiments were conducted.

3.2. Friction and Wear Experiment

In Section 3.1, a multi-point collection analysis was performed on the surface topography of grinding under different operating conditions. Overall, the surface quality of the grinding under electrified conditions was significantly better than that of conventional grinding. Due to the uneven characteristics of high-concentration SiC/Al composite materials, the SiC particles exhibited high concentrations at certain locations. As a result, there were significant variations in material removal at different positions on the same workpiece. Taking the operating conditions of 500 A, 200 Hz, 50% as an example, Figure 13a,b show different positions on the same workpiece. Due to the excessively high local SiC concentration, at the workpiece positions shown in Figure 13a, the SiC particles lose the holding power of Al towards them, leading to the occurrence of large fractured pits. Moreover, continuous SiC particle fragmentation makes it difficult for the Al to extend into and effectively heal these fractured pits, resulting in poor surface quality in localized areas. Similarly, as shown in Figure 13b, when the SiC particle concentration was lower, smaller crushing pits were formed under the grip of Al. Moreover, the Al was more likely to spread on the surface and effectively heal these fractured pits and grooves. In addition, the surface quality, as shown in Figure 13a, was even worse than that of some surfaces in the conventional grinding experiment, as shown in Figure 13c. It can be seen that the high concentration of SiC particles in localized areas led to significant fluctuations in the machined surface. This objective fact also resulted in significant fluctuations in the results of the friction and wear experiments. Figure 13d,e show the microscopic morphologies of the abrasion marks at different positions on the same workpiece. Due to the high concentrations of SiC particles in localized areas, there was no Al buffer between the SiC particles during friction at the location shown in Figure 13d. Additionally, the presence of more exposed SiC particles increased the contact force during the friction and wear process, leading to an increase in the friction coefficient. Conversely, as shown in Figure 13e, a large amount of Al reduced the contact force during the friction process, resulting in a lower friction coefficient. Furthermore, the microscopic morphology of the abrasion marks shown in Figure 13d was even worse than that for the conventional grinding surface with conventional abrasion marks, as shown in Figure 13f.

The surface fluctuations also posed challenges in the statistical analysis of the friction coefficient. Figure 14 presents the friction coefficients of the grinding surfaces under different operating conditions. It can be observed that, compared to conventionally machined surfaces, the initial friction coefficient rise rate and the friction coefficient during the stable wear stage were reduced after applying the pulse current. Based on the aforementioned analysis of the machined surface topography, it is believed that the application of the pulse current resulted in the finer fragmentation of the SiC particles on the surface, while increasing the proportion of Al. The flocculent Al formed a “web-like” overall structure on the surface, which was particularly evident under high pulse current conditions. Figure 15 illustrates the force analysis of the friction process on the workpiece with different proportions of Al on the surface. Compared to the sliding contact between the steel ball and the Al surface, a greater contact force F was observed when the steel ball slid on the

exposed silicon carbide. As shown in Figure 15a, the proportion of Al on the conventionally machined surface was relatively low, with a higher proportion of exposed SiC particles, resulting in a higher friction coefficient. Moreover, due to the fragmented nature of the Al on the conventionally machined surface, it was prone to detachment during the friction process, leading to the exposure of more and larger SiC particles on the surface, thereby exacerbating the surface wear. However, the “web-like” overall structure formed by the Al on the surface under the electric-assisted grinding conditions exhibited superior bonding characteristics with the material matrix. It was less prone to detachment during the friction process and could tightly encapsulate the fine SiC particles on the surface, resulting in a lower overall friction coefficient.

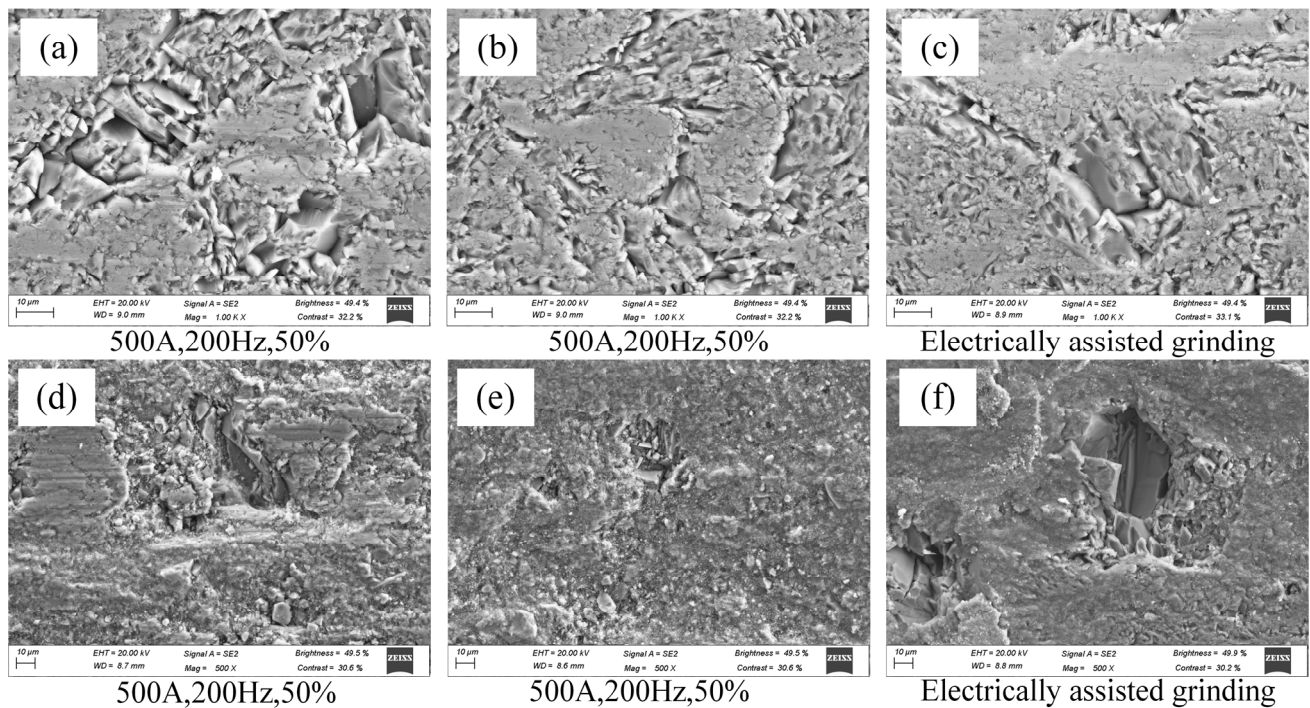


Figure 13. SEM microstructure of workpiece surface. (a–c) Electrically assisted grinding surface, (d–f) worn-out surface.

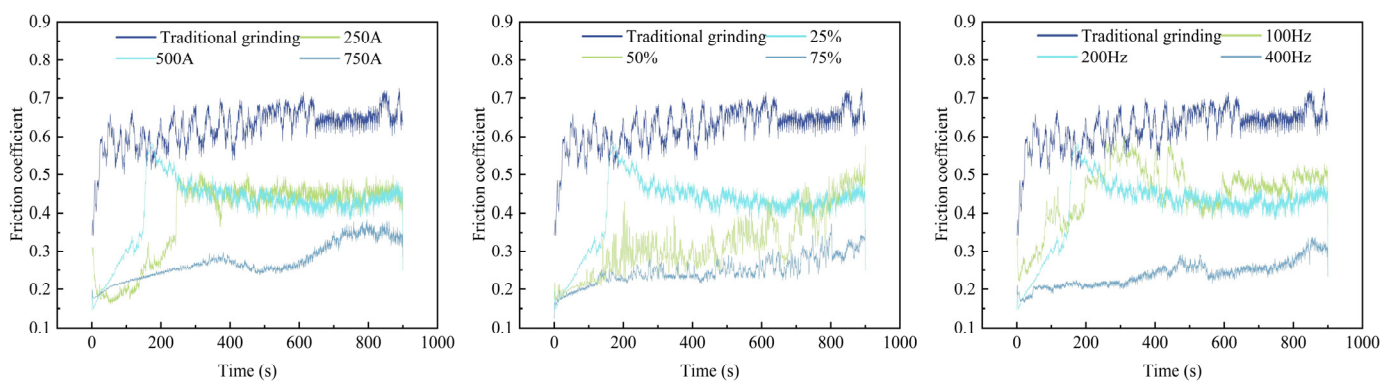


Figure 14. Variation curve of friction coefficient on workpiece surface.

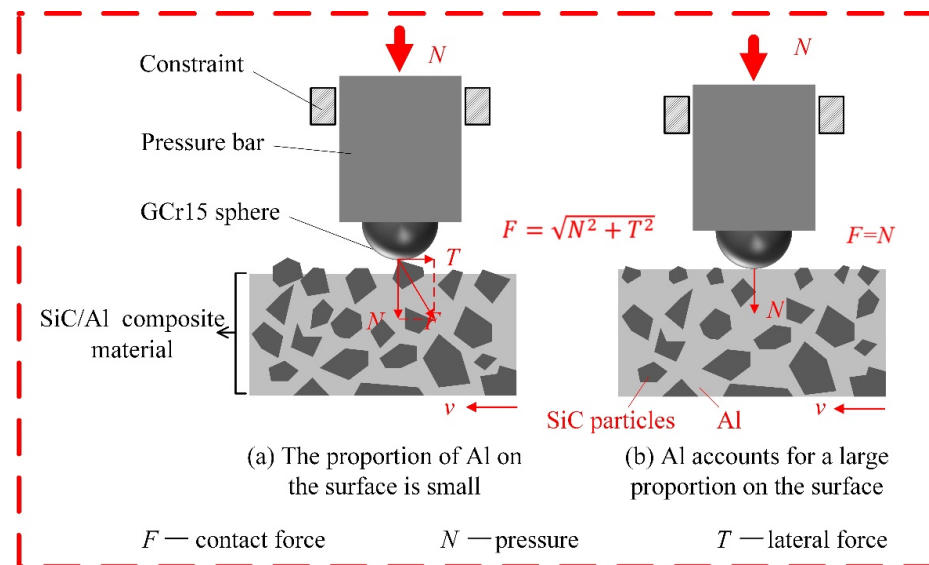


Figure 15. The stress analysis diagram of materials with different adhesion degrees of Al on the surface.

4. Conclusions

Experiments were conducted on SiC/Al composite materials using different electrical parameters in grinding and friction–wear tests to investigate the effects of the pulse current on the surface quality and wear resistance of the machined surfaces. The following conclusions can be drawn.

- (I) The application of a pulse current significantly reduces the surface roughness and improves the surface morphology of the workpiece compared to conventional grinding. Under the operating conditions of 500 A, 200 Hz, and a 50% duty ratio, the average surface roughness value R_a is 1.053 μm , which is 25.6% lower than the average surface roughness value R_a of 1.416 μm obtained from conventional grinding.
- (II) Increasing the pulse current and duty ratio leads to a significant reduction in surface roughness. Increasing the pulse current from 250 A to 750 A results in a decrease in surface roughness from 1.166 to 0.863, a reduction of 26%. Similarly, increasing the duty ratio from 25% to 75% leads to a decrease in surface roughness from 1.173 to 0.924, a reduction of 21.3%. However, the frequency has no significant influence on the surface roughness. Increasing the frequency from 100 Hz to 400 Hz only leads to a slight reduction in surface roughness from 1.058 to 1.033, a decrease of only 2.4%.
- (III) The workpiece surface obtained from electric-assisted grinding exhibits higher wear resistance compared to that obtained with conventional grinding. The refinement of the SiC particles on the machined surface and the web-like overall structure formed by the flocculent Al under the influence of the pulse current reduce the contact force during the friction–wear process, resulting in a decrease in the friction coefficient. This is evident from the significant reduction in the initial rise rate of the friction coefficient during the early stage of friction–wear and the corresponding decrease in the friction coefficient observed in the later stage of friction–wear.

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