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SURFACE INTEGRITY OF SILICON CARBIDE MACHINED BY DIAMOND WIRE SAWING: EFFECT OF FEED RATE

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Abstract: *This study investigates the influence of feed rate on the surface integrity of silicon carbide (SiC) machined by the diamond wire sawing (DWS) process. SiC is a ceramic material extensively used in strategic applications due to its high hardness, chemical stability, and thermal resistance; however, it poses significant challenges in machining, often resulting in severe surface damage. The experiments were performed using a precision endless diamond wire saw with controlled cutting parameters. The cutting speed and wire tension were kept constant at 17 m/s and 20 N, respectively, while the feed rate varied at 0.5, 1.0, and 1.5 mm/min. Surface morphology was analyzed by scanning electron microscopy (SEM), and surface roughness was measured using a contact profilometer. The results showed that lower feed rates favored the ductile removal regime, leading to surfaces with better quality, lower roughness ($R_a = 0.42$ μm), fewer microcracks, and more uniform morphology. In contrast, higher feed rates promoted brittle fracture mechanisms, resulting in higher roughness ($R_a = 1.21$ μm), deeper grooves, and a significant increase in microcracks and surface defects. The functional roughness parameters (R_{sk} and R_{ku}) confirmed the topographical degradation at higher feed rates, with negative skewness indicating the predominance of valleys from intergranular fractures and high kurtosis reflecting sharp topographical features. The study highlights that controlling the feed rate is crucial for optimizing the balance between productivity and surface integrity in SiC machining by DWS.*

Keywords*: silicon carbide, diamond wire sawing, surface integrity, machining parameters, brittle materials.*

1. INTRODUCTION

Silicon carbide (SiC) is a ceramic material widely recognized for its exceptional combination of mechanical, thermal, chemical, and electronic properties. Due to its high hardness, excellent thermal conductivity, low thermal expansion, high chemical stability, and wide bandgap, SiC is extensively employed in strategic industries such as aerospace, semiconductor manufacturing, high-power electronics, and precision optics (Goel et al., 2015; Kimoto, 2014).

Despite its desirable properties for functional applications, SiC presents significant challenges from a manufacturing standpoint. Its high hardness and brittleness result in poor machinability, leading to extensive tool wear, surface damage, and the risk of subsurface cracks during conventional machining processes (Bifano et al., 1991; Klocke, 2008). Consequently, the development of optimized machining strategies for SiC is essential to ensure the dimensional accuracy, surface quality, and mechanical integrity required in high-performance components.

Among the available techniques, diamond wire sawing (DWS) has emerged as an efficient and precise method for machining hard and brittle materials such as SiC, sapphire, and monocrystalline silicon. DWS utilizes a metal wire coated with diamond abrasive grains, which performs material removal through micro-cutting and micro-fracture mechanisms. Compared to conventional slurry-based wire saws, the DWS process offers higher cutting efficiency, reduced environmental impact, and better control of surface quality (Wu, 2016; Bidiville et al., 2010; Yu et al., 2012; Knoblauch et al., 2017; Costa, 2019).

The machining of SiC is governed by two predominant material removal regimes: the ductile regime, characterized by plastic deformation and smoother surfaces, and the brittle regime, dominated by crack initiation, propagation, and material fragmentation (Bifano et al., 1991; Gao et al., 2004). The transition between these regimes is strongly influenced by process parameters such as cutting speed, feed rate, and abrasive grain size. Specifically, the undeformed chip thickness plays a critical role in determining whether the material undergoes plastic deformation or brittle fracture (Yan et al., 2016; Wu, 2012).

Previous studies have demonstrated that maintaining the cutting conditions below the critical depth of cut favors the ductile regime, resulting in higher surface integrity with minimal microcracks and subsurface damage (Goel et al., 2015).

Conversely, higher feed rates and insufficient control of tool-workpiece interaction often lead to a transition toward brittle fracture, severely compromising surface quality (Wu, 2016).

Given the industrial demand for SiC components with high surface integrity and tight dimensional tolerances, it is crucial to understand how DWS process parameters influence surface quality. While several studies have focused on diamond wire sawing of silicon for photovoltaic applications (Bidiville et al., 2010; Yu et al., 2012; Wu, 2016), and others have addressed the fundamentals of DWS applied to monocrystalline silicon and the technological evolution of wire saw systems (Knoblauch et al., 2017; Costa, 2019), fewer investigations have systematically explored the machining of silicon carbide under varying process parameters, particularly feed rate.

In this context, the present study aims to investigate the influence of feed rate on the surface integrity of SiC during the diamond wire sawing process. The research focuses on evaluating surface morphology, damage mechanisms, and roughness evolution under different feed rates conditions, providing insights into the optimal machining parameters that promote a transition to the ductile regime and minimize surface degradation. The findings contribute to the scientific understanding of DWS applied to SiC and offer practical guidelines for industries seeking to improve productivity while maintaining stringent surface quality requirements.

2. MATERIALS AND METHODS

This section describes the materials, equipment, and experimental procedures employed in this study. The cutting setup, machining parameters, sample preparation, and surface characterization techniques are detailed in the following subsections to ensure the reproducibility of the experiments and the reliability of the obtained results.

2.1 Diamond Wire Saw Machine

The experiments were carried out at the Precision Mechanics Laboratory (LMP) of the Federal University of Santa Catarina (UFSC), employing an endless diamond wire saw specifically designed for high-precision machining of hard and brittle materials. The machine was developed by Knoblauch et al. (2017), based on the prototype proposed by Stoeterau (1999), and features high structural rigidity and dimensional stability.

The equipment is powered by a 370 W motor and allows for the adjustment of cutting speed between 7 and 26 m/s and a feed rate starting from 0.08 mm/min. The cutting system consists of two main axes (A and A'), guided by Teflon pulleys that ensure precise wire alignment. The wire motion is driven by an electric motor controlled via a frequency inverter, enabling stable speed regulation.

The auxiliary axis (A') is supported by an air-bearing system that reduces friction and enhances the smoothness of linear motion. Wire tension is maintained by a pneumatic actuator combined with a spring system, ensuring constant tension during operation. Feed movement is performed by the Y-axis, with a maximum stroke of 400 mm, while thickness adjustment is performed via the Z-axis, which uses a micrometric adjustment mechanism with a maximum range of 65 mm. A schematic of the machine setup is shown in Fig. 1.

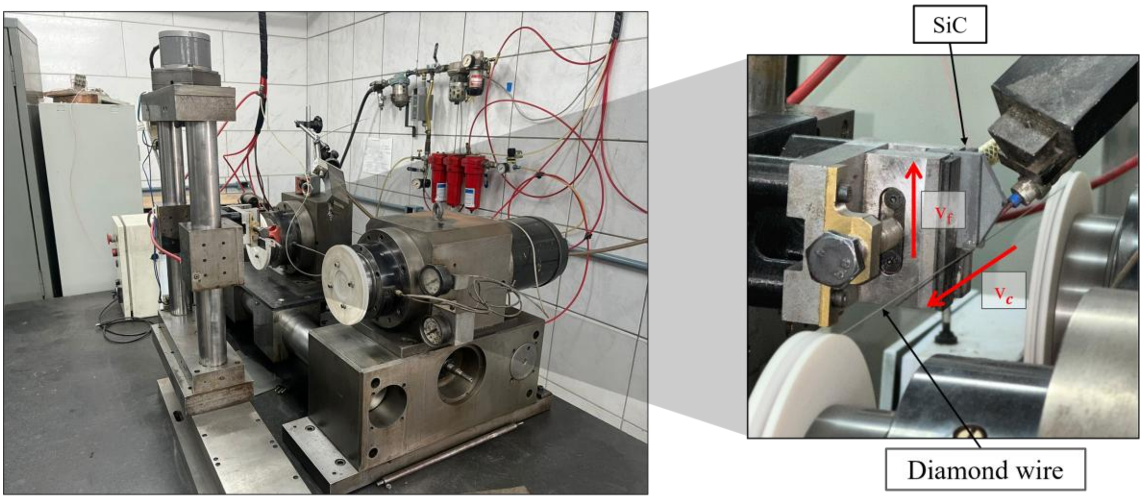

Figure 1. Diamond wire saw machine used for cutting silicon carbide samples.

2.2 Cutting Tool

The cutting tool consists of an endless diamond wire with a nominal diameter of 450 µm, supplied by ENSOLL. The wire is electroplated with nickel (Ni), which binds diamond abrasive grains with an average size of approximately 45 µm

uniformly distributed along its surface. This configuration provides an optimal balance between cutting efficiency and tool durability, particularly when machining hard and brittle materials such as silicon carbide (SiC).
A detailed view of the wire's surface, obtained by scanning electron microscopy (SEM), is presented in Fig. 2, highlighting the abrasive grain distribution and bonding characteristics.

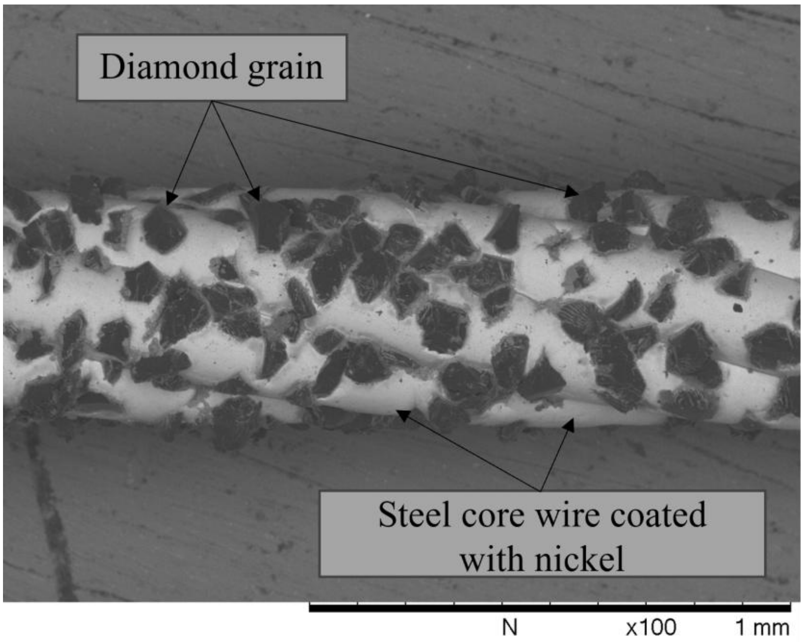

Figure 2. SEM image of the diamond wire surface, showing the distribution of abrasive grains.

2.3 Workpiece

The material used in this study was a silicon carbide (SiC) block with an initial hexagonal geometry. The workpiece was sectioned using the diamond wire saw to produce samples with final dimensions of 10 mm × 7 mm × 2 mm, as illustrated in Fig. 3.

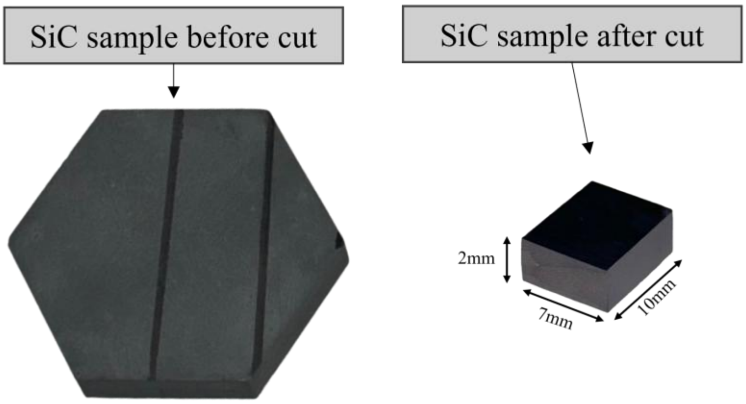

Figure 3. (a) Original silicon carbide sample marked for cutting; (b) Sample after the cutting process.

The preparation process was conducted to ensure high dimensional accuracy and minimize surface and subsurface damage. This step was essential to guarantee the reliability of subsequent morphological and surface quality analyses.

2.4 Surface Characterization

The surface characterization of the machined silicon carbide samples was carried out through qualitative and quantitative analyses. This procedure aimed to evaluate both the morphological features and the topographical quality of the surfaces generated under different machining conditions. The adopted methods provided a comprehensive understanding of the material removal mechanisms and their influence on surface integrity. The following subsections detail the techniques used for morphological evaluation by scanning electron microscopy (SEM) and the quantitative assessment of surface roughness parameters through profilometry.

2.4.1 Morphological Analysis

Surface morphology was assessed using scanning electron microscopy (SEM) to investigate the effects of different feed rates on the topography and damage mechanisms of the machined SiC surfaces. The analysis focused on identifying surface features associated with brittle and ductile material removal regimes, including grooves, microcracks, craters, and fracture patterns.

The SEM analyses were conducted using a Hitachi TM-3030 microscope operating at an accelerating voltage of 15 kV, with magnifications of 500×, 1500× and 2000×. All samples produced under the various cutting conditions were analyzed under identical parameters to ensure comparative consistency.

2.4.2 Roughness Measurements

Surface roughness measurements were performed using a Taylor Hobson Talysurf profilometer, offering a lateral resolution of 0.1 µm and a vertical resolution of 0.01 µm. Each sample underwent three measurements, taken over a scan length of 5 mm, with the arithmetic mean used for data analysis.

The *MountainsMap* software was employed to process the 2D profiles, following the ISO 16610-31 standard. The data processing included:

- Gap filling by interpolation of missing data;
- Form removal via linear detrending to flatten the baseline;
- Waviness filtering with a Gaussian filter and a cut-off wavelength of 0.8 mm to isolate the roughness component.

The extracted roughness parameters included:

- R_a (arithmetical mean roughness),
- R_q (root mean square roughness),
- R_{sk} (skewness), and
- R_{ku} (kurtosis).

These parameters enabled a detailed evaluation of the surface quality and allowed correlation with the material removal mechanisms under different feed conditions.

2.5 Experimental Design

The investigation was structured to systematically evaluate the influence of cutting parameters on the surface integrity of silicon carbide during the diamond wire sawing process. The primary objective was to isolate the effect of feed rate while maintaining other parameters constant. This section presents the cutting conditions applied and the organization of the experimental matrix used to ensure the reliability and reproducibility of the results.

The experiments aimed to evaluate the effect of feed rate (v_f) on the surface integrity of silicon carbide during the diamond wire sawing process. The cutting speed (v_c) was fixed at 17 m/s, and the wire tension (T_{wire}) was maintained at 20 N. The feed rate was varied at three levels: 0.5 mm/min, 1.0 mm/min, and 1.5 mm/min.

All experiments were performed under dry conditions to eliminate the influence of lubrication. For each condition, three repetitions were executed, totaling nine cutting tests. The cutting parameters are presented in Tab. 1.

Table 1. Cutting parameters applied in the experiments.

Condition	Cutting Speed (v_c) (m/s)	Wire tension (N) (T_{wire})	Feed rate (v_f) (mm/min)
A	17	20	0.5
B	17	20	1.0
C	17	20	1.5

The experimental design consisted of varying the feed rate while maintaining constant cutting speed and wire tension, allowing the isolated analysis of its effect on surface morphology and roughness.

A total of nine cutting operations were carried out, with one replica and one triplicate for each condition. For the surface characterization, three roughness measurements were performed per sample, resulting in a total of 27 measurements.

The complete experimental matrix comprised:

- 9 cutting tests, corresponding to the process performance evaluation,
- 27 surface roughness measurements, for assessing the surface integrity.

This approach ensured high reliability in evaluating the influence of feed rate on the diamond wire sawing of silicon carbide, providing statistically significant results for correlating machining parameters with surface integrity outcomes.

3. RESULTS AND DISCUSSION

This section presents the influence of feed rate on the surface integrity of silicon carbide (SiC) machined by diamond wire cutting. The analysis is based on SEM images and surface roughness measurements, focusing on the material removal mechanisms and resulting surface quality.

3.1 Surface Morphology

This analysis is divided into the evaluation of surface morphology and roughness to understand how feed rate affects surface integrity.

The analysis of the surface morphology of the silicon carbide (SiC) specimens after the diamond wire sawing process is presented in Fig. 4, which shows the surface conditions obtained for different feed rates (v_f), under constant cutting speed (v_c=17 m/s) and wire tension (T_{wire}=20 N).

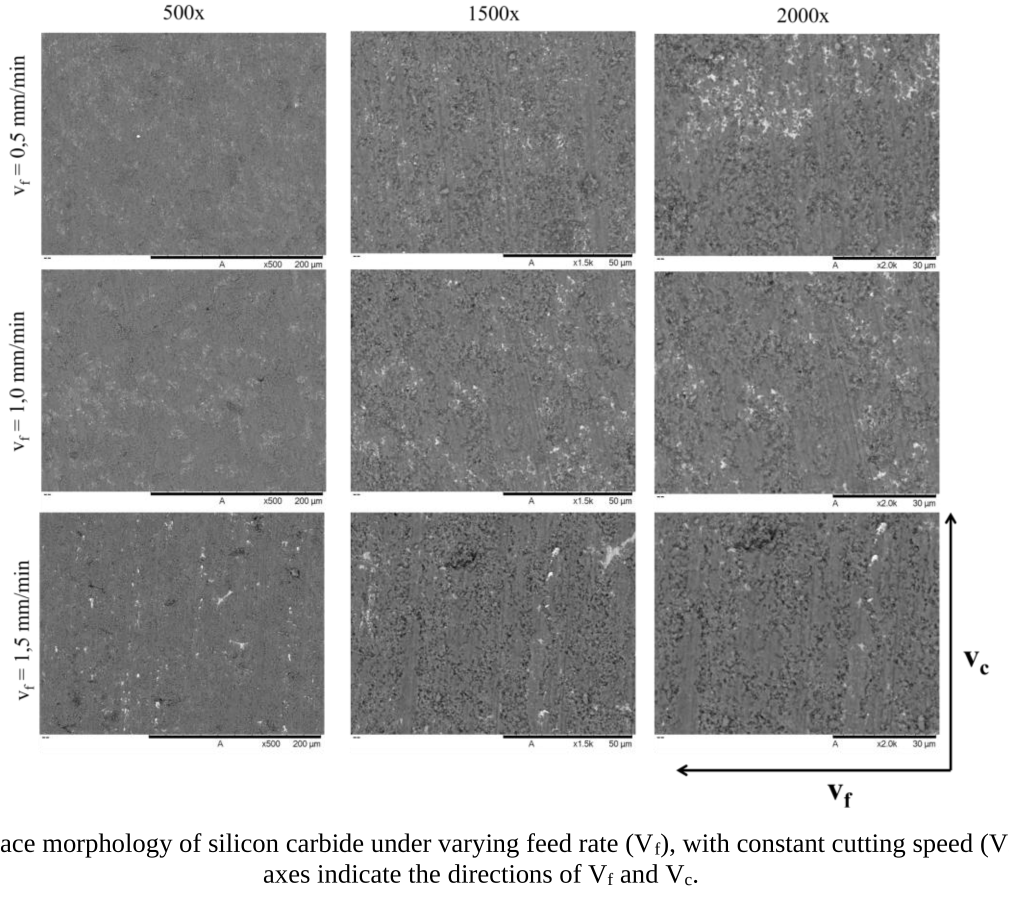

Figure 4. Surface morphology of silicon carbide under varying feed rate (V_f), with constant cutting speed (V_c). Vector axes indicate the directions of V_f and V_c.

The scanning electron microscopy (SEM) images reveal the presence of parallel grooves aligned with the feed direction of the diamond wire, a phenomenon also reported by Bidiville et al. (2010) and Yu et al. (2012). A noticeable variation in the predominance of material removal mechanisms, ductile or brittle, is observed depending on the feed rate applied. At the lowest feed rate (v_f=0.5 mm/min), the surface morphology exhibits feature typical of the ductile removal regime, characterized by reduced damage, low microcrack density, and well-defined grooves. This behavior is attributed to maintaining the average undeformed chip thickness (h_{cu}) below the critical depth ($h_{cu,crith}$), promoting localized plastic deformation rather than fracture.

In contrast, the brittle removal regime leads to surfaces with significant asymmetry (negative R_{sk}), a high concentration of valleys, and sharp height distributions (high R_{ku}), which compromise surface integrity. This degradation is not limited to surface roughness; it also involves the formation of microcracks, subsurface damage, and the generation of residual tensile stresses, all of which can reduce the mechanical reliability of the component. In brittle materials such as silicon carbide, a surface dominated by valleys often results from grain detachment and intergranular fracture, which act as stress concentrators. These features may serve as crack initiation sites under thermal or mechanical loading, increasing the likelihood of failure during service, especially in applications requiring high structural integrity, such as electronics, aerospace, or optics.

At lower feed rates, ductile removal mechanisms such as plastic deformation and material smearing are present, contributing to smoother surfaces and limited subsurface damage. When the feed rate is increased to 1.5 mm/min, the surfaces present features associated with the brittle removal regime, including an increase in microcrack density, the formation of craters, and topographical irregularities. This surface degradation is related to the increase in cutting energy and abrasive grain penetration depth, which exceeds the critical depth of cut. As a result, material removal occurs primarily through crack initiation and propagation, leading to fracture-driven surface formation, as reported by Wu (2012).

Furthermore, Fig. 4 emphasizes the influence of the feed rate on groove formation. As the feed rate increases, both the critical depth and sharpness of the machining grooves increase significantly. This behavior results from the reduced overlap between consecutive abrasive grain paths, a consequence of the higher linear displacement per unit of feed.

Figure 5 provides detailed views of the damage progression. At 500× magnification, a mixed behavior is observed, with regions showing both brittle fracture and ductile removal, suggesting non-homogeneous material-tool interaction at higher feed rates. The 1500× magnification highlights a significant increase in surface microcracks and craters of varying sizes, indicating residual stresses generated during the process and localized material removal by fracture mechanisms.

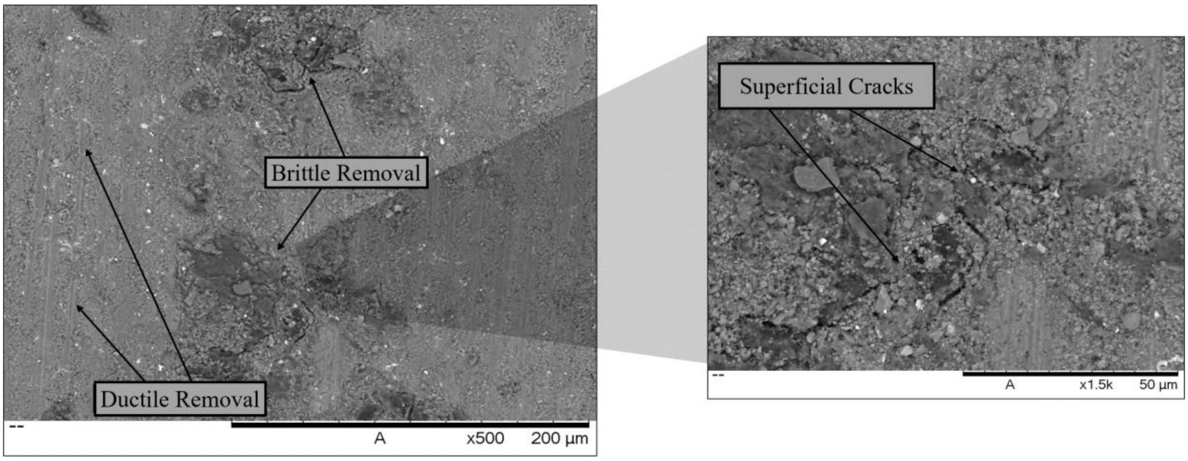

Figure 5. SiC surface morphology images highlighting brittle fracture, ductile material removal (500x), and surface cracks (1500x).

At lower feed rates, the grooves are shallower, smoother, and more evenly distributed, enabling more stable and controlled material removal. In contrast, higher feed rates lead to deeper and more pronounced grooves, coupled with greater variability in the effective cutting depth, severely compromising surface quality and geometric accuracy, particularly critical for applications requiring high-precision finishes.

3.2 Surface Roughness (R_a, Rq, R_{sk}, and R_{ku})

The evolution of surface roughness as a function of the feed rate is presented in Fig. 6, which displays the mean values of R_a (arithmetical mean roughness) and R_q (root mean square roughness) with their respective standard deviations.

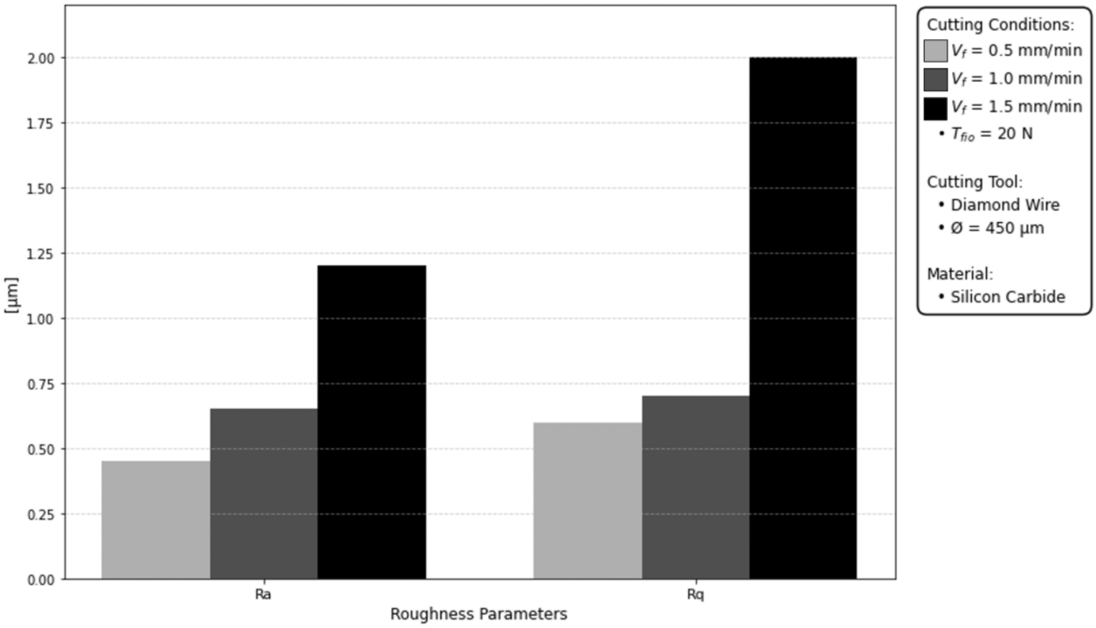

Figure 6. Comparative graph of roughness parameters (Ra and Rq) for different feed rates (Vf = 0.5, 1.0, and 1.5 mm/min).

The results reveal a progressive increase in both R_a and R_q with increasing feed rate. Specifically, R_a increases from 0.42 µm at v_f=0.5 mm/ min to 1.21 µm at v_f=1.5 mm/min. Similarly, R_q rises from 0.57 µm to 1.88 µm under the same conditions. The total roughness follows a similar trend, ranging from 0.49 µm to 1.54 µm.

This behavior directly reflects the impact of the average cutting depth (h_{cu}) on the removal mechanisms. Lower feed rates maintain the cutting process below the critical depth threshold, promoting ductile material removal, which results in smoother surfaces with fewer defects. In contrast, higher feed rates surpass the critical depth, leading to brittle fracture removal characterized by increased roughness, microcracks, and crater formation, corroborating the findings of Bifano et al. (1991).

From a practical perspective, the results highlight the importance of strict control over the feed rate to achieve high-quality surfaces. Although lower feed rates reduce process productivity, they are indispensable for high-value applications such as semiconductor manufacturing and precision optics, where surface integrity is paramount.

The functional roughness parameters, presented in Fig. 7, provide a deeper understanding of the topographical characteristics resulting from the diamond wire sawing process.

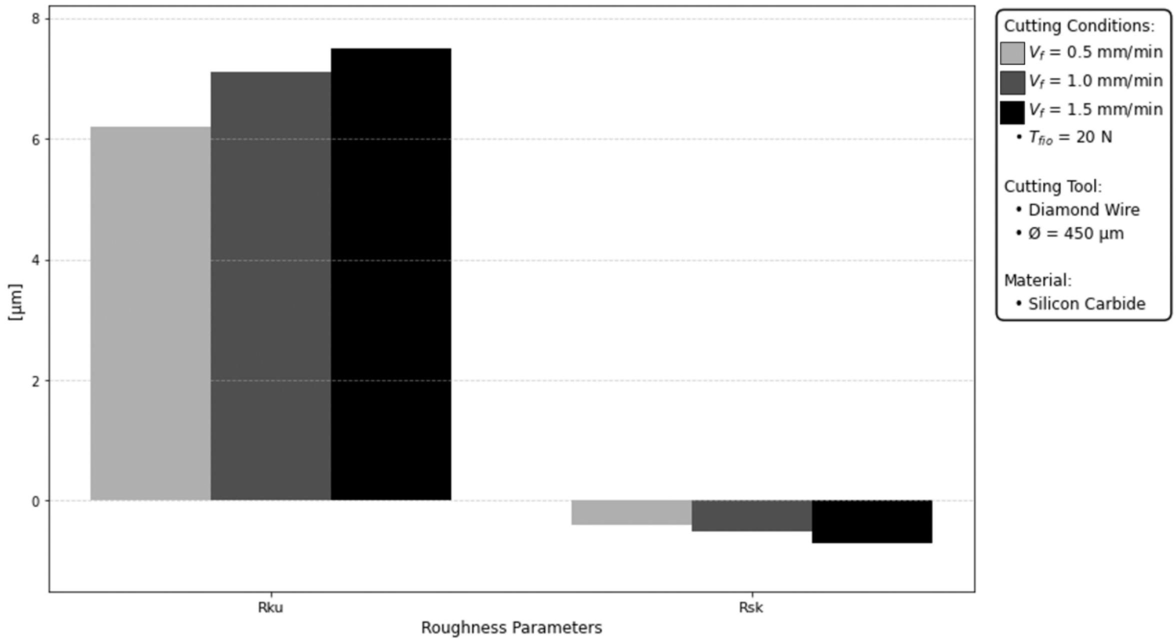

Figure 7. Comparative graph of functional roughness parameters (R_{ku} and R_{sk}) for different feed rates (V_f = 0.5, 1.0, and 1.5 mm/min).

The kurtosis parameter (R_{ku}) exhibited consistently high values across all tested conditions, indicating surfaces with sharper distributions characterized by extreme peaks and valleys. This behavior results from the abrasive interaction between the diamond wire and the SiC material, whose high hardness and low fracture toughness promote severe surface discontinuities.

The skewness parameter (Rsk) showed negative values under all conditions, reflecting the predominance of valleys over peaks in the surface profile. This is typical of materials subjected to intergranular brittle fracture, a common phenomenon in the machining of ceramic materials such as SiC. The negative skewness further indicates that material removal occurs preferentially through the detachment of grains or localized fracture.

This interpretation is consistent with the findings of Yang et al. (2024), who investigated the material removal mechanisms of polycrystalline silicon carbide machined by diamond wire sawing. Their study revealed that the machined surface exhibits both ductile and brittle features, with material removal dominated by mechanisms such as dislocation slip and intragranular amorphization. Notably, SEM and FIB-TEM analyses showed evidence of brittle fracture and grain detachment, supporting the presence of valley-dominated surface profiles characterized by negative skewness..

Moreover, an increase in the feed rate directly correlates with an increase in the overall roughness, indicating that higher feed rates produce rougher surfaces. This is attributed to the accelerated wear of the diamond wire and the reduced ability of the process to maintain stable material removal under elevated feed conditions. In summary, the functional parameters analysis confirms that the ductile removal regime is associated with smoother surfaces, featuring lower R_a and R_q values, R_{sk} values close to zero, and moderate R_{ku} values. In contrast, the brittle removal regime leads to surfaces with significant asymmetry (negative R_{sk}) a high concentration of valleys, and sharp height distributions (R_{ku}), severely compromising surface integrity.

4. CONCLUSIONS

This study provided a comprehensive assessment of the influence of feed rate on the machining of silicon carbide (SiC) using the diamond wire sawing (DWS) process, with a focus on understanding surface integrity and the prevailing material removal mechanisms. The results demonstrated that lower feed rates (v_f=0.5 mm/min) promote the ductile material removal regime, leading to surfaces with superior quality characterized by lower roughness, reduced occurrence of microcracks, and higher morphological uniformity. These conditions are ideal for applications requiring high surface precision and minimal subsurface damage, such as in the semiconductor and optical industries.

In contrast, higher feed rates (v_f=1.5 mm/min) induce a transition to the brittle removal regime, which is characterized by a significant increase in surface roughness, the formation of deep grooves, higher density of microcracks, and the appearance of craters. This degradation occurs due to the exceeding of the critical depth of cut, promoting fracture-dominated material removal. The analysis of functional roughness parameters (R_{sk} and R_{ku}) further corroborated the topographic degradation associated with higher feed rates. Negative skewness values reflected the predominance of valleys formed by intergranular fracture, while high kurtosis values indicated the presence of sharp peaks and valleys, both strongly correlated with the brittle removal regime.

In conclusion, this study highlights the critical role of feed rate in balancing productivity and surface integrity during the diamond wire sawing of silicon carbide. Lower feed rates, although less productive, are crucial for achieving superior surface quality with minimal defects. Future work should explore the influence of additional process parameters, including abrasive grain size, wire wear, and the use of lubrication or cooling systems. Moreover, investigating subsurface damage, residual stresses, and possible phase transformations will further advance the understanding and optimization of the DWS process for ceramic materials like SiC.

5. REFERENCES

Bidiville, A., Wasmer, K., Michler, J., Nasch, P. M., Van der Meer, M., & Ballif, C. (2010). Mechanisms of wafer sawing and impact on wafer properties. Progress in Photovoltaics: Research and Applications, 18(8), 563–572. https://doi.org/10.1002/pip.972

Bifano, T. G., Dow, T. A., & Scattergood, R. O. (1991). Ductile-regime grinding: A new technology for machining brittle materials. Journal of Engineering for Industry, 113(2), 184–190. https://doi.org/10.1115/1.28996

Costa, E. C. (2019). Corte de silício monocristalino com fio diamantado contínuo (Dissertação de Mestrado). Universidade Federal de Santa Catarina, Florianópolis, Brasil.

Gao, W., Patten, J. A., & Yasuto, K. (2004). Ductile regime nanomachining of single crystal silicon carbide. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 218(7), 789–798. https://doi.org/10.1115/1.1949614

Goel, S., Luo, X., Reuben, R. L., & Cox, A. (2015). A theoretical assessment of surface defect machining and hot machining of nanocrystalline silicon carbide. Computational Materials Science, 96, 327–334. https://doi.org/10.1115/1.4026297

Kimoto, T. (2014). Physics and applications of SiC. Progress in Solid State Chemistry.

Klocke, F. (2008). Manufacturing processes 2: Grinding, honing, lapping. Springer, Berlin, Germany.

Knoblauch, R., Costa, J. V. M. R., Weingaertner, W. L., Xavier, F. A., & Wegener, K. (2017). Endless diamond wire saw for monocrystalline silicon cutting. In Proceedings of the 17th International Conference of the European Society for Precision Engineering and Nanotechnology (EUSPEN) (pp. 11–15).

Stoeterau, R. L. (1999). Desenvolvimento do protótipo de uma máquina-ferramenta comandada numericamente para usinagem de ultraprecisão com ferramenta de geometria definitiva (Dissertação de Mestrado). Universidade Federal de Santa Catarina, Florianópolis, Brasil.

Wu, H. (2012). Fundamental investigations of cutting of silicon for photovoltaic applications (Doctoral Dissertation). Georgia Institute of Technology.

Wu, H. (2016). Wire sawing technology: A state-of-the-art review. Precision Engineering, 43, 1–9. https://doi.org/10.1016/j.precisioneng.2015.08.008

Yang H, Fu M, Zhang X, Zhu K, Cao L, Hu C. Material Removal Mechanisms of Polycrystalline Silicon Carbide Ceramic Cut by a Diamond Wire Saw. Materials (Basel). 2024 Aug 27;17(17):4238. doi: 10.3390/ma17174238. PMID: 39274628; PMCID: PMC11395942.

Yu, X., Wang, P., Li, X., & Yang, D. (2012). Thin Czochralski silicon solar cells based on diamond wire sawing technology. Solar Energy Materials and Solar Cells, 98, 337–342. https://doi.org/10.1016/j.solmat.2011.11.028

6. ACKNOWLEDGMENTS

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7. RESPONSIBILITY FOR THE CONTENT

The authors take full responsibility for the content of this work.