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Machinability analysis of thin-walled carbon fiber reinforced ceramic composites based on wire electrical discharge machining

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Abstract

We propose employing wire electrical discharge machining (WEDM) for shaping thin-walled, multidirectional, carbon fiber reinforced silicon carbide (Cf-SiC) composite parts. Ceramic matrix composite Cf-SiC combines the outstanding mechanical properties of the carbon fiber with oxidation, abrasive wear, corrosion resistance, and high strength at the high temperature of the silicon carbide matrix. The impact of time-related electrical discharge machining parameters (pulse ON-time and break OFF-time) on the material removal rate and surface roughness are analyzed. The material removal rate of the Cf-SiC is proved to be 36% lower than that for machined steel grade 55. The high thermal stresses and interaction of the composite accompanying WEDM are also discussed. Furthermore, an alternative mechanism to the WEDM of metals has been investigated and confirmed by a scanning electron microscopy (SEM) analysis. The morphology of the machined Cf-SiC surface demonstrates the dominance of the carbon fibers' fracture mechanism, both the transverse and longitudinal forms, with interphase detachment over craters and micro-cracks, pitting, and spalling on the SiC matrix. Satisfactory roughness indicators ($Sa = 2$ µm) are obtained in 3D topography measurements of the Cf-SiC surfaces. Concluding, the WEDM should be considered a good alternative to Cf-SiC abrasive machining when cutting holes, grooves, keyways, splines, and other complex shapes.

Introduction

A wire electrical discharge process is an alternative shaping route for difficult-to-machine brittle, thin-walled, or complex component shapes and materials. The WEDM has proven to be very effective in shaping not only tool steels but also hard-to-machine materials such as cemented carbides, as mentioned by Wiśniewska et al. (Wiśniewska et al., 2022), and nickel-based alloys, titanium alloys, or shape memory alloys, as mentioned by Poroś (Poroś, 2021). It becomes possible to reduce such problems associated with WEDM to microcracks, the forming of a white layer, or high surface roughness.

Pulse ON-time, pulse OFF-time, servo voltage, wire tension, and dielectric pressure have commonly been considered as input parameters, whereas components geometry, surface roughness, and material removal rate are the selected responses. Analysis of variance (ANOVA) has shown that pulse ON-time and pulse OFF-time are the two influential control factors for material removal rate (MRR), surface roughness (*Ra*), and tool geometry for the WEDM of tool steels, as described by Ishfaq et al. (Ishfaq et al., 2018). A few works, for example by Buk (Buk, 2022), focus on the peak current and electrode's infeed and the influence on the machined Inconel surface parameters. The WEDM of the shape memory alloy Ni55.8Ti research has been carried out by Gupta (Gupta, 2021) by analysis of four process parameters, i.e., the servo voltage, pulse ON-time, pulse OFF-time, and wire feed rate using a Taguchi L16 robust design of the experiment technique. Silicon carbide is characterized by low abrasive wear and resistance to high temperatures and can be used in composite materials both as a reinforcing phase and as a matrix, as mentioned by Gábrišová et al. (Gábrišová, Švec & Brusilová, 2020).

Ceramic matrix composites are based on carbon fibers, and the silicon carbide matrix acts as the structure of the composite material. Industrialization of the Cf-SiC manufacturing processes is still in its development phase. The engineers and final users still lack machining experience with this new structural material. The carbon fibers generally increase the durability of the SiC considerably. Silicon carbide reinforced with carbon fiber composite components strength lies in the same order of magnitude as for gray cast iron. Liquid silicon infiltration (LSI) is considered the most capable process for industrial products, especially with regard to costs. The field of application for Cf-SiC expands to the economically attractive structures in the energy industry. Recent research focuses on the manufacturing processes and surface coatings for the long-term exploitation of Cf-SiC composites under aggressive conditions. The Cf-SiC ceramics are applied to furnace engineering as charging devices or components support for metal hardening as a substitute for high-temperature resistant metals. Cf-SiC are considerably lighter and have a lower tendency to distort at elevated temperatures, for instance, when implementing a double-pipe heat exchanger. Substituting monolithic ceramics, Cf-SiC is applied to the oxygen probe tubes, thermocouple protection tubes, pouring gutters, or nozzles used in metallurgy. The novel application areas for the Cf-SiC include housings and components for optical systems, charging devices for thermal processing, or lightweight materials for ballistic protection. Krenkel (Krenkel, 2005) conducted research pertaining to gaining basic manufacturing knowledge as well as implementation-specific experience.

The main advantages of conventional machining methods of carbon fiber reinforced ceramic matrix composites are simple operation, well-known technology, and low equipment investment. However, the problem of tool wear results in increased cutting tool costs, lowered machining efficiency, and machining cost growth. The PCD tool wear is lower, and the machined quality is better, but the initial cost of cutting tools is higher, as mentioned by Wiśniewska et al. (Wiśniewska et al., 2022). It is also notable that conventional machining methods are not fully qualified for the processing requirements for complicated shapes of these composite structural parts. The scope of previous research relating to the machinability of ceramic composites mainly pertains to traditional cutting and abrasive processes. For milling in two different machining directions, the impact of spindle speed, feed rate, and depth on cutting force and surface roughness were analyzed in the work of Zhang et al. (Zhang et al., 2020). From the experiment results, it is determined that the measured cutting force of the machining direction was different in two perpendicular directions under the same parameters. The grinding of the ceramic matrix composites (CMC) with the electrolytic dressing process showed an increased stability in the grinding force for high stock removal and produced a significantly lower dulled area at the edge, compared with conventional grinding. Within the paper by Fujihara et al. (Fujihara et al., 1997), CBN and diamond wheels that use various grit sizes and bonds were applied as tools.

The scope of the Cf-SiC machinability in recent research includes various modern technologies such as laser cutting – as mentioned by Dong and Shin (Dong & Shin, 2017) – and high-energy abrasive waterjet machining, as described by Hamatani and Ramulu (Hamatani & Ramulu, 1990) and Armanios et al. (Armanios et al., 2001). Based on this research and one of the recent reviews of past advances in CMC composite machining, Du et al. (Du et al., 2019) concluded that in order to reduce the defects caused by conventional machining, parameter optimization and new tools should be developed.

Wire electrical discharge machining (WEDM) refers to a method of removing the workpiece material by electrical discharges between the wire electrode and workpiece electrode in a dielectric fluid. This causes a tremendous increase in temperature, causing a localized melting and vaporization of the electrically conductive materials. Theoretically, since analyzed fiber-reinforced composites containing ceramic matrix provide poor electrical conductivity, the material removal rate should be low for the WEDM of Cf-SiC, as Du et al. (Du et al., 2019) argued. Therefore, the number of studies is scarce, but include the paper of Hocheng et al. (Hocheng, Guu & Tai, 1998) on WEDM of fiber-reinforced silicon carbide composites.

Wei et al. (Wei et al., 2015) analyzed the machining mechanism of the fiber-reinforced ceramic composites by EDM and obtained the methods for improving the material removal rate (MRR) and surface integrity. The measured performance exceeded the effects predicted based on the thermal and electrical composite properties. Guu et al. (Guu et al., 2001) observed that for the EDM of the carbon fiber reinforced carbon composites, a smaller pulse energy could help obtain better performance, and, finally, the optimized parameters used to improve the MRR were proposed. A study by He et al. (He et al., 2019) shows that the orientation of the carbon fibers relative to the machining directions in the WEDM method of the 2D C/SiC composite affects the machining process and the quality. The use of two different machining directions in relation to the unidirectional arrangement of carbon fibers had a significant effect on the machined surface quality. Interfacial debonding between carbon fibers and SiC matrix is an important material removal mechanism. In addition, transverse and longitudinal cracking of the carbon fibers and microcracking of the matrix were also observed and described by He et al. (He et al., 2019). It can be deduced from the above that the unconventional machining of carbon fiber-reinforced ceramic matrix composites exhibits properties superior to the effects of conventional machining. Non-contact machining can be carried out using special equipment that produces high temperatures, high pressures, or high frequencies of vibrations. In WEDM, the contact stresses are negligible so that the material damage can be reduced, and typical defects such as chipping, burrs, cracks, fiber pulling, and other processing damage are effectively reduced. As mentioned by Du et al. (Du et al., 2018), the surface quality has considerably improved, and WEDM has great potential for development.

Planning of the experiment

Composites feature a wide range of properties and different machinability. The criteria for choosing the correct method depends on the component size and shape, cutting efficiency, surface roughness, stresses generated during machining, etc. The use of improper cutting techniques may lead to delamination, chipping, or cracking of the composite structure around the cutting edge. The machining of composite materials by a variety of methods, as well as the selection of appropriate parameters and tools, is aimed at reducing delamination, as Neubrand et al. (Neubrand et al., 2015) pointed out.

The purpose of this paper involves the planning of four stages of research:

- Application of a central composite experiment planning and response surface methodology to model WEDM according to Polański (Polański, 1984).
- Investigation of the relationship between WEDM time parameters and MRR for grade 55 steel and multidirectional Cf-SiC.
- Presentation, analysis, and discussion of SEM images displaying the morphology of the machined Cf-SiC.
- Presentation and discussion of 3D plots for the surface roughness parameters *Ra* and *Sa*, according to ISO 25178 for Cf-SiC composite after WEDM treatment.

The machine applied to WEDM for Cf-SiC is categorized as a wearable wire feeding mechanism type (Figure 1). Composite samples were fabricated using the liquid silicon infiltration (LSI) method. Ceramic matrix composite (CMC) material (Cf-SiC) with a 15 mm height and wall thickness of 4 mm were used for the test.

Figure 2 shows a scanning electron microscopy (SEM) image of the microstructure. The SEM images were taken at several magnification scales and, when necessary in a few cases, a gold layer of about 10 nm thick was sputtered. The SEM image of the composite shows fibers with a diameter of about 5 μm weaved with cross-direction carbon fiber bundles. Around the carbon fibers is the matrix material. The weaved 22.5 or 67.5° carbon fiber is spread over in subsequent layers. The inside and outside of the samples were coated with a SiC layer. Figure 3 displays an SEM image of the sample cross-section, and Table 1 provides the main properties of the Cf-SiC composite.

The samples were machined with a CNC WEDM with a low feed rate and a disposable CuZn37 brass wire with a diameter of 0.25 mm, which can be used to machine components with very stringent requirements for accuracy and surface finish. The consumable wire electrode travels through a continuously flushed gap, runs smoothly, has a constant diameter, and has fewer vibrations that, in combination, result in excellent cutting accuracy.

In contrast to previous work on the matter, realized with a unidirectional carbon fiber reinforced ceramic composite, the analyzed machined material was composed of multidirectional carbon fibers

Figure 1. ZAP BP 800 wire electrical discharge machine (workstation and cutting area are shown)

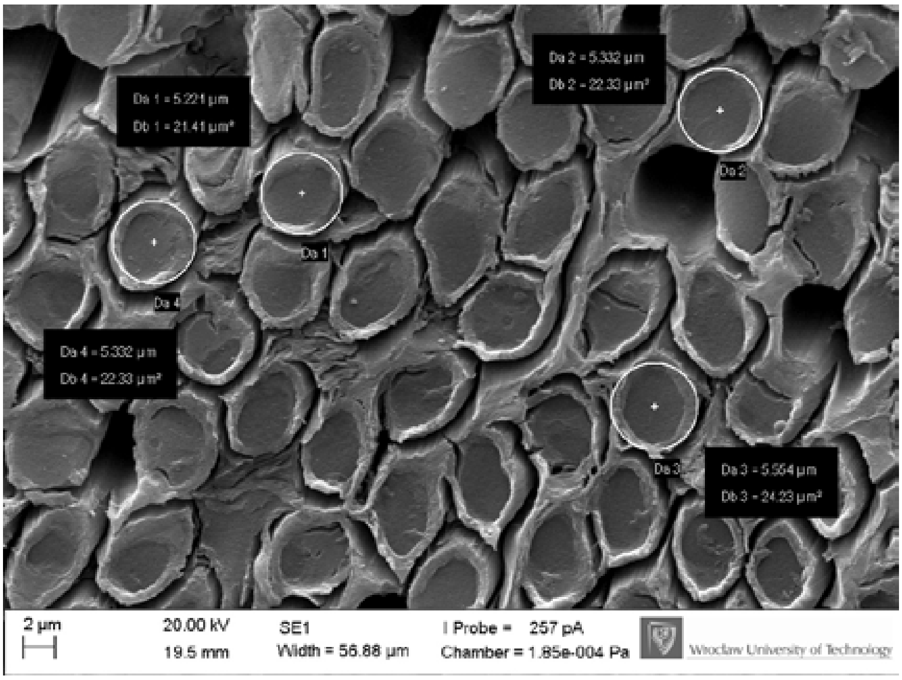

Figure 2. SEM image with the sample fibers size and cross-section shown

and manufactured by the liquid silicon infiltration process (LSI). Compared to chemical vapor infiltration, a well-established process for uniform coating, the latter is less expensive and less time-consuming. One major manufacturing process of the carbon fiber reinforced SiC composite materials is the silicon infiltration of a porous Cf preform to form a Cf-SiC composite, first compiled in Germany as described by Krenkel (Krenkel, 2005). It consists of the pyrolysis of carbon fiber reinforced plastic (CFRP) and then a liquid Si infiltration of the Cf composite. The oxidation resistance of the Cf composite is significantly increased by the Si infiltration and the formation of an Sf-SiC zone. A definition of the regression function of the experiment object was applied, which describes the time parameters in relationship with the process efficiency statistical PS/DS-P: λ (Polański, 1984) program.

A rotatable design on the second order was adopted. It was assumed that MRR significantly depends on discharge time-ON [µs] and brake time-OFF [µs]. A statistical definition of the object function formed as a second-degree polynomial. In turn, scope, central values, and unit variables coding relations

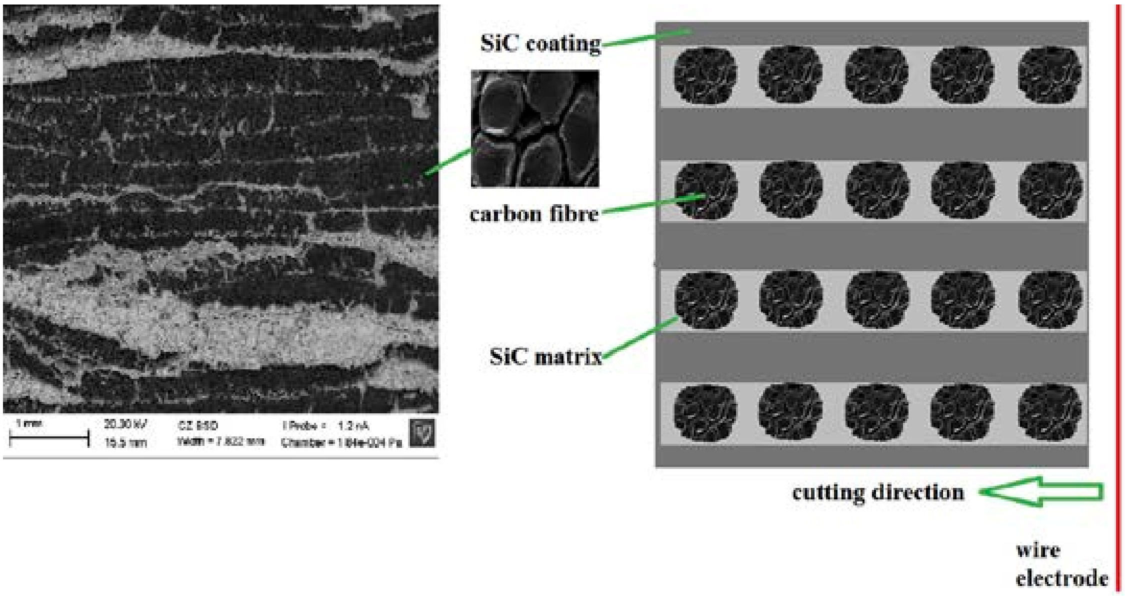

Figure 3. SEM image of the sample cross-section (carbon fibers, coating layers, and SiC matrix are visible) with a schematic of the composite structure, including the perpendicular machining direction

Table 1. Properties of the composite analyzed in the tests according to Du et al. (Du et al., 2018)

	High-strength carbon fiber	SiC
Electrical resistivity [Ω·cm]	$1.53 \cdot 10^{-3}$ (along fiber axis) $1.53 \cdot 10^{-2}$ (vertical to fiber axis)	5000
Thermal conductivity [W/m·K]	10 (along fiber axis) 2 (vertical to fiber axis)	490
Specific heat [$J \cdot kg^{-1} \cdot K^{-1}$]	710	690
Density [kg/m^3]	1800	3217
Thermal expansion coefficient [K^{-1}]	$-1.7 \cdot 10^{-6}$ (along fiber axis) $5 \cdot 10^{-6}$ (vertical to fiber axis)	$4.3 \cdot 10^{-6}$
Young modulus [GPa]	234	440
Poisson ratio	0.27	0.17

were carried out. The measurements were then realized. The program PS/DS-P: λ is required to make measurements in four configurations in a "core" of the program ($n_k = 2{\times}2 = 4$), two in a "center" of the program ($n_0 = 2$), and four in "star points" ($n_\alpha = 2{\times}2 = 4$). With recurrence, we have $r = 3$.

A regression ratio for regression analysis in second-degree planning was estimated (Polański, 1984). Then, the adequacy of the acquired function was evaluated for significance level ($\alpha = 0.05$). Discharge ON-time and break OFF-time were the variables, and the rest of the parameters were constant. Dielectric pressure, wire tension, wire speed, current, and voltage were invariable during the experiment. The machining direction was perpendicular to the carbon fiber layer. The process was carried out with deionized water as the dielectric fluid. The 2D and 3D surface roughness of the cut parts and the 3D surface profiles were measured and performed using a Mitutoyo SV-3200 profilographometer. For the purpose of this publication, only the parameters *Ra* and *Sa* were considered due to their high popularity and preliminary form of testing.

Results and discussion

MRR of the WEDM

The MRR of the WEDM process was determined as a cutting rate multiplied by workpiece height. The effect of time-related parameters on areal efficiency is presented in Figure 4. Due to technical distinction, experiments with steel grade 55 and Cf-SiC were performed with the same set of parameters. Increasing the ON-time or decreasing the OFF-time interval results in an increase in the MRR of the WEDM process with both machined materials. The MRR graph of machining Cf-SiC composite shows that the maximum was reached. Increasing the ON-time beyond the technological flushing barrier results in a decrease in the number of effective discharges, which were disrupted by composite particles filling the interelectrode gap. This may be due to inefficiencies in the gap-flushing system. The maximum MRR of the steel is far higher than that of the Cf-SiC composite. The achieved performance results showed that the cutting of steel 55 was about 36% faster than the analyzed composite.

Theoretically, EDM is most effective at processing materials with a high electrical conductivity, such as metals. Generally, the lower the thermal conductivity and melting point of the machined materials, the higher their WEDM machining speeds. It is noteworthy that, in the analyzed composite, both the silicon carbide and carbon fiber have a high sublimation, high resistance, and high thermal conductivity. Thus, based on theoretical considerations, the WEDM speed of the Cf-SiC is expected to be lower than that of the steel grade 55. Contemplating other research findings by He et al. (He et al., 2019) concerning WEDM with a molybdenum wire, the MRR values are comparable to brass electrodes, notwithstanding the characteristic higher discharge energy in the gap. The anisotropy of the machined composite results in various MRR from metallic materials. In his work, the SEM surface layer analysis confirmed that carbon fibers were removed as a result of the transverse and longitudinal fractures. These results are difficult to contrast with the present work due to the different workstations, generators, and wire electrode materials.

However, the measured values diverge from those obtained by Yue et al. (Yue, Li & Yang, 2020). In their research, WEDM was applied with a brass wire characterized by a smaller electrode diameter of 0.2 mm. The authors of this paper claimed that certain features of the surface layer would appear depending on the direction of the cut in relation to the fiber alignment. A smaller diameter wire electrode could affect lower energy in the gap during WEDM. For the brass wire, it was noticed that the MRR for unidirectional Cf-SiC was higher than in the presented research and even exceeded the results for mold steel. The superior results, according to the authors of this paper, are a consequence of the use of a modern generator with more efficient current pulse characteristics, optimization of process parameters for optimal WEDM performance and, last but not least, the type of unidirectional fiber. This type of fiber alignment during WEDM perpendicular to the carbon fibers is characterized by a high process stability, reduced amount of discharge interference compared to those analyzed in this work, and multidirectional fiber alignment composites.

The WEDM material removal rate of the composite is higher than that of cutting SiC or carbon fiber separately. The authors of this work stand by the thesis that the difference in thermal expansion of carbon fiber (negative in parallel direction) and silicon carbide (positive) could affect the enhancement of the WEDM performance. In addition to evaporation and melting, carbon fiber fracture is a major contributor to the removal of the allowance. In the following study, the surface morphology of the Cf-SiC composite was analyzed using SEM images to discuss the above thesis further. However, the author considers that the experimental results shown in Figure 4 are partially contrary to expectations. In the WEDM process, a temperature gradient of thousands of degrees Celsius occurs at the discharge spot, which leads to significant thermal stresses. SiC is a brittle material and very sensitive to thermal stresses. The thermal stresses caused by the large difference in the thermal expansion coefficients of the carbon fiber and SiC also significantly affect the fracture of carbon fiber. Analysis of the microscopic images aimed to locate any evidence of carbon fiber cracking caused by excessive thermal stresses. Such traces would prove that thermal stresses exceeded the strength of carbon fiber and SiC matrix during WEDM.

Surface roughness

The isotropic structure is covered with craters on the surface of the metals after WEDM, which

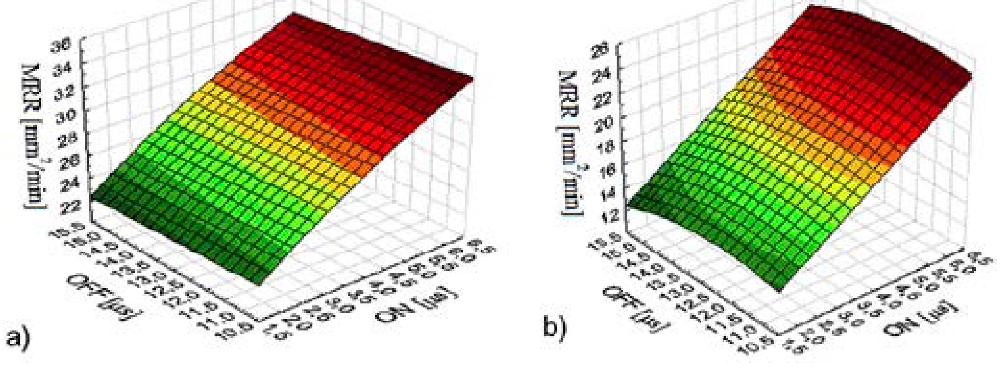

Figure 4. Impact of the time parameters of the WEDM on the MRR of the machined: a) steel and b) Cf-SiC

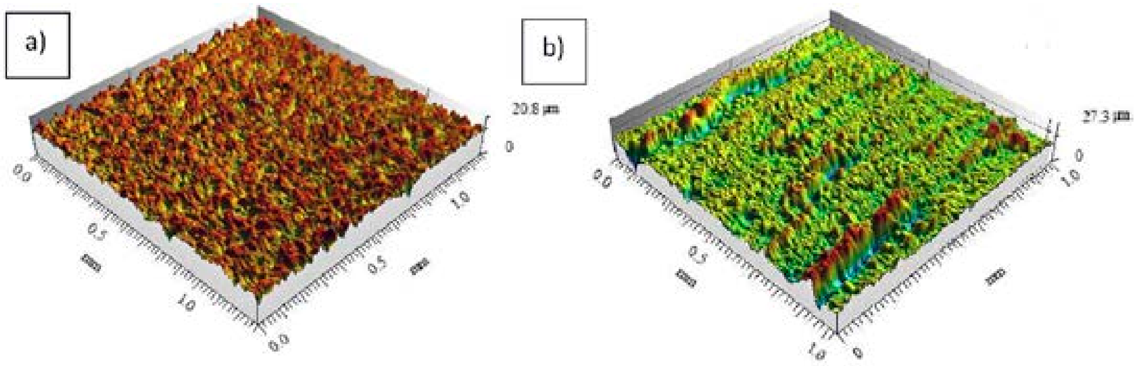

Figure 5. Lowest roughness *Sa* of the WEDM surfaces: a) steel grade 55 and b) Cf-SiC

is one of the characteristic features of this process. Figure 5a shows a 3D view of the surface roughness machined steel grade 55. Surface roughness values are lower than for WEDM of Cf-SiC. There are no traces of fracture of the material; we can see specific craters in all the analyzed areas.

Values measured on the surface of Cf-SiC are higher than those for steel (Figure 5b). The dominant elements of the Cf-SiC surface after WEDM are bundles of fiber, a washed-out SiC matrix, and the cavities left by the pores present in the composite material. The measured values of $Ra = 2.5$ µm and $Sa = 2.0$ µm (Cf-SiC surface roughness parameters) after WEDM are acceptable. He et al. (He et al., 2019) argued that, for a cutting perpendicular to the fiber alignment, a lower surface roughness was obtained than for a WEDM direction along the fibers. The relative contribution of transverse and longitudinal microcracks of the fibers to the MRR depends on the direction of the cut relative to the fiber alignment. The authors reasoned that carbon fiber alignment has a greater impact on the surface roughness than on MRR in WEDM of the analyzed Cf-SiC. In Figure 5b, we can observe the anisotropic texture of the composite after WEDM. We also have directional fiber bundles. A partially melted matrix of Cf-SiC with extensive amounts of pores and micro-cracks creates short rows on the surface. The selected average roughness height indices do not seem to sufficiently and unambiguously characterize the analyzed surfaces.

SEM surface morphology images

Since the analyzed fiber-reinforced composites contain a ceramic matrix that provides poor electrical conductivity, the material removal rate should be low for WEDM Cf-SiC, as claimed by Du et al. (Du et al., 2018). When the cutting electrode is perpendicular to the carbon fiber layer, a cutting off of a large portion of the carbon fiber along its radial direction is induced by discharges. For a vertical direction to the fiber layup, cracks across the fibers play a dominant role. As a result of the electrical discharge process, the carbon fiber undergoes transverse fracture and then detaches from the remainder part of the carbon fiber under the impulse interval. This also supports the theory submitted by He et al. (He et al., 2019) that the relative position of the wire electrode and the fiber has a significant effect on the material removal mechanism. In contrast, for a cutting direction parallel to the carbon fiber layup, inter-phase debonding of the fiber and matrix gain significance for MRR. Pitting can then be observed on the machined surface of the composite, and a layer of recrystallized material can be seen. In addition, the measured MRR values are higher for WEDM perpendicular to the location of the carbon fibers, which is supported by the results obtained by Yue et al. (Yue, Li & Yang, 2020) when cutting the unidirectional composite. MRR then exceeds the results obtained during WEDM of mold steel. Moreover, in research by He et al. (He et al., 2019) on WEDM with a molybdenum wire, an MRR was noted to be higher in the direction perpendicular to the fiber alignment than for the parallel cutting direction. Therefore, it can be concluded that the transverse fracture of carbon fibers at an angle of 90° plays a dominant role in the material removal process. From the view of the surface layer (Figure 6), it can be inferred that the interphase delamination at the fiber/SiC interface also occurs due to incompatible micro-deformation between the fibers and SiC.

Pitting and over-melting formed during the discharge on the machined surface of the matrix can be seen; fractures also develop on the matrix surface. The formation of micro-cracks can be explained by thermal expansion and local micro-bursts induced by the discharge energy. Strong shock waves occur that propagate from the center of the carbon fiber when

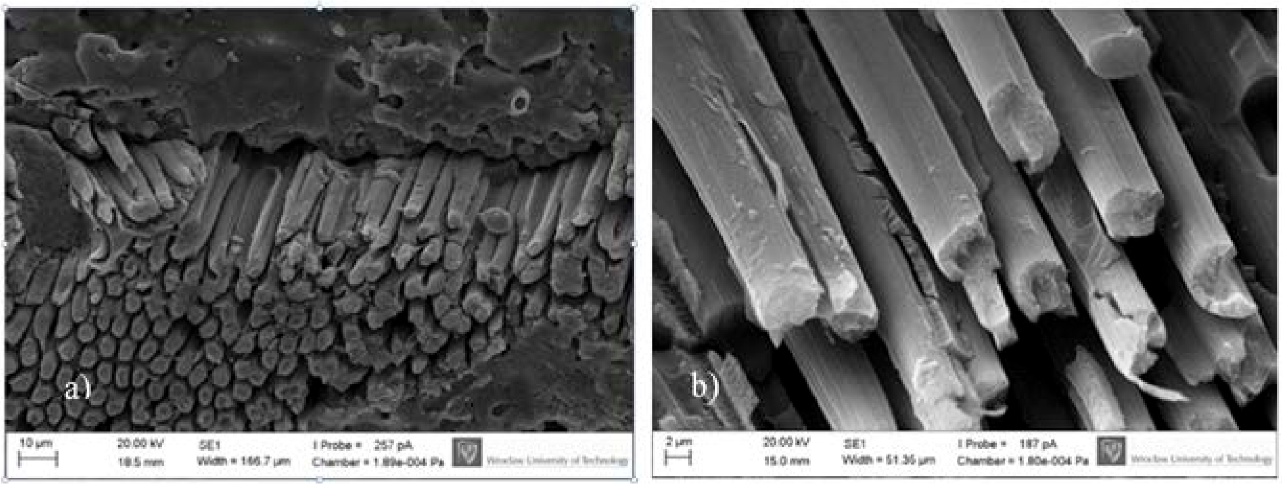

Figure 6. SEM image with two magnifications: a) melted SiC matrix, pores, gaps, and fiber bundle and b) transverse fractures of carbon fibers without a melted SiC matrix

the wire electrode moves toward the center of the carbon fiber. On the basis of the SEM surface topography analysis, 3D roughness views determined that thermal stress plays a significant role in the material removal in the WEDM of Cf-SiC composite. Thus, the astoundingly high cutting speed of the Cf-SiC composite can be attributed to the action of the thermal stress caused by the electrical discharges.

From the above, it can be concluded that unconventional machining of ceramic matrix composites reinforced with carbon fibers shows properties superior to the effects of traditional cutting or abrasive processes. Non-contact machining can be performed by equipment that induces a high heating, high pressure, or high vibration frequency. As Du et al. (Du et al., 2018) mention, surface quality is continuously improved, and WEDM has enormous potential for development. During WEDM of ceramic composites, heat-affected zones can be greatly decreased by proper process parameters selection, omission of contact stresses, and effective diminishing of typical defects such as chipping, burring, cracking, fiber pulling, and other composite machining-related damage.

Conclusions

The cutting performance of Cf-SiC exceeds the predicted value considering the low electrical conductivity, high sublimation temperature, or high thermal conductivity of the composite. The surface performance results showed that the cutting of steel grade 55 was about 36% quicker than the analyzed composite. A further increase in the discharge energy due to a longer pulse ON-time does not increase the performance. This may be due to the inefficiency of the gap flushing system.

As opposed to the isotropic metal surface after WEDM, the Cf-SiC surface after WEDM is directional and strongly anisotropic according to the fiber arrangement in the composite. Moreover, the measured values of the surface roughness parameters $Ra = 2.5$ and $Sa = 2$ µm for Cf-SiC after WEDM treatment are acceptable but indicate that additional finishing operations are needed. However, their average values do not seem to sufficiently and unambiguously characterize the analyzed surfaces. The difference in thermal expansion of the carbon fiber (negative) and the silicon carbide (positive) affects the enhancement of the WEDM performance. The WEDM material removal rate of the composite is higher than that of the cutting SiC or carbon fiber alone.

The fractured carbon fibers observed in microscopic SEM images indicate that carbon fiber cracking due to excessive thermal stresses is the predominant material removal mechanism in the WEDM of the CF-SiC composite material. Thermal stresses induced by electrical discharge exceed the strength of the carbon fibers and SiC matrix. The dominant elements of the Cf-SiC surface after WEDM are fractured carbon fibers, a washed-out SiC matrix, and the cavities left by the pores present in the composite material.

The multidirectional orientation of the carbon fibers makes it more difficult to analyze the EDM machinability. Other machining effects, parallel and perpendicular to the fiber alignment surface (unidirectional), are mentioned in the literature. WEDM should be considered a good alternative to Cf-SiC abrasive machining when cutting holes, grooves, keyways, splines, and other complex shapes.

The authors report there are no competing interests to declare.

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