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Technological Considerations in WEDM of Carbon Fiber Reinforced Silicon Carbide Composites (Cf-SiC)

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Wire electrical discharge machining (WEDM) was employed to process thin-walled, multidirectional carbon fiber-reinforced silicon carbide (Cf-SiC) composites. This study investigates the effects of key WEDM parameters, including gap voltage (Vg), pulse on-time (Ton), pulse off-time (Toff), and wire electrode type on material removal rate (MRR) and surface roughness (SR). All experimental planning, data analysis, optimization, and result visualization were conducted using MATLAB software. Results indicate that using CuZn50-coated wire electrodes increases MRR by 11% compared to CuZn37 bare brass wire. Scanning electron microscopy (SEM) confirmed the inverse thermal expansion-based material removal mechanism, revealing surface defects such as fiber fractures, interfacial detachment, craters, and micro-cracks. Surface roughness, as indicated by 3D topographic measurements was found acceptable with an average Ra between 2 and 3 µm. Overall, WEDM proves effective for machining Cf-SiC, especially for complex geometries such as holes, grooves, keyways, and splines when appropriate electrodes and parameters are applied.

Keywords: WEDM, Wire electrode, Ceramic matrix composites, Cf-SiC, Matlab

1 Introduction

This research investigates the effectiveness of wire electrical discharge machining (WEDM) on carbon fiber-reinforced silicon carbide (Cf-SiC), comparing the performance of two distinct electrode materials. The first electrode used is a standard CuZn37 brass wire with a diameter of 0.25 mm, while the second is a modified wire featuring a CuZn20 core with an outer CuZn50 coating. The primary goal is to assess whether WEDM with the coated electrode can serve as a more efficient alternative to the traditional brass wire when machining Cf-SiC. This study presents an analysis of the three-dimensional geometry of the Cf-SiC surface following WEDM, highlighting both the potential and limitations of this method for machining Cf-SiC components.

1.1 WEDM of composites and other hard-to-machine materials

WEDM is highly effective not only for tool steels but also for materials that are difficult to machine, such as cemented carbides, composites, nickel-based alloys, titanium alloys, and shape memory alloys. It offers abrasion-free machining with minimal surface damage. Extended research [1] has examined the performance of WEDM on porous materials like aluminum foam and the EN AW 5005 alloy, evaluating cutting widths, surface structures, and dimensional accuracy through microscopic observations. This study [2] emphasized how WEDM parameters, such as gap voltage and pulse duration, affect the machining of Ti6Al4V alloy, focusing on optimizing cutting speed to balance efficiency and surface finish quality. Another study [3] examined the influence of WEDM on steel 11 373.0, revealing that thermal load during the process alters the surface structure and affects cutting forces in subsequent milling operations. These findings underscore the importance of thermal management to maintain the structural integrity of materials during and after machining.

One of an emerging areas of research is the application of wire electrical discharge machining (WEDM) to composite materials, particularly ceramic matrix composites (CMCs). One study [4] highlighted the development of Cf-SiC composites, which combine carbon fibers with a silicon carbide matrix, offering strength comparable to grey cast iron. These composites, produced via liquid silicon infiltration (LSI), are gaining traction in industrial applications due to their lightweight nature and stability at high temperatures. They are used in heat exchangers, thermocouple protection tubes, and other high-temperature components, with potential applications in optical systems and ballistic protection. WEDM has proven useful for mitigating common machining issues such as micro-cracks, white layer formation, and high surface roughness. Key process parameters like pulse on-time, pulse off-time, and servo voltage are crucial in optimizing material removal rate (MRR) and surface quality. Authors of [5] demonstrated the significant impact of

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these parameters on WEDM of tool steels, while another study [6] explored the influence of peak current and electrode feed on the surface characteristics of Inconel. The WEDM process has advantages over traditional machining methods, which struggle with excessive tool wear and high costs, especially in carbon fiber-reinforced ceramic matrix composites (Cf-SiC). Conventional techniques, such as milling and grinding, often face challenges like internal defects, cutting forces and surface quality. Research [9] examined these effects in milling, while another study [10] explored increased tool wear flat and grain breakage with grinding wheels, revealing that non-conventional methods provide greater stability. More recent investigations [12] into Cf-SiC machining have focused on technologies like laser cutting [11] and abrasive water-jet machining [13]. However, due to the poor electrical conductivity of Cf-SiC, MRR in WEDM remains low, limiting its broader use. Other studies of WEDM [14] and EDM [15] explored methods to enhance WEDM performance on fiber-reinforced composites, finding that high frequency, lower pulse energy improves MRR and surface quality. Research [16] emphasized the importance of carbon fiber orientation in WEDM, with machining directions significantly affecting surface quality and interfacial delamination between fibers and the SiC matrix. Transverse and longitudinal cracking of fibers, alongside matrix microcracking, were observed.

In summary, unconventional machining methods, particularly WEDM, demonstrate clear advantages over traditional techniques for carbon fiber-reinforced ceramic matrix composites[15]. WEDM has shown great potential in producing high-quality surfaces and intricate geometries while effectively reducing contact stresses and minimizing defects, as evidenced by numerous studies [18].

2 Experiment planning

Composites exhibit a diverse range of properties and varying degrees of machinability. The selection of the appropriate cutting method depends on factors such as the size and shape of the component, cutting efficiency, surface roughness and stresses generated during the machining process. Selecting an unsuitable cutting technique can result in debonding, chipping or cracking of the composite material near the cutting edge. As highlighted by study [19], the main objective of machining composite materials, including the selection of parameters and tools, is to minimize delamination. The WEDM machine used for Cf-SiC is of a wearable wire feeding mechanism type (Fig. 1). The composite samples were manufactured using the Liquid Silicon Infiltration (LSI) method. The ceramic matrix composite (CMC) material (Cf-SiC) used for the test had a height of 15 mm and a wall thickness of 4 mm. Pulse on-time, pulse off-time and Vg - gap voltage were the variables, while the rest of the parameters were kept constant. Dielectric pressure, wire tension, wire speed and current remained unchanged during the experiment. The machining direction was perpendicular to the carbon fiber layer. The process was conducted using deionized water as the dielectric fluid. The surface roughness (2D and 3D) of the cut parts and three-dimensional surface profiles were measured using a Mitutoyo SV – 3200 profilometer. For the purpose of this publication, only the Ra parameter was considered due to the preliminary nature of the testing.

Fig. 1 *Wire electrical discharge machine ZAP BP 800– parameter control panel and cutting area*

This study provides a structured approach to analyzing, modeling, and optimizing the experimental data for MRR and SR using the Taguchi method, regression models, and response surface methodology. Following steps were applied for calculations and visualization of results. Author implemented MATLAB code for analyzing Material Removal Rate (MRR) and Surface Roughness (SR) using Taguchi analysis, regression models, and optimization:

- Taguchi experiment planning matrix was applied. ANOVA variance analysis was used to identify and investigate significance of WEDM parameters on MRR and SR (L9 and boxplots). MRR_L9 and SR_L9 contain the experimental values for material removal rate and surface roughness expressed by Ra for each combination of input parameters Ton - pulse on -time, Toff - pulse off -time, Vg - gap voltage values. Replications for each parameter combination was three.
- Boxplots to visualize relationships were generated to analyze the distribution of MRR and SR values with respect to each parameter (Ton, Toff, and Vg). This helps to observe the effect of varying levels of the input parameters on MRR and SR. ANOVA (Analysis of Variance) was applied to identify which parameters have the most significant impact on the response variables.
- The regression models predict MRR and SR as a function of \`Ton\`, \`Toff\`, and \`Vg\`. The quadratic term (\`$Ton^2$\`) accounts for any potential non-linear relationship between Ton and the responses. These models were created using the \`fitlm\` function, which builds a linear regression model based on the provided formula.
- The 3D scatter plots were implemented for response surface visualization to show how the MRR and SR responses vary with the three input parameters. This is a type of 4D visualization useful for models with three variables, where each point represents an experimental combination of Ton, Toff, and Vg, with the colour of the points corresponding to the measured MRR(SR) values.
- Optimization for MRR and SR: The function \`fmincon\` is implemented to maximize MRR by minimizing the negative of the predicted MRR (i.e., maximizing \`-MRR\`), minimizes SR by directly minimizing the predicted values from the SR model and Simultaneous Optimization (MRR and SR): - simultaneously maximizes MRR and minimizes SR by normalizing the predicted values and combining them with weights for effects (w_MRR and w_SR = 0.5).
- Scanning Electron Microscope (SEM) images showcasing the morphology of machined Cf-SiC were presented, analysed, and thoroughly discussed.
- The surface roughness parameters Ra and Sa, as defined by ISO 25178 for Cf-SiC composites following WEDM, were illustrated on 3D plots and discussed.

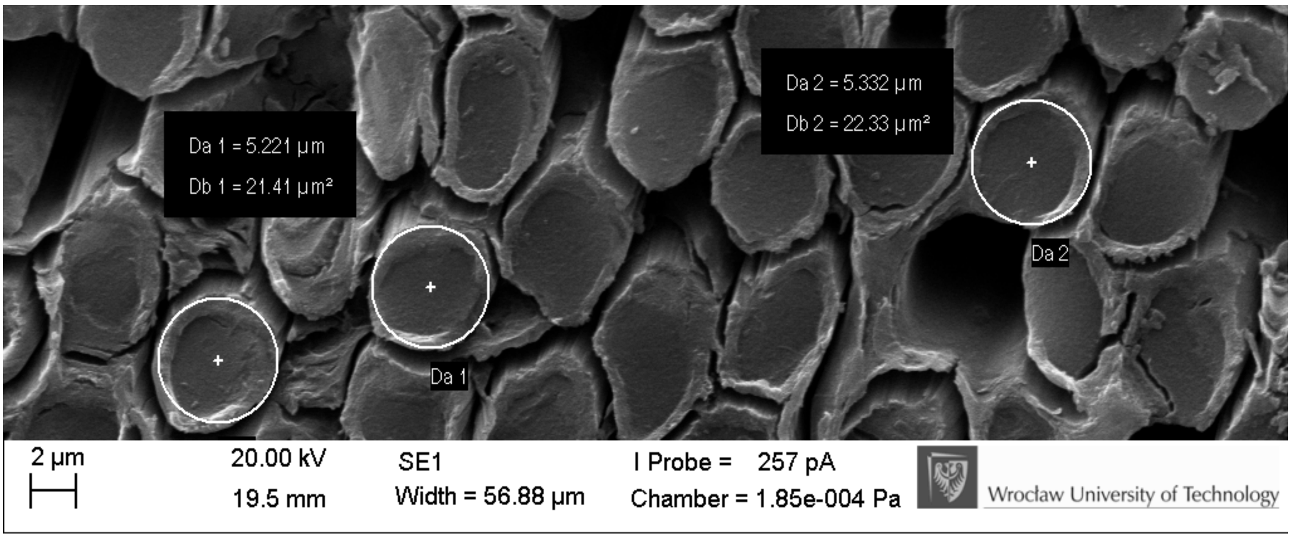

***Fig. 2** SEM image showing sample carbon fiber size and SiC matrix*

Fig. 2 illustrates the microstructure with measurements. SEM images were captured at various magnification scales, and in certain cases, a gold layer approximately 10 nm thick was sputtered. The SEM images of the composite show fibers with a diameter of about 5 μm, woven with cross-directional carbon fiber bundles. The matrix material surrounds the carbon fibers, with the woven 22.5° or 67.5° carbon fibers spread across subsequent layers. Both the inside and outside of the samples were coated with a SiC layer. SEM image of the sample cross-section is demonstrated on Fig. 3 (visible carbon fibers, coating layers, and SiC matrix) with a schematic of the composite structure, including perpendicular wire machining direction. Tab. 1 presents the main properties of the tested Cf-SiC composite. The samples were processed using a CNC WEDM at a low feed rate with a disposable wire electrode. The consumable wire electrode moves through a continuously flushed gap, ensuring smooth operation, consistent diameter, minimal vibration, and excellent cutting precision. Unlike previous studies on unidirectional carbon fiber reinforced ceramic composites, the analyzed and machined material in this research consisted of multidirectional carbon fibers. Wire electrical discharge machining (WEDM) systems are commonly divided into two categories based on the wire feed speed.

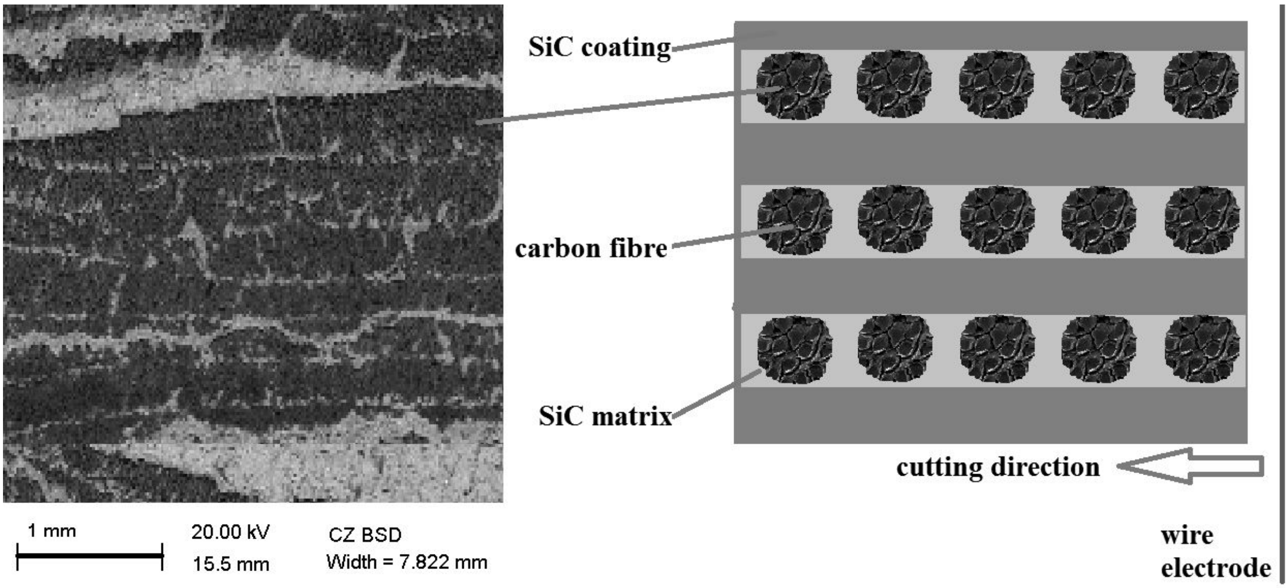

Fig. 3 *The sample cross-section with a schematic structure (carbon fibers, coating layers, and SiC matrix visible), including perpendicular wire electrode position*

Tab. 1 *Physicochemical properties of Cf-SiC composite analyzed in tests*

	High strength carbon fibre	**SiC**
Density [kg.m^{-3}]	1800	3217
Young modulus [GPa]	234	440
Electrical resistivity [Ω·cm]	1,53 x 10-3 (along fibre axis)	5000
	1,53 x 10-2 (vertical to fibre axis)	
Specific heat [J·kg-1·K-1]	710	690
Poisson ratio	0.27	0.17
Thermal expansion coefficient [K-1]	-1.7 x 10-6 (along fibre axis)	4.3 x e-6
	5 x 10-6 (vertical to fibre axis)	
Thermal conductivity [W/m·K]	10 (along fibre axis)	490
	2 (vertical to fibre axis)	

The first type includes CNC low-speed wire-cut EDM machines, which use consumable electrodes such as brass, copper, or wires coated with multiple layers. The second type involves CNC high-speed wire-cut EDM machines, which typically employ non-consumable molybdenum electrodes. This distinction is widely recognized in the market. In low-speed wire-cut EDM machines, illustrated in Fig. 1, the wire moves continuously at a slow pace, approximately 0.2 m.s^{-1}, and the consumable electrode is discarded after use. These machines are designed to operate with minimal vibration and maintain a consistent wire diameter, ensuring superior cutting precision and surface finish. The geometry of the test workpiece is shown in Fig. 1, while the material properties are outlined in Tab. 1.

3 Experimental procedure and results

Two types of wire electrodes were used in this study. The first was a consumable brass electrode (CuZn37) with a diameter of 0.25 mm and a tensile strength of 450 MPa. The second electrode was a coated wire consisting of a CuZn50 exterior with a CuZn20 core, designed to improve material removal rates due to its thicker diffusion layer and more elastic core. This coated wire offers an optimal balance of cutting speed, accuracy, wear resistance, and surface quality, making it well-suited for achieving narrow kerfs and precise internal corners. The coated wire's improved strength contributes to better wall straightness and reduces the likelihood of wire breakage, a common issue with standard brass wires. The electrode specifications used in this study are summarized in Tab. 2. The data consists of MRR and SR values for different sets of machining parameters: Ton (pulse on-time), Toff (pulse off-time), and Vg (gap voltage). mean_MRR and mean_SR are calculated to find the average MRR and SR across each experiment. Boxplots on Fig. 4 and Fig. 5 visualize the relationship between MRR/SR and the parameters to understand how Ton, Toff, and Vg affect MRR and SR.

Tab. 2 *The most significant properties of the chosen electrode materials*

	CuZn37	CuZn20/CuZn50
Melt. point [°C]	925	940/905
Vapor. point [°C]	1100	1150/ 1000
Thermal conductivity, [W/mK]	120-130	120-130
Electrical conductivity [MS/m]	16,2	17/16
Tensile strength, [MPa]	450	480

Analysis of Variance (ANOVA) is conducted separately for MRR and SR to determine the statistical significance of each machining parameter (Ton, Toff, Vg) on MRR and SR. The p-values from the ANOVA tests are stored and displayed in a table. The ANOVA analysis will reveal which parameters (Ton, Toff, Vg) have a statistically significant effect on MRR and SR. Parameters for WEDM are presented in Tab. 3 and Tab. 4. Parameters with lower p-values are more influential. Pulse on - time for both MRR and SR is the most critical parameter for both wire types in determining MRR. It has the strongest impact, meaning that changes in Ton significantly influence both material removal and surface roughness. Pulse off - time is only significant for the coated wire (CuZn50) both for material removal rate as for surface roughness. Toff does not significantly affect either MRR or SR for CuZn37 wire electrode as shown by high p-values. This situation can be related to lower MMR measured for uncoated wire. Smaller volume of a material is removed and there was enough time for effective flushing of the gap. But for higher MMR when WEDM with coated wire then increased Toff helps to evacuate eroded material. Vg (Gap voltage) is not significant for either MRR or SR implying that the voltage variation has little effect on the outcomes within the tested range. Gap voltage increase with inter-electrode gap width and this is why it has less significance in analysed range. Linear regression models are built to predict MRR and SR based on the parameters. The predicted, by application of "fitlm" function of MATLAB.

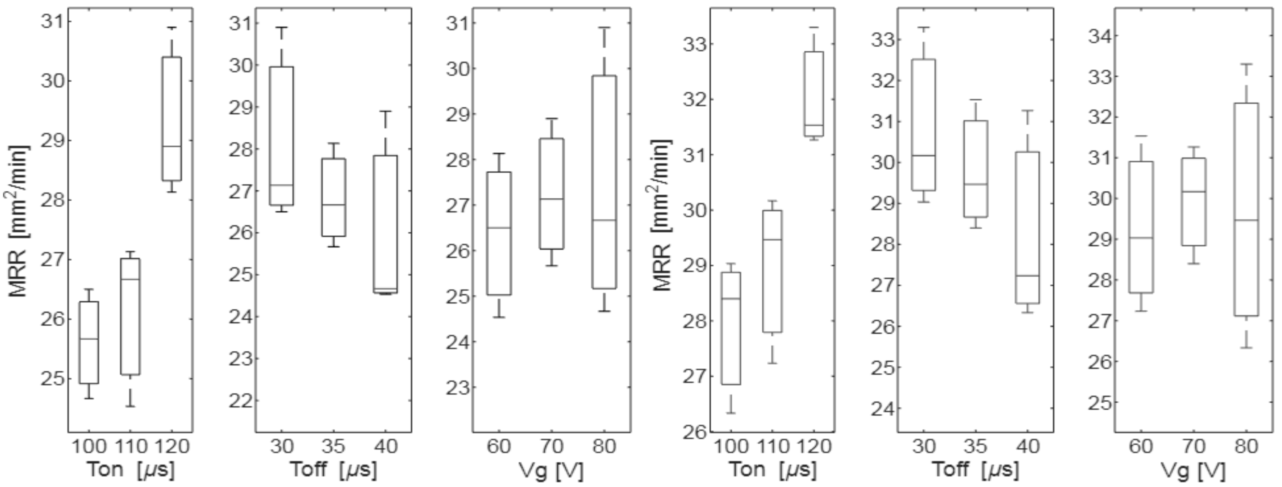

Fig. 4 *Boxplot presenting how each machining parameter (Ton, Toff, Vg) affecting MRR: uncoated wire – blue, coated wire – red*

Values of MRR and SR from the models are compared with the experimental data to evaluate the accuracy of the models. Results of verification are presented in Tab. 5 and Tab. 6.

Linear regression model:

$$MRR \sim 1 + Ton + Toff + Vg + Ton^2 \quad (1)$$

Both models for MRR, with R^2 values of 0.966 (bare wire) and 0.973 (coated wire), indicating that the process parameters explain most of the variation in MRR. For the CuZn37 wire the effect of Ton is more pronounced, with a significant p-value of 0.028, while for the coated wire it is slightly less impactful, with a marginal p-value of 0.062. For both wire types, Ton has a negative linear relationship with MRR but also the significant quadratic Ton^2 factor. In both models, increasing Ton improves MRR, but over a certain point (about100μs), as it is presented on the plots. The effect of Toff is high significant for both electrodes and indicating that flushing efficiency is even more crucial for coated wire. The negative relationship between Toff and MRR suggests that shorter off-times help maintain higher MRR by decreasing the interval between pulses. Voltage has a marginal influence on MRR for both wire types, This suggests that, under the conditions tested, voltage optimization plays a lesser role in determining MRR compared to Ton and Toff.

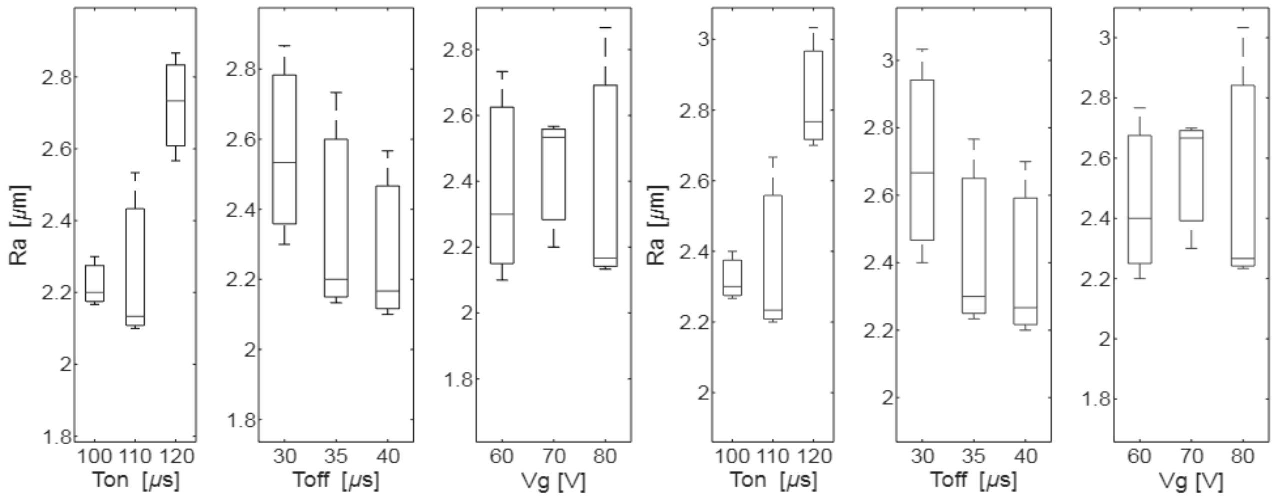

***Fig. 5** Boxplot presenting how each machining parameter (Ton, Toff, Vg) affecting average height of surface roughness Ra: uncoated wire – blue, coated wire – red*

***Tab. 3** ANOVA Table for MRR*

Parameter	P_value_MRR (CuZn37)	P_value_MRR (Coated)
Ton	0.0451	0.0003
Toff	0.3987	0.0128
Vg	0.9253	0.1269

The models for SR using bare and coated wires highlight the influence of process parameters on surface finish quality represented by average height of roughness Ra.

Linear regression model:

$$SR \sim 1 + Ton + Toff + Vg + Ton^2 \quad (2)$$

Both SR models show strong explanatory power, with R^2 values of 0.929 (bare wire) and 0.916 (coated wire). Ton is slightly more significant for the bare wire ($p = 0.053$) compared to the coated wire ($p = 0.078$), when it comes to surface finish. Toff plays a key role in controlling SR for both wire types, with a highly significant negative effect in both models. Longer off-times allow for better flushing and minimizing thermal damage to the surface. Vg shows no significant impact on SR for either wire type, with both models indicating that voltage variations have little to no effect on surface finish within the tested range. Both electrode regression analyses for MRR and SR underline the critical role of Ton and Toff in optimizing performance in WEDM cutting, regardless of wire type. The quadratic effect of Ton indicates that fine-tuning the pulse duration is essential to balance material removal and surface finish.

***Tab. 4** ANOVA Table for SR*

Parameter	P_value_SR (CuZn37)	P_value_SR (Coated)
Ton	0.0312	0.0006
Toff	0.5124	0.0713
Vg	0.8769	0.8739

Tab. 5 *Regression Model parameters for MRR bare – CuZn37 and coated wire - CuZn50*

CuZn37	**Estimate**	**SE**	**tStat**	**pValue**
(Intercept)	173.04	45.61	3.7939	0.019204
Ton	-2.785	0.83205	-3.3472	0.028644
Toff	-0.21444	0.043656	-4.9121	0.0079743
Vg	0.051111	0.021828	2.3415	0.079246
Ton^2	0.0135	0.0037807	3.5707	0.02336
RMSE = 0.535; p-value = 0.00336				
CuZn50	**Estimate**	**SE**	**tStat**	**pValue**
(Intercept)	137.46	43.616	3.1516	0.034461
Ton	-2.0433	0.79568	-2.568	0.062108
Toff	-0.25556	0.041748	-6.1214	0.0036073
Vg	0.021667	0.020874	1.038	0.35791
Ton^2	0.010222	0.0036155	2.8273	0.047473
RMSE = 0.511, p-value = 0.00217				

Tab. 6 *Regression Model parameters for SR bare – CuZn37 and coated wire - CuZn50*

CuZn37	**Estimate**	**SE**	**tStat**	**pValue**
(Intercept)	26.694	9.122	2.9264	0.042968
Ton	-0.45167	0.16641	-2.7142	0.053306
Toff	-0.028889	0.0087312	-3.3087	0.029691
Vg	0.00055556	0.0043656	0.12726	0.90488
Ton^2	0.0021667	0.00075615	2.8654	0.04568
RMSE = 0.107, p-value = 0.0146				
CuZn50	**Estimate**	**SE**	**tStat**	**pValue**
(Intercept)	25.994	10.236	2.5396	0.06401
Ton	-0.43889	0.18673	-2.3504	0.07848
Toff	-0.031111	0.0097973	-3.1755	0.033681
Vg	0.0027778	0.0048987	0.56705	0.60099
Ton^2	0.0021111	0.00084847	2.4881	0.06762
RMSE = 0.12, p-value = 0.0198				

3.1 Material Removal Rate (MRR)

The MRR in the WEDM process was calculated as the cutting rate multiplied by the height of the workpiece. Fig. 6 shows the impact of time-related parameters and gap voltage on material removal rate. The experiments using both electrodes were conducted with identical parameter settings due to their technical distinctions. The CuZn50-coated wire consistently demonstrated higher MRR than the uncoated wire, with an increase ranging from 8.15% to 11.43% across all tests. This improvement is attributed to the enhanced flushing ability of the coated wire, which promotes better debris removal from the inter-electrode gap, as the increased amount of zinc vaporization aids in gas production and reduces melted debris. Ton directly influenced MRR, as longer discharge times provided more energy for material removal. It is noteworthy, that when discharge on - time is long beyond optimal flushing limit, there will be a drop of a number of effective discharges because of cumulated debris inside the gap. Shorter Toff values facilitated higher MRR, as more frequent discharges occurred. The coated wire particularly benefited from this, consistently outperforming the uncoated wire. Voltage (Vg) had a notable impact on MRR for both wires, as higher voltages increased discharge energy, further enhancing the MRR especially for the coated wire due to its superior flushing capabilities. The MRR graph for the Cf-SiC composite indicates that the maximum was reached and values are surprisingly high regardless low current conductivity what will be commented in the following part of the article. In optimizing the linear model using 'fmincon' MATLAB function to maximize material removal rate (MRR) within the specified parameter range, an MRR of 30.9 mm^2/min was obtained for the uncoated electrode and 33.5 mm^2/min for the coated electrode, both with parameter settings of Ton = 120 μs, Toff = 30 μs, and

Vg = 80 V. The anisotropy of the composite leads to variations in MRR when compared to metallic materials. In theory, EDM is most efficient when processing materials with high electrical conductivity, such as metals. Generally, the lower the thermal conductivity and melting point of a material, the higher its WEDM speed. Both silicon carbide and carbon fiber in the analyzed composite have high sublimation points, high resistance, and high thermal conductivity. Research [17] on WEDM using molybdenum wire shows MRR values comparable to those achieved with a brass electrode and SEM analysis in this work confirmed that carbon fibers were removed due to transverse and longitudinal fractures. However, these results are challenging to compare directly with this study due to differences in composite structure, workstations, generators, and wire electrode materials. The authors of [19], who used a smaller diameter (0.2 mm) brass wire electrode which may influence lower discharge energy in the gap during WEDM. In the work under discussion, MRR for unidirectional Cf-SiC was higher than in this research. According to the authors, the superior results are due to the use of a modern generator with enhanced current pulse characteristics, optimization of process parameters, and the type of unidirectional fiber used. The fiber alignment perpendicular to the carbon fibers ensures greater process stability and fewer discharge interferences compared to the multidirectional fiber alignment in the current study.

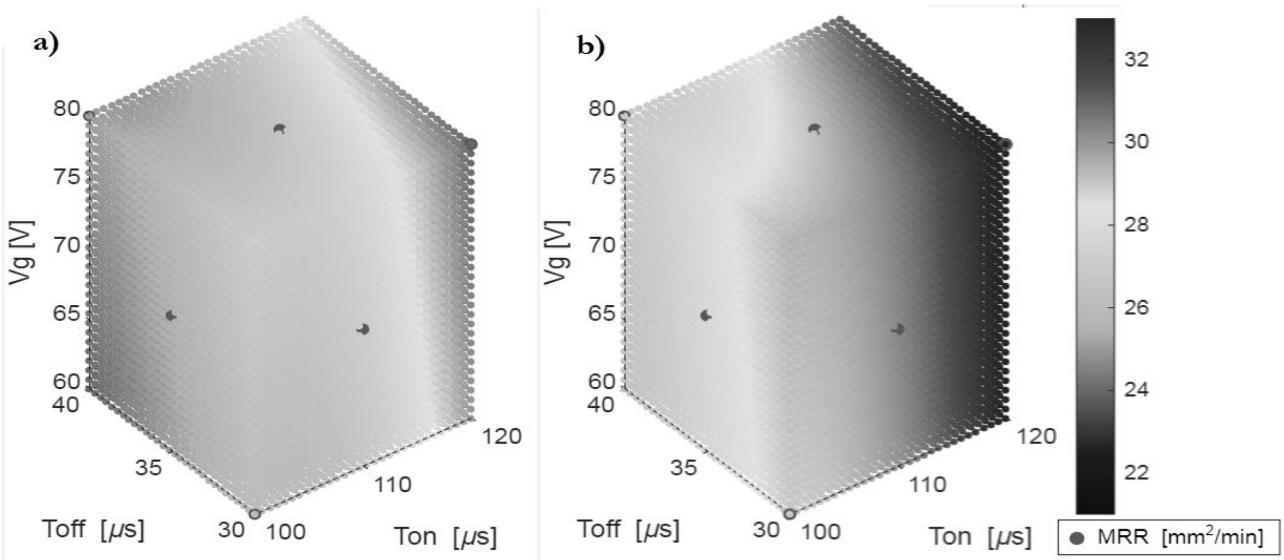

Fig. 6 *Effect of WEDM parameters on MRR in Cf-SiC machining: a) bare brass wire, b) coated wire*

3.2 Surface Roughness

The dependence of surface roughness Ra upon ON/OFF – times and Vg-gap voltage was obtained through regression model as shown in Fig. 7. The coated wire resulted in slightly higher surface roughness across most tests. Values for the coated wire were consistently higher, with increases from 3.7% to 8.7% compared to the uncoated wire. The greater amount of zinc vaporization in the coated wire led to more effective material removal but also rougher finishes. The highest Ra = 3,1 μm (Fig7b) is seen at Ton = 120 μs and Toff = 30 μs, which likely corresponds to the most aggressive discharge conditions. Such roughness involves a undesirable heat affected zone. However, shorter discharge time for brass wire resulted in roughness Ra around 2 μm (Fig. 7a), significantly reducing the heat affected zone. Increasing Ton values worsened surface roughness, particularly for the coated wire, as higher energy discharges produced rougher surfaces due to the larger volume of material removed per discharge. For higher-energy discharges, increasing pulse off-time to extend flushing time appears to be an effective method of improving surface roughness. Vg had minimal effect on surface roughness, although slightly higher sensitivity to gap voltage was observed for the coated wire. In optimizing the linear model using 'fmincon' function to surface roughness (SR) minimization, a surface roughness Ra of 2.03 μm was achieved with the uncoated electrode and 2.1 μm with the coated electrode, under parameter conditions of Ton = 105 μs, Toff = 40 μs, and Vg = 60 V. For combined optimization, a balanced set of parameters is found that optimizes both MRR and SR, considering the trade-off between them. A combined optimization with equal weighting (0.5), resulted in an MRR of 25.4 mm^2/min and Ra of 2.1 μm for the uncoated brass electrode at Ton = 110 μs, Toff = 40 μs, and Vg = 80 V. For the coated electrode, the MRR was 30.8 mm^2/min and Ra was 2.6 μm under the same Ton and Vg settings, but with Toff = 30 μs. The optimized Ton, Toff and Vg values provide guidelines for selecting processing parameters to achieve maximum MRR or minimum SR based on user requirements.

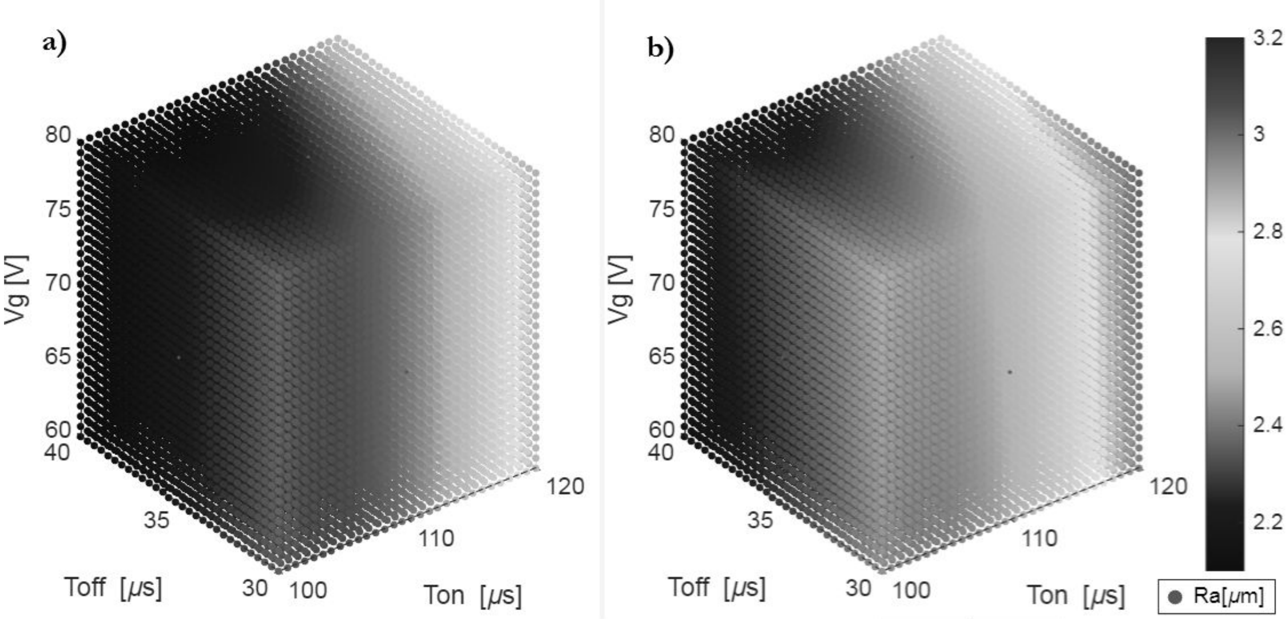

Fig. 7 *Surface roughness Ra upon ON/OFF – times and Vg-gap voltage: a) bare brass wire, b) coated wire*

The worth to notice advantage of electro-discharge machining is isotropicity of the geometric structure (Fig.8.) on the surface, especially important for applications when oriented texture is not allowed. Fig. 8b shows the 3D view of surface roughness after cutting with brass electrode, with lower roughness values than those observed for coated wire. Micro - fractures in material, prominent fiber bundles, an eroded SiC matrix, and cavities from the composite's inherent pores were observed. After WEDM with bare brass wire, the surface roughness parameters for Cf-SiC were lower and acceptable but suggest the need for further finishing. The author of [18] found that cutting perpendicular to fiber alignment resulted in lower surface roughness than cutting parallel to the fibers. The current study finds that fiber alignment affects surface roughness even more than MRR in WEDM of Cf-SiC. The anisotropic texture of the composite can be seen in Fig. 8, with high fiber bundles and a partially melted Cf-SiC matrix full of pores and microcracks. The average roughness parameters alone do not fully describe the complexity of the surface.

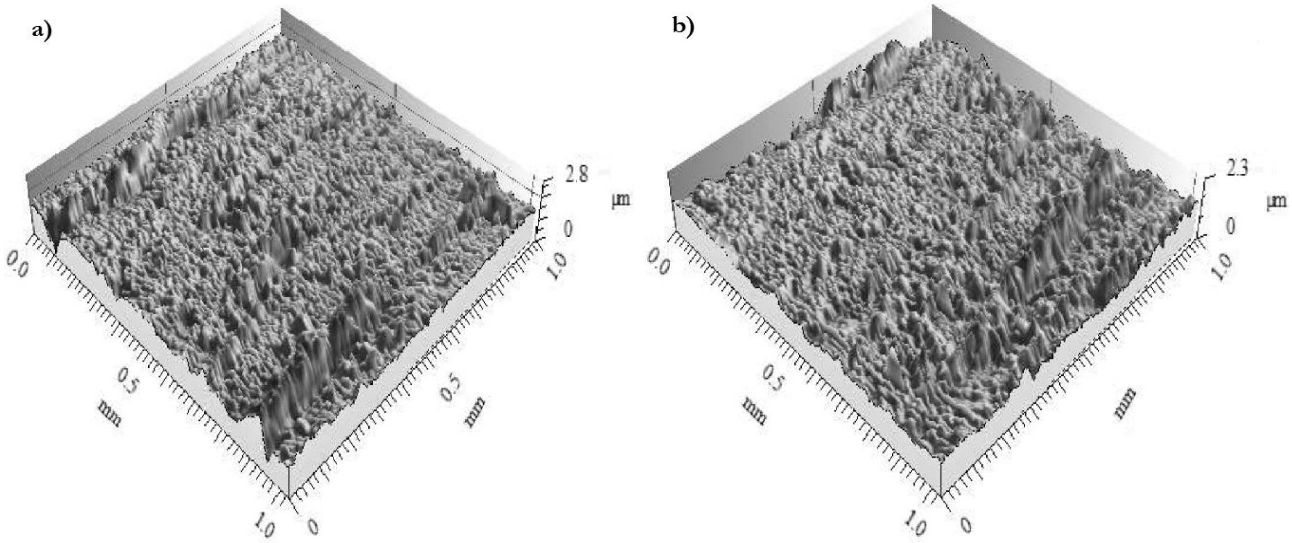

Fig. 8. *3D roughness view for WEDM: a) coated wire, b) brass wire*

3.3 SEM Surface morphology

The MRR of the composite is higher than when cutting SiC or carbon fiber separately. The authors suggest that the differing thermal expansion coefficients of carbon fiber (negative in the parallel direction) and silicon carbide (positive) enhance WEDM performance. In addition to evaporation and melting, carbon fiber fracture appears to be a major factor contributing to material removal. Further investigation into Cf-SiC surface morphology via SEM analysis was conducted to expand on this thesis. However, the author acknowledges that the experimental results in Fig. 6 partially contradict expectations. During WEDM, a significant temperature gradient develops at the discharge site, leading to high thermal stresses. SiC is a brittle material that is highly sensitive to thermal stresses. These stresses, caused by difference in the thermal expansion coefficients of carbon fiber and SiC, also significantly affect carbon fiber fracture. SEM images presented in Fig. 9 were analysed to identify evidence of fiber cracking due to excessive thermal stresses, which would suggest that the thermal stresses during WEDM exceeded the strength of the carbon fibers and the SiC matrix. Due to the poor electrical conductivity of the ceramic matrix in fiber-reinforced composites, the MRR in WEDM Cf-SiC should theoretically be low, as noted by the author of [19]. When the electrode cuts perpendicular to the carbon fiber layers, large portions of the fibers are severed radially by discharges. For perpendicular cutting, transverse fiber fractures dominate. During electrical discharge, carbon fibers undergo transverse fractures, detaching from the remaining fibers. The authors of [18] support the theory that a relative position of the wire electrode to the fiber significantly affects the material removal mechanism. When cutting parallel to the fiber layup, inter-phase debonding between fiber and matrix becomes a key factor for MRR, and pitting appears on the composite surface. Cutting perpendicular to the fibers results in higher MRR, consistent with [20], who observed suprisingly high MRR in unidirectional composites greater than in mold steel. Other authors noted that MRR was higher when cutting perpendicular to the fibers, even with molybdenum wire.

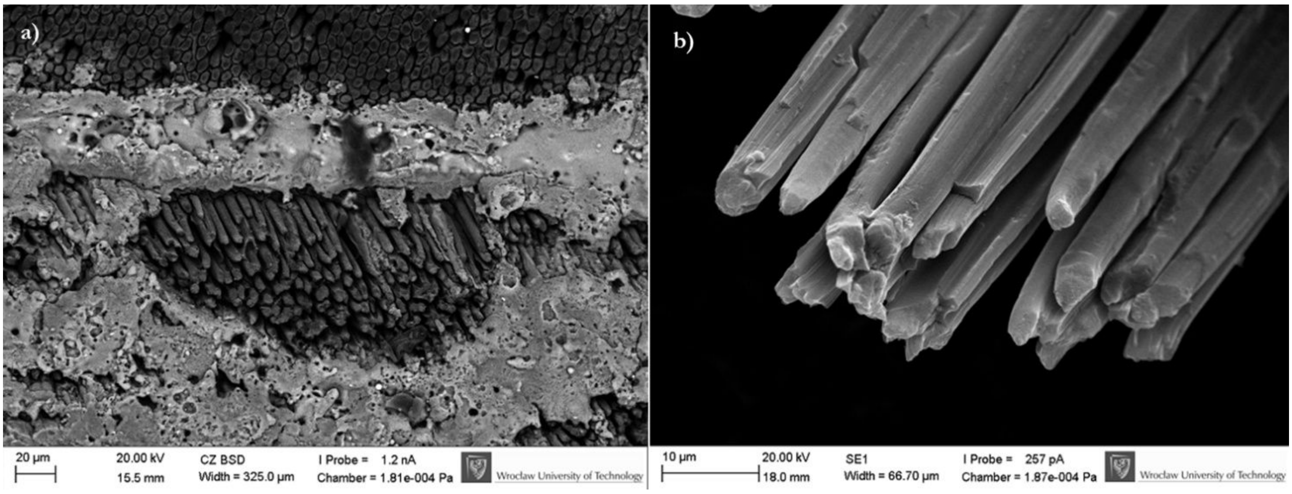

Fig. 9 *SEM images at two magnifications: a) melted SiC matrix with pores, gaps, and pulled fiber bundles, b) carbon fiber fractured without melted SiC matrix*

Therefore, it is concluded that transverse fiber fracture at a 90° angle plays a dominant role in material removal [18]. SEM surface analysis in Fig. 9 show evidence of fiber/matrix delamination, likely caused by the differing micro-deformations between fibers and SiC. The machining of Cf-SiC composites using WEDM relies on the interaction between carbon fibers and silicon carbide. The thermal expansion mismatch between these materials during machining generates significant thermal stresses, leading to fiber fractures and material removal (Fig. 9b). This mechanism, combinedwith the directional fiber structure, resulted in a patterned surface after machining. SEM images revealed that fiber pull-out and cracking were common due to the thermal stresses imposed during discharge, especially in areas with complex fiber orientations. Surface pitting and over-melting caused by discharge are evident on the machined surface, with cracks developing on the matrix (Fig. 9a). Strong shock waves propagate from the carbon fiber center as the wire electrode approaches.

4 Conclusion

This study compares the performance of uncoated CuZn37 brass wire and CuZn50-coated brass wire in the wire electrical discharge machining (WEDM) of silicon carbide matrix composites reinforced with carbon fibers (Cf-SiC). The analysis focused on material removal rate (MRR), surface roughness (SR), and the influence of key machining parameters such as pulse on-time (Ton), pulse off-time (Toff), and gap voltage (Vg). What was also confirmed by other studies [19], surface quality continues to improve and WEDM offers significant development potential. Proper selection of process parameters during WEDM of electrically conductive ceramic composites can significantly reduce the heat-affected zone, eliminate contact stresses, and minimize typical defects like chipping, burring, cracking, and fiber pull-out. The zinc vaporization from the coated wire enhances debris flushing, leading to higher MRR, but the increased number of effective discharges causes rougher surface. Optimizing parameters such as Ton, Toff, and Vg is crucial for balancing the trade-off between MRR and SR. The results indicated that WEDM, particularly with coated wires, holds potential for efficient machining of complex, low-conductivity materials like Cf-SiC composites.

- The CuZn50 - coated wire consistently outperforms the CuZn37- bare brass wire in terms of material removal rate, with an improvement of around 11.43%. This is due to the enhanced debris flushing ability provided by the zinc vaporization, which reduces the amount of debris remaining in the gap.
- The coated electrode, while improving MRR, leads to worse surface roughness (an increase of 8.7%). The higher SR values are a result of the more aggressive material removal and increased volume of craters, which produces rougher surfaces. The uncoated wire, while yielding lower MRR, offered a smoother finish, making it more suitable for applications where surface quality is critical.
- Higher pulse on-times improve MRR by increasing discharge energy, but also degrade SR. Both wires benefit from higher Ton values in terms of material removal, though the coated wire sees more pronounced gains related to superior flushing condition.
- Shorter pulse off-times boost MRR by allowing more frequent discharges, but have little impact on SR. The coated wire remains more efficient across varying Toff values, suggesting its advantage in handling debris and molten material.
- Higher gap voltages contribute to both higher MRR what came at the cost of increased SR values, highlighting the trade-off between faster material removal and maintaining surface finish quality. The coated wire outperforms the uncoated wire under all voltage conditions.
- 'fmincon' function of MATLAB is a robust tool for optimizing complex, nonlinear models with multiple parameters and constraints. It efficiently finds optimal solutions for both single-objective and multi-objective problems, like balancing focused on maximizing (MRR) and minimizing (SR) using both uncoated and coated electrodes.
- Based on SEM surface analysis and 3D roughness views, it can be concluded that thermal stress plays a significant role in material removal during WEDM of Cf-SiC composites. Consequently, the unexpectedly high cutting speed of Cf-SiC can be attributed to the thermal stress induced by electrical discharges.

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