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Effect of Machining Parameters on the Tool Wear in Drilling of 3D PF C/C Composite

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Abstract

Carbon–carbon (C/C) composites are broadly used in aerospace, defence, shipbuilding, chemical, and nuclear industries owing to their high strength-to-weight and stiffness-to-weight ratios. However, they are brittle, anisotropic and non-homogeneous in nature, making them difficult to machine. Incorrect machining parameters can cause defects such as burrs, delamination, and fibre bundles pullout. This paper aims to study the hole surface and tool wear during drilling of 3D pierced fabric (PF) carbon-carbon (C/C) composite using plain carbide and tungsten carbide drills by varying spindle speed and feed rates under dry conditions. A scanning electron microscope (SEM) was employed to analyse the tool wear and defects in the drilled hole. Energy-dispersive X-ray spectroscopy (EDS) was carried out to examine the chemical composition of the carbide tools and the adhesion after drilling. From the experiments, it was observed that breakage and edge shedding are the primary tool wear mechanisms in the tungsten carbide drill. In contrast to tungsten carbides, mechanical abrasion and carbon powder deposition were observed in the plain carbide drill. The quality of the hole entrance was superior to that of the hole middle and exit regions, regardless of the machining parameters. Typical defects in the hole included tearing and burrs, while the hole edges exhibited uncut fibres, fibre outcrops, and delamination.

Keywords: 3D C/C PF composite, drilling, carbide, tungsten carbide, tool wear

INTRODUCTION

Carbon/Carbon (C/C) composites are known for their high strength, stiffness, thermal shock resistance, and thermal stability in non-oxidising environments [1]. Due to their excellent specific strength and toughness, they are perfectly suited for lightweight thermo-structural applications in industries like aerospace and nuclear. C/C components, including nose cones, aircraft brake discs, and rocket nozzles, are commonly used in extreme conditions. The largest application is aircraft brake systems, where they provide 300 % higher heat capacity than steel, approximately 50 % weight reduction, and nearly double service life.

The quality of C/C composites is influenced by several factors involved in their fabrication. These include the quality of the polymer matrix composite used for producing C/C, the selection of pitch, which significantly affects carbon yield, and the type of carbon fibre employed. In addition, the microstructure of pitch-based materials plays an important role, along with the weave pattern of the carbon fabric. Other important factors are the fibre-matrix bond strength, the carbonisation method, and surface treatment applied to carbon fibres [1, 2]. Composites are manufactured with various weave architectures and reinforcement patterns. The reinforcement pattern serves as the basic

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framework and is selected based on the required structural and thermal properties and the loads the component will face during service.

Although C/C composite components are made to near-net shape, post-machining is still required to achieve better surface quality and dimensional accuracy. Additionally, they often need to be joined with heat-resistant structural elements for engineering needs. Drilling is a common machining process used to make holes in C/C composites for assembly. However, material heterogeneity and high hardness lead to poor hole quality, severe defects, and tool wear [1].

Few studies have investigated the drilling of carbon-based composites by focusing on tool wear, hole quality, and machining parameter optimisation. Li et al. [3] studied the hole surface morphology and tool wear mechanisms in 3D braided C/C composites utilising a bronze-sintered diamond core tool, finding superior hole entrance quality regardless of machining parameters. Shan et al. [4] compared three drilling methods for C/C composites and identified rotary ultrasonic drilling as the most effective method for the tested machining parameters. Sastry et al [5] optimised process parameters such as point angle, feed and spindle speed affecting the delamination factor on drilling of C/C composite with a TiN-coated carbide tool, while Isbilir et al. [6] developed a 3D progressive failure model to predict and control delamination in CFRP drilling. Adda et al. [7] optimised drilling parameters for woven Jute Fibre/polyester bio-composites and concluded that lower feed rates and smaller-diameter drills minimise delamination. Ferreira et al. [8] compared three different tool materials for CFRC turning and determined that PCD is the best for finishing, while carbide is applicable for rough turning with restrictions. Belmonte et al. [9] studied the cutting forces and wear behaviour of uncoated and coated tools in CFRC turning, finding that carbide tools exhibited increasing wear and cutting force with speed, whereas CVD-coated tools maintained consistent forces even at higher speeds.

Du et al. [10] reviewed conventional and unconventional machining methods for CFRP composites, addressing challenges and solutions. Ravikumar et al. [11] studied the effects of process parameters such as abrasive grit size, extrusion pressure, type of abrasive, and number of cycles in abrasive flow machining on the surface texture of a 3D C/C composite. Zhang et al. [12] adopted a macro-orthogonal cutting model to investigate the C/C composite cutting forces and defects while machining using finite element analysis. The simulated cutting forces demonstrated good agreement with the experimental results for different fibre orientations (0°, 45°, and 90°).

Rajasekaran et al. [13] proposed a fuzzy model to predict cutting forces during the machining of CFRP composites. The developed model shows good performance in the experimental results; hence, these models can be used effectively to predict cutting forces. In another study, Rajasekaran et al. [14] studied the role of machining parameters on surface roughness and found that a ceramic cutting tool offers good surface characteristics.

Danish et al. [15] explored sustainable machining performance and the appropriate choice of machining parameters for machining CFRP composites. Subsequently, response surface methodology and advanced optimisation techniques are utilised to develop the relationship between responses to machining conditions. Norbert et al. [16] reviewed difficulties, challenges and expectations during drilling of CFRPs. Drilling of CFRPs implicates the generation of different types of severe damage, including delamination, burrs, fragmentation, fibre pull-outs, micro-cracks, and matrix smearing. Further, control of the process properties, such as cutting forces, machining temperatures, and tool wear, still remains a challenging issue in the industrial drilling of CFRPs. Careful selection of drilling parameters plays a vital role in minimising the detrimental mechanical-thermo effects resulting from the drilling operation.

Many researchers have studied the machining of Carbon Fibre-reinforced carbon composites; limited data are available on the drilling characteristics of 3D pierced fabric (PF) carbon-carbon (C/C) composites. This study aims to explore tool wear and hole surfaces during the drilling of 3D PF C/C composites utilising plain and tungsten carbide drill tools.

MATERIALS AND METHODS

The 3D PF C/C composite selected for this study was developed via the Liquid Pitch impregnation process and was cut into small rectangular blocks. It consists of an 8H satin-weave PAN-based carbon fabric, reinforced with carbon-epoxy pultruded rods placed perpendicular to the fabric layers (Z direction). Figure 1 illustrates the 3D PF composite structure, showing the 8H satin-weave fabric and Ø2 mm carbon rods arranged 8 mm apart. The composite was manufactured using a standard process developed at the Advanced Systems Laboratory (ASL) and densified with coal tar pitch until reaching a density of 1900 kg/m³. The densification cycles involving impregnation, high-pressure impregnation, carbonization, and graphitization were repeated until the required density was achieved. Table 1 summarizes the reinforcement architecture, matrix details, fibre volume fractions, and fabrication parameters of the composite. Table 2 presents the properties of the reinforcement material used for composite fabrication. Figure 2 a shows the fabricated 3D PF C/C composite, while Figure 2 b shows the microscopic image of the composite. Specimens of the required dimensions were prepared from the main billet for further analysis, and the samples prepared for machining studies are shown in Figure 3.

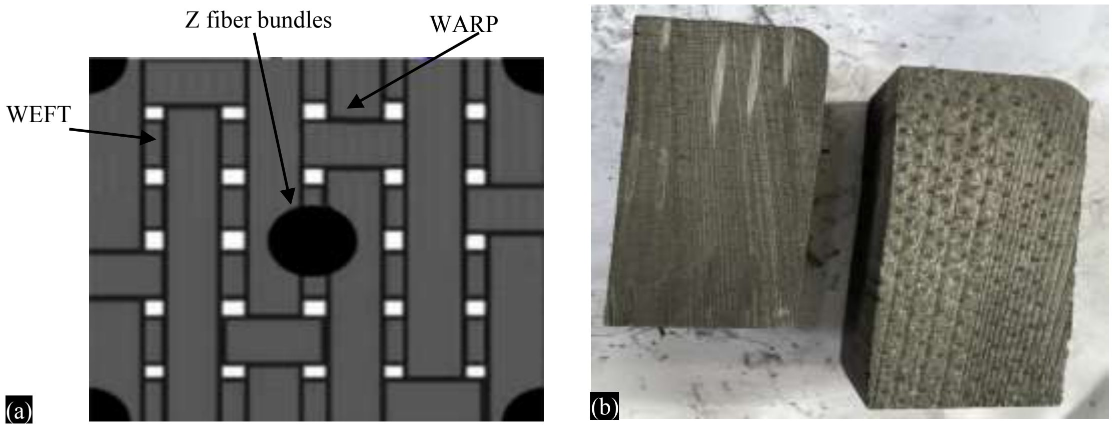

Figure 1. (a), (b) Preform architecture and 3DPF C/C composite.

Table 1. 3D PF C/C elements and their process parameters.

The type of principal reinforcement	The type of Matrix	Production process	HTT [°C]	Density [kg/m³]	Fiber volume fraction [%)]		
					Vf_x	Vf_y	Vf_z
PAN-based T-300 carbon fabric	Coal tar pitch-based carbon	Liquid Impregnation Technique	>2200°C	1920	25.0	25.0	5.0

Table 2. Properties of carbon fabric used in composite fabrication.

Major reinforcement	Type of weave	Carbon content [%]	Thickness[mm]	Tensile strength [N/m]
PAN based T-300 carbon fabric	8H Satin weave	92	3.5	69496

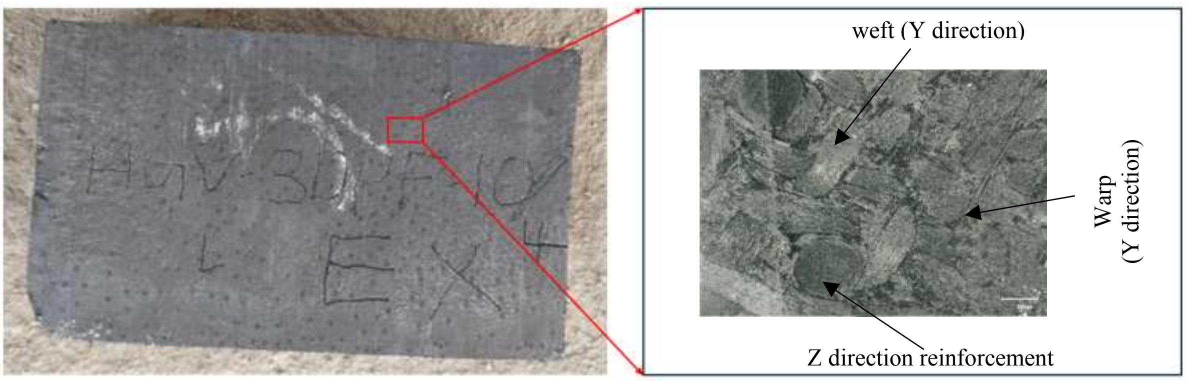

Figure 2. (a) Fabricated 3D PF C/C composite and (b) Microscopic image of 3D PF C/C composite.

Plain carbide and tungsten carbide tools were used to drill the composite. The drilled holes were arranged in an array with a 10 mm spacing between them (Figure 3). Holes were drilled under dry conditions at spindle speeds from 600 to 1000 RPM and a feed rate of 20 to 60 mm/min. SEM was employed to analyse tool wear (Figure 4), and EDS analyses were carried out to examine the chemical composition of the carbide tools and the adhesion after drilling.

RESULTS AND DISCUSSION

Tool Wear on Plain Carbide and Tungsten Carbide Drills

Figure 5 (a-f) shows the tool wear of a plain carbide drill insert after machining a 3D PF C/C composite. Chipping of the tool edge is observed under high-speed conditions due to the brittle nature of the C/C composite material. Severe tool wear is observed owing to the abrasive nature of C/C composites. Edge chipping and wear indicate that the tool experiences high stresses during drilling. Additionally, carbon powder deposition is observed on the drill bit flank surface. Carbon powder accumulation may influence machining performance, potentially requiring optimised cutting parameters or improved tool coatings. Tool breakage occurs in the form of chips on the tool surface due to drilling temperature, and higher spindle speeds increase the tool wear area. The surface integrity of the drilled hole may be affected, necessitating further investigation into alternative tool materials or cutting strategies.

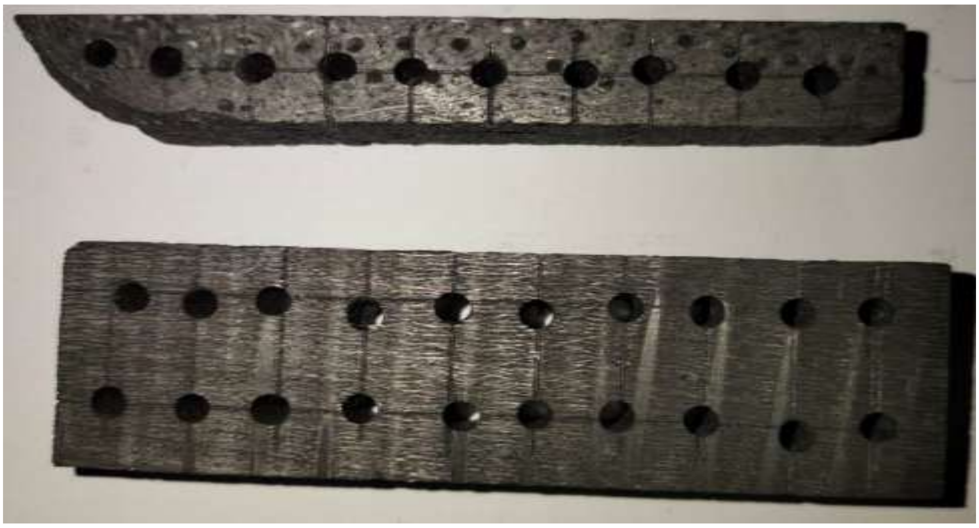

Figure 3. 3D PFC/C composite samples after performing drilling.

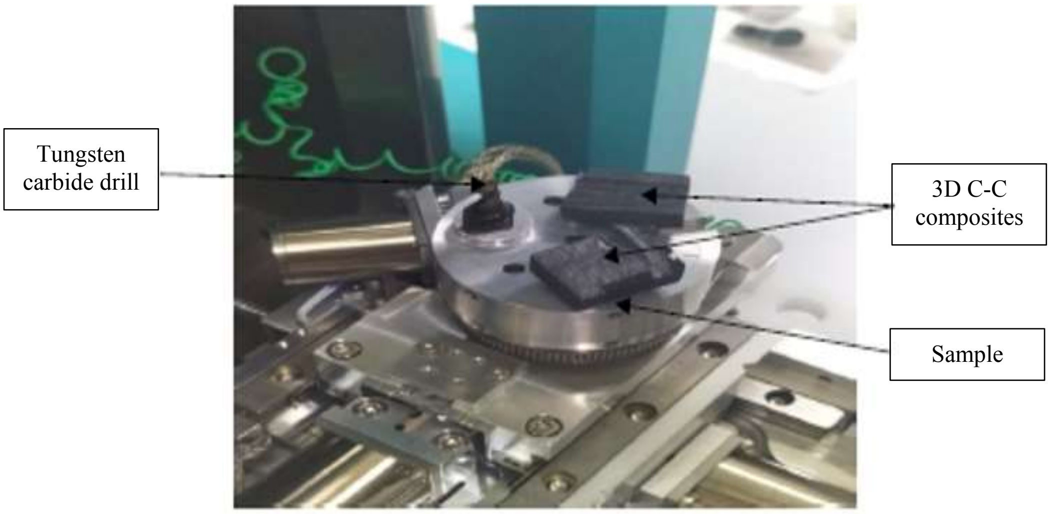

Figure 4. Sample positions for SEM analysis.

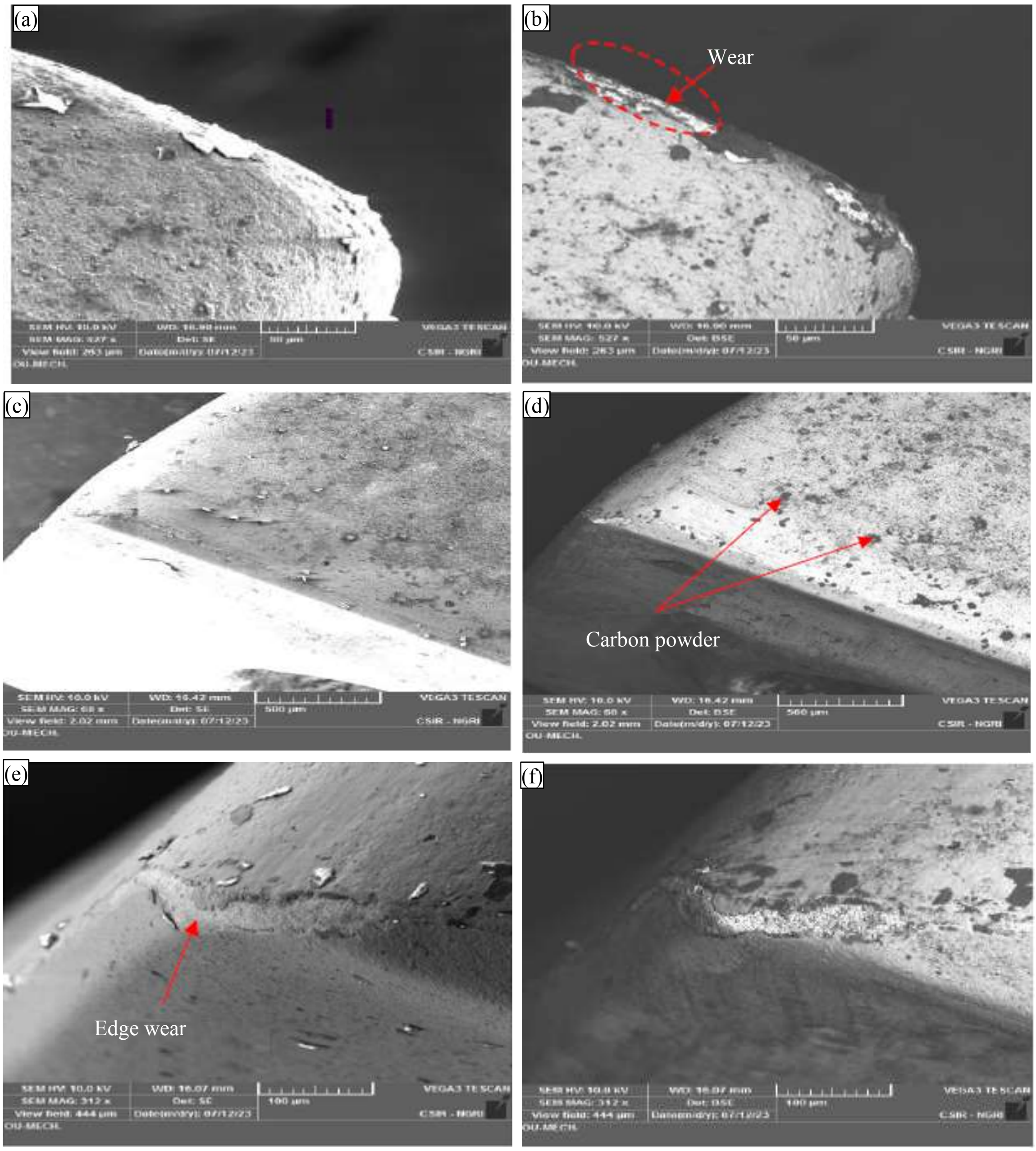

Figure 5. (a)–(f) SEM images of plain carbide drill insert after machining.

From Figure 6 (a-f), it is observed that the drill bit has been damaged at the cutting edge, shedding and surface wear occurring due to the high hardness of the 3D PF C/C composite material. Carbon powder has been deposited on the tool surface due to the breakage of carbon fibres and the matrix during machining. Edge wear and the presence of carbon powder suggest that the tungsten electrode is gradually wearing due to friction and heat. The powder might result from the mechanical wear of the composite. The tungsten carbide has melted, and scratches are visible on the tool's surface due to high-temperature conditions during machining. Highlighted scratches, likely due to abrasive interactions between the tungsten electrode and the C/C composite, cause a rough surface. Breakage, indicating localised cracking or material failure, possibly due to excessive heat generation or mechanical stress concentration. Breakage and chipping of the tool can be observed due to the sudden impact of high-speed and high-feed conditions, as well as the abrupt force exerted on the tool upon contact with the composite material.

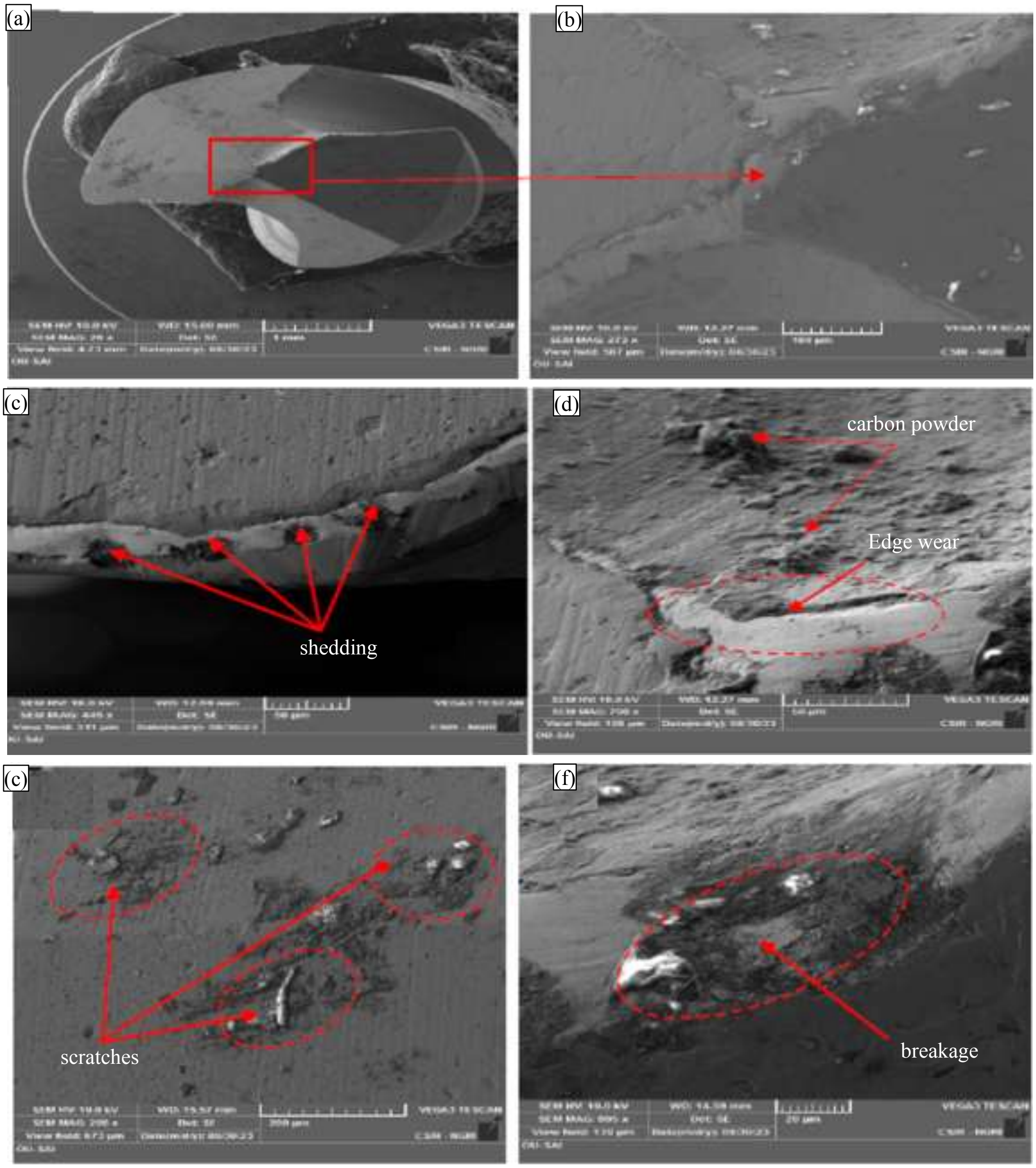

Figure 6. (a)–(f) SEM images of tungsten carbide twist drill bits after machining.

Surface Morphology in 3d Carbon-Carbon Composites

In Figure 7(a), Region-1 is specified where fibre pull-out has occurred. Carbon fibres observed at the edge of the hole appear longer, and fibre fractures are evident on the C/C fibres, as depicted in Figure 7(c). Small fibre chips are located at the edges of the fibre fractures, and debonding is observed due to high drilling temperatures during machining, as depicted in Figure 7(d). The C/C matrix and fibres are visible on the drilled surface of the hole, as depicted in Figure 7(e). Matrix cohesion has occurred, and cracks are observed on the drilled surface.

Higher magnification observations in image (d) reveal significant fibre-matrix debonding and the formation of fibre chips, indicating inadequate support from matrix under cutting forces. Image (e) highlights the presence of matric pores, which may act as stress concentration sites and promote crack initiation during machining.

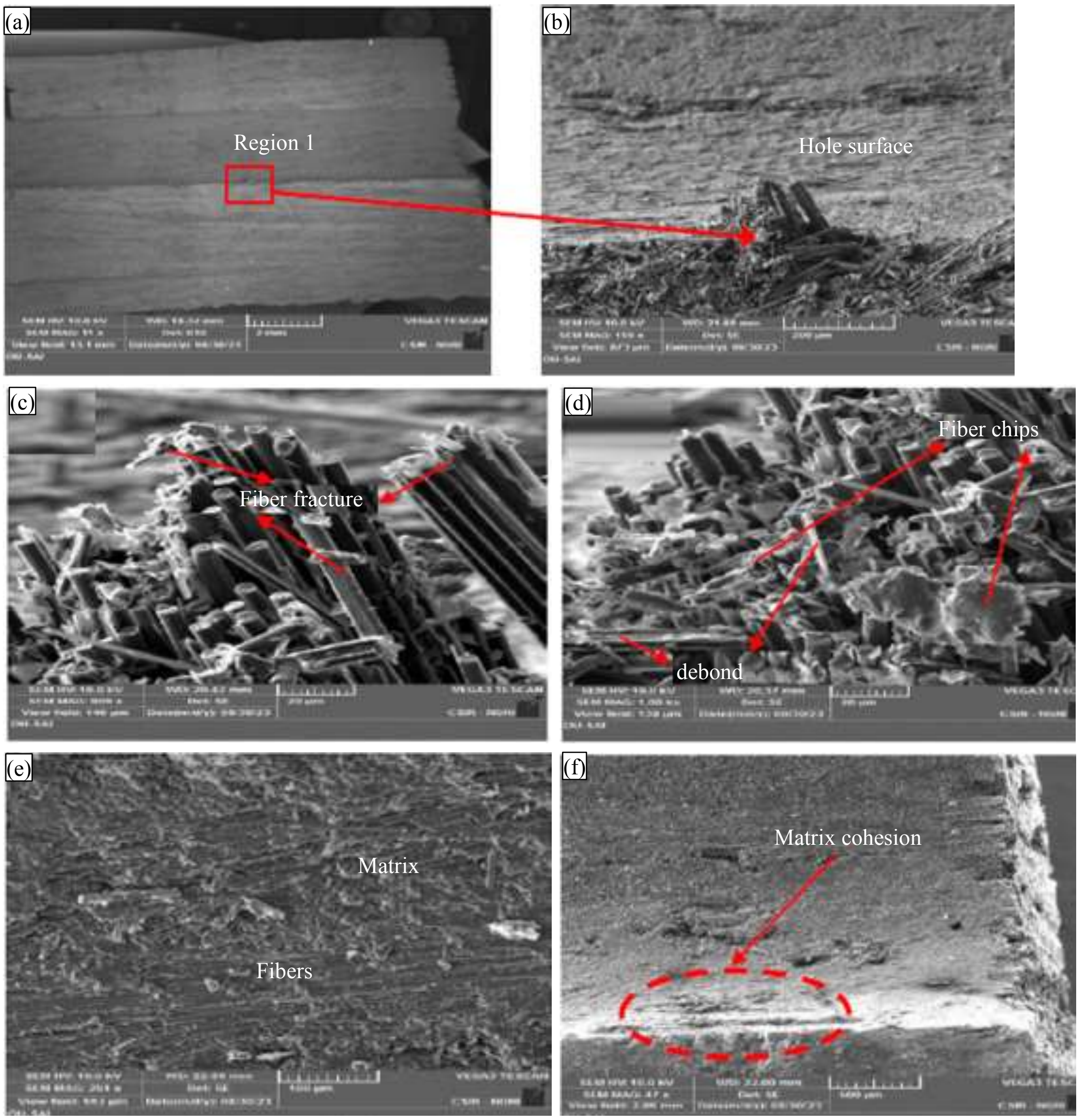

Figure 7. (a)–(f) Surface morphology of the machined composite.

Furthermore, image (f) shows porosity and fibre bundle debonding, demonstrating localised damage within the composite architecture. Overall, the surface morphology suggests that machining at 1000 rpm and 60 mm/min is characterised by fibre breakage, matrix degradation, interfacial debonding, and pore exposure, resulting in a comparatively rough machined surface and reduced surface integrity.

Elemental Composition Analysis

As a crucial analytical method, "Energy-dispersive X-ray spectroscopy (EDS)" was utilised to inspect the elemental composition and chemical properties of the plain carbide insert. EDS is a non-destructive technique that measures the energy of X-rays emitted when excited electrons are released from their inner orbital shells. This enables both qualitative and quantitative analysis of the elements present in a material. In our study, EDS was applied to analyse the surface composition of the plain carbide insert (Figure 9 & 10), providing valuable insights into its elemental makeup. This method revealed important details about the insert's manufacturing quality and any material variations by identifying the presence and distribution of elements such as tungsten (W), cobalt (Co), chlorine (Cl), and ytterbium (Yb) (as shown in Figure 11 and listed in Table 3).

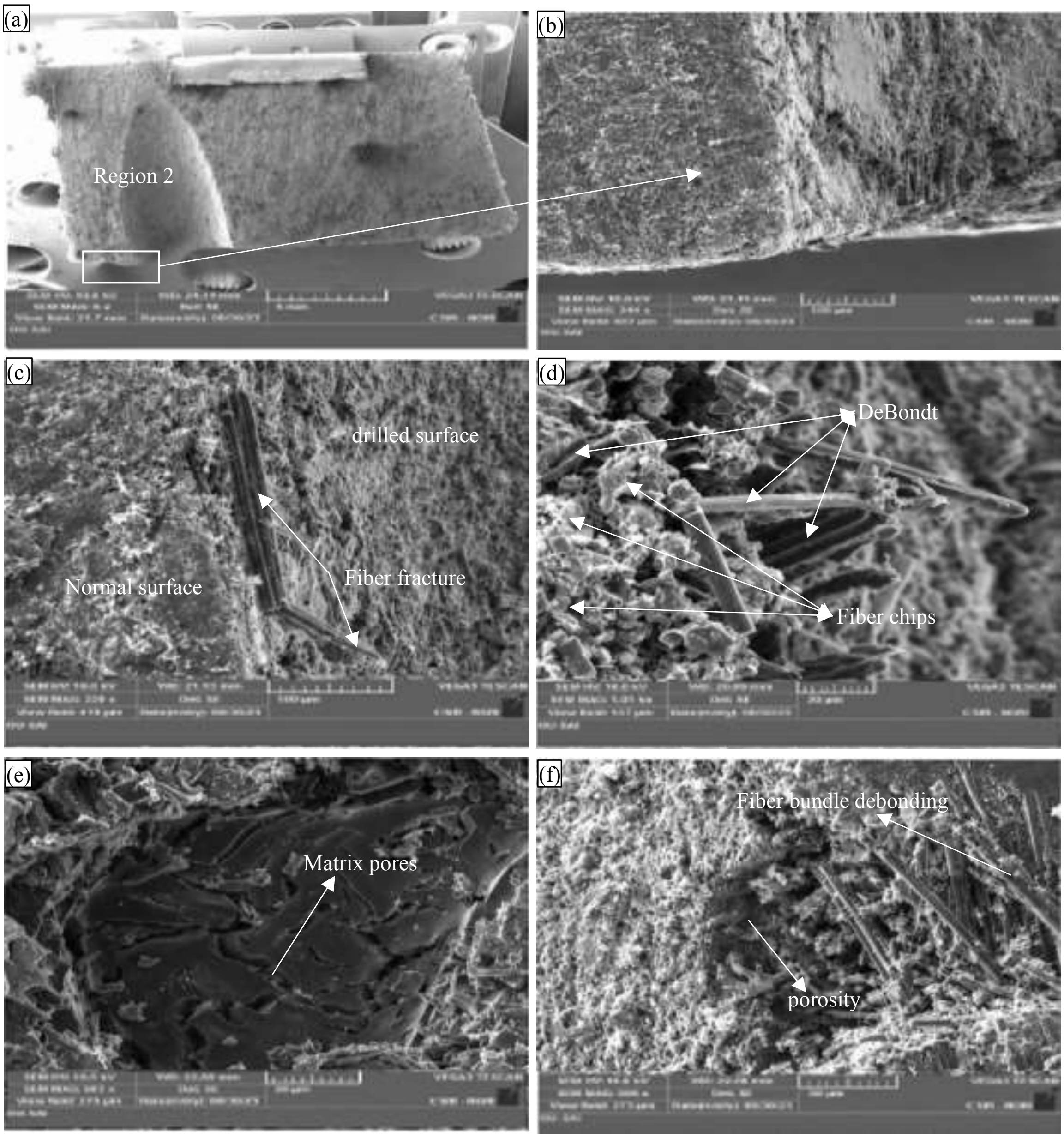

Figure 8. (a)–(f)Surface morphology under spindle speed of 1000 rpm and feed rate of 60 mm/min.

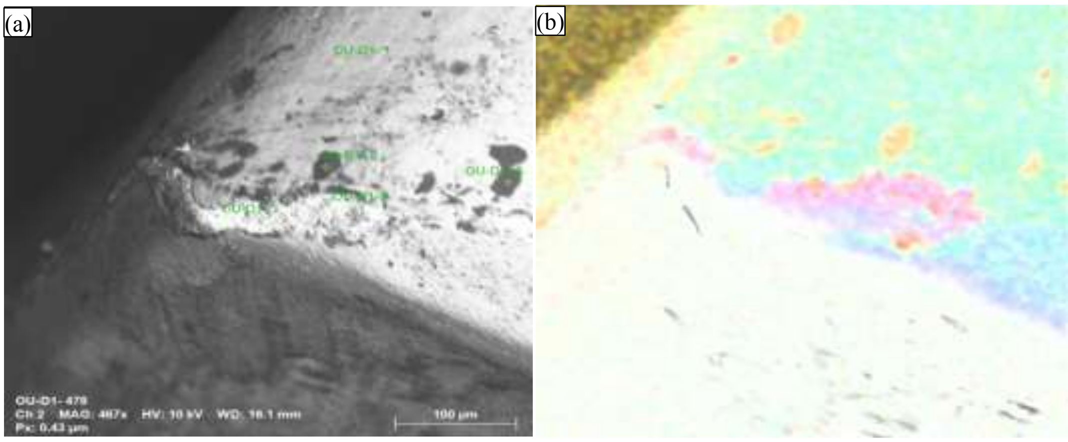

Figure 9. (a), (b) EDS analysis on the plain carbide inserts after machining the C/C composite.

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In addition to confirming the elemental composition of tungsten carbide drills—such as titanium (Ti), tungsten (W), aluminium (Al), and silicon (Si), as shown in Table 4—the EDS analysis detected potential contaminants or impurities. This comprehensive evaluation helped assess the drill bit's suitability for machining applications. The EDS results (Figure 12) provided critical data for further refining the performance of tungsten carbide drills, ensuring their reliability and efficiency across various machining processes. Overall, EDS played a crucial role in characterising the material composition of tungsten carbide drills, enhancing our understanding of their structural properties, and contributing to the development of improved cutting tools for machining applications.

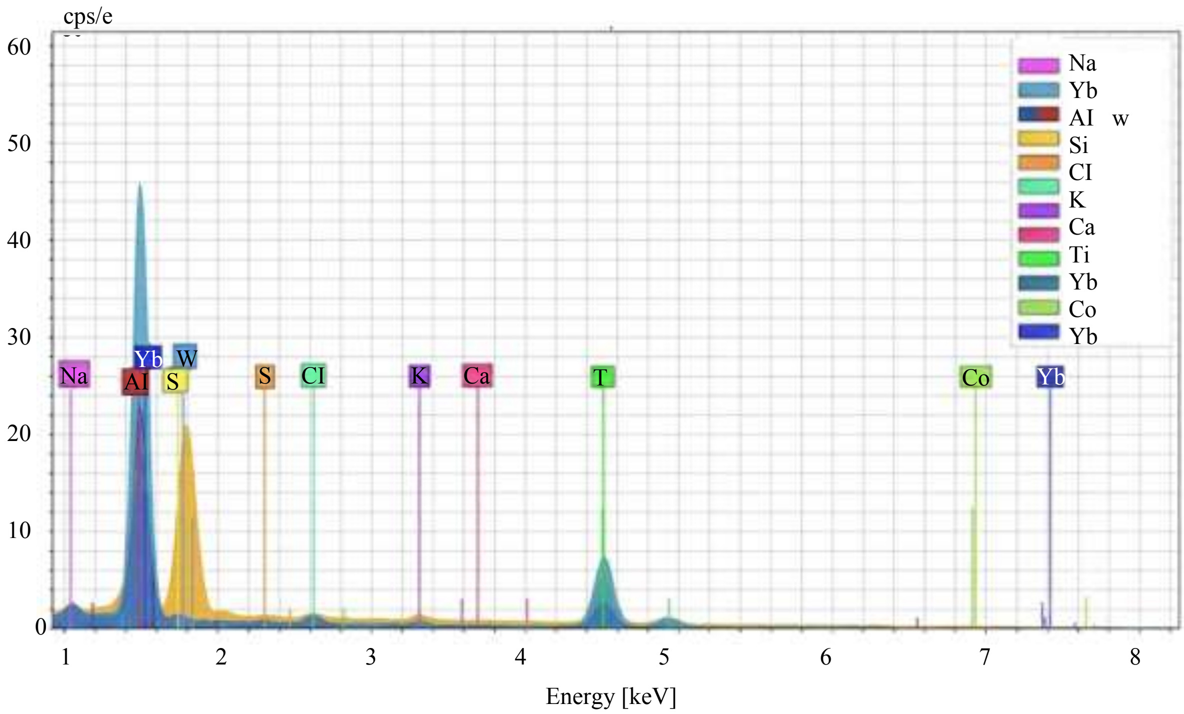

Figure 10. EDS spectrum of plain carbide inserts.

Table 3. Element results of plain carbide drill insert from EDS analysis.

Spectrum	O (%)	Cl (%)	Co (%)	Yb (%)	W (%)	Al_2O_3 (%)	TiO_2 (%)	Na_2O_2 (%)	SiO_2 (%)	SO_3 (%)	K_2O (%)	CaO (%)
D1-1	0.00	—	—	7.57	—	42.67	49.76	—	—	—	—	—
D1-2	0.00	7.09	—	—	—	19.17	7.60	17.50	14.23	18.59	8.53	7.30
D1-3	0.00	—	—	—	—	80.16	19.84	—	—	—	—	—
D1-4	0.00	—	1.57	—	34.24	23.23	39.90	—	—	—	1.06	—
D1-5	0.00	1.87	—	—	—	51.01	41.80	3.63	—	—	1.69	—

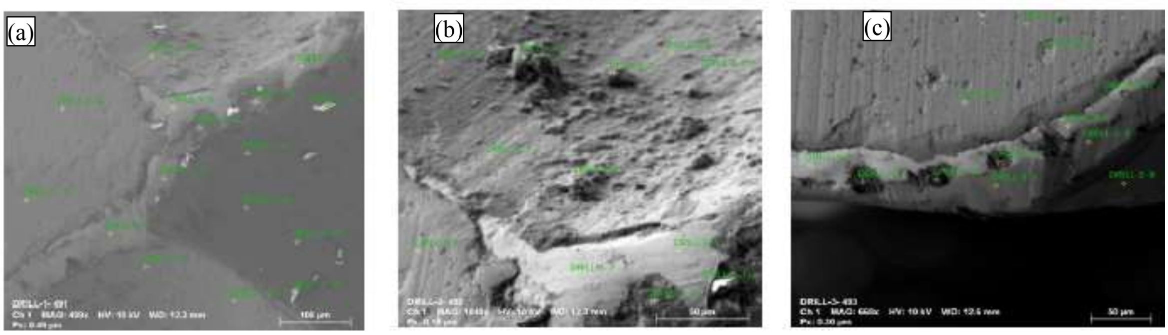

Figure 12. EDS images of tungsten carbide drill bit.

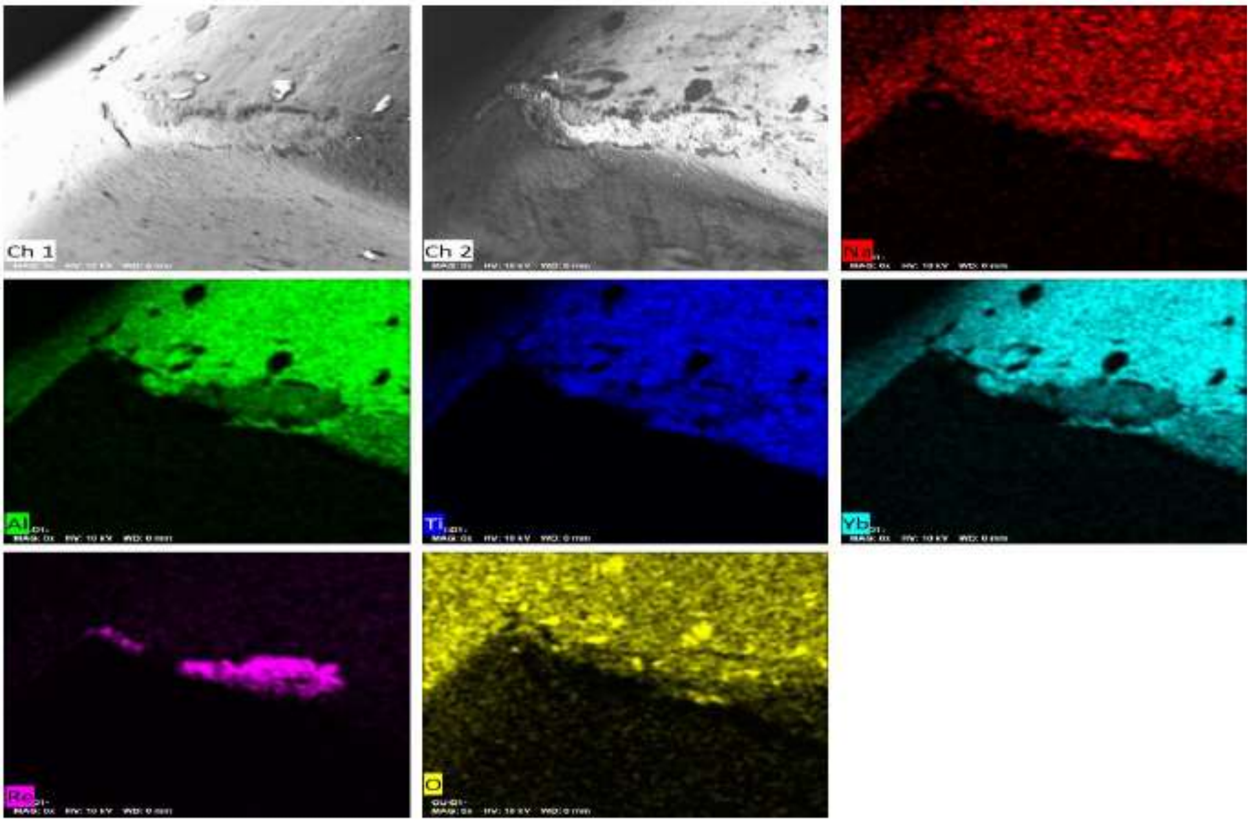

Figure 11. Elements in plain carbide drill insert after machining the 3D C/C composite.

Table 4. Element results of the tungsten carbide drill bit from EDS analysis.

Spectrum	O	Na	Mg	Al	Si	S	Cl	Ca	Ti	Cr	Fe	Co	Yb	W	Tl
DRILL-3-1	2.24	—	—	—	—	—	—	—	2.38	1.41	—	4.67	—	89.31	—
DRILL-3-2	17.60	—	—	16.61	—	—	—	0.82	2.70	1.50	—	1.49	—	59.27	—
DRILL-3-3	35.86	2.40	—	8.31	10.09	6.84	15.94	—	—	—	20.56	—	—	—	—
DRILL-3-4	39.49	—	—	21.57	—	—	—	—	30.39	—	—	—	—	8.55	—
DRILL-3-5	37.40	—	—	14.27	—	—	—	—	36.96	—	—	—	—	11.37	—
DRILL-3-6	1.04	—	—	—	—	—	—	—	0.56	1.44	—	2.37	—	94.58	—
DRILL-3-7	41.46	—	—	—	4.95	—	—	—	53.59	—	—	—	—	—	—
DRILL-3-8	41.56	—	—	—	5.33	—	—	—	53.11	—	—	—	—	—	—
DRILL-3-9	39.83	—	—	44.78	—	—	—	—	—	—	—	—	15.39	—	—
DRILL-3-10	41.61	—	—	—	5.50	—	—	—	52.89	—	—	—	—	—	—
DRILL-3-11	25.63	1.08	0.48	3.70	10.66	—	13.81	13.97	—	—	13.73	14.74	—	—	2.20
DRILL-3-12	1.20	—	—	—	—	—	—	—	0.73	1.54	—	3.83	—	92.70	—

Delamination Factor (Fd)

Delamination is one of the most crucial damage mechanisms in composites. It occurs due to the separation of adjacent layers within the composite and is generally initiated by matrix cracking, bending cracks, and shear cracks. Delamination substantially reduces the compression strength and can eventually lead to structural failure through buckling of the composite. Under impact loading, stresses generated within the composite initiate cracks that propagate between layers, resulting in delamination and severe damage. During both low and high-velocity impacts, several damage modes may occur, including matrix cracking, delamination, fibre fracture, and fibre pull-out. The extent of these damages depends upon the impact parameters. Larger impactors generally tend to generate greater delamination. The delamination factor (Fd) is calculated as shown in Figure 13

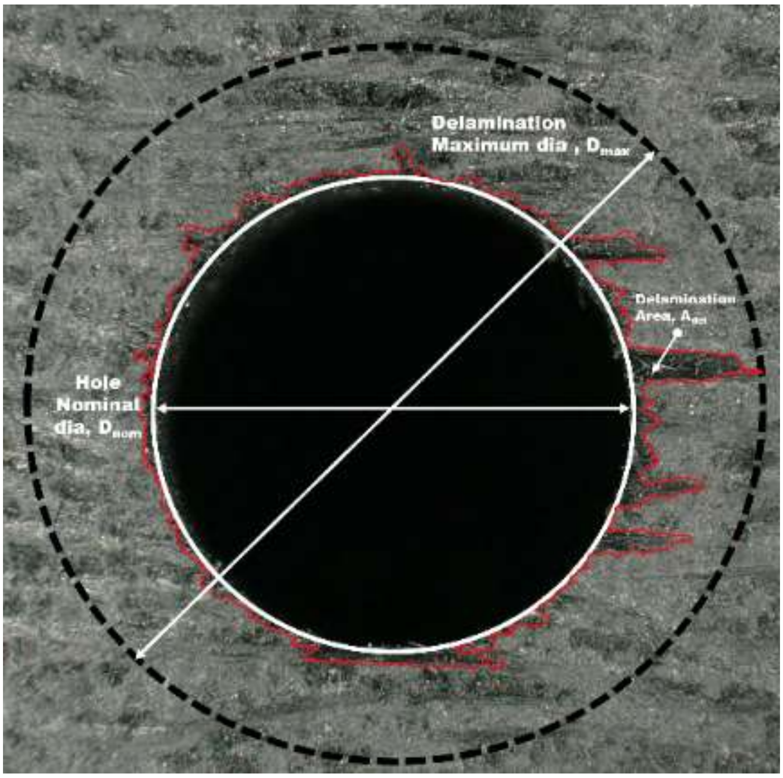

Figure 13. Delamination

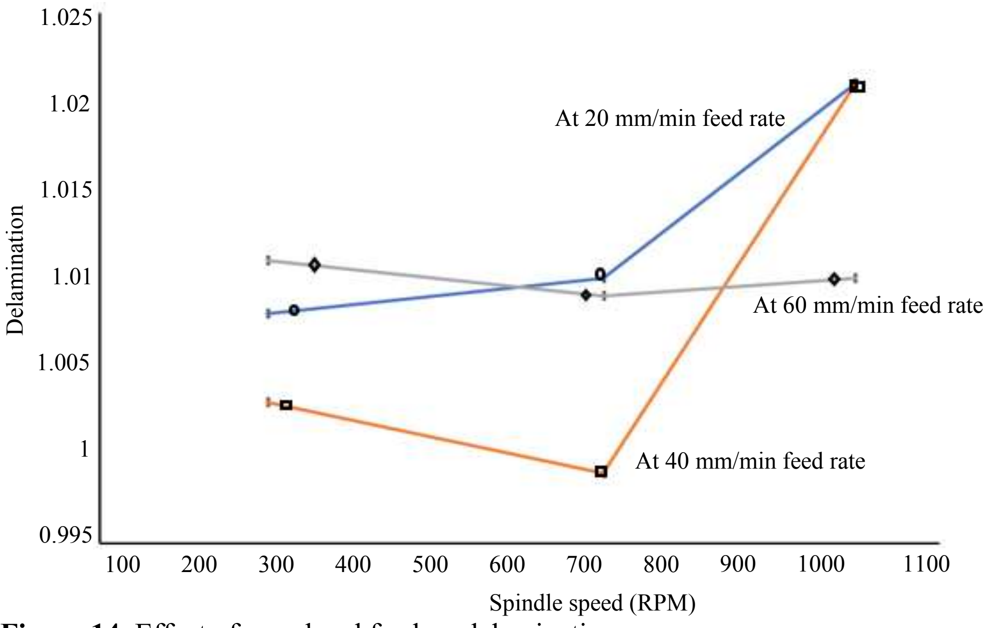

Figure 14. Effect of speed and feed on delamination.

$$F_d = \frac{D_{max}}{D_{nominal}} \quad (1)$$

Where D_{max} is the maximum damaged diameter and $D_{nominal}$ is the nominal hole diameter

The variation of delamination factor with spindle speed at different feed rates is shown in Figure 14. The delamination factor remained close to unity (0.999-1.021), indicating minimal delamination during drilling with tungsten carbide. For feed rates of 20 and 60 mm/min, the delamination factor varied only slightly with increasing speed, remaining close to 1.01, indicating stable machining conditions and limited damage. In contrast, at a feed rate of 40 mm/min, the delamination factor initially decreased from 1.003 at 300 rpm to 0.999 at 700 rpm, then increased sharply to 1.020 at 1000 rpm. The highest delamination factor was observed at 1000 rpm and 40 mm/min, suggesting that the combined effect of higher cutting speed and thrust force promoted greater laminate damage. Overall, the delamination factor remained close to unity for all machining conditions, indicating minimal delamination during the machining of the composite with tungsten carbide.

CONCLUSIONS

The quality of the hole entrance was superior to that of the hole middle and exit regions, regardless of the machining parameters. Typical defects in the hole included tearing and burrs, while the hole edges exhibited uncut fibres, fibre outcrops, and delamination. Plain carbide tools show significant wear and edge degradation, indicating limited durability for drilling C/C composites. High temperatures and abrasive carbon Fibres contribute to rapid tool wear. Alternative tool materials, such as coated carbide or PCD (polycrystalline diamond) tools, may offer better wear resistance and improved hole quality.

The drilling process leads to significant wear on the tungsten electrode, edge rounding, and material debris deposition. The C/C composite undergoes different forms of damage, including fibre shedding, surface scratches, and localised breakage.

At 1000 rpm and 60 mm/min, the machined surface exhibited fibre fracture, fibre–matrix debonding, porosity, and matrix damage, indicating poor surface integrity and severe machining-induced defects in the 3D PF Cf/C composite. Optimising drilling parameters (feed rate, spindle speed and geometry of tool) may help reduce these defects and improve surface integrity.

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