Impact of Process Parameters on the Surface Integrity of Fiber Reinforced Composites (FRC) during the Milling Process

[1]Muhammad Adnan Khan, [1]Muhammad Wasif, [1]Muhammad Tufail, [1]Syed Amir Iqbal, [1]Irshad Ullah

***Abstract*— The aim of the research is to optimize the process parameters to attain the desired outcomes of milling the composite materials; glass-fiber reinforced polymers (GFRP), carbon-fiber reinforced polymers (CFRP) and Kevlar-fiber reinforced polymers (KFRP). To enhance the surface integrity and tool life, optimal spindle speed and feed rate for the milling operations are determined. Using the design of experiment techniques, number of experiments are designed, which are replicated and randomized for the accuracy of the results. For the milling of three types of composites, PVD coated carbide milling inserts are mounted in a milling cutter of 16mm. Sides of composite plates are machined (milled) in each experiment, after which the surface roughness is measured at four different locations using high resolution surface roughness gauge. Mean surface roughness is determined for each sample of composite material. It has been observed through the enhanced images of the milling inserts that there is no crater or flank wear were present. Whereas, chipping and damages in the coating occurred at the higher cutting speed and feed rates on the milling inserts.**

***Index Terms*— Surface roughness, composite materials, spindle speed, tool wear.**

I. Introduction

COMPOSITE contains two or more materials, manufactured to enhance the physical and mechanical properties of the resultant material, which cannot be achieved with the individual materials [1]. Demand of composite materials are increased since these materials can be altered to modify the mechanical properties according to the outstanding requirements and extensive properties needed in the advanced engineering applications [2]. High specific stiffness, specific strength, greater dimensional stability are the main characteristics of composites which are available under a vast range of severe application conditions such as higher temperature, pressure and humidity. These conditions are the core requirements of precision applications, such as; high pressure vessels, wind turbines, armors, helmets, satellites, aerospace, rocket components, etc. Composites have become the first choice in aerospace and other associated applications due to its higher specific strength. In composites, condition monitoring of the material is also possible by embedding the monitoring sensors at the critical location inside the equipment [3]. Sensors are embedded inside the composite bodies, specially in aircraft wings, high pressure vessels and aerodynamic shapes to measure the deflection, stagnation pressure and other environmental variables.

Composites are composed of a matrix material and a reinforcement fibers, particles or other form, that are combined in a specific proportion to achieve the desired characteristics of the composite. Matrix materials are the medium which embed the reinforcement materials together. These matrix materials are usually the polymers, metals or ceramics. Polymer matrix composites (PCMs) are widely used in the aerospace, automobile and domestic industries in large number of applications [3]. Most common matrix polymers are; epoxy, polyester, phenol formaldehydes resins etc.

Curing is the process of hardening of a thermosetting plastic by the cross-linking of the material chains, which usually occurs either at room temperature or may require high pressure and temperature. Epoxy based composites have limitation of forming decimation and deformation while cured in autoclaved with higher temperature and pressure. Whereas, the most common problem while curing these composites in out-of-autoclave (OOA) process is presence of voids and larger bends [4].

The reinforcement materials which provide complementary properties to the composites may be; fibers, particles or honeycomb structures. Fibers are the widely used reinforcement materials in the industry, such as; aramid, carbon, glass, Kevlar or other organic long and short fibers [5].

Composite products are produced through distinct types of composite manufacturing processes, namely; filament winding, hand lay-up, pultrusion, liquid composite molding etc. Composite products formed by either of these processes, are usually standardized in geometry and need modifications and customizations due to the requirements of applications. Due to the limitation of reproducibility of the molds, it is quite difficult to embed detailed features within the cavity or mold for the manufacturing of composites [4]. Specially for the customized composite products, it is not suitable to include the varying features into the cavity or mold. To embed the geometric features, such as; pockets (cavities), groves (round-cuts) and holes into the composite products,

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[1] NED University of Engineering and Technology, Karachi, Pakistan. Corresponding author: mwasif80@gmail.com

machining processes are frequently applied onto it [5].

Literature review highlighting the milling of PCMs and its parameters effect on tool life and surface integrity is divided into three categories;

1. Developing models and optimizing the milling process parameters for higher surface integrity
2. Optimization and selection of tool geometry and process parameters for least wear
3. Optimization of machining environment for least tool wear and higher surface integrity.

Hence the following text presents a comprehensive literature review highlighting the previous research conducted in this field.

Ferriera et. al, highlighted that the FRP composites are generally manufactured using molding techniques, whereas machining operation is inevitable in most of the workpieces for trimming the edges to achieve required tolerances in finished workpiece. These materials are abrasive in nature thus increasing the importance of surface integrity and tool life to be studied in detail. They highlighted the importance of tool selection and conditions while machining the composite materials [6]. Zhang et. al, studied the polymer based composite material and reported the kinematics of cutting. They identified that the cause of delamination and damage in composite workpiece are due to the undesired thrust forces due to the variation in spindle speed and feed rates during the machining. They studied the influence of orientation of fiber and manufacturing methodology on the integrity of the machined surfaces during the cutting, drilling and grinding [7]. Teti presented an overview of tool design and machining parameters selection using the traditional machining processes. He presented a solution to overcome the damages in composites during the machining [8]. Wang and Zhang focused on the sub-surface damage in epoxy based CFRP machined with different parameters [9]. They concluded that the curing condition of the composite have no effect over the cutting force, sub-surface damage and surface finish rather it influences the mechanical properties of the materials [8]. Paulo and Mata used the Taguchi’s Method and ANOVA to analyze the influence of turning velocity and feed rate over the surface finish of GFRP using cutter system based on polycrystalline diamond (PCD) inserts [10]. Boudelier et. al, presented a methodology to optimize the process parameters to achieve the minimum roughness of CFRP during the milling process. Their research reveals that the surface integrity of the CFRP samples are largely dependent upon the grit size of diamond tools, whereas feed rate also plays important roles for providing the required surface finish [11]. Dandekar and Shin presented a research review analysis for the composite machining. They reviewed polymer based composite GFRP and CFRP and the particulate metal matrix composite [12]. The article presents the effect of cutting force, tool-particle interaction, cutting temperature and composite sub-surface damages over different types of composites. Azmi et. al, proposed a research for the milling of GFRP to determine the relationship between the process parameters with the surface roughness, tool life and machining forces. ANOVA is used out to analyze the influence of milling parameters on machinability [13]. Lopresto et. al, reviewed articles presenting chip kinematics, machined surface integrity, cutting forces and tool wear developments [14]. Xu and Zhang investigated the impact of process parameters on the wear patterns during the milling process, on surface integrity of polymer composite. They highlighted the use of ultrasonic vibrations during the milling process to decrease the cutting forces and hence curtailing the wear [15]. Fernández-Péreza and Ku et. al, presented the impact of milling parameters, that is feed rate and cutting speed over the surface integrity of hole and wear in the tool. They analyzed the optimal parameters for the least wear in tools and higher hole quality in CFRP [16, 17]. Xiang et. al, studied the effect of microtextured diamond coating and variation in it, over the tool life of cutting inserts, used for the machining of CFRP [18]. Sorrentino et. al, performed the similar kind of research and applied different types of coatings over the carbide tool used for the milling of CFRP. They enhanced the study to investigate effect of coating over the cutting force, tool life and surface finish [19]. They used a diamond film coated carbide tool and non-coated carbide tool. Their research revealed that the surface integrity, adhesion and wear were improved by performing the milling operation using the diamond coated carbide tool [18, 19].

Ozkan et. al, further expanded the study of hard diamond coating on carbide tools for the milling of CFRP and used different types of tool geometry to observe the least wear and roughness on the workpiece [20]. Henerichs et. al, performed an experimental study to analyze the effect of fiber orientation and tool geometry over the wear of the tool. This group of researchers presented the model for optimal tool geometry for the least wear and surface damage during the milling of CFRP composites [21]. Caprino et. al, proposed a model that presents the relation of the tool geometry over the induced cutting force and tool wear during the milling process of GFRP in unidirectional cutting. They found the relationship between the fluctuation in vertical forces with the wear in the tools [22].

Azmi performed online monitoring of tool wear using the ANFIS model and RMSE model during the milling of GFRP. His research infers that the ANFIS model is better to measure the real-time cutting stresses and hence wear, whereas, feed force is dominant during the milling process of GFRP composites [23]. Wan et. al, performed a comprehensive review to study various mathematical and FEA models, they developed a prediction model for the cutting forces induced during the machining of PCMs. They provided the summary relating the advantages and disadvantage of these models [24]. Karataş et. al, presented another review research, presenting the prediction of optimal cutting parameters for the GFRP and CFRP using the analytical, statistical and FEM techniques [25]. They discussed the effect of different tools, workpiece and machining parameters over the surface integrity of the composites and the wear of tools and the effectiveness of the models in predicting them.

Karataş et. al, concluded that generally, the low feed rate and high spindle speed during the milling, drilling or turning of GFRP and CFRP reduces the required cutting forces of the machining, but cause a lower surface finish [25]. Saoubi et. al, presented a comparative review over the machining of aerospace alloy and polymeric composite materials, focusing on hybrid machining strategies and cooling strategies during the machining, such as; in cryogenic or high-pressure environment. They discussed the advancement in materials and challenges faced by the machining industry [25]. Yildiz et. al, discussed a review over the cutting of composite material in cryogenic environment. Advantages and limitations of the machining in cryogenic environment is discussed in detail [27]. Khairusshima et. al, analyzed the effect of dry machining and cold air machining during the milling of CFRP. Their research concluded that the surface integrity and carbide tool wear are much improved during the chilled air machining [28].

All the research cited above are focused on optimal milling parameters and tool geometry for the specific polymer composite materials (PCMs) [5-28]. The cited research is conducted for the large-scale manufacturing of PCMs, hence are feasible for the specific PCMs and expensive milling cutters [5-28]. Recommended cutting tool material for the milling of PCMs are usually poly crystalline diamond (PCD). But due to the higher cost, this type of tooling system leads towards the higher cost of the finished product. In process-oriented requirements, it is in high demand of the aerospace and manufacturing industry to use a generic milling tool, which is productive for several composite materials. Hence to address the requirement research-based institution, producing customized composite products, such as; motor casing, blades of wind turbine, safety helmets etc., a unique research is conducted to determine the optimal machining parameters for three types of composite material, providing enhanced surface integrity and enhanced tool life. Proposed research is performed for the milling of glass reinforced fiber composite (GFRP), carbon reinforced fiber composite (CFRP) and Kevlar reinforced fiber composite (KFRP) using the cemented carbide with PVD-coated tooling. Optimal milling conditions for the three types of composite materials has been determined considering the same fiber orientations in the composite materials. The core outcome of the research presents the optimal spindle speed and feed rate for the higher surface finish. This research also investigates the effect of these parameters over the wear and protective coating of the milling inserts. Hence by reducing the grinding and other finishing operations, and achieving better surface finish, application of this research ultimately leads to lower cost of manufacturing.

The research article consists of four section, section one presents the literature review and research problem. Section two presents the experimental setup, arrangements and methodology has been defined in detail. In section three, analysis on the gathered data through the experimentation has been performed, whereas, last section concludes the inferred result based on the analysis.

II. Experimental Setup

As per research statement, core outcome of the research objective is to evaluate the optimal parameters for milling operations with highest possible surface finish and tool wear for the three types of composite materials. To conduct the research and analysis, following sequential methodology and components are discussed in detail;

1. Workpiece of composite materials
2. Tooling system
3. Designing experiments
4. CNC machine tool
5. Measurement of surface roughness
6. Detection of tool wear

A. *Workpiece of Composite Materials*

Samples of GFRP, CFRP and KFRP are produced using the vacuum infusion technique. Table I presents the mechanical properties of three types of reinforcement used in the samples. The properties are based on the catalogues supplied by the Chinese Supplier.

TABLE I
Mechanical Properties of Fiber Reinforcements

Type	Dia (mm)	Density (Kg/m3)	Tensile Strength (MPa)	Strain to Failure (%)
GFRP	0.36	0.0025	3447.37	5.6
CFRP	0.20	0.0018	5033.17	1.6
KFRP	0.47	0.0014	3792.11	2.8

Plain bi-directional, symmetric, woven fabric of GFRP, CFRP and KFRP are prepared. The characteristics of the fabric are presented in Table II.

TABLE II
Mechanical Properties of Fiber Reinforcements

Fiber	Type	No of Stacks	Sequence	Height of Stack (mm)
GFRP	610 GSM	8	$(0^o\text{-}90^o)_8$	~1
CFRP	230 GSM	8	$(0^o\text{-}90^o)_8$	~1
KFRP	175 GSM	8	$(0^o\text{-}90^o)_8$	~1.32

Thermosetting epoxy resin (LY 556) is used as the matrix material to form the specimen providing the same strength and characteristics as used in wind turbines and other aerospace and industrial applications. The matrix epoxy resin having Young's modulus of 3.23GPa with density of 1080kg/m^3 is suitable to prepare the samples with all three types of fiber-reinforcements. Hence this polymer epoxy with its hardener are well mixed together with the weighted ratio of 10:1. These samples are cured in the autoclave at a pressure of 6 bar and temperature of 130˚C for the specified period. Six samples of each types of fiber reinforcements are produced having the size of 1000mm x 150mm x 8mm with the volume fraction of 65:35 (fiber to resin). Here the volume fraction has been calculated using the relation in equation 1 [29];

$$V_f = \frac{\frac{m_f}{\rho_f}}{\frac{m_m}{\rho_m} + \frac{m_f}{\rho_f}} \quad (1)$$

Where, V_f is the volume fraction of fiber determined using the relation of mass (m) and density (ρ) in equation 1. Here subscript "f" represents mass and density of fiber, whereas, subscript "*m*" is used for matrix material.

B. *Tooling System*

Most of the work on fiber reinforced polymers (FRP) machining recommend the use of carbides or polycrystalline PCD tools. PCD tools are preferred for their better resistance to wear, while carbide tools are chosen for their lower cost [30]. An indexable tooling system has been selected from KYOCERA Precision Tools [31, 32]. Standard tooling of 16mm of diameter is chosen, with the indexable PVD coated carbide milling inserts (LOMU100408ER-GM PR1510). The selection of tooling system is entirely based on the recommendation of KYOCERA tool selection system for the aerospace and precision manufacturing of composites. Insert designation LOMU100408ER-GM defines the rectangular shape tool with; 20° axial rake angle, 7mm edge length, 4 mm thickness, corner radius of 0.8mm and double-sided four-edge insert. Figure 1 shows the selected tool insert and its dimensions. PVD coated carbide grades inserts have thin film coating of ceramic which are reported to be efficient for turning, milling, drilling, threading and other machining processes. High toughness of carbide phase and new PVD-coating technology provides extended tool life and efficient machining [31, 32].

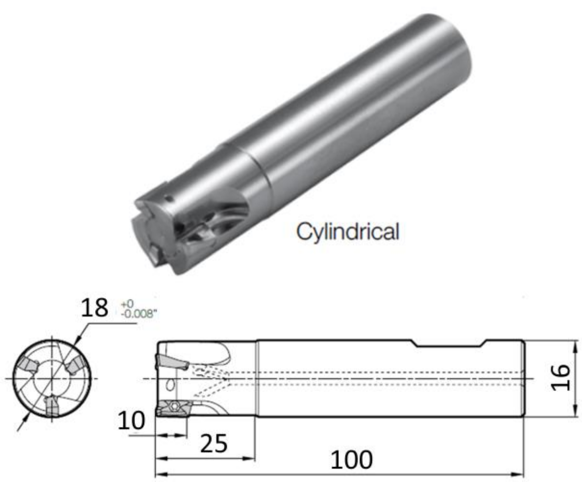


Fig. 1: Milling inserts geometry (KYOCERA) [28]

KYOCERA tool holder of designation MEW-S16-10-2T is selected which is compatible with the chosen insert, having; diameter of 16mm, tool length of 100mm and working length of 25mm. Figure 2 shows the geometry of the tool holder selected for the milling operations. Three cutting edges (inserts) can be incorporated in the cutting system.

C. *Designing Experiments*

Experiments design is full-factorial design of experiment technique. Three parameters of the experiments; workpiece material, spindle speed and feed rate are varied and taken as the controllable input factors. Table III presents the factors and levels of the parameters.

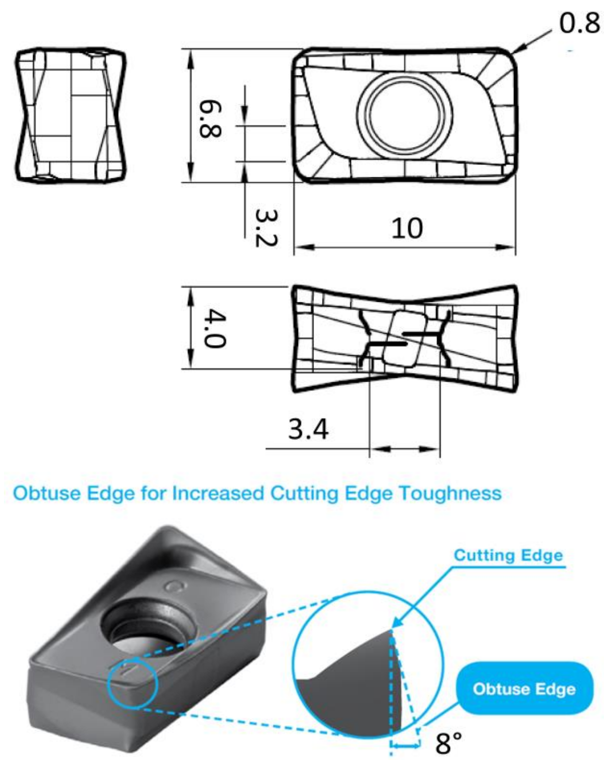


Fig. 2: Tool holder geometry (KYOCERA) [28]

TABLE III
Controllable Milling Parameters

Parameter	1	2	3
Sample Material	GFRP	CFRP	KFRP
Spindle Speed (rpm)	2000	3000	4000
Feed Rate (mm/min)	480	720	960

Feed rate of the milling operation is mainly dependent upon the spindle speed, hence factually there are only two main controllable parameters, which are; workpiece material and spindle speed.

To limit the number of experiments and analysis, several parameters are kept constant, such as;

- Selected material and geometry of the tooling system
- Three (3) cutting edges are used on tooling system
- Feed during the milling is set to be 0.08mm/rev/teeth
- Depth of cut is set to be 3mm
- Epoxy based matrix material
- Length of cut is set to be 1000mm in each sample

Response variable is the surface roughness of the composite milled surface which can be measured, whereas tool wear is another response of the experiments, which is observed qualitatively. Hence nine combinations of experiments are designed, which are duplicated to enhance the accuracy of the experiments. Six samples of each GFRP, CFRP and KFRP are produced having two sets of common specifications. Cutting velocity and feed rate of the milling processes are calculated. A length of 1000mm of each sample are cut, keeping 3mm depth of cut in the composite material without any interruption. To perform the DOE and analyze the results, statistical software Minitab is used. Sequence and randomization of experiments are taken in consideration to void the biasness during the experiments.

D. CNC Machine Tool

A CNC five-axis machining center FEELER is used to conduct the milling on composite samples. This milling machine has the capability to attain a maximum of 6000rpm and a maximum feed rate of 3000mm/min, with the x, y and z axes limits of 19000mm, 5900mm and 2900mm respectively. To conduct each random experiment, fresh milling inserts are mounted in the tooling system, which are replaced after each experiment. Milling inserts of tooling system, machining the three types of composite materials, are marked with different color coding to trace their usability on each type of material. Table IV presents the calculated feed rate, cutting speed and assigned color coding to the tool inserts.

TABLE IV
Parameters and Dependent Variables

Spindle Speed (rpm)	**Feed Rate (mm/min)**	**Cutting Speed (mm/min)**	**Type of Fiber**	**Colour Coding**
2000	480	100.5		White (W1)
3000	720	150.8	GFRP	Yellow (Y1)
4000	960	201.1		Blue (B1
2000	480	100.5		White (W2)
3000	720	150.8	CFRP	Yellow (Y2)
4000	960	201.1		Blue (B2
2000	480	100.5		White (W3)
3000	720	150.8	KFRP	Yellow (Y3)
4000	960	201.1		Blue (B3

E. Measurement of Surface Roughness

Roughness in surface is primarily analyzed using the Meiji EMZ-8TR-PBH Zoom Stereo Microscope with the magnification range of 10 to 45x. Stereo microscope is used for capturing high quality images of samples i.e. GFRP, CFRP, KFRP workpieces after performing the milling operation. Precise surface roughness of each machined samples is measured using the ConturoMatic T2 Surface roughness meter. ConturoMatic T2 can measure up to 250mm x 320mm of workpiece with a resolution of 0.033µm. Surface roughness of machined length (1000mm) is measured at locations A, B, C and D, which are situated at distances of 250mm, 500mm, 750mm and 950mm along the machine length as shown in Figure 3.

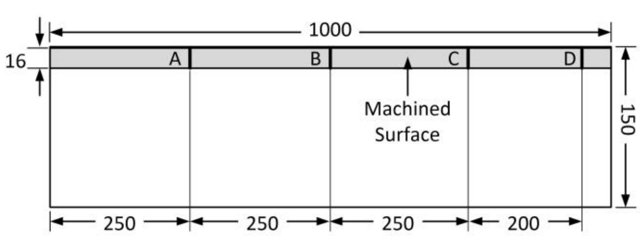


Fig. 3: Location of surface roughness measurements

The stylus of the surface roughness meter is moved along the machined thickness on the workpiece at each four locations and the continuous surface roughness along each thickness are measured separately. ContourMatic T2 provides the average surface roughness at the location with the roughness profile. Figure 4 shows a sample result of surface roughness of a machined composite, measurement along the thickness of the sample.

Average surface roughness measured over the unmachined surfaces of GFRP, CFRP and KFRP are measured as 0.4046mm, 0.2581mm and 0.3806mm respectively. The roughness is measured near the machined slot at the same distances as mentioned in Figure 4.

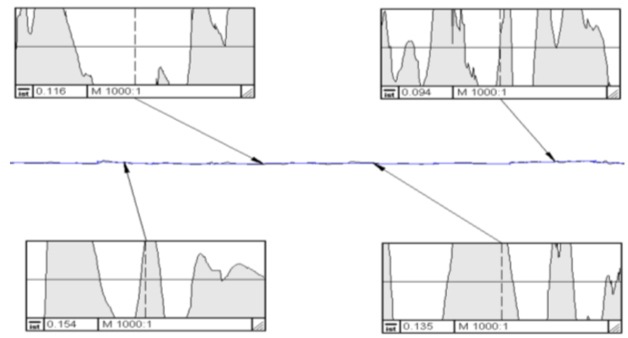


Fig. 4: Surface roughness of milled surface along thickness in GFRP (2000RPM)

Table V shows the average surface roughness measured in samples machined using the selected input parameters. Each average surface roughness is taken along the thickness of the machined surface for the two samples for which average is taken for the precise reading. Comparison between surface roughness over machined and unmachined surface clearly shows that the surface integrity is improved after the machining with the selected process parameters.

F. Detection of Tool Wear

Electron microscopy is an effective tool used for observing the samples with very high resolution and magnification. It evaluates significant data of mechanical, chemical and physical characteristics of the materials. Scanning electron microscope (SEM) of model FEI Quanta 200 is used to observe the tool wear on the milling inserts after the machining. Each of used milling inserts are placed inside the prescribed location inside the SEM and analyzed with the magnification of 200 times. Scanned images of the milling inserts are compared with one another for the analysis.

TABLE V
Average surface roughness measured along thickness

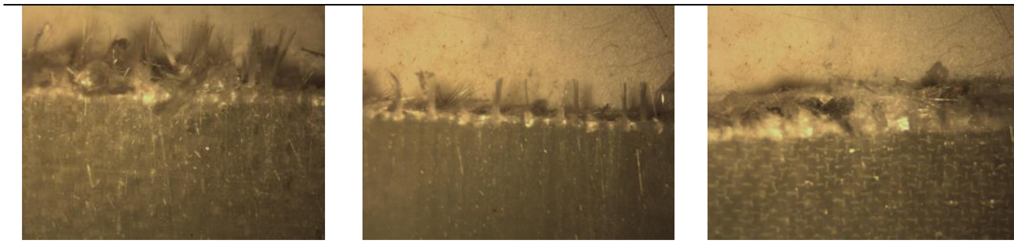
Colour Code	Average Surface Roughness (mm)					
	@A (250mm)	@B (500mm)	@C (750mm)	@D (950mm)	Mean	St Dev
W1	0.154	0.116	0.135	0.094	0.125	0.026
Y1	0.136	0.158	0.066	0.086	0.111	0.043
B1	0.086	0.092	0.103	0.125	0.101	0.017
W2	0.050	0.069	0.098	0.098	0.079	0.024
Y2	0.081	0.060	0.060	0.027	0.057	0.022
B2	0.077	0.077	0.077	0.050	0.070	0.014
W3	0.120	0.141	0.061	0.144	0.116	0.039
Y3	0.054	0.169	0.118	0.131	0.118	0.048
B3	0.048	0.072	0.081	0.097	0.074	0.020

III. Result and Analysis

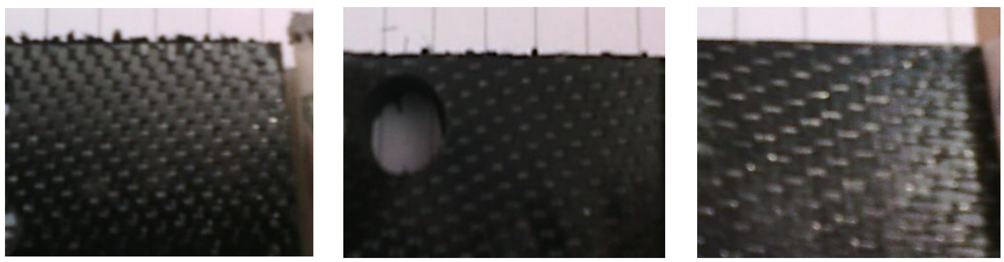
Eighteen samples, comprising six samples each of GFRP, CFRP and KFRP are machined using the PVD coated carbide

TABLE VI
Surface Roughness Images

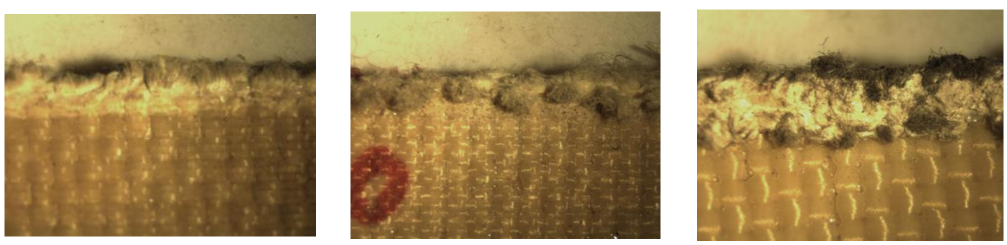
Spindle Speed = 2000rpm Feed rate = 480mm/min	Spindle Speed = 3000rpm Feed rate = 720mm/min	Spindle Speed = 4000rpm Feed rate = 960mm/min



Glass-fiber reinforced polymer (GFRP)



Carbon-fiber reinforced polymer (CFRP)



Kevlar-fiber reinforced polymer (KFRP)

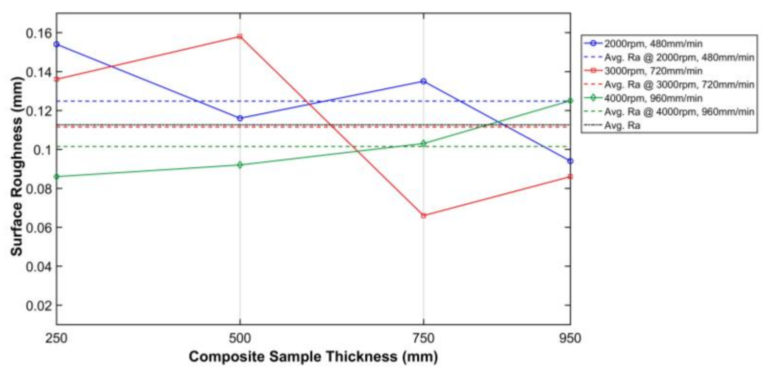


Fig. 5: Average Surface roughness along thickness of GFRP machined surface

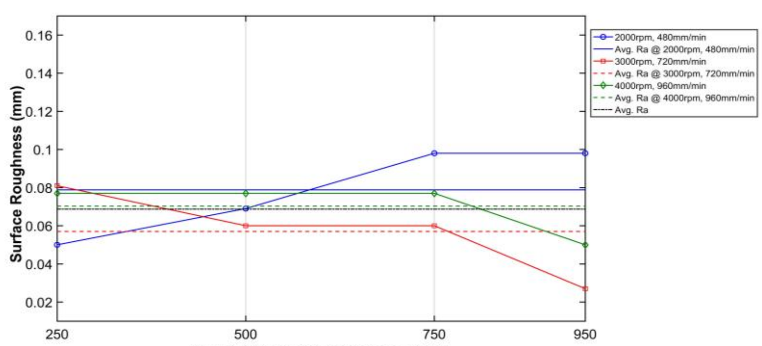


Fig. 6: Average Surface roughness along the thickness of CFRP machined surface

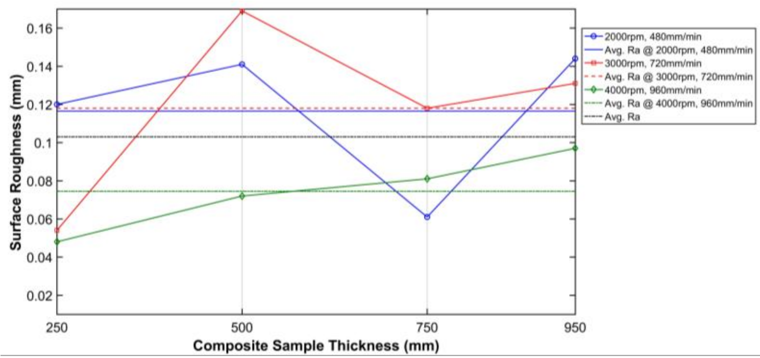
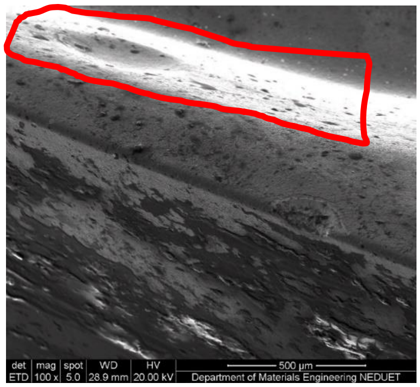
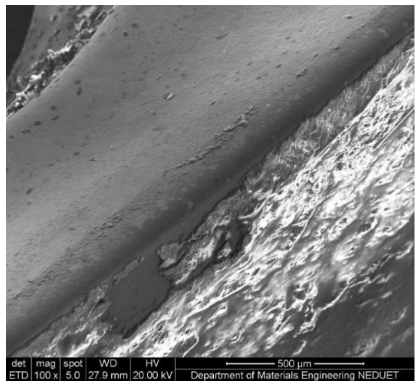
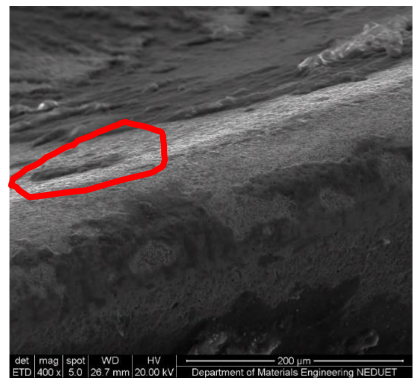
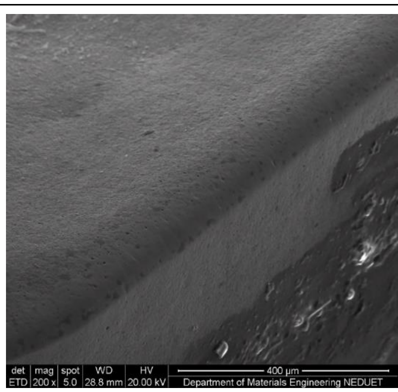
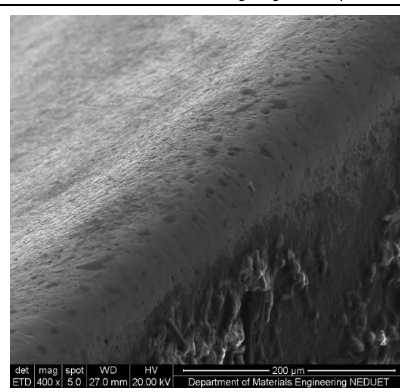
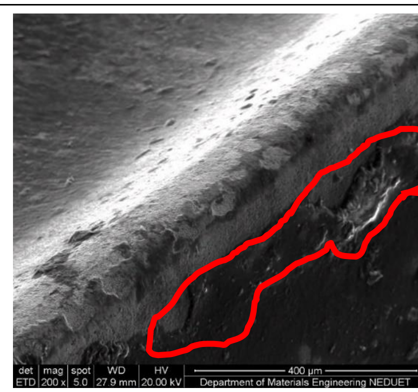
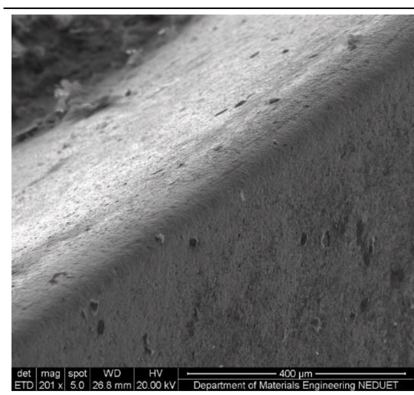
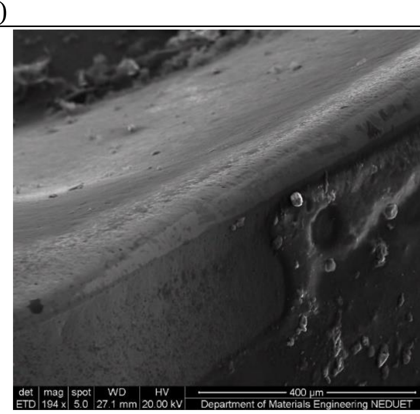


Fig. 7: Average Surface roughness along the thickness of KFRP machined surface

TABLE VII
Enlarged Images of Milling Inserts

000 rpm – 480 mm/min	3000 rpm – 720mm/min	4000 rpm – 960mm/min
		
Glass-fiber reinforced polymer (GFRP)		
		
Carbon-fiber reinforced polymer (CFRP)		
		
Kevlar-fiber reinforced polymer (KFRP)		

milling inserts and tooling system with five-axis milling machine. A cut of 1000mm was machined on each workpiece using the new set of inserts each time.

A. Surface Roughness

Surface roughness gauge is used to measure the surface roughness of the machined surfaces, whereas wear in the tool inserts are also detected using the Scanning Electron Microscope (SEM). Stereo microscope is used for imaging of the samples. Table VI presents the images of the samples showing the surface roughness produced by the specific milling parameters.

The first row of the Table VI shows the enhanced images of the GFRP workpiece machined with the spindle speed and federate. It can be clearly seen that uncut fibers of the GFRPs are prominent, which are at the lower spindle speed. Whereas, at the spindle speed of 2000rpm and feed rate of 960mm/min, the fibers are cut while machining but are also compressed against the machined side, causing a low surface finish. Hence it shows that surface roughness cannot be described using the final workpiece machined. Average surface roughness along the thickness of GFRP machined surface at the four locations are shown in the Figure 5 based on the data for W1, Y1 and B1, provided in Table V. In Figure 5, the magnitude of surface roughness is fluctuating along four locations, on the GFRP composite, machined with the spindle speeds of 2000rpm (480mm/min) and 3000rpm (480mm/min). Whereas, it shows increasing trend but lower magnitudes while cut with the spindle speed of 4000rpm (960mm/min). It can be observed in the figure that the surface roughness is improved at the 4000rpm and 960mm/min at four locations of the machined surface for the GFRP.

The second row of Table VI presents the images of CFRP machined with the varying process parameters. It clearly shows that the surface finish improves with the higher spindle speed and the higher feed rate. Unlike the GFRPs, the fibers of the CFRPs are properly cut during machining. The same observation is also evident from the Figure 6. In Figure 6, the surface roughness in the CFRP composite increases from 250mm to 950mm at 2000rpm (480mm/min). In the same figure, surface roughness along the thickness is improved in the machined surface at the spindle speed of 3000rpm and 4000rpm. Least magnitudes of average surface roughness are observed when the workpiece is machined at 3000rpm and feed rate of 760mm/min. The fluctuating trend in surface roughness in CFRP along the length of sample is due to accumulation of heat near the machining zone, it causes the melting of epoxy and the fiber entanglement. Hence non-uniform fluctuating pattern is observed in Figure 6.

The last row of the Table VI shows the zoomed images of KFRP workpieces, machined through varying spindle speed and feed rates during the milling process. It also shows an erratic behavior of the surface finish while varying the spindle speed and feed rate. It is due to nature of the Kevlar fibers, which are quite rough and are not hard as compared to the GFRPs and CFRPs. The surface finish is largely disturbed due to compression of Kevlar fibers. In these composites, the surface finish is not good by milling it with either the process parameters.

In case of KFRP, see Figure 7 based on data W3, Y3 and B3, where the surface roughness trend is fluctuating for the machined surface, milled with 2000rpm (480mm/min) and 3000rpm (720mm/min) having the higher magnitudes. Whereas, it has increasing trend but lower magnitudes in case of 4000rpm and 960mm/min. Fluctuation in surface roughness along the length of sample is also due to the same reason of high heat zone and blurred KFRP, which causes irregular roughness along the length of sample. Deformation in epoxy and breakage irregularity of fibers cause the non-predictable pattern of fluctuation.

Intervals and mean of each surface roughness are taken to observe the overall surface roughness of the machined surface. Mean surface roughness of all three types of FRP materials are plotted in Figure 8. Three levels of spindle speed are taken along x-axis of the plot and magnitude of surface roughness in millimeters are taken along the y-axis. The whiskers show the deviation of surface roughness. During the milling of GFRP samples, least magnitude of surface roughness (0.11mm) is noted at the highest cutting speed of the three values (4000rpm), while for CFRP workpieces, the optimal spindle speed is 3000RPM (0.056mm). In KFRP samples, least magnitude if surface roughness (0.85mm) is observed at 4000rpm. Comparing the magnitudes of surface roughness in all the three fiber reinforced composites, spindle speed is the dominator factor affecting the surface roughness magnitude as shown in the Figure 8.

Referring to Figure 8, minimum average surface roughness of 0.057mm is observed in the CFRP at the spindle speed of 3000rpm and 720mm/min. It is also evident from Table V that the surface finish in the machined carbon reinforced composites are much better than glass and KFRP. While machining the GFRP with an rpm of 2000, maximum average surface roughness is observed in workpieces, which reveals that the lower spindle speeds are suitable and thus recommended to machine the GFRPs.

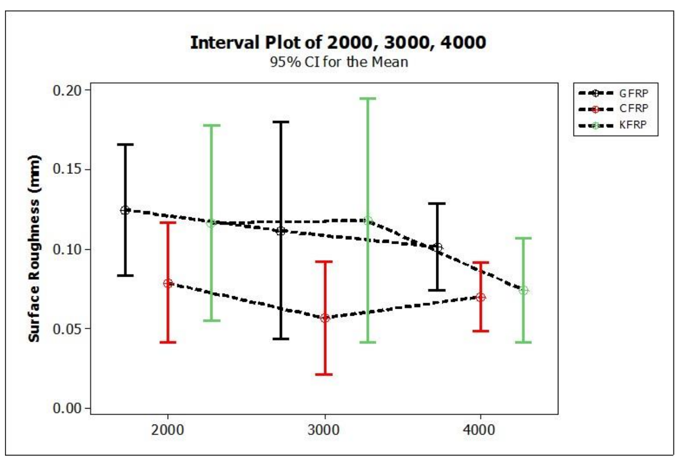


Fig. 8: Surface roughness measured on the three composite samples

B. Tool Weal

To observe the impact of machining parameters on the tool wear, SEM images of the milling inserts are taken. The magnitude of magnification is enhanced 100 to 400 times (as mentioned as *mag* in caption of images in Table VII) to observe the wear pattern on the milling inserts. Table VII presents the images of used milling inserts machining the 1000mm surface of the fiber reinforced composite. An enlarged image of unused milling insert is also shown in Figure 9, the image of the unused insert is comparable with used inserts to observe the wear or delamination of coating patterns.

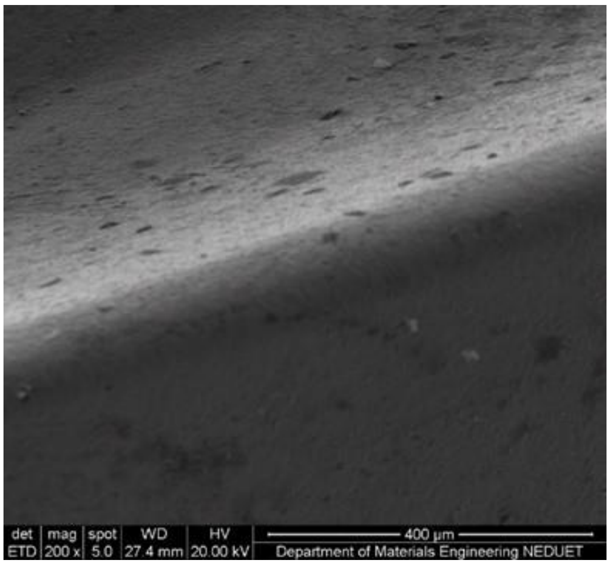


Fig. 9: Magnified view of unused milling insert

While milling GFRP, the conditions of milling inserts were investigated. It was noted that the milling inserts used for machining GFRP with the 2000rpm, 3000rpm and 4000rpm had their PVD coating damaged i.e. chipping occurred on the cutting edge of the inserts shown in the first row of Table VII. The larger coating damaged was observed when GFRP was machined with the 3000rpm and 720mm/min feed rate. The lightest PVD coating damage is observed while cutting with the 4000rpm and 960mm/min. The milling inserts used for machining the CFRP were found to have no large wear on them, only the PVD coating was depleted. It is evident from the figures that the PVD coating distortion increased with the higher spindle speed as shown in row 2 of Table VII. While milling the KFRP, it is observed that no wear or PVD coating distortion is observed in the milling inserts. Sticking of KFRP on the tool insert is evident in the third row of the Table VII.

Based upon the observation of the SEM images of cutting inserts, it can be inferred that no significant relationship exists between the two-response variables. Even it is evident from Table VII that no wear has been detected in the insert used for the milling of GFRP, CFRP and KFRP. No prominent wear was observed, however PVD coating was damaged while cutting all three types of composite.

Conclusion

Composite samples with 8mm thickness of GFRP, CFRP and KFRP are machined using the milling operations with a tooling system of diameter 16mm, having indexable type milling inserts. Influence of spindle speed (rpm) and feedrate (mm/min) is observed on surface roughness of machined composites. Magnitude of surface roughness are measured and wear on the inserts are observed.

Following results are concluded from the research;

i. In milling GFRP and KFRP samples, when the spindle speed is increased, means surface roughness decreases and observed least at the highest spindle speed. Hence surface finish is improved at the higher spindle speed and feed rate (4000rpm and 960mm/min) in these two composite materials.

ii. In case of CFRP samples, moderate spindle speed (3000 rpm) provides better mean surface finish with the minimum magnitude of surface roughness. It is due to the elastic nature of carbon fibers which elongates and broken due to high temperature interface at machining zone.

iii. It is also observed from the data and analysis that the surface roughness in CFRP composites have the least magnitudes after the milling operations which is also evident from the images taken on machined surfaces. Whereas, highest surface roughness is observed in the GFRP composites due to the brittle nature of fibers causing breakage rather cutting during the milling process.

No prominent tool wear has been observed on the PVD coated cemented carbide inserts during the milling of all three types of composites. Higher diminution of the PVD coating is observed while increasing the cutting speed, that caused the chipping and built-up adherence of composites over the milling inserts.

It can finally be concluded that the current research provides the guidelines for selecting optimal parameter of milling operations for three types of composite materials with the specific geometric parameters. This research is purely applicable to the process-oriented organization, where switching tools and performing setup for different material cause delay and increased cost for acquiring different tools and setup for various types of composite materials.

The future work of this research can be extended to develop regression models for prediction of surface roughness with several combinations of workpiece geometric parameters and process parameters. Furthermore, work can be enhanced to investigate the influence of parameters over the strength after machining.

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