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COMPREHENSIVE REVIEW ON MACHINING OF CARBON FIBRE REINFORCED POLYMER (CFRP) COMPOSITES

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Abstract: Carbon Fibre Reinforced Polymer (CFRP) composites have inflation and replacing conventional materials with their excellent strength and low specific weight properties. These materials are desirable choices in engineering applications. CFRP is worn as structural materials in various industries due to cutting force essential over machining a polymeric material is lower than that of conventional materials. Hence, the flexibility of machining is to be tested in order to reduce the machining time and cost. The previous conventional and unconventional machining studies suggested that input process parameters and cutting forces have a great influence on the machined surface quality of CFRP composites. In this analysis, a research survey was addressed the surface failure mechanisms, machined surface topography and machinability of CFRP composite materials. Moreover, this literature study has focussed on different statistical techniques used to achieve better-machined surface integrity. The initiation and propagation of machining composite failure occurred due to not only manufacturing characteristics, but also influenced by machining conditions.

***Keywords*:** Machinability, Carbon Fibre Reinforced Polymer (CFRP), Composite machining surface quality, Machining damage, Surface integrity.

1. Introduction

CFRP is widely used nowadays and its uses are developing day by day in the industrial application include aerospace industries, automobile industries, sporting goods, marine, naval, space, machine tools, transportation structures, post-strengthening of concrete begins, strengthening trade shear walls in seismically active regions[1-5].CFRP has mechanical properties like static, dynamic, thermal and chemical properties. CFRP has a high strength to mass ratio, high damping, low thermal expansion, good corrosion and wears resistance. A composite developer cannot be directly used for a specific application. Machining is inevitable when composites are mating with other conventional metallic materials in drilling, milling, slotting and finishing keyholes and corners for assembly and finish the edges and corners to remove the burrs [6].

Drilling is similar and is most frequently used operationally for CFRP structure during this operation typical defects are formed it includes stress concentration, interlaminar crack propagation, microcracking fibre breakage, spalling, debonding fibre below, matrix cracking thermal damage, delamination etc[7-9]. Among these defects, the major defect is delamination which affects the performance of the holes. In drilling the delamination is majorly occurring both at the entrance and exit planes of the workpiece [10, 11]. The delamination is an important phenomenon and is measured with different techniques. The commonly employed techniques are digital image processing [12], C-scan, ultrasonic [13], X- ray [14] and laser-based imaging [15]. Several types of research are carried out experiments on the drilling of CFRP composites. A list of recommended tests in order to identify the behavior of CFRP laminates. Davim and Reis [16] conducted tests of the Taguchi technique and analysis of variance (ANOVA) to develop a comprehensive approach to select cutting criteria for damage-free drilling in CFRP materials. The interrelationship surrounded by cutting velocity and feed rate with delamination was derived by them. Chen [17] suggested that the delamination factor was analyzed by over the drilling of CFRP materials. Using the proper choice of tool geometry and drilling criteria, he concluded that the delamination free drilling can be achieved.

Milling of CFRP is a complex task due to its composition it arises some problems such as surface delamination materialize while machining process. Milling is the machining process is generally used in the manufacturing of FRP to produce well specified and high-quality surfaces and removal of the excess material to control tolerance [18]. The philosophy of cutting tools is necessary to optimize cutting mechanics and machinability in milling. The required quality of surface roughness depends on tool geometry and cutting tool parameters. Everstine and Rogers[19] were conferred the first study on machining of FRPs in 1971 and experimental investigation is carried out. For better surface finish the cutting speed has to be increased was suggested by Santhanakrishnan et al. [20] and Ramulu et al. [21]The machinability of fibre adaptation on the cut quality, cutting forces and tool wear were studied by Hocheng et al.[22]. Hintze Wolfgang et al. [23] authorized during milling of CFRP the delamination factor of the primary layer while milling operation by using a tape milling process and showed that delamination depends on fibre orientation and the tool sharpness. While the handling of CFRP the cutting temperature is higher than the glass transition temperature of the matrix resin is not favorable as they destruct the laminates that were proved by Yashiro et al. [24]

Shaping and Edge trimming of CFRPs is commonly tested for the assumed orthogonal cutting condition. The first preparatory investigation in CFRP machining was achieved on an instrumented shaping machine by Koplev[25] proposed that the reduced orthogonal process differentiate by well define the geometry. Ramulu et al. [26] performed edge trimming to study the response of fibre orientation on surface roughness of the machined CFRP composite by using a polycrystalline diamond. Similar work was done by Wang et al.[27]in edge trimming of unidirectional CFRPs generally, chip formation, cutting theories, and analytical force forecasting can be effectively investigated, an underspecified condition through orthogonal CFRP cutting tests performed by shaping or edge trimming, due to the relatively simple interaction between the CFRP components and cutting tools.

2. Influence of input process parameters on machinability indices

The research studies on CFRP machining were carried out, the machining criteria were namely cutting speed, feed rate and depth of cut can be distinguished. Uncoated tungsten carbides, ceramics and cubic boron nitride (CBN) are three types of the cutting tool that were held to worn for machining of two types of specimens, short (discontinuous) and length(continuous) fibre carbon epoxy composites. As short carbon fibre composites, preparatory statistics show that the tool wear, the cutting force and the surface finish fluctuate with respect to the depth of cut, the cutting speed and the feed rate. Anyhow, considering long fibre carbon composites, as a rigid material of removal rate, the tool wear was a decrease when the CFRP composites have been machined at lower cutting speeds. In extension, CBN inserts showed superior tool to wear properties and better surface finishes as related to ceramic inserts and tungsten carbide ceramic inserts.

2.1 Effect of input process parameters on machining force and surface roughness

I.S.N.V.R. Prasanth et al. [28] conducted experiments on FRP composites with 5 different customized end mill tools and concluded that it is relevant to minimize the machining forces to obtain sustainable outcomes of machining; it is directly or indirectly influenced by all the input variables of milling process such as spindle speed, feed rate, depth of cut, cutting tool geometry, Workpiece material, tool-workpiece interface characteristics, tool temperature, and machining vibrations. His work focused on studying the effects of the spindle speed, feed rate, depth of cut, and cutting tool type, i.e., geometry on the performance characteristics of the milled surface in terms of Fm and Ra. Fm and Ra value have been decreased with an increased value of spindle speed and again start increasing after attending their optimum value of 1950 rpm and feed rate is the moderate value at 1mm/sec for Fm, 1.2mm/sec for Ra, the depth of cut as 1mm for Fm and 1.5mm for Ra. It is concluded by I.S.N.V.R. Prasanth et al. [28]. The tool signature place a vital role in milling and machining forces observed when milled with a generalized four-fluted tool having a low rake angle and clearance angle [29, 30]. It leads to the effect of compressive forces in high and the possibility of high induced friction between tool and workpiece. It leads to high machining force poor surface quality [31]. When the use of a two-fluted customized tool having a rake angle of 35^0 and high clearance angle 14^0 has resulted in the provision of fewer values of Fm and Ra. It produces a better surface finish, less friction and compressive forces.

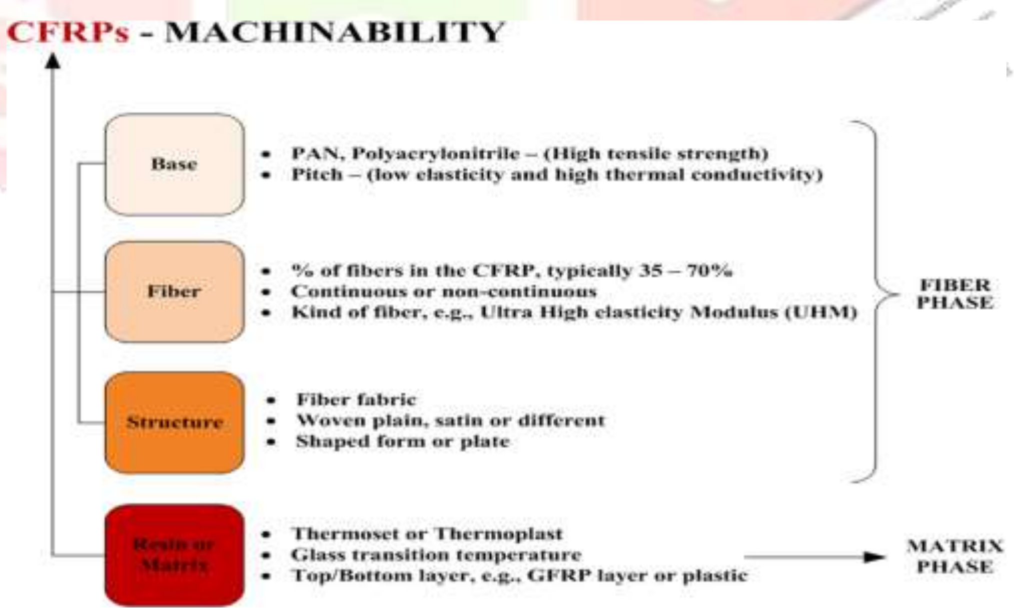

Fig 1: Material properties of CFRPs governing the machinability of CFRPs [32]

2.2. Machining forces and topology investigations of CFRP

The cutting forces grown up over machining are to be decreased in order to minimize the machining conjoin damages. In precise, the thrust force and torque developed over drilling have been mostly approached by the researchers past the decades. On the sisal-reinforced polylactic acid composite the drilling operation is performed that the thrust force, torque and drilling damage generated, ease with the increase of spindle speed and as force increase along with the rise of spindle speed. Also, it has been observed that the type of drill geometry has a significant impact on machinability. The choice of drill geometry for natural and synthetic fibre composite is not at all identical in quality [35].

An investigation over drilling on the sisal fiber-reinforced composites recorded that the torque and thrust force is more with the maximum in feed rate and point angle. Again, the torque lightly declines with the inflated of spindle speed [36]. In one more research over drilling, it was recorded for the thrust force can be the easiest drilling through the lowest feed rate and towards the highest spindle speed [37]. A study on the impact of twist drill and dagger drill over drilling a CFRP laminate terminated that feed rate is particularly affecting the surface finish go after with the spindle speed. Beyond, the dagger drill is beginning to be more relevant to ease the drilling defects than the twist drill [38].

2.3. Damage investigations

Damage over drilling develops both at the entrance and at the exit surface of the workpiece. The damage which occurred about a hole which is drilled called as damage factor or delamination factor or deface. The scientist researched the experiments about the damage over drilling. An experimental study related the response to variant drill geometry over the machinability and terminated that a step drill built the least delamination, which is followed by a twist drill. The worn by Brad and Spur drill, enlarge the delamination due to the elevation of thrust force [39]. In one more research, drilling experiments have been managed on glass and polyester sheet reinforced hybrid composites. It has been recorded that spindle speed, flute length, and feed rate are the dominating factors considering the hole damage. The collection of levels for input factors is very significant in producing improved machinability. In general, a low feed rate of the spindle will be an applicable option for strengthening the machinability. The point angle of the drill has a major impact on the hole damage. Drilling with a high point angle raises the area of contact between the drill and work surface. This affects the major thrust force of the work and extrudes the hole damage [40]. Hence, a low feed rate and a low point angle are a relevant option for contracting the drilling conjoins damages [41, 42].

The number of flutes existing on the tool affects the damage evolved over machining. An experimental study on the milling of CFRP composite terminated that a two fluted end mill and less damage as compared to that of a six fluted end mill [43]. The choice of tool material is one more significant parameter at the time of viewing the machinability. Research work over the drilling of CFRP laminates recorded that the tungsten carbide tool is better than the polycrystalline diamond tool in contact with the damage and for economical operations [44].In one more investigation, the uncut fibre factor and delamination factor have been researched over balsa wood composite. It has been concluded that the influence of feed rate, spindle speed, and tool diameter on the delamination and uncut fibre factor are similar [45]. Hence, the machining factors must be exactly investigated over the machining of FRPs in order to alleviate the damages.

2.3.1. Conventional machining

By forcing plastic deformation the material gets ejected from the work piece in addition to conventional machining techniques are the capacity concern involved in the objective of physical interaction among tool and workpiece. The traditionally conventional machining process is using the physical contact tool machining process are drilling, cutting, trimming and milling. In this area, we will discuss surface characteristics and frequent damages that arise through cutting, drilling and trimming.

2.3.2. Quality of machined surface

Due to damage take place in machining, the machining surface becomes rougher and considerably the composite part of the geometric precision is affected. In application to this, by using probable criteria the surface quality of machining composite needs to be outlined. Also, the damages created in machining such as peaks, valleys, and micro-cracks, which are possibly lowering the mechanical performance [46]. To represent the machined surface of roughness criteria (Surface roughness, Ra), composites have been engaging generally in the industry.

The response of feed speed and cutting speed on top of surface roughness can be observed [47]. An increase of feed speed and a decrease of cutting speed lead to developing surface roughness for both Ra and Rz. These can be elucidated by the fact that the increase of chip thickness due to enhancement of feed speed increases or lower cutting speed makes machining more difficult and as an outcome the rougher surface quality is attained.

Anyhow, when examining the effect of feed rate and cutting speed on surface roughness of multidirectional CFRP at giant cutting speed conditions, Haddad et al. Revealed conflicting results [48]. Corresponding to their outcome, machining CFRP at low feed rate and high cutting speed, major resistance is developed which will accelerate the cutting temperatures and cause tool wear to increase giving rise to lower surface quality. If the temperature is greater than the glass evaluation temperature, the matrix is softened, which facilitates setting against and fibre abandon. This circumstance is also considered in the investigation performance of Konig et al. [49] when cutting speed reaches over 1130 m/min.

If the wear of cutting tool increases the surface roughness also increases. This is described in the work of Ghidoshi et al. [50] when machining unidirectional carbon/epoxy. Tool wear, in this case, has affected that increase of cutting distance leads to an increase in cutting edge radius. As a result, machining is more crucial and a ridged machined surface is achieved. The several authors have experimented with their research study on the effect of tool wear in terms of cutting distance has also been observed by authors such as Janardhan et al. [51] or Haddad et al. [48]. Janardhan et al. have recorded that surface quality are also relying on trimming configuration, it is proved that the machining CFRP by burr tool with cutting speed of 100 m/min combined with two values of feed rates (2.54 and 5.08 m/min). The surface quality achieved by down milling is lower when compared to that of up milling. This difference can be linked directly to the process of chip formation in which fibre and matrix is mainly groomed in up milling. In concert, buckling and cracking occur in the case of down milling [51]. The same results are also discussed for surface roughness when machining CFRP with straight flute PCD cutter [52].

Wang et al. [53] tested the response of tool geometry and depth of cut on the surface roughness at orthogonal machining of the unidirectional laminate was carried out. Based on their research study and observation, surface roughness is identical in the case of fibre orientation transferable between 0° and 90° negligent of the value of depth of cut (0.001 and 0.05 mm). However, taking into account fibre orientation between 90° and 150°, the variation of surface roughness is clear when machining was carried out with formerly considered the depth of cut (Fig. 2)

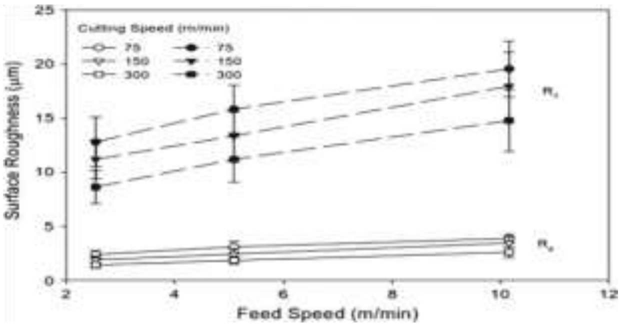

Fig 2: Evolution of surface roughness versus feed speed when machining multidirectional CFRP [47].

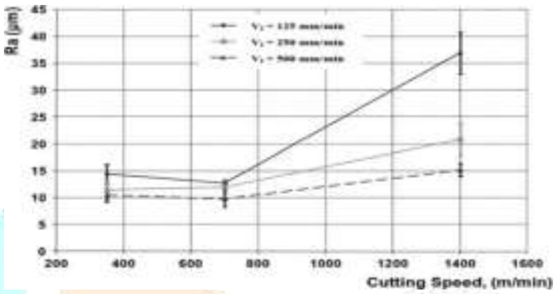

Fig 3: Effect of cutting parameters on surface roughness (Ra) when machining CFRP at the high cutting speed [48].

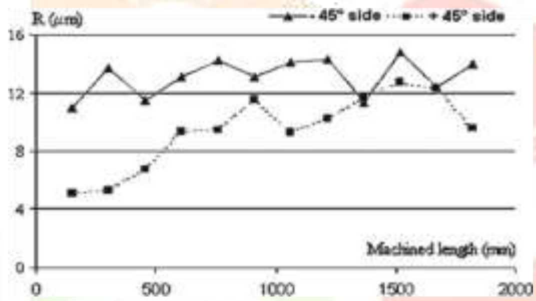

Fig 4: Evolution of surface roughness as a function of machining distance for the −45° and +45° sides of the carbon/epoxy specimens [50].

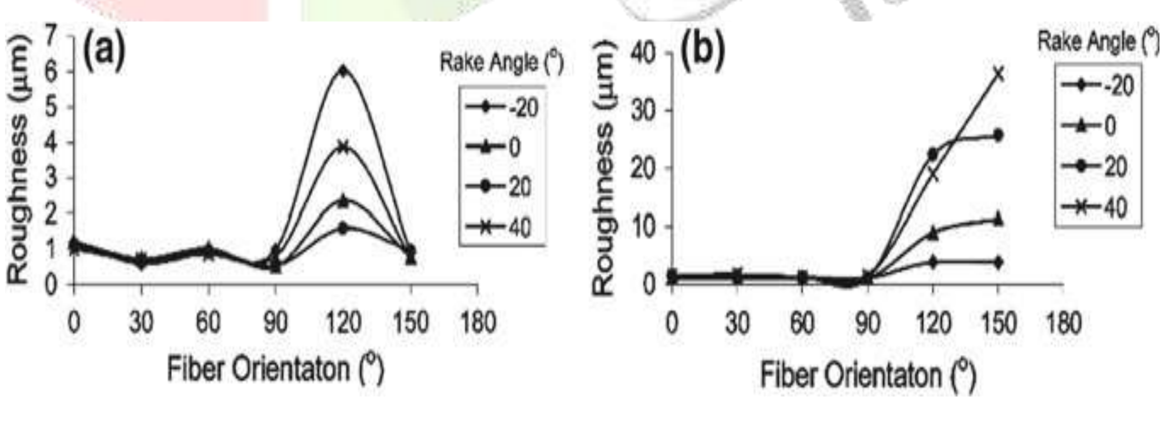

Fig 5: Effect of fibre orientation on surface roughness. The depths of cut were **a** 0.001 mm and **b** 0.05mm [53].

2.3.3. Non-conventional processes

2.3.3.1. Abrasive Water Jet (AWJ) Machining (Milling)

In this approach, the particular size of abrasive particles is merged along the pressurized water in addition to it is enforced by way of a very small nozzle shaping a high-velocity water jet; on the workpiece, the abrasive particles are being carried out by fine high-velocity water jet. The hard abrasive particles' impingement workpiece surface and material is removed by the mechanism of disintegration, which varies accordingly for brittle and ductile workpiece materials. The FRP materials are brittle materials and the material is removed from erosion and brittle fracture. This mechanism is widely used for trimming FRPs and recently it also used for pocket milling (Depth milling) of FRPs.

The AWJ trimming studies on graphite/epoxy composite by Arolaetal.[54] prove that cut surfaces have three distinct characteristic regions, viz., initial damage region (IDR), smooth cutting region (SCR), and a rough cutting region (RCR) as shown in Fig.6. He mentioned that the size and extent of these three regions are strongly influenced by cutting parameters and the nature of the machine material.

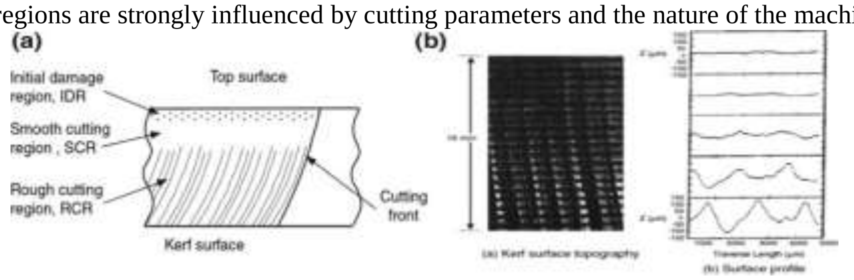

Fig 6: **a** Schematic diagram showing different surface regions on the kerf wall of AWJ cut graphite/epoxy composite. **b** Kerf wall and corresponding roughness profiles[54].

Delamination is a major defect while machining FRP composites. Abrasive water jet machining is no option of this defect. In this research experimented by Shanmugam et al. [55], it was found that the fracture tips were caused due to the stroke of the shock wave of the water jet at the basic cutting stage, while delamination is a emerge of water penetration into the fracture tips that develops abrasive embedment and water force. Once the crack tips are formed due to the shock waves, the crack propagation happens due to continuous stress acting on the crack tips. When the jet impinges on the workpiece, material removal occurs due to the spoiling phenomenon in the active region of a jet giving rise to a kerf. Apart from this, the water jet enlarges in the eroded spaces on the kerf walls, thereby rising secondary stresses; this further opens up the crack. Finally, abrasive particles enter the crevices and their shearing action gives rise to delamination (Fig. 7).

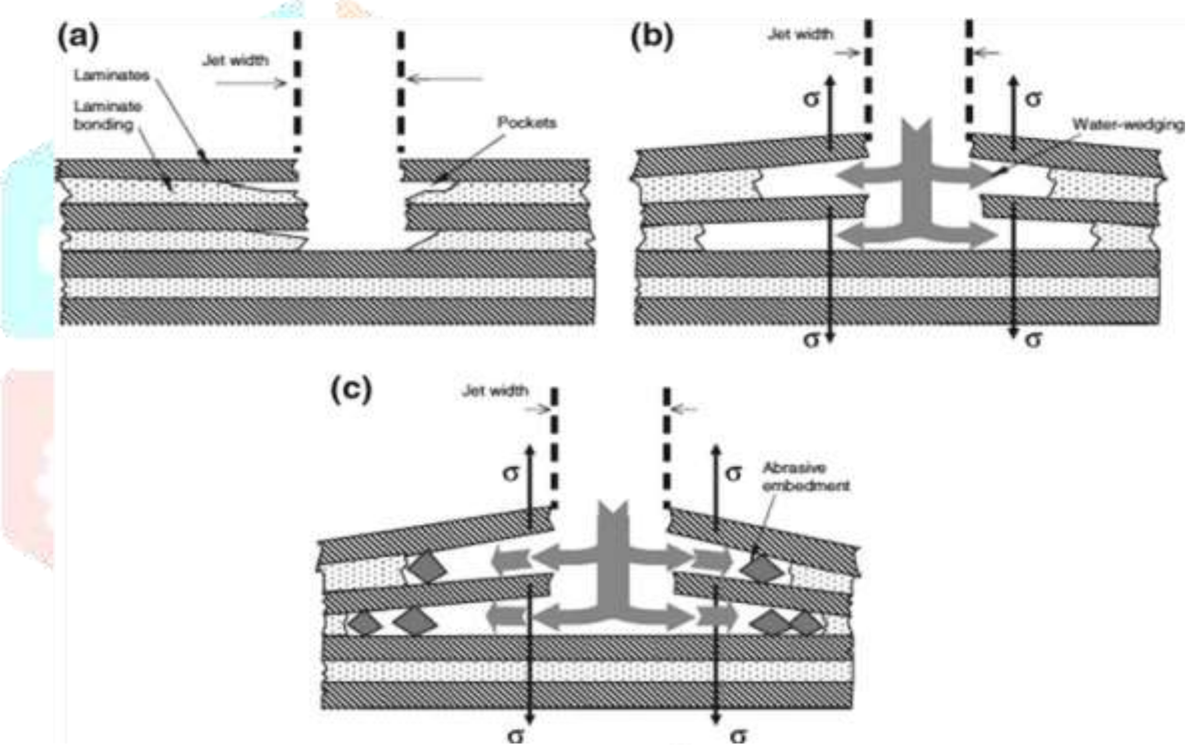

Fig 7: Schematic view of the delamination mechanism during trimming with AWJ: **a** Damage initiation, **b** water wedging, **c** abrasive grit embedment between the plies [55].

The shearing action of the abrasive grits plays a major role in the material erosion mechanism. With the delay in introducing abrasive particles in the jet stream, the workpiece is eroded mostly by the shockwave impact of the water jet that results in an unclear cut with eroded spaces in between the plies of the laminate. The low material removal rate allows enough time for the fracture to begin by the shock wave impact of the water jet. The crack tips formed to allow the penetration of water inside which develops a wedging action, triggering the propagation of the cracks. Later, the abrasive grit particles are introduced in the cracks which embed in between the plies and lead to further wedging action. The embedment of the abrasive particles also keeps the crack open [55].

2.4. Statistical and design tools for machinability assessment

For the determination of machining criteria the integrated tools play a significant role. The Taguchi technique is most commonly used for the determination of machining. Grey Relational Analysis (GRA) is one more process worn as optimization of machining criterion. In this particular approach, grey relational grades move tall by hand-operated and worn as optimization of responses independently [56]. Artificial Neural Network (ANN) program is one more extensively worn system as forecasting the machinability. An investigative study worn ANN method to forecast the torque, thrust force, and damage over drilling at fiber-reinforced composite. It has been recorded that the ANN technique precisely forecasts the feedback with reference to the complying trials and the fault is established to be lower than 4% [57].

Fuzzy logic is one more significant method worn by the scientist for forecasting of optimum parameters over machining. A research study about the thrust force, including torque over the drilling of hybrid composites, it has been recorded that the fuzzy method precisely forecasts the optimum values of feedback in distinguishing to the complying trials [58, 59]. Response surface method (RSM) is an extensively worn method for complications contain numerous feedback responses. Central composite design, D-optimal design, and Box Behnken design are greatly worn RSM for determining the machinability. An experimental work recorded that in association with the RSM, D-optimal design is primarily calculated for the sake of the issues handled with distinct height for its factors. One more great influence of this technique is it develops the obstacles that contain both categorical and numerical factors [60]. Regression analysis and ANOVA are the most frequently worn techniques over machining of composites. The regression analysis gives a measurable forecast of output parameters in terms of input parameters. The ANOVA technique helps to demonstrate the contribution and influence of input factors on the output parameters [61, 62].

Particle Swarm Optimization (PSO) is a significant integrated modeling tool used for machining studies. It is a population-based stochastic optimization method used for optimization and modeling of output responses. A research study on the minimization of burr size over drilling recorded that the modeling employing PSO is eminently satisfactory and the burr size is high with a rise in the feed rates and speed [63]. Genetic Algorithm (GA) is also one more way of considering the machinability conditions.

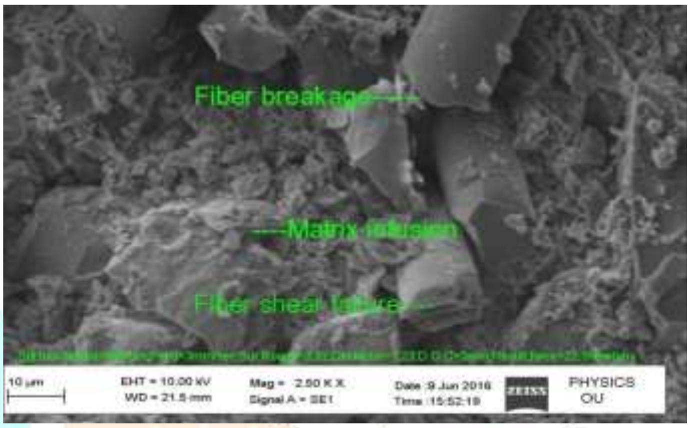

Fig 8: (a) SEM images for machined surface damages of GFRP laminate with two fluted customized carbides tipped tool, when the spindle speed is 690 rpm and the feed rate is 3 mm/s [64].

CONCLUSION:

This review paper has made a complete analysis of numerous issues that emerged throughout the machining of CFRP. The primary conclusions were as mentioned below:

1. During machining of composite, we have considered the various machining parameters; the parameters depend on the composite polymer of CFRP due to its mechanical properties.

2. The mechanical behavior of CFRP while machining with AWJ the delamination factor and the surface finish were characterized.

3. The selection of statistical tools plays an important role during the optimization of CFRP. While machining of CFRP the available input-output factors has to be considered

4. While machining of CFRP at a different speed, depth of cut and feeds where influenced on machining parameters.

5. The most suitable for non-conventional machining techniques like milling, drilling, shaping and edge trimming in CFRP. The operating and machining costs should be considered for a suitable method that could be adopted for machining plastic composites.

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