

## Effects of Cutting Parameters on Delamination in Machining for S 2 Glass Fiber Reinforced Polymer Composites

Murat Koyunbakan<sup>1\*</sup> & Zafer Kaya<sup>2</sup>

<sup>1</sup>Mechanical Engineering Department, <sup>2</sup>Department of Mechatronics, Kütahya Dumlupınar University, Simav-Kutahya, Turkey

*Received 02 January 2024; revised 06 September 2024; accepted 22 November 2024*

Fiber-reinforced polymer composite materials are new engineering materials that are preferred in engineering applications due to their superior properties. Today, S 2 glass fibers are used as reinforcement elements in composite applications requiring high strength. Polymer composite materials are usually produced close to their final shape. In order to perform mechanical joining operations on these materials, additional machining operations are required. Drilling and milling operations are the most preferred machining processes for polymer composites. The holes and grooves opened for the bolts and rivets used in the joining processes are required to be of high quality. In this study, the machinability properties of S 2 glass fiber-reinforced polymer composite materials with an average thickness of 1.8 mm are investigated by drilling and grooving operations. Machinability experiments are carried out in a dry environment using different cutting parameters in a CNC milling machine (Drilling-VMC850B branded CNC, Grooving-Skilled 2040 CNC). The deformation on the surfaces has been visualized and examined using an optical microscope. As a result of machining operations, it has been determined that the drill bit angle is the most important parameter for the drilling process, and there is less deformation in the channels opened in the 45° direction for the grooving process. The roughnesses formed on the hole and groove surfaces were measured and the most effective parameters were found. The effective parameters for drilling tests were the tip angle; for grooving tests, the speed and the number of revolutions.

**Keywords:** Delamination, Drilling process, Grooving process, S 2 glass fiber, Surface roughness

### Introduction

Fiber-reinforced polymer composite materials have different properties than metals and non-reinforced polymers.<sup>1-3</sup> They are often preferred in engineering fields due to their good strength properties and rigidity, as well as their ability to be produced close to their final shape.<sup>4</sup>

Although fiber-reinforced polymer composites can be produced close to their final shape with different molding methods, additional manufacturing processes such as milling, turning and drilling are also needed to bring them to the desired dimensions and tolerances.<sup>5</sup> Fiber-reinforced polymer composite materials, with their structure consisting of soft matrix and hard reinforcement elements, bring quality problems such as delamination, thermal degradation, spalling and fiber shrinkage during machining operations. These problems make it difficult for the machinability of these materials compared to metals.<sup>6</sup> The problems listed above are also seen as types of damages caused by the machining process in the composite structure.

These damages occur especially in fiber-reinforced laminated composites due to anisotropy resulting from fiber orientation and layer symmetry.<sup>7</sup> Drilling is the most widely used method for machining fiber-reinforced composites. The quality of the drilled holes can be critical to the life of the riveted joints for which the holes are used.<sup>8</sup> Composite structures are usually drilled with conventional methods.<sup>9</sup> Obtaining the appropriate values of the machining parameters is an important criterion for high-quality machining.<sup>7,10-12</sup> During the drilling of glass fiber-reinforced polymer composites, the thrust force must be low, the hole must have low roughness surface and the deformation must be low.

There are many studies on the drilling of fiber-reinforced laminated composites in the literature. Researchers have been working on input and output delaminations and the effects of cutting parameters on delamination have been investigated both experimentally and analytically.<sup>13-17</sup> The delamination mechanism in holes is observed in the form of curling and pulling (peel-up) at the hole entrances, pushing out (push-out) at the hole outputs.<sup>8</sup> Khashaba *et al.*, has studied the drilling of glass fiber-reinforced

\*Author for Correspondence  
E-mail: murat.koyunbakan@dpu.edu.tr

composites and investigated the effect of shear parameters on thrust force and delamination. They concluded that increasing the cutting speed and feed rate leads to increased delamination, and as the feed rate increases, the thrust force and delamination increase.<sup>18</sup> Similar results were obtained in different studies.<sup>15,19–21</sup>

In addition to the cutting parameters, the effects of drill geometry on delamination are investigated. Can and Ünüvar<sup>22</sup>, examined the thrust forces and input and output deformations in the drilling of composite materials in their studies and investigated the effects of the change of tip angles on the results. Abrao *et al.*, investigated the thrust force and delamination in the drilling of glass fiber-reinforced polymer composite materials with different cutting tool geometries and materials. They found that the small tip angle was more suitable for the results.<sup>23</sup> Koyunbakan *et al.*, drilled holes in glass fiber-reinforced polymer composite materials using wood drills of different diameters. They examined the thrust force and delamination.<sup>24</sup> Yıldırım *et al.* investigated the delamination of three-dimensional cavity glass fiber-reinforced polymer composites when drilling and milling grooving processes. They found that the feed should be low in order to obtain low deformation for both processes.<sup>25</sup>

When the literature on the machinability of S 2 glass fiber reinforced polymer composites has been examined, not many studies are found on the subject. Among the studies found, Koklu *et al.*, studied the effects of cryogenic cooling on the drilling of fiber-reinforced polymer composites from S 2 glass prepreg material obtained by autoclave production method.<sup>26</sup> In this study, S 2 glass fiber reinforced polymer composite material produced by Kaya *et al.* used as the experimental material. In addition to the resin and hardener duo used, this composite material has its own characteristics in terms of production method. The mechanical properties of this composite under different conditions were investigated and included in the scientific literature.<sup>27</sup> When composite structures are produced as plates, they are assembled with different connecting elements. They can be drilled or milled grooving before joining processes. In this study, unlike the literature, machinability properties are detailed by performing milling in different directions (warp, weft, 45°) tests as well as drilling tests. The machinability properties of S 2 glass fiber reinforced polymer composite materials are

investigated by using different cutting parameters. Drilling and grooving operations were performed and the delamination factors occurring on the upper and lower surfaces were investigated. Additionally, the roughness of the machined surfaces was measured and the cutting parameters that affected them were investigated.

## Materials and Methods

### Materials

The S 2 glass fabric used in the production of plates manufactured by Seal company, weighs 190 g/m<sup>2</sup>, has a thickness of 130 µm, warp/weft ratio of 28.7/ 27.5. The production was carried out with 8 layers of the same directional fabric. Plate thicknesses were on average 1.8 mm. The matrix material was obtained by combining hardener (Hexion H287) and epoxy resin (Hexion MGS L285) in a ratio of 40:100 by weight. Vacuum Resin Transfer Method (VARTM) was used as the production method and 50 × 40 cm composite plates were produced. Each plate produced was pre-cured at room temperature for 24 hours, and then secondary cured at 80°C for 5 hours, according to the recommendation of Hexion company.<sup>27</sup>

### Determination of Mechanical Properties

Tensile and compression tests to determine the mechanical properties of the produced S 2 glass fiber reinforced polymer composite plates were carried out at 20°C laboratory conditions and at 5 mm/min test device holding jaw speeds. The tests were carried out by the following standards; ASTM D3039/3039M-08 and ASTM D 3410/D 3410M-03.<sup>28–30</sup> As a result of the tensile tests, the tensile strength ( $T_1$ ) and modulus of elasticity ( $E_1$ ) in the warp direction, as well as the tensile strength ( $T_2$ ) and modulus of elasticity ( $E_2$ ) in the weft direction were found. The elastic properties of used S 2 glass fiber and epoxy resin are given in Table 1. The properties of composite plates obtained as a result of mechanical tests are shown in Table 2.

Table 1 — The material properties of fiber material and epoxy resin

Material Properties	Fiber Material (S 2 Glass) <sup>31</sup>	Matrix Material (Hexion Epoxy Resin) <sup>32</sup>
Young's modulus (E) in GPa	86–93	3.2
Shear modulus (G) in GPa	35–39	1.18
Poisson's ratio ( $\nu$ )	0.21	0.36
Tensile strength in MPa	4700–4800	70–80
Compressive strength in MPa	4000–5000	120–140

Table 2 — Mechanical properties of composite plate<sup>27</sup>

Holding jaw speeds (mm/min)	T <sub>1</sub>		T <sub>2</sub>		C <sub>1</sub>		C <sub>2</sub>		E <sub>1</sub> (GPa)	E <sub>2</sub> (GPa)
	Stress (MPa)	Strain (mm/mm)	Stress (MPa)	Strain (mm/mm)	Stress (MPa)	Strain (mm/mm)	Stress (MPa)	Strain (mm/mm)		
5	364.64	0.0326	336.92	0.0217	314.42	0.098	326.80	0.1199	16.92	17.39

**Drilling Tests**

Drilling operations of S 2 glass fiber reinforced polymer composite material were performed in VMC850B branded CNC milling machining center. This machine has a maximum of 8000 rpm. Drilling experiments with different cutting parameters were carried out in a dry environment by using MTE brand uncoated HSS drill bits with 6 mm diameter and different tip angles as a cutting tool.

The cutting parameters used in drilling experiments are shown in Table 3. The recommendations of the cutting tool providers and the literature taken into consideration while determining the cutting parameters. There are studies on drilling fiber-reinforced polymer composites using drill bits with different geometries.<sup>4,33</sup> Standard HSS and carbide drills with different tip angles are used extensively and it is seen that differences in drill bit angles have important effects on hole quality.<sup>24</sup>

The drilling experiments were performed three times and new drill bits were used each time. The drill bits used in the experiments are given in Fig. 1. The L27 (3<sup>3</sup>) orthogonal experiment design was made for drilling experiments. Using the Taguchi method with MINITAB 17, the effects of cutting parameters on machinability were determined. In addition, the effects of independent variables (experimental parameters) on dependent variables (measured results) were determined by Analyzing Variance (ANOVA).

Deformation occurs on the upper and bottom surfaces of the drilled fiber-reinforced laminated polymer composites. The damage mechanism is shown schematically in Fig. 2. It is known that deformation occurs in the transformation zone from the natural colour of the material to white. The amount of deformation is often defined by determining the deformation factor, which is a non-destructive testing technique. This factor is found by dividing the largest measured damage diameter by the drill diameter.<sup>24</sup>

In this study, Insize ISM-PM 200SB brand optical microscope is used to detect surface deformation damages after drilling experiments. The deformation factor is defined as the ratio of the damage caused by the drill bit around the hole on the input and output surfaces of the composite material to the drill diameter and calculated by Eq. (1).<sup>(34)</sup>

Table 3 — Cutting parameters for the drilling test

Parameters	Level 1	Level 2	Level 3
Spindle Speed (rpm)	265.25	530.51	795.77
Feed (mm/rev)	0.05	0.075	0.1
Tip Angle (degrees)	100	118	140

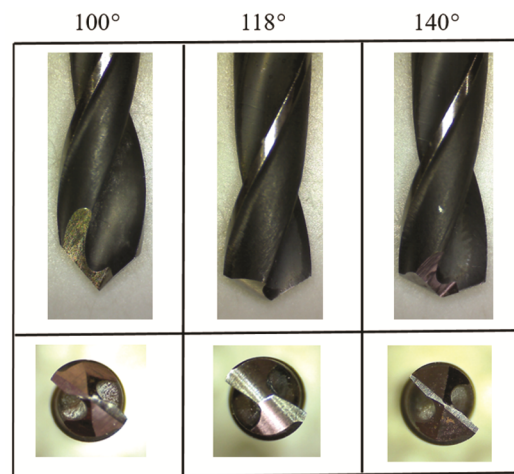


Fig. 1 — Drill bits (Ø 6 mm)

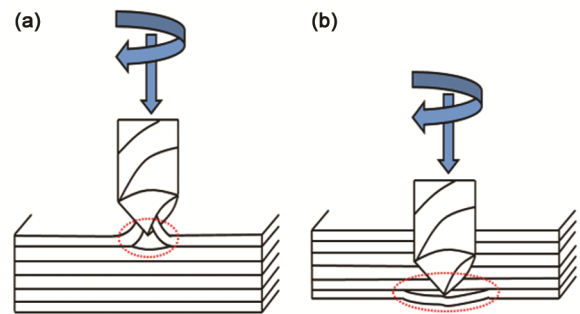


Fig. 2 — Schematic picture of the deformation: (a) Peel-up delamination, (b) Push-out delamination

Here,  $F_D$  = Deformation factor,  $D_{max}$  = Maximum damage diameter,  $D$  = Drill diameter. How to find the deformation factor using optical microscope is given in Fig. 3.

$$F_D = \frac{D_{max}}{D} \quad \dots(1)$$

**Grooving Tests with End Mill**

In another stage of the study, groove making was performed to determine the machinability properties

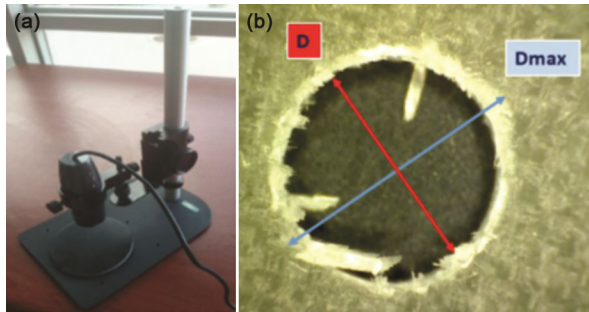


Fig. 3 — (a) Optical microscope used for deformation study, (b) Deformation factor elements

Table 4 — Grooving cutting parameters

End Mill	Parameters		
	Diameter (mm)	Spindle speed (rpm)	Feed (mm/min)
HSS	6	1000	100
		5000	300
		10000	500

of S 2 glass fiber reinforced polymer composite material. Grooving experiments were carried out with different cutting parameters by using Karcan Cutting Tools brand HSS end mill with 6 mm diameter. The experiments were carried out in a dry environment on a Skilled 2040 CNC milling machine that can work at a maximum of 18000 rpm. The cutting parameters used in grooving operations are given in Table 4.

When the grooving process of fiber-reinforced polymer composites is performed, surface damage is similar to the drilling process. In order to measure the deformation, the damage around the groove is measured, similar to the process performed in drilling. The deformation factor is found by proportioning the damage to the groove width (Eq. (2)). Here;  $F_D$ : Deformation factor,  $W_{max}$ : Maximum damage width,  $W$ : Groove width.<sup>35</sup>

$$F_D = \frac{W_{max}}{W} \quad \dots (2)$$

The grooving operations are performed on test specimens cut in a triangular profile at an angle of  $45^\circ$ - $45^\circ$ - $90^\circ$ . The purpose of cutting a triangle is to align the grooving surfaces and the end mill well when the test specimen is fixed to the machine. By using different cutting parameters, the grooved capability of the test sample in three directions as weft, warp, and  $45^\circ$  angle is investigated. An example image of the test sample and the determination of the

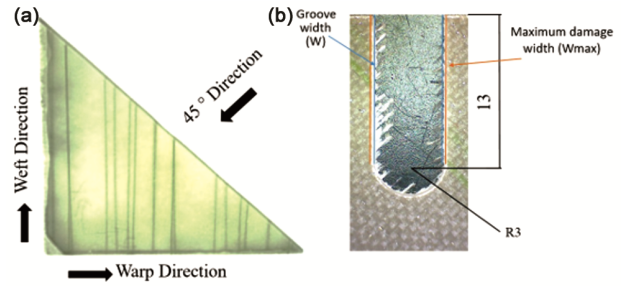


Fig. 4 — a) Experimental sample, and b) Deformation around the groove

deformation factor in the grooving process is given in Fig. 4.

The  $L9(3^2)$  orthogonal experiment design was made for the grooving experiments. The effects of cutting parameters on machinability were determined using the Taguchi method and Analysis Of Variance (ANOVA) was performed. The MINITAB 17 program was used in the analyses.

#### Roughness of Machined Surfaces

The surface quality of the work piece is an important attribute of quality in any machining operation. Many factors affect the surface quality during machining.<sup>36</sup> The surface roughnesses of the hole and groove surfaces of the samples to which drilling and channel opening processes were applied were measured with the TR-200 (3200) surface roughness measuring device. Three measurements were made from different regions and their averages were taken. The measurement range was set to  $0.25 \times 5$  mm under the thickness of the samples.

#### Results and Discussion

Although the effects of cutting parameters are generally known in the literature on the machinability of glass fiber-reinforced polymer composite materials, it is difficult to make definitive judgments about drill bit geometries.<sup>37</sup> In this study, S 2 glass fiber-reinforced polymer composite material was both drilled with HSS drill bits with different tip angles and grooves were opened into the test specimens using a four-edged HSS end mill. The deformation factors for the input and output surfaces as a result of the drilling tests are given in Fig. 5.

When the results are examined, the lowest value for the deformation factors measured on the input surface is obtained at the first levels of the cutting parameters. It has also been stated in other studies in the literature that low feed and tip angle have a positive effect on deformation. Tsao<sup>38</sup>, observed also

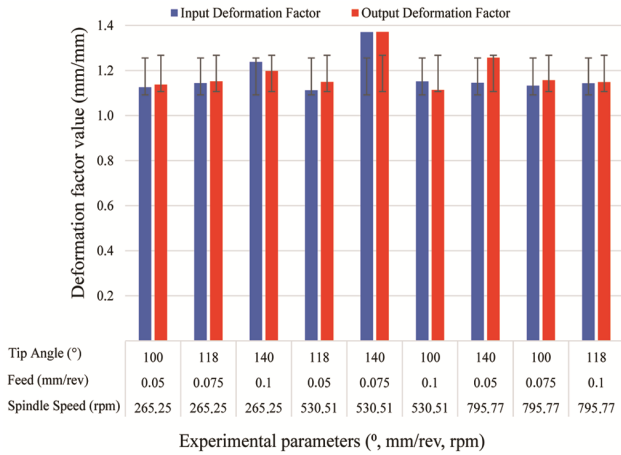


Fig. 5 — L27 (3<sup>3</sup>) orthogonal test design and deformation factor results for drilling

supports this situation that the thrust force is generally low at low feed rates, which reduces layer separation. The most surprising point in the literature, when compared to studies conducted with other types of glass, is that S 2 glass fabric behaves much more stably. Thanks to its compatibility with epoxy resin, the layers' good adhesion to each other has reduced the entry deformation.

The lowest value for the deformation factors measured at the output surface is obtained when the drill bit angle is small and the cutting speed is moderate. Contrary to the input surface, the deformation factor value decreased when the feed rate is high at the output surface. The fact that the drill bit angle is small for a low deformation factor on both surfaces is consistent with the literature.<sup>23</sup> The high-ratio silicon structure of S 2 glass also brings brittleness. Low cutting speed causes increasing stress accumulation, while high cutting speed causes instant high-stress accumulation. With these stress accumulations, the brittle S 2 glass showed sudden corner fractures. For this reason, the medium cutting speed was an ideal value in terms of exit deformation.

The deformation factors that occurred and are calculated on the upper and bottom surface of the sample as a result of the experiments performed for grooving are given in Fig. 6. When the results were examined, high consistency could not be achieved for the effect of cutting parameters for all directions, but understandable results were obtained. Similar results are also valid for the deformations in the bottom surface. In general, it is observed that the deformation is less in the experiments where the revolutions per minute and the feed are low. The lowest deformation

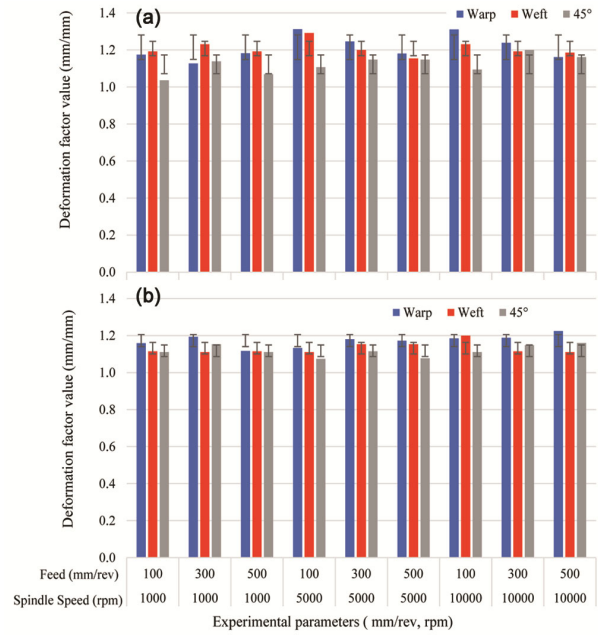


Fig. 6 — L9 (3<sup>2</sup>) orthogonal test design and deformation factor results for grooving: (a) upper, (b) bottom

in the warp direction on the upper side is obtained with a deformation factor of 1.182192 at 1000 rpm and 500 mm/rev feed parameters. In the Weft direction, the lowest deformation factor is obtained at the parameters of 5000 rpm and 500 mm/rev. Compared to other directions, the least deformations occurred in the grooving operations performed in the 45° direction. The least deformation occurred at the lowest values of revolution and feed rate and the deformation factor of 1.0357142 is calculated. S 2 glass fabric is produced in satin weave type in terms of its structure. In this structure, different numbers of loops pass over each other in the weft and warp directions. The non-homogeneous structure in this looped structure of the fabric is exposed to different types of stress at each contact point when the end milling cutter touches the composite plate. At the same time, the helical structure of the end milling cutter pulls the fabric fibers from bottom to top with the screwing effect while cutting on one side. In addition, the composite plate and the fibers forming the plate are also exposed to tensile, compressive, and torsional stresses in the direction of advancement of the end milling cutter. As a result of these multivariable effects, different deformations were observed on the upper and lower surfaces of the composite plate.

In terms of all results, the best results for deformations on the upper surface are obtained in the

45° direction. It can be said that less deformation occurs in the weft direction than in the warp direction. With medium cutting speed and low feed, less deformation factor is obtained in grooving operation in all directions. The deformation is less in the groove in the 45° direction on the lower surface. This situation is similar to the upper surface. The minimum deformation factor is calculated as 1.0740740 at a speed of 5000 rpm and a feed of 100 mm/rev. Similar to the upper surface, the deformation factors calculated in the weft direction are less than in the warp direction. Direction of 45° grooving was a processing direction where compression and shear stresses perpendicular to the fiber cross-section were not formed in both the weft and warp directions. Since the end mill cutter did not encounter a 90° perpendicular surface in the advancement direction, it showed a more comfortable cutting performance. The S2 glass fabric, which can be easily cut, left a lower chip load during cutting, which also revealed a less deformation image.

The results obtained from the experiments on 3D glass fiber materials by Yıldırım *et al.*<sup>25</sup> are consistent

with the results found in this study. Experiments in the 45° direction is an addition in the current study.

Surface roughness is a highly significant output of cutting parameters and cutting tool performance. The surface roughness of holes significantly affects the mechanical properties and operational efficiency of assemblies using pins, bolts, and rivets.<sup>39</sup> Surface roughnesses measured after drilling and grooving tests are given in Tables 5 and 6.

A statistical performance measure known as the S/N ratio is used to analyze the results using the Taguchi method. The experimental results are evaluated by converting the signal-to-noise ratio (S/N). In the S/N ratio, S denotes the signal factor and N denotes the noise factor. The signal factor refers to the actual value obtained from the experiments, while the noise factor refers to the factors that cannot be included in the experimental design but affect the test result. Noise sources are all variables that cause the desired performance characteristics to deviate from the target value. It is desired that the deformation factor is low in the drilling and making of grooves of

Table 5 — Surface roughness for drilling tests

EN	SS (rpm)	F (mm/rev)	TA (°)	SR (μm)	EN	SS (rpm)	F (mm/rev)	TA (°)	SR (μm)
1	265.25	0.05	100	1.085	15	530.51	0.075	140	1.595
2	265.25	0.05	100	1.35	16	530.51	0.1	100	1.862
3	265.25	0.05	100	0.93	17	530.51	0.1	100	1.484
4	265.25	0.075	118	1.523	18	530.51	0.1	100	2.002
5	265.25	0.075	118	1.489	19	795.77	0.05	140	0.776
6	265.25	0.075	118	1.509	20	795.77	0.05	140	1.69
7	265.25	0.1	140	1.985	21	795.77	0.05	140	1.264
8	265.25	0.1	140	1.895	22	795.77	0.075	100	0.833
9	265.25	0.1	140	1.938	23	795.77	0.075	100	1.576
10	530.51	0.05	118	0.308	24	795.77	0.075	100	0.97
11	530.51	0.05	118	0.289	25	795.77	0.1	118	0.4
12	530.51	0.05	118	0.222	26	795.77	0.1	118	0.385
13	530.51	0.075	140	1.706	27	795.77	0.1	118	0.324
14	530.51	0.075	140	1.648					

(EN: Experiment number, SS: Spindle speed, F: Feed, TA: Tip angle, SR: Surface roughness)

Table 6 — Surface roughness for grooving

EN	SS (rpm)	F (mm/rev)	SR-Warf (μm)	SR-Weft (μm)	SR-45° (μm)
1	1000	100	1.281	1.413	1.728
2	1000	300	0.903	1.351	1.403
3	1000	500	1.169	1.394	1.414
4	5000	100	1.729	1.134	1.286
5	5000	300	1.552	0.916	1.197
6	5000	500	1.698	1.061	0.948
7	10000	100	1.906	1.732	2.936
8	10000	300	1.734	1.675	1.631
9	10000	500	1.839	1.697	1.688

(EN: Experiment number, SS: Spindle speed, F: Feed, SR: Surface roughness)

S 2 glass fiber-reinforced polymer composite materials. For this reason, the "smaller-better" performance characteristic is chosen for the S/N ratio. Eq. (3) used to calculate the S/N ratios is given below.<sup>40</sup>

$$S/N_{SB} = \eta = -10 \log \left[ \frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad \dots (3)$$

As a result of the analysis, the S/N ratios for the drilling experiments are given in the input and output main effect graphs in Fig. 7, and the response table is given in Table 7. When the main effect graphs are examined, the third level of cutting speed, the first level of feed, and the second level of the tip angle are the optimum parameters in terms of the input surface. It has been seen that the first levels of cutting speed and tip angle and the third level of feed are the optimum parameters for the output surface. Generally,

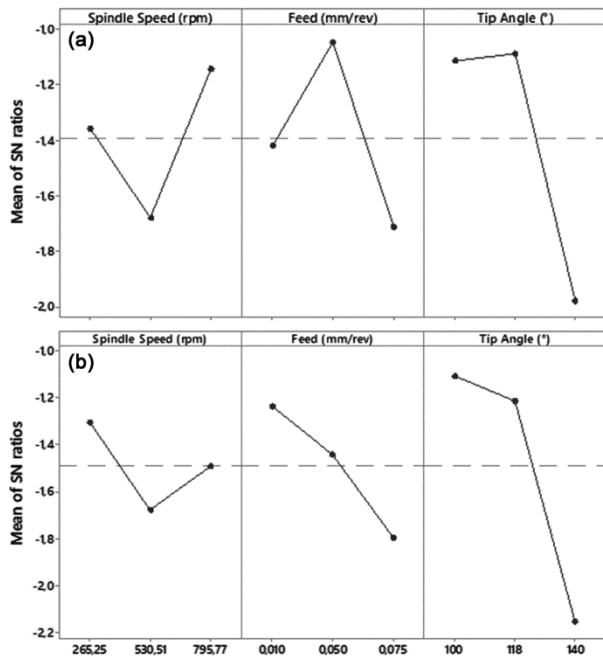


Fig. 7 — Main effect plots (data means) for S/N ratios (*Signal-to-noise: Smaller is better*) in drilling experiments: (a) Input, (b) Output

the low tip angle has a decreasing effect on the deformation factor.

When Table 5 is examined, it is seen that the drill bit angle is the most important cutting parameter in the drilling of S 2 glass fiber-reinforced polymer composites.

The upper deformation factors S/N ratios for grooving experiments are given in the main effect graphs in Fig. 8, and the response table is given in

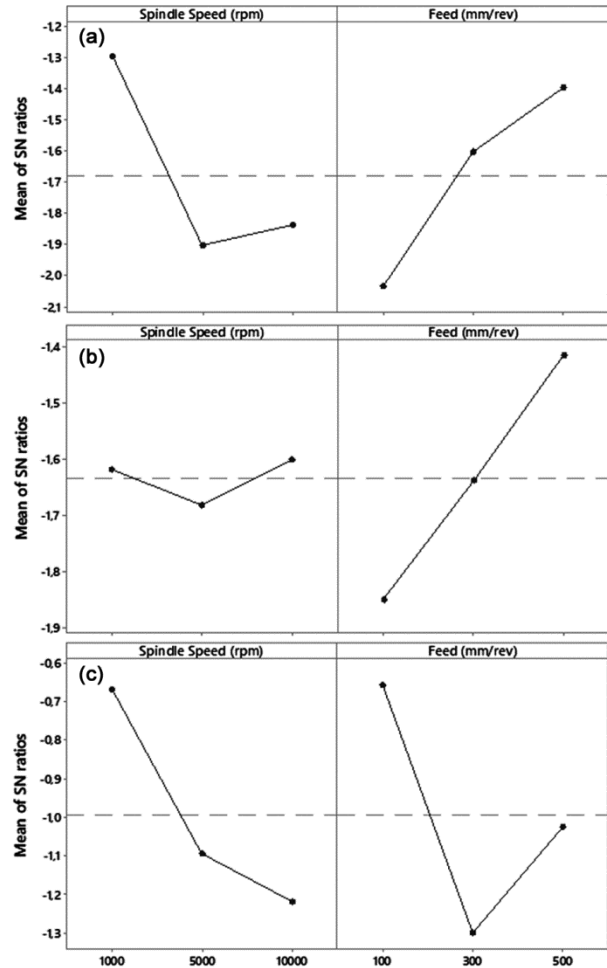


Fig. 8 — Main effect plots (data means) for upper surface deformation factors S/N ratios (*Signal-to-noise: Smaller is better*) in grooving: (a) Warf, (b) Weft, (c) 45°

Table 7 — Response table for S/N ratios in drilling experiments

Level	Input deformation factor			Output deformation factor		
	Spindle speed (rpm)	Feed (mm/rev)	Tip angle (°)	Spindle speed (rpm)	Feed (mm/rev)	Tip angle (°)
1	-1.355	-1.045	-1.112	-1.305	-1.441	-1.106
2	-1.681	-1.712	-1.085	-1.676	-1.795	-1.214
3	-1.140	-1.420	-1.979	-1.491	-1.236	-2.153
Gap	0.541	0.667	0.894	0.371	0.559	1.047
Severity rating	3	2	1	3	2	1

Table 8 — Responses table for upper surface deformation factors S/N ratios in grooving experiments

Level	Warp		Weft		45°	
	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)
1	-1.297	-2.035	-1.620	-1.851	-0.6688	-0.6556
2	-1.902	-1.603	-1.683	-1.638	-1.0946	-1.3019
3	-1.836	-1.397	-1.602	-1.415	-1.2199	-1.0258
Gap	0.605	0.638	0.081	0.436	0.5511	0.6464
Severity rating	2	1	2	1	2	1

Table 9 — Responses table for bottom surface deformation factors S/N ratios in grooving experiments

Level	Warp		Weft		45°	
	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)
1	-1.260	-1.280	-0.9374	-1.1491	-1.0244	-0.8170
2	-1.304	-1.493	-1.1337	-1.0355	-0.7376	-1.1304
3	-1.578	-1.369	-1.1491	-1.0355	-1.1347	-0.9493
Gap	0.318	0.213	0.2117	0.1136	0.3971	0.3134
Severity rating	1	2	1	2	1	2

Table 8. It is seen that feed is the most important cutting parameter for all directions when the figure and table are examined. Low cutting speed is found to be appropriate in experiments for all directions. In the analysis of the Warp and Weft directions, it is concluded that the feed is high, while in the 45° direction, both parameters should be low. The least deformation factors in grooving operations are obtained in the experiments carried out in the 45° direction. When Table 8 is examined, it is seen that feed is the most important cutting parameter in grooving on S 2 glass fiber-reinforced polymer composites.

The bottom surface deformation factors S/N ratios main effect graph is given in Fig. 9, and the response table is given in Table 9. Unlike the analysis for the upper deformation factor, it is seen that the cutting speed is the most important parameter. It is understood that the first level of cutting speed is appropriate in the Warp and Weft directions, while the second level is appropriate in the 45° direction. It is found that the feed should be low in the warp and 45° directions. Similar to the upper surface, the deformation on the bottom surface is less in the groove opened in the 45° direction. The minimum deformation factor is calculated as 1.0740740 at 5000 rpm and 100 mm/rev feed. Similar to the upper surface, the deformation factors calculated in the weft direction are less than in the warp direction.

The following results are obtained from the experiments performed to determine the machinability properties of S 2 glass fiber reinforced polymer composites. It was understood that the feed should be low for the deformation factors examined in the

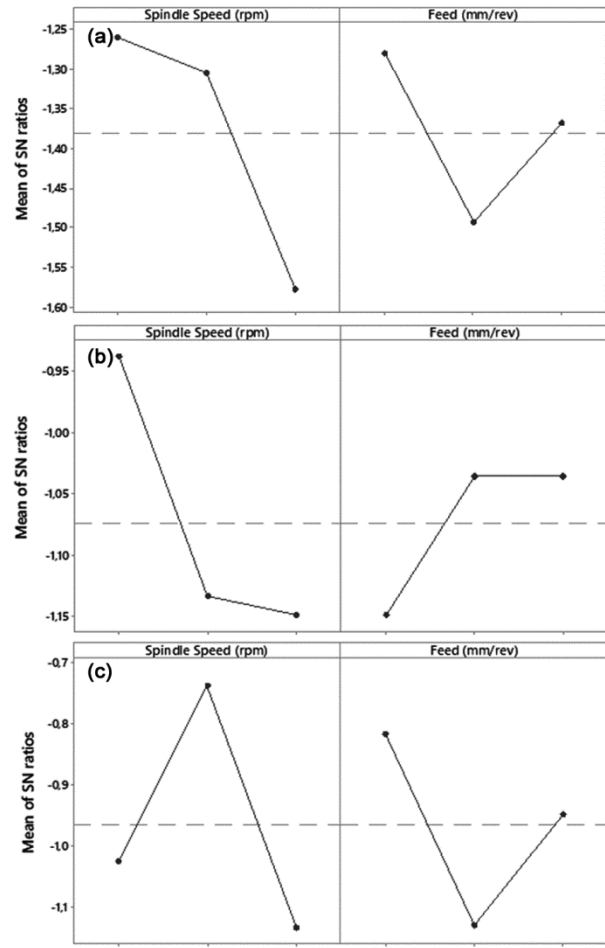


Fig. 9 — Main effect plots (data means) for bottom surface deformation factors S/N ratios (*Signal-to-noise: Smaller is better*) in grooving: (a) Warp, (b) Weft, (c) 45°

drilling and grooving processes. For the deformation to be low, the drill bit angle should be low in the

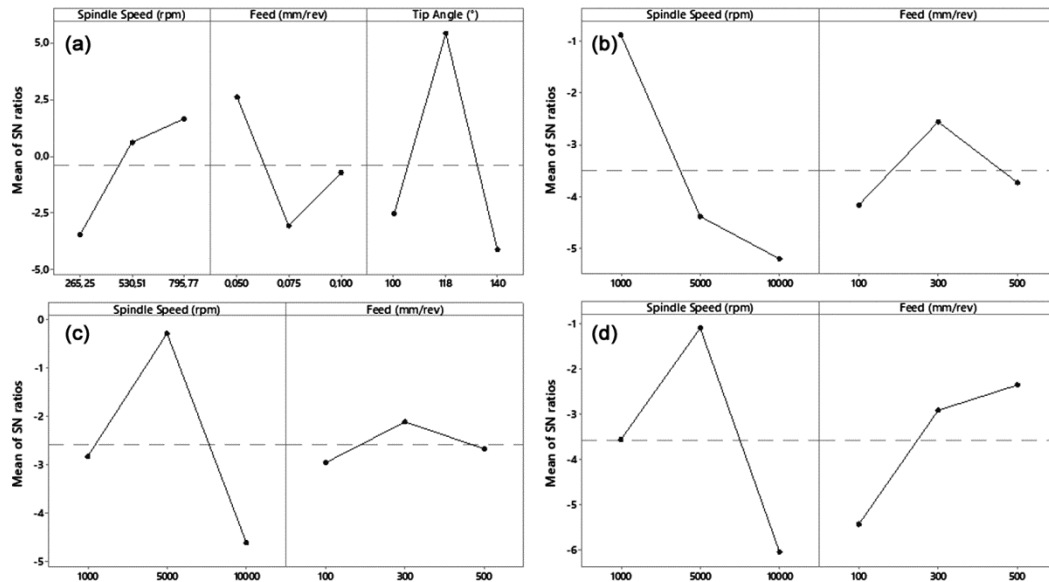


Fig. 10 — Main effect plots (data means) for surface roughness S/N ratios (*Signal-to-noise: Smaller is better*) in machining experiments: (a) Drilling, (b) Warf, (c) Weft, (d) 45°.

Table 10 — Responses table for surface roughness S/N ratios in drilling experiments

Level	Surface roughness		
	Spindle speed (rpm)	Feed (mm/rev)	Tip angle (°)
1	-3.4724	2.6105	-2.5208
2	0.5869	-3.0967	5.4150
3	1.6555	-0.7438	-4.1242
Gap	5.127	5.7072	9.5393
Severity rating	3	2	1

drilling process, and in the grooving process, it will be appropriate to process the part in the 45° direction.

As a result of the analysis, the S/N ratios for the machining experiments are given in the surface roughness main effect graphs in Fig. 10, and the response tables is presented in Table 10 and Table 11. When the main effect graphs for surface roughness were examined, it was found that the optimum parameters for minimizing the surface roughness after drilling experiments were 795.77 rpm spindle speed, 0.05 mm/rev feed, and 118° tip angle. When the answer table in Table 10 is examined, the tip angle is the most effective parameter. When the main effect graphs for grooving experiments were analyzed, the optimum parameters differed for channels opened in each direction. The most suitable results for delamination results occurred in the direction of 45°. Similarly, for surface roughness, low surface roughness values were found in the channels opened in the 45° direction. The optimum parameters for

channels opened in this direction were 5000 rpm spindle speed and 300 mm/rev feed. Palanikumar<sup>36</sup> says in his study that surface roughness increases with increasing cutting speed. He also found that very high cutting speed causes a large deformation rate in glass fiber and leads to defects on the surface.

The relationship between surface roughness and cutting parameters is different from the theoretical relationship valid for metals. The formation of inhomogeneous microstructure causes this situation due to reasons such as fiber ends protruding and breaking of the bond between the fibers and the matrix.<sup>41</sup> Normally higher cutting speed is suitable for machining GFRP composites to obtain good surface quality. However, higher cutting speed should not be more than the critical speed.<sup>36</sup> In this study, while less surface roughness was obtained at high speeds for drilling experiments, medium speed was the optimum parameter for 45° grooving operations.

In addition to the optimization analyses using the Taguchi method for surface roughness, variance analysis was performed (Table 12) for drilling and grooving experiments, and the contributions of cutting parameters to the results were determined. From the variance analysis for the S/N ratios of drilling experiments and for the 45° direction, the most suitable results were obtained in the grooving experiments. It has been seen that the most important parameter affecting the input and output deformation factors in drilling experiments is the drill bit angle. It

Table 11 — Responses table for surface roughness S/N ratios in grooving experiments

Level	Warf		Weft		45°	
	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)	Spindle speed (rpm)	Feed (mm/rev)
1	-0.8737	-4.1698	-2.8337	-2.9554	-3.567	-5.430
2	-4.3908	-2.5709	-0.2815	-2.1104	-1.094	-2.917
3	-5.2250	-3.7489	-4.6150	-2.6644	-6.051	-2.364
Gap	4.3513	1.5989	4.3335	0.8449	4.956	3.066
Severity rating	1	2	1	2	1	2

Table 12 — Analysis of variance for different parameters

Source	DF	Sum of squares		Average squares		F-Ratio		% Contribution	
		IDF	ODF	IDF	ODF	IDF	ODF	IDF	ODF
Drilling experiments S/N ratios									
Spindle speed	2	0.4444	0.2061	0.2222	0.1031	1.06	0.76	14.4	6.9
Feed	2	0.6713	0.4791	0.3356	0.2396	1.60	1.77	21.7	16.2
Tip angle	2	1.5516	1.9893	0.7758	0.9947	3.71	7.36	50.2	67.5
Error	2	0.4185	0.2701	0.2092	0.1351				
Total	8	3.0858	2.9447						
IDF = Input deformation factor, ODF = Output deformation factor									
Grooving experiments in the 45° direction (Upper)									
Spindle Speed	2	0.5008		0.25040		8.68		40	
Feed	2	0.6311		0.31554		10.94		50.59	
Error	4	0.1154		0.02884					
Total	8	1.2473							
Grooving experiments in the 45° direction (Bottom)									
Spindle Speed	2	0.25215		0.12608		7.60		54.8	
Feed	2	0.14856		0.07428		4.48		31.8	
Error	4	0.06634		0.01658					
Total	8	0.46705							
Surface roughness drilling experiments S/N ratios									
Spindle Speed	2	43.91		21.96		0.93		14.79	
Feed	2	49.36		24.68		1.05		16.62	
Tip angle	2	156.55		78.27		3.33		52.73	
Error	2	47.05		23.52					
Total	8	296.87							
Surface roughness 45° grooving experiments S/N ratios									
Spindle Speed	2	36.847		18.423		11.62		62.29	
Feed	2	16.021		8.011		5.05		27.05	
Error	2	6.344		1.586					
Total	8	59.212							

has an effect of 50.2% and 67.5% for input and output deformation factors, respectively. The most effective parameter for drilling experiments was the tip angle with 52.73%. The most suitable results in channel opening operations were obtained at 45°, similar to the delamination results. Variance analysis was also performed for these experimental results. The most effective parameter was the spindle speed with 62.29%.

In summary, drilling and grooving experiments to examine the machinability properties of S 2 glass fiber reinforced polymer composite materials are carried out using different cutting parameters. In drilling experiments, the most important contribution to the input and output deformation factors are the drill bit

angle. And it has an effect of 50.2% and 67.5% for input and output, respectively. While the feed provided the greatest effect on the deformation on the upper surface at the rate of 50.59% in grooving operations in the 45° direction, the cutting speed is effective at 54.8% on the bottom surface. Similarly, while the tip angle was the effective parameter for the surface roughness measured in the drilling experiments, the number of revolutions was the effective parameter for the roughness on the groove surfaces.

## Conclusions

Among the cutting speed, feed and drill bit angle variables, the drill bit angle was the most important

parameter in the deformation factor calculations. The small tip angle had a positive effect on the results. If S2 glass epoxy polymer composite materials are used as plates, it would be appropriate to position them at 45° in terms of fabric direction for a precise connection. In the analyses performed with the Taguchi method, the drill tip angle is the effective parameter on the input and output deformation. For the grooving experiments, it has been determined that the feed on the upper surface, and the cutting speed on the bottom surface are the effective parameters. The analyses made for surface roughness found that high speed, low feed, and 118° tip angle were the optimum parameters on hole surfaces. Spindle speed was the most effective parameter for the roughnesses formed on 45° groove surfaces. This study can be further improved by processing the S glass fiber polymer composite material used in the study with different cutting tool materials and geometries.

## References

- Azmi A I, Lin R J T & Bhattacharyya D, Experimental study of machinability of GFRP composites by end milling, *Mater Manuf Processes*, **27(10)** (2012) 1045–1050, doi: 10.1080/10426914.2012.677917.
- Kulkarni P, Dhoble A & Padole P, A review of research and recent trends in analysis of composite plates, *Sadhana-Acad P Eng S*, **43(6)** (2018) 1–20, doi: 10.1007/s12046-018-0867-1.
- Wosu S N & Xie Q, The effect of penetrator geometry on the dynamic response of woven graphite/epoxy composites, *J Mater Eng Perform*, **23(3)** (2014) 833–842, doi: 10.1007/s11665-013-0824-4.
- Nagarajan V A, Sundaram S, Thyagarajan K, Selwin Rajadurai J & Rajan T P D, Measuring delamination severity of glass fiber-reinforced epoxy composites during drilling process, *Exp Techniques*, **37(2)** (2013) 66–73, doi: 10.1111/j.1747-1567.2012.00809.x.
- Morkavuk S, Köklü U, Bağcı M & Gemi L, Cryogenic machining of carbon fiber reinforced plastic (CFRP) composites and the effects of cryogenic treatment on tensile properties: A comparative study, *Compos B Eng*, **147** (2018) 1–11, doi: 10.1016/j.compositesb.2018.04.024.
- Davim J P & Reis P, Drilling carbon fiber reinforced plastics manufactured by autoclave—experimental and statistical study, *Mater Design*, **24(5)** (2003) 315–324, doi: 10.1016/S0261-3069(03)00062-1.
- Tzeng C J, Lin Y H, Yang Y K & Jeng M C, Optimization of turning operations with multiple performance characteristics using the Taguchi method and Grey relational analysis, *J Mater Process Tech*, **209(6)** (2009) 2753–2759, doi: 10.1016/j.jmatprotec.2008.06.046.
- El-Sonbaty I, Khashaba U A & Machaly T, Factors affecting the machinability of GFR/epoxy composites, *Compos Struct*, **63(3–4)** (2004) 329–338, doi: 10.1016/S0263-8223(03)00181-8.
- Tsao C C, Experimental study of drilling composite materials with step-core drill, *Mater Design*, **29(9)** (2008) 1740–1744, doi: 10.1016/j.matdes.2008.03.022.
- Tosun N, Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis, *J Adv Manuf Technol*, **28(5–6)** (2006) 450–455, doi: 10.1007/s00170-004-2386-y.
- Yang Y K, Shie J R & Huang C H, Optimization of dry machining parameters for high-purity graphite in end-milling process, *Mater Manuf Processes*, **21(8)** (2006) 832–837, doi: 10.1080/03602550600728141.
- Sharma S C, Krishna M & Narasimha M H N, Delamination during drilling in polyurethane foam composite sandwich structures, *J Mater Eng Perform*, **15(3)** (2006) 306–310, doi: 10.1361/105994906X108710.
- Hocheng H & Tsao C C, Comprehensive analysis of delamination in drilling of composite materials with various drill bits, *J Mater Process Tech*, **140(1–3)** (2003) 335–339, doi: 10.1016/S0924-0136(03)00749-0.
- Davim J P, Reis P & António C C, Drilling fiber reinforced plastics (FRPs) manufactured by hand lay-up: Influence of matrix (Viapal VHP 9731 and ATLAC 382-05), *J Mater Process Tech*, **155-156(1–3)** (2004) 1828–1833, doi: 10.1016/j.jmatprotec.2004.04.173.
- Davim J P, Reis P & António C C, Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up, *Compos Sci Technol*, **64(2)** (2004) 289–297, doi: 10.1016/S0266-3538(03)00253-7.
- Khashaba U A, Delamination in drilling GFR-thermoset composites, *Compos Struct*, **63(3–4)** (2004) 313–327, doi: 10.1016/S0263-8223(03)00180-6.
- Ali H M, Iqbal A & Liang L, A comparative study on the use of drilling and milling processes in hole making of GFRP composite, *Sadhana-Acad P Eng S*, **38(4)** (2013) 743–760, doi: 10.1007/s12046-013-0186-5.
- Khashaba U A, El-Sonbaty I A, Selmy A I & Megahed A A, Machinability analysis in drilling woven GFR/epoxy composites: Part II - Effect of drill wear, *Compos Part A-Appl S*, **41(9)** (2010) 1130–1137, doi: 10.1016/j.compositesa.2010.04.011.
- Gupta A, Vaishya R, Kumar R, Khan K L A, Chhabra S, Verma A S & Bharadwaj A, Effect of drilling process parameters on delamination factor in drilling of pultruded glass fiber reinforced polymer composite, *Mater Today-Proc*, **64(3)** (2022) 1290–1294, doi: 10.1016/j.matpr.2022.04.110.
- Ünüvar A, Koyunbakan M & Bağcı M, Optimization and effects of machining parameters on delamination in drilling of pure and Al<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub>-added GFRP composites, *Int J Adv Manuf Tech*, **119(1–2)** (2022) 657–675, doi: 10.1007/s00170-021-08258-x.
- Mohan N S, Kulkarni S M & Ramachandra A, Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials, *J Mater Process Tech*, **186(1–3)** (2007) 265–271, doi: 10.1016/j.jmatprotec.2006.12.043.
- Can A & Ünüvar A, Optimization of process parameters in drilling of SMC composites using Taguchi method, *Then Vjesn*, **24(2)** (2017) 435–442, doi: 10.17559/TV-20160103215256.
- Abrão A M, Rubio J C C, Faria P E & Davim J P, The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite, *Mater Design*, **29(2)** (2008) 508–513, doi: 10.1016/j.matdes.2007.01.016.

- 24 Koyunbakan M, Ünüvar A, Eskizeybek V & Avcı A, CETP kompozitlerin ağaç matkabiliteyle delinme performanslarının deneysel incelenmesi, *NÖHÜ Müh Bilim Derg*, **10(2)** (2021) 770–776, doi: 10.28948/ngumuh.830262.
- 25 Yıldırım F, Koyunbakan M, Aydın M & Avcı A, Üç boyutlu boşluklu polimer kompozitin delinme ve frezelenme özelliklerinin incelenmesi, *8 International Symposium on Machining 2017*, 352–363.
- 26 Koklu U, Morkavuk S, Featherston C, Haddad M, Sanders D, Aamir M, Pimenov D Y & Giasin K, The effect of cryogenic machining of S 2 glass fibre composite on the hole form and dimensional tolerances, *Int J Adv Manuf Tech*, **115(1–2)** (2021) 125–140, doi: 10.1007/s00170-021-07150-y.
- 27 Kaya Z, Ersen H & Halit G, The strain rate and temperature effects on the static and dynamic properties of S 2 glass / epoxy composites, *Appl Phys A-Mater*, **126(8)** (2020) 1–15, doi: 10.1007/s00339-020-03855-1.
- 28 Mullaikodi S M, Shanmugasundaram K, Rao V S & Rengarajan S, Synthesis, characterization and machinability studies on thin hybrid composites with SiC nano particles, *Mater Res Express*, **6(6)** (2019) 065321, doi: 10.1088/2053-1591/ab0ddc.
- 29 Okoli O I & Smith G F, The effect of strain rate and fibre content on the Poisson's ratio of glass/epoxy composites, *Compos Struct*, **48(1–3)** (2000) 157–161, [https://doi.org/10.1016/S0263-8223\(99\)00089-6](https://doi.org/10.1016/S0263-8223(99)00089-6).
- 30 Sugiman S, Gozali M H & Setyawan P D, Hygrothermal effects of glass fiber reinforced unsaturated polyester resin composites aged in steady and fluctuating conditions, *Adv Compos Mater*, **28(1)** (2017) 87–102, doi: 10.1080/09243046.2017.1405597.
- 31 AZO Materials S-Glass Fibre July 23 2019, <https://www.azom.com/properties.aspx?ArticleID=769>, (accessed July 23, 2019).
- 32 HEXION® Specialty Chemicals. Laminating Resin MGS® L 285 Hardeners MGS® 285–287, Technical Data Sheet. July 23, 2019, <https://www.hexion.com/en-US/search?id=30303>, (accessed July 23, 2019).
- 33 Kilickap E, Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite, *Expert Syst Appl*, **37(8)** (2010) 6116–6122, doi: 10.1016/j.eswa.2010.02.023.
- 34 Zhang Y, Chen T, Li H, Duan Z & Li H, Influence of tool parameters on ultrasonic assisted drilling of GFRP composites, *Adv Compos Mater*, **32(3)** (2023) 303–323, doi: 10.1080/09243046.2022.2085646.
- 35 Morkavuk S, Köklü U & Bağcı M, Karbon fiber takviyeli kompozit malzemelerin yüksek ilerleme hızı ile kuru ve kriyojenik koşullarda frezelenmesi, *7. Uluslararası Talaşlı İmalat Sempozyumu*, (2016).
- 36 Palanikumar K, Modelling and analysis for surface roughness in machining glass fibre reinforced plastics using response surface methodology, *Mater Des*, **28(10)** (2007) 2611–2618, doi: 10.1016/j.matdes.2006.10.001.
- 37 Gemi L, Morkavuk S, Köklü U & Gemi D S, An experimental study on the effects of various drill types on drilling performance of GFRP composite pipes and damage formation, *Compos Part B-Eng*, **172** (2019) 186–194, doi: 10.1016/j.compositesb.2019.05.023.
- 38 Tsao C C, Thrust force and delamination of core-saw drill during drilling of carbon fiber reinforced plastics (CFRP), *Int J Adv Manuf Tech*, **37(1–2)** (2008) 23–28, doi: 10.1007/s00170-007-0963-6.
- 39 Engin K E & Yaka H, Effect of drilling parameters on hole quality in drilling of pultruded GFRP composite material: Surface roughness, thrust force and delamination factor, *NÖHÜ Müh Bilim Derg*, **12(4)** (2023) 1573–1580, doi: 10.28948/ngumuh.1335448.
- 40 Kacal A & Gulesin M, Determination of optimal cutting conditions in finish turning of austempered ductile iron using Taguchi design method, *J Sci Ind Res*, **70(4)** (2011) 278–283.
- 41 Eriksen E, Influence from production parameters on the surface roughness of a machined short fibre reinforced thermoplastic, *Int J Mach Tools Manuf*, **39(10)** (1999) 1611–1618, doi: 10.1016/S0890-6955(99)00017-6.