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Investigation of Drillability of CFRP/Al 7075 Stack

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1. Introduction

High fuel efficiency standards and long service life are desired in the aerospace and aircraft industry. Therefore, research and development has increased for advanced light metallic alloys and composite materials in recent years [1-3].

Carbon fiber reinforced polymer composites are the most widely used composite materials in aerospace structures. The advantages of these composites, such as their low weight, high strength and stiffness, and better corrosion resistance, make them the preferred choice for aerospace applications [4-6]. Composite/metal stacks materials consisting of carbon fiber reinforced polymer (CFRP) composites and aluminium, or titanium alloy (Al or Ti) are widely used in the aerospace industry. However, composite/metal stack drilling is an extremely challenging process due to the different machinability properties of the two materials used. During assembly of composite/metal components, tens of thousands of holes are required to meet the demand for mechanical bolting or riveting. However, drilling operation constitutes 40% of all machining operations and 60% of them are not suitable for desired tolerances indicates need for more work in this issue [7, 8]. Assembly accuracy depends on the quality of the machined holes and it vital to the flight performance of airplanes. Various hole defects occur frequently, which seriously affect assembly accuracy. During drilling of stack materials, hole quality defects such as poor diameter tolerance, poor hole surface quality, matrix resin degradation, fiber burrs and delamination are observed [9-11].

In the literature, it has been seen that many studies have been carried out on drillability of carbon fiber reinforced polymer composites. On the other hand, it has been determined that the studies on the composite/metal stacked structure are less. Zitoune et al., drilling tests were carried out on the CFRP/Al 2024 stacked structure with different diameters of drill under dry conditions. Experimental results show that the quality of holes can be improved with the right choice of cutting parameters. As a result of the tests, it was seen that the surface roughness increased as the feed rate increased for all diameters, but the effect of spindle speed on the surface roughness was less and the surface roughness and circularity of aluminium was better compared to CFRP. In the wear tests, it has been shown that the cutting force is stable between 30 and 60 holes, therefore this region can be attributed to the normal wear region [12]. Meshreki et al. investigated the effect of drilling conditions such as tool material, geometry and lubrication on hole quality and tool wear in drilling CFRP/Al stacks structure. As a result of the study, it was observed that there is mostly no delamination at exit of holes due to support of CFRP with aluminium and entrance delamination does not occur in dry and flood cooling. However, it has been stated that drilling causes high force and temperature differences in dry conditions [13]. D'Orazio et al. investigated drillability of the CFRP/Al 7075 stacks structure. In the study, 170 holes were drilled using two DLS TiAlN and coated cutting tools with a diameter of 6.8 mm. DLS coated cutting tool caused less delamination than TiAlN coating. Delamination was observed due to Al 7075 discharge at the exit of CFRP. It has been determined that the thrust force and delamination are directly proportional to the tool wear [14]. Mahdi et al. investigated effects of drilling direction on hole quality, thrust force and surface quality when drilling CFRP/Al stacks material in dry conditions. Experimental results showed that the thrust force does not change with the position of the stack, the cutting speed affects the delamination the most, and the change in the material order affects the surface quality [15]. Hassan et al. observed effects of drill geometry and drilling parameters on the drillability of CFRP/Al7075-T6. As a result of the study, it was determined that the thrust force depends on the feed rate and the most suitable tool parameters were determined as a helix angle of 30°, primary clearance angle of 6° and point angle of 130°, chisel edge angle of 30°, speed of 2600 rev/min and feed rate of 0.05 mm/rev [16].

The aim of this study to examine the effects of different cutting and feed rates and the change of hole drilling direction on the delamination, surface roughness, thrust force and tool wear in CFRP/Al 7075 stacking structure. In addition, it has been seen in the literature that drilling using internal cooling is less studied, therefore the drillability of the stacked material using drill that has internal cooling has been investigated.

2. Materials and methods

CFRP and Al 7075 alloy used in the aerospace industry were stacked. CFRP was prepared by absorbing 43% Cycom-985 graphite epoxy resin on 5-pack woven fabrics weighing 281.26 gr/m^2. It was cut at 0/90° and 45° angles from the prepreg sheet, which was prepared in rolls, weighing 496.53 gr/m^2 and having 0° fiber orientation, and was laid on a glass surface. In order to produce 4.5 mm thick CFRP, a 12-layer array was performed with a cured 0.35 mm nominal layer. After the sequencing process was completed, the prepreg sheets were subjected to bagging and vacuuming processes and were cured in an autoclave with bag molding method at 1770° C and 6 bar pressure for a total of 120 minutes. After this process, 280x140x4.5 mm CFRP composite material was obtained. 280x140x10 mm Al 7075-T6 alloy was used to form CFRP/Al 7075 stacks material. The chemical properties of Al 7075- T6 alloy are shown in Table 1.

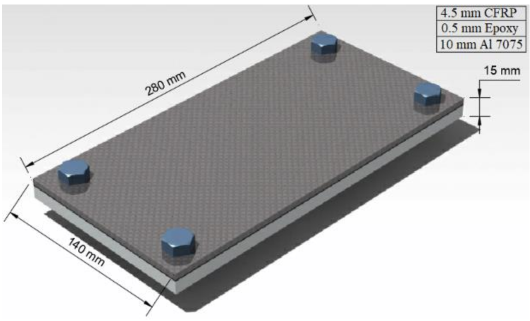
Table 1

Chemical Properties of Al 7075

Fe	Si	Cu	Mn	Mg	Zn	Cr	Ti
0.15-0.16	0.08-0.10	1.6	0.04-0.05	2.5	5.7	0.20-0.21	0.3

The stacking materials on which the drilling tests were carried out were prepared using CFRP in 280x140x4.5 mm dimensions and Al 7075 in 280x140x10 mm dimensions. CFRP and Al 7075 layers were joined by applying 0.5 mm Diall fast-curing two-component epoxy metal adhesive between them [17]. The adhesive was evenly applied to the surface of Al 7075 and then CFRP was adhered. The adhered samples were kept under the printing machine for 10 The adhered materials were tightened with M8 bolts at all four corners [15]. A total of three specimens with a thickness of 15 mm, shown in Fig. 1, were used in the experiments.

a



b

Fig. 1 CFRP/Al 7075 Stacks Material: a - specimen; b - geometry of specimen

The cutting tool used in the experiments is an uncoated internally cooled carbide tool with a diameter of 9 mm and a point angle of 138°. The cutting tool dimensions are shown in Fig. 2.

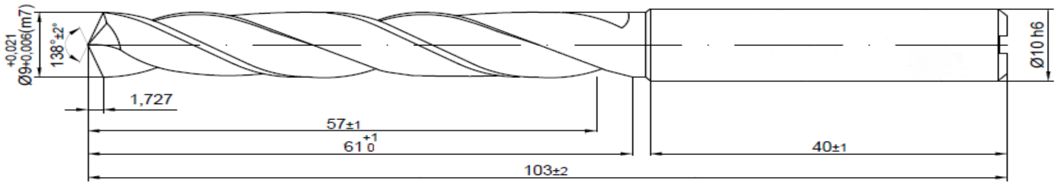


Fig. 2 Uncoated carbide cutting tool dimensions

Experiments were carried out using Mikron VCP 800 CNC vertical machining center and hyperMILL 2020 CAD/CAM software. Drilling was done by using coolant to prevent smearing of Al 7075 on the cutting tool and other defects. 15 mm thick CFRP/Al 7075 stacks material was connected to CNC vertical machining centre by means of 9 mm diameter carbide tools with internal cooling feature and drilled using boron oil with 7% emission at 65 bar pressure. Drill is connected to the Spike_mobile dynamometer to measure the thrust force during drilling. Fig. 3 shows the specimen attached to the bench.

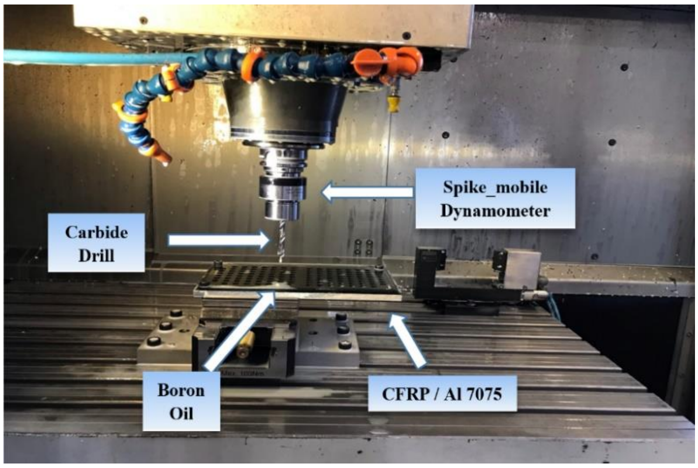


Fig. 3 CFRP/Al 7075 attached to the bench

High cutting speeds are required to increase the production speed in the industry. However, lower cutting speeds and feed rates were taken to reduce the unexpected effects of cutting tool and workpiece vibrations and thermal effects on delamination [3]. In addition, high cutting speed negatively affects tool life [10, 12]. Cutting speed 50 m/min and feed rate 0.10 mm/rev for CFRP and 200 m/min and 0.20 mm/rev for Al 7075 were chosen because they are suitable cutting parameters used in the literature and recommended by the cutting tool manufacturer [3, 14, 18-22]. Drilling of stacks material was repeated as entering from CFRP, exiting from Al 7075 and vice versa. A total of six experiments were conducted with constant cutting and feed rate, variable cutting and feed rate, as well as changing drilling direction. A new drill was used to measure tool wear for each experiment and it drilled 62 holes for each specimen. Table 2 shows the experiment conditions.

Table 2

Experiment parameters

Experiment 1	Entrance		Exit	
	CFRP		Al 7075	
Variable cutting speed and feed rate	Cutting speed *Vc*, m/min	Feed rate *f*, mm/rev	Cutting speed *Vc*, m/min	Feed rate *f*, mm/rev
	50	0.10	200	0.20
Experiment 2	Entrance		Exit	
	Al 7075		CFRP	
Variable cutting speed and feed rate	Cutting speed *Vc*, m/min	Feed rate *f*, mm/rev	Cutting speed *Vc*, m/min	Feed rate *f*, mm/rev
	200	0.20	50	0.10
Experiment 3	Entrance		Exit	
	CFRP		Al 7075	
Constant cutting speed and feed rate	Cutting speed *Vc*, m/min		Feed rate *f*, mm/rev)	
	50		0.10	
Experiment 4	Entrance		Exit	
	Al 7075		CFRP	
Constant cutting speed and feed rate	Cutting speed *Vc*, m/min		Feed rate *f*, mm/rev	
	50		0.10	
Experiment 5	Entrance		Exit	
	CFRP		Al 7075	
Constant cutting speed and feed rate	Cutting speed *Vc*, m/min		Feed rate *f*, mm/rev	
	200		0.20	
Experiment 6	Entrance		Exit	
	Al 7075		CFRP	
Constant cutting speed and feed rate	Cutting speed *Vc*, m/min		Feed rate *f*, mm/rev	
	200		0.20	

Spike_mobile dynamometer was used to measure thrust force F_z applied by the cutting tool to the material during drilling. The effect of thrust force was determined on the delamination, surface roughness and tool wear in the material by measurements. Spike_Mobile dynamometer measures thrust force with a measuring unit to which cutting tool is connected, a receiver with a wireless network connection to which the data is transferred and Spike_measurement software. Thrust force was measured separately for CFRP and Al 7075 in each experiment.

Hole surface roughness *Ra* measurements were made with Mitutuyo and SJ-410 model portable surface roughness tester after the completion of drilling operations. Surface roughness values were measured separately for CFRP and Al 7075 in 6 specimens. The surface roughness value was calculated by taking the average of the measurement from 3 different points of the 1st, 10th, 20th, 30th, 40th, 50th, 60th and 62nd holes of each specimen. The surface roughness *Ra* of the hole was measured with a surface roughness ester with a sampling length of 0.8 mm. The through-hole measurement length for CFRP is 3.2 mm (0.8 x 4 = 3.2 mm), and for aluminium the measurement length is 8 mm (0.8 x 10 = 8 mm).

During drilling, damage known as delamination occurs at the entrance and exit of the CFRP, which negatively affects the structural integrity of the material and its resistance to fatigue [2, 4, 23]. Quantitative evaluation of this damage is done by delamination factor F_d. As seen in Fig. 4, the maximum diameter of the damage area D_{max} and the hole diameter (D_0) are determined [19, 24, 25].

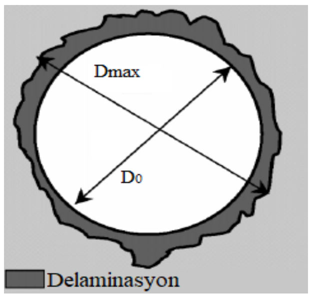


Fig. 4 Diameter of damage area and hole

The delamination factor F_d is calculated with the formula shown in Eq. (1) [26-28].

$$F_d = \frac{D_{max}}{D_0}. \quad (1)$$

The hole entrance and exit of the CFRP were measured with an optical microscope. Optical microscope: It consists of optical magnification sample image camera, 10 / 40 / 100X optical magnification system, imaging (image acquisition and analysis) unit software and computer-controlled moving table. Delamination images were recorded using the image analysis software of the Qness 10A+ device, and the images approached in the 3X-4X range, which were viewed with an optical magnification image acquisition camera.

Cutting tool wear amounts are usually measured from the first cutting edge to wear with an electronic or optical microscope [29]. Tool wear measurements were made with an optical microscope after the 62nd hole of each experiment was drilled. Wear measurements were taken for the four blades of the cutting tool. The amount of wear was calculated with the arithmetic average of the total measured wear.

3. Results and discussion

CFRP/Al 7075 stacks material drilling process was completed with 6 experiments. Thrust forces acting on CFRP and Al 7075 alloy during drilling tests, delamination on the hole entrance and exit surfaces of CFRP composite material after drilling process, the inner hole surface roughness values of the materials and the wear of the cutting tools were evaluated.

3.1. Evaluation of delamination

After the drilling tests, the images of the hole entrances and exits of the CFRP were examined with optic microscope then delamination factor F_d were calculated with the ratio of the largest damage diameter value to the tool diameter. Delamination factor was calculated by measuring holes 1st, 10th, 20th, 30th, 40th, 50th, 60th, 62nd for each sample. It is seen that the delamination factor increases due to increasing of tool wear and thrust force depending on the number of holes [19, 30]. In the literature, it is said that the increase in cutting speed and feed rate causes increasing of delamination [15, 17, 25, 27]. However, the increasing of cutting speed and feed rate in stacks drilling shows that delamination decreases in the areas where CFRP contacts aluminium [12, 13]. This decrease can be explained with friction. Cutting edge motion reduces in the number of passes passing through the same region. Therefore, the friction between the cutting edges and the surface causes the temperature to rise and the matrix phase to soften, thus reducing damage [31].

The results of the 2nd, 4th, and 6th experiments in the exit delamination graph show that delamination damage is higher than the other experiments (Fig. 5). Al 7075/CFRP stacking structure were used in these experiments. It is thought that the delamination increased with the entry of the cutting tool from Al 7075 by chip formation. [15]. CFRP/Al 7075 sequence appears to give better results [29, 32].

3.2. Evaluation of thrust forces

The thrust forces measured by the Spike_mobile dynamometer during the drilling operations were recorded separately for CFRP and Al 7075. The change in thrust force depending on the number of holes is shown in Fig. 6. In Fig. 6, the highest thrust value of 517 N for CFRP and 1725 N for Al 7075 was obtained at variable cutting speeds and feed rates (Experiment 1). As the number of holes increased, the thrust forces gradually increased in both CFRP and aluminium due to tool wear [29]. It was also found that the thrust recorded during the drilling of Al 7075 was approximately twice that recorded during the drilling of the CFRP. This can be explained by the difference in specific cutting pressures between the cutting tool and the workpiece [11, 16, 33].

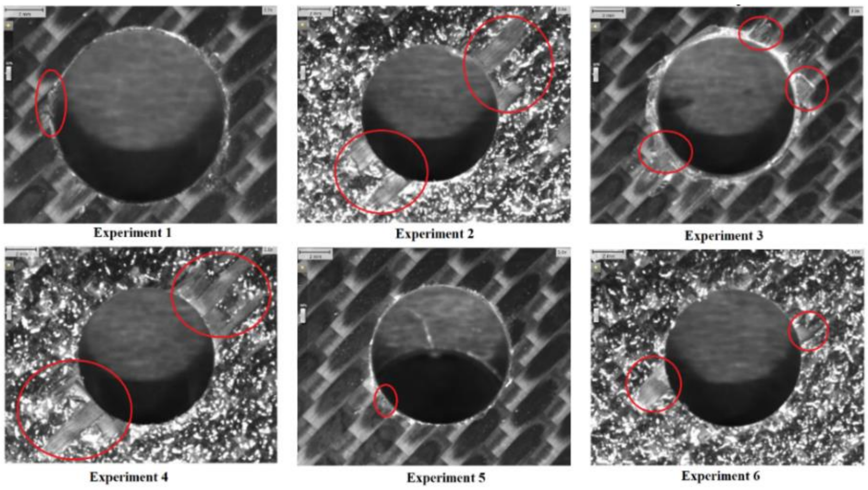


Fig. 5 Exit Delamination images for each experiment in the 3X-4X range

In the second experiment performed at variable cutting speed and feed rates, the thrust force is positive in Al 7075, but negative thrust is observed in CFRP with the reduction of cutting speed and feed rate. As the cutting tool exits the CFRP, negative thrust occurs with cutting at large positive rake angle at the lips. Since the friction angle is smaller than the effective rake angle after the feed motion in Al 7075, the negative pressure component raises the back of the workpiece plate. Negative thrust promotes tool penetration with the force of upward loading of the workpiece [3].

When the experiments performed at constant cutting speeds are examined, it is seen that the thrust force acting on the CFRP decreases with the increase of the cutting speed [27]. However, it was determined that the thrust forces remained approximately the same in Al 7075.

The thrust force acting on Al 7075 remained approximately the same in the experiments carried out at constant feed rates. It is seen that the change of cutting direction does not affect the thrust force in the experiments performed with constant cutting and feed rates. Experiment 1 shows that the thrust forces acting on Al 7075 are approximately 2.5 times higher than in all other experiments. Reason for this is that the cutting tool increases the cutting speed and feed rate without leaving the hole while passing from CFRP to Al 7075.

3.3. Evaluation of surface roughness

Surface roughness was measured by the average of the values taken from 3 different points of the 1st, 10th, 20th, 30th, 40th, 50th, 60th, and 62nd holes for each experiment. Figure 7 shows the average surface roughness value graph for each experiment. The surface roughness of Al 7075 is better than CFRP. This may be due to the isotropy of the material [12, 13]. Surface roughness values were determined as *Ra*<3.2 µm for CFRP and *Ra*<1.6 µm for aluminium in stacked structures [16, 17, 33, 34]. Fig. 7 shows, the maximum surface roughness values are 3.343 µm for CFRP in experiment 6 and 1.212 µm for Al 7075 in Experiment 3. This result means that drilling in Al 7075/CFRP structure cannot be done at 200 m/min cutting speed and 0.20 mm/rev feed rate, since it is above the desired value (*Ra*<3.2 µm) for CFRP. It can be said that the roughness values in the material increase due to thermal expansion and rapid chip accumulation at high cutting speed and feed rate. In Experiment 5, the CFRP roughness value is 3.188 µm. Since this value is equal to the acceptable limit (*Ra*<3.2 µm), it is not appropriate to use the cutting parameters of the experiment. The increase in cutting speed and feed rate caused a significant increase in the roughness value for CFRP material. The literature shows that the feed rate is the most effective factor on the roughness value [12, 31, 35].

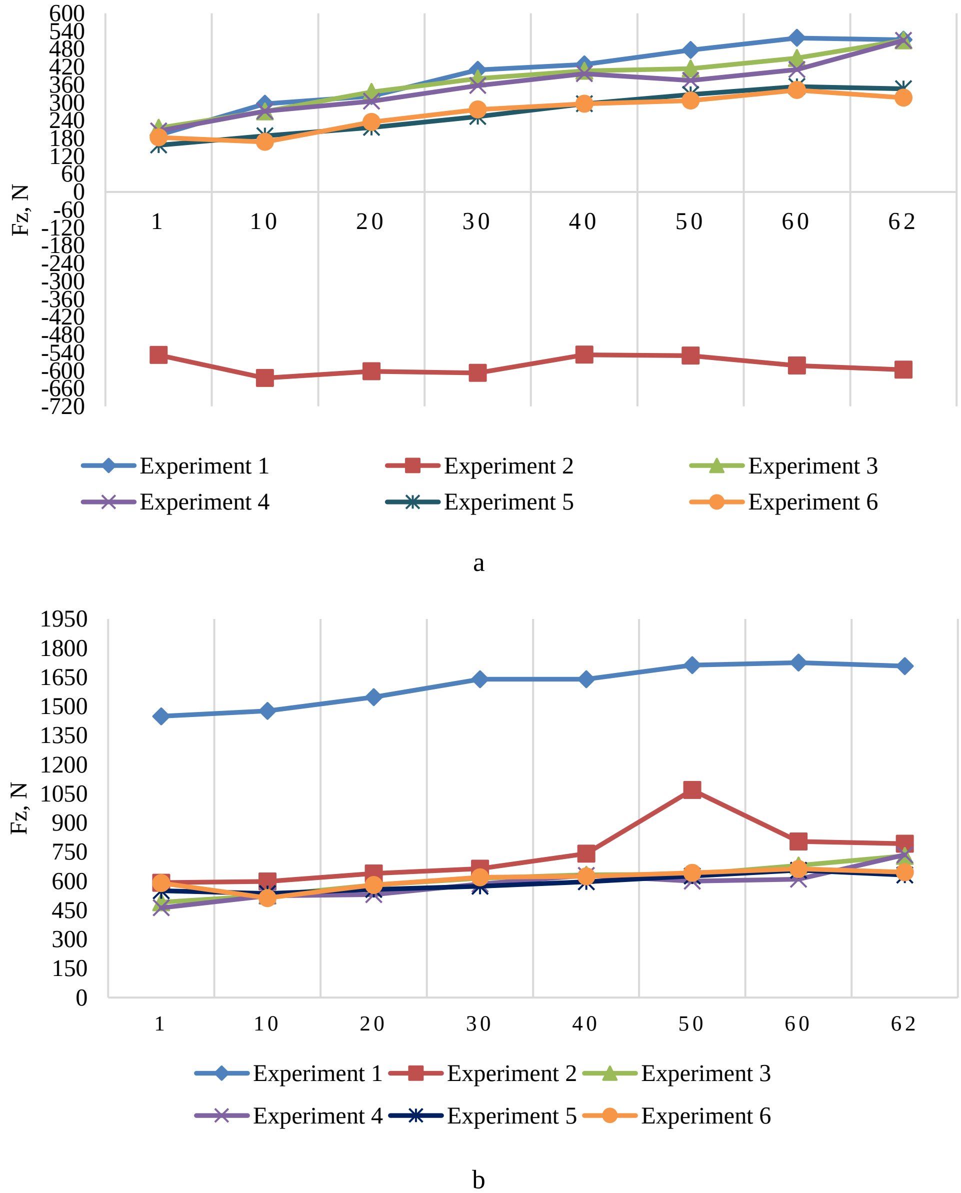
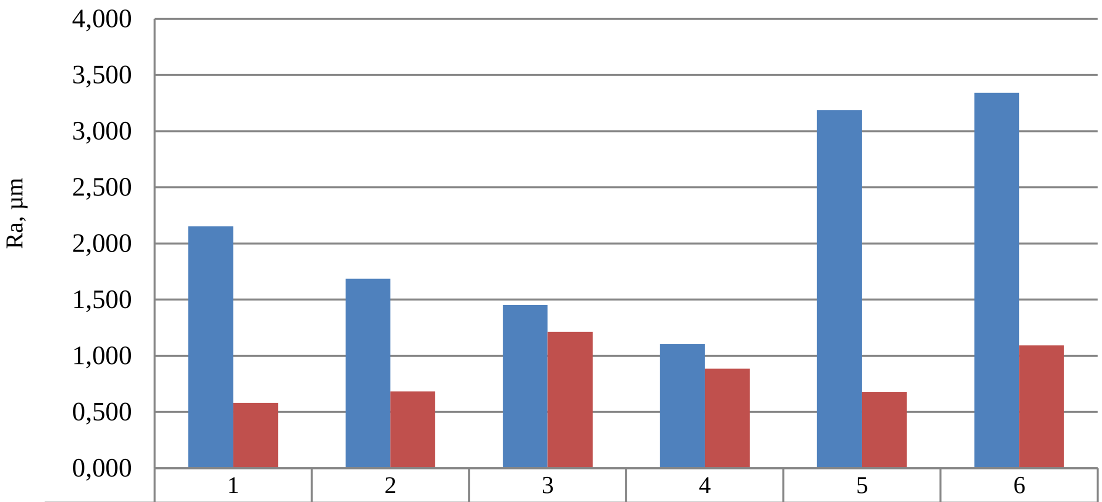


Fig. 6 Variation of thrust forces according to number of holes; a - for CFRP; b - for Al 7075

3.4. Evaluation of tool wear

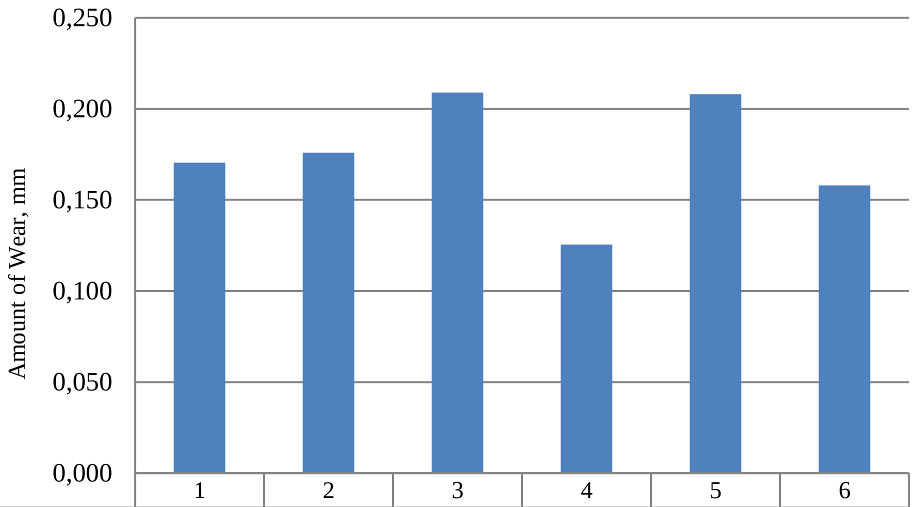
A new drill was used in each experiment. 62 holes were drilled with a tool for one sample. Amounts of wear occur different between drilling CFRP and metal separately and drilling CFRP/metal stacks material [36]. In addition, when Fig. 8 is examined, the change of drilling direction affected the amount of wear in the experiments performed at constant speeds (3, 4, 5 and 6). Less wear is seen in the experiments performed with Al 7075 / CFRP sequence. In the variable speed experiments (1 and 2), it is seen that the tool wear amounts are approximate.

Fig. 9 shows the unused cutting tool (a) and the cutting tool used in the experiment 3 (b) where wear is the most. Fig. 9 shows, aluminium plastered to form built-up edge (BUE) on cutting edges of the drill due to the chemical reactivity of aluminium increasing with temperature [37]. However, there was no cutting-edge breakage and strain during drilling. Since internal cooling was used in the experiments, the accumulation of aluminium chips or the effects of carbon dust in the cutting tool channels were not observed. As a result of experiments, there was no situation that would adversely affect the tool life in the selected cutting conditions. It is considered that the biggest factor in this is the internal coolant [38].



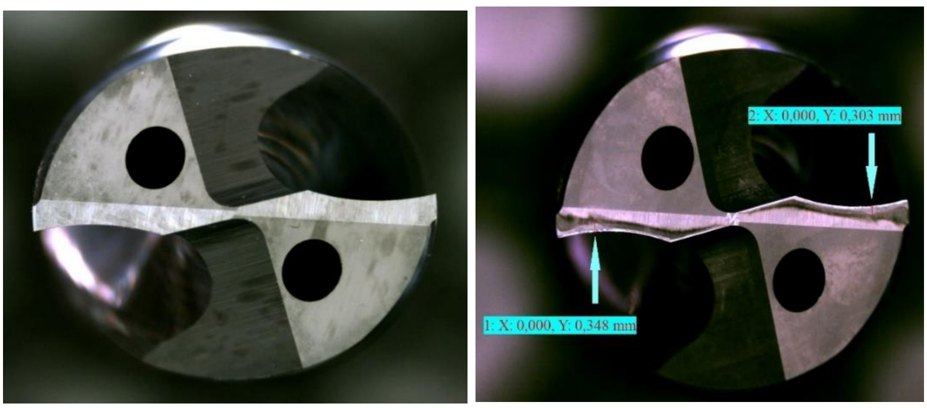
	1	2	3	4	5	6
CFRP	2,153	1,685	1,452	1,104	3,188	3,343
Al 7075	0,582	0,683	1,212	0,886	0,677	1,095

Fig. 7 Average surface roughness values for each experiment



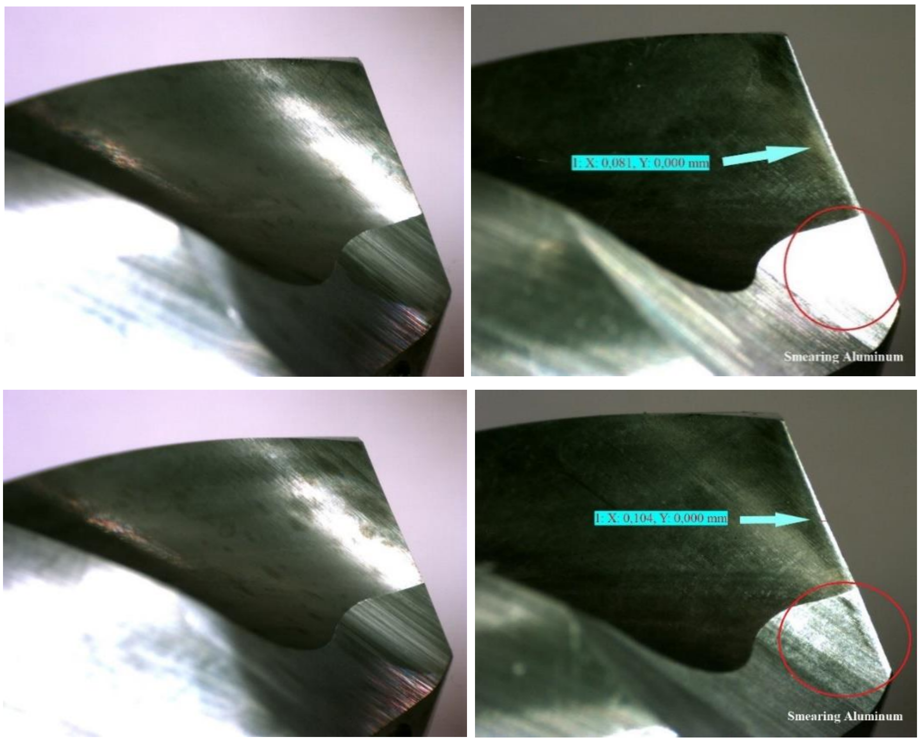
	1	2	3	4	5	6
Tool Wear	0,171	0,176	0,209	0,125	0,208	0,158

Fig. 8 Wear amounts of tools



a b

Fig. 9 a - Image of unused cutting tool; b - the wear image of the cutting tool used in Experiment 3



a b

Fig. 9 Continuation

4. Conclusions

In this study, the drilling of carbon fiber reinforced polymer composite material and Al 7075 alloy in stacked structure was analyzed at variable cutting speeds and feed rates and constant cutting speeds and feed rates. In order to examine the effect of the drilling direction in the experiments, each experiment was repeated by changing the drilling direction of the stacked structure. The thrust forces acting on the test specimens, the delamination of the CFRP material, the surface roughness of both materials and tool wear were investigated. The findings obtained as a result of the experimental study are presented below:

• It has been observed that the delamination values of the CFRP composite material are high at high cutting and feed rates. However, in the stacking structure, the delamination values differ at the hole entrance and exit depending on the entry direction of the cutting tool. It was observed that the delamination values were low in the region adjacent to the Al 7075 alloy. High cutting speed and feed rate for Al 7075/CFRP and low cutting speed and feed rate for CFRP/Al 7075 have a positive effect on delamination values.

• It has been observed that the thrust force decreases on the CFRP composite material at high cutting and feed rates. The speed changes have no effect on the thrust force in Al 7075. It has been determined that the drilling direction has no effect on the thrust force for both materials at constant cutting speeds and feed rates, and the force increase depending on the number of holes. As a result of drilling performed at variable speeds in the direction of CFRP/Al 7075, it was observed that the drill exerted 2.5 times more force on Al 7075 than other experiments.

• It has been determined that the increasing of cutting speed and feed rate has a significant effect on the surface roughness and that causes outside the desired standards of hole surface roughness of CFRP. The lowest surface roughness was observed where the highest thrust force was performed on the Al 7075 alloy.

• The increasing of cutting speed and feed rate causes an increase in tool wear. It has been observed that changing the drilling direction at constant cutting and feed rates has a positive effect on tool wear. Tool wear decreases when tool exits from CFRP composite material. Internal cooling ensured that no bulit-up egde on the cutting tool, no chips are accumulated in the tool grooves, and no negative effects of carbon dust on the tool surface.

Acknowledgment

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INVESTIGATION OF DRILLABILITY
OF CFRP/AL 7075 STACK

S u m m a r y

Composite/metal stack materials, which have excellent mechanical properties, are wideyl used in aerospace industry. However, their machining operation is challenging due to two different material. In this study stack materials consisting of CFRP and Al 7075-T6 were drilled with different drilling paremeters to investigate delamination defect, thrust force, inner surface roughness of hole and wear of the cutting tool. Cutting speeds of 50 and 200 m/min, feed rates of 0.10 and 0.20 mm/rev were selected as cutting parameters. The materials were drilled respectively in CFRP/Al 7075 and Al 7075/CFRP directions to observe effect of machining direction in the experiments Drilling experiments were carried out with an uncoated 9 mm diameter drill at variable and constant speeds. Experimental results showed that the surface roughness increased with the increase of cutting speed and feed rate, delamination increased in experiments where cutting tool came out of CFRP, thrust force at variable speeds increased and low amount of wear of cutting tool thanks to internal cooling.

Keywords: Materials testing, CFRP, aircraft, drilling, Al 7075.

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