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Ultrasonic Assisted Drilling of Carbon Fiber Reinforced Plastic Composites with Non-Rotating Vibratory Tool

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KEYWORDS

Ultrasonic;
CFRP;
Drilling;
Delamination;
Cutting Force.

ABSTRACT

In recent years, the use of various polymer composites in the aerospace, marine, and automotive industries have expanded due to their low weight and high mechanical strength. Due to hard phases and layered-type material structure, problems like poor surface quality, high cutting forces, and severe tool wear occur in the drilling of carbon fiber reinforced composites. A method that can reduce the mentioned effects in CFRP drilling is using ultrasonic waves in the drilling. In this paper, the idea of using a non-rotating vibratory tool ultrasonic method for drilling CFRP has been introduced and the effect of exerting ultrasonic waves on non-rotating drilling tool has been studied. The composite specimens were prepared by the layering method under load. The design of experiments using the Taguchi method was carried out, the optimal drilling parameters were determined, and the effects of ultrasonic on the surface roughness, surface quality (delamination, cracks, un-cut fibers), and cutting forces were investigated. The results indicated that ultrasonic waves in CFRP drilling could significantly reduce surface roughness (up to 49% surface roughness improvement) and the average axial force could decrease up to 57% compared with the condition that no ultrasonic waves have applied. Delamination of the drilled surface also decreased with the use of ultrasonic waves. This indicates that the idea of non-rotating ultrasonic tool can have similar effects as a rotating ultrasonic tool in drilling CFRPs.

1. Introduction

Advanced composites with plastic as a base material are being widely used in industries like aerospace and automotive due to their high mechanical strength, fatigue and creep resistance, and very low weight. Among the various types of plastic composites, carbon fiber reinforced plastics (CFRP) are widely utilized in today's aerospace structures. The usage of this composite material is such that 53% of Airbus™ A350 XWB modern airplane is composed of composites [1-3], and CFRPs are used as a material for wings, doors, tail cone, skin panel, and frames for this airplane. The main machining operation used for CFRPs is the drilling operation needed for the assembly of parts. Typically, CFRPs are very brittle due to the existence of carbon fibers in their structure, and this leads to challenges of high machining forces and tool wear in the drilling operations. Other problems commonly occur during the drilling of CFRPs are hole surface damage and the delamination effect [4,5]. One approach proposed for overcoming the mentioned problems associated with the drilling of CFRPs is using ultrasonic waves to reduce cutting forces, tool wear, and defects. In this method, the high frequency (typically>16 kHz) ultrasonic vibration, mostly in the axial direction, exerts on the tool or workpiece during the normal drilling operation. Ultrasonic waves can be applied to the tool or workpiece. High frequency and periodic contact and separation cycles of tool and workpiece during machining, reduce friction between chip and tool face and the cutting forces in operation. Several works cited the advantages of the ultrasonically assisted drilling (UAD) process compared with the conventional drilling

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(CD) method [6-11]. In recent work, a productivity improvement of up to 100% was reported by authors for drilling stainless steel 316 material, maintaining the surface roughness and Run-out geometrical tolerance [10]. The other capability of ultrasonically assisted drilling is the possibility of deep drilling of soft and hard materials with higher tool life and lower cutting forces. It was found that UAD reduced torque up to 5 times and temperature six times compared with CD in deep drilling of Al-6061 alloy [12]. Using the ultrasonic waves made it possible to make deep holes in the Inconel 738LC superalloy with depth-to-diameter of up to 10 [13].

Few researchers investigated the ultrasonic effects on the drilling process of CFRPs. Mehbudi et al. [5] investigated the cutting forces and delamination in ultrasonic-assisted drilling of GFRP composites. They found that the drilling thrust force and delamination would decrease by up to 50 percent with this method. This force reduction is also reported by up to 60% for ultrasonic-assisted drilling of CFRP, which is achieved at a drill spindle speed of 40 rpm and feed of 16mm/min [14]. Ultrasonic assisted drilling of CFRP with a small diameter drill bit (Ø=3mm) was conducted in [15] with dramatically reduced cutting force and surface roughness.

Gupta [16] investigated the cutting forces and surface damages in the drilling of CFRP using UAD compared with CD and found that the thrust force of drilling is decreased in UAD and to achieve minimum workpiece damage during drilling, variable spindle speed is required. Guofeng et al. [17] investigated the effect of longitudinal–torsional coupled ultrasonic vibrations on the cutting force and defects during drilling of CFRP with a rotating vibratory tool. Their experimental results indicated that cutting forces are much lower than conventional drilling for longitudinal–torsional coupled approach (39% lower thrust force), and the defects of delamination and burr are decreased.

Applying ultrasonic waves to the tool for all previous research works was inserting the vibration into the rotating tool. This method is expensive and hard to apply. The method proposed in this work is using the non-rotating vibratory tool and giving rotation to the workpiece to keep the relative motion required for drilling operation. This method is very simple and can be applied to the lathe machine tool with minimum extra instrumentation and cost. The effect of this kind of ultrasonic vibration employment on the cutting forces, tool wear, and delamination factor were investigated in the current work.

2. Experimental Work

2.1. Experimental Setup

A universal lathe (TN50D Model from Machine Sazi Tabriz company) has been modified to install the fixture of a vibratory tool on the transverse axis (Fig. 1). The Fixture design was L-shaped (Fig. 2) and contained a plane perpendicular to the X-axis of the lathe machine and the high-power ultrasonic transducer installed on this plane. The fixture's design was such that the transducer center could change easily with screws for drilling at different heights. An ultrasonic transducer with a nominal (designed) resonance frequency of 20kHz and maximum power of 1kW has been used. The ultrasonic generator was made by the Alfa Power company (ULPS2000 type). The ultrasonic system's required power and frequency were selected similar to previous works for ultrasonic-assisted drilling of composites and metals[5-14]. The design of the transducer has been performed using the analytical method. More details on the calculations and assumptions can be found in [18].

cutting forces were measured with Kistler 9257B dynamometer version. As shown in Fig. 2 dynamometer was installed at the bottom of the fixture using screws. The ultrasonic transducer is started first for measuring drilling forces, and then the lathe machine is operated. After starting the drilling operation, the dynamometer is started. The measured resonance frequency was 21.7kHz. The workpiece was clamped in a special fixture that is clamped onto the three-jaw chuck of the machine. The fixture was designed such that the workpiece can move in the radial direction of the spindle [18]. For the tests, after each drilling test, the workpiece traveled along the radial direction and the drilling was implemented in the center of the spindle. The experiments used an insert-type twist drill with a diameter of 10 mm.

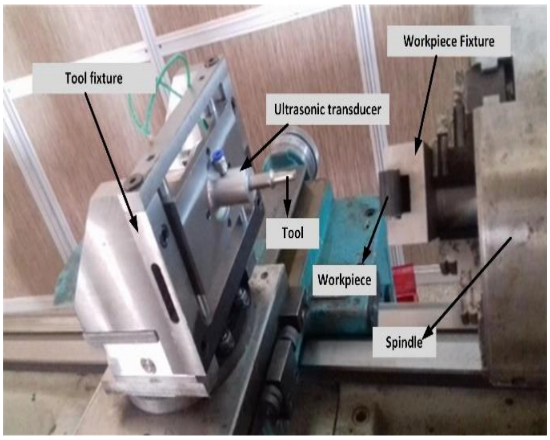

Fig. 1. Experimental setup for UAD

Tool material was WC with TiN coating. A schematic representation of the mentioned components of the experimental test rig is shown in Fig. 2. for surface roughness measurements Mahrsurf PS1 surface roughness tester with a stylus tip radius of 2μ and measurement uncertainty of less than 10% was utilized.

2.2. CFRP Samples Manufacturing

For the preparation of CFRP samples, bidirectional carbon fibers (10 layers) were arranged on the top and bottom of the stack, and 32 uni-directional layers with the configuration shown in Fig. 3 were sandwiched between them.

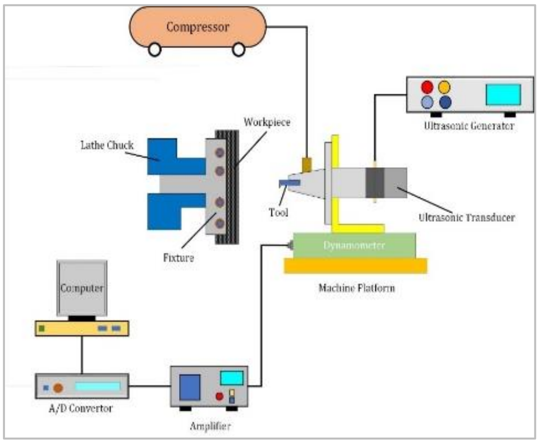

Fig. 2. Schematic representation of the experimental setup

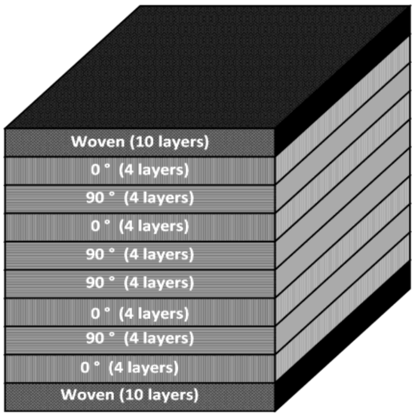

Fig. 3. Model of CFRP sample's structure

Fig. 4. Fabricated CFRP pressed in a fixture

The carbon fibers were made by the Sika company. Fibers are attached with epoxy resin. For stiffening the resin, hardener CH-80-2 Sika was employed with a weight ratio of 30%. The layering method was manual, and the layered was clamped with the special fixture. The fixture (Fig. 4.) contained steel flat and fine plates for accurately pressing the composite. Angles of uni-directional fibers were 0◦ and 90°, as shown in Fig. 3. The samples were exposed to the free air for one week after pressing. The sample plane with dimensions of 250mm × 250 mm × 11 mm was then cut with the waterjet method to convert to the required sizes for drilling experiments with dimensions of 250mm × 25 mm × 11 mm.

2.3. Design of Experiments

To better understand the effect of parameters on the drilling process of CFRP with ultrasonic waves, the design of experiment method was utilized to select the experimental parameters. For the designing of experiments, the Taguchi method was utilized with two parameters of the feed rate and spindle (spindle) speed for two conditions of conventional and ultrasonic assisted drilling. Feed rate and spindle speed were considered on three levels. All factors with their levels are listed in table 1. Ignoring interactions, an L9 orthogonal array was used to perform the tests with three factors by three levels. The orthogonal array is summarized in table 2. Thrust force, surface roughness, and delamination factor were then measured and analyzed for all the experimental trials.

Table 1. Input parameters and assigned levels

Parameter	Level 1	Level 2	Level 3
Spindle speed (Rev/min)	500	710	1000
Feed rate (mm/Rev)	0.08	0.12	0.16

Table 2. Experiments test matrix

No.	Feed rate (mm/Rev)	Spindle speed (Rev/min)	Type
1	0.08	500	UAD CD
2	0.12	500	UAD CD
3	0.16	500	UAD CD
4	0.08	710	UAD CD
5	0.12	710	UAD CD
6	0.16	710	UAD CD
7	0.08	1000	UAD CD
8	0.12	1000	UAD CD
9	0.16	1000	UAD CD

3. Results

3.1. Thrust Force Investigation

To evaluate the effect of axial ultrasonic vibration on CFRP drilling, thrust force for all experimental tests designed in section 2.3 was measured using a dynamometer. The force diagram versus time is shown in Fig. 5 for three measurement directions (X, Y, Z). As illustrated in this diagram, thrust force (axial force or force in the X direction) is the most dominant component compared with forces in the other directions (Y, Z). As expected, the force values in dimensions of Y and Z are much lower and neglectable than thrust force. Forces in Y and Z directions are also not similar to theoretical expectations.

It could be due to the effect of ultrasonic waves' traverse modes and workpiece material dimension variations in the drilled hole.

For removing the fluctuations and smoothing the thrust force curve, a moving average filter with a period of 20 has been utilized [19]. This filter removes the force versus time curve fluctuations and noises by creating a series of averages of different subsets of the full data set. This method is also used in [20] for averaging the force measurement results.

Results of thrust force measurement for spindle speed of 710 rpm and feed rate of 0.16 mm/revolution are shown in Fig. 6. It should be noted that the curve is smoothed for better illustration. As shown in this figure, the thrust force increases at the start of the drilling operation before the complete entrance of the tool head into the composite part. After that, it is decreased versus time and reaches a constant value. This constant value is for the stable phase of the drilling cycle. This trend was observed in all drilling cases. It is clearly detectable from this figure that using ultrasonic waves can reduce thrust force in the drilling of CFRP.

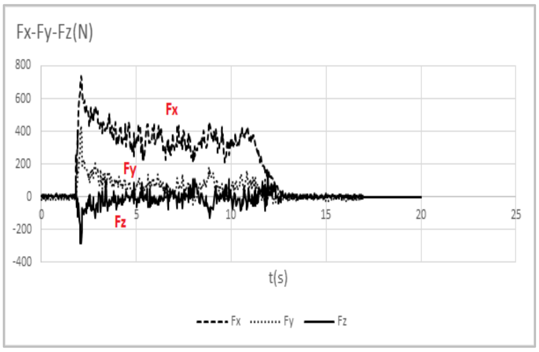

Fig. 5. Cutting force versus time in three directions of X, Y, Z

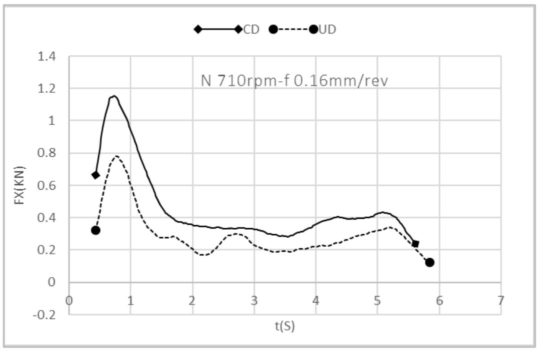

Fig.6. Thrust force for ultrasonic and conventional drilling versus time for spindle speed of 710 rpm and feed rate of 0.16 mm/revolution

It should also be noted that the thrust force curve shape is very similar to other similar works [21-23] that used rotational ultrasonic tools, and it proves that using the non-rotating ultrasonic tool can have a similar effect on the thrust force.

The average thrust force is then calculated for all cases, from start to end of drilling time. The thrust force curve has an approximately constant value, so the consistent average (Arithmetic) was used. It should be noted that the drilling time was not constant for all experimental trials and depended on the feed rate. A summary of the average force for nine experiments is shown in table 3.

Table 3. Thrust force results and the corresponding S/N ratio

Test No.	Spindle Speed (RPM)	Feed rate (mm/Rev)	Average Thrust force for UAD (N)	S/N ration for average Thrust force (UAD)	Average Thrust force for CD (N)	S/N ration for average Thrust force (CD)	Force decrease percentage in UAD
1	500	0.08	205	-46.2	239	-47.6	16.6%
2	500	0.12	235	-47.4	308	-49.8	31%
3	500	0.16	290	-49.3	356	-51.0	23%
4	710	0.08	274	-48.8	332	-50.4	21%
5	710	0.12	235	-47.4	323	-50.2	37%
6	710	0.16	285	-49.0	448	-53.0	57%
7	1000	0.08	204	-46.2	245	-47.8	20%
8	1000	0.12	256	-48.2	317	-50.0	24%
9	1000	0.16	322	-50.2	457	-53.2	42%

The S/N ratio values of the thrust force are calculated and mentioned, using the smaller, the better characteristics. As indicated in this table, for all cases using ultrasonic waves in drilling will reduce thrust force and the reduction range is between 17-57 percent. Results also indicated that the cutting force for both investigated cases (CD and UAD) is more sensitive to the federate parameter in comparison with the spindle speed parameter. This can be justified due to the application of axial ultrasonic vibrations. It is also obtained that the effect of ultrasonic waves in force reduction is more in higher feed rates. Based on the calculated S/N ratio values and interaction effect plot shown in Fig. 7, it was derived that the feed rate has more effect on the thrust force than the spindle speed.

3.2. Surface Quality Investigation

Surface roughness is one of the main machining parameters that are expected to be affected by ultrasonic waves' impact on the UAD of composites. Results of surface roughness investigation in various experimental conditions are shown in Fig. 8. It should be noted here that for ensuring the reliability of results, each test has been repeated three times, and the average surface roughness has been reported.

Using ultrasonic waves in the drilling of CFRP, friction, and temperature of the workpiece are decreased, which will improve the delamination of the composite. And due to this fact, the surface roughness decreases in the case of using ultrasonic waves. It was also derived from results that for CFRP, decreasing the spindle speed could enhance the surface quality of the machined surface and the effect of spindle speed on the surface roughness of CFRP is similar to the metals.

As shown in Fig. 8, for all test conditions using ultrasonic waves in drilling would decrease the surface roughness, and the ultrasonic effect decreases the surface roughness value between 16-49%. Results are also complied with [24] as in that work the Ra surface roughness criterion has been measured.

The S/N ratio data is shown in Fig. 9 for surface roughness versus feed rate and spindle speed for both CD and UD cases. This figure shows that spindle speed is a more effective parameter than the feed rate for surface roughness determination in CFRP drilling.

Other surface quality parameters are delamination and crack. To study of the effect of ultrasonic waves on the surface quality, the cross-section area of the drilled CFRP samples has been investigated using SEM method.

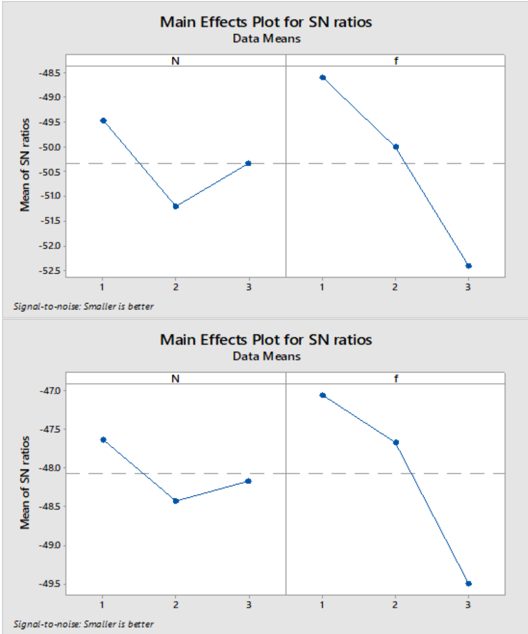

Fig. 7. S/N ratio plot for thrust force in CD (Up) and UD (Down)

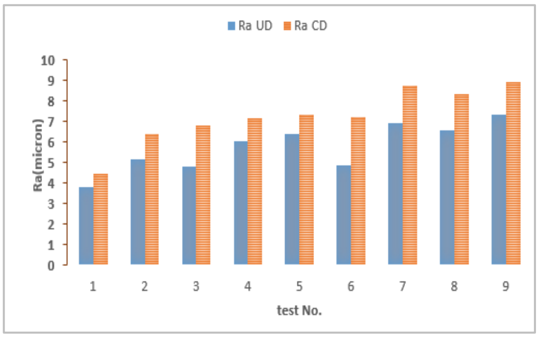

Fig. 8. Surface roughness of workpiece for all experiments (UD and CD)

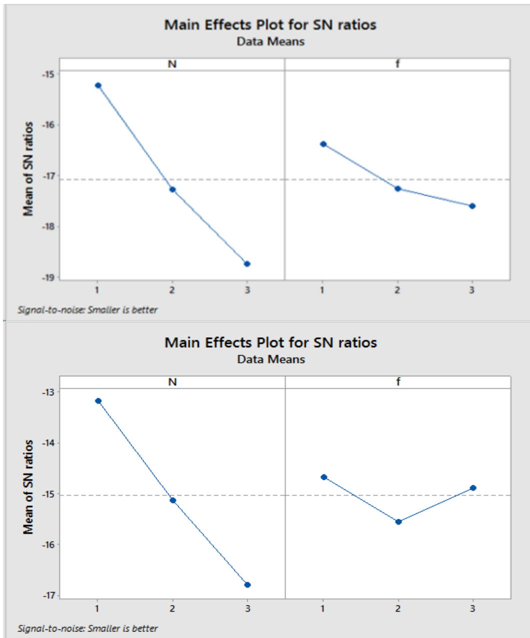

Fig. 9. S/N ratio plot for surface roughness in CD (Up) and UD (Down)

Sample SEM image for machining condition of N=1000 rpm and f=0.08 mm/rev is shown in Fig. 10. It is clearly visualized in this figure that using ultrasonic waves could totally decrease and even eliminate the uncut and Pull-out fibers, cracks, and tears from the surface of the drilled composite. This phenomenon has been apperceived in all conditions. The crack size investigation in Fig. 11 also revealed that ultrasonic waves could reduce the crack size and improve the surface integrity.

Another hole quality parameter that determines the accuracy of the drilled hole is delamination size. This parameter is measured using the images captured with an optical microscope. A dino-lite AM413MT microscope was applied for this purpose. The captured images were analyzed using MATLAB software image processing code to calculate the delamination factor Fa which is defined concerning the following equation [25]:

$$Fa = Ad/A0 \quad (1)$$

where Ad is the delamination area, and A0 is the nominal hole area. The sample image indicating the method of calculation is shown in Fig. 12.

The delamination factor was calculated in three test conditions (constant spindle speed and various feed rates) to evaluate the ultrasonic effect in the current test configuration. The results are shown in Fig. 13.

As shown in this figure, delamination suppresses by using ultrasonic waves in CFRP drilling. The delamination factor will reduce in the case of axial ultrasonic vibration assistance in drilling. Results indicated that in higher feed rates, due to the higher temperatures and softening effect of the CFRP epoxy resin, delamination increases, and the machined hole accuracy decreases. It is apparent in Fig. 12 that the ultrasonic waves can decrease the delamination factor up to 29%, showing a significant effect of vibrations in CFRP on the hole accuracy after drilling.

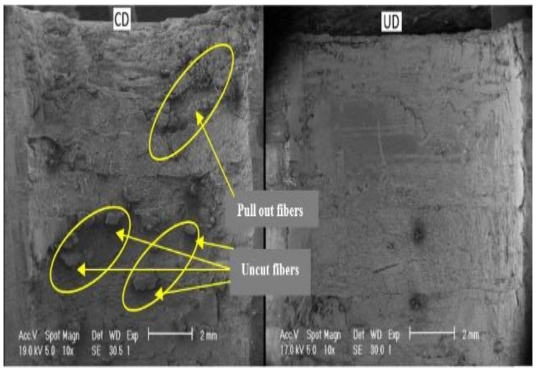

Fig. 10. Uncut and pull-out fibers for CFRP sample after drilling with (right) and without (left) ultrasonic waves (magnification=10X, N=1000 RPM, f=0.08 mm/rev)

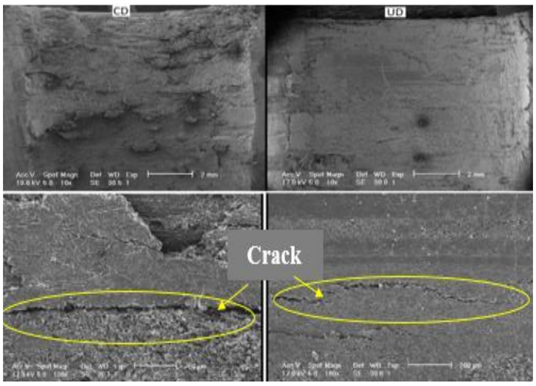

Fig. 11. Crack size for CFRP sample after drilling with (right) and without (left) ultrasonic waves (magnification=10X, N=1000 RPM, f=0.08 mm/rev)

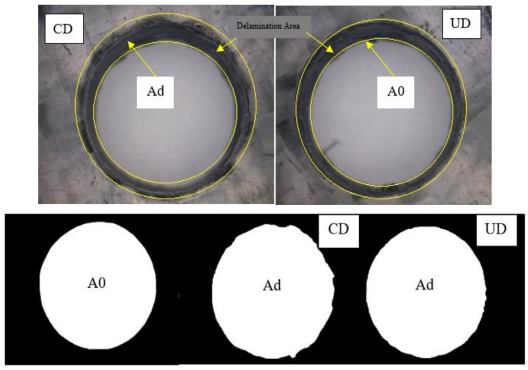

Fig. 12. Delamination factor calculation(up) and the image processing of the machined hole image (down)

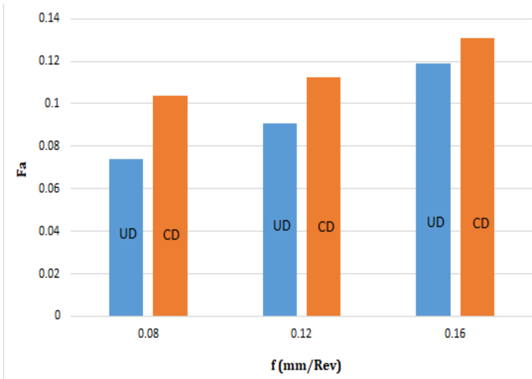

Fig. 13. Delamination factor for spindle speed of 500 RPM and various feed rates for two cases of conventional and ultrasonic drilling

4. Conclusion

In the present work, the concept of a non-rotating vibratory tool for ultrasonic-assisted drilling of CFRP has been developed. The experimental setup was organized on the lathe machine with minimum changes. To investigate the process parameter's effect on the thrust force and surface quality and do sensitivity analysis, the design of experiments method has been applied. Taguchi method was applied with two feed rate and spindle speed parameters for ultrasonic and conventional drilling methods. Results indicated that with this ultrasonic insertion configuration (non-rotating vibratory tool), ultrasonic waves could decrease the thrust force by up to 57%. The design of the experiment investigation also revealed that the thrust force in drilling CFRP is more sensitive to feed rate than spindle speed. Experiments also concluded that using ultrasonic vibration can improve surface quality very well, and the surface roughness decrease in the case of ultrasonic assistance could be up to 49%. One important conclusion was that despite the drilling of metals, increasing the spindle speed will decrease surface roughness due to the formation of surface defects in higher temperatures when CFRP is drilled. It is also apparent from experimental tests that the ultrasonic waves could drastically reduce hole surface imperfections like crack, tear, and uncut fibers. It is also derived that ultrasonic waves have decreased delamination of the composite surface. It is also concluded that ultrasonic-assisted drilling with a non-rotating vibratory tool is applicable for drilling components made with CFRP composites.

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References

[1] Jens, B., Carme, H., Stéphanie, B., 2017. Environmental analysis of innovative sustainable com use in aviation sector—A life cycle assessment review. *Science China Technological Sciences*, 60(9), pp. 1301-1317.

[2] Kolesnikov, B., Herbeck, L., Fink, A., 2008. CFRP/titanium hybrid material for improving composite bolted joints. *Composites Structructures*, 83(4), pp. 368-380.

[3] Lee, C.K., 2009. Structure, electrochemical and wear-corrosion properties of electroless nickel–phosphorus deposition on CFRP composites. *Materials Chemistry and Physics,* 114, pp. 125-133.

[4] Sheikh-Ahmad, J.Y., 2009. *Machining of Polymer Composites.* Springer Science+ Business Media, LLC.

[5] Mehbudi, P., Baghlania, V., Akbari, J., Bushroa, A.R., Mardi, N.A., 2013. Applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates. *Procedia CIRP,* 6, pp. 577 – 582.

[6] Barani, A., Amini, S., Paktinat, H., Fadaei, A., 2014. A Built-up edge investigation in vibration drilling of Al2024-T6. *Ultrasonics*, 54, pp. 1300–1310.

[7] Pujana, J., Rivero, A., Celaya, A., Lo´pez, L.N ., 2009. Analysis of ultrasonic-assisted drilling of Ti6Al4V. *International Journal of Machine Tools and Manufacture,* 49, pp. 500-508.

[8] Azarhoushang, B., Akbari, J., 2007. Ultrasonic-assisted drilling of Inconel 738-LC. *International Journal of Machine Tools and Manufacture,* 47, pp. 1027–1033

[9] Moghaddas, M.A., Short, M.A., Wiley, N.R., Yi, A.Y., Graff, K.F., 2017. Performance of an ultrasonic-assisted drilling module. *International Journal of Advanced Manufacturing Technology*, 94 (9-12), pp. 3019-3028.

[10] Moghaddas, M.A., Short, M.A., Wiley, N.R., Yi, A.Y., Graff, K.F., 2018. Improving Productivity in an Ultrasonic Assisted Drilling Vertical Machining Center. *Journal of Manufacturing Science and Engineering,* 140(6), p. 061002.

[11] Vedvik, N., 2015. Assessment of ultrasonic assisted drilling. (Msc dissertation, Norwegian University of Science and Technology).

[12] Chu, N-H., Nguyen, V-D., Do, T-V., 2018. Ultrasonic-Assisted Cutting: A Beneficial Application for Temperature, Torque Reduction, and Cutting Ability Improvement in Deep Drilling of Al-6061. *Applied Sciences*, 8(0), pp.1-11.

[13] Baghlani, V., Mehbudi, P., Akbari, J., Sohrabi, M., 2013. Ultrasonic assisted deep drilling of Inconel 738LC superalloy. *Procedia CIRP*, 6, pp. 571 – 576.

[14] Makhdum, F., Jennings, L.T,, Roy, A., Silberschmid, V.V., 2012. Cutting forces in ultrasonically assisted drilling of carbon fibre-reinforced plastics. *Journal of Physics: Conference Series,* 382, p. 01 2019.

[15] Makhdum, F., Phadnis, V.A., Roy, A,, Silberschmid, V.V., 2014. Effect of ultrasonically-assisted drilling on carbon-fibre-reinforced plastics. *Journal of Sound and Vibration*, 333, pp. 5939–5952.

[16] Gupta, A., 2016. Study of Cutting Speed on Ultrasonic Assisted Drilling of Carbon Fibre Reinforced Plastics. (PhD dissertation, University of Warwick).

[17] Guofeng, M.A,, Renke, K., Zhigang, D., Sen, Y., Yan, B., Dongming, G., 2020. Hole quality in longitudinal–torsional coupled ultrasonic vibration assisted drilling of carbon fiber reinforced plastics. *Frontiers of Mechanical Engineering*, 15, pp. 538-546

[18] Nikmanesh, M., 2018. Design and manufacturing of the transducer for ultrasonic assiteddrilling, Bsc Disseration, Semnan University, Semnan, Iran.

[19] Karimpour, H., Abedini, V., Hajialimohammadi, A., 2022. Effects of process parameters on machining forces and surface roughness during turning 304L steel using SiO2 nanofluid, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, First Published: 23 March 2022, doi: 10.1177/09544089221089140. https://journals.sagepub.com/doi/abs/10. 1177/09544089221089140

[20] Saligheh, A., Hajialimohammadi, A., Abedini, V., 2020. Cutting Forces and Tool Wear Investigation for Face Milling of Bimetallic Composite Parts Made of Aluminum and Cast Iron Alloys, *International Journal of Engineering*, 33 (6), pp.1142-1148.

[21] MA, G., Kang, R., Yan, C., Bao, Y., Zhu, X., Dong, Z., 2022. Mechanical model of thrust force and torque in longitudinal-torsional coupled ultrasonic-assisted drilling of CFRP, *The International Journal of Advanced Manufacturing Technology*. 119, pp. 189-202.

[22] Don, S., Liao, W., Zheng, K., Ma, W., 2020. Investigation on thrust force in rotary ultrasonic drilling of CFRP/aluminum stacks. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 243(2), pp. 1-11.

[23] Zhang, C., Lu, M., 2021. Investigation on a novel variant-dimension vibration-assisted drilling system for CFRP: locus model, control strategy, and machining experiments. *The International Journal of Advanced Manufacturing Technology,* 113, pp. 2629-2650.

[24] Shao, Z., Jiang, X., Li, Z., Geng, D., Li, S., Zhang, D., Feasibility study on ultrasonic-assisted drilling of CFRP/Ti stacks by single-shot under dry condition. 2019, *The International Journal of Advanced Manufacturing Technology*, 105, pp. 1259-1273.

[25] Ishida, T., Noma, K., Kakinuma, Y., Aoyama, T., Hamada, S., Ogawa, H., Higaino, T., 2014. Helical Milling of Carbon Fiber Reinforced Plastics Using Ultrasonic Vibration and Liquid Nitrogen. *Procedia CIRP,* 24, pp. 13–18.