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Procedia CIRP 6 (2013) 577 – 582
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The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)

Applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates

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Abstract

Delamination is a major problem in drilling of fiber-reinforced composite materials. Thrust force is an important factor leading to propagation of delamination during drilling process. One of effective methods to reduce machining forces is application of ultrasonic vibrations. In this study ultrasonic assisted drilling is applied to reduce thrust force in drilling of GFRP laminates. In order to conduct experiments a setup is designed and fabricated to apply both vibrations and rotation to drill bits. Using Taguchi method, a set of experiments is conducted with feed rate, spindle speed, and ultrasonic vibration amplitude as control factors. The results show that applying ultrasonic vibration reduces the thrust force and therefore the drilling induced delamination dramatically.

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Keywords: Ultrasonic assisted drilling, GFRP laminates, Drilling induced delamination, Taguchi method

1. Introduction

Using composite materials in order to fabricate various mechanical parts is spreading constantly. Many industries such as aerospace, automobile, marine machines and even sporting goods have an increasing demand for Fiber Reinforced Plastics (FRP). This is due to the superior properties of these materials such as: high specific stiffness, high specific strength, great fatigue resistance and low coefficient of thermal expansion. Although composite parts are fabricated with near net shape, at the assembly stage they have to be drilled in order to be joined to other parts. One of problems of composite laminates rises in this stage and that is drilling-induced delimitation which may be a very serious damage. It has been reported that in aircraft industry, the rejection of parts consists of composite laminates due to drilling induced delamination damage during final assembly was as high as 60% [1,2]. This damage has been subject of many studies and researchers have tried to reduce this damage by different methods. Many researchers have shown that drilling thrust force is the main responsible for propagation of delamination damage [3-5]. Some researchers have conducted experiments to investigate effect of different drill bit geometries on thrust force and delamination [6, 7]. They found that drill bit geometry is an effective factor which can affect delamination significantly. Some researchers have applied nonconventional methods to reduce delamination in drilling [8]. High speed drilling with high spindle speed up to 100,000 rpm have been used in some studies to minimize drilling induced delamination [9-11].These studies showed that applying high speed may reduce delamination however, the important objection in this method is the wear of drill bits which happens very quickly. Furthermore some studies have been conducted on abrasive drilling [8, 9]. Some researchers, on the other hand, have conducted experiments to recognize the effect of vibration-assisted drilling on thrust force and delamination [12-14]. These studies showed that applying vibration may reduce the amount of thrust force, delamination and wear of tool. All of these studies applied frequencies lower than 600

Selection and/or peer-review under responsibility of Professor Bert Lauwers
doi:10.1016/j.procir.2013.03.097

Hz and applied vibration amplitudes up to 20µm. The main weakness in this method is applying vibration to workpiece and dependence of the results on the applied frequency. In the present study applying both rotation and vibration to drill bits, GFRP workpiece have been drilled and the results are compared with those of conventional method. In order to apply rotation and vibration to drill bit a special setup is designed and fabricated.

2. Experiments

2.1. Experimental setup

In order to apply both rotation and vibration to drill bit a setup was designed and fabricated (Fig. 1). This setup consists of a cylindrical container and a slip ring to feed electrical power to transducer which is held inside the container. The horn is fastened to the transducer by a set screw then they are clamped inside the container by means of a ring around the horn which is the horn vibration node. Modal analysis has been conducted using finite element method and the horn has been designed in its most efficient geometry. This horn works in frequency of 22 kHz which is its resonance frequency. The ultrasonic generator is controlled using Labview® software developed by Mastersonic Company. During experiments a Kistler dynamometer under fixture sends force signals to a computer after being magnified by an amplifier. The force results are processed using Kistler Dynoware® software then graphs and mean values of force for any drilling test are available. The experimental setup consists of (Fig. 2):

- Universal lathe machine (Tabriz-TN40A): for turning the ultrasonic head,
- Generator (Mastersonic MMM generator – MSG.1200.IX): to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency range of the generator is 19 to 46 kHz and the frequency resolution is 1 Hz. The full power of the generator is 1200 W and the maximum output current is 3 A.
- A computer which utilizes the software Labview® developed by Mastersonic to control power and frequency of the transducer.
- Dynamometer Kistler type 9257B and related amplifier in order to measure machining forces. This dynamometer is capable of measuring forces and moments in three directions.
- A computer which utilized Dynoware® (of Kistler) software to plot and keep records of force results.
- Standard high speed steel drill bits ϕ 5.

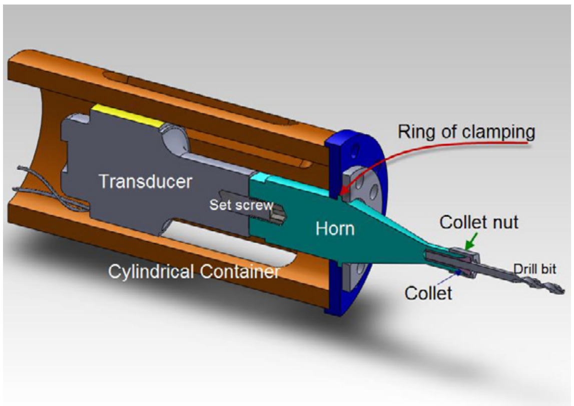

Fig. 1. The horn inside the cylindrical container

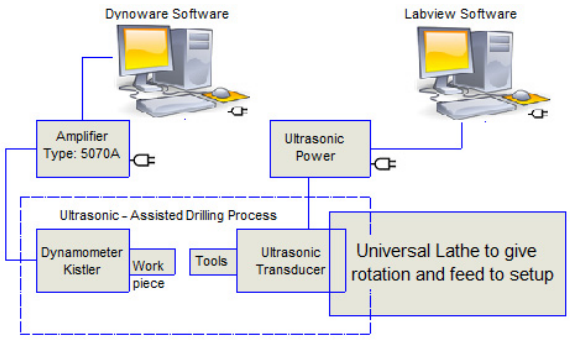

Fig. 2. Schematic of the experimental setup

- Woven GFRP laminate with 16 layers and total thickness of 13 mm and epoxy resin as the matrix. The composite laminate was fabricated in "Iran Composite Institute".

In order to prevent the drill bits to slide in the horn while applying vibrations, a collet and nut is used. In order to have a better comparison between ultrasonic assisted and conventional drilling tests, for conventional experiments the same setup is used as the ultrasonic assisted experiments setup except that the ultrasonic transducer would be off.

2.2. Design of experiments (Taguchi method)

Taguchi method of designing experiments has been used widely by engineers and industries in order to obtain information about the effects of different factors on a given process. This technique is based on orthogonal arrays to reduce number of experiment to be executed. Here we have three factors each of which has three levels for ultrasonic assisted tests and two factors with three levels for conventional tests. An L9 orthogonal array is chosen to conduct ultrasonic tests.

Table 1. Design factors and there levels for drilling

	level	vibration amplitude (micrometer)	spindle speed (rpm)	feed rate (mm/min)
Ultrasonic assisted drilling	1	5	355	50
	2	10	710	80
	3	15	1000	110
Conventional drilling	1	-	355	50
	2	-	710	80
	3	-	1000	110

Table 2. Taguchi orthogonal array for ultrasonic assisted experiments

Test No.	Vibration amplitude	Spindle speed	Feed rate
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3. Orthogonal array for conventional drilling tests

Test No.	Spindle speed	Feed rate
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

For the conventional tests an L9 design of experiments would be the full factor test. Table 1 shows the factors with their levels in conventional and ultrasonic tests and the L9 array is shown in table 2. The L9 array for conventional tests is shown in table 3. There are three categories of quality properties in the analysis of SN ratio. These categories are: “smaller is better”, “higher is better” and “nominal is best”. In the present study it is desired to minimize the thrust force and delamination factor. Therefore, the “smaller is better” category is used with the Eq. 1 [15]:

$$S/N = -10\log\left[\frac{1}{n}\sum y^2\right] \quad (1)$$

3. Results and discussion

3.1. Thrust force

The results of thrust force during each test in ultrasonic assisted drilling are listed in table 4. The main effect of each factor is shown in Fig. 3. In order to include effects of noise, in Fig. 4 SN ratios for all factors are shown. These graphs show the effect of each factor on drilling thrust force clearly.

Table 4. Force results in ultrasonic assisted drilling tests

Test No.	First trial(N)	Second trial(N)	Third trial(N)
1	24.7	22.3	25.3
2	30.9	28.8	32.1
3	42.3	44.1	40.6
4	32.2	34.7	36.4
5	38.7	40.1	35.8
6	12.6	14.6	10.9
7	22.7	18.5	19.7
8	10.6	6.2	7.9
9	13.9	15.2	15.5

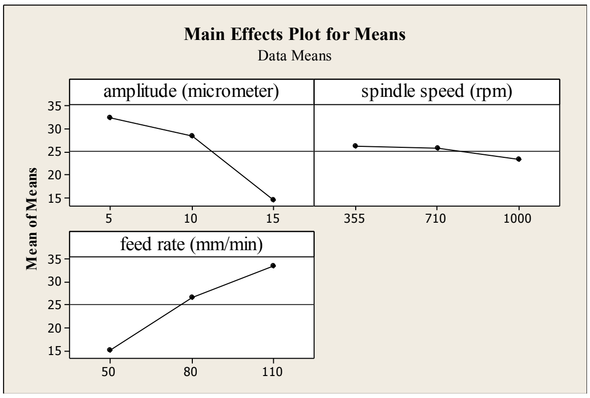

Fig. 3 Force results in ultrasonic assisted drilling (N)

According to these graphs, the most important factors on thrust force are feed rate and amplitude of ultrasonic vibration while the spindle speed is the least important factor. The reason why increasing ultrasonic amplitude affects the force decreasing so much, is that by increasing vibration amplitude chip breakage is facilitated and the contact duration between tool and workpiece is reduced; therefore the friction of drilling is reduced significantly. When the feed rate is increased, obviously the material removal rate and the uncut chip

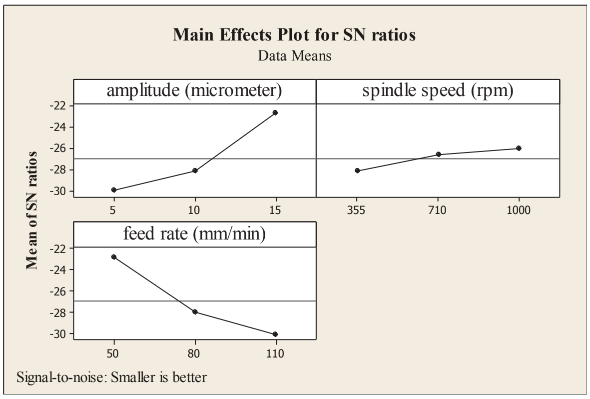

Fig. 4. SN ratios for thrust force results in ultrasonic assisted tests

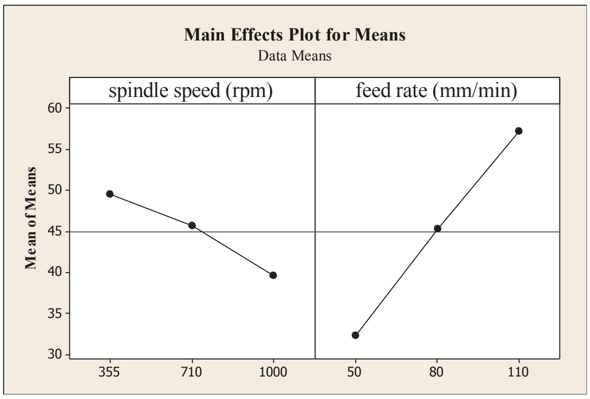

Fig. 5. Force results in conventional drilling tests (N)

Table 5. Thrust force results in conventional tests

Test No.	First trial(N)	Second trial(N)	Third trial(N)
1	38.8	35.4	33.2
2	51.6	52.5	50.1
3	62.4	57.8	63.9
4	34.7	33.3	37.1
5	44.2	45.7	44.8
6	58.2	58.9	54.6
7	23.6	25.8	29.7
8	38.3	39.1	41.4
9	52.9	56.1	50.5

thickness are increased. Therefore, there will be an increase in cutting forces. When cutting speed is increased although material removal rate is constant, the uncut chip thickness is reduced and the forces will diminish a little. Another reason why the thrust force decreases by increasing spindle speed is the growth of temperature which may soften the polymeric matrix of the GFRP workpiece.

Table 5 lists the results of conventional drilling thrust force in each trial. Fig. 5 and 6 show the main effect of spindle speed and feed rate on the mean values of thrust force and SN ratios in conventional drilling experiments respectively. The trend of effects of spindle speed and feed rate on thrust force is similar to ultrasonic assisted tests. Fig. 7 is the comparison of the thrust force between conventional and ultrasonic assisted tests. This figure shows how considerable may be to apply ultrasonic vibrations in reducing thrust force. This outstanding reduction in force is because of chip breakage and the reduction in friction due to ultrasonic vibration. During drilling process the tangential cutting speed is different along the cutting edges and increases with radius. Therefore in drilling process always there is a zone in which cutting speed is very low (mostly it happens in chisel edge area) and consequently the back rake angle is negative. As a result in this area the thrust force

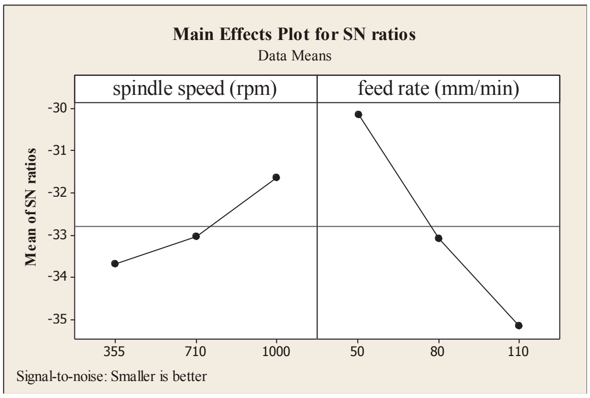

Fig. 6. SN ratios for thrust force results in conventional tests (dB)

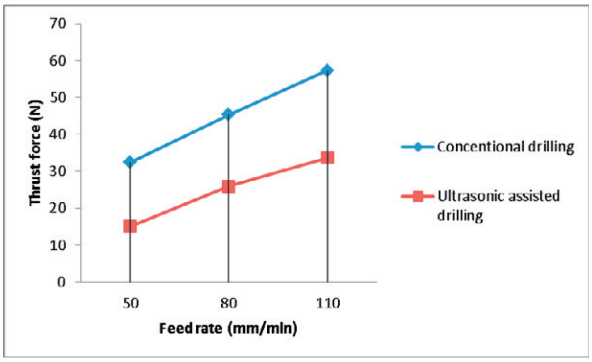

Fig. 7. Comparison of thrust force in different feed rates

is increased. When using ultrasonic vibrations with proper amplitude, there will be an impact regime in this area which may reduce thrust force by making cracks in reinforcement fibres in this area.

3.2. Delamination factor

In order to measure delamination factor digital photographs of the holes are taken and the maximum diameter of the damaged area is determined (Fig. 8).

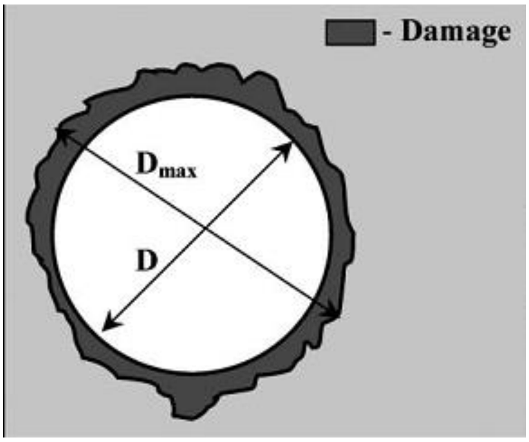

Fig. 8. Schema of measuring maximum diameter of damaged zone

Table 6. Delamination factor at drill exit in ultrasonic assisted tests

Test No.	First trial	Second trial	Third trial
1	1.32	1.34	1.35
2	1.41	1.38	1.42
3	1.45	1.46	1.42
4	1.39	1.38	1.42
5	1.38	1.41	1.44
6	1.23	1.26	1.33
7	1.32	1.3	1.33
8	1.2	1.23	1.19
9	1.24	1.21	1.28

Table 7. Delamination factor at drill exit in conventional tests

Test No.	First trial	Second trial	Third trial
1	1.73	1.74	1.71
2	1.78	1.75	1.74
3	1.88	1.86	1.83
4	1.67	1.69	1.74
5	1.76	1.8	1.75
6	1.81	1.79	1.86
7	1.65	1.6	1.67
8	1.72	1.72	1.8
9	1.78	1.84	1.79

The value of delamination factor is defined as the following equation:

$$F_d = \frac{D_{\max}}{D} \qquad (2)$$

in which D_{max} is the maximum diameter of damage around the hole and D is diameter of the hole.

The results of delamination factor in ultrasonic tests are listed in table 6. Fig. 9 and 10 show the main effect

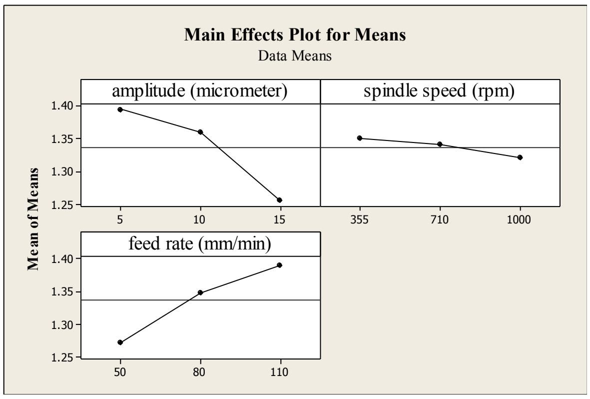

Fig. 9. The effect of different factors on delamination factor in ultrasonic assisted drilling

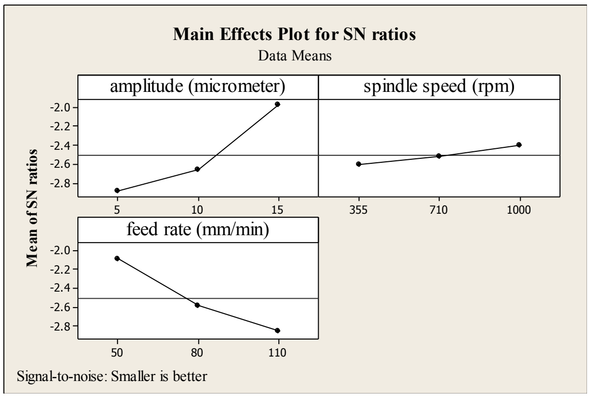

Fig. 10. SN ratio for delamination factor results in ultrasonic assisted drilling

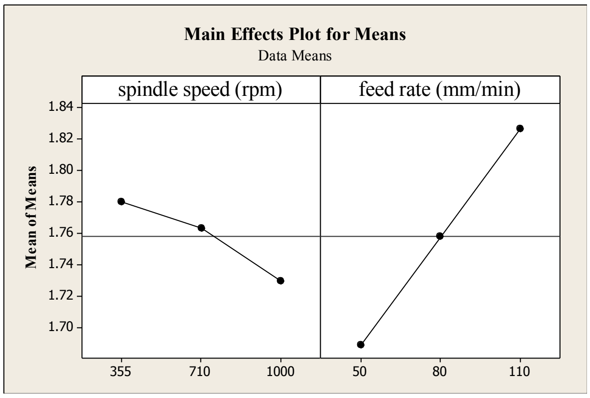

Fig. 11. The effect of spindle speed and feed rate on delamination factor in conventional drilling

of factors on mean value and SN ratios in delamination factor data. According to these figures, increasing ultrasonic vibration amplitude results in reduction of delamination factor. On the whole, the effect of factors on delamination results is very similar to their effect on thrust force which is due to the fact that the main reason for propagation of delamination is thrust force.

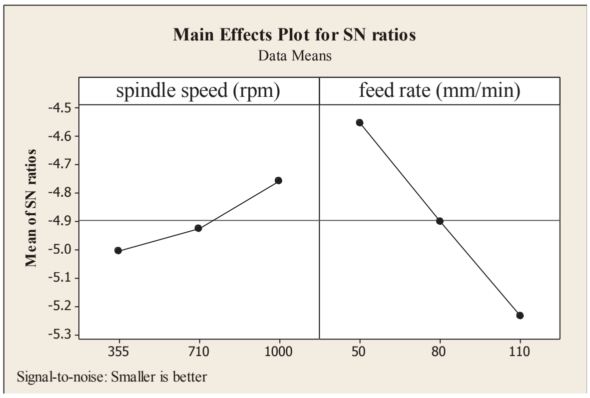

Fig. 12. The effect spindle speed and feed rate on SN ratios of delamination factor data in conventional drilling

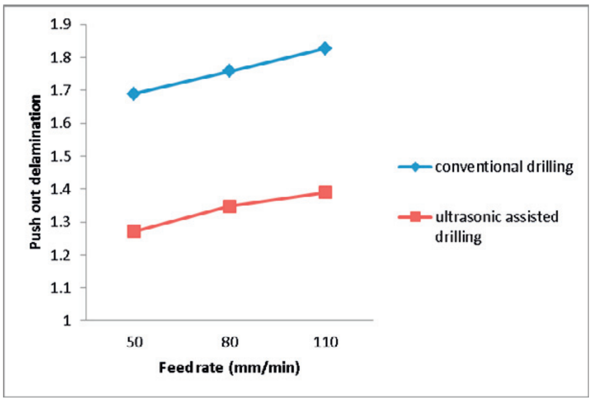

Fig. 13. Comparison of delamination factor in different feed rates

Fig. 11 and 12 show the main effect of spindle speed and feed rate on mean value and the SN ratio in delamination factor data in conventional testes which is very similar to their effect in ultrasonic assisted drilling. Fig. 13 is a comparison between delamination factor in ultrasonic and conventional tests which shows outstanding reduction in delamination factor by applying ultrasonic results. As it was discussed, the most important factor in propagation of drilling induced delamination is thrust force. Therefore great reduction in delamination damage in ultrasonic assisted tests may be attributed to the reduction in thrust force.

4. Conclusion

A setup for making holes in composite laminates was designed and fabricated which was capable of giving rotation and ultrasonic vibration to drill bits. It was concluded that increasing vibration amplitude may thrust force and delamination damage significantly. The results of ultrasonic-assisted drilling were compared with conventional drilling results. This comparison showed applying ultrasonic vibrations during drilling GFRP laminate may reduce the drilling thrust force and drilling-induced delamination up to 50 per cent. It was observed that using ultrasonic vibration is an effective method to improve hole quality in drilling of GFRP laminates.

Acknowledgments

The support given by the Centre of Excellence in Design, Robotics and Automation, Sharif University of Technology is greatly appreciated. The authors would also like to acknowledge the support given by University of Malaya and the Ministry of Higher Education, Malaysia with the high impact research (HIR) grant number of HIR-MOHE-16001-00-D000027.

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