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Rotary ultrasonic machining of CFRP using cold air as coolant: feasible regions

W.L. Cong, Z.J. Pei [*], T.W. Deines
Department of Industrial and Manufacturing Systems Engineering,
Kansas State University,
Manhattan, KS 66506, USA

C. Treadwell
Sonic-Mill, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA

Keywords:

Carbon fiber reinforced plastic composite, Cold air, Drilling, Feasible region, Rotary ultrasonic machining, Vortex tube.

Abstract

Carbon fiber reinforced plastic (CFRP) composites are attractive for a variety of applications due to their superior properties. Drilling is involved in many CFRP applications. Experiments have been successfully conducted to use rotary ultrasonic machining (RUM) for CFRP drilling. These experiments were conducted using either cutting fluids or cold air as coolant. RUM of CFRP

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[*] Corresponding author. Tel.: +1 785 532 3436; fax: +1 785 532 3738.

E-mail address: zpei@ksu.edu (Z.J. Pei).

composites without cutting fluids can eliminate problems caused by cutting fluids, such as high cost of cutting fluids and their disposal, pollution to the environment, and harm to human health. However, dry machining (machining without cutting fluids) also has its limitations, such as burning of machined surface, more friction and adhesion between tool and workpiece, and reduction in tool life. This paper presents an experimental study on feasible regions in rotary ultrasonic machining of CFRP using cold air as coolant. Three criteria (burning of machined surface, delamination, and tool blockage) were used to determine feasible regions. Each of four input variables (feedrate, tool rotation speed, ultrasonic power, and cold air pressure) was changed over a wide range so that its feasible region could be found.

1 Introduction

Carbon fiber reinforced plastic (CFRP) composites have strong carbon fibers surrounded by a weaker plastic matrix. The fibers are to support the load. The matrix serves to distribute, hold, and protect the fibers and also to transmit the load to the fibers [Gay et al., 2003; Tong et al., 2002; Chung 2010].

Superior prosperities of CFRP composites include low density (lower than aluminum), high strength (as strong as high-strength steels), high stiffness (stiffer than titanium), good fatigue resistance, good creep resistance, low friction coefficient, good wear resistance, good toughness and damage tolerance, corrosion resistance, good dimensional stability (about zero coefficient of thermal expansion), and high vibration damping ability [Arul et al., 2006; Sadat, 1995; Davim and Reis, 2003; Lambert, 1987; Sadat, 1995; Guu et al., 2001; Chung, 2010; Mallick, 1997; Schwartz, 1992; Morgan, 2005].

Due to their superior properties, CFRP composites are attractive for a variety of applications. They are used in many types of structures including aircraft, spacecraft, automobile, ship, bridge, athletic equipment, and leisure goods. They are employed in engine blades, power transmission shafts, machine spindles, robot arms, pressure vessels, and chemical containers [Park et al., 1995; Ruegg and Habermeier, 1981; Gay et al., 2003; Guu et al., 2001; Arul et al., 2006; Sadat, 1995].

Drilling is involved in many CFRP applications. Rotary ultrasonic machining (RUM) has been successfully used in CFRP drilling with and without cutting fluids as coolant [Li et al., 2007; Cong et al., 2011a]. It is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 1 illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency (for example, 20 kHz) and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and keeps cutting temperature low.

Because cutting fluids have several detrimental effects, dry machining (machining without direct contact between cutting fluids and the tool-workpiece interface) is preferred when possible. The advantages of dry machining include less or no pollution to the environment as well as reduced cost in disposal of chips and cutting fluids. Deployment of cutting fluids counts for about 7-17% of the total cost of machining, while cutting tools count for only approximately 2-4% [Klock and Eisenblatter, 1997]. It is estimated that over 380 million liters of cutting fluids are used annually in the US and 1.2 million US workers are exposed to cutting fluids each year [Byers, 1994]. Some cutting fluids might be harmful to human health [Sreejith and Ngoi, 2000].

However, dry machining can potentially cause burning of machined surface, more friction and adhesion between tool and workpiece, reduction in tool life, noise of compressed air flow, ribbon-like chips which can lead to tool jam and high surface roughness [Liu and Hu, 1997; Sreejith and Ngoi, 2000; Nguyen and Zhang, 2003].

Experiments have been conducted to use cold air (instead of cutting fluids) as coolant in RUM of CRFP. Effects of input variables (ultrasonic power, tool rotation speed, and feedrate) on cutting force, torque, surface roughness, and machined surface burning were studied [Cong et al., 2011a]. However, some values of these input variables were not feasible for practical use because they resulted in burning of machined surface, or workpiece delamination, or tool (core drill) blockage. It is desirable to know what values of each input variable are feasible. In the current literature, there are no reports on feasible regions of these input variables.

This paper reports an experimental study on feasible regions for RUM of CFRP using cold air as coolant. Three criteria (burning of machined surface, delamination, and tool blockage) were used to determine the feasible regions for each of the input variables (feedrate, tool rotation speed, ultrasonic power, and cold air pressure). There are four sections in this paper. Following this introduction section, Section 2 describes experimental conditions, workpiece material properties, and measurement procedures. Section 3 presents and discusses experimental results. Finally, conclusions are summarized in Section 4.

2 Experimental conditions and evaluation criteria

2.1 Experimental set-up

Drilling experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 2. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was mainly comprised of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) AC output. This high frequency electrical energy was provided to a piezoelectric converter (located inside the ultrasonic spindle) that converted electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and transmitted to the rotary tool. This caused the diamond tool attached to the spindle to vibrate in the direction perpendicular to the tool end face at 20 thousand times per second. The amplitude of ultrasonic vibration was adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the motor speed controller. The cooling system mainly included a vortex tube, air compressor, pressure regulator and valve, and pressure meters. It provided cold air to the spindle and the cutting interface.

The cold air in this study was generated by a vortex tube (VT). As illustrated in Figure 3, VT is a simple mechanical device without any moving components. It separates a stream of compressed air into a hot and a cool branch [Ahlborn et al., 1994]. Compressed air is injected into a swirl chamber and accelerates to a high rotation rate. Due to the conical nozzle at the end of the tube, only the outer shell of the compressed air is allowed to escape at that end. The remainder of the air is forced to return in an inner vortex of a reduced diameter within the outer vortex. The hot air comes out of one end of the tube and cold air out of the other. A small control valve at the hot end, adjustable with the control valve, is used to control the air volume and temperature released from the cold end [Liu and Chou, 2005 & 2007; AiRTX 2010; Hilsch, 1947; Cong et al., 2008].

Metal-bonded diamond core drills (NBR Diamond tool corp., LaGrangeville, NY, USA), as illustrated in Figure 4, were used. The outer and inner diameters (OD and ID) of the drills were 9.54 mm and 7.82 mm, respectively, and the tuning length was 45 mm. The diamond abrasives had mesh size of 60/80 and concentration of 100. The metal bond was of B type.

2.2 Workpiece size and material properties

The size of workpiece was 200 mm × 150 mm × 16 mm. The workpiece material was carbon fiber reinforced plastic (CFRP) composite, as illustrated in Figure 5. It was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers with an orientation of 0/90 degrees was used. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fibers. Workpiece material properties are listed in Table 1.

2.3 Experimental conditions

On the basis of the experience from preliminary experiments and due to the limitations of the experimental set-up (for example, vibration frequency was fixed at 20 kHz on the machine), the experiments were focused on the study of the following input variables:

- Tool rotation speed: Rotational speed of tool;
- Feedrate: Feedrate of tool;

- Ultrasonic power: Percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude;
- Cold air pressure: Pressure of cold air at cold outlet of VT.

These input variables and their values are shown in Table 2. Four holes were drilled under each machining condition. Only two levels of cold air pressure, 40 psi and 50 psi, were used in the experiments, because the cooling system could not endure any air pressure higher than 50 psi. Furthermore, when cold air pressure was lower than 40 psi, feasible regions became very small.

2.4 Criteria of feasible regions

Feasible regions were determined by three criteria:

- **Burning** sometimes happened on machined hole surfaces. During machining, the epoxy resin could be burned if cutting temperature was higher than a certain value. Burning of machined surface could result in many problems, such as higher surface roughness, lower hole accuracy, and lower strength [Rawat and Attia, 2009; Liu and Hu, 1997; Sreejith and Ngoi, 2000; Nguyen and Zhang, 2003].
- **Delamination** was caused by splitting or separating of a laminate into layers. It was one of the principle damages often observed when drilling of laminate composite materials. Figure 6 illustrates delamination damage (peel-up and push-down delamination) in

composite material at the entrance and exit of the hole drilled by RUM. Delamination damage could result in lower hole accuracy, reduced tolerance, and lower strength [Campos Rubio et al, 2008ab; Jain and Yang, 1994; Stone and Krishnamurthy, 1996; Gaitonde et al., 2007; Paulo Davim et al., 2003 & 2007].

- **Tool blockage** would happen if the machined rod was stuck inside the core of the drill during RUM drilling process. Figure 7 shows tool blockage during RUM of CFRP. Tool blockage could lead to tool breakage.

Each of the input variables in Table 2 was tested over a wide range. If one of these three criteria (burning of machined surface, workpiece delamination, and tool blockage) occurred under a value of an input variable, this value was marked as outside the feasible regions.

3 Experimental results

3.1 Feasible regions of tool rotation speed and feedrate

Figure 8 shows the feasible regions of tool rotation speed and feedrate. The range of tool rotation speed was from 500 to 6000 rpm and the range of feedrate was from 0.1 to 0.9 mm/s. The ultrasonic power was set at 40%.

Figure 8(a) shows the feasible region with cold air pressure of 40 psi. When tool rotation speed was 1000 rpm or lower, dry machining was not feasible at any level of feedrate. Tool blockage (indicated by letter “T” in Figure 8) happened under all of these conditions. Burning (indicated by letter “B” in Figure 8) could be observed on most of machined holes. Holes drilled with higher feedrate always had delamination (indicated by letter “D” in Figure 8). When tool rotation speed was 4000 rpm, dry machining was feasible at all levels of feedrate. At other levels of tool rotation speed (instead of 500, 1000, and 4000 rpm), dry machining was feasible at some levels of feedrate. For example, dry machining was feasible when tool rotation speed was 3000 or 5000 rpm and feedrate was from 0.1 to 0.7 mm/s, when tool rotation speed was 2000 rpm and feedrate was 0.1 or 0.3 mm/s, as well as when tool rotation speed was 6000 rpm and feedrate was 0.5 or 0.7 mm/s. Burning was the primary limiting criterion under these conditions, although workpiece delamination and tool blockage also occurred under some conditions.

Figure 8(b) shows the feasible region with cold air pressure of 50 psi. The feasible region was larger than that with cold air pressure of 40 psi. When tool rotation speed was from 3000 to 5000 rpm, dry machining was feasible at all levels of feedrate. However, when tool rotation speed was 1000 rpm or lower, dry machining was not feasible when feedrate = 0.1 mm/s and tool rotation speed = 1000 rpm). When tool rotation speed was 2000 rpm, dry machining was feasible only when feedrate was from 0.1 to 0.5 mm/s. When tool rotation speed was 6000 rpm, dry machining was feasible at all levels of feedrate except 0.1 mm/s.

3.2 Feasible regions of ultrasonic power and feedrate

Figure 9 shows feasible regions of ultrasonic power and feedrate. Ultrasonic power was changed from 0 to 100% with an interval of 20%, feedrate was changed from 0.1 to 0.9 mm/s with an interval of 0.2 mm/s, and tool rotation speed was set at 3000 rpm.

With cold air pressure of 40 psi, dry machining was feasible when ultrasonic power ≤ 60% and feedrate ≤ 0.7 mm/s. A combination of high feedrate (0.9 mm/s) and low ultrasonic power (≤ 40%) or a combination of low feedrate and high ultrasonic power would cause burning of machined surface or tool blockage. The feasible region became large when cold air pressure was increased from 40 to 50 psi.

3.3 Feasible regions of tool rotation speed and ultrasonic power

Figure 10 shows feasible regions of tool rotation speed and ultrasonic power. The range of tool rotation speed was from 500 to 6000 rpm with an interval of 1000 (except 500 from 500 to 1000), the range of ultrasonic power was from 0% to 100% with an interval of 20%, and feedrate was fixed at 0.5 mm/s.

When tool rotation speed was ≥ 3000 rpm, dry machining was feasible under most conditions except when ultrasonic power = 100% and tool rotation speed = 3000 or 6000 rpm and when ultrasonic power = 0 and tool rotation speed ≥ 5000 rpm (these combinations would result in burning of machined workpiece). When tool rotation speed was ≤ 2000 rpm, dry machining was only feasible when tool rotation speed = 2000 rpm and ultrasonic power = 60% or 80%. Other conditions would cause burning of machined surface, or burning and tool blockage, or burning and tool blockage and workpiece delamination. The feasible region became large when cold air pressure was increased from 40 to 50 psi. With cold air pressure of 50 psi, dry machining was feasible when tool rotation speed ≥ 2000 rpm (at all levels of ultrasonic power).

4 Conclusions

This paper reports an experimental study on rotary ultrasonic machining of CFRP using cold air as coolant. The aim of this study is to determine the feasible regions of input variables. The following conclusions are drawn from this study:

(a) Higher cold air pressure led to larger feasible regions.

(b) Dry machining was not feasible when tool rotation speed was too low (≤ 2000 rpm) regardless of what levels of feedrate and ultrasonic power.

(c) Dry machining was not feasible when high ultrasonic power (≥ 80%) combined with low feedrate (≤ 0.7 mm/s).

The work report in this paper was experimental. In the future, fundamental research will be conducted to understand the mechanisms of these experimental results. For example, hypotheses will be proposed to explain why higher air pressure led to larger feasible regions. One hypothesis would be that higher air pressure reduces cutting temperature and lower temperature allows feasible regions to become larger. In order to test this hypothesis, cutting temperature will be measured with different levels of air pressure. Cutting temperature in rotary ultrasonic machining of titanium has been measured [Cong et al., 2011b] and the same measurement method can be used for the proposed fundamental research.

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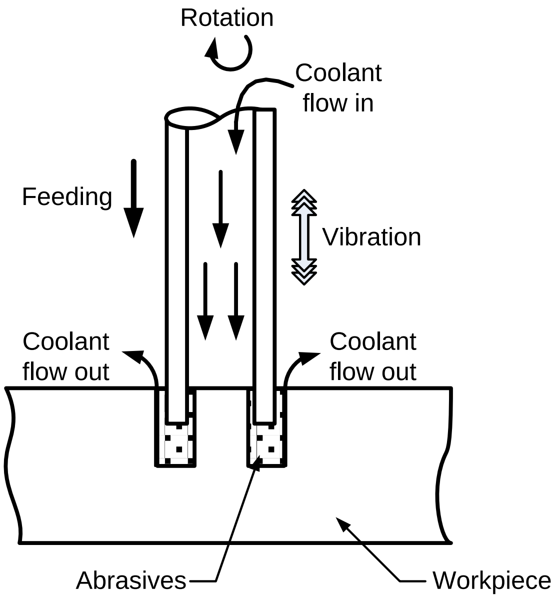


Figure 1 Illustration of rotary ultrasonic machining.

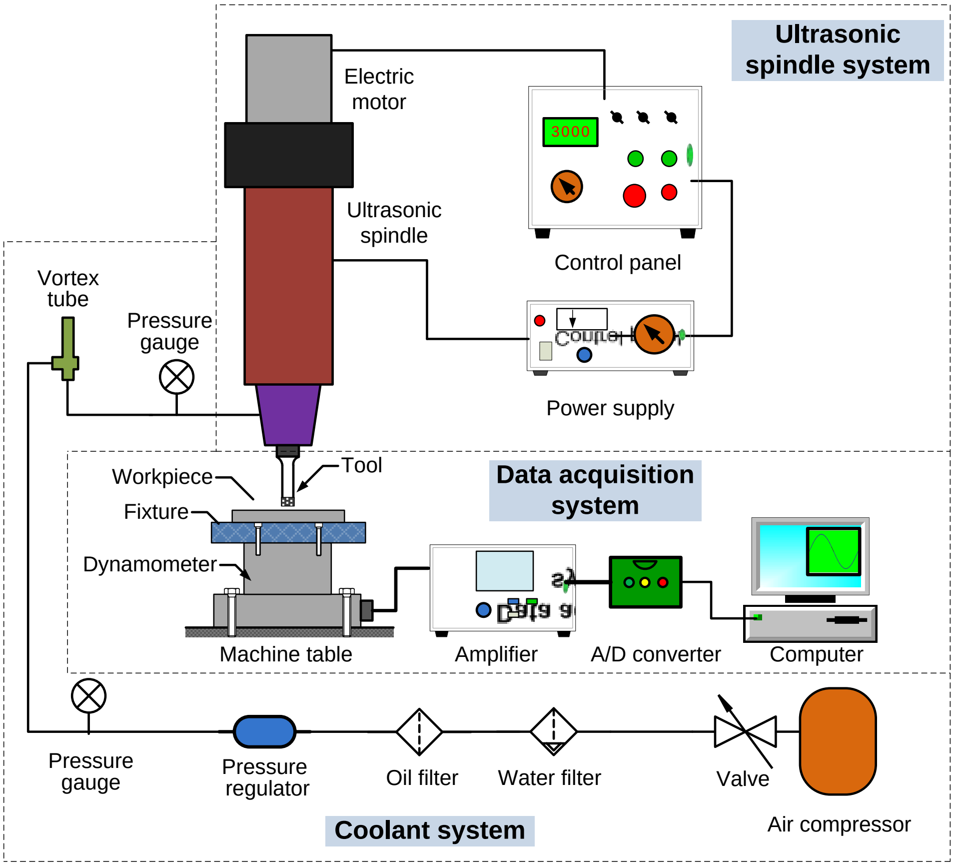


Figure 2 Illustration of experimental set-up.

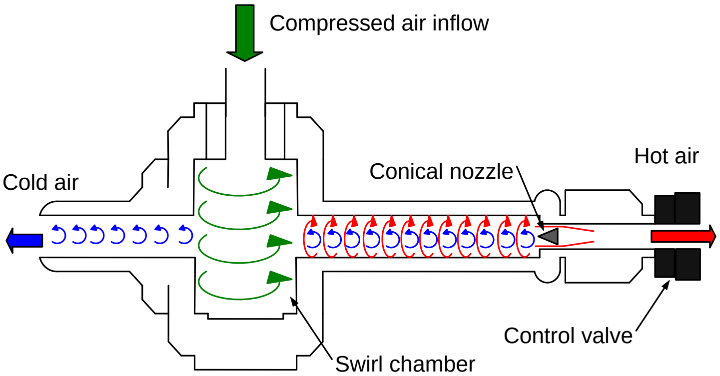


Figure 3 Illustration of vortex tube (after [AiRTX, 2008; Hilsch, 1947; Cong et al., 2008]).

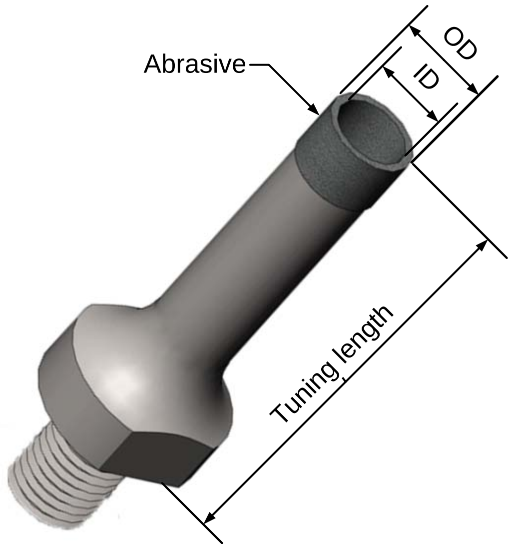


Figure 4 Illustration of a metal-bonded diamond core drill.

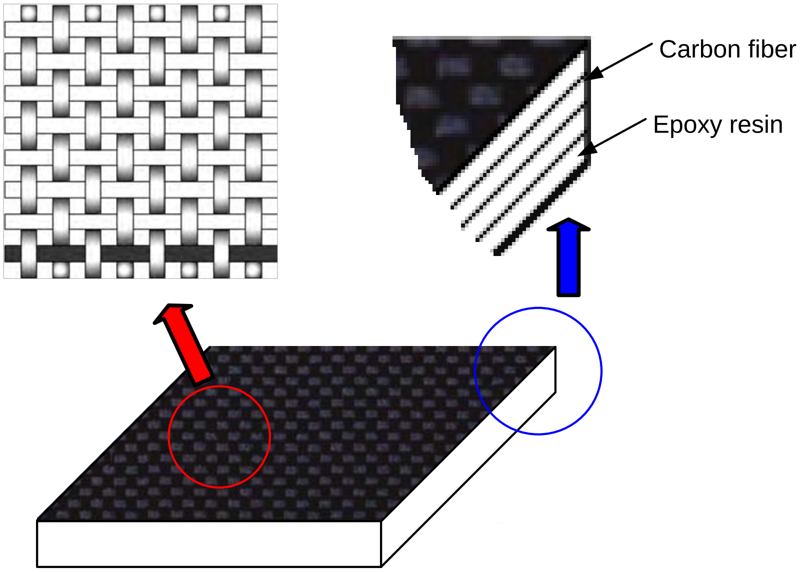


Figure 5 Illustration of CFRP.

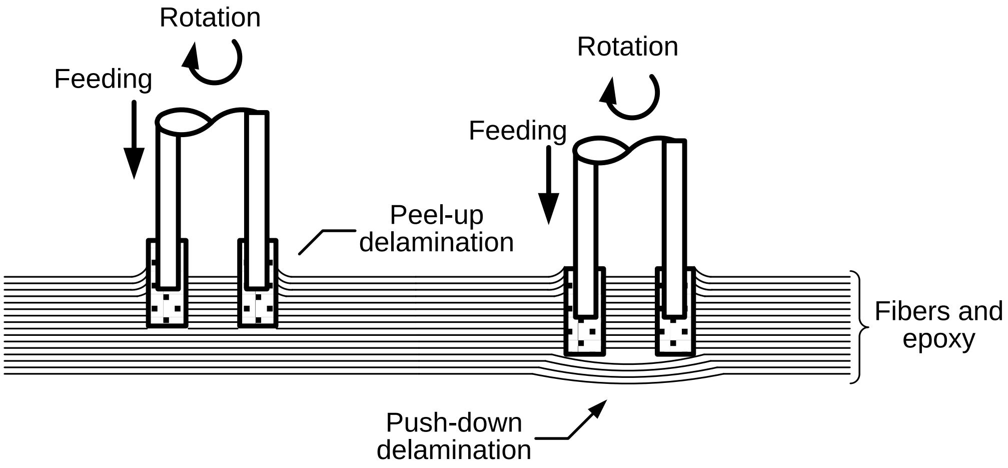


Figure 6 Illustration of delamination.

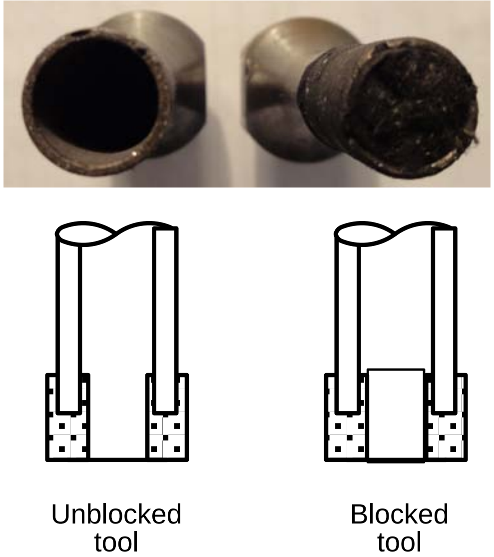
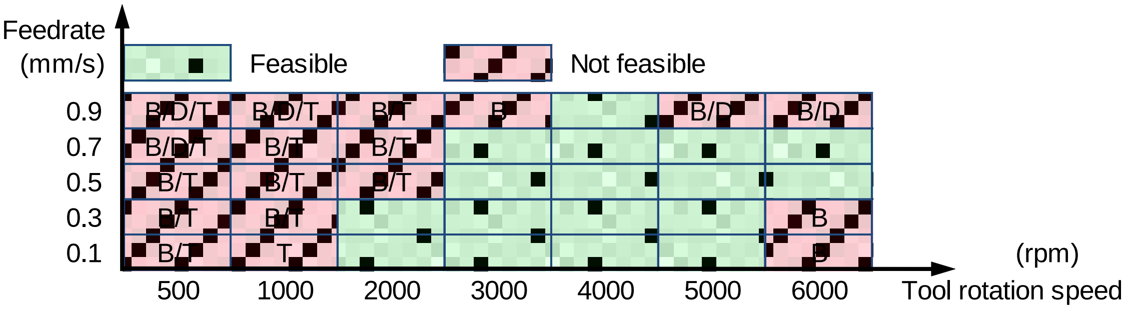
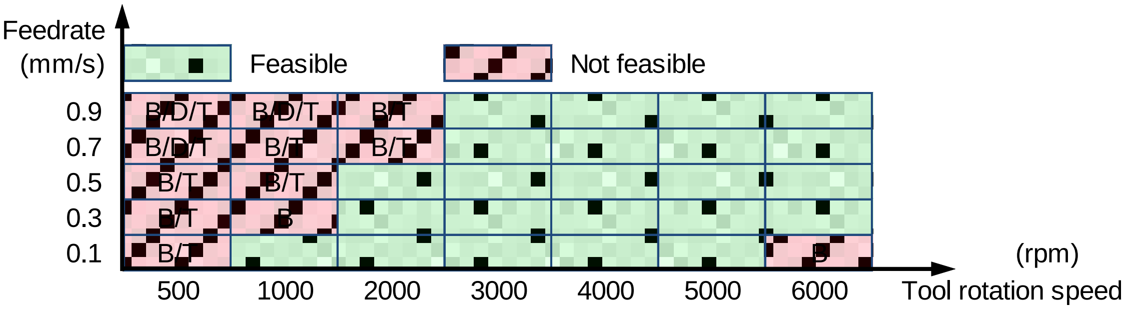


Figure 7 Illustration of tool blockage.



Feedrate (mm/s)	500	1000	2000	3000	4000	5000	6000
0.9	B/D/T	B/D/T	B/T	B		B/D	B/D
0.7	B/D/T	B/T	B/T				
0.5	B/T	B/T	B/T				
0.3	B/T	B/T					B
0.1	B/T	T					B

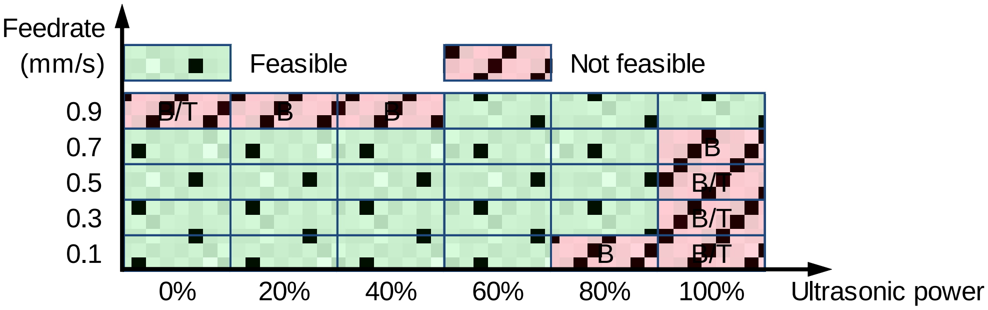
(a) Cold air pressure = 40 psi.



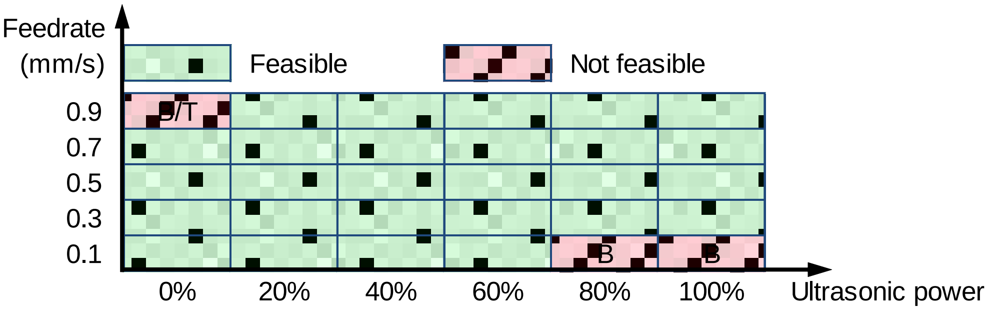
Feedrate (mm/s)	500	1000	2000	3000	4000	5000	6000
0.9	B/D/T	B/D/T	B/T				
0.7	B/D/T	B/T	B/T				
0.5	B/T	B/T					
0.3	B/T	B					
0.1	B/T						B

(b) Cold air pressure = 50 psi.

Figure 8 Feasible regions of tool rotation speed and feedrate.

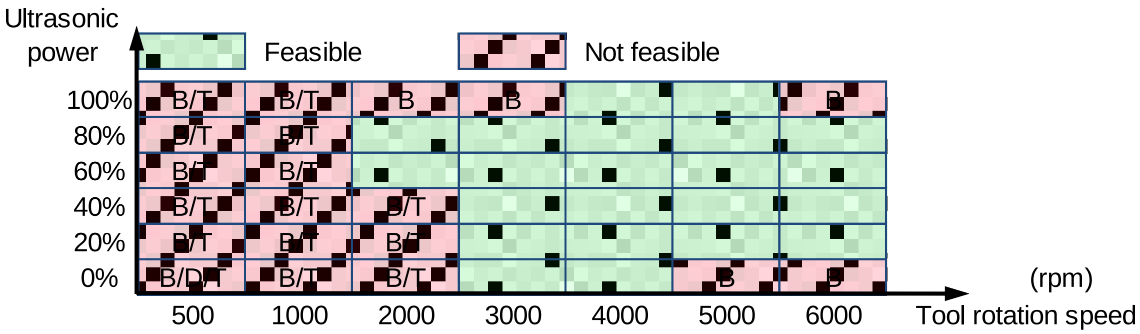


(a) Cold air pressure = 40 psi.



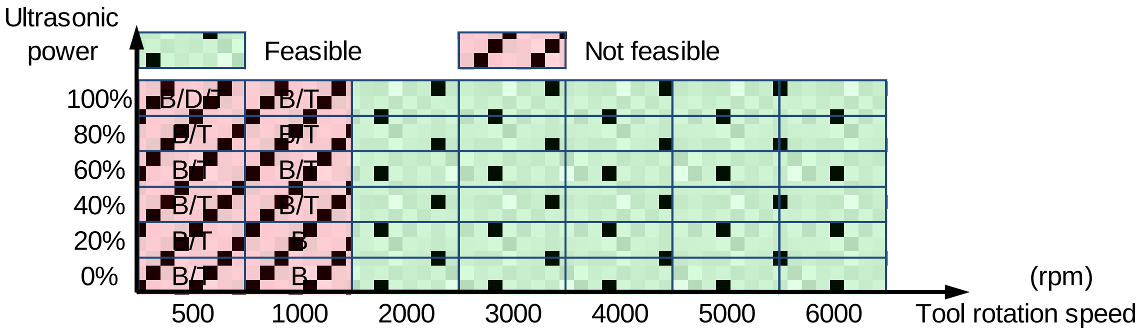
(b) Cold air pressure = 50 psi.

Figure 9 Feasible regions of ultrasonic power and feedrate.



Ultrasonic power	500	1000	2000	3000	4000	5000	6000
100%	🟥 B/T	🟥 B/T	🟥 B	🟥 B	🟩	🟩	🟥 B
80%	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
60%	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
40%	🟥 B/T	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩
20%	🟥 B/T	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩
0%	🟥 B/D/T	🟥 B/T	🟥 B/T	🟩	🟩	🟥 B	🟥 B

(a) Cold air pressure = 40 psi.



Ultrasonic power	500	1000	2000	3000	4000	5000	6000
100%	🟥 B/D/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
80%	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
60%	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
40%	🟥 B/T	🟥 B/T	🟩	🟩	🟩	🟩	🟩
20%	🟥 B/T	🟥 B	🟩	🟩	🟩	🟩	🟩
0%	🟥 B/T	🟥 B	🟩	🟩	🟩	🟩	🟩

(b) Cold air pressure = 50 psi.

Figure 10 Feasible regions of tool rotation speed and ultrasonic power.

Table 1. Workpiece material properties.

Property	Unit	Value
Density	kg/m^3	1550
Hardness (Rockwell)	HRB	70-75
Elastic modulus of epoxy matrix	GPa	2.06 - 2.15
Tensile strength of epoxy matrix	MPa	80 - 85
Elastic modulus of carbon fiber	GPa	75 - 80
Tensile strength of carbon fiber	MPa	400 - 450

Table 2. Input variables and their values.

Variable	Value
Ultrasonic power (%)	0; 20; 40; 60; 80
Tool rotation speed (rpm)	500; 1000; 2000; 3000; 4000; 5000; 6000
Feedrate (mm/s)	0.05; 0.1; 0.3; 0.5; 0.7; 0.9
Cold air pressure (psi)	40; 50
Cold air flow rate (lpm)	1.5

Table 3 Tool parameters and their values.

Parameter	Value
Outer diameter (mm)	9.6
Inner diameter (mm)	7.8
Tuning length (mm)	4.45
Grit size (mesh #)	60/80
Concentration	100
Number of slots	0
Bond type	B