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Rotary ultrasonic machining of CFRP/Ti stacks using variable feedrate

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Abstract

Rotary ultrasonic machining (RUM) has been successfully used to drill Ti (titanium and its alloy), CFRP, and CFRP/Ti stacks. In all studies on RUM reported in the literature, feedrate was fixed during each experimental test. It has been shown that low feedrate should be used for RUM of Ti, but RUM of CFRP could be done using feedrate ten times higher. This paper, for the first time, reports a study on RUM of CFRP/Ti stacks using variable feedrate (high feedrate for CFRP and low feedrate for Ti). It also makes comparisons on RUM of CFRP/Ti stacks using fixed and variable feedrate.

1. Introduction

To decrease fuel consumption, increase aircraft life, and save maintenance cost, carbon fiber reinforced plastic (CFRP) composites are increasingly used in the aircraft industry [Denkena et al., 2008; Davim and Reis, 2003, Lambert, 1987; Sadat, 1995; Guu et al., 2001; Chung, 2010] [Borchure, 2009; Mangalgiri, 1999; Cookson, 2009; Denkena et al., 2008; Garrick, 2007; Kanirura, 2005]. In aircraft assembly, bolting and riveting are currently the preferred methods for fastening CFRP and Ti structural parts [Bennett, 1985, Ramulu et al., 2001; Shyha 2010]. As a result, a large number of holes need to be drilled in CFRP/Ti stacks [Shyha 2010; Boeing web, Zitoune et al., 2010; Ramulu et al., 2001; Massarweh et al, 1992; Shyha 2010; Lambert, 1979].

Problems in drilling of CFRP/Ti stacks using traditional methods include high cutting force and torque [Ramulu et al., 2001; Lambert, 1979] and high tool wear [Lambert, 1979; Ramulu et al., 2001; Weiss 1989], large exit Ti burr [Kim et al., 2001; Ramulu et al., 2001] and composite delamination [Ramulu et al., 2001; Davim and Reis 2003], large groove depth in composite [Weiss 1989], and poor hole quality [Kim et al., 2001; Ramulu et al., 2001]. Rotary ultrasonic machining (RUM) could be a solution to overcome these problems. RUM is illustrated in Figure 1. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf, and prevents the tool from jamming and overheating.

RUM has been successfully used to drill Ti [Churi et al. 2005, 2006, 2007ab; Cong et al., 2011_Ti], CFRP [Li et al. 2007; Cong et al, 2011, 2012ab], and CFRP/Ti stacks [feasibility study]. In all studies on RUM reported in the literature, feedrate was fixed during each experimental test. It has been shown that, in order to achieve good quality and reasonable tool life, low feedrate (below 0.05 mm/s) should be used in RUM of Ti [Cong et al., 2011a], but feedrate in RUM of CFRP could be ten time higher [Cong et al., 2011bc; 2012ab]. When RUM of CFRP/Ti stacks, if a fixed low feedrate is used, cycle time will be too long; if a fixed high feedrate is used, tool life will be too short. A solution to this dilemma is to use variable feedrate (high feedrate for CFRP and low feedrate for Ti). This paper presents results of such a study. It also makes comparisons on RUM of CFRP/Ti stacks using fixed feedrate and variable feedrate.

There are four sections in this paper. Following this introduction section, Section 2 describes workpiece material properties, experimental set-up, and measurement procedures. Section 3 presents and discusses experimental results. Finally, Section 4 draws conclusions.

2. Experiments

2.1. Properties of workpiece materials

CFRP/Ti stacks used in this study were formed by joining a CFRP plate (108 mm × 58 mm × 14

mm) and a Ti plate (108 mm × 58 mm × 7 mm) together using adhesive (Ultra Bond super glue, Permatex Inc., Solon, OH, USA). The CFRP was composed of carbon fibers and epoxy resin matrix. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, as illustrated in Figure 2. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The CFRP contained 21 layers of fabric (42 layers of carbon fiber). The Ti workpiece material was titanium alloy (Ti-6Al-4V). Material properties of CFRP and Ti are listed in Table 1 and Table 2, respectively.

2.2. Experimental set-up

Experiments were performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 3. It mainly consisted of an ultrasonic spindle system, a data acquisition system, and a coolant system. The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply, an electric motor, and a control panel. The power supply converted conventional (60 Hz) electrical supply to high-frequency (20 kHz) electrical energy. This high-frequency electrical energy was provided to a piezoelectric converter that changed high-frequency electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and transmitted to the cutting tool. This caused the cutting tool to vibrate axially at the frequency of 20 kHz. The amplitude of ultrasonic vibration could be adjusted by changing the level of output control of the power supply. The motor atop the ultrasonic spindle supplied the rotational motion of the tool and

different speeds could be obtained by adjusting the motor speed controller on the control panel.

The data acquisition system, including dynamometer, charge amplifier, A/D convertor, and

computer with software, was used for measurement of cutting force and torque. More details

about this system will be described in Section 2.4 (measurement procedures). The coolant system

was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and

valves. The coolant system provided coolant to the spindle and the interface of machining.

The cutting tools, as illustrated in Figure 4, were metal-bonded diamond core drills (N.B.R.

Diamond Tool Corp., LaGrangeville, NY, USA). The outer and inner diameters (OD and ID) of

the cutting tools were 9.54 mm and 7.82 mm, respectively, and the tuning length was 45 mm.

The diamond abrasives had mesh size of 80/100 and concentration of 100. The metal bond was

of B type.

2.3. Experimental conditions

Considering the limitations of the experimental set-up (for example, vibration frequency was

fixed at 20 kHz on the machine), only the following input variables were changed in the

experiments:

- Ultrasonic power: Percentage of power from ultrasonic power supply to control the ultrasonic

vibration amplitude;

- Tool rotation speed: Rotational speed of cutting tool;

- Feedrate: Feedrate of cutting tool.

    Values of these input variables used in this study are listed in Table 3.

Two types of feedrate were used. If using fixed feedrate, the entire hole was drilled using a feedrate of 0.05 mm/s. If using variable feedrate, feedrate of 0.5 mm/s was used to drill CFRP and feedrate of 0.05 mm/s was used to drill Ti. Feedrate was changed from 0.5 mm/s to 0.05 mm/s during a period of 10 s towards the end of CFRP machining. Figure 5 compared these two different types of feedrate as a function of feeding depth (the distance between workpiece top surface and tool-workpiece interface, as illustrated in Figure 6).

2.4. Measurement procedures

A dynamometer (Model 9272, Kistler Inc., Winterthur, Switzerland) was used to measure the cutting force (Fz) in the axial direction and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Winterthur, Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynoware software (Type 2815A, Kistler Inc., Winterthur, Switzerland). The sampling rate was

20 Hz. The measured cutting force fluctuated with time within a certain range, as illustrated in Figure 7. The maximum cutting force of the cutting force-time curve was used to represent the cutting force for drilling of each hole. Similarly, the maximum torque of the torque-time curve was used to represent the torque for drilling of each hole. It is noted that the maximum cutting force and torque were obtained during drilling Ti for both types of feedrate.

In this paper, tool wear was defined as the weight loss of the cutting tool during each test. It was the difference between tool weights before and after a test. To remove any residuals left on the tool, the tool was cleaned using methanol and acetone and then was dried using a hand dryer before measurement. The weight of the tool was measured by a high-accuracy scale (Model APX-200, Denver Instrument, Denver, CO, USA).

Surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used to measure surface roughness of the hole surface and groove depth. Surface roughness was measured on the machined surfaces of CFRP and Ti along the axial direction of the hole. The surface roughness reported in this paper was Ra (average surface roughness). The test range and cut-off length of surface roughness measurement were set at 4 mm and 0.8 mm, respectively. Groove depth (CFRP material near the interface between CFRP and Ti was overcut and a groove was formed) was measured on machined CFRP surface near the interface between CFRP and Ti. The details of measurement were illustrated in Figure 8. For both surface roughness and groove

depth, four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. For each hole, there were eight values and the average of these eight values was used.

3. Results and discussion

3.1. Cycle time

Cycle time was the period of time it took to drill a hole through a CFRP/Ti stack. Figure 9 shows a comparison of cycle time between using fixed and variable feedrate. Compared with cycle time of 426 s using fixed feedrate, cycle time using variable feedrate was about 200 s.

3.2. Cutting force

Figure 10 shows a comparison of cutting force between using fixed and variable feedrate at different levels of ultrasonic power. In Figure 10 (as well as Figures 11 − 19), each data point is the average value for the four holes drilled under one test condition. Error bars represent the minimum and maximum values among the four holes. It also can be seen from Figure 10 that cutting force using variable feedrate was lower than that using fixed feedrate at every level of ultrasonic power. The differences in cutting force between using fixed and variable feedrate were about the same when ultrasonic power was 0%, 20%, or 60%. When ultrasonic power was 40%, the largest difference occurred.

A comparison of cutting force between using fixed and variable feedrate at different levels of tool rotation speed is shown in Figure 11. Using fixed feedrate always led to higher cutting force than using variable feedrate at all levels of tool rotation speed. The differences in cuttings force between using fixed and variable feedrate were not the same at different levels of tool rotation speed. When tool rotation speed was 2000 rpm, the difference in cutting force between using fixed variable feedrate was the largest. When tool rotation speed was 7000 rpm, the difference in cutting force was smallest.

3.3. Torque

Figure 12 compares toque between using fixed and variable feedrate at different levels of ultrasonic power. Using fixed feedrate led to larger torque than using variable feedrate at all levels of ultrasonic power. Difference in torque between using fixed and variable feedrate reached the maximum when ultrasonic power was 20% and reached the minimum when ultrasonic power was 0%.

A comparison of torque between using fixed and variable at different levels of tool rotation speed is shown in Figure 13. At all levels of tool rotation speed, torque using variable feedrate was smaller than that using fixed feedrate except when the tool rotation speed was 7000 rpm where torque using variable feedrate was slightly larger than that using fixed feedrate. The difference in torque between using fixed and variable feedrate varied at different levels of tool rotation speed.

The difference in torque reached the maximum when tool rotation speed was 2000 rpm, and reached the minimum when tool rotation speed was 7000 rpm.

3.4. Tool wear

Figure 14 compares tool wear (tool weight loss) between using fixed and variable feedrate at different levels of ultrasonic power. When ultrasonic power was 0%, 20%, or 40%, tool weight loss using fixed feedrate was larger than that using variable feedrate. However, when ultrasonic power was 60%, tool weight loss using fixed feedrate was smaller than that using variable feedrate. The difference in tool wear between using fixed and variable feedrate reached the maximum when ultrasonic power was 0% and reached the minimum when ultrasonic power was 40%.

A comparison of tool wear (tool weight loss) between using fixed and variable feedrate at different levels of tool rotation speed is shown in Figure 15. When tool rotation speed was 2000 or 3000 rpm, tool wear using variable feedrate was larger than that using fixed feedrate. In contrast, when tool rotation speed was 4000 or 7000 rpm, the difference in tool wear was negligible; and when tool rotation speed was 5000 or 6000 rpm, tool wear using variable feedrate was larger than that using fixed feedrate. The difference in tool wear between using fixed and variable feedrate, tool wear using both fixed and variable feedrate, reached the maximum when tool rotation speed was 2000 rpm.

3.5. Surface roughness

Figure 16 (a) compares surface roughness on machined CFRP surface between using fixed and variable feedrate at different levels of ultrasonic power. Using variable feedrate led to higher surface roughness than using fixed feedrate at all levels of ultrasonic power. The difference in surface roughness between using fixed and variable feedrate was the smallest when ultrasonic power was 0% and largest when ultrasonic power was 60%.

Figure 16 (b) compares surface roughness on machined Ti surface between using fixed and variable feedrate at different levels of ultrasonic power. Using fixed feedrate led to higher surface roughness than using variable feedrate when ultrasonic power was 0% or 20%, whereas, using fixed feedrate led to lower surface roughness than using variable feedrate when ultrasonic power was 60%. Surface roughness using fixed feedrate was similar to that using variable feedrate when ultrasonic power was 40%. Difference in surface roughness between using fixed and variable feedrate at 0% of ultrasonic power was larger than that at 20%, 40%, or 60% of ultrasonic power.

Figure 17 (a) compares of surface roughness on machined CFRP surface between using fixed and variable feedrate at different levels of tool rotation speed. Surface roughness using fixed feedrate was lower than that using variable feedrate at all levels of tool rotation speed. The

difference in surface roughness between using fixed and variable feedrate was less than 1 μm. The maximum and minimum of difference were observed when tool rotation speed was 7000 and 4000 rpm, respectively.

Figure 17 (b) compares surface roughness on machined Ti surface between using fixed and variable feedrate at different levels of tool rotation speed. When tool rotation speed was 2000 rpm, using variable feedrate led to remarkably higher surface roughness than using fixed feedrate. When tool rotation speed was 3000 or 4000 rpm, surface roughness was similar using both types of feedrate. However, when tool rotation speed was from 5000 to 7000 rpm, using variable feedrate led to smaller surface roughness than using fixed feedrate.

3.6. Groove depth

A comparison of groove depth between using fixed and variable feedrate at different levels of ultrasonic power is shown in Figure 18. At each level of ultrasonic power, groove depth using variable feedrate was larger than that using fixed feedrate. The difference in groove depth between using fixed and variable feedrate decreased with the increase of ultrasonic power.

Figure 19 compares groove depth between using fixed and variable feedrate at different levels of tool rotation speed. At all levels of tool rotation speed, groove depth using variable feedrate was larger than that using fixed feedrate. The largest difference in groove depth between using fixed

and variable feedrate was at 2000 rpm, and the smallest difference was obtained when tool rotation speed was 6000 rpm where the values of groove depth overlapped using both types of feedrate.

4. Conclusions

This paper reports a study on rotary ultrasonic machining (drilling) of CFRP/Ti stacks - using variable feedrate (using a faster feedrate to drill CFRP and a slower feedrate to drill Ti). Comparisons between using fixed and variable feedrate at different levels of ultrasonic power and tool rotation speed have been made.

The following conclusions are drawn from this study:

(a) Cycle time using variable feedrate was shorter than that using fixed feedrate.

(b) Using variable feedrate led to a lower cutting force than using fixed feedrate at all levels of ultrasonic power and tool rotation speed. This was true for torque at all levels of ultrasonic power and all levels of tool rotation speed except for 7000 rpm.

(c) When ultrasonic power was low (0%, 20%, and 40%), using variable feedrate led to lower tool wear than using fixed feedrate. When tool rotation speed was 2000 rpm, using variable feedrate led to remarkably higher tool wear than using fixed feedrate

(d) Using variable feedrate always led to higher surface roughness on machined CFRP surface. When ultrasonic vibration was off, using variable feedrate resulted in

remarkably lower surface roughness on machined Ti surface than using fixed feedrate. When tool rotation speed was 2000 rpm, using variable feedrate led to higher surface roughness on machined Ti surface than using fixed feedrate.

(e) Using variable feedrate led to larger groove depth at all levels of ultrasonic power than using fixed feedrate.

Acknowledgements

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Table 1. Material properties of CFRP and its components.

Property	Unit	Value
Density of CFRP	kg/m^3	1550
Hardness (Rockwell)	HRB	70-75
Density of epoxy matrix	kg/m^3	1200
Elastic modulus of epoxy matrix	GPa	4.5
Tensile strength of epoxy matrix	MPa	130
Poisson's ratio of epoxy matrix		0.2
Density of carbon fiber	kg/m^3	1800
Elastic modulus of carbon fiber	GPa	230
Tensile strength of carbon fiber	GPa	5
Poisson's ratio of carbon fiber		0.3
Melting point of carbon fiber	°C	3552

Table 2. Material properties of titanium alloy (Ti-6Al-4V).

Property	Unit	Value
Density	kg/m^3	4510
Hardness (Rockwell)	HRC	36
Elastic modulus	GPa	113.8
Tensile strength	MPa	950
Melting point	°C	1660

Table 3. Input variables and their values.

Variable	Unit	Value
Ultrasonic power	%	0; 20; 40; 60
Tool rotation speed	rpm	2000; 3000; 4000; 5000; 6000; 7000
Feedrate	mm/s	0.05 (Fixed); 0.5 / 0.05 (Variable)
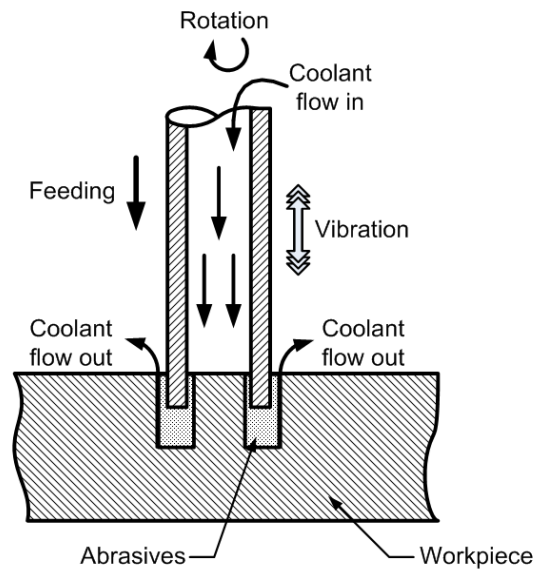
Figure 1 Illustration of rotary ultrasonic machining.
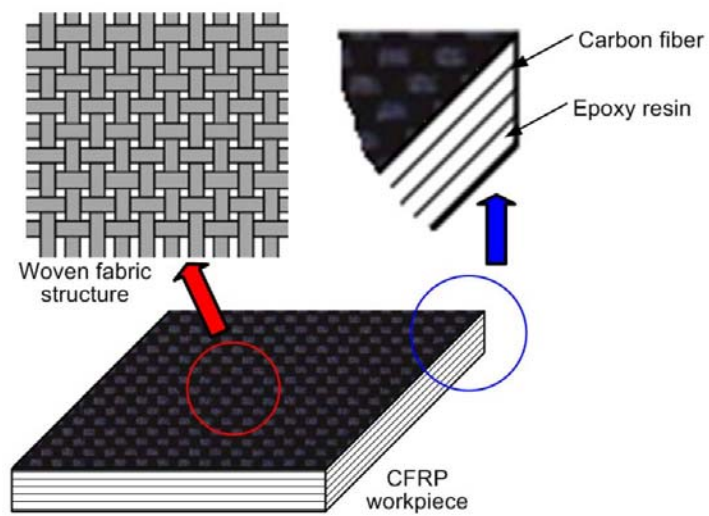
Figure 2 Illustrations of woven fabric and CFRP structures.
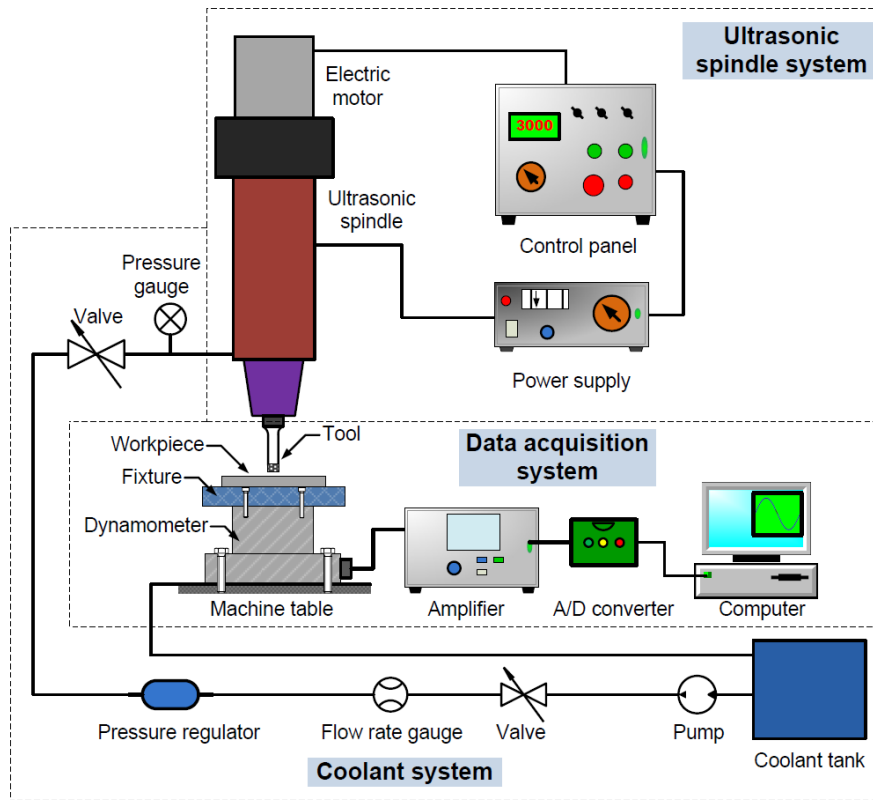
Figure 3 RUM experimental set-up.
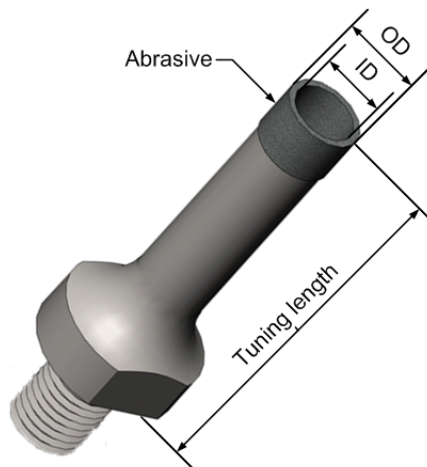
Figure 4 Illustration of RUM cutting tool.
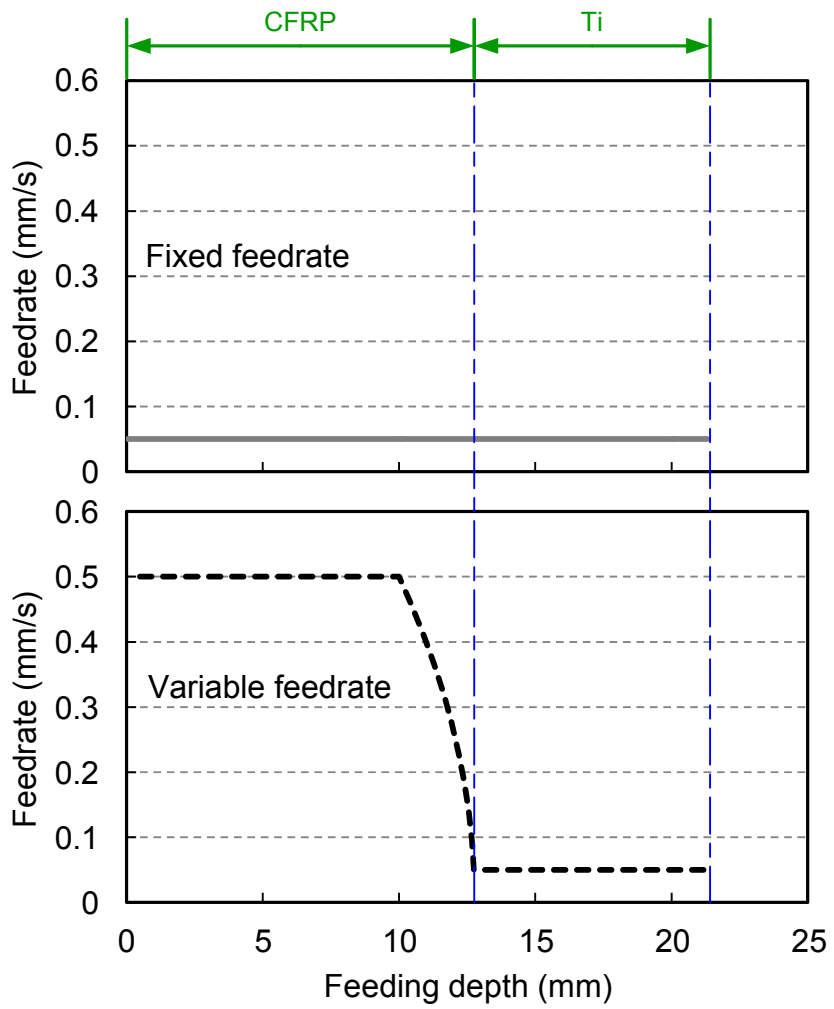
Figure 5 Illustrations of fixed feedrate and variable feedrate.
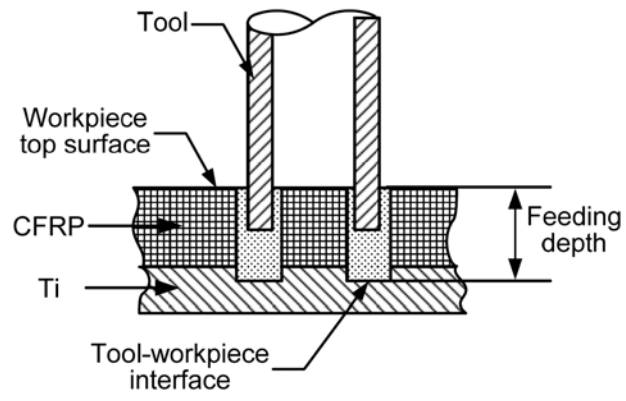
Figure 6 Illustration of feeding depth.
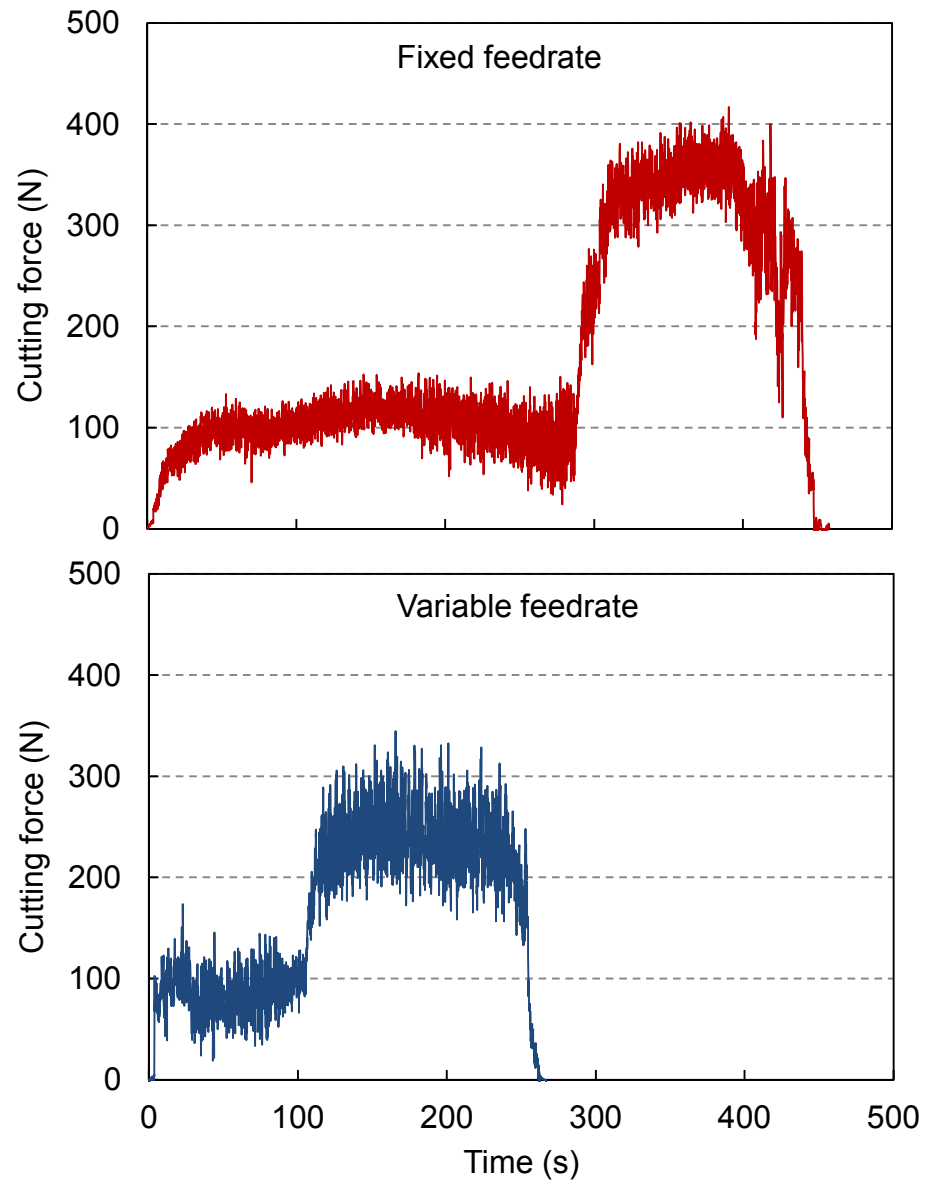
Figure 7 Typical cutting force-time curves using fixed and variable feedrate.

(a) CFRP surface roughness measurement
(b) CFRP groove depth measurement
(c) Ti surface roughness measurement
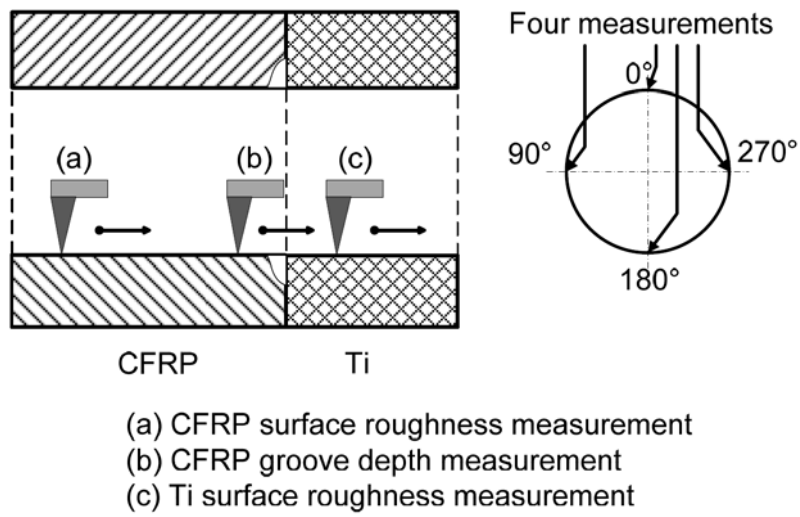
Figure 8 Surface roughness and groove depth measurements.
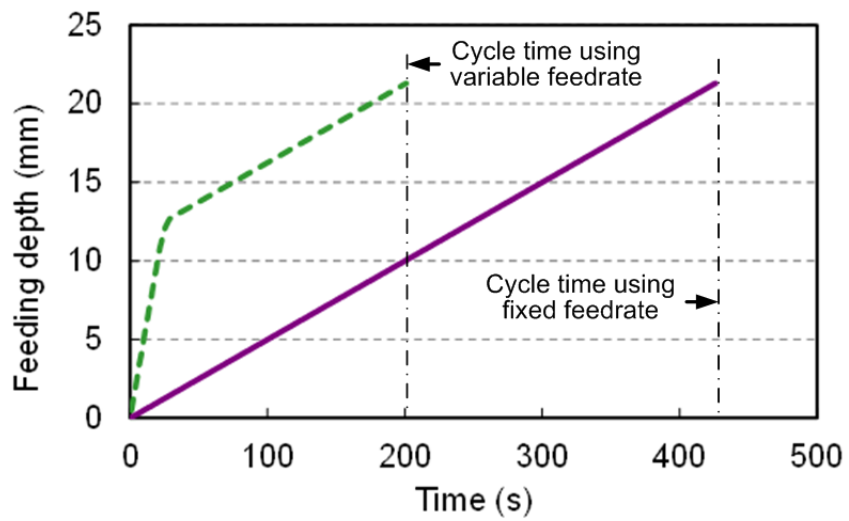
Figure 9 Comparison of cycle time.
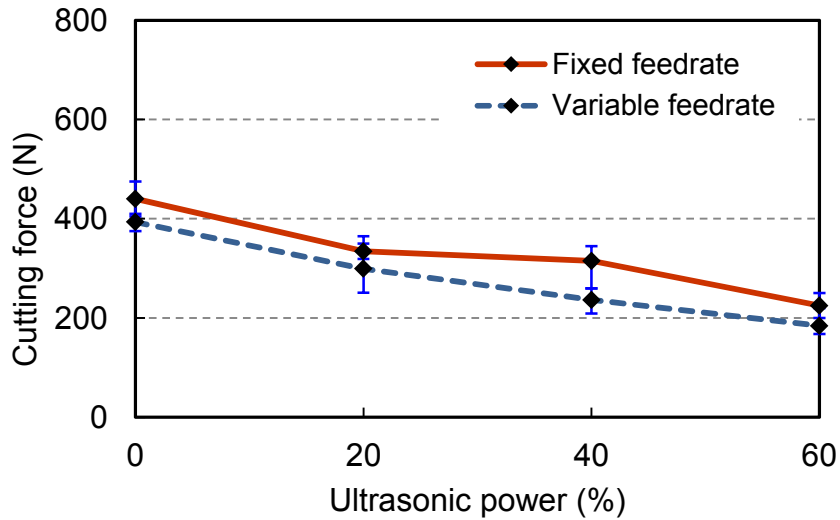
Tool rotation speed = 4000 rpm
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

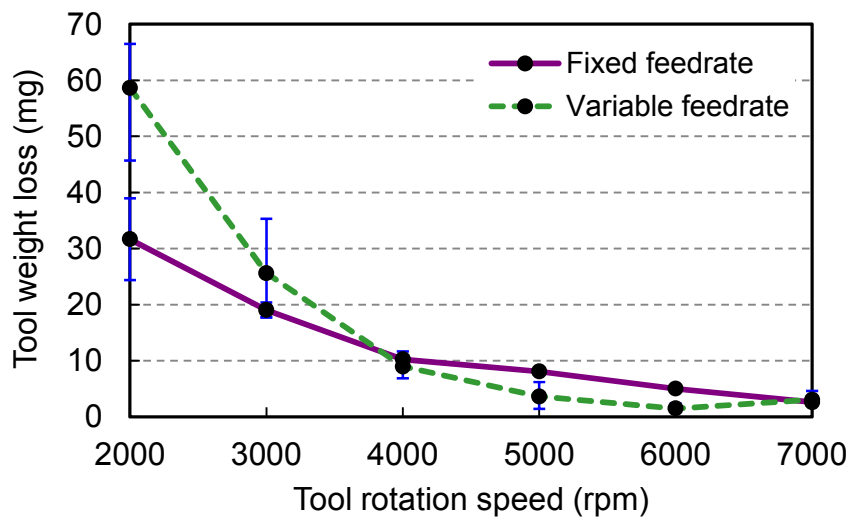Figure 10 Comparison of cutting force at different levels of ultrasonic power.
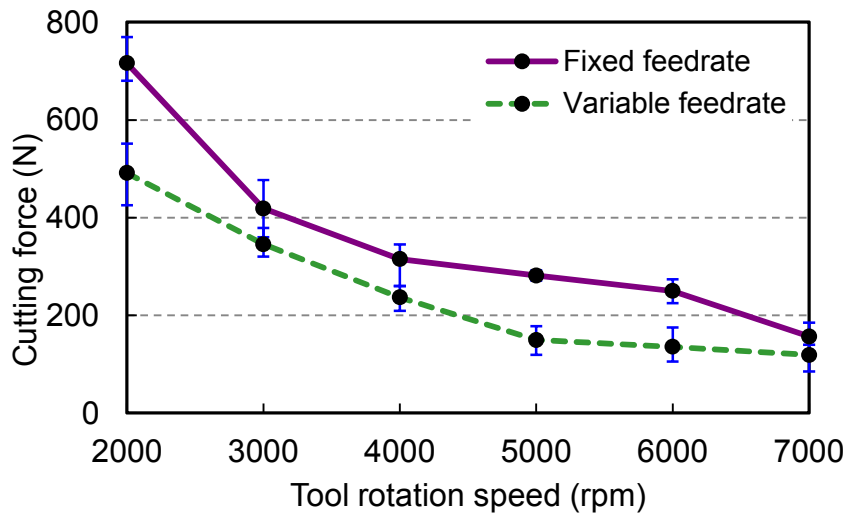
Ultrasonic power = 40%
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 11 Comparison of cutting force at different levels of tool rotation speed
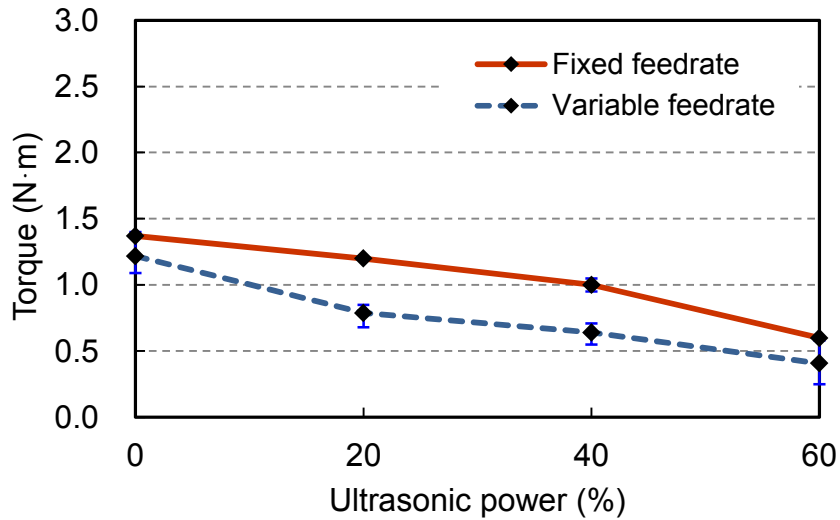
Tool rotation speed = 4000 rpm
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 12 Comparison of torque at different levels of ultrasonic power.
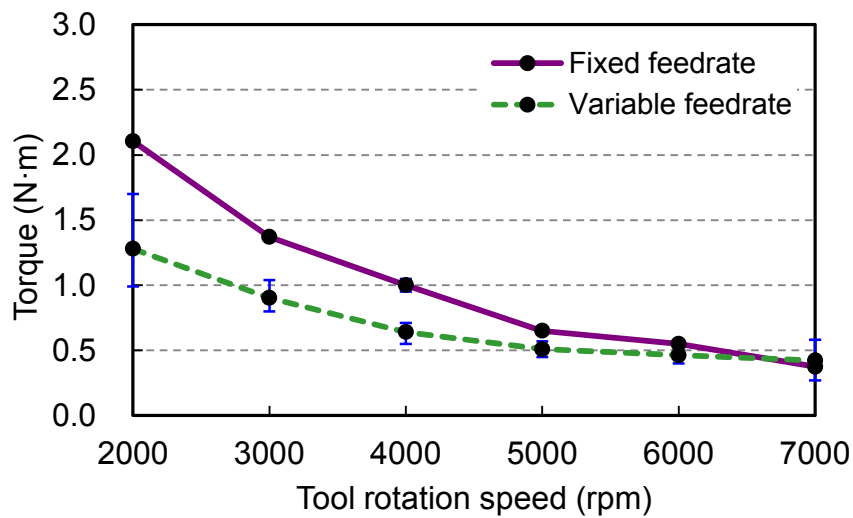
Ultrasonic power = 40%
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

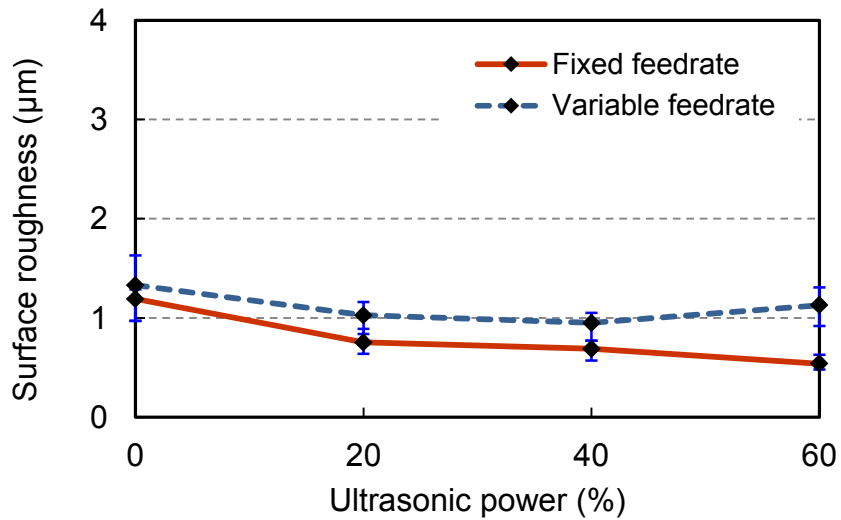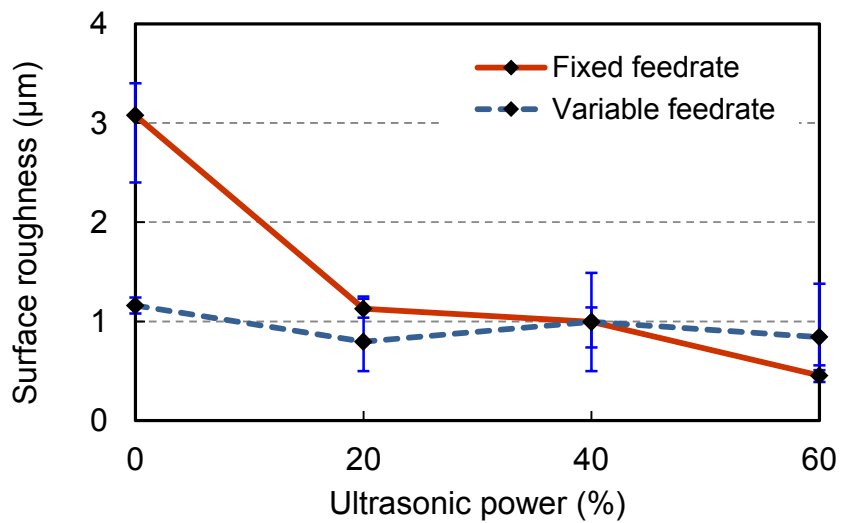Figure 13 Comparison of torque at different levels of tool rotation speed.
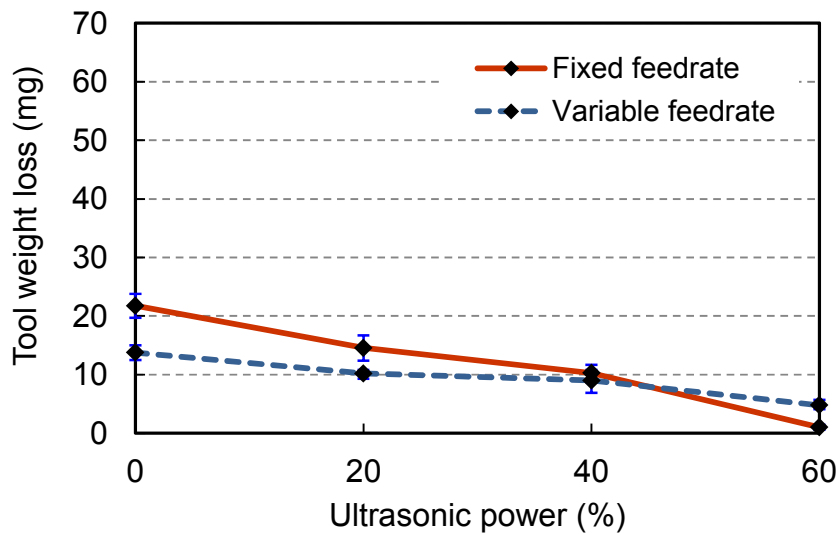
Tool rotation speed = 4000 rpm
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 14 Comparison of tool wear at different levels of ultrasonic power.

Ultrasonic power = 40%
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 15 Comparison of tool wear at different levels of tool rotation speed.
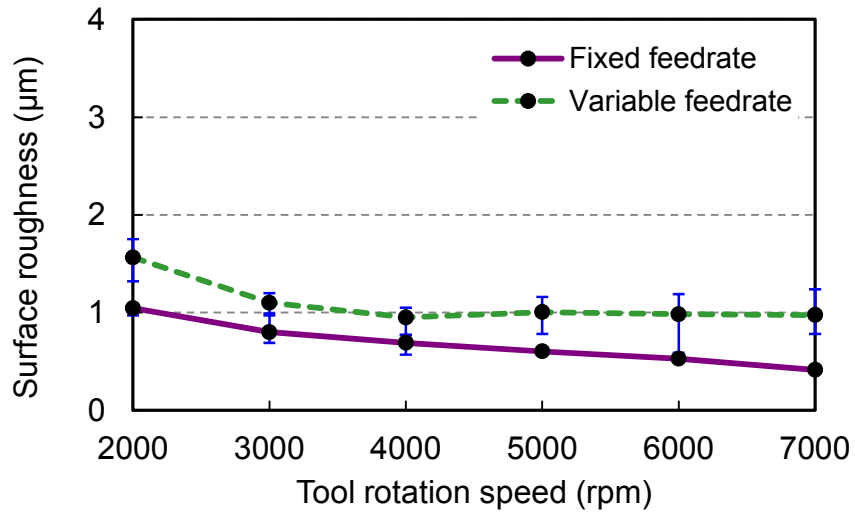
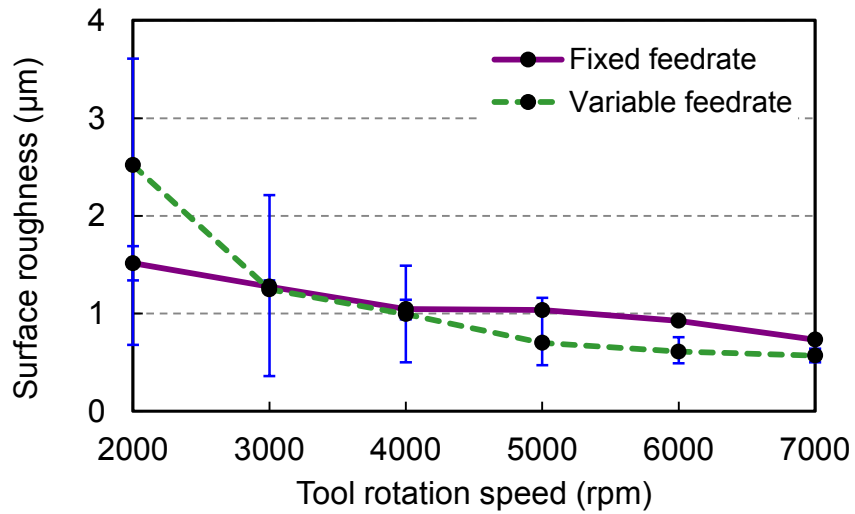(a) Machined CFRP surface

(b) Machined Ti surface

Tool rotation speed = 4000 rpm
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 16 Comparison of surface roughness at different levels of ultrasonic power.
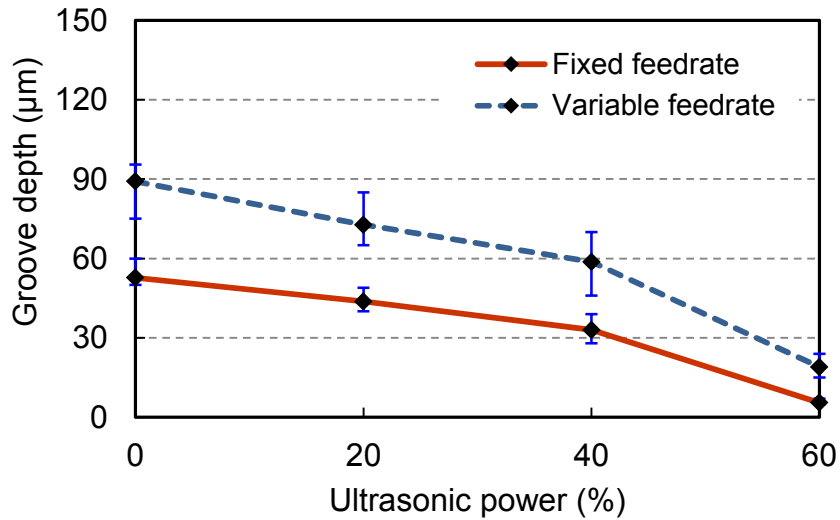
(a) Machined CFRP surface

Ultrasonic power = 40%
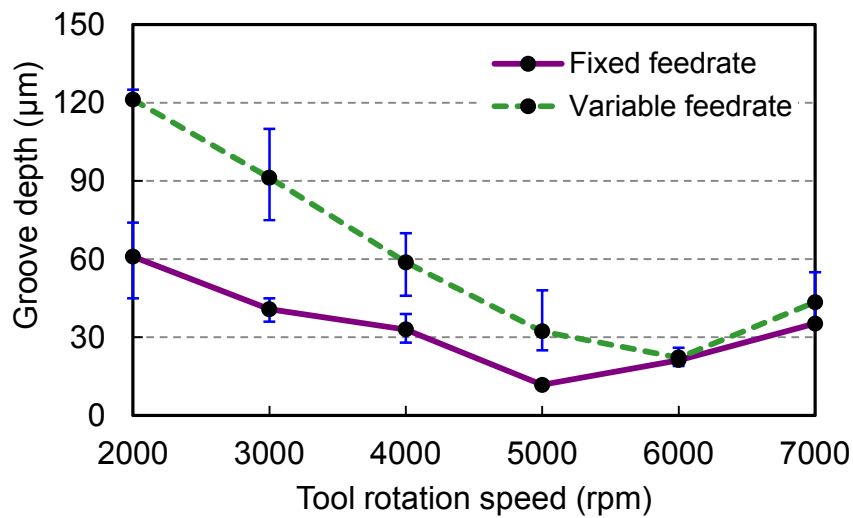Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 17 Comparison of surface roughness at different levels of tool rotation speed.

Tool rotation speed = 4000 rpm
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 18 Comparison of groove depth at different levels of ultrasonic power.

Ultrasonic power = 40%
Feedrate = 0.05 mm/s (using fixed feedrate)
Feedrate = 0.5 / 0.05 mm/s (using variable feedrate)

Figure 19 Comparison of groove depth at different levels of tool rotation speed.