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Rotary Ultrasonic Surface Machining of Silicon: Effects of Ultrasonic Power and Tool Rotational Speed

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Abstract

The surging demand for monocrystalline silicon materials in the production of microelectronic components highlights its crucial role in the semiconductor and optic industries. Hence it is inevitable to produce a silicon workpiece with high quality finish to meet the demand in semiconductor industries. Due to high brittleness, controlling the quality of silicon in surface machining is quite difficult. Traditional manufacturing processes induce issues like rough surfaces and edge chipping. It was reported that rotary ultrasonic surface machining (RUSM) can effectively reduce cutting force, roughness, and edge chipping in machining of brittle materials. There have been several studies on drilling and sliding silicon materials using rotary ultrasonic machining investigating the effects of machining parameters on the output variables such as cutting force, torque, edge chipping, surface roughness etc. However, to the best of the authors' knowledge, there are no reported investigations on effects of machining variables (ultrasonic power and tool rotation speed) in surface machining of silicon materials using the rotary ultrasonic machining. This study aimed to investigate the impacts of ultrasonic power and tool rotation speed on the cutting force, edge chipping, and surface roughness. Experimental results show that the ultrasonic vibration and tool rotation speed had a notable impact on edge chipping and cutting forces. Lastly, the current research has paved the way for widening the research on investigating grinding of the silicon wafer in semiconductor manufacturing with ultrasonic vibration and high rotation speed. In semiconductor wafer manufacturing, grinding process is used to reduce the flatness but generate surface and subsurface damage. With further investigations, RUSM can contribute to reducing these damages.

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Keywords: Rotary ultrasonic surface machining; Silicon; Brittle material; Cutting force; Edge chipping; Surface roughness.

1. Introduction

Silicon, a hard and brittle material, at the same time is inexpensive and advantageous to mechanical and thermal properties, making it an unavoidable selection for semiconductor industries [1]. The associated application in semiconductor industry also covers but not limited to communication industry and automobile industry. Since it has been widely used as a substrate material for micro electromechanical system (MEMS), microelectronics, surface flatness and integrity are an essential requirement [2].

Machining of silicon under the conventional condition is not easy because of the fracture mode material removal [3]. In

addition to this, it produces high cutting forces that makes a reduced tool life and poor machining surface [4]. Therefore, a non-traditional machining approach is being widely used in surface machining. Non-traditional machines (NTM) induce lower cutting force and better surface finish as it does not necessarily use mechanical energy and direct tool contact with workpieces [5]. Although electro-chemical machining (a NTM method) produces no damage on the surface but significantly lowers the processing efficiency [6]. In addition, thermal NTM produces heat affected zone and reduces strength of the silicon [6]. There are a few reported investigations on machining of brittle materials using abrasive jet machining (AJM) and abrasive water jet (AWJ) but concluded with limitations such

as reduced machined surface feature due to free abrasives [7-9]. Ultrasonic machining (USM) is capable of machining materials like silicon, but several investigations reported geometrical error in USM process [10, 11].

To overcome these issues RUSM is used with the combination of vertical ultrasonic vibration that vibrates along the vertical axis with a frequency of 20 kHz. It is a hybrid process consisting of a rotating tool impregnated with abrasives and removing the necessity of using slurry. Rotary ultrasonic machining (RUM) process is relatively low cost and appropriate for a wide range of applications.

There are several reported investigations on RUM and RUSM and are still going on to provide a better machinability solution to the industries. Rotary ultrasonic machining reduces the cutting force which leads to reduce brittle cracking. Qu et al. [12] experimented ultrasonic assisted double scratching test and observed when the diamond abrasive moving distance is smaller than the lateral crack in one vibration cycle, it reduces the initiation of radial crack as well as sub-surface damage. It was reported that higher tool rotation and ultrasonic power along with a lower feed rate reduced the edge chipping in drilling of silicon solar panel using rotary ultrasonic machining process [13]. It has been reported that cutting forces has been reduced with an improved surface finish when machining of brittle materials using RUSM [14]. Ultrasonic vibration was found effective in reducing surface roughness when interacts with spindle speed for stainless steel in RUM [15]. G Ya et al. [16] investigated the impact of ultrasonic vibration and found that cutting force is reduced and surface fineness is enhanced. The effects of tool speed, feed rate, ultrasonic power, and coolant pressure on the MRR, surface roughness, and cutting force when machining of quartz ceramic was examined [17]. Feed rate was found significant to increase surface roughness when machining of zirconia ceramic on RUSM [18]. It has also been reported that rotary ultrasonic micro machining can reduce the edge chipping phenomenon [19]. A study was conducted on the machining of nickel alloy in RUSM and the analysis of micro structure revealed that the crack propagation was attained by the plastic deformation which was a result of ductile fracture [20]. Depth of cut was found insignificant when machining of alumina based ceramics [21]. However, reports on RUSM is still limited [22]. As far as author knows, there are still a lack of studies on the RUSM of single crystal silicon materials.

Reported investigations clearly indicating that the influence of vibration amplitude, cutting speed, feed rate has a positive relationship with cutting force, surface roughness, torque, and edge chipping [23, 24]. However, the above-mentioned findings were basically dealt with general brittle materials (such as ceramics) and no investigation on the influence of process parameters for RUSM of silicon is available. Thus, investigation is required on this to identify optimum process parameters.

This study investigated the effects of machining parameters on the cutting forces, surface roughness and edge chipping characteristics of silicon disc. RUSM process was used to surface machined the silicon using an abrasive diamond cutting tool.

Impacts were analysed by varying ultrasonic power and tool rotation speed under a constant feed rate and depth of cut. Feed rate was kept constant cause this study doesn't focuses on the MRR.

Nomenclature

USM	Ultrasonic machining
RUM	Rotary ultrasonic machining
RUSM	Rotary surface machining
MEMS	Micro electromechanical system
NTM	Non-traditional machining
AJM	Abrasive jet machining
AWJ	Abrasive water jet
SR	Surface roughness
MRR	Material removal rate

2. Materials and Method

2.1 Materials

In this experiment, a silicon disc with a diameter of 55.25 mm, and a thickness of 9.25 mm was used for surface machining. Diamond abrasive coated surface grinder cutting tool (NBR diamond tool) with a diameter of 6 mm was used. An illustrative figure of RUSM process is provided in Fig. 1.

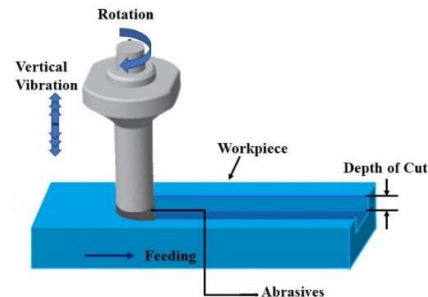


Fig.1: Illustrative figure of RUSM process.

2.2 Experimental Setup

A rotary ultrasonic vertical machine (Series-10 Sonic-Mill, Albuquerque, NM, USA) was used for surface machining. Fig. 2 shows the illustrations and photographs of machining setup. The system has an ultrasonic tooling system, a linear feeding system, coolant and data acquisition system. Ultrasonic tooling system composed of an ultrasonic spindle, a motor with speed control unit, and an ultrasonic power supply. The low frequency electricity is converted to high frequency (20 kHz) electrical energy by ultrasonic power supply in the ultrasonic tooling system. Ultrasonic vibration is then attained by the piezoelectric converter and transmitted to the cutting tool attached with the ultrasonic spindle. In ultrasonic vibration assisted machining, the amplitude is controlled by ultrasonic power, and it was reported that the amplitude increases with an increase in ultrasonic power [25]. There are several reported investigations stating that amplitude has a direct influence on almost all the response parameters [15, 26-28]. Different levels of ultrasonic power were used in this study to determine the

effectiveness of machining. The motor mounted above the ultrasonic spindle provides the rotation. Horizontal feeding is supported by the linear stage and a motor controller (NSC-A1, Newmark, Rancho Santa Margarita, California, USA) and the software (QuickMotion NSC-A1, Newmark, Rancho Santa

Margarita, California, USA) controls the federate. Machine table and dynamometer are both mounted on the linear stage. Details of the data acquisition system are discussed in the measurement section.

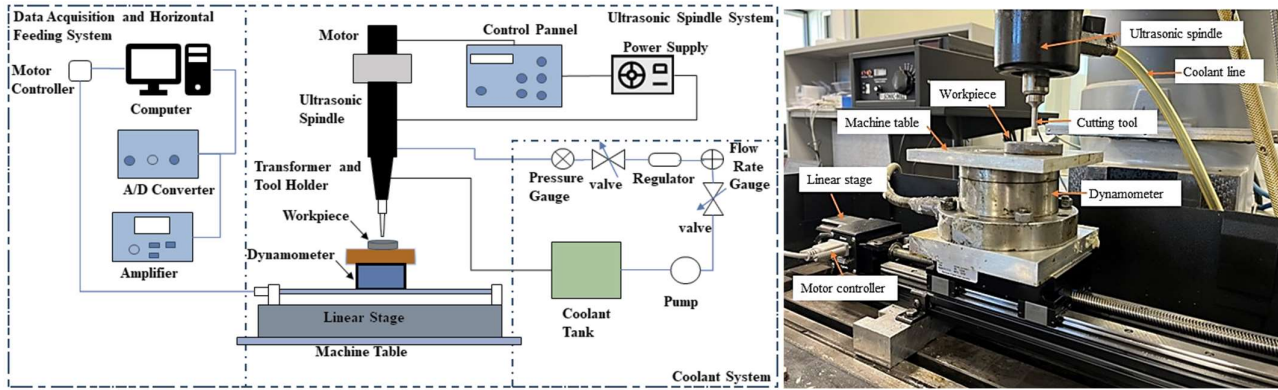


Fig. 2: Schematic and experimental setup in RUSM

2.3 Experimental Condition

The silicon disc was attached to machine table using a silicone glue. The cutting tool was set inside the ultrasonic spindle and the workpiece was moved up until the cutting tool touched the workpiece tightly. Then the tool was moved away from the workpiece and positioned on the left side of the workpiece, however, the position was later changed to right when we machined the surface from the other sides of the silicon disc. As this study aimed to investigate the effects of ultrasonic power and tool rotation speed, feed rate of 0.1 mm/s and a depth of cut of 0.5 mm were kept constant. The speed of linear stage was 300 mm/s. Table 1 shows the experimental design of the investigation.

Table 1: Design of experiment on the effects of ultrasonic power and tool speed

Experiment No.	Ultrasonic Power (%)	Tool Rotation (RPM)
1	0%	2500
2		3000
3		3500
4	20%	2500
5		3000
6		3500
7	40%	2500
8		3000
9		3500
10	60%	2500
11		3000
12		3500

2.4 Measurement Procedures

Measurement of cutting force was done by a data acquisition system. A dynamometer of type 9272, Kistler Inc., Switzerland was applied for measuring the F_x (horizontal direction) and F_z (vertical direction). The electrical signals were transmitted from dynamometer to the charge amplifier (type 5070, Kistler Inc., Winterthur, Switzerland) for amplification. In order to

transform the amplified electrical signals into digital signals an A/D converter (type 5697A, Kistler Inc., Winterthur, Switzerland) was used. Lastly, the digital signals were obtained from the DynoWare software (Type 2825D-02, Kistler Inc., Winterthur, Switzerland).

Surface roughness was measured according to ISO1997 by the surface profilometer (model: Mitutoyo SJ-210, Japan). In the measurement process, the distance probe travels for a single measurement (λ_c) was set as 0.25mm; the width of the smallest feature (λ_s) was set as 2.5 μ m; the number of consecutive measurement for averaging (N) was 5, and finally the measurement speed was default as 0.5 mm/s. In the measurement process, four readings were taken for averaging the R_a value.

An optical microscope (OM) (DSX-510, OLYMPUS, TOKYO, Japan) was used to analysis the machined surface. This microscope provided 3D contour images which were used to inspect the depth and morphology of the machined surface. The image was later processed at ImageJ software to determine edge chipping area of the machined surfaces. An illustration of edge chipping analysis is given in the Fig. 3.

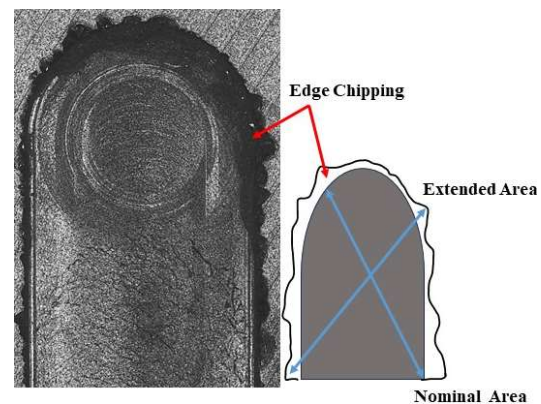


Fig. 3: Illustration of edge chipping analysis

3. Results and Discussion

3.1 Effects on Surface Roughness

Fig. 4 shows an illustrative overview to understand the effects of ultrasonic power and tool rotation on surface roughness. The results clearly elucidate that roughness is lower without the assistance of ultrasonic vibration and with an increase of ultrasonic power, the roughness tends to be higher. It happened because higher ultrasonic power produced more micro cracks on the workpiece with a tool having abrasive grains [29]. In addition, a heavy micro crushing action against the machining surface also occurred at higher ultrasonic power [25, 28]. The highest Ra value was observed as $0.720\text{ }\mu\text{m}$ under a low tool speed of 2500 RPM and high ultrasonic power of 60%, which is 68% higher in compared to the roughness value attained for the surface without ultrasonic vibration against the same tool rotation. The lowest Ra value was observed as $0.184\text{ }\mu\text{m}$ for surface machined without ultrasonic vibration (0%) at 3500 RPM.

Fig. 5 shows surface roughness of the machined part with respect to tool rotation under different ultrasonic power. The Ra value was observed higher at the lower tool speed and roughness seemed to be decreasing with higher tool speed. Increasing tool rotational speed decreases axial force which contributes less tool wear and surface damage [30, 31]. In addition, higher speed reduces the interface friction between tool and workpiece. An increase in tool rotation speed also increases kinematic overlap which lowers the Ra value [32].

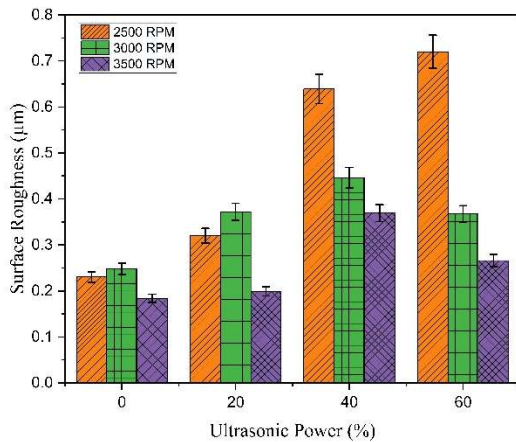
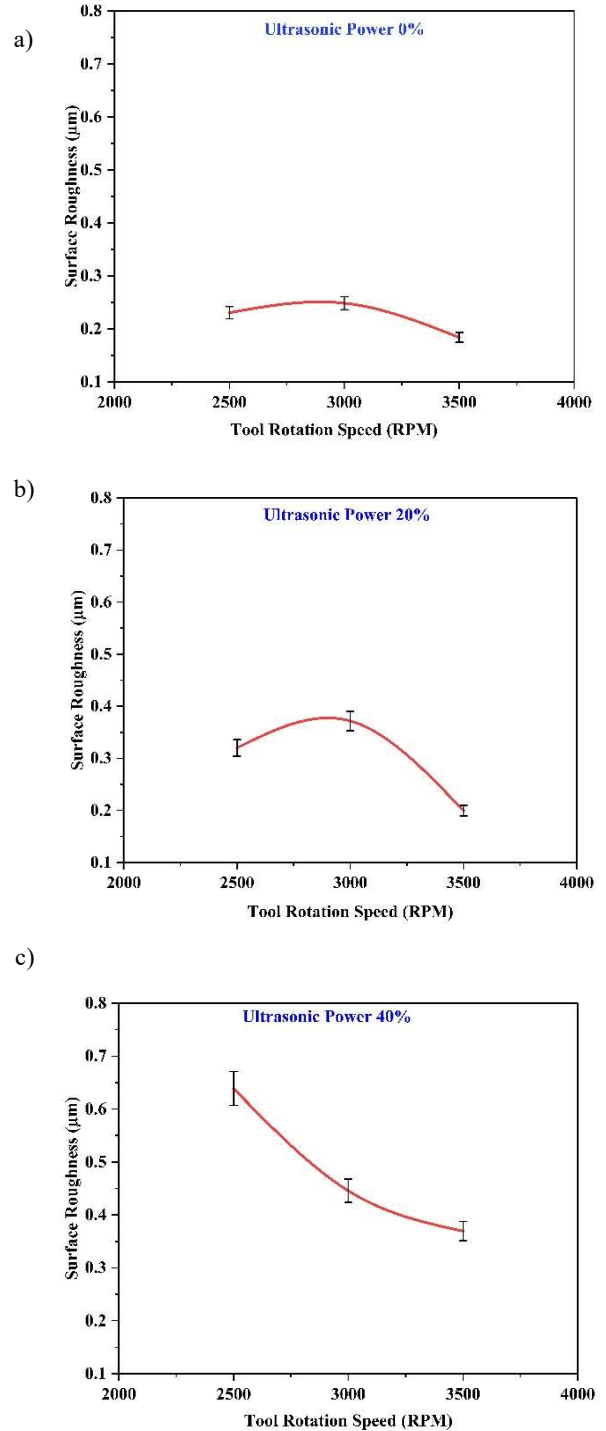


Fig. 4: Comparative relationship between surface roughness and ultrasonic power under different tool rotational speeds.



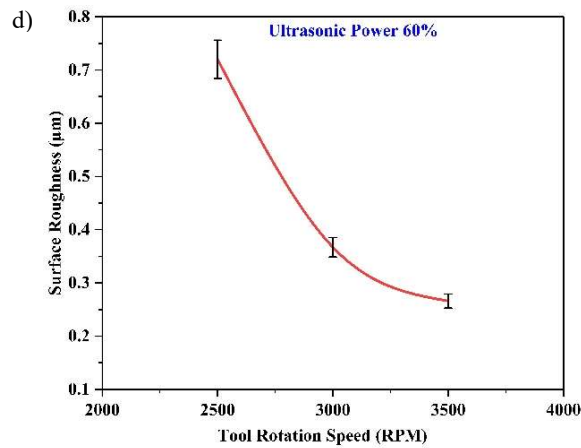


Fig. 5: Effects tool rotation speed on surface roughness (a) without ultrasonic power (b) 20% ultrasonic power (c) 40% ultrasonic power (d) 60% ultrasonic power

3.2 Effects on Edge Chipping

Fig. 6 depicts the effects of ultrasonic power and tool rotation on the edge chipping of machined surfaces. Edge chipping was observed higher without ultrasonic vibration and seemed to be decreasing with the assistance of ultrasonic vibration. It is due to the less cutting force generated when machining with ultrasonic vibrations. Several studies have reported that the cutting force is the main parameter affecting edge chipping [33, 34]. Lowest edge chipping was observed as 4.96 mm² at 20% ultrasonic power and 3500 RPM of tool rotation speed. On the other hand, highest edge chipping was observed as 13.59 mm² at 2500 RPM of tool rotation speed and without applying ultrasonic vibration.

Fig. 7 shows the relationship between edge chipping and tool rotation under different ultrasonic powers. Edge chipping area was found to be lower when the speed was higher and vice versa. This phenomenon was common in both with and without ultrasonic vibration.

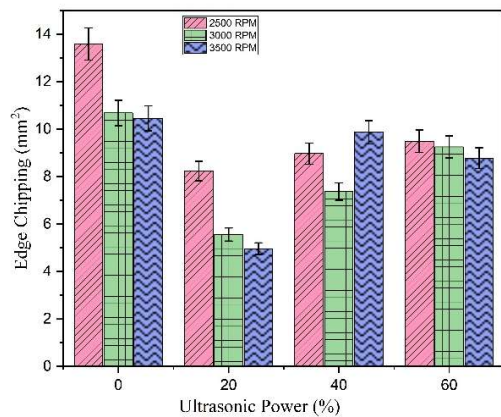


Fig. 6: Comparative relationship between edge chipping and ultrasonic power under different rotational speeds

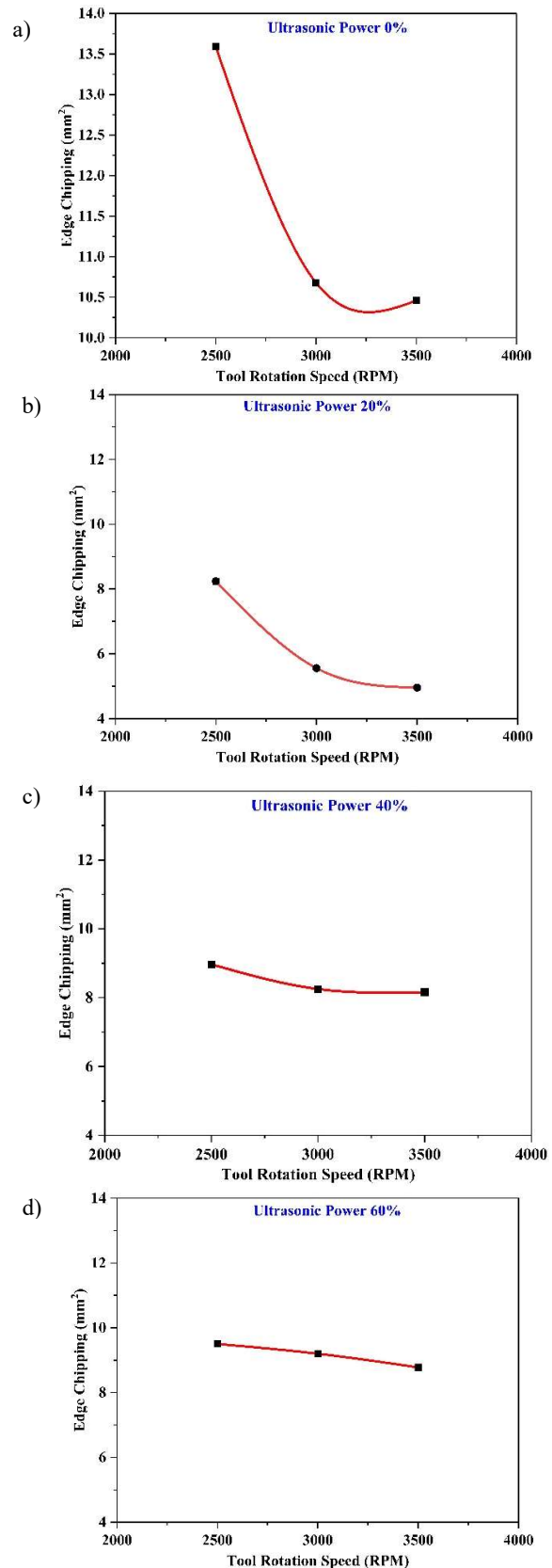


Fig. 7: Effects tool rotation speed on edge chipping (a) without ultrasonic power (b) 20% ultrasonic power (c) 40% ultrasonic power (d) 60% ultrasonic power

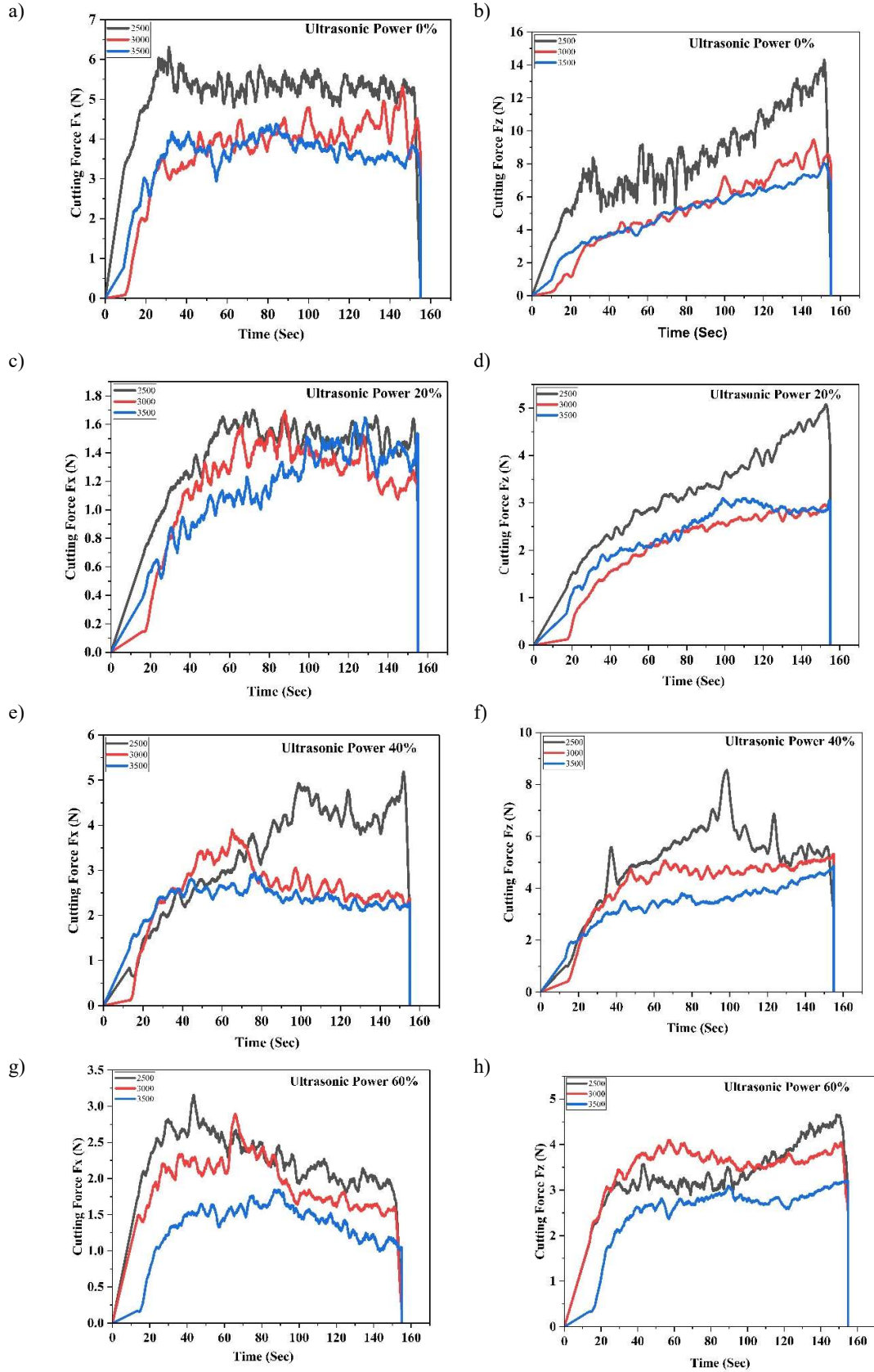


Fig. 8: Effects of tool rotation speed on cutting forces F_x and F_z (a) (b) without ultrasonic power (c) (d) 20% ultrasonic power (e) (f) 40% ultrasonic power (g) (h) 60% ultrasonic power

3.3 Effects on Cutting Force

Fig.8 shows the effects of rotational speed and ultrasonic power on cutting force in feeding (F_z) and axial (F_x) direction. The results clearly showed that the ultrasonic vibration has a positive impact on cutting force. F_x was seen to be higher without ultrasonic vibration and decreased rigorously at 20% ultrasonic power. MRR is usually easier with higher ultrasonic amplitude and caused less contact between workpiece and tool making a reduced friction and axial force [31, 35]. However, cutting forces were found to be higher with 40% and 60% ultrasonic power in compared to 20% ultrasonic power, as because higher amplitude generates more compressive force, making a much more clearance for the rotating tool to create edge chipping. The results obtained from the edge chipping under higher ultrasonic power also approve this statement. In addition to this, rotation also had a positive relationship with cutting forces. Higher tool rotation speed generated lower cutting forces in both directions.

4 Conclusion

In this study, a brittle material (silicon disc) was surface machined with a rotating abrasive grinding tool by rotary ultrasonic machining process. Tool rotation and ultrasonic power were varied to investigate their effect on surface roughness, edge chipping and cutting force. The following conclusions have been drawn.

- I. Vertical ultrasonic vibration was not seen to reduce surface roughness. However, tool rotation speed had a positive impact on surface roughness. Higher speed generates lower surface roughness.
- II. Edge chipping was found to be lower with the assistance of ultrasonic vibration in compared to without vibrations. However, the lowest edge chipping area was noticed with 20% ultrasonic power and the edge chipping was higher with the increase of more ultrasonic power. This had concluded that the higher cutting forces played a vital role in generating edge chipping. In addition, higher tool rotation speed was better in reducing edge chipping.
- III. Ultrasonic vibration had a significant impact on cutting force. Although cutting forces were found to be decreased under ultrasonic effect but higher ultrasonic power induced larger compressive force resulting edge chipping. Cutting forces were seen to be decreased with increasing tool rotation speed.

Lastly, this investigation only focuses on the effects of low to medium tool rotation speed and vertical ultrasonic power on the cutting forces, surface roughness, and edge chipping. In the future, authors intended to investigate the effects of higher tool rotation speed ($> 10,000$ RPM) and horizontal ultrasonic power.

Acknowledgements

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