Reduction of drilled-hole fracture and burr by rotary ultrasonic machining technology

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Abstract. In this paper, rotary ultrasonic machining (RUM) is introduced to process the micro-drilling on graphite and brass. The best combinations of process parameters are presented as the experimental results on this research. On the basis that graphite offers efficient electrical conductivity and low hardness, and that brass as copper-zinc alloys provides convenience for processing, fractures or edge collapses are often evident after machining. This research focuses on proposing improvements by cooperating RUM with Taguchi method, from which the optimizations of process parameters and parameter verifications can be conducted. Control factors include spindle speed of the drill-bit, peck drilling, processing feed rate, and ultrasonic power. Each factor is inspected by three levels. Quality features are determined by the fracture area.

This research reveals that the difficulty in removing shavings leads to the breakage of machining tools inside the drilled holes. Incorrect process parameters cause failure at processing the micro-drilling on graphite and brass.

1. Introduction

Traditional metal cutting generates the burr, which is the protrusion on the edge made by the shape deformation in the cutting process. The burr decreases machining precision and hinders the following assembly process [1]. Cases show that the cost of deburring takes up 25% of the total production cost [2]. RUM is able to decrease the burr height by performing high-frequency and low-amplitude vibrations in feeding direction [3].

Takeyama and Sato [4] employed RUM to reduce the drilling burr. Drilling ductile materials generated the burr, while brittle materials and composite materials displayed cracked or damaged edges. Takeyama’s research concluded that radial ultrasonic vibrations improved the process of deburring. Lin and Shyu [5] conducted a research on drilling stainless steel and found that tuning the feed rate would prolong tool durability and diminish the burr. Properly coated tools and coolants were able to reduce the friction between the tools and the materials, to change the drilling feed rate, and to decrease the size of the burr.

With Taguchi method, Nian et al. [6] designated cutting speed, feed rate and cutting depth as the control factors. Using analysis of variance (ANOVA) to analyze various quality features: tool durability, cutting ability and surface roughness, the research achieved an optimized result. Li [7], also adopting Taguchi method, arranged spindle speed, feed rate, frequency and amplitude as the control factors in order to evaluate quality results, including reaming amount, circularity, hole surface roughness, position precision and the burr. In 1963, Balamuth [8] proposed the concept of combining ultrasonic with spindle in rotation machining. In 1970, Tyrrell [9] bettered the lapping surface by adhering the abrasive to the
tool. In 1977, Markov [10] gained a great success in processing non-metal materials. He attached the diamond abrasive to the tool by means of electroforming, and subsequently advanced the ultrasonic spindle machining technology.

As we know, both graphite and brass are excellent conductive materials. In terms of material properties, graphite is a brittle material, while brass is a ductile material. They can be used as probe holders for semiconductor chip probing. In order to allow the chip probe passing through a micro holes (0.1mm diameter). Drilling micro holes are required in graphite and brass. However, it is easy to produce cleavage cracks in graphite. And there will be burrs in brass. Therefore, this paper is devoted to applying RUM to process graphite and brass, from which the micro-cleavage and burr can be diminished, optimization of process parameters can be achieved, and process evaluation and design can be developed. Control factors include spindle speed, peck drilling, processing feed rate and ultrasonic power. Each factor is experimented by three levels. Quality features are determined by the fracture area.

2. Methodology

2.1. Rotary ultrasonic machining

Rotary Ultrasonic Machining (RUM) is a nontraditional manufacturing process that removes material from the surface of a part through high frequency, low amplitude vibrations of a tool against the material surface. The device subtracts material by hammer blowing, grinding and ripping. The process is accompanied by the coolant in order to remove particles from the material. Figure 1 shows the RUM tool holder. The ultrasonic driver transforms electricity and generates ultrasonic. The ultrasonic power and frequency will be controlled by CNC machine. The power can mainly adjust the amplitude in the Z direction, and the frequency will be affected by the mass and geometry of the tool.

![Figure 1. RUM tool holder (BT-40).](image1)

![graphite](image2)

![brass](image3)

Figure 2. Experimental material, graphite, and brass.

2.2. Experimental design

The materials used in this experiment are graphite and brass, respectively. The dimension is 50mm x 50mm x 2mm shown in Figure 2. Drill bit is 0.1mm in diameter. Effective blade length is 2.5mm Figure 3.
In this experiment RUM is conducted to process peck drilling on graphite and brass. Taguchi Method is applied to set up experiment design and to find the optimal cutting parameters. The optimized results can be obtained by the minimum experimental trials. The orthogonal array $L_9(3^4)$ is considered so that nine experiments are carried out and each experiment contains 5 holes. Control factors can include spindle speed, feed rate, peck drilling and ultrasonic power. The fracture areas are examined as the quality results. Table 1 and Table 2 are the parameters of this experiment.

### Table 1. Control factors and levels for graphite.

| Factor | Indication            | Level 1 | Level 2 | Level 3 |
|--------|-----------------------|---------|---------|---------|
| A      | spindle speed (rpm)   | 8,000   | 10,000  | 12,000  |
| B      | feed rate (mm/min)    | 40      | 60      | 80      |
| C      | peck drilling (mm)    | 0.02    | 0.025   | 0.03    |
| D      | ultrasonic power (%)  | 60      | 80      | 100     |

### Table 2. Control factors and levels for brass.

| Factor | Indication            | Level 1 | Level 2 | Level 3 |
|--------|-----------------------|---------|---------|---------|
| A      | spindle speed (rpm)   | 6,000   | 8,000   | 10,000  |
| B      | feed rate (mm/min)    | 80      | 100     | 120     |
| C      | peck drilling (mm)    | 0.01    | 0.015   | 0.02    |
| D      | ultrasonic power (%)  | 60      | 80      | 100     |

2.3. Experimental procedure
The first step is parameter setup. Using Taguchi orthogonal array, less effective factors are excluded through signal/noise ratio ($S/N$ ratio) and analysis of variance (ANOVA) in order to achieve the best parameter combination. Secondly, machining is performed based on orthogonal array. The result is photographed by CCD camera and examined. The fracture area is calculated in the imaging software. After data analysis, the outcome is inspected to see whether it reaches the expected target or not. If not, the experimental parameters are corrected. Figure 4 shows the experimental flow chart.

2.4. Experimental equipment
Figure 5 shows a 5-axis machining center (Tongtai GT-630) that is capable of rotary ultrasonic assisted machining. The brass is fixed by the fixture of the vise and it is being drilled. The digital microscope Keyence VHX-900F is used to photograph the holes after processing shown as figure 6.
Photoshop is then utilized to analyse the photo pixels that are further calculated to determine the drilled area.

2.5. Evaluation model of the fracture fraction

Figure 7 and 8 represent a 1000-time magnified photograph for a hole in graphite and brass, respectively. Through the analysis of Adobe Photoshop, the overall area of the photo obtained by the microscope is 238910.52mm² (i.e. 564.4mm × 423.3mm) corresponding to 1,920,000 pixels. When the circle outline of the micro-drilled hole is selected in the photo, the corresponding pixels $P_{drilled\ hole}$ can be substituted into equation (1) to obtain the drilled area $A$.

$$A = \frac{238910.52}{1920000} \times P_{drilled\ hole} \quad (1)$$

The drilling area consists of two parts, one part is the circular area of the drill bit, and the other part is the fracture area caused by the drilling. The ideal value of circular area is $(0.1)^2 \times \pi/4 \approx 0.007854$ mm².

**Figure 4.** Experimental flow chart.

![Experimental flow chart](image)

**Figure 5.** (a) Ultrasonic assisted machining center; (b) a drilling process is performed on brass.
3. Results

3.1. Graphite drilling experiment

In the graphite drilling experiment, the nine experimental results in Orthogonal Array present the measurements of drilling area. Figure 9 shows the bar graph of the drilling area. The fifth experiment gives the minimum average drilling area that the measured value is 0.0151 mm². In this analysis, the drilling area is a quality characteristic. Therefore, the higher the S/N ratio is, the better quality it has. It indicates a smaller drilling area. Using S/N ratio to quantify the quality, the experiment calculates each control factor response and observes the effects made by the control factors. The results are shown on Table 3 and Figure 10.

| Table 3. S/N ratio factor response of graphite drilling area. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| A. spindle speed              | B. feed rate    | C. peck drilling | D. ultrasonic power |
| level1                        | 35.2631         | 35.6592         | 35.8311         | 35.7395         |
| level2                        | 36.2121         | 35.8403         | 35.5498         | 35.4385         |
| level3                        | 35.4781         | 35.4538         | 35.5725         | 35.7754         |
| effect                        | 0.9490          | 0.3865          | 0.2814          | 0.3370          |
| rank                          | 1               | 2               | 4               | 3               |
Figure 10. S/N ratio response of graphite drilling area.

From the factor response in Table 3, spindle speed is evident to be the most dominant factor that affects the result. The second and the third are the feed rate and the ultrasonic power, respectively. The least influential is the peck drilling.

On the final step, ANOVA is adopted to calculate the S/N ratio of the drilling area. As shown in Table 4, the factor effect vectors and the confidence levels of the four control factors are presented and the inspections conclude that the most dominant parameter that affects the quality is spindle speed. Confidence level on this factor is more than 95%, which shows its great influence on the quality feature.

| Factor | SS      | DOF | Var     | F      | Probability | Confidence | Significant |
|--------|---------|-----|---------|--------|-------------|------------|-------------|
| A      | 2.407E-05 | 2   | 1.203E-05 | 4.877  | 0.013       | 98.664     | YES         |
| B      | 3.278E-06 | 2   | 1.639E-06 | 0.664  | 0.521       | 47.910     | NO          |
| C      | 3.123E-06 | 2   | 1.565E-06 | 0.634  | 0.536       | 46.382     | NO          |
| D      | 4.522E-06 | 2   | 2.261E-06 | 0.916  | 0.409       | 59.084     | NO          |
| Error  | 8.883E-05 | 36  | 2.468E-06 |        |             |            |             |
| Total  | 12.383E-05 | 44  |         | 44     |             |            |             |

Table 4. ANOVA of graphite S/N ratio.

Note: At least 95% confidence

3.2. Brass drilling experiment

The same experiment is conducted on brass. The results of the average drilling area are shown in Figure 11. It is observed that the first group has the minimum average burr, which comes to 0.0141 mm². Moreover, the control factor response and factor effect are shown on Table 5 and Figure 11.

According to the factor response table, Table 5, spindle speed is evident to be the most dominant factor that affects the result. The second and the third is the peck drilling and the ultrasonic power respectively. The least influential is the feed rate.

On the final step, ANOVA is adopted to calculate the S/N Ratio of the drilling area shown in Figure 12. As shown in Table 6, the factor effect vectors and the confidence levels of the four control factors are presented and the inspections conclude that the most dominant parameter that affects the quality is spindle speed. The second and the third is respectively the peck drilling and the ultrasonic power. The least influential is the feed rate. All the confidence levels of four control factors are more than 95%, which show their dominance on the quality features.
Figure 1. Average results of the drilling area for brass.

Table 5. S/N ratio factor response of the drilling area for brass.

|          | A. spindle speed | B. feed rate | C. peck drilling | D. ultrasonic power |
|----------|------------------|--------------|------------------|---------------------|
| Level 1  | 35.26944         | 33.67790     | 35.13656         | 34.59155            |
| Level 2  | 33.31428         | 34.55797     | 33.30097         | 33.21699            |
| Level 3  | 33.10804         | 33.45588     | 33.25423         | 33.88322            |
| effect   | 2.16140          | 1.10208      | 1.88232          | 1.37455             |
| rank     | 1                | 4            | 2                | 3                   |

Figure 12. S/N ratio response of drilling area for brass.
Comparison of experiment verification and predicted values

3.3.1 Graphite. Based on the maximum value of the S/N ratio response, A2, B2, C1 and D3 can be obtained. Spindle speed A2 is 10,000rpm. Feed rate B2 is 60 (mm/min). Peck drilling C1 is 0.02mm. Ultrasonic power D3 is 100%. In Table 7, the new S/N ratio is higher than the nine S/N ratios by 3.288315, which can be presented as the optimized parameter.

3.3.2 Brass. From S/N ratio response, The A1, B2, C1, and D1 can be determined. Spindle speed is A1 is 6,000rpm. Feed rate B2 is 100 (mm/min). Peck drilling C1 is 0.01mm. Ultrasonic power D1 is 60%. In Table 8, the new S/N ratio is higher than the nine S/N ratios by 2.18798, which can be presented as the optimized parameter.

Table 6. ANOVA of brass S/N ratio.

| Factor | SS    | DOF | Var  | F     | Probability | Confidence | Significant |
|--------|-------|-----|------|-------|-------------|------------|-------------|
| A      | 21.254E-05 | 2  | 10.627E-05 | 38.109 | 1.295E-09  | 99.999     | YES         |
| B      | 6.953E-05  | 2  | 3.476E-05  | 12.466 | 7.694E-05  | 99.992     | YES         |
| C      | 16.747E-05 | 2  | 8.374E-05  | 30.027 | 2.128E-08  | 99.999     | YES         |
| D      | 7.150E-05  | 2  | 3.575E-05  | 12.820 | 6.250E-05  | 99.994     | YES         |
| Error  | 10.039E-05 | 36 | 2.789E-06  |        |             |            |             |
| Total  | 62.144E-05 | 44 |       |        |             |            |             |

Note: At least 95% confidence

Table 7. Graphite experiment verification and predicted values.

|                | Ave. | S     | S/N  |
|----------------|------|-------|------|
| Original       | 0.01645 | 0.00141 | 35.65116 |
| Optimal        | 0.00952 | 0.00584 | 39.03948 |

Table 8. Brass experiment verification and predicted values.

|                | Ave. | S     | S/N  |
|----------------|------|-------|------|
| Original       | 0.01693 | 0.00184 | 35.20027 |
| Optimal        | 0.01346 | 0.00119 | 37.38825 |

4. Conclusions

In this research RUM is introduced to conduct the drilling on graphite and brass. The optimization of parameter factors is examined and determined. Based on the results from the RUM and Taguchi method, the conclusions are as follows:

1. Spindle speed is the most dominant factor that affects the ultimate quality.
2. In the graphite drilling, spindle speed is evident to be the most dominant factor that affects the result. The second and the third is the feed rate and the ultrasonic power respectively. The least influential is the peck drilling.
3. In the brass drilling, spindle speed is evident to be the most dominant factor that affects the result. The second and the third is the peck drilling and the ultrasonic power respectively. The least influential is the feed rate.
4. Graphite generates the maximum drilling area at 12,000rpm and gives the minimum at 10,000rpm. The best outcome falls on 10,000rpm.

5. In term of brass, the maximum drilling area appears at 10,000rpm and the minimum occurs at 6,000rpm. The best result comes from 6,000rpm.

6. Taguchi method is adopted to optimize the parameters of micro-machining on graphite and brass. The parameters are shown as following:

(1) Advised process parameters for graphite machining: spindle speed 10,000rpm, feed rate 60mm/min, peck drilling 0.02mm, and ultrasonic power 100(%). Moreover, the optimal drilling area is 0.00952mm².

(2) Advised process parameters for brass machining: spindle speed 6,000rpm, feed rate 100mm/min, peck drilling 0.01mm, and ultrasonic power 60(%). The optimal drilling area is 0.01346mm².

This study can successfully explore the optimization on the reduction of the drilling area by rotary ultrasonic machining graphite and brass with a diameter of 0.1mm. Because of the brittleness of graphite, the geometry of the drill hole can be observed more irregularly circle. The surface of the hole is cracked more obviously. However, compared with graphite, the ductile brass has more serious burrs and a more uniform drilling profile.

If traditional drilling graphite and brass are used, the average drilling area is 0.01962 mm² and 0.02202mm², respectively. The average drilling area of graphite and brass with ultrasonic assisted drilling technology is 0.00952mm² and 0.01346mm², both of which can be greatly reduced the drilling area. The reduction rate of drilling area is 51.48% and 38.87% of traditional drilling for the graphite and brass.

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