Micro Grinding Blind Holes in Hard Tungsten Carbide with Polycrystalline Diamond Micro Tools

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Abstract
This paper describes a micro hole drilling technique using micro electro-discharge machining (µEDM) and polycrystalline diamond (PCD) micro tools to improve the precision of holes drilled in hard tungsten carbide. A two-step technique is described for achieving faster, more precise and accurate holes. First, the hole is drilled with µEDM using tungsten electrodes shaped by WEDG. Next, the holes are improved by grinding with PCD micro tools, which are also shaped by WEDG. It is found that holes fabricated with PCD micro tools are superior since they have less heat-affected zone, exhibit improved surface finish, and have less form error. Also, the hole size is more accurately controlled with PCD tools, since no gap exists between the tool and workpiece and because tool wear is less than electrode wear during µEDM.

Key words: micro grinding, micro-EDM, polycrystalline diamond

1. Introduction

Electro-discharge machining was developed for drilling micro holes in hard materials like tungsten carbide. In 1968 Kurafuji and Masuzawa[1] were able to achieve a 6 micrometer hole in a carbide block 50 micrometers thick. Through the years, the material removal rates improved but the precision and accuracy remains limited by discharge energy, electrode wear, and heat affected zone. When drilling through-holes, the tool wear is not a problem because the tool can be continually fed so that discharges occur on unworn regions of the electrode. For blind holes tool wear is an issue, therefore typically a multistep EDM process is used to achieve precise holes with good form. Multiple µEDM steps are time consuming, therefore this paper presents a new hybrid technique which uses a polycrystalline diamond (PCD) micro tool. The hybrid process consists of two steps. First the hole is machined with a high discharge energy µEDM process, and then a PCD micro tool is used to grind the hole surface. The PCD tool removes the recast layer and heat affected zone created by the µEDM process. This improves the control of hole size, improves surface finish, and reduces form error.

2. Shaping PCD Tools with µEDM

At present, PCD micro tools, which resemble miniature end mills, are not widely available. Therefore, a brief description is given of the steps necessary to prepare high-quality micro tools using a series of electro-discharge operations. The PCD tools are prepared from tungsten carbide wafers with over 1 mm of PCD (Sumitomo Electric DA 200) that are cut into cylindrical blanks by wire electro discharge machining (wire EDM). The diamond grains, which average 0.5 μm in size, are sintered with metallic cobalt under high temperature and pressure. Figure 1 shows an SEM micrograph of the end of a 21 mm x 12 mm cylindrical blank, and the transition from tungsten carbide to PCD is evident at the junction between light and dark gray. After wire EDM, the surface of the cylindrical PCD blank is rough, consisting of aggregated clusters
of material as shown in the inset of Figure 1. The cylindrical PCD blanks are further shaped into tools with one or more operations on a commercial \( \mu \)EDM machine (Panasonic MG-ED82W). For our experiments, the shape of the tool is first rough-cut by wire electro-discharge grinding (WEDG)[2]. WEDG is similar to turning on a lathe except that material is removed by erosion with electrical discharges. Micro tools intended for drilling holes require a means of removing particles. For this purpose, we produce tools similar to those reported by Egashira and Mizutani[3], in which half the shank is removed in a second WEDG operation conducted without rotating the PCD tool. Figure 2 shows the protruding nature of the diamond grains after shaping the tool by WEDG or \( \mu \)EDM.

Figure 2 also shows a custom designed and fabricated mandrel (Professional Instruments Co.) that incorporates an integral collet. The collet dramatically improves the stiffness of the tool holder compared to the machine’s standard tool holder. Alignment of the PCD tool’s centerline is established automatically since the PCD tool is held in the mandrel/collet during WEDG and subsequent grinding operations.

3. Drilling and Grinding Processes

The hybrid hole drilling experiments are conducted using tungsten carbide compound workpieces, HC US10 from Hydro Carbide. Two faces of two tungsten carbide blocks (25×25×12mm) are polished flat and then wrung together with a lateral offset. The blocks are clamped together, and the end of the composite workpiece is ground to provide a flat surface perpendicular to the hole axis. The lateral offset visually indicates the location of the seam between the two blocks, which vanishes when the endface is ground. The compound workpiece is held on the worktable of the \( \mu \)EDM machine during all of the drilling experiments. A series of holes are drilled along the seam between the two blocks using the technique described in the following paragraph. After drilling the holes, the blocks are separated to reveal the two halves of the holes. This enables inspection of the holes using scanning electron microscopy (SEM) and metrology of the holes’ form, waviness, and roughness.

Figure 3 illustrates the sequence of operations during the hole fabrication. A tungsten tool of 90 micrometers in diameter is fabricated for the \( \mu \)EDM hole drilling step and a PCD tool of 100 micrometers in diameter is fabricated for the grinding step. The highest discharge energy for the Panasonic machine, a voltage of 110 and a capacitance of 3300 pF, are chosen for the EDM drilling step since the surface roughness and straightness of the hole should not affect the finished hole. During the grinding step a pecking routine is implemented which feeds the PCD tool downward at a rate of 2 micrometers per second in 50 micrometer increments and then backs out of the hole to allow the swarf to exit the cutting zone, see Figure 3. Four holes are machined and measured to provide statistical information for the straightness, waviness, and roughness of the holes.

4. Metrology of Micro Holes

Metrology is conducted with scanning white light interferometry (SWLI). Three-dimensional surface profiles of the holes are measured by placing the tungsten carbide blocks on their side and scanning in the trough of the hole. The interferometer can only measure approximately one-quarter of the hole due to scattering of the light near the vertical side walls, but the data is sufficient for characterizing the straightness and rough-
Step 1: Drill a ø90 μm hole 200 μm deep with μEDM
Step 2: Grind the hole with a ø100 μm PCD tool, 50 μm deep
Step 3: Retract the tool, then grind the hole 100 μm deep
Step 4: Retract the tool, then grind the hole 150 μm deep
Step 5: Retract the tool, then grind the hole 200 μm deep

Fig. 3. Hybrid drilling process composed of μEDM hole drilling (step 1) and grinding with PCD tools (steps 2-5)

ness of the holes. The 3D surface is analyzed using scripts written for the Matlab mathematics application. First, the best fit cylinder removed from the data with a least squares method. The x, y, z coordinates for a cylinder can be written as shown in Eq (1), where a, b, c is the direction cosine of the cylinder axis, x0, y0, z0 are a point on the axis, and R is the cylinder radius.[7]

\[
[c(y - y_0) - b(z - z_0)]^2 + [a(z - z_0) - c(x - x_0)]^2 + [b(x - x_0) - a(y - y_0)]^2 = R^2 \quad (1)
\]

The distance from a point \((x_i, y_i, z_i)\) to the cylinder is given by Eqs (2)-(5).

\[
d_i = \frac{\sqrt{u_i^2 + v_i^2 + w_i^2}}{\sqrt{a^2 + b^2 + c^2}} - R \quad (2)
\]

where

\[
u_i = c(y_i - y_0) - b(z_i - z_0) \quad (3)
\]

\[
w_i = b(x_i - x_0) - a(y_i - y_0) \quad (5)
\]

The parameters \(a, b, c, x_0, y_0, z_0,\)and \(R\) are found by minimization using Eq (6) and the Gauss-Newton method for solving nonlinear least-squares problems.[8]

\[
\min \left[ \frac{1}{2} \sum_i d_i^2 \right] \quad (6)
\]

Due to tool wear at the tip of each hole, as shown in Figure 4, only the top three-fourths of the hole is used for the cylindrical fit. Once the cylinder has been removed, see Figure 5, two-dimensional profiles are acquired which run the length of the hole. These profiles are filtered with a simplified gaussian filter[6] to separate the form, waviness and roughness profiles of the edge of the holes. A form-to-waviness cut-off wavelength of 18 micrometers and waviness-to-roughness cutoff wavelength of 3.39 micrometers is chosen based on our experience with cylindrical tools.[4] Figure 6 shows an example of the profiles obtained with the modified gaussian filter. Twenty profiles are extracted from each hole to provide more data for the statistical analysis.

Fig. 4. 3D scan of micro hole with 2d profiles. The blind bottom and open end are on the left and right of the data, respectively.

Fig. 5. 3D scan of micro hole with 2d profiles after cylinder removal

Fig. 6. Example of profile filtering
5. Results

Figure 7 shows an SEM micrograph of one of the holes machined with the hybrid process. Some debris remains in the hole, but, except for the debris the hole is smooth and straight. The bottom center of the hole is still rough, but these are remnants from micro EDM predrill step. The PCD grinding step did not drill down as far as the EDM step due to a tool zero problem. This error can be eliminated in future implementations. The side of the groove is free of imperfections due to the EDM predrill step, therefore it is suitable for the metrology measurements.

Figure 8 is a statistical boxplot of the resulting straightness, waviness, and roughness of the grooves. This data shows that the averages for straightness, waviness, and roughness are 493, 311, and 65 nanometers respectively.

6. Conclusion

Statistical data shows that straightness, waviness, and roughness of holes drilled in hard, conductive materials, like tungsten carbide, can be improved with the hybrid process described in this paper. Optimization of the process parameters, such as µEDM predrill size and pecking routine, will yield holes free of imperfections or swarf.

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References