Electric Discharge Machining of Tungsten Carbide using Uncoated and Coated Wire Electrodes: Analysis of Cutting Speed and Workpiece Geometrical Accuracy

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Abstract. Tungsten carbide is an important tool and die material due to its excellent mechanical properties such as high hardness, good toughness, and wear resistance. Wire electric discharge machining (WEDM) is regarded as a process capable of machining complex geometries and curved features in difficult-to-cut tungsten carbide. The present research work is carried out to study the influence of wire electrode, workpiece taper angle, and WEDM parameters on cutting speed and geometrical error of curved profile machined in tungsten carbide. Experiments are performed based on Taguchi’s L18 orthogonal array using two types of wires; uncoated brass wire and zinc-coated brass wire. Experimental results indicate that zinc-coated brass wire offers higher cutting speed as compared to uncoated brass wire. Main effects plots show that pulse-on time and pulse-off time are the most significant factors affecting cutting speed while taper angle is the most significant factor for geometrical error.

1. Introduction

Tungsten Carbide (WC) is a well known material for manufacturing of cutting tools, dies, molds, and other wear resistant parts due to its high hardness and strength at a wide range of temperatures [1]. High hardness of WC imparts brittleness making this material difficult to machine. The requirement of rigid machining setup and expensive tooling along with the difficulty in producing complex profiles in conventional machining of WC necessitates using non-conventional machining methods for processing of this material. Wire electric discharge machining (WEDM) is an established non-conventional process for machining of complex features and tapered profiles in very hard materials like carbides, metal matrix composites, titanium based alloys, and nickel based super alloys [2]. This process uses electrode in the form of a thin wire to erode the workpiece material. Along with other electrical and mechanical parameters, the performance of WEDM process also depends upon the properties of wire electrode. There are various types of wires that have been developed to be used as a tool for WEDM operation. As the requirements of higher productivity, better surface finish and higher precision in WEDM operation are increasing, therefore, there is a need to evaluate the machining performance of different types of wire electrodes.

Researchers have studied the performance of various types of coated and uncoated wires for electric discharge machining of titanium alloys, nickel based super alloys, and metal matrix composites. Antar et al. [3] compared the performance of two types of coated wires (copper core with CuZn50 coating and copper core with zinc rich brass coating) with uncoated brass wire for machining of aerospace alloys. They found that cutting rate of coated wires was upto 70% higher than that of
brass wire. Moreover, 25% thinner recast layer was obtained with coated wires. Klocke et al. [4] evaluated the machining performance of three types of wire electrodes including uncoated brass wire, zinc-rich brass coated copper wire, and nickel coated copper wire for generation of fir tree slots in Inconel 718. The results revealed that uncoated brass wire produced best accuracy and surface integrity with almost zero recast layer but its cutting speed was lower than that of zinc-rich brass coated copper wire. Ramamurthy et al. [5] analyzed the effect of three types of wire electrodes including plain brass wire, zinc coated brass wire, and diffusion coated brass wire on machining characteristics of Ti-6Al-4V alloy. The results showed that diffusion coated brass wire produced the lowest surface roughness and minimum kerf width. Patil et al. [6] studied the effect of wire material properties on machining performance of ceramic particle reinforced aluminum matrix composites. They found that copper core CuZn50-coated wire offered higher cutting speed and lower kerf width as compared to plain brass wire but surface roughness was significantly increased by the use of coated wire.

A review of literature related to WEDM of tungsten carbide revealed that though several type of wires have been employed for machining of this material [7-10] but the effect of wire properties on machining performance has never been studied. Also, no research work was found addressing the machining of curved profiles in taper mode in WC by using coated wire. Therefore, the present study is undertaken to fill this gap.

This research work is carried out to evaluate the machining performance of uncoated brass wire and zinc-coated brass wire in terms of cutting speed and geometrical error of curved profile in tungsten carbide. Main effects plots are drawn in order to study the influence of workpiece taper angle and WEDM parameters on performance characteristics.

2. Experimentation

Tungsten carbide workpiece was machined on CHMER G43S WEDM using de-ionized water as a dielectric fluid. The chemical composition of workpiece material is presented in Table 1. Machining setup and geometry of workpiece are shown in Fig. 1 and Fig. 2, respectively. A concave curved profile having a radius of 5 mm was generated on workpiece in taper cutting mode. Two types of wire electrodes, uncoated brass wire (Wire A) and zinc-coated brass wire (Wire B), having a diameter of 0.2 mm were used to perform experimentation.

| Table 1. Chemical Composition of Tungsten Carbide |
|---------|-------|-------|-------|-------|-------|-------|
| **Element** | W     | C     | Co    | Ni    | Fe    | Ti    |
| **Weight (%)** | 87.6  | 5     | 6.5   | 0.18  | 0.06  | 0.6   |

![Clamping Wire electrode Workpiece](image1)

**Figure 1.** Machining setup

![Concave Profile](image2)

**Figure 2.** Geometry of machined workpiece

Experimental design was based on Taguchi’s L18 orthogonal array. There were five control factors namely taper angle, pulse-on time, pulse-off time, servo voltage and wire tension. Variable control factors and their levels are presented in Table 2. Constant parameters for WEDM were open voltage =
85 volt, arc-on time = 0.2 µsec, arc-off time = 20 µsec, wire feed = 140 mm/sec, and dielectric pressure (upper nozzle = 10 kg/cm², lower nozzle = 8 kg/cm²).

Table 2. Variable Control Factors and Their Levels

| Sr. No | Control Factor | Symbol | Unit | Level 1 | Level 2 | Level 3 |
|--------|----------------|--------|------|---------|---------|---------|
| 1      | Taper Angle    | TA     | Degree | 5       | 10.5    | ---     |
| 2      | Pulse-on time  | ON     | µsec  | 0.2     | 0.3     | 0.4     |
| 3      | Pulse-off time | OFF    | µsec  | 20      | 25      | 30      |
| 4      | Servo voltage  | SV     | Volt  | 45      | 50      | 55      |
| 5      | Wire tension   | WT     | g     | 630     | 730     | 870     |

There were two response variables namely cutting speed (CS) and geometrical error (GE) of machined profile. Cutting speed was directly noted from WEDM display. Radius of curved profile was measured using video camera option of co-ordinate measuring machine (Model: CHEN WEI CE-450DV). After recording the measurement values, geometrical error was calculated by Eq. (1):

\[
\text{Geometrical Error} = \text{Nominal Radius} - \text{Measured Radius} \quad (1)
\]

3. Results And Analysis

Table 3. Taguchi L18 Orthogonal Array and Response Variables

| Exp. No. | TA  | ON  | OFF | SV  | WT  | Cutting Speed (CS) | Geometrical Error (GE) |
|----------|-----|-----|-----|-----|-----|--------------------|------------------------|
|          |     |     |     |     |     | mm/min             | µm                     |
|          |     |     |     |     |     | Wire A            | Wire B                    |
|          |     |     |     |     |     | Wire A            | Wire B                    |
| 1        | 5   | 0.2 | 20  | 45  | 630 | 0.86              | 0.93                    |
| 2        | 5   | 0.2 | 25  | 50  | 730 | 0.75              | 0.79                    |
| 3        | 5   | 0.2 | 30  | 55  | 870 | 0.65              | 0.72                    |
| 4        | 5   | 0.3 | 20  | 45  | 730 | 1.07              | 1.19                    |
| 5        | 5   | 0.3 | 25  | 50  | 870 | 0.97              | 1.04                    |
| 6        | 5   | 0.3 | 30  | 55  | 630 | 0.82              | 0.92                    |
| 7        | 5   | 0.4 | 20  | 50  | 630 | 1.27              | 1.37                    |
| 8        | 5   | 0.4 | 25  | 55  | 730 | 1.09              | 1.19                    |
| 9        | 5   | 0.4 | 30  | 45  | 870 | 1.09              | 1.17                    |
| 10       | 10.5| 0.2 | 20  | 55  | 870 | 0.87              | 0.95                    |
| 11       | 10.5| 0.2 | 25  | 45  | 630 | 0.79              | 0.87                    |
| 12       | 10.5| 0.2 | 30  | 50  | 730 | 0.68              | 0.77                    |
| 13       | 10.5| 0.3 | 20  | 50  | 870 | 1.09              | 1.27                    |
| 14       | 10.5| 0.3 | 25  | 55  | 630 | 0.90              | 1.03                    |
| 15       | 10.5| 0.3 | 30  | 45  | 730 | 0.88              | 0.95                    |
| 16       | 10.5| 0.4 | 20  | 55  | 730 | 1.23              | 1.40                    |
| 17       | 10.5| 0.4 | 25  | 45  | 870 | 1.19              | 1.34                    |
| 18       | 10.5| 0.4 | 30  | 50  | 630 | 1.02              | 1.11                    |

Comparison of cutting speed for wire A and wire B against each experimental condition is presented in Fig. 3. It can be seen that cutting speed of wire B is higher than that of wire A. This may be attributed to presence of zinc coating on wire B. Zinc has very low melting point (419°C) and even
its boiling temperature (906°C) is lower than the melting temperature of brass (930°C). Very low melting temperature of zinc helps to improve spark formation by reducing the ionization time of dielectric fluid [3]. In addition, low melting/vaporization temperature of wire coating also affects the distribution of discharge energy between wire and workpiece. Lesser energy is absorbed by zinc-coated wire electrode as compared to plain brass wire having high melting/evaporation temperature [6]. Therefore, most of the gap energy is supplied to the workpiece. This is the possible reason for obtaining higher cutting speed when machining is performed using zinc-coated wire.

Maximum improvement (16.5%) in cutting speed using wire B is obtained for Exp. No. 13. Cutting speed of wire B can be further enhanced by increasing pulse-on time but then frequent wire breakage occurs making the process unstable.

Figure 3. Comparison of cutting speeds for wire A and wire B

3.1. Effect of Control Factors on Performance Measures
Influence of control factors on performance measures is studied with the help of main effects plots. In order to draw the plot of a factor, the average value of response variable against each level of that factor is required. These averages are calculated by using data from Table 3.

For cutting speed, both the wires have shown similar trends as depicted in Fig. 4. Pulse-on time (ON) is the most significant factor followed by pulse-off time (OFF). Cutting speed increases with increase in pulse-on time. At higher pulse-on time, greater discharge energy is supplied to the spark gap resulting in melting and evaporation of material at a faster rate hence cutting rate increases. Cutting speed has shown a decreasing trend with increase in pulse-off time (OFF) and servo voltage (SV). Number of discharges occurring in a given time period decreases with increase in time interval between two consecutive pulses (pulse-off time) causing a reduction in cutting speed. Increase in servo voltage widens the gap between wire and workpiece, therefore, spark intensity is reduced and cutting speed becomes slow. For wire tension (WT), cutting speed is higher at level 3 (870g). The higher value of wire tension causes a reduction in amplitude of wire vibrations so the kerf width is reduced and higher cutting speed is obtained for the same value of discharge energy [11].

Figure 4. Main effects plots for cutting speed (wire A and wire B)
It can be seen from Table 3 that the value of geometrical error (GE) is positive for all experiments. It means that measured radius of concave curved profile is always lesser than the nominal radius of 5 mm.

Main effects plots for geometrical error in curved profile machined using wire A and wire B are presented in Fig. 5. It can be seen that taper angle (TA) is the most significant parameter. Geometrical error is higher for the workpiece that is machined at higher taper angle. This may be due to the reason that at high value of taper angle, wire cannot adapt to the geometry of the guides due to its rigidity and there is a large deviation between programmed shape and actual shape of wire [12]. When machining is performed with this deformed wire, higher value of geometrical error is experienced. Geometrical error decreases with increase in pulse-on time, pulse-off time, and servo voltage. Higher value of pulse-on time causes more erosion of workpiece material, resulting in increased radius of curved profile so the geometrical error is reduced. Increase in pulse-off time minimizes the chances of re-deposition of debris due to better flushing and higher servo voltage increases sparking gap width thereby stabilizing the WEDM process. Increase in wire tension (WT) results in increased geometrical error. This may be attributed to reduced amplitude of wire vibrations at higher WT causing a decrease in kerf width, therefore, the radius of concave curved profile decreases [13] resulting in higher value of geometrical error.

**Figure 5.** Main effects plots for geometrical error (wire A and wire B)

### 4. Conclusions
In present research work, the performance of uncoated brass wire and zinc-coated brass wire is evaluated for machining of curved profile in tungsten carbide in taper cutting mode of WEDM under various experimental conditions. Following conclusions can be drawn from experimental results and analysis:

- Cutting speed of zinc-coated brass wire is up to 16.5% higher as compared to that of uncoated brass wire.
- Pulse-on time and pulse-off time are the most significant parameters affecting cutting speed for both the wires.
- Geometrical accuracy of curved profile is significantly affected by the value of workpiece taper angle. Higher value of taper angle gives rise to geometrical error.

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