A STUDY ON THE PERFORMANCE OF COPPER-GRAPHITE AS TOOL MATERIAL IN MICROMACHINING BY MICRO ELECTRO DISCHARGE MACHINING

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INTRODUCTION

Micro products and components offer unique advantages. They occupy less space and consume less energy and material. They can be cheaper. Hence there is a strong demand for miniaturized components from diverse industries such as electronics, medical and aviation. Product miniaturization demands innovative manufacturing methods. Lithography based MEMS fabrication technologies are capable of producing micro and sub-micrometer size features. However the MEMS techniques do have limitations such as restricted choice of work materials, inability to produce complex geometries, huge capital investment and inevitable cleanroom environment. To complement MEMS techniques, various existing macro machining processes are being modified to perform micromachining. Electro discharge machining (EDM) is one such process used for the machining of electrically conductive materials especially hard metals. By reducing the tool dimensions and the discharge energy, EDM has been successfully downscaled to suit the requirements of micromachining such as reduced unit removal [1]. Unlike EDM, which typically uses a wide range of electrode materials such as graphite, copper, brass and their combinations, the micro EDM process predominantly uses tungsten as tool material due to its low wear [2]. However the major concern is that micro EDM is a slow process when compared to its mechanical counterparts like micro drilling, milling and turning. Search for alternate micro EDM tool material to increase the micro EDM productivity is a vibrant research area [3, 4].

This paper presents the outcome of experimental investigations carried out to assess the performance of copper-graphite as tool electrode material in micro EDM. Micro hole and micro slot machining were conducted on hardened tool steel. The results were compared with that of tungsten, the de-facto standard micro EDM tool electrode.

EXPERIMENTAL DETAILS

Micro EDM studies were conducted in Panasonic micro EDM (MG-ED72W) with standard setup. Experimental work involves spark erosion of three sets of micro holes and micro slot machining in tool steel using copper-graphite and tungsten electrodes. The experimental conditions are shown in *TABLE 1*.

TABLE 1. Experimental conditions.

Work material	Tool steel XW42
Tool material (Ø ~ 300 μm)	Copper-graphite Tungsten
Dielectric	Commonwealth 185
Open circuit voltage	110 (V)
Capacitance	3300 (pF)
Programmed feed	800,50 μm for micro hole, slot respectively
Programmed feed rate	3 μm/sec
Tool rotation	~ 3000 RPM
Polarity	Tool electrode negative and workpiece positive

The tungsten and copper-graphite tool electrodes were machined to Ø ~ 82 and 90 μm respectively, using the built-in wire electro discharge grinding process. The physical properties of the materials used are shown in *TABLE 2*.

The surface roughness was measured by WYKO laser interferometer. The micro holes were measured using optical microscope. Hitachi S-3000 N scanning electron microscope was used to examine the craters produced by micro EDM.

TABLE 2. Physical properties of the materials.

Property	XW42	Cu-graphite	Tung-sten
Density (g/cm^3)	7.86	3.05	19.3
Thermal conductivity (Wm^{-1}K^{-1})	26	-	174
Melting point (K)	1697	-	3695
Boiling point (K)	~ 3000	-	5828
Young's modulus (GPa)	200	-	345
Resistivity (μΩcm)	17.4	305	5.4

RESULTS AND DISCUSSION

Electrode wear

The programmed feed for the micro drilling is 800 μm. The hole depth and tool wear obtained for this feed for both the electrodes is shown in *FIGURE 1*. From the *FIGURE 1* it can be seen that the tool wear is more for copper-graphite electrode. The worn out graphite particle suspended in dielectric medium cause a reduction in the breakdown voltage of the dielectric and as a result both material removal rate and tool wear increases [5].

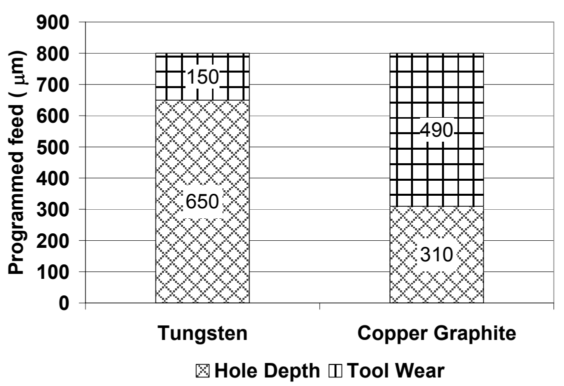

FIGURE 1. The hole depth achieved and the tool wear in tungsten and copper-graphite electrodes.

The time taken by the tool electrodes to attain the programmed feed is shown in *FIGURE 2.* The average feed rate achieved by copper-graphite is 2.83 μm/s, which is uniform through out the machining. For the tungsten electrode two phases can be seen. A feed rate of 1.63 μm/s is achieved up to about 600 μm. Above this, the feed rate has fallen to 0.69 μm/s. Since the density of copper-graphite, as can be seen from *TABLE 2*, is lower than the other two materials, the lighter debris produced by copper-graphite can be easily flushed out of the sparking zone.

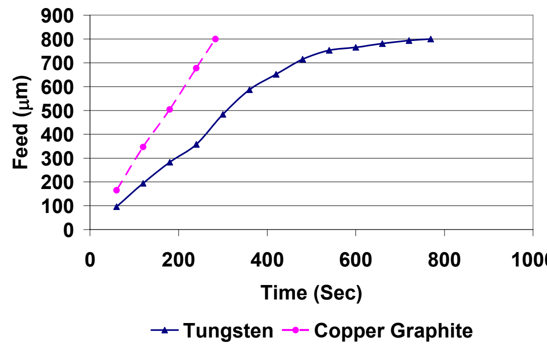

FIGURE 2. Feed vs. time for tungsten and copper graphite electrodes.

Moreover, from *FIGURE 1*, it is evident that most of the material removal in the case of copper-graphite is from the tool and hence the hole drilled is shallower and the debris removal is easier.Consequently, the feed rate achieved by copper-graphite is very close to the programmed feed rate of 3 μm/s. Similarly for tungsten too, higher feed rate is achieved for lower hole depth. When the hole depth increases, debris removal becomes difficult and the machining process is hindered. Hence the feed rate falls down during latter stage. From *FIGURE 1* it is clear that the tool wear is much less for tungsten and hence it is preferable for applications requiring better profile accuracy.

Material removal rate

The material removal rate was calculated from the hole / slot depth and the machining time for both the electrodes and is given in *FIGURE 3*.

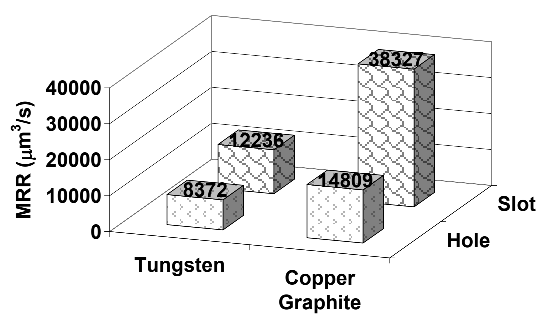

FIGURE 3. MRR for tungsten and copper-graphite electrodes during micro drilling and micro slot machining.

The MRR achieved by copper-graphite in micro drilling is about 77% higher than that of tungsten. This may be due to the material effect or it may be due to the easier debris removal in the case of copper-graphite, as discussed in the previous section. To clear this ambiguity, it was decided to machine shallow micro slots using both the electrodes. The programmed depth of the micro slot was only 50 µm to keep it shallow. This facilitates easier debris removal and ensures smoother machining. The slots machined were measured using an optical microscope and found that the average volume of material removed in slot machining is 1541786 µm^3 and 766542 µm^3 respectively for the slots machined by tungsten and copper-graphite. The corresponding machining time were 126 seconds and 20 seconds. This clearly demonstrates the tool electrode material effect on MRR. Since the MRR is higher for the copper-graphite electrode, it can be used for bulk material removal, where profile accuracy is not relevant (e.g. through hole drilling).

Surface roughness

As the spark eroded surface is characterized by the overlapping of randomly spaced craters, the surface roughness is essentially based on the crater size and shape. The crater size is dependent on number of factors, such as discharge energy, material properties, flushing conditions etc. During the electrical discharge a plasma channel is formed between the tool and the workpiece as shown schematically in *FIGURE 4.*

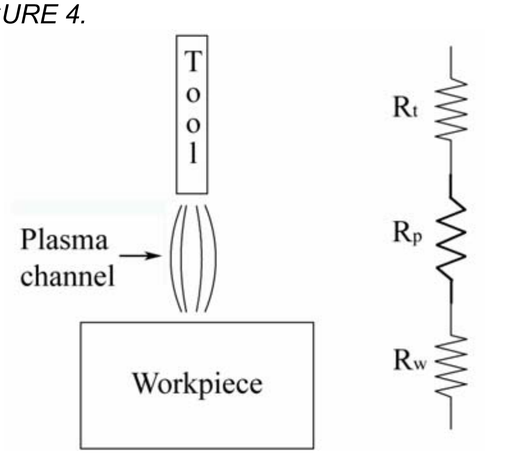

FIGURE 4. Schematic and electrical circuit of sparking zone.

The electrical resistance in the sparking zone is given by

$$R=R_t+R_p+R_w \quad (1)$$

where,

R_t = Resistance of the tool electrode
R_p = Resistance in the plasma channel
R_w = Resistance of the workpiece

When the workpiece is kept constant, the resistance (R) in equation 1 is dependent on the resistance of the tool electrode.

$$R \propto R_t \quad (2)$$

As per the Ohm's law, for the given discharge voltage (V), the relationship between the discharge current (I) and the resistance (R) is given by

$$I \propto \frac{1}{R} \quad (3)$$

Combaining equations 2 and 3, it is clear that the discharge current is dependent on tool electrode resistance as shown below.

$$I \propto \frac{1}{R_t} \quad (4)$$

Actually this discharge and current flow takes place between two asperities (points) in the tool and the workpiece. Considering a point current source on the surface of the workpiece, the current density (J_r) at any distance r from the point is given by

$$J_r = \frac{I}{2\pi r^2} \quad (5)$$

As per the electric field force hypothesis, if a critical current density J_c is required for the removal of a fragment of work material at radius r, the radius at which this current density exists is given by [6]

$$r = \sqrt{\frac{I}{2\pi J_c}} \quad (6)$$

From Equation 6 it is seen that the radius of the crater should be directly proportional to the discharge current. It is also clear from equations 4 and 6 that the crater radius is inversely proportional to the resistance of the tool electrode. Since the resistance of copper-graphite (see Table 2) is higher than that of tungsten, the crater produced by it is to be smaller than the crater produced by tungsten electrode according to the above discussion. The scanning electron microscope (SEM) image of the surfaces machined by the two tool electrodes are shown in *FIGURE 5*.

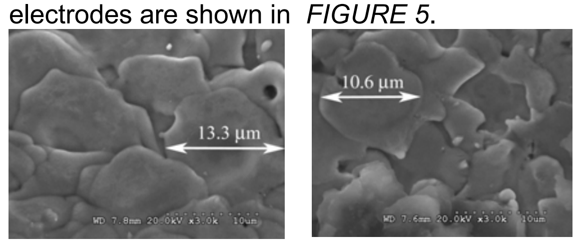

FIGURE 5. SEM images of the machined surfaces. (Left) Surface machined by tungsten electrode (Right) Surface machined by copper-graphite

It is noticed that the size (radius) of a typical crater produced by copper graphite electrode is smaller than the crater size produced by tungsten electrode. This experimental result confirms the theoretical prediction discussed above. Since the copper-tungsten electrode produces smaller craters, the surface roughness produced by this tool is expected to be smaller. The machined surfaces were inspected by laser interferometer to measure the surface roughness achieved by both the electrodes. The results are shown in *FIGURE 6*. As per the prediction, it is noticed that smoother surface is achieved when copper-graphite is used as tool electrode.

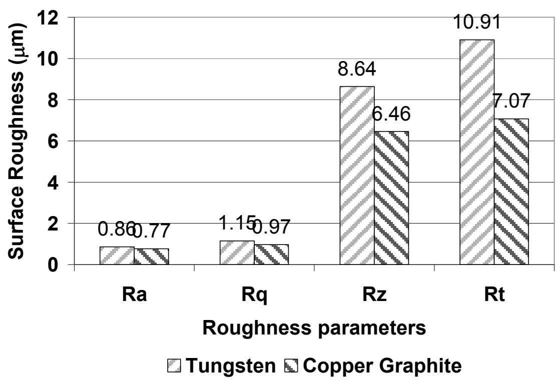

FIGURE 6. Surface roughness produced by tungsten and copper-graphite electrodes.

Spark gap

The spark gap resulted for tungsten and copper-graphite electrodes is shown in *FIGURE 7*.

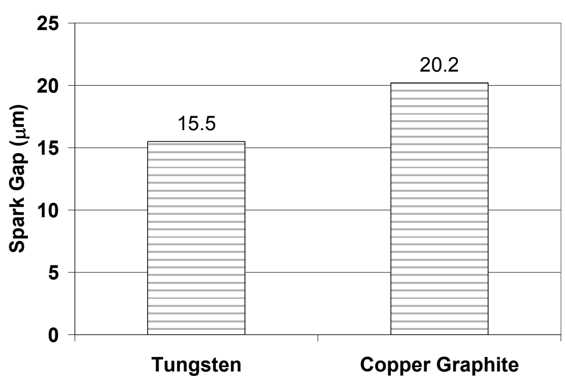

FIGURE 7. Spark gap produced by tungsten and copper-graphite electrodes.

It should be noted that the apparently high spark gaps are due to the rough machining conditions. Even under this rough machining conditions, the spark gap achieved by tungsten is lower that that of copper-graphite. As copper-graphite wears out more rapidly, the dielectric medium will be having more suspended powder materials. These suspended materials cause an increased gap distance. *FIGURE 7* indicates that the profile accuracy will be better when tungsten is used as tool electrode.

CONCLUSIONS

Experiments were carried out to asses the performance of copper-graphite as tool electrode in Micro EDM. Comparison of the results suggests that the productivity can be improved when copper-graphite is used as tool electrode. The machined surface is also smoother than that achieved with tungsten electrode. Hence copper-graphite can be used as tool electrode in applications such as through hole drilling. On the other hand, the tool wear and the spark gap are much lower when tungsten is used. Hence it is preferable to use tungsten as tool electrode for applications such as three-dimensional sculpture machining and micro mould machining where profile accuracy is important. Theoretical prediction and SEM image show that the typical crater size in the machined surface using copper-graphite electrode is smaller than that obtained with tungsten electrode.

ACKNOWLEDGEMENTS

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REFERENCES

1. Masuzawa, T., 2000, State of the Art of Micromachining, *Annals of the CIRP*, 49 (2): 473-488.
2. Tsai, Y.-Y. and Masuzawa, T., 2004, An index to evaluate the wear resistance of the electrode in micro-EDM, *Journal of Materials Processing Technology*, 149: 304-309.
3. Sundaram, M.M., Yeo, S. H., and Rajurkar K.P., 2005, A Study of Tool Electrode Materials and Flushing Techniques in Micro EDM *Proceedings of the ASPE Annual Meeting* 37: 492-495
4. Murali, M. and S. H. Yeo, 2004, A Novel Micro Erosion Technique for the Fabrication of High Aspect Ratio Micro-grooves, *Microsystem Technologies*, 10 (8-9): 628-632
5. Jeswani, M. L., 1981, Effect of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining, *Wear*, 70: 133-139.
6. Williams, E. M., 1952, Theory of electric spark machining, *Electrical Engineering*, 71: 257-260.