EDM Die Sinking of Tool Steel: Performance Evaluation of Electrode Materials for Surface Roughness and Dimensional Accuracy

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Abstract

Electric Discharge Machining (EDM) is one of the most widely used non-conventional metal cutting processes to manufacture close–tolerance products such as dies and molds. The cost of EDM manufactured part is essentially estimated from the cost of electrode, which is determined by the cost of its raw material and manufacturing process. The present work reports an experimental investigation to study the effects of three different electrode materials, *i.e.,* graphite, copper, and copper–tungsten under the same machining conditions. The pulse current, pulse on–time, spark voltage and depth of cut are considered as control process variables, whereas, surface roughness (SR) and dimensional accuracy in terms of side and bottom overcut (OC) are taken as response characteristics for AISI P20. A full factorial design of experimentation approach is adopted to conduct the machining tests. The results reveal that the copper–tungsten is a better performer for a smooth surface finish and better dimensional accuracy than graphite and copper. This study concludes that the copper–tungsten electrode material is a preferable choice for EDM of AISI P20 to improve the life expectancy of dies and molds.

Keywords
AISI P20, Electrode Materials, Full Factorial Design, Surface Roughness, Dimensional Accuracy,

1. Introduction
The machining of dies and molds is considered as a fundamental link in the entire manufacturing chain; almost every discrete part production line uses them particularly the automotive industry (Altan et al. 2001). The surface quality of dies and molds and their cost of manufacturing are crucial because they affect the economy of mass production. Thus, this compels the manufacture to develop the latest technologies. Electric discharge machining is considered one of the promising non-conventional cutting technologies for the manufacturing of dies and moulds. The machining problems such as mechanical stresses and vibrations which alter the surface quality and the dimensionally accuracy, are eliminated in EDM process as there is no physical contact between the tool and the work piece.

During the EDM process, the tool and the work piece act as electrodes and are separated by a minute gap immersed in a dielectric medium. The spark discharges energy, which generates excessive temperature on the work piece surface.

The temperature increases up to 30,000°C causing a small portion of the work piece to vaporize. This creates a tiny crater, which grows as the discharge resumes and take the exact shape of the electrode (Younis et al. 2015).

2. Literature Review

Enormous studies are available on surface quality evaluation with respect to EDM parameters such as pulse current and the pulse on–time (Vikas et al. 2014, Khundrakpam et al. 2013, Kumar et al. 2012, Shabgard et al. 2011). The recent research trend in EDM is skewed towards the effect analysis of electrode material and its geometry (Younis et al. 2015, Kumar et al. 2016, Malhotra et al. 2017, Mascaraque–Ramírez et al. 2018, Bhaumik and Maity 2019).

Of the work, Bhaumik and Maity (2019), evaluate the effects of three different electrode materials, *i.e.*, copper, zinc and brass on the surface integrity of Titanium alloys. While working on the AISI P20 die steel, Bhattacharya et al. (2007), conclude that the increase in discharge voltage, pulse current and pulse duration deteriorates the surface finish. For AISI D2, another grade of die steel, Pradhan and Biswas (2009), investigate the effects of EDM process parameters such as peak current, pulse on–time and pulse off–time on surface roughness. The study reveals that the surface roughness decreased with an increase in pulse off–time and a contrary effect is visualized in case of peak current and pulse on–time. The study recommends copper electrode over zinc and brass for high surface finish. Similarly, Younis et al. (2015), study the effects of two different graphite grades on the surface roughness of tool steel. Dura graphite and Poco graphite are selected as electrodes with pulse current (15, 30, 50 A) and pulse on–time (20-180 µs with 20 µs interval) as process parameters. Dura graphite electrode material appears to have a detrimental effect on the surface quality of the machined part.

The literature review presented above shows that this area still needs to be explored thoroughly; thus, provides an motivation to evaluate the various electrode materials during the EDM of tool/die steel. The present study estimates the effects of three different electrodes materials, *i.e.*, copper, graphite and copper–tungsten on surface quality and dimensional accuracy of AISI P20, a widely used die and mold material for automotive sectors (Zahoor et al., 2018). Pulse current, pulse on–time, spark voltage and depth of cut are considered as process variables.

3. Experimental Details

Being a preferred choice for a die and mold material in regards to the automotive and aerospace industries (Zahoor et al., 2018), AISI P20 tool steel was considered as a work piece material during this research. The spectroscopic elemental composition of AISI P20 is given in Table 1. Moreover, the important thermo–mechanical properties with respect to EDM are also listed in Table 2.

Table 1. Elemental composition of AISI P20

Element	C	Si	Mn	Mo	Cr	S	Fe
Weight (%)	0.299	0.404	1.07	0.15	1.92	0.037	Balance

Table 2. Thermo–mechanical properties of AISI P20

Properties	Value
Density (lb/m$^{3)}$	0.284
Compressive strength (MPa)	862
Thermal conductivity (W m^{-1} K^{-1})	41.5
Melting point (ºF)	2600

EDM was performed on rectangular bars (150×60×10 mm^3) of AISI P20 using RJ–230 EDM die sinking (Creator, Taiwan). With regards to EDM process variables, pulse current, pulse on–time, spark voltage and depth of cut were taken after a careful literature review (Gopalalkannam and Senthilvelan, 2012 and Bhaumik and Maity, 2019), see Table 3 for more details and Kerosene oil was used as dielectric fluid for flushing.

Table 3. Machining conditions used during the EDM of AISI P20

Parameter	Specification
Pulse current (A)	6,8,10,12,14
Pulse on–time (μsec)	60,70,80,90,100
Spark voltage (V)	20
Depth of cut (mm)	0.5
Electric polarity	Positive
Dielectric used	Kerosene oil

The main objective of this research is to investigate the effects of different electrode materials on the response characteristics which are considered vital for the die and mold manufacturing, *i.e.*, surface quality and the dimensional accuracy. For surface quality measurement, the widely used arithmetic average surface roughness (R_a) parameter was considered and measured using Surtronic 5128 surface texture meter (Taylor Hobbson, England) after setting up the parameters at 4 mm evaluation length and a 0.8 mm cut–off length. While for the dimensional accuracy measurement, overcut (OC) parameter was taken and measured using CE 450DV coordinate measuring machine (Chein Wei, Taiwan). In EDM die sinking, the machined profile is always larger than the electrode geometrical dimensions and this difference is called OC as shown in Fig. 1. It is influenced by the side sparks produced during the process and varied according to pulse current, pulse on–time and electrode material (Sing et al., 2004). Eq. 1 was used to calculate the side and bottom overcut. A full factorial design of experimentation scheme was used and same was replicated for all the three electrode materials. A statistical analysis of input variables were carried out to examine their behavior for the response attributes.

$$OC = D_{achieved} - D_{electrode\ tool} \quad (1)$$

Where; D is used for dimension of the profile

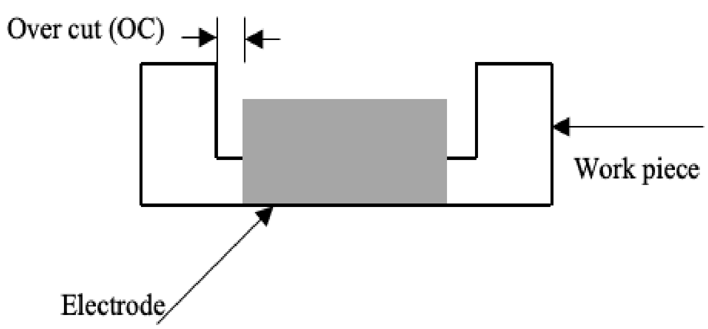

Figure 1. Schematic of overcut

3.1 Electrode Materials

The performance success of an electrode depends primarily on the cutting conditions and the work piece material. However, materials with high melting point and low electric resistance are considered best suited for the process. Therefore, electrodes materials such as copper, graphite and copper–tungsten are widely recommended for the EDM of tool/die steel (Gopalalkannam and Senthilvelan, 2012). The physical properties of all the three electrode materials employed during the current experimental investigation are listed in Table 4. A square geometry of 18×18 mm electrode was consumed to machine a profile on the work piece.

Table 4. Physical properties of electrode material

Material	Graphite	Copper	Copper–tungsten
Composition	100%	100%	75% tungsten–25% copper
Density (g/cm^3)	1.811	8.96	14.84
Melting point (ºc)	3675	1084	3410
Electrical resistivity (µΩ cm)	14	9	3.83

4. Experimental Results and Discussion

The cost of EDM manufactured component is essentially estimated from the cost of an electrode, which is determined by the cost of its raw material and manufacturing process. More than 70% of the EDM operation cost is dedicated to the electrode cost (Czelusniak et al., 2019). Therefore, this study evaluates the performance of three different electrode materials for the surface quality and the dimensional accuracy of AISI P20 employed under the same machining conditions and are discussed in the subsequent sections.

4.1 Effects of Electrode Materials on Surface Roughness, (SR) Under the Same Machining Conditions

The measured surface roughness results after the machining tests using full factorial approach are presented in Table 5 below. In this design approach, data is obtained at every possible combination of parametric levels to evaluate all the main effects and interactions. During this experimental study, one variable at five levels (5^1)and three variables at level one (1^3) were considered. A set of five test runs were conducted with three replications (to measure the data dispersion) for each data set.

Table 5. Surface roughness values of AISI P20 using full factorial approach

Test run	Input variable	Constant variable	Surface roughness (µm)		
	Pulse current (A)	Spark voltage (V) 20	Graphite	Copper	Copper–tungsten
1	6	Pulse on–time (µsec) 80	6.86	8.13	5.336
2	8	Depth of cut (mm) 0.5	8.45	9.53	6.9
3	10		9.433	10.43	7.8
4	12		9.87	11.746	9.45
5	14		11.522	13.01	10.53
	Pulse on–time (µsec)	Spark voltage (V) 20	Graphite	Copper	Copper–tungsten
6	60	Pulse current (A) 10	11.50	8.06	9.87
7	70	Depth of cut (mm) 0.5	10.68	9.53	8.45
8	80		10.53	11.02	8.09
9	90		11.78	12.13	7.13
10	100		12.64	13.02	6.86

From Figure 2, it can be seen that the pulse current exhibits an increasing trend in case of surface roughness. Regardless of the electrode materials, the SR values are increased with the increase in pulse current. However, for the range of pulse current used during this study, *i.e*., 6 A–12 A, copper–tungsten electrode shows better performance for SR compared to the other two materials. The copper electrode has produced the poorest surface quality, while the graphite falls in between of them. It is attributed to the fact that the high pulse current results in high material removal rate, which leads to the formation of larger and deeper craters. Moreover, high melting point of graphite (3675 ºc) offers less electrode wear as compared to the copper electrode; hence, produces better surface finish.

On the other hand, copper–tungsten electrode stands out with the minimum SR values. The copper–tungsten provides an edge by combining the properties of copper (high electric conductivity) and tungsten (high melting point). This contibutes to low electrode wear and fine surface quality. These results are in agreement with the available literature (Salman and Kayacan, 2008). Salman and Kayacan (2008), compare the effects of copper–tungsten electrodes with graphite on surface roughness of D2 steel during the EDM. The study concludes that the copper–tungsten electrode performs better than graphite for surface quality.

Considering the pulse on–time, almost a similar pattern to pulse current can be observed from Fig. 3. in the case of graphite and copper electrodes. The time duration allows the current to flow in each cycle, an increase in time duration increases the surface roughness values. A large time duration causes more tool wear, which deteriorates the surface finish. In contrast, copper–tungsten electrode demonstrates a decreasing trend with increase in pulse on–time. Figure 3 illustrates that graphite and copper electrode yielded comparable results while copper–tungsten produced smaller SR values compared to them.

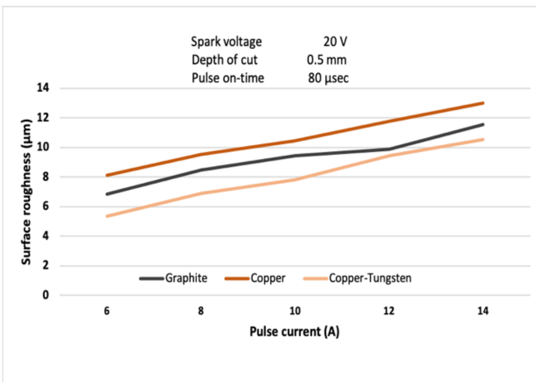

Figure 2. Effects of pulse current on surface roughness of AISI P20

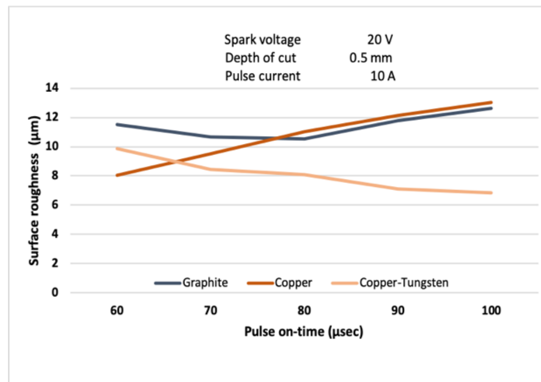

Figure 3. Effects of pulse on–time on surface roughness of AISI P20

4.2 Effects of Electrode Materials on Side and Bottom Overcut (OC), Under the Same Machining Conditions

The calculated side and bottom overcut results after the machining tests using full factorial approach are presented in Table 6 and Table 7, respectively.

Table 6. Overcut values of AISI P20 using full factorial approach

Test run	Input variable	Constant variable		Overcut (mm)		
	Pulse current (A)	Spark voltage (V) Pulse on–time (µsec) Depth of cut (mm)	20 80 0.5	Graphite	Copper	Copper–tungsten
1	6			0.15 (side) 0.16 (bottom)	0.15 (side) 0.16 (bottom)	0.07 (side) 0.08 (bottom)
2	8			0.16 (side) 0.16 (bottom)	0.13 (side) 0.14 (bottom)	0.06 (side) 0.07 (bottom)
3	10			0.18 (side) 0.17 (bottom)	0.11 (side) 0.14 (bottom)	0.06 (side) 0.06 (bottom)
4	12			0.20 (side) 0.19 (bottom)	0.12 (side) 0.13 (bottom)	0.05 (side) 0.05 (bottom)
5	14			0.21 (side) 0.20 (bottom)	0.10 (side) 0.11 (bottom)	0.04 (side) 0.05 (bottom)

Table 7. Overcut values of AISI P20 using full factorial approach

Test run	Input variable: Pulse on–time (μsec)	Constant variable		Overcut (mm): Graphite	Copper	Copper–tungsten
		Spark voltage (V)	20			
		Pulse current (A)	10			
6	60	Depth of cut (mm)	0.5	0.17 (side) 0.18 (bottom)	0.16 (side) 0.15 (bottom)	0.08 (side) 0.07 (bottom)
7	70			0.16 (side) 0.16 (bottom)	0.16 (side) 0.16 (bottom)	0.06 (side) 0.05 (bottom)
8	80			0.19 (side) 0.16 (bottom)	0.14 (side) 0.15 (bottom)	0.07 (side) 0.05 (bottom)
9	90			0.21 (side) 0.18 (bottom)	0.13 (side) 0.14 (bottom)	0.05 (side) 0.04 (bottom)
10	100			0.23 (side) 0.19 (bottom)	0.12 (side) 0.12 (bottom)	0.05 (side) 0.03 (bottom)

The dimensional accuracy is vital for applications where close–tolerance product is required such as dies and molds manufacturing for aerospace and automotive industries. Generally, the low overcut values are associated with the low pulse current and pulse on–time which is attributed to the low erosion rate. Figures 4 and 5 show the side and bottom overcut values produced by the three different electrode materials, respectively. In the case of graphite, a similar trend can be observed, *i.e.,* small values of pulse current results low overcut values and in good agreement with the literature (Gopalalkannam and Senthilvelan, 2012). Gopalalkannam and Senthilvelan (2012), present the results for the diametral overcut of AISI 316 steel. The study reveals that small overcut is achieved at low pulse current values. It is attributed to its high spark dispersing effects.

In the contrary, the copper–tungsten electrode gives small and consistent overcut values of 0.01 mm for side and bottom overcut at high values of pulse current. The overcut values of copper is also in decreasing trend at high pulse current. The overcut not only depends on the pulse current but also on pulse on–time as shown in Fig. 6 and 7.

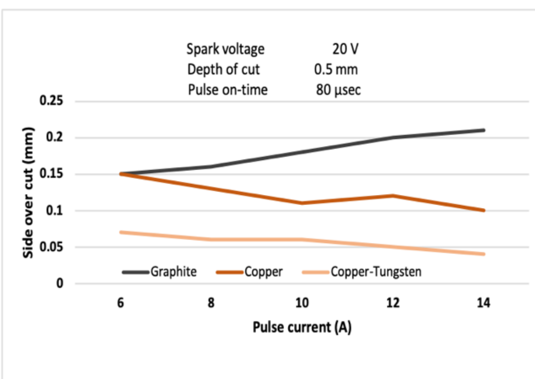

Figure 4. Effects of pulse current on side overcut

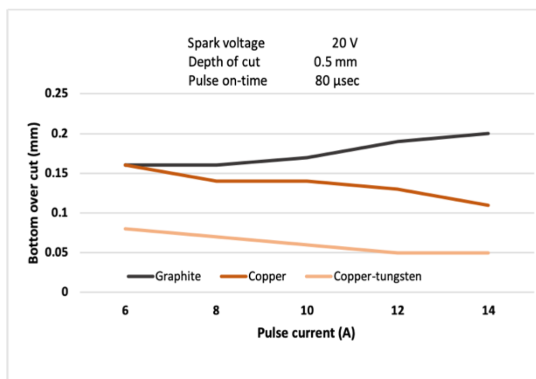

Figure 5. Effects of pulse current on bottom overcut

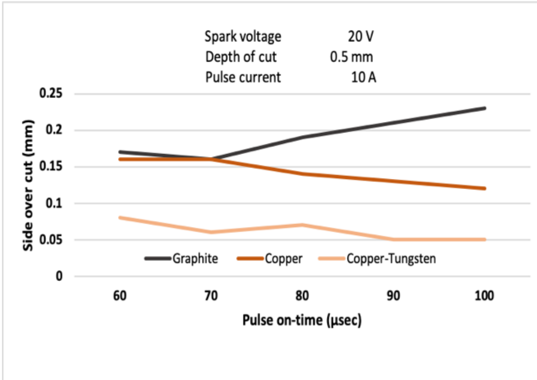

Figure 6. Effects of pulse on–time on side overcut

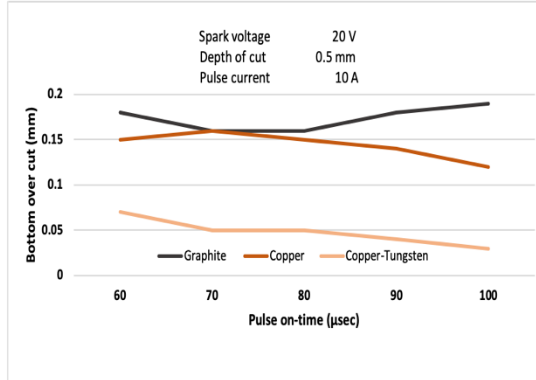

Figure 7. Effects of pulse on–time on bottom overcut

5. Conclusions

With the aim to improve the surface quality and the dimensional accuracy, three electrode materials were experimentally investigated under the same EDM machining conditions for AISI P20 tool steel. After the main effects analysis and discussion, the following inferences are made:

I. The copper–tungsten electrode offers comparatively better surface finish for the tested work material whereas, the copper and graphite electrodes show poor performance resulting in high values of surface roughness.
II. Regardless the electrode material, pulse current has an almost linear increasing relationship with the surface roughness. However, the copper–tungsten electrode presents small surface roughness value of 5.336 μm at 6 A pulse current. Moreover, the copper electrode offers the poorest surface quality.
III. In case of pulse on–time, the copper–tungsten electrode possesses a decreasing trend at high values of pulse on–time though. Yet a high value of surface roughness 5.60 μm is achieved at 100 μsec pulse on–time compared to pulse current.
IV. For the dimensional accuracy, copper–tungsten electrode gives low side and bottom overcut with a consistent interval of 0.01 mm than copper and graphite materials.
V. Both pulse current and pulse on–time demonstrate a decreasing trend at high values for copper and copper–tungsten electrodes, whereas, graphite exhibits an opposite pattern.
VI. This study concludes that the copper–tungsten electrode material is a preferable choice for EDM of AISI P20 to improve the life expectancy of dies and molds.

The process cost analysis will be considered for the future work extension in the journal submission.

References

Altan, T., Lilly, B., Yen, Y.C., Altan, T., Manufacturing of dies and molds, *CIRP Annals*, vol. 50, no. 2, pp. 404-422, 2001.

Bhaumik, M., Maity, K., Effect of electrode materials on different EDM aspects of titanium alloy, *Silicon*, vol. 11, pp. 187-196, 2019.

Bhattacharya, B., Gangopadhyay, S., Sarkar, B.R., Modeling and analysis of EDMED job surface integrity, *Journal of Materials Processing Technology,* vol. 189, no. 1-3, pp. 169-177, 2007.

Czelusniak, T., Higa, C.F., Torres, R.D., Laurindo, C.A.H., Fernandes de Paiva Júnior, J.M., Lohrengel, A., Amorim, F.L., Materials used for sinking EDM electrodes: a review, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, no. 14, 2019.

Gopalakannan, S., Senthilvelan, T., Effect of electrode materials on electric discharge machining of 316 L and 17-4 PH stainless steels, *Journal of Minerals and Materials Characterization and Engineering*, vol. 11, pp. 685-690, 2012.

Kumar, S., Dave, H.K., Desai, K.P., Experimental investigation on performance of different tool movement strategies in EDM process for boring operation, *International Journal of Advanced Manufacturing Technology*, vol. 87, no. 5, pp. 1609–1620, 2016.

Kumar, N., Kumar, L., Tewatia, H., Yadav, R., Comparative study for MRR on die-sinking EDM using electrode of copper and graphite. *International Journal of Advanced Technology and Engineering Research*, vol. 2, no. 2, pp.170–4, 2012.
Khundrakpam, N.S., Singh, H., Kumar, S., Brar, G.S., Investigation and modeling of silicon powder mixed EDM using response surface method, *International Journal of Current Engineering Technology*, 2014.
Masacaraque–Ramírez, C. Franco, P., Experimental study of tool degradation in EDM processes: electrode material loss at the border and central zones. *International Journal of Advanced Manufacturing Technology*, vol. 95, pp. 3497–3511, 2018.
Malhotra, P., Ambashta, H., Mehndiratta, C., Sachdeva, L., Effect of tool geometry on the performance of EDM, *International Research Journal of Engineering Technology*, vol. 4, no. 10, pp. 82–86, 2017.
Pradhan, M.K., Biswas, C.K., Modeling and analysis of process parameters on surface roughness in EDM of AISI D2 tool steel by RSM approach. *International Journal of Engineering and Applied Sciences*, vol. 5, no. 5, pp. 346–351, 2009.
Salman, Ö., Kayacan, M.C., Evolutionary programming method for modeling the EDM parameters for roughness, *Journal of Materials Processing Technology*, vol. 200, pp. 347–355, 2008.
Shabgard, M.R., Seyedzavvar, M., Oliaei, S.N.B., Influence of input parameters on the characteristics of the EDM process. Journal of Mechanical Engineering, 57,9, pp. 689-696, 2011.
Singh, S., Maheshwari, S., Pandey, P.C., Some investigations into the electric discharge machining of hardened tool steel using different electrode materials, *Journal of Materials Processing Technology,* vol. 149, no. 1-3, pp. 272-277, 2004.
Vikas, Roy, A.K., Kumar, K., Effect and optimization of various machine process parameters on the surface roughness in EDM for an EN41 material using Grey-Taguchi, *Procedia Materials Sciences*, vol. 6, pp. 383-390, 2014.
Younis, M.A., Abbas, M.S., Goudac, M.A., Mahmoud, F.H., Abd Allah, S.A., Effect of electrode material on electrical discharge machining of tool steel surface, *Mechanical Engineering*, vol. 6, no. 3, pp. 977-986, 2015.
Zahoor, S., Mufti, N.A., Saleem, M.Q., Mughal, M.P., Qureshi, M.A.M. Effect of machine tool's spindle forced vibrations on surface roughness, dimensional accuracy and tool wear in vertical milling of AISI P20, *International Journal of Advanced Manufacturing Technology*, vol. 89, pp. 3671-3679, 2018.

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