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Analysis of various graphite types for electrical discharge finishing

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Abstract
Nowadays graphite and copper are the most used tool electrode materials for electrical discharge machining (EDM). Especially for roughing operations to machine mould inserts made of steel, graphite allows high material removal rates, with high discharge energies and reduced relative tool wear. In addition, graphite is characterized by better machinability compared to copper, which leads to a cost-effective production of complex tool electrode geometries. To take advantage of the machinability and flexibility in producing complex tool electrode geometries, graphite is also used for EDM finishing. However, in EDM finishing, graphite shows still higher material removal rates but is also characterised by significantly higher relative tool wear compared to copper. This relative tool wear is fundamentally dependent on the material properties and the used process parameters. Therefore, this paper presents an approach for using graphite in EDM finishing operations. A parameter study was carried out using five different types of graphite to machine steel components. Within the investigations, different types of graphite with grain sizes in the range of $1.0\ \mu m < D_g < 10.0\ \mu m$ were applied. Furthermore, the characteristic EDM parameters discharge current, discharge duration, pause interval time, open circuit voltage as well as servo voltage were varied. The experimental results showed three sets of parameters that lead to a relative tool wear of $\vartheta \leq 1.4$ % and a surface roughness of $Ra \leq 1.2\ \mu m$. Using the default parameters of the machine tool for a surface roughness $Ra = 0.8\ \mu m$ the relative tool wear was $\vartheta > 11.0$ %. Therefore, the experiments showed a great improvement regarding the relative tool wear for graphite. Ten additional graphite types will be used for further investigations to gain a deeper understanding of the tool wear mechanisms. This will enable the reliable and efficient application of graphite as a tool electrode material for EDM finishing.

Electrical discharge machining, EDM, graphite

1. Introduction

Electrical discharge machining (EDM) is a commonly used technology in tool and mould making industry. It enables the processing of electrically conductive materials independent of the hardness H. In sinking EDM, tool electrodes are shaped by milling and the negative contours of the electrodes are transferred into the workpiece. The most common tool electrode materials are graphite for roughing operations and copper for finishing operations [1]. Due to relative tool wear ϑ, typically several individual tool electrodes made of copper are required for finishing technologies to achieve the final workpiece geometry. As mentioned, finishing operations are carried out using copper electrodes, since copper shows a relative tool wear ϑ up to 50% lower than electrodes made of graphite [2]. Graphite, however, enables a more suitable milling of burr-free structures with higher material removal rates Q_w and reduced process times t_p. Therefore, the material properties of graphite make it desirable to use for finishing operations [3].

This paper presents investigations on the influence of material properties and machine parameters on material removal rate $\dot{V}_w$, relative tool wear ϑ and surface roughness Ra using electrodes made of graphite. This aims towards extending the state of the art for using graphite as an economically and technologically advanced tool electrode material in EDM finishing operations.

2. Methods and materials

For the use of graphite in EDM finishing operations, EDM roughing followed by a finishing EDM process was investigated. Therefore, the experimental study was carried out in two phases. First, five graphite types with different material properties were chosen and a workpiece made of steel type ELMAX, VOESTALPINE AG, Linz, Austria, was eroded with three different sets of parameters for each graphite type. According to the used graphite types, the highest performing regarding relative tool wear ϑ was taken for further experiments to find the best process parameters for finishing operations in the investigated process area. The chosen graphite materials, which were provided by POCO GRAPHITE INC., Decatur, USA, and their respective grain sizes D_g are specified in **Table 1.**

Table 1 Investigated graphite types using different grain sizes Dg

Graphite specification	Grain size D_g in µm
EDM-AF5	1.0
EDM-3	< 5.0
EDM-C3*	< 5.0
EDM-200	10.0
EDM-C200*	10.0

*copper infiltrated

Since grain size D_g is one key factor for finishing operations, a wide range of grain sizes D_g were considered for the experimental investigations [4]. Each graphite type was used to sink a specific cavity of an area of A = 20 mm x 20 mm into the steel mould type ELMAX, VOESTALPINE AG, Linz, Austria. Three different parameter sets for roughing, finishing and polishing were used with the corresponding surface roughnesses $Ra = 6.3\ \mu m$, $Ra = 1.6\ \mu m$ and $Ra = 0.8\ \mu m$ according to VDI3400 grade 36, grade 24 and grade 18 [5].

Using VDI3400 grade 36, a sinking depth of $d_s = 3$ mm, for grade 24 a sinking depth of $d_s = 0.2$ mm and for grade 18 a sinking depth of $d_s = 0.1$ mm were applied. The experiments were performed on the machine tool Genius 1000, ZIMMER & KREIM GMBH & CO. KG, Brensbach, Germany. Based on this, the best performing graphite type with the minimum relative tool wear ϑ and the minimum surface roughness Ra was chosen. According to the default machine parameters for achieving a surface roughness of Ra = 0.8 µm, as specified in **Table 3**, the parameters discharge current i_e, discharge duration t_e, pulse interval time t_0, open circuit voltage $\hat{u}_i$ as well as feed voltage u_s were varied. The different parameter sets were calculated starting from the default machine parameters by varying each parameter by a randomized value according to UHLMANN ET AL. [6]. The experiments were carried out concerning the generated parameter sets and evaluated regarding the relative tool wear ϑ and the surface roughness Ra. The parameter set, which leads to the best results in the investigated range was the starting point for the next parameter variation. This resulted in a total of 47 different parameter sets from 3 iterations of parameter variations. The relative tool wear ϑ was measured optically using the focus variation microscope Infinitie Focus, ALICONA IMAGING GMBH, Raaba, Austria, by determining the worn tool electrode volume V_t and setting it in relation to the removed workpiece volume V_w. The surface roughness Ra was measured tactilely using a nanoscan 855, JENOPTIK AG, Jena, Germany.

3. Results

The results of the comparison of five graphite electrodes are shown in **Table 2**. Generally, it was determined that all graphite types performed best for the highest surface roughness Ra according to VDI3400 grade 36, which corresponds to the state of the art. For lower surface roughnesses Ra, the material removal rate $\dot{V}_w$ decreased and the relative tool wear ϑ increased significantly. For VDI3400 grade 18, EDM-AF5 showed the lowest relative tool wear ϑ from the investigated five graphite types. Therefore, EDM-AF5 was chosen for the further experiments.

Table 2 Results of the comparison of different graphite types for different target surface roughnesses Ra according to VDI3400

Graphite specification	Ra = 6.3 µm		Ra = 1.6 µm		Ra = 0.8 µm	
	MRR◊	RTW†	MRR◊	RTW†	MRR◊	RTW†
EDM-AF5	13.39	1.4	1.77	9.1	0.52	30.9
EDM-3	15.89	0.6	1.94	56.5	0.96	61.1
EDM-C3*	18.13	0.4	0.95	71.5	0.81	61.9
EDM-200	21.09	1.1	1.13	56.9	0.69	68.5
EDM-C200*	21.42	1.9	1.05	64.5	0.31	78.7

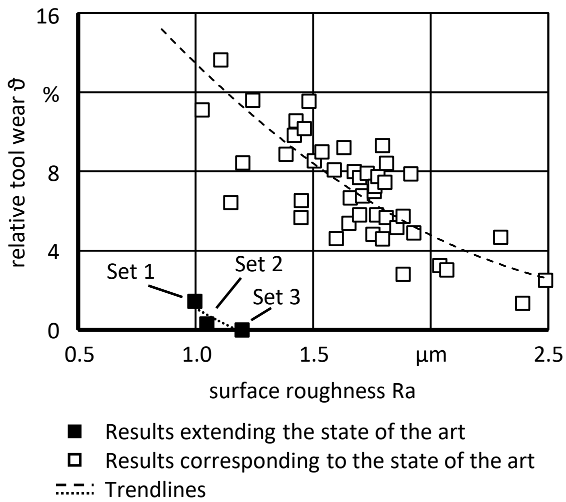
*copper infiltrated
◊MRR = material removal rate $\dot{V}_w$ in mm³ / min
†RTW = relative tool wear ϑ in %

The results of the experiments are shown in **Figure 1**. The parameters used for these three experiments are displayed in **Table 3** with the default machine parameters for a surface roughness Ra = 0.8 µm according to VDI3400 grade 18.

Table 3 Notable parameter sets to extand the state of the art in relation to default machine parameters for VDI3400 grade 18

Parameter sets	i_e in A	t_e in µs	t_0 in µs	u_i in V	u_V in V	Ra in µm	ϑ in %
VDI 18	1.7	12	25	180	40	1.03	11.1
Set 1	2.3	27	25	202	27	1.00	1.4
Set 2	2.2	41	25	191	30	1.05	0.3
Set 3	2.3	14	25	188	52	1.20	0.0

Each marker represents a different set of machine parameters. Their coordinates correspond to the achieved surface roughness Ra on the workpiece and the relative tool wear ϑ. It was determined that for most parameter sets the relative tool wear ϑ increased noticeably with a decreasing surface roughness Ra. However, three sets of parameters showed significant improvements for the relative tool wear ϑ and the lowest surface roughness Ra.



Machine tool:	Genius 1000, ZIMMER & KREIM
Tool electrode material:	EDM-AF5, POCO GRAPHITE SA
Workpiece material:	ELMAX tool steel
Dielectric:	Ionoplus IME-MH, OELHELD
Process parameters:	
Discharge current	1.5 A ≤ i_e ≤ 4.2 A
Discharge duration	5.0 µs ≤ t_e ≤ 60.0 µs
Pulse interval time	10.0 µs ≤ t_0 ≤ 70.0 µs
Open circuit voltage	80.0 V ≤ $\hat{u}_i$ ≤ 280.0 V
Feed voltage	25.0 V ≤ u_s ≤ 55.0 V

Figure 1. Results of the experiments using EDM-AF5 graphite with randomized parameter variations

4. Conclusions and outlook

The results show that it is possible to use graphite tool electrodes for sinking EDM finishing operations while maintaining relatively low relative tool wear ϑ. By choosing a graphite type with a grain size of D_g = 1 µm and deploying customized machine parameters, a relative tool wear ϑ ≤ 1.4 % was achieved while maintaining a surface roughness of Ra ≤ 1.2 µm. This corresponds to a reduction of the relative tool wear by more than 85 %. Based on this, the presented results demonstrate an extension of the current state of the art for EDM finishing operations. However, since the respective parameter sets were achieved through randomized parameter variations, the physical mechanisms that led to the promising results still need to be identified. Therefore, the achieved results are further investigated by extensive experiments on the material properties of graphite as well as an analysis of the electrical signals during the EDM-process and on the influence of the surface topology of tool and workpiece electrodes and their chemical composition on machining will be carried out.

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