SURFACE MODIFICATION OF TUNGSTEN CARBIDE USING ELECTRICAL DISCHARGE COATING WITH INCLUSION OF QUARRY DUST POWDER

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ABSTRACT: *In this paper, the surface modification of the tungsten carbide was carried out by using quarry dust powder mixed electrical discharge machining (PMEDM) method, which is also called as Electrical Discharge Coating (EDC). The characteristics of the quarry dust in terms of composition, particle size and micrograph were discussed in this paper. Moreover, the effects of the parameters (discharge voltage (Vd), peak current (Ip), pulse on time (Ton) and pulse off time (Toff)) on the surface roughness and microhardness of the coating surface were also investigated by using Fractional Factorial DoE matrix. Results show that Ton poses the most significant effect on the Vickers microhardness of coating surface, whereas Ip poses the most significant effect on the surface roughness. The optimum parameters were at Vd=40V, Ip=3A, Ton=300µs and Toff=30µs.*

Index Terms: Electrical Discharge Coating (EDC), Quarry dust, Surface modification, Tungsten carbide.

I. INTRODUCTION

Among composite materials, tungsten carbide has a huge application in the industrial sector, especially used as mould and die material. However, tungsten carbide mould and die wear out after some service time. Considering the hardness and high cost of tungsten carbide, most industries decide to dispose and buy new moulds and dies rather than repair them after wear. Thus, the surface modification of tungsten carbide is necessary to increase its lifespan and service time. This goal can be achieved using the powder mixed electrical discharge machining (PMEDM) method with quarry dust waste suspension.

PMEDM or electrical discharge coating (EDC) is an extension process from the novel application and utilisation of electrical discharge machine (EDM) [1]. It is the new technological trend that uses the EDM Die Sinker to deposit a layer of coating onto workpiece surfaces [2]. PMEDM or EDC can modify the surface of manufacturing equipment such as moulds, dies, and drills. Its ability to enhance the characteristics of original equipment surface makes PMEDM or EDC suitable for industrial application [3].

Quarry dust is a by-product from the crushing process of granite stone or rock to produce concrete aggregate [4]. Unfortunately, quarry dust poses a highly significant environmental impact especially on air and water pollution [5]. Recently, the recycling and reuse of quarry dust has raised the attention of researchers all over the world to investigate to new applications [6]. For example, the depletion and deficiency of natural river sand has led to the use of quarry dust as its replacement in construction fields [7]. Moreover, Othman et al. [8] also concluded that a nickel-quarry dust composite produced by electrodeposition technique able to improve the hardness and wear resistance of aluminium 6061 workpiece due to the high content of silica and alumina of quarry dust.

Therefore, in this study, the surface modification of tungsten carbide was conducted to enhance its surface properties by using quarry dust and the PMEDM method. Simultaneously, this method achieves the goal of industrial sustainability to reuse and recycle quarry dust waste in the surface modification of mould and die materials.

II. METHODOLOGY

A. Equipment and Experimental Condition

In this research, a Sodick AQ35L die-sinker EDM machine was used to conduct the PMEDM process. This die-sinker EDM has a 3-axis linear motor drive system and a vibration free servo system. Tungsten carbide was chosen as the workpiece material. A 6 mm-diameter copper electrode was selected to conduct this experiment. The electrode surface is polished and cleaned before the experiment. The materials and conditions of this research are listed in Table 1.

Table 1: The materials and condition of research

Materials/ Research condition	Description
Workpiece material	WC-Co (25 mm × 25 mm × 5 mm)
Electrode material	Copper electrode (6mm diameter)
Dielectric fluid	EDM LS (low smell) kerosene oil
The polarity (Reverse polarity)	WC workpiece- negative; Cu electrode-positive
Powder	Quarry dust
Surfactant	Span 85
Machining time	30 minutes
Quarry dust concentration	20g/ℓ

B. Fractional Factorial DoE Matrix

A DoE matrix created by using Fractional Factorial was used to determine the parameter effects and the optimum parameters (discharge voltage (V_d), peak current (I_p), pulse on time (T_{on}) and pulse off time (T_{off})) of this research. The experiment had a total of 27 runs, including 3 replications and centre point. The working parameters used in this research are listed in Table 2.

Table 2: The working parameters

Working parameters	Values	
	Low	High
Peak current (I_p)	3A	5A
Voltage (V_d)	20V	40V
Pulse on time (T_{on})	100µs	300µs
Pulse off time (T_{off})	10 µs	30µs

C. Measurement and Analysis

The characterisation of quarry dust in terms of composition, particle size and micrograph were investigated by using a Siemens SRS 303 X-ray Fluorescence (XRF), particle size analyser (PSA) model Mastersizer 2000 and scanning electron microscopy (SEM) model Zeiss EVO 50, respectively.

Moreover, the microhardness of the coating surface was determined by using a Mitutoyo HM-210/220 Series 810 micro vickers hardness testing machine. A Mitutoyo SJ-301 portable surface roughness testing machine was used to investigate the surface roughness of coating.

III. RESULTS AND DISCUSSION

A. Characteristics of Quarry Dust

1) Composition of Quarry Dust

The quarry dust used in this research was gained from the Department of Mineral and Geoscience Malaysia (JMG). The mass percentages of elements of quarry dust determined by using the XRF are listed in Table 3.

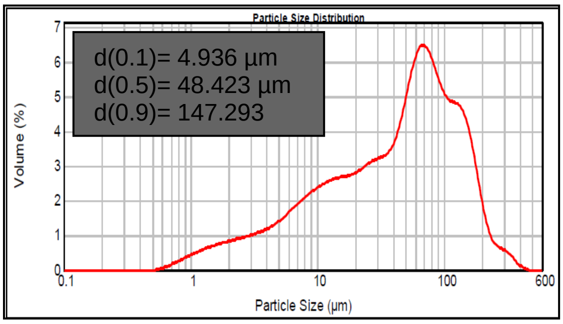
Table 3: The elements mass percentage of quarry dust

Element	Si	Na	Al	K	Fe	Ca	Mg	Ti	Zr	Eu	Cr	Rb
Percentage (mass %)	54.0	22.5	10.3	7.0	2.4	1.5	1.3	0.4	0.2	0.1	0.1	0.1

The results show that Silica (Si) has the highest mass percentage (54.0%) compared with other elements. This composition is due to quarry dust is the by-product of the crushing process of granite stone or rock, which is mainly composed of Si [9].

2) Particle Size and Micrograph of Quarry Dust

Fig. 1 and fig. 2 show the particle size and micrograph of quarry dust obtained by using PSA and SEM, respectively.



The PSA shows that the quarry dust has an average particle size of approximately 48.423 µm, whereas SEM with 100X of magnification shows that it has a non-uniform shape.

Fig. 1: The particle size of quarry dust

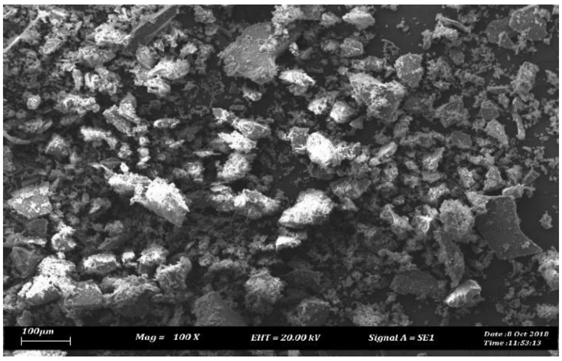


Fig. 2: The micrograph of quarry dust

B. Effect of Working Parameters to the Coating Characteristics (Microhardness and Surface Roughness)

1) The Fractional Factorial DoE Matrix

The Fractional Factorial DoE 2^{4-1} matrix was used in this research to gain the complete list of various parameters that effectively affect the characteristics of quarry dust coating [10]. According to De Lima et al. [10], Fractional Factorial Design can be used to reduce the number of experiment runs, machining time, and experiment cost as well as to achieve a better result. The matrix generated a total of 27 runs, including three replications and centre point. The results of the average microhardness and surface roughness are listed in Table 4.

Table 4: Fractional Factorial DoE Matrix with micro hardness and surface roughness result

Standard Order	Run Order	I_p	V_d	T_{on}	T_{off}	Micro Hardness (HV)	Surface Roughness (µm)
5	1	3	20	300	30	1267.8	4.57
23	2	3	40	300	10	1261.5	3.47
12	3	5	40	100	10	1188.4	5.33
18	4	5	20	100	30	1201.9	6.37
10	5	5	20	100	30	1289.5	6.26
26	6	4	30	200	20	1274.0	5.69
15	7	3	40	300	10	1059.7	3.11
16	8	5	40	300	30	1350.4	4.78
2	9	5	20	100	30	1046.8	4.85
6	10	5	20	300	10	1526.2	4.63
20	11	5	40	100	10	1293.5	4.97
27	12	4	30	200	20	1046.7	4.56
1	13	3	20	100	10	1097.7	1.72
19	14	3	40	100	30	1064.9	1.82
4	15	5	40	100	10	1055.5	3.20
25	16	4	30	200	20	1106.4	3.86
22	17	5	20	300	10	1104.0	6.53
24	18	5	40	300	30	1399.9	6.40
13	19	3	20	300	30	1392.7	3.47
11	20	3	40	100	30	1252.2	2.33
14	21	5	20	300	10	1236.7	5.13
7	22	3	40	300	10	1147.0	3.24
17	23	3	20	100	10	1088.9	4.20
8	24	5	40	300	30	1247.1	4.49
21	25	3	20	300	30	1088.9	4.62
3	26	3	40	100	30	1025.1	4.14
9	27	3	20	100	10	1065.2	2.74

2) The Vickers Microhardness

According to Fig. 3, Minitab generated the main effect plot of parameters (V_d, I_p, T_{on}, and T_{off}) on the microhardness of coating surface. Besides, Equation (1) presents the regression equation developed by Minitab for the optimization and validation of EDC parameters to Vickers micro-hardness.

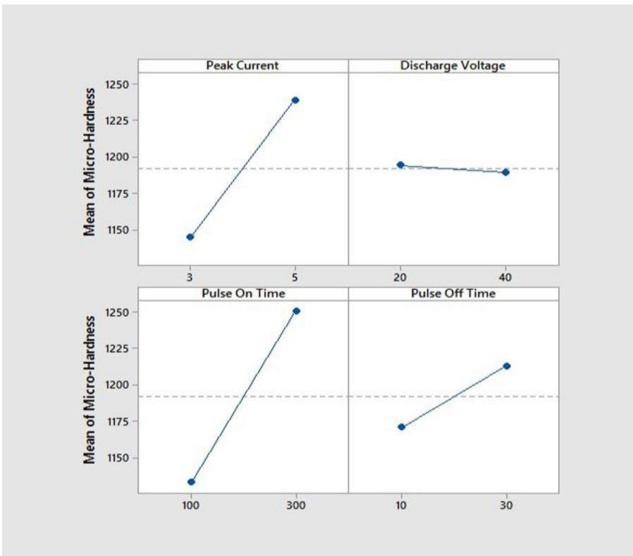


Fig. 3: The main effect plot for micro-hardness of coating

$$Vickers\ Micro\text{-}hardness = 851.7803 + 47.0194 I_p - 0.2544 V_d + 0.5884 T_{on} + 2.0947 T_{off} \quad (1)$$

surface

Based on Fig. 3, I_p and T_{on} exert a highly significant effect on the microhardness of the coating surface. With increased I_p and T_{on}, the microhardness of coating surface increases. This phenomenon can be explained from the viewpoint of discharge erosion. The amount of discharge erosion depends on the amount of electrical discharge, which is the factor of I_p and T_{on}. When I_p and T_{on} increase, the discharge erosion increases and causes a large amount of quarry dust to melt and deposit onto the surface of tungsten carbide, resulting in increased microhardness.

Moreover, the coating microhardness increases with increased T_{off}. With increased T_{off}, the ionisation process takes longer and the melted material by electrical discharge acquires sufficient time to achieve a full solidification. Therefore, a higher value of microhardness can be achieved by increasing the T_{off}, this finding are similar and supported by Kumar et al. [11].

However, the discharge voltage shows a less significant effect on the coating microhardness. The trend shows that the microhardness decreases as V_d increases. This result can be explained by material deposition. With increased V_d, the distance of the spark gap between the electrode and workpiece increases, causing the molten material to be easily flushed away by the dielectric fluid [2]. Thus, the low deposition of material results in decreased microhardness with increased V_d.

On the other hand, after EDC process, the highest microhardness of the coating achieved is 1526.2 HV, which is about 1.7 times harder than the WC-Co workpiece (average microhardness is 922.7 HV). This is due to the chemical reaction during the EDC process. In high coating temperature, quarry dust melted and decompose Si elements. The Si elements was then reacted with C elements that released from the long carbon chain of kerosene oil and become SiC compound (about 2800HV [12]). This theory is supported by the research of Molinetti and his co-workers [12]. As a result, the formation of SiC compound in the coating enhanced the microhardness of WC-Co workpiece.

Table 5: The prediction of optimum parameters and result

Predicted optimum parameter	Values
I_p	3A
T_{on}	300µs
T_{off}	30µs
V_d	40V
Predicted result	
Vickers-microhardness	**Surface roughness**
1222.0235 HV	3.5211µm

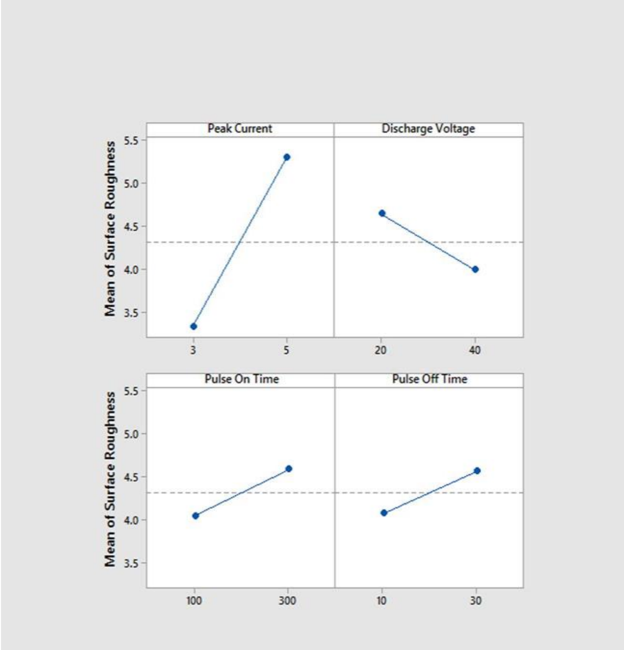


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Fig. 4: The main effect plot for surface roughness of coating surface

$$Surface\ Roughness = 0.3407 + 0.98050 I_p - 0.03254 V_d + 0.00271 T_{on} + 0.02425 T_{off} \quad (2)$$

3. **Surface Roughnes**

Equation (2) provides the regression equation developed by Minitab for the optimization and validation of EDC parameters to surface roughness of EDC samples. The main effect plot for surface roughness is shown in Fig. 4. Based on Fig. 4, I_p exerts a highly significant effect on the surface roughness of coating. The high I_p leads to higher discharge energy and cause a non-uniform coating on the workpiece surface. Similarly, Rahang and Patowari [13] found that the lowest surface roughness value was found at 3 A of I_p, whereas the highest surface roughness value was found at 6 A of high I_p setting. This proves that the value of surface roughness is increasing with the I_p setting.

The value of surface roughness increases with increased T_{on} and T_{off}. This result may be explained by the fact that material deposition during EDC is directly proportional to the amount of supplied discharge energy while it is controlled by the T_{on} and T_{off}. Therefore, the increase in T_{on} and T_{off} causes more material to melt and coat or deposit onto the workpiece surface, resulting in increased surface roughness.

Table 6: Result of the validation test

Respond	Predicted result	Experimental result				Error%
		Replicate1	Replicate2	Replicate3	Average	
Vickers micro hardness	1222.0235 HV	1215.0 HV	1212.8 HV	1210.2 HV	1212.7 HV	0.763%
Surface roughness	3.5211µm	3.619 µm	3.647 µm	3.612 µm	3.626 µm	2.979%

Moreover, Fig. 4 shows that the mean of surface roughness value decreases with increased V_d from 20 V to 40 V. This phenomenon can be explained from the viewpoint of discharge density. As the setting of V_d increased, the ionisation channel widens and leads to low discharge density. Hence, a lower value of surface roughness can be achieved by apply a high V_d setting

B. OPTIMISATION OF PARAMETERS AND VALIDATION TEST

1) Optimisation of Parameters

An optimisation plot was generated during the Fractional Factorial analysis, and its details are listed in Table 5.

2) Validation Test

A validation test of the optimum parameters was conducted to validate the accuracy of the predictions. Table 6 shows the results of the validation test.

The error of the validation test is 0.763% for Vickers microhardness and 2.979% for surface roughness. With the confidence level of this experiment at 95%, all errors that do not exceed 5% are considered qualified. Therefore, the predictions of the optimum parameters are considered accurate.

II. CONCLUSION

The surface modification of tungsten carbide was conducted by using the EDC process with inclusion of quarry dust powder. The characteristics of quarry dust and the parameter effects on the coating surface in terms of microhardness and surface roughness were investigated. The validation test of the optimum parameter was performed to validate the accuracy of the predictions. Therefore, the following conclusions can be drawn based on the analysis in this research:

(1) T_{on} poses the most significant effect on the Vickers microhardness of coating surface, whereas I_p poses the most significant effect on the surface roughness.

(2) With increased I_p, $T_{on,}$ and T_{off}, the values of Vickers microhardness and surface roughness of coating surface increase.

(3) With increased V_d, both values of Vickers microhardness and surface roughness of coating surface decreases.

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