A Research Study on Surface Roughness, Corrosion Rate, and Wire Erosion during WEDM of WC-Co Composites

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Abstract

Tungsten carbide (WC) composites are specialized materials that have been found effective and useful for many industrial applications. This article reports the results of a research study conducted on wire electric discharge (WEDM) of WC-Co composites. Effects of WEDM parameters such as wire feed rate, voltage, pulse-on time, and pulse-off time on root mean square surface roughness of WC-Co samples have been investigated by conducting twenty-nine experiments. Process productivity in terms of material removal rate has also been investigated. It was found that the discharge energy is the key to obtain the desired surface quality during WEDM of WC-Co. Sample machined at low discharge energy parameter setting has better surface roughness and corrosion resistance as compared to one machined at high discharge energy parameter combination at a compromise with the material removal rate. Wire morphology study also confirms the suitability of low discharge energy parameter setting at which low wire erosion can be obtained.

Keywords
Erosion, Composite, Corrosion, Surface roughness, WEDM

1. Introduction
Composites are specialized materials developed to replace the traditional engineering materials for fulfilling the special application requirements in defence, aerospace, automotive, and scientific fields. Tungsten cobalt (WC-Co) composite is one of the important composite materials and is used for a number of industrial applications such as cutting tools, machineries, instruments, and jewellery etc. (Mehrotra et al. 2015). The cobalt present in this composite acts a binder and according to the percentage of binder the mechanical, physical and chemical characteristics alters. This is widely accepted material for the cutting tool, die and punches etc. due to its unique characteristics of high strength, high temperature resistance and excellent corrosion resistance (Mehrotra et al. 2015). These properties make this material unique and need appropriate manufacturing processes which can impart these properties into it. Composite materials including WC-Co, are difficult to process by conventional machining methods (Banerjee et al. 2021). An alternate can be to process by non-traditional or advanced type machining technologies. Spark erosion (or electric discharge) based machining processes have gained popularity to machine a wide range of difficult-to-machine (DTM) materials (Akıncıoğlu 2022, Sidhu 2021). Wire electric discharge machining Wire-EDM or WEDM, is one of the important variants of electric discharge machining. The material removal in the WEDM process takes place by the localized heat developed by repetitive sparks generated due to energy discharge between workpiece and a travelling wire. The debris induced during the machining process are removed by the flowing dielectric (deionized water). The control of WEDM process via its parameters such as pulse duration, pulse off time, voltage, current, and wire feed rate, is an important aspect to obtain a balance from the point of view of part quality and process productivity (Singh et al. 2020, Chaubey and Gupta 2023). Like other machining operations, WEDM performance can also be evaluated by considering various machinability indicators such as product surface roughness and geometric accuracy, process productivity, and sustainability etc. (Perec 2022, Zolpakar et al. 2021). Surface roughness parameters help to determine the part quality by providing an estimate of irregularities on the machined surface. Rq which is the root mean square RMS parameter is one of the important and can be considered to analyse the performance of machining processes like WEDM.

Author has conducted a review of the available literature on WEDM of DTM materials including composites and carbides. Some of the important are discussed here as under.

WEDM of titanium alloys was attempted by various researchers in recent past (Wang et al. 2028, Kesavan et al. 2021). Strategies like vibration and magnetic field assisted WEDM were adopted to simultaneously obtain high productivity and good surface quality. Implementation of optimization techniques both statistical as well as evolutionary, was also followed to achieve better surface integrity of the WEDM machined parts (Kesavan et al. 2021, Bose and Nandi 2023). WEDM has also been successfully used to machine typical shapes and features like curved profiles and grooves on difficult to machine materials, for different applications (Farooq et al. 2020, Basak et al. 2022). When it comes on machining of composites, WEDM has been found successful to perform the required operation and obtain the required quality. In an important investigation, ZrSiO4p/6063 Aluminium metal matrix composite was machined by WEDM (Garg and Sharma 2017). Desirability analysis-based optimization of WEDM process done that could reduce the dimensional deviation of the ZrSiO4p/6063 composite parts. Another important study reported WEDM cutting of concave and convex curved profiles on tungsten carbide-cobalt composites (Naveed et al. 2017). It was reported that defect-free and accurate profiles are possible if machining is done on the optimum combinations of WEDM parameters. Important research on WEDM of boron carbide emphasized that pulse duration and current, which are mainly responsible for discharge energy, are required to be kept low to get good surface finish for composites (Bobbili et al. 2015). Researchers in the past studies also highlighted the fact that the voltage and wire tension significantly affect MRR and surface roughness (Srinivasan and Palani 2019).

It has been observed that the research attempts on WC-Co machining by WEDM are scarce which gives room to further investigations. The present work attempts to fulfil this gap by investigating on WEDM of WC-Co. This paper reports some parts of investigation, specifically the effect of WEDM parameters on surface quality in terms of root mean square roughness, corrosion behavior of WC-Co composite machined by WEDM, and erosion of wire at various machining combinations.

2. Experimental Procedure

In the present research, WC-Co composite of 200mm×8mm×8mm size is used as a workpiece from where specimens of size 15mm×5mm×8mm have been extracted. The physical characteristics of the WC-Co composites are given as density: 15.63 g/cm3; melting point: 2870°C; Thermal conductivity: 84.02 W/mK; coefficient of thermal expansion: 5.8 µm/mK; Hardness: 1990HV and Elastic modulus: 550GPa. The chemical composition of WC-Co used in present work are C: 5.6%; Co: 5.5%; O: 0.02% and W: 88.88%. WC-Co composite is machined by Electronica make Ecocut (Elplus 15) WEDM at different settings of process parameters. WEDM has number of process parameters, which affects the output responses. After the preliminary experiments, four significant process parameters were identified.

Box Behnken design of response surface methodology has designed twenty-nine experimental combinations for studying the WEDM of WC-Co (Table 1). For corrosion study, the combinations of process parameters were selected after the initial experiments i.e. one combination providing minimum discharge energy (minimum surface roughness) however, another combination gives maximum discharge energy (maximum surface roughness value) as shown in Table 2. Other parameters kept constant as peak current 10 machine units; servo feed: 1900; temperature: 23°C; conductivity 20 mho; flushing pressure: 6kg/cm2 and wire tension: 7N. The process flow diagram of overall research is depicted in Figure 1.

A five-axis Ecocut (ELPLUS-15) CNC WEDM with zinc coated brass wire is used for the experimentation purpose. The machine tool has a number of input process variables like servo voltage, wire feed, water pressure, servo feed, pulse on-time, offset, peak current, pulse off-time, etc. In current research, four process parameters such as wire feed 'WF' (3m/min-12m/min), servo voltage 'SV' (i.e. 35V-65V), pulse off-time 'Poff' (i.e. 20 µs-40 µs) and pulse on-time 'Pon' (i.e. 108 µs-116 µs) are controlled. The machine tool settings out of these ranges cause the wire-breakage. The corrosion behavior of machined surface is evaluated using Metrohm Autolab potentiostat (The Netherland make) equipped with NOVA software in the presence of coolant to develop the same working conditions in which WC-Co composite is to be used. The surface roughness of the specimens was measured with the Mitutoyo make surface roughness tester.

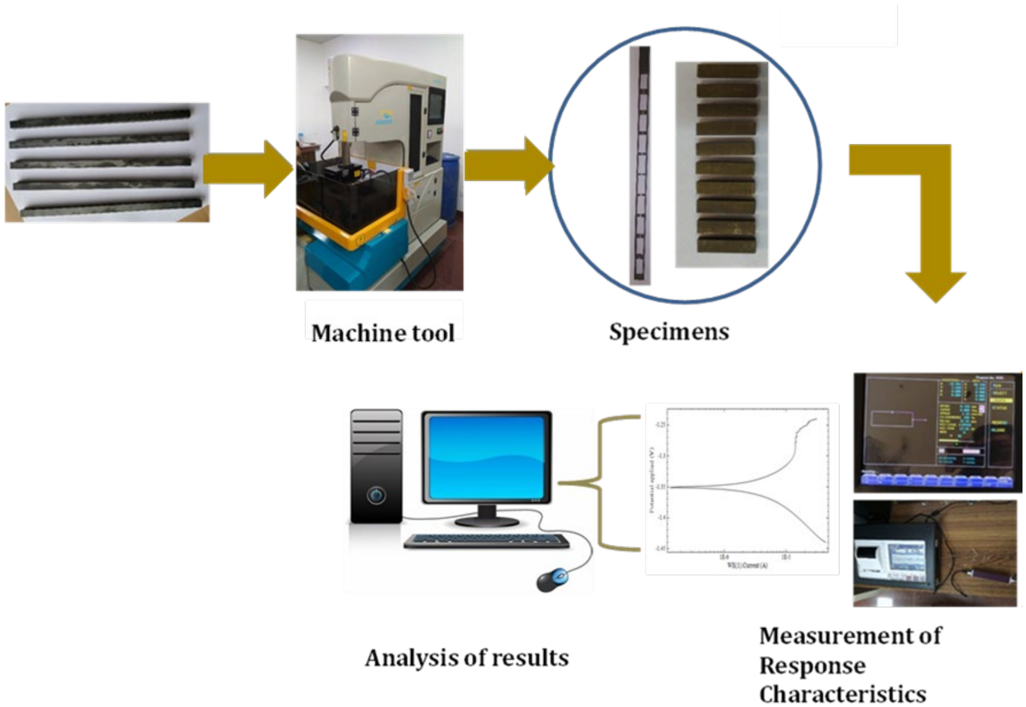


Figure1. Research strategy for the present investigation.

3. Results and Discussion

Table 1 presents the results at all twenty-nine combinations of machining parameters. The trends of variation of Rq with WEDM parameters are shown in Figure 2. The scope of this paper is limited to describing the effect of WEDM parameters on Rq only. It is evident from Figure. 2 that medium WF, medium SV, medium Poff and low Pon have produced the lowest Rq value. This is due to low discharge energy at this process parameters setting. Consequently, small amount of material has been removed from the work-surface and formed small and shallow craters that led to smoother surface generation.

Table 1: Experimental array and corresponding results (Gupta 2021).

Run	WF (m/min)	SV (V)	Poff (µs)	Pon (µs)	Rq (µm)
1	9	50	40	108	3.26
2	6	50	20	112	4.67
3	9	50	30	112	3.87
4	9	65	40	112	4.54
5	12	50	40	112	4.19
6	12	50	30	108	3.24
7	9	50	30	112	3.83
8	12	50	30	116	5.28
9	9	35	30	108	3.62
10	9	65	30	116	5.33
11	9	50	30	112	3.94
12	6	50	30	116	5.12
13	9	50	40	116	5.01
14	9	35	30	116	5.32
15	6	50	30	108	3.3
16	9	50	30	112	3.85
17	9	65	20	112	4.71
18	6	35	30	112	4.49

19	9	50	20	108	3.35
20	9	35	40	112	4.58
21	12	35	30	112	4.55
22	12	65	30	112	4.39
23	9	50	30	112	3.97
24	9	35	20	112	4.74
25	12	50	20	112	4.71
26	6	65	30	112	4.32
27	9	50	20	116	5.99
28	9	65	30	108	3.41
29	6	50	40	112	3.98

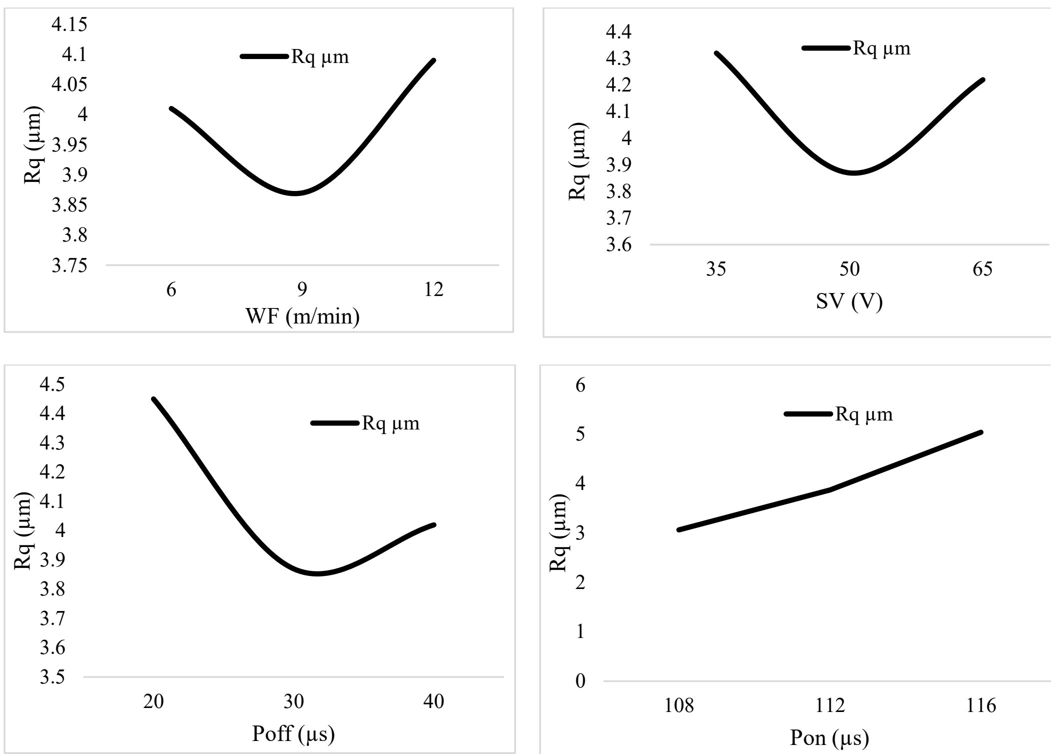


Figure 2. Variation of Rq with WEDM process variables.

For corrosion study, sample 1, as shown in Table 2, is the sample machined at low discharge energy level i.e. WF: 6m/min; SV: 50V; Poff: 30µs; Pon: 108 µs. Therefore, small size craters are removed precisely from the surface of workpiece. The root mean square surface roughness of the sample machined at low discharge energy is 3.3 µm. Sample 2 is the one which was machined at high discharge energy levels i.e. WF: 9m/min; SV: 50V; Poff: 20µs; Pon: 116 µs. At this setting, more number of sparks are generated due to increase in the current density in between the spark gap. Material removal takes place by leaving larger size deeper craters are which consequently increased the roughness depth of machined surface up to 6 µm.

When the linear polarization is performed on these samples in the presence of 5% NaCl solution, the surface is affected. Both the samples (Sample 1 and Sample 2) are placed in the environment of 5% NaCl for different exposure time. Initially, both samples are placed for 1 hour of exposure time. In the another set of experiment, both samples were placed in 5% NaCl for 12 hours to observe the severity of corrosion behavior.
The voltage potential (Ecorr), current potential (Icorr), polarization resistance and corrosion rate are given in Table 3 for both samples. Figure. 3a and Figure. 3b represent the polarization curve for both samples of WC-Co composite i.e. sample 1 machined at lower discharge energy parameter combination and sample 2 machined at higher discharge energy parameter combination respectively. It is evident from the polarization resistance that the sample 1 exhibits a

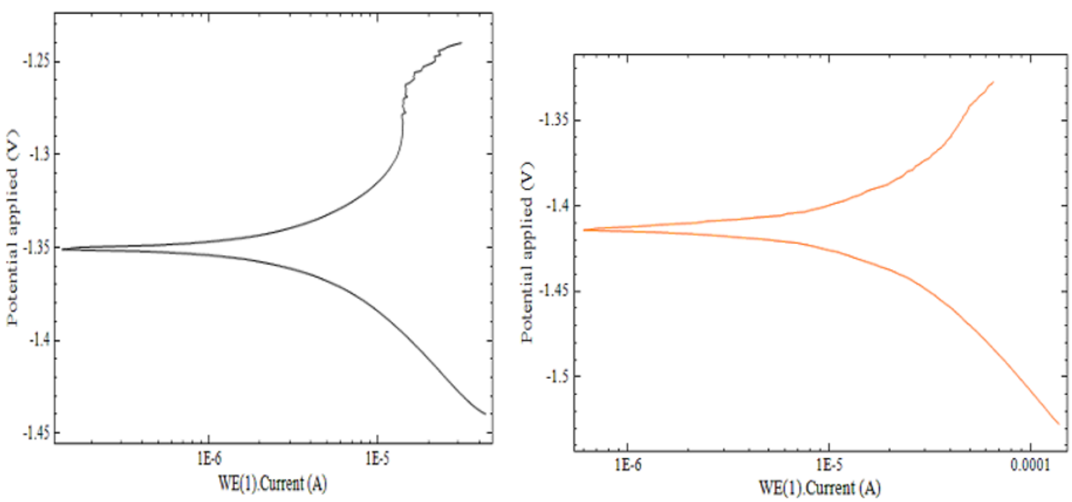
better polarization resistance than sample 2. Its polarization resistance is ~3times greater than the polarization resistance of sample 2. This polarization resistance is corresponding to the corrosion resistance. Therefore, sample 1 is more corrosion resistant as compared to sample 2. The similar observations are identified by the values of corrosion rate. The main reason for large corrosion rate of sample 2 is the increase in exposed surface area. The corrosion is a surface phenomenon and the sample machined at higher discharge energy exhibit more surface roughness and irregularities. Therefore, the exposed surface area in this sample is greater than the sample machined at lower discharge energy.

Table 2. Process parameters combinations with corresponding values of roughness.

Sample no.	**Wire Feed (m/min)**	**Servo Voltage (V)**	**Pulse off-time (µs)**	**Pulse on-time (µs)**	**Surface Roughness Rq (µm)**
1	6	50	30	108	3.3
2	9	50	20	116	5.99

Table 3. Corrosion rate and other characteristics.

Sample No	**$E_{corr.}$ (V)**	**$I_{corr.}$ (A)**	**Polarization resistance (Ω)**	**Corrosion rate (mm/year)**
Sample 1	-1.3502	0.0000154	3560.3	0.34067
Sample 2	-1.4134	0.0000421	1288.0	0.92992

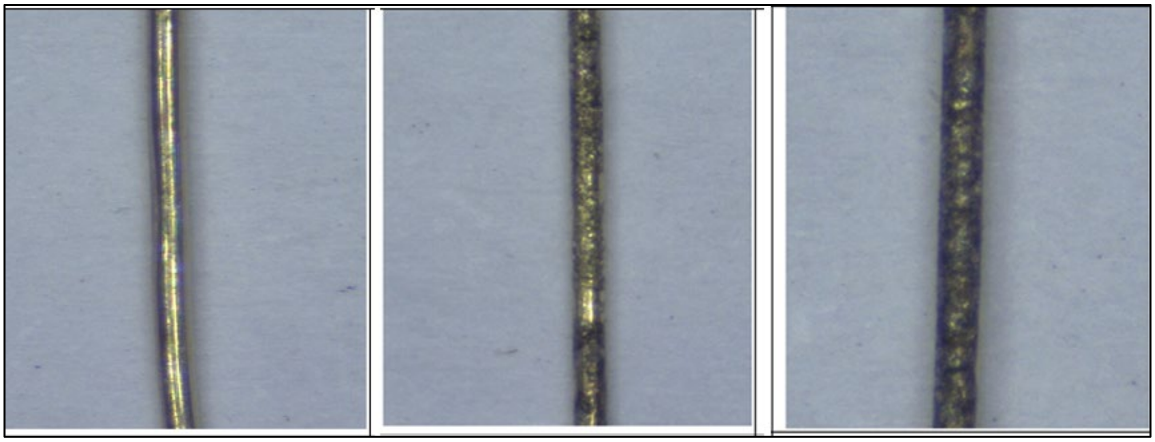


(a) (b)

Figure 3. Potentiodynamic polarization curve for (a) Sample 1 (b) Sample 2

The mechanism of WEDM is based on the principle of thermoelectric erosion of workpiece using travelling wire and the erosion of its own. After machining, the used wire is collected in a box. The spark gap in between the wire and workpiece is maintained with the help of in-built micro-processors. When the circuit is on, the discharge energy is induced in the form of discrete spark and erodes the material in form of micro-chips (debris), which are flushed by the dielectric. Depending upon the amount of discharge energy, the material removal rate changes. The amount of discharge energy depends on the combination of input parameters.

In this work, the samples of both electrodes (anode-workpiece and cathode- wire) were collected after machining WC-Co composite. Figure 4a-c shows the wire morphology during some settings of WEDM parameters when machining WC-Co. Figure 4a presents the morphology of a new fresh wire. As the rate of material removal increases, the erosion rate of wire is also increased. Figure 4b shows the morphology of wire after machining sample 1 as given in Table 2. The effect of low discharge energy parameter setting is evident which produced small size craters with few wear marks on wire. At one place, lumps are also observed, which are due to the deposition of material being flushed by dielectric on wire during the passage of discharge energy. Figure. 4c shows the wire morphology corresponding to sample 2 of Table 2. Due to high discharge energy in the spark gap, a high erosion of wire has taken place. In addition, large-size craters were observed on the worn-out wire. This morphology of wire-electrode depicts the high amount of wear.



(a) (b) (c)

Figure 4. Micrograph of the wire specimen (a) New wire (b)Wire used at (WF- 6 m/min, SV- 50 V, Poff- 30 µs, Pon- 108 µs) (c) Wire used at (WF- 9 m/min, SV- 50 V, Poff- 20 µs, Pon- 116 µs).

4. Conclusion

The following conclusions are drawn from the present research:

1. In WEDM of WC-Co composites, discharge energy plays a prominent role to obtain the desired surface quality. High discharge energy combination/setting of parameters can lead to high productivity but at the cost of high wire erosion, and poor surface roughness; whereas low discharge energy setting of parameters produces low wire wear and better surface quality.
2. The variation of Rq with WEDM parameters indicates machining to be done at medium wire feed rate, medium servo voltage, medium pulse-off time, and low pulse-on time to obtain better surface quality characteristics.
3. The corrosion rate of WC-Co composite machined at low discharge energy parameter setting is 0.35067 mm/year which is 265% lower than that of the sample machined at high discharge energy parameters combination 0.92992 mm/year.
4. The outcomes evidenced the presence of a trade-off between quality and productivity while machining WC-Co composites using WEDM.

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Biography

Kapil Gupta is working as Professor at University of Johannesburg, South Africa. He obtained PhD in Mechanical engineering. He has over ten years of professional experience. He has authored more than eighty research and review articles. He has also authored and edited twenty international books. His area of specialization is advanced manufacturing and modern industrial engineering. He has carried out research projects in lean manufacturing, modern machining, materials engineering. He is holding positions on the editorial board of international journals. He has supervised five doctorate and twelve masters student.