Wire electro discharge grinding: surface finish optimisation

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Abstract

This paper investigates the technological capabilities of a micro machining process for performing Wire Electro Discharge Grinding (WEDG). In particular, micro Wire Electrical Discharge Machining (µWEDM) is employed in combination with a rotating submergible spindle to perform WEDG. In this paper, the effects of different factors on the achievable surface finish after WEDG are investigated. In particular, an experimental study employing the Taguchi parameter design method is conducted to identify the most important main cut machining parameters that affect the surface quality of the machined parts. Then, the obtained results are used to analyse the effects of the investigated parameters on the achievable surface roughness, and ultimately to select the optimum technological parameters for performing WEDG. The process parameters that statistically have a significant influence on the surface finish are presented. The study shows that by optimising the main cut machining parameters of WEDG a level of surface finish comparable to that of µWEDM can be achieved.

Keywords: Micro EDM, micro machining, WEDG

1. Introduction

Micro wire electrical discharge machining (µWEDM) is a widely employed material removal process used to manufacture micro components requiring intricate shapes and profiles with high levels of surface finish in the nanometre range. Unlike traditional cutting and grinding processes, which rely on the force generated by a harder tool or abrasive materials to remove the softer workpiece material, the EDM process utilises electrical sparks or thermal energy to erode the unwanted material and generate the desired shape.

By applying µWEDM it is possible to machine complex, ruled surfaces, and precision components employing wire electrodes with diameters down to 0.02 mm and achieve a surface finish down to Ra 0.07 µm. The electrode is usually a plain brass or coated wire, such as zinc coated brass or coated steel wires. Varying wire orientations can be achieved during machining by controlling the position of both the upper and lower guiding heads in the horizontal planes. In this way a variety of ruled surfaces can be generated. To perform the operation, both the workpiece and the wire electrode are submerged in either de-ionised, de-mineralised water or hydrocarbon oil [1]. The dielectric insulating properties aids in avoiding the electrolysis effect on the wire electrode during the EDM process [1]. In addition, the removal of material through µWEDM when the workpiece is submerged leads to temperature stabilisation in the processing area and efficient flushing especially in cases where the workpiece has varying thickness [2].

To broaden the application area of µWEDM and the range of parts manufactured applying this technology, a rotary submergible spindle can be added to allow the machining of cylindrical components. This type of machining is termed as WEDG [3]. Traditionally however, the WEDG process is applied in combination with EDM die-sinking [4] as illustrated in Figure 1. Such an implementation of WEDG has demonstrated extremely high surface finishes when used in conjunction with processes like lapping as reported by Masuzawa et al [5]. Generally though, surface finishes for WEDG are in the region of Ra 0.8 µm [6]. Although the process of WEDG is capable of producing electrodes with a diameter of 5 µm when used in combination with EDM die-sinking [4], the main application for this technology is restricted to the manufacture of on-the-machine electrodes or pins. In particular, such traditional implementation of WEDG shows limitations for producing cylindrical components with high aspect ratios features.

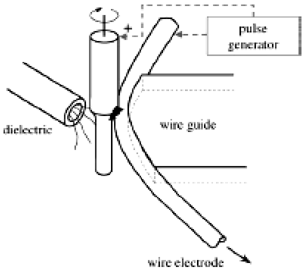

Fig. 1. WEDG principle [7]

In this research, the process of WEDG is investigated when implemented in combination with µWEDM. In this case, no wire guide is required at the point of contact between the electrode wire and the rotating workpiece. This characteristic provides a higher degree of design flexibility allowing the process to lend itself well to the manufacture of cylindrical components. Such WEDG implementation however is limited to the machining of diameters in excess of 60 microns [3].

Figure 2 depicts the difference in machining "footprints" between conventional µWEDM and WEDG after performing one main and three trim cuts operations if the process is not optimised for the specific process conditions that arise as a result of the workpiece rotation. In particular, in these trial cuts both tungsten carbide workpieces were produced using the same technological parameters that were developed for conventional µWEDM. The comparison clearly shows that a better surface finish is obtainable by performing µWEDM, approximately Ra 0.20 µm, compared to Ra

Multi-Material Micro Manufacture
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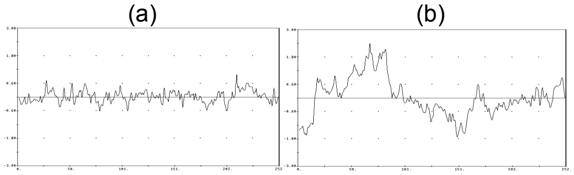

Fig. 2. Surface profiles resulting after (a) conventional µWEDM and (b) WEDG

0.51 µm achieved by WEDG. It is not difficult to conclude that the selected processing parameters do not take into account the changes in the EDM conditions due to the workpiece rotation and thus are not suitable for WEDG. Therefore, it is important to study the factors that have such a detrimental effect on the resulting surface integrity.

For this reason, an experimental study that investigates the parameters affecting the process behaviour in WEDG when used in combination with µWEDM is reported in this paper. In particular, the objective is to demonstrate that by optimising its process parameters it is possible to produce axis-symmetric components with surface finish that matches that achievable when performing a conventional µWEDM.

2. Implementations of WEDG

As illustrated in Figure 1, the WEDG process relies on an electrical discharge between a travelling wire and a rotating electrode. Extensive research has been carried out on WEDG when implemented with µEDM. In particular, it is a proven method for on-the-machine manufacture of micro electrodes for EDM drilling and milling [4, 8].

In recent years, a number of researchers have investigated the implementation of WEDG with WEDM. For example, Piltz et al [3] studied the effect of three different approaches for producing cylindrical components through the process of EDM. In particular the process behaviour in terms of pulse stability, hydrodynamic behaviour of dielectrics and machine dependent gap and feed control were investigated. Attempts to optimise surface finish were not covered during this research.

A similar approach for machining of free form cylindrical parts was investigated by Qu et al. [9-10] that extended the capabilities of the conventional WEDM technology by introducing an additional rotary axis to the machine set-up. In particular, the effects of pulse on-time, part rotational speed and wire feed rate on the surface integrity and roundness of produced parts were analysed. However, the process was studied in the context of machining macro-components and thus, its findings are not directly applicable at the micro scale.

In the study conducted by Juhr et al. [11], the importance of the correct selection of process parameter for performing the main cut during WEDM was highlighted. The research concluded that the material properties and surface finish resulting after the main cut could be improved only marginally by performing follow up cuts. Therefore, when machining micro components employing the WEDG process, the surface quality obtained after the main cut is very important and determines to a larger extent the achievable final surface finish.

Therefore, this research investigates the effects of spindle speed, flushing pressure, pulse OFF time, open circuit voltage and pulse ON time on the resulting surface finish after performing the main cut in WEDG. An experimental study was carried out employing the Taguchi parameter design method in order to identify the most important factors affecting the surface quality. The obtained results were used to analyse the individual contributions of these factors on the achievable surface roughness and also to select the optimum technological parameter for performing WEDG.

3. Experiments

3.1. Machining set up

To study the effects of the main cut technological parameters of WEDG on surface finish a rotating submergible spindle is added to a conventional machine for µWEDM. Figure 3 shows the system configuration and its working principle. A 50 µm brass coated steel wire was used as an electrode. A test piece 3 mm in diameter composed of 94% tungsten carbide and 6% cobalt was used in this experimental study. The workpiece material was produced through sintering with an average grain size of 0.3 µm. In the proposed experimental set-up, the test piece was fixed on the machine employing the collet of the rotating spindle.

3.2. Experimental Design

As it was already stated the main objective of this experimental study is to investigate the influence of a set of process parameters on the resulting surface roughness after WEDG. In particular, the parameters considered in this experimental study are:

- *Spindle speed.* The speed at which the workpiece is rotated.
- *Flushing.* Although the workpiece during the experiments was completely submerged, extra flushing was introduced through the upper and lower heads of the machine. The extra flushing does not only provide additional evacuation of the debris from the erosion area, it also helps the wire electrode to remain stable during the machining.
- *Pulse OFF time.* This is the time duration between the pulses. It is set by the power-supply controller of the machine.
- *Open circuit voltage*. The voltage between the electrode and the workpiece when the distance between them is too great to allow ionisation of the dielectric fluid.
- *Pulse ON time.* The time when the spark's electric current may flow as set by the machine power-supply controller.

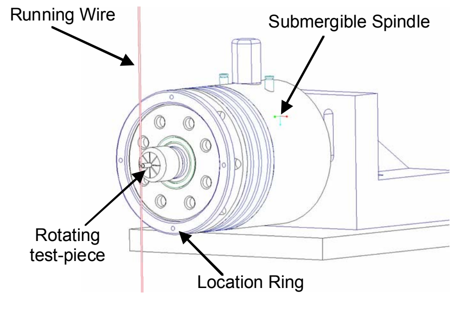

Fig. 3. Experimental design set up

These particular process parameters were selected because only their values can be modified by the machine operator when performing WEDG. In Table 1, the parameter values used to carry out the machining trials are provided. The range of each parameter ensures that consistent results are obtained from the process. Three values for each parameter were selected in order to study their effects in an experimental “window” as broad as possible.

Given that five parameters at three levels each are considered, it is possible to design 243 different experiments. However, by employing an orthogonal array (OA) based on the basic Taguchi L_{27} OA [12], the number of experiments was reduced to 27. These 27 experimental runs were carried out in a random order to minimise the influence of possible stochastic factors on the resulting surface finish after WEDG.

The surface topography was measured once at the same position on each machined cylindrical component by employing a white light interferometric profiling microscope. Then, in order to obtain the Ra measurements, the scanned profiles were analysed along a sampling length of 250 µm and a high-pass filter was applied to remove their waviness components.

Table 2 shows the 27 combinations of process parameters used in the experimental runs together with the achieved surface roughness with each of them. Due to time and cost constraints, the experiments were not repeated and thus, only one run was performed for each parameter combination.

4. Analysis of the results

4.1. Optimum parameters levels

For each parameter level, the average Ra value achieved was calculated to determine its effects on the resulting surface roughness. In particular, the value of a given parameter is considered to be optimum, the best of the selected three levels, if its corresponding average Ra roughness is the lowest [12]. Figure 4 shows the results obtained for the five analysed parameters in this experimental study.

By applying this method, it is possible to identify the theoretical best set of machining parameters within the investigated processing window in regards to achievable surface roughness, in particular:

- A3: spindle speed = 1500 rpm
- B3: flushing pressure = 2 bar
- C1: pulse OFF time = 42.5 µsec
- D1: open circuit voltage = 100 volts
- E1: pulse ON time = 4.5 µsec

4.2. Confirmation experiment

Given that the identified optimum combination of parameters did not correspond to any of the 27 experimental runs, one more trial was carried out in order to confirm its validity. The surface roughness achieved with this combination of parameters’ values was Ra 0.57 µm. If this result is compared with the other measurements in Table 2, it is clear that the achieved surface finish is better than the lowest roughness, Ra 0.64 µm, obtained in the 27 experimental runs. Additional machining tests and surface measurements would be beneficial to confirm this initial result. However, this suggests that the identified combination of parameters’ values within the considered processing window results in the best surface roughness.

Table 1. Machining parameters and their levels

Parameter	Code	Level 1	Level 2	Level 3
Spindle speed (rpm)	A	500	1000	1500
Flushing pressure (bar)	B	0	1	2
Pulse OFF time (µsec)	C	42.5	27.5	12.5
Open circuit voltage (V)	D	100	150	200
Pulse ON time (µsec)	E	4.5	28.55	52.4

Table 2. L27 orthogonal array

	A	B	C	D	E	Ra (µm)
1	1	1	1	1	1	1.32
2	1	1	1	1	2	1.09
3	1	1	1	1	3	0.64
4	1	2	2	2	1	1.66
5	1	2	2	2	2	1.70
6	1	2	2	2	3	2.12
7	1	3	3	3	1	1.27
8	1	3	3	3	2	1.58
9	1	3	3	3	3	1.70
10	2	1	2	3	1	1.09
11	2	1	2	3	2	3.20
12	2	1	2	3	3	2.09
13	2	2	3	1	1	1.34
14	2	2	3	1	2	0.89
15	2	2	3	1	3	1.14
16	2	3	1	2	1	1.02
17	2	3	1	2	2	0.80
18	2	3	1	2	3	1.54
19	3	1	3	2	1	1.05
20	3	1	3	2	2	1.17
21	3	1	3	2	3	1.04
22	3	2	1	3	1	0.87
23	3	2	1	3	2	0.96
24	3	2	1	3	3	1.18
25	3	3	2	1	1	1.51
26	3	3	2	1	2	1.05
27	3	3	2	1	3	0.93

In addition, a subsequent trim cut machining operation was performed on the workpiece and the surface roughness obtained was Ra 0.21 µm. This is comparable with the value of Ra 0.20 µm achieved with the conventional µWEDM by applying an optimised technology (see Section 1). This result demonstrates that after a thorough process optimisation the surface finish of components produced by WEDG can match the one achievable with the conventional µWEDM.

4.3. Significant parameters

Based on the results in Table 2, an analysis of variance (ANOVA) was carried out in order to assess the significance of each machining parameters on the achievable surface roughness. The results of ANOVA are given in Table 3.

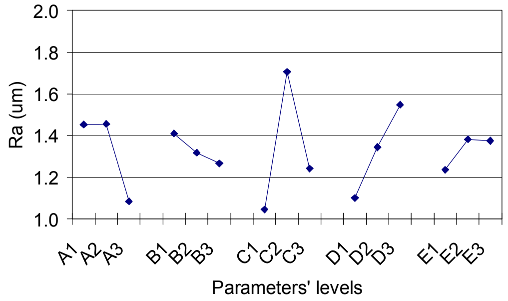

Fig. 4. Main effects

Table 3. ANOVA

Parameter	DoF	SS	V	F
A (spindle speed)	2	0.824	0.412	2.40
B (flushing)	2	0.095	pooled	-
C (Pulse OFF time)	2	2.061	1.031	6.01
D (Open circuit voltage)	2	0.905	0.452	2.64
E (pulse ON time)	2	0.122	pooled	-
Error	20	3.430	0.171	
Total	26	7.220		

Note: DoF denotes the degree of freedom, SS – the sum of squares, V – variance and F - variance ratio.

For each parameter, the variance ratio value, F, was compared with the values from standard F-tables for given statistical levels of significance. In this way, it was observed that:

- The parameters "*flushing*", "*pulse ON time*" and "*spindle speed*" had no statistical significance on the achievable surface roughness.
- The parameter "*open circuit voltage*" is statistically significant at 90% confidence level.
- The parameter "*pulse OFF time*" has the highest statistical significance in regards to the achievable surface roughness, a confidence level of 99%.

4.4 Comparison with µWEDM

The optimum results obtained from the investigation show that the process of WEDG requires the discharge energy to be reduced to allow the process to achieve a surface roughness that is comparable to the µWEDM process. To evaluate whether a reduction in discharge energy to the level used in WEDG will improve the surface roughness of conventional µWEDM, a further experiment was carried out. In particular, the surface roughness of two test pieces machined with µWEDM was compared. The first test piece was produced using set-up parameters optimised for WEDG and the second one using the conventional parameters optimised for µWEDM. The resultant surface finishes from the WEDG and µWEDM parameters were Ra 0.19 µm and Ra 0.20 µm respectively. The result demonstrates that for conventional µWEDM, reducing the discharge energy to the level required in WEDG is specific to that process.

5. Conclusions

In this study, the effects of five process parameters on the achievable surface finish after WEDG were investigated. The conducted experimental study showed that only the process parameters, pulse OFF time and open circuit voltage, have statistically significant effects on the obtainable surface roughness.

The results also demonstrated that by optimising the main cut machining parameters of WEDG it is possible to obtain a surface finish comparable to that achievable with a conventional µWEDM. In particular, by applying the identified processing parameters it was possible to achieve Ra 0.57 µm after the main cut and then to bring the roughness down to Ra 0.21 µm through a subsequent trim cut.

For the process of WEDG to obtain high degrees of surface finish, the technological parameters are significantly different from the process of conventional µWEDM. In particular, lower discharge energy is required to provide a lower value of surface roughness in WEDG. However, applying the same value of discharge energy to conventional µWEDM does not improve the surface finish.

Acknowledgements

The research reported in this paper is funded under the MicroBridge programme supported by Welsh Assembly Government and the UK Department of Trade and Industry, the EPSRC Programme "The Cardiff Innovative Manufacturing Research Centre" and the ERDF Programme "Supporting Innovative Product Engineering and Responsive Manufacture". Also, it was carried out within the framework of the EC FP6 Networks of Excellence, "Multi-Material Micro Manufacture (4M): Technologies and Applications" and "Innovative Production Machines and Systems (I*PROMS)". The authors gratefully acknowledge the support given to the Networks by the European Commission.

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