COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0800
Influence of process variables on geometrical deviations in WEDM trim cuts

Maria Vitoria Sikora
e-mail: maria.v.siko@gmail.com
Universidade Federal de Santa Catarina (UFSC)
Campus Universitário Reitor João David Ferreira Lima - R. Delfino Conti - Florianópolis - SC, 88040-900, Brazil

Paulo Matheus Borges Esteves
e-mail: borges@iwf.mavt.ethz.ch
Konrad Wegener
e-mail: wegener@iwf.mavt.ethz.ch
Michal Kuffa
e-mail: kuffa@iwf.mavt.ethz.ch
Swiss Federal Institute of Technology in Zürich (ETH)
Leonhardstrasse 21 - 8092 Zürich - Switzerland

Abstract. *Wire electrical discharge machining (WEDM) is a non-conventional machining method capable of cutting complex shapes on hard electrically conductive materials. The die manufacturing and aerospace sectors, main applications of WEDM, require high workpiece precision. In WEDM the kerf (cutting width) might not be constant along the wire which may cause deviations on the workpiece. The kerf value is affected by tool erosion and inhomogeneous cutting conditions like flushing, concentration of debris, wire vibration, cutting parameters, etc. When comparing the top and bottom of the workpiece, a deviation labeled conicity may appear and can compromise accuracy. Nevertheless, the causes of this difference are yet unidentified. Given the importance of workpiece precision in this specific process, it is essential to explore which variables influence this geometrical deviation. Therefore, this study aims to investigate the influence of individual process variables on the conicity produced by WEDM trim cuts. Using brass CuZn37 (DIN CW508L) wire as the tool and AISI D2 steel as workpiece material, a design of experiments (DOE) is elaborated varying: flushing conditions, unwinding speed, pulse energy, piece height and pulse-off time while tracking the cutting duration, total number of discharges and short circuits. The conicity of the produced pieces is measured with a micrometer caliper. A variable to represent the physical aspect of the wire wear is created using the calculated pulse frequency, piece height, unwinding speed and pulse energy. The results are interpreted with an analysis of variance (ANOVA) and a graphical comparison. The flushing conditions, cutting duration, and pulse-off time were shown not to be statistically relevant. The most relevant parameters were the unwinding speed, pulse energy and wire wear variable. This result suggests that the conicity phenomenon is caused rather by the tool erosion than by cutting conditions.*

Keywords: *WEDM, geometrical deviations, wire wear, tool erosion*

1. INTRODUCTION

Wire electrical discharge machining (WEDM) is a non-conventional machining process. Being a non-contact technique of removal, it is able to machine complex shapes on hard electrically conductive materials. Its common applications are in aircraft, dies and tool industries which require great accuracy. To guarantee precision, several trim cuts are performed on the workpiece.

According to Islam et al. (2010) WEDM is perceived to be accurate for a few reasons. One of them is the lack of contact between workpiece and tool eliminates adverse effects such as chatter, vibration or mechanical stresses as normally present in traditional machining. Another reason is the small diameter of the wire (0.07 to 0.30 mm), which delivers fine cuts and the highly accurate Computer Numerical Controlled (CNC) system diminishes conventional machining errors. Three key dimensional accuracy characteristics in WEDM are described. First being flatness, a condition in which a surface of the workpiece must lie within an envelope of two parallel planes. Another way of visualizing it is to have one plane fit all elements of the surface. Second being perpendicularity, which can be understood as the accuracy of the corners' angle. Third being the linear dimension, the characteristic of the lengths of the workpiece to fall inside the tolerance, which may be affected by the spark overcut.

Ho et al. (2004) reported that the two major phenomena for lack of precision in WEDM are wire lag and wire vibration which are caused by various forces - mechanical from bubbles, electrodynamics from spark formation, hydraulic from flushing - causing the wire to go off its path.

Jameson (2001) defines the kerf in a WEDM main cut as the electrode diameter plus two times the spark overcut. Tosun et al. (2004) says that the kerf determines the dimensional accuracy of finished parts, but it is hard to optimize it since there are too many adjustable parameters. Using an Analysis of Variance (ANOVA), they concluded that the kerf is highly affected by pulse duration and open circuit voltage, being the second one three times more important. Other parameters like flushing pressure and wire speed were less effective factors.

When sparks happen, not only the workpiece, but also the wire gets eroded. This means that during a cut, the geometry of the wire changes and, therefore, the kerf. Kneubühler et al. (2020) investigated the wire wear and found out that it is proportional to the spark frequency and current, and inversely proportional to the wire unwinding speed.

König and Klocke (1997) state that due to cutting conditions (e.g. wire tension, workpiece height, quantity and size of debries) the walls generated in WEDM have geometrical deviations. They define *"conicity"* as the slope that arises between top and bottom of the workpiece. Still, there are no specifications of what exactly could cause it. Further investigations into literature were not conclusive.

Given the significance of precision in WEDM and its applications, it is of uttermost importance to study what causes or influences the wall deviations. The lack of references and research on the conicity observed in WEDM workpieces opens a new field of research. Therefore, the objective of this study is to investigate which process variables have an influence on the conicity produced in WEDM trim cuts.

2. METHODOLOGY

To perform the investigation of influential variables on the conicity a Design of Experiment (DOE) was executed as recommended by Montgomery and Runger (1994). The chosen parameters for the study are listed in Tab. 1. From this list, the number of pulses, N, and cutting duration, t, are observational. It is possible to differentiate the number pulses, N, between the number of short circuits, N_s, and number of discharges, N_d. They are differentiated by the establishment or not of the open voltage.

Flushing condition, Q, is categorical and separated in flushing on upper nozzle only, Q_1, flushing on lower nozzle only, Q_2, and flushing on upper and lower nozzles, Q_3, all of them at 50 kPa. The workpiece height, H, investigated were 100, 55 and 10 mm. The wire unwinding speed, Aw, has two levels: 2 and 12 m/min.

The I correlates to the energy of the pulses given by the generator. It indicates the maximum electrical current of the pulse and has two levels: 140 and 230 A. In these energy levels, the discharges last between 0.75 and 1 μs. The T_{off} is the time between the end of a spark and the start of another. For this parameter, two levels were chosen: 25.2 and 7.64 μs.

Table 1. Table with investigated parameters

Variable	Description
Aw	Wire Unwinding Speed
H	Workpiece Height
Q	Flushing Condition
N	Number of pulses
t	Cutting duration
T_{off}	Pulse time-off
I	Maximum current

2.1 Materials and Experiments

The experiments were performed on a WEDM Machine from *AgieCharmilles* model CUT-P350. The wire material used was brass CuZn37 (DIN CW508L) and AISI D2 steel for the workpiece material. The cuts for the experiments are divided in three steps: a main cut to have the desired geometry, a trim cut to even the surface, which will be referred as trim shape, and the trim with the studied parameters, which will be referred as trim study.

First a rectangular nominal shape of 6 x 13.5 mm is cut - the height, H, is variable - as represented in Fig. 1 (a). The wire is unwinded from top to bottom region. Then the trim shape is executed on the same geometry. Both these main and trim shape are done with the parameters recommended by the machine. In the trim study, the parameters are also the ones recommended by the machine except Aw, Q, I and T_{off}.

For each combination of parameters in the trim study a length of 2.5 mm is cut - the sufficient to achieve a stable cut in the process and to measure with the micrometer. The cut with a given combination is made on the left and the corresponded area on right side. A total of 5 different combinations are done on each workpiece. To avoid corner interactions a length of 1 mm is left with no trim study, which later is cut off when the workpiece gets separated from the metal block. Figure 1

(b) shows a top view of the cut. Each stripe of 2.5 mm represents a different combination of parameters and the 1 mm stripe will be the one cut off. Ten workpieces were cut - a total of 50 different combinations.

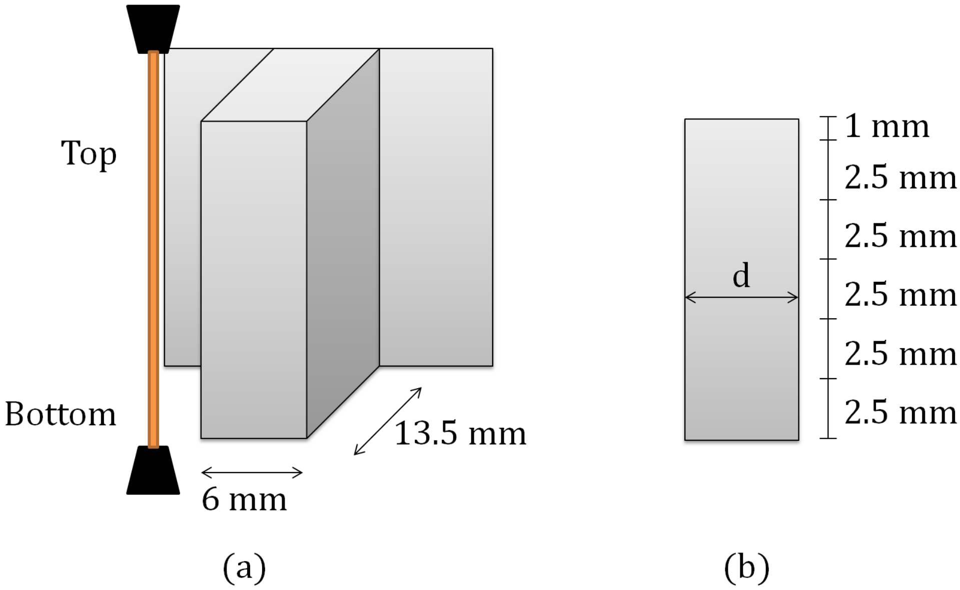


Figure 1. Representation of the study cut where (a) differentiates top and bottom region (b) shows a top view of the workpiece

2.2 Measurements

In this work, the conicity is defined in Eq. (1). Top and bottom region are represented in Fig. 1 (a) and the distance d is represented in Fig. 1 (b). In Eq. (1), d_{top} is the length measured in the top region of the workpiece and d_{bot} is the length measured in the bottom region. The distance d is measured three times with a point micrometer caliper with 1 μm uncertainty and the Con value is the mean of these measurements. The measurements are made in each stripe cut with a given set of parameters - five different measurement spots per workpiece.

$$Con = \frac{d_{top} - d_{bot}}{2} \tag{1}$$

2.3 Data Analysis

As stated in the introduction, the kerf is key to precision and it is affected by the wire wear. With that in mind, the Eq. (2) was created in order to represent the tool erosion.

In essence, a section of the wire is eroded during the time it is exposed to the workpiece - workpiece height, H divided by wire unwinding speed, Aw. This erosion will be more severe depending on the frequency of sparks - number of pulses, N, divided by cutting time, t - and the given energy, which will be proportional with the maximum current, I.

It is also possible to differentiate this variable between the erosion caused by short circuits, WW_s, and the erosion caused by discharges, WW_d, by replacing N for N_s and N_s, respectively. The data is analyzed graphically and with an ANOVA in the following section.

$$WW = \frac{H}{Aw}\frac{N}{t}I \tag{2}$$

3. RESULTS

Conicity values ranging from -35.5 μm and 4.5 μm were found. With a mean value of -5.3 μm, the majority of Con values are negative - meaning the workpiece is larger at the bottom. According to Tab. 2 the most relevant parameters were Aw, WW_d and I in this order.

To better understand the data, a deeper analysis with the variables Aw, I, H and WW_d is performed.

Table 2. ANOVA table

Source	Sum Sq.	d.f.	Mean Squared	F	Prob(>F)	Significance
H	0.353	1	0.353	0.0402	0.8421	
I	47.49	1	47.49	5.41	0.0256	.
Q	36.28	2	18.14	2.06	0.141	
Aw	137.53	1	137.54	15.66	$3.31e^{-4}$	***
T_{off}	18.25	1	18.26	2.08	0.158	
t	20.85	1	20.85	2.37	0.132	
WW_d	68.19	1	68.19	7.76	0.0084	*
WW_s	3.44	1	3.44	0.391	0.535	
N_d	0.170	1	0.170	0.019	0.89	
N_s	0.223	1	0.223	0.025	0.874	
Error	325.02	37	8.78			
Total	3987.94	48				
Statistical significance (α) codes:	0 '***'	0.001	'**' 0.01	'*' 0.05	'.' 0.1	' ' 1

3.1 Aw Analysis

The variable Aw is the most relevant variable by the ANOVA. According to Fig. 2, for lower values of Aw the Con measured is bigger in absolute value and has a bigger deviation. For Aw at 12 m/min, Con values are slightly positive - top of workpiece larger - but near zero with a small deviation.

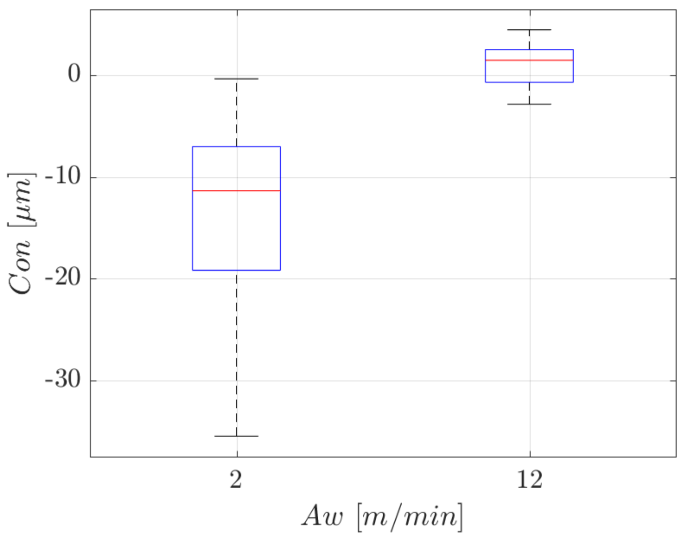


Figure 2. Boxplot Aw

3.2 I Analysis

The parameter I is the third most relevant. Figure 3 shows that the mean of I do not differentiate between the two studied levels. However, for the higher value of I a bigger deviation on the Con is observed.

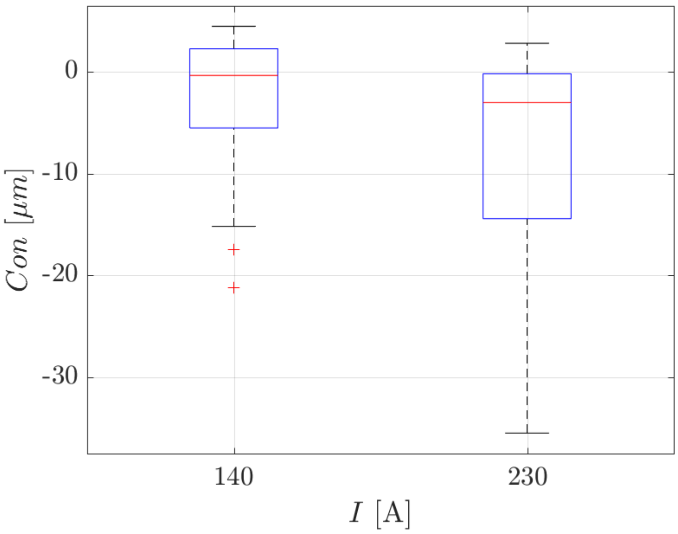


Figure 3. Boxplot I

3.3 H Analysis

The H did not appear as relevant in the ANOVA presented in Tab. 2. Even though there is no clear differentiation in the means in H, as seen in Fig. 4, the higher the piece height, the higher deviation in the Con values. This points out to a heteroscedasticity.

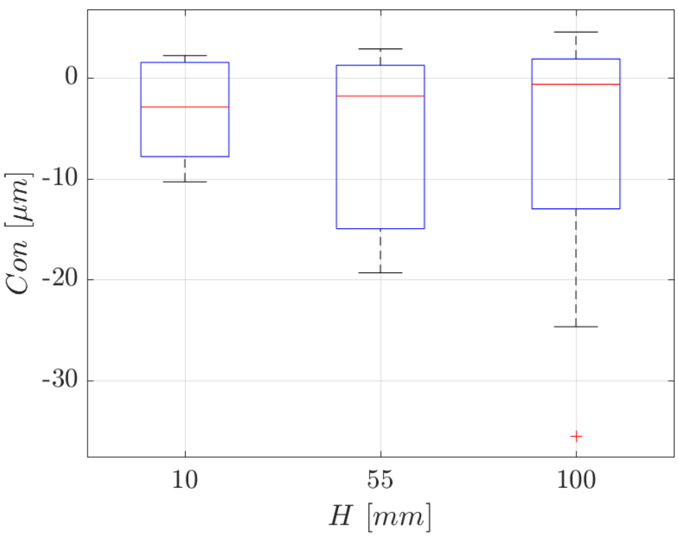


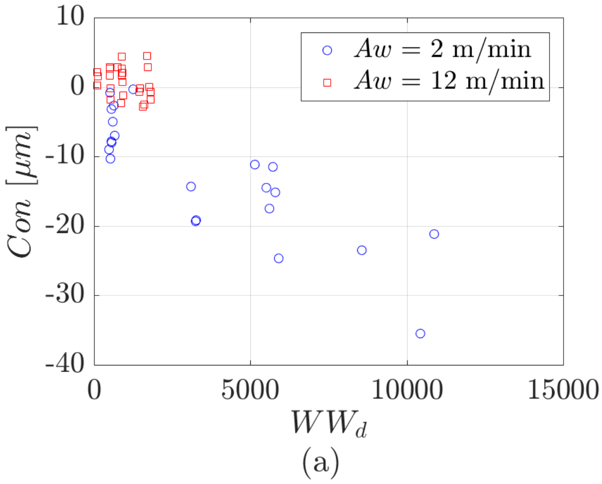
Figure 4. Boxplot H

3.4 $\mathbf{WW_d}$ Analysis

The created variable WW_d is the second most relevant in the ANOVA. To better understand it, plots of the Con and WW_d divided into the different values of Aw and H in Fig. 5 (a) and Fig. 5 (b) respectively were made.

Crossing the Aw and WW_d variables, it is possible to observe in Fig. 5 (a) that lower values of Aw present higher values of WW_d and dispersion of the Con. Higher values of Aw also correspond to lower values of WW_d and centralize the conicity around zero.

However, Fig. 5 (b) shows that observations of H at 100 mm covers the biggest interval in both Con and WW_d. For H at 10 mm, the Con observations were the smallest and exhibited the lower WW_d values.



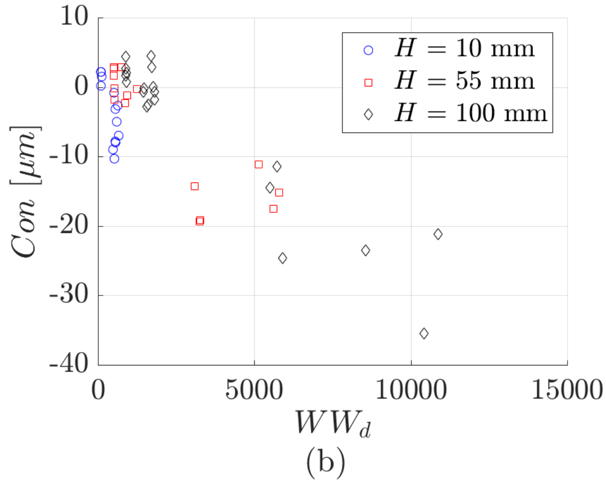


Figure 5. (a) Con by WW_d separating by Aw (b) Con by WW_d separating by H

3.5 Other parameters

The flushing condition, Q, showed no statistical relevance on the Con. It is interesting to point out that although WW_d has a strong influence on the Con, WW_s seems not to be relevant to explain it.

The cutting time, t, has no influence on the Con. However, it was observed that t is directly proportional to H and inversely proportional to T_{off}. Similarly, N_d and N_s are directly proportional to H. The T_{off} showed not to be statistically relevant.

4. CONCLUSIONS

According to the results, the most influential variables in the conicity ($\alpha < 5\%$) were Aw, I and the WW_d. Other parameters like Q, T_{off}, t, N_d and N_s were not statistically relevant.

From the literature, it is possible to interpret that there are two main reasons for the conicity: inhomogeneous cutting conditions (e.g. quantity and size of debries) or tool erosion - different kerf values throughout the wire. The lack of relevance of Q and T_{off} suggests that cutting conditions are not the main reason for the conicity. Moreover, the relevance of Aw, I and the WW_d suggest that the conicity deviations arises because of wire phenomena. The findings suggests that in this case the conicity deviations are originated mostly due to tool erosion and not cutting conditions.

It is interesting to point out that WW_d was relevant while WW_s was not. It was an unexpected result and further investigations are needed.

Heterocedasticity, unequal variance at different levels, in the Con was observed for the H, as well Aw and I parameters. This result requires a careful inspections of the data along with a graphical analysis.

5. ACKNOWLEDGEMENTS

The financial support from Innosuisse under project number 28789.1 is greatly acknowledged.

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