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INVESTIGATION OF THE INFLUENCE OF PROCESS PARAMETERS ON SHAPE DEVIATION AFTER WIRE ELECTRICAL DISCHARGE MACHINING

New materials require the use of advanced technology in manufacturing parts of complex shape. One of the modern non-conventional technology of manufacturing difficult to cut materials is the wire electrical discharge machining (WEDM). The article presents the results of theoretical and experimental research in the influence of the WEDM conditions and parameters on the shape deviation during a rough cut. A numerical model of the dielectric flow in the gap (ANSYS) was developed. The influence of the dielectric velocity field in the gap on the debris evacuation and stability of WEDM process was discussed. Furthermore, response surface methodology (RSM) was used to build empirical models for influence of the wire speed V_d, wire tension force F_n, the volume flow rate of the dielectric Q_v on the flatness deviation after the WEDM.

Keywords: wire electrical discharge machining, WEDM, shape deviaton, CFD

1. Introduction

Wire electrical discharge machining (WEDM) is wieldy used to manufacture difficult-to-cut conductive materials. In the WEDM process, the material is removed from the substrate through the electrical discharges occurring in the gap between the electrode and the workpiece. The tool electrode is a thin wire with a diameter from 0.02 to 0.5 mm, most commonly made of brass. During the WEDM, the electrodes are insulated one from another by the flowing dielectric (deionized water), which is supplied into the gap under pressure from both the upper and the lower nozzle. Removal mechanism of the material in WEDM is mainly the result of the electrical discharges, which cause melting and evaporation in local surface layers of both the workpiece and the wire electrode. The heat also causes evaporation of the dielectric liquid and induces high pressure waves which wash the molten and vaporized metal. The volume of the material to be removed in a single pulse is in the ranges from 10^{-6} to 10^{-4} mm^3. In the WEDM, more than 10 000 electrical discharges take place per second. A large number of electrical discharges lead to stabilization of the conditions in the gap which plays a key role in the process. Dielectric properties ensure stable discharges and contribute to cooling the workpiece and electrode surface, flushing the debris particles from the gap and quenching the plasma channel. The breakdown process in the dielectric and the growth of plasma channels can be facilitated by the bridge of conductive particles. The research [1-3] indicate that ionization of plasma channel with conductive particles in the dielectric fluid occurs in the larger gap relative to the pure dielectric. The concentration of machining products reduces the dielectric resistance, which can result in multiple electrical discharges in the same place [4-6]. The main parameters which influence the WEDM can be split into two areas. Parameters which define the electrical discharge (discharge current, discharge voltage, pulse time) and processing conditions (the electrode material, the workpiece material, type of the dielectric) [7-11]. To satisfy the low surface roughness requirement, many works have focused on improving surface integrity after the WEDM [12-15]. Important research has also been done in analyzing the influence process parameters on the geometrical accuracy of the machined parts [16-20]. However, most of the works are focused on the accuracy of the programmed tool path, especially on obtaining high accuracy in the corner cut [21-23]. The quality of the surface after the WEDM process does not always meet expectations therefore additional technological operations are used [24-27] to improve surface quality. However, the use of additional treatments significantly increases the production costs.

The published literature indicate that just few studies have reported on the analysis of minimizing the shape deviation in WEDM by taking into account the electrical discharge parameters [28-32]. Therefore, in this paper, theoretical and experimental investigation of the WEDM condition and parameters like the dielectric volumetric flow Q_v, wire tension F_n and wire speed on shape deviation for the cut parts was conducted.

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2. Materials and methods

Industry applications of WEDM in machining the tall parts (over 100 mm) is limited by the obtainable geometrical accuracy. The purpose of the conducted research was to determine the influence of the WEDM conditions and parameters on the shape deviation for the rough cut. In the first stage of research, the theoretical analysis for the efficiency of debris removal from the gap were conducted. The CFD simulations of the dielectric flow in the gap during WEDM was performed using commercial software ANSYS CFX. The following assumptions were made: dielectric is Newtonian liquid (water), the workpiece height H = 100 mm, wire electrode diameter Φ = 0.25 mm, the gap between the electrodes S = 0.063 mm, dielectric directly flows to the gap from upper and lower nozzle with the velocity V = 30 m/s (the distance between the nozzles and the cut material was not included). It was assumed that the atmospheric pressure level exists in a place of free outflow of liquid from the gap. For the developed model, some simplifications were adopted: regard of wire neglected dynamics, including its vibration, neglected regard of the gas phase and solid phase built up by the electrical discharges.

In the second stage of research, the experimental studies were carried out in order to confirm theoretical assumptions of WEDM conditions influence on shape errors during the rough cut. To achieve this goal, experimental research was carried out applying a rotatable, five-level experimental design with three parameters. The experiments were conducted for the following machining conditions presented in Table 1.

TABLE 1

WEDM parameters used in study

WEDM parameters	
dielectric volumetric flow rate Q_v	28-80 [l/min]
wire tension F_n	0.4-1.6 [daN]
wire velocity V_w	8-15 [m/min]
discharge voltage U	30 [V]
pulse time t_{on}	1.6 [µs]
discharge current I	170 [A]

The selected range of the adopted parameters in the experimental design was based on the available references and earlier preliminary study focused on the stability of the discharges when machining a part of the height 100 mm, without the wire breakage, for the main cut (roughing).

The experimental studies were conducted on the wire electrical discharge machine Charmilles Robofil 290. The electrode used was brass wire of diameter 0.25 mm and the deionised water was used as the dielectric. Heat-treated tool steel X165CrV12 (60 HRC) was used as the workpiece. Tool steel X165CrV12 was chosen because of its wide industry applications for dies and die inserts. The samples were cut from one clamped block of material. Sixteen samples were cut with dimensions of 10×10 mm with a height of 100 mm.

Investigation of the surface flatness deviation after the WEDM was carried out on a 3D CNC Carl Zeiss Coordinate Measuring Machine, model Vista. The flatness deviation W was measured on a samples surface area of 10×100 mm with 300 points using the raster strategy. Machining parameters used in the experimental design and measured deviation of the machined shape are presented in Table 2.

TABLE 2

WEDM machining parameters in the design of experiment

Ex. No	**WEDM parameters** Q_v **[l/min]**	F_n **[daN]**	V_w **[m/min]**	**Measured flatness deviation** W **[mm]**
1	38.4	0.64	9.4	0.0337
2	38.4	0.64	13.6	0.0243
3	38.4	1.36	9.4	0.0264
4	38.4	1.36	13.6	0.039
5	70	0.64	9.4	0.0257
6	70	0.64	13.6	0.021
7	70	1.36	9.4	0.032
8	70	1.36	13.6	0.0454
9	28	1	11.5	0.029
10	80	1	11.5	0.0267
11	54	0.4	11.5	0.022
12	54	1.6	11.5	0.0364
13	54	1	8	0.0234
14	54	1	15	0.0261
15	54	1	11.5	0.0473
16	54	1	11.5	0.0183

3. Results and discussion

3.1. Analysis of the velocity field of the dielectric fluid in the gap

The results of the CFD simulation of velocity field of the dielectric fluid in the gap is presented in Fig. 1. The cross-sections of the developed model were selected at different heights of the cut material. The first section A – A at a height of 5 mm, second section B – B at a height of 15 mm, third section C – C at a height of 25 mm and last two sections D – D at a height of 45 mm and section E – E at the height of 50 mm from the place of the dielectric inflow from the nozzles.

Presented results of CFD model indicate that the velocity of the dielectric significantly decreases at a distance of about 15 mm (cross-section B – B) from flow to the gap from the upper and down nozzle. The velocity in the front and lateral gap drops from about 26 m/s to 16 m/s. At the height of 50 mm of cut material, two dielectric streams collide and the flow velocity drops to about 1 m/s (Fig. 1 – cross-section E – E). This leads to a local concentration of machining products at half the height of the machined workpiece. Retention of erosion products, debris, and gas bubbles can lead to a reduction of the dielectric resistivity, which contributes to the increase in the number of discharges in this place. Non-uniform distribution of discharges across the

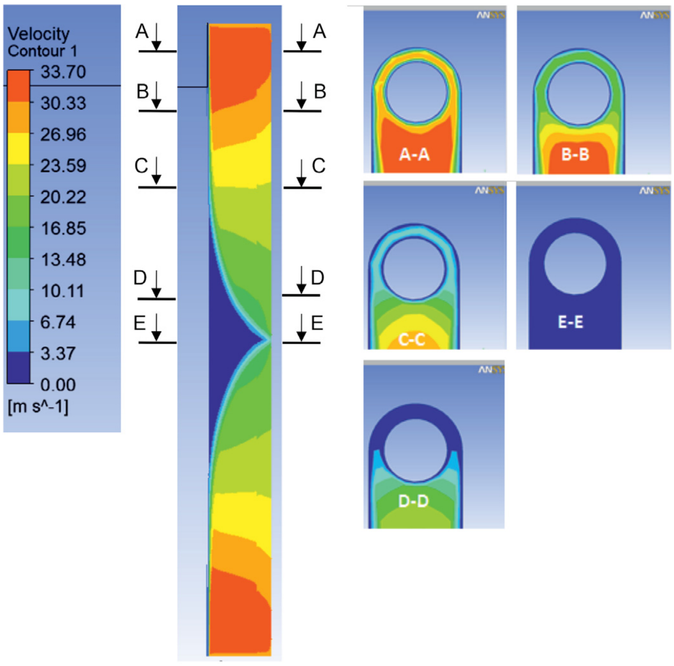

Fig. 1. Distribution of the velocity flow of the dielectric in the gap in the section: the longitudinal and crosswise at different heights

surface of the wire electrode can lead to the wire vibration. Deflection of the electrode is the biggest at the half of a workpiece height. A local reduction of the distance between the electrode and the work surface contributes to the increase in probability of the electrical discharge in this area.

3.2. Experimental research

Experimental investigation of the influence of the WEDM parameters on the shape deviation was carried out using response surface methodology. In RSM, the dependence between the desired response and the independent variables can be represented by the Eq. (1):

$$Y = f(Q_v, F_n, V_w) \pm \varepsilon \qquad (1)$$

where Y – the response; f – the response function; ε – the experimental error; Q_v – volumetric flow; F_n – wire tension and V_w – wire speed are independent parameters.

Analysis of variance (ANOVA) was used to check the significance of each independent variable in the response function. The ANOVA test was conducted at a 95 % confidence level. The F-value corresponded to a continuous probability distribution. If this probability (Prob > f) value for each factor was less than 0.05, this indicated that the model factor was significant. Values of Prob > f higher than 0.05 indicated that a model factor was non-significant. Regression analysis with a backward elimination process was performed. For the developed model, the coefficient of determination R-squared and the adjusted coefficient of determination R-Adj were calculated. The ANOVA results are presented in Table 3.

TABLE 3

ANOVA table after elimination non significant factor

Source	Sum of squares	Degrees of freedom	Mean square	F-Value	Prob > f
Q_v	0.000208	1	0.000208	36.6574	0.000123
Q_v^2	0.000029	1	0.000029	5.0433	0.048530
F_n	0.000705	1	0.000705	124.2801	0.000001
F_n^2	0.000092	1	0.000092	16.2553	0.002393
$F_n V_W$	0.000024	1	0.000024	4.3212	0.044334
Error	0.000057	10	0.000006		
Total SS	0.001092	15			
R^2 = 0.95	R^2-Adj = 0.93				

After eliminating the non-significant factors in the response equations for the flatness deviation W, the following polynomial function was established (Eq. 2):

$$W = 0.074 - 0.00046\, Q_v + 0.000007\, Q_v^2 + \\ - 0.067\, F_n + 0.022\, F_n^2 + 0.00024\, F_n V_W \qquad (2)$$

Analyses of the results of the ANOVA for the developed model showed that the values of the R-squared for flatness deviation W is over 95 %. This result indicated that model provided an excellent explanation of the relationship between the independent variables and the response W. Differences between the R-squared and the R-adjustable were smaller than 0.2, which indicated that the established model was adequate in representing the process. Residuals analysis was performed for the confirmation of the developed model adequacy. Analysis of the residual normal probability plots (Fig. 2) indicate that the residuals had normal distributions. Plots of the residuals versus the predicted values (Fig. 3) and the residuals versus the case number values (Fig. 4) indicate that the residuals are of a stochastic nature. The analysis of the plotted residuals versus the case values shows that the error terms were independent of one another. The analysis of the residuals confirmed that the developed models were adequate.

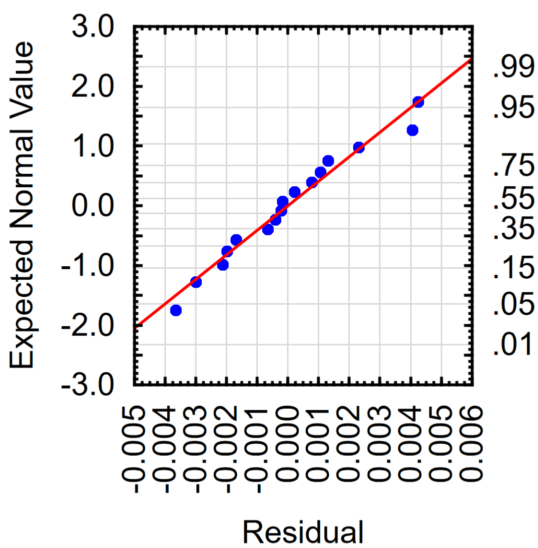

Fig. 2. The normal plot of residuals

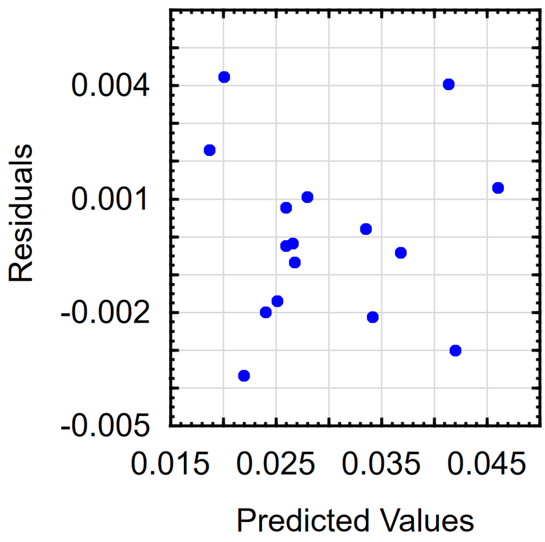

Fig. 3. The residuals versus the predicted values

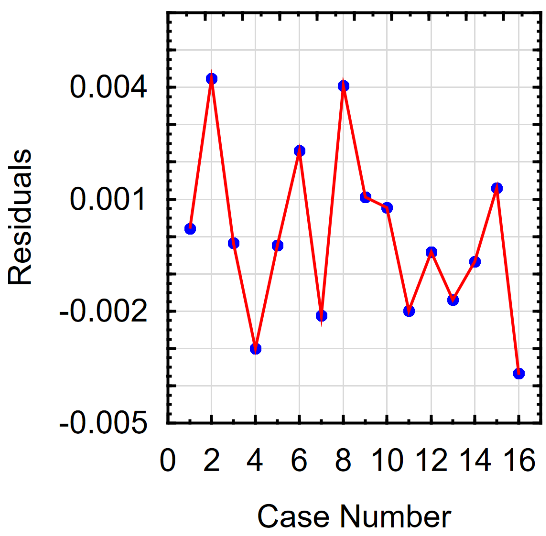

Fig. 4. The residuals versus the case values

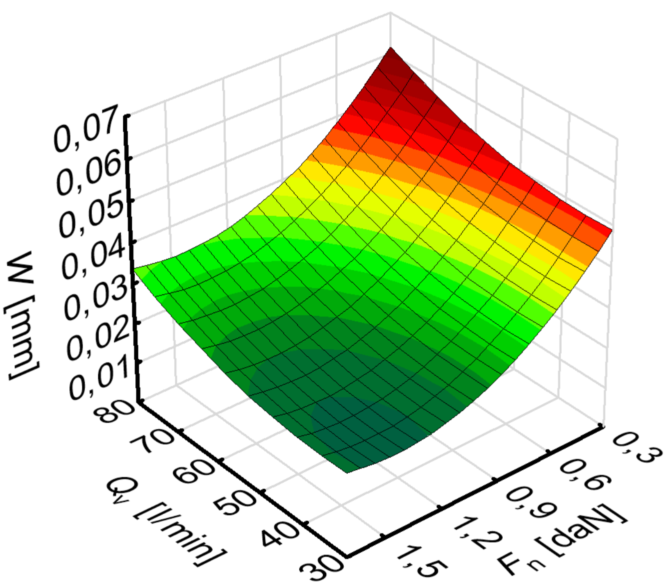

Fig. 5. Estimated response surface for flatness deviation W, at the constant wire speed V_w = 11.5 m/min

Based on the developed model (Eq. 2), the response surface plots were estimated (Fig. 5-7) in order to have a better understanding of the influence of wire tension F_n, wire velocity V_w and volumetric flow rate Q_v on flatness deviation W after the WEDM.

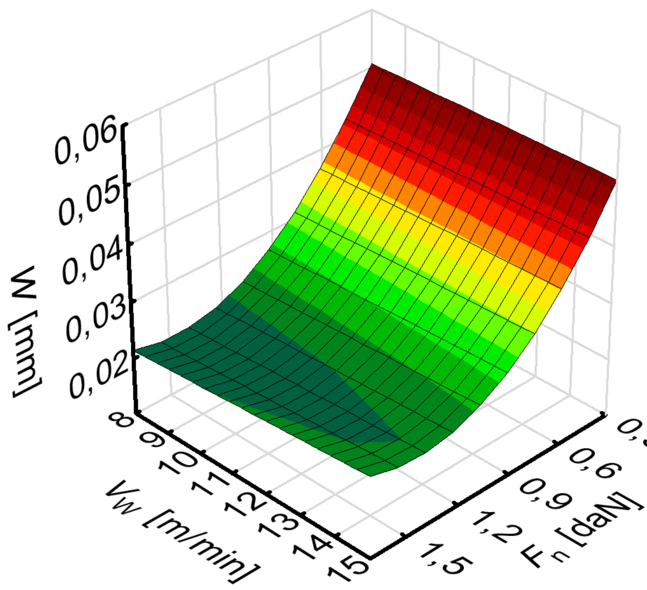

Fig. 6. Estimated response surface for flatness deviation W, at the constant dielectric volumetric flow rate Q_v = 54 l/min

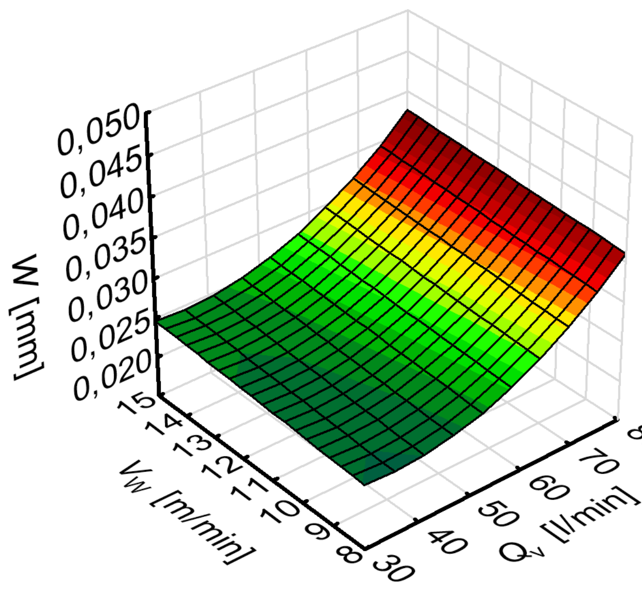

Fig. 7. Estimated response surface for flatness deviation W, at the constant wire tension F_n = 1 daN

Analysis of the estimated response surface graphs (Fig. 5-7) indicates that the main parameter influencing the flatness deviation after WEDM is the wire tension F_n and volumetric flow rate Q_v. With the increase the wire tension force and the reduction of the dielectric flow rate Q_v, the flatness deviation decreases (from about 0.06 mm to about 0.02 mm) (Fig. 5). The higher F_n value contributes to "stiffening" of the tool electrode and reduction of the tool electrode vibration. The volumetric flow rate of the dielectric significantly influences on the flatness deviation. With the increase of parameter Q_v, the tool electrode may be set in vibration, which contributes to the occurrence of the error of shape. Wire velocity V_w does not have a strong influence on the investigated shape deviation (Fig. 6, 7), but will significantly affect the production cost. The presented results show that even with wire velocity V_w as low as 8 m/min, the cutting process is stable.

3.3. Analysis of the sources of shape deviation after the WEDM

During the WEDM process, thousands of simultaneous electrical discharges occur across the height of the cut element between the workpiece and the electrode. It results in filling the gap with the erosion products (eroded material, gas). These products are removed from the gap with the flowing dielectric fluid. Their local concentration in the dielectric modifies its properties. The eroded material, gas molecules formed by the dissociation of water may increase the number of electrical discharge (decrease dielectric resistance) in one place. Non-uniform distribution of the electrical discharges hitting the tool electrode results in wire vibration. The amplitude of the vibration is "reflected" on the workpiece (Fig. 8). Maximum of the shape error deviation is at half of the height of the machined workpiece. Analysis of the material removal process shows that the dielectric fluid flow in the gap affects the geometrical accuracy of the machined parts. Considering the developed model of fluid flow in the gap, it can be seen that the dielectric velocity is rapidly reduced in the place of two streams collision. A low velocity value of the liquid causes a "retention" of machining products at half of the height of the cut material. The eroded debris imparts the number of electrical discharges. Non-uniform distribution of electrical discharges on the tool electrode causes vibration. The amplitude of vibration of the wire is "mapped" into the workpiece; there are concave surface areas. The theoretical distribution of the velocity field of the dielectric coincides with traces of machining, visible on the surface of machined samples (Fig. 8). The errors are associated with the vibrations of the tool electrode.

4. Conclusions

In the article, the sources of shape errors after the WEDM process are described, which are related to vibrations of the tool electrode caused by an non-uniform distribution of electrical discharges. The maximum value of the amplitude of the electrode vibrations is mapped in the form of a local enlargement of the inter-electrode gap (flatness deviation). Based on theoretical analysis and experimental research, the following conclusions could be drawn:

- The developed model of the dielectric fluid flow in the gap indicates that a low velocity value of the liquid causes a "retention" of machining products which imparts non-uniform distribution of the electrical discharges. These physical phenomena cause a vibration of the wire electrode and imparts concave shape errors.
- The main process parameter influencing the flatness deviation after the wire EDM in the rough cut is the wire tension F_n. The higher F_n value contributes to "stiffening" of the tool electrode and reduction of the tool electrode vibration.

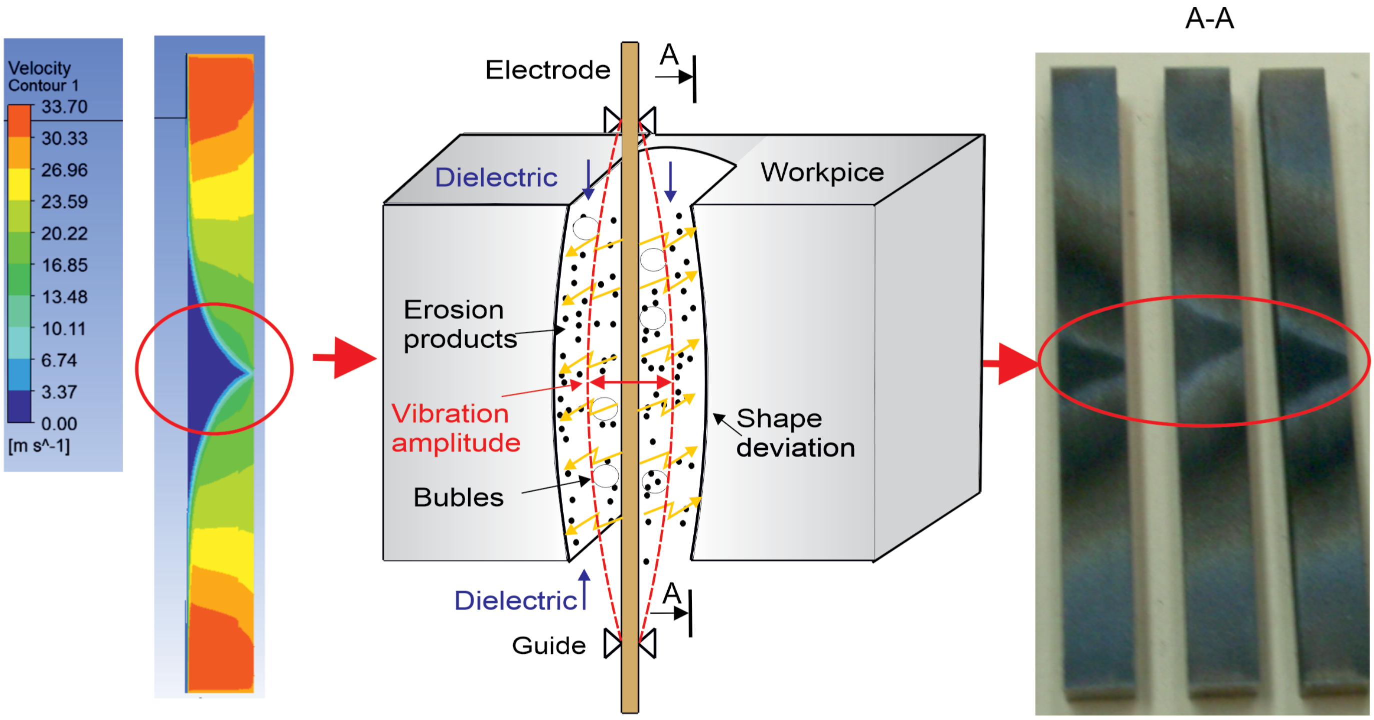

Fig. 8. Analysis of the dielectric fluid flow model: (a) the distribution of the velocity field, (b) scheme of generating shape deviations, (c) visible traces of erosion on machined samples

- Volumetric flow rate Q_v has insignificantly influenced the flatness deviation. With the increasing parameter Q_v, the tool electrode may be set in vibration which contributes to the occurrence of the error of shape.

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