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Wire Deflection Investigation during WEDM of AISI 304 Stainless Steel: An Experimental and Numerical Study

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Cover Page Footnote

The author would like to acknowledge the Faculty of Engineering – Mansoura University – Egypt for providing the required facilities in performing the experimental work. Also, she would like to acknowledge Shoman Company – Egypt for their valuable support in supplying the required workpiece specifications.

ORIGINAL STUDY

Wire Deflection Investigation During WEDM of AISI 304 Stainless Steel: An Experimental and Numerical Study

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Abstract

Wire electrical discharge machining (WEDM) is a specific form of electrical discharge machining that uses a small-diameter wire electrode to cut a narrow kerf in the workpiece. Since the wire deflection has a negative effect on the performed cutting, this research seeks to study the resultant wire deflection during WEDM of AISI 304 stainless steel. This study is performed with the help of three types of modeling, namely, mathematical modeling, experimental modeling, and thermomechanical finite-element modeling. Mathematical modeling is performed to analyze the stresses and the wire lag, while the experimental modeling is achieved to observe the wire deflection and the cutting forces. Thermomechanical finite-element modeling is accomplished with the help of ABAQUS software to forecast the wire deflection and make a correlation between the experimental and computational works. The results indicate the accuracy of the proposed models. The obtained wire deflection increases at a shorter machining length and then it is decreased. The wire deflection is larger in the case of cutting without a working fluid compared to with a working fluid. In addition, the direction of the wire deflection is in the same cutting direction in the case of without a working fluid, while it is reversed in the case of a working fluid flow.

Keywords: Experimental modeling, Mathematical modeling, Thermomechanical finite-element modeling, Wire electrical discharge machining, Wire deflection

1. Introduction

Wire electrical discharge machining (WEDM) is a type of electrical discharge machining that cuts a thin kerf in the workpiece with a small-diameter wire electrode. The complicated erosion effect of quick and discrete spark discharges that occur between the wire and the workpiece in the presence of a dielectric medium fulfills the material removal process. WEDM is used effectively and without the need for highly qualified labor to cut intricate shapes in hard materials such as cams, punches, stripper plates, extrusion dies, etc (El-Bahloul, 2020; Ho et al., 2016).

During machining, the wire electrode's mechanical behavior is incredibly complex. This is owing to the presence of highly stochastic sparks between the wire and the workpiece. As a result, the magnitudes and orientations of various forces impacting the wire are not constant. Fig. 1 illustrates the difference between the forces imposed on the wire during machining. The principal forces acting along or on the wire are those caused by gas bubbles created by the erosion process plasma, electrostatic force, hydraulic forces caused by flushing, and electrodynamic force. The wire deflection and vibration are caused by all of these forces. Hence, it is expected that such deflection would have an impact on the dimensional accuracy, productivity, and stability of the parts machined by WEDM (Zhang et al., 2016).

Many kinds of research have been performed on WEDM considering many issues. El-Bahloul and

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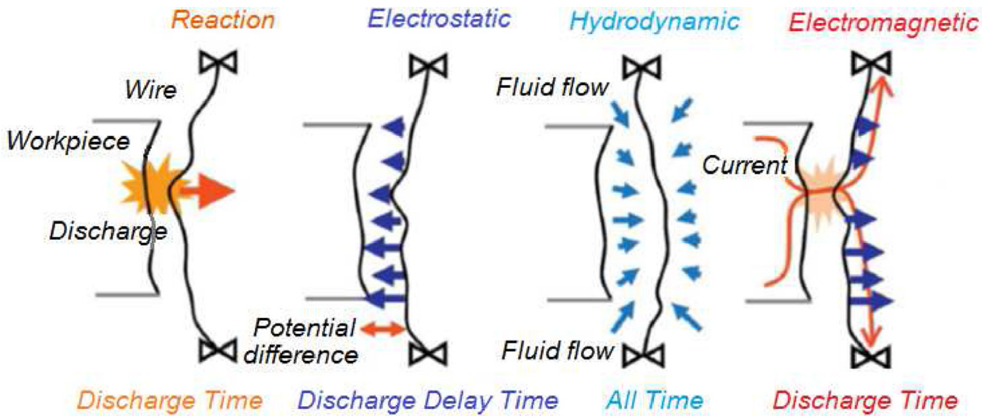


Fig. 1. Different forces acting on the wire.

Mostafa (2021) studied the machinability behavior of WEDM for a fabricated Udimet700 by hot isostatic pressing using a Taguchi-based GRA technique. The practical and forecasted findings demonstrated the viability of the methodology used to improve the WEDM of Udimet700 nickel-base superalloy by attaining the best surface finish, material removal rate, and microhardness. Chen et al. (2020) investigated the material removal rate and micro reciprocated machining gap of WEDM for SKD11. When open voltage reached a specific threshold, the rate of material removal first increased with it but subsequently tended to remain constant. As the open voltage, discharge capacitance, and pulse duration grew, the machining gap expanded, resulting in enormous discharge force and electromagnetic force, and hence severe wire vibration.

Rajmohan and Kumar (2017) reported that the wire deflection resulted in a variation of the wire gap, and therefore the kerf width varied as well. This in turn would affect the dimensional accuracy of the cut. Varun and Venkaiah (2014) reported that the deflection of the wire affected the kerf width and, therefore, the accuracy of the cut. Using a high-speed video camera, Habib and Okada (2016), examined the tungsten wire electrode movement. The breadth of the machining kerf and the vibration amplitude of the wire electrode both reduced as wire tension increased. In comparison to the parallel cutting route, the amplitude perpendicular to it was substantially smaller. Chen et al. (2014) studied the corner error by designing three sets of experiments to evaluate the effect of different control factors on the corner error. The major causes of right and obtuse-angle corner-error cutting were determined to be wire deflection and vibration, whereas the discharge concentration phenomenon was found to be relevant in acute-angle corner-error cutting.

Therefore, wire deflection should be predicted before optimizing the machining conditions and therefore minimizing the effects of the deflection. There exist many works that were conducted for this purpose. Among them was the analytical model developed by Abyar et al. (2018) where they presented an analytical model for calculating the wire deflection, which was a function of the reaction forces on the wire and the geometrical features of the cut region. The developed model was then used to predict geometrical errors in kerf width. However, Zhang et al. (2014) introduced a macroscopic model that could be used for calculating wire deflection in terms of geometrical features of the resultant force of the cut region, wire tension, wire speed, and flexural rigidity. However, analytical models lack the capability of providing a full description of the displacement field of the wire, which can be an obstacle to an accurate description of the effect on the workpiece. To avoid these limitations, Ebisu et al. (2018) conducted a CFD-based numerical analysis to determine the effect of jet flushing flow in terms of pressure distribution acting on the wire surface. Okada et al. (2015) analyzed wire deflections, wire-acting hydrodynamic stress, flow fields, and period of debris residency in the kerf using a numerical approach. According to the analysis, wire breaking occurred at a shorter length of the kerf. Also, the wire deflection induced by jet flushing increased, and the debris quickly accumulated in the gap at small kerf lengths, resulting in more wire breaking.

From the literature review, it is obvious that the combined influence of predominant forces exerted upon or within the wire during WEDM causes wire deflection and vibration. Consequently, it is foreseeable that the said deflection will significantly affect the dimensional accuracy, productivity, and overall stability of the machined components fabricated through the use of WEDM. The main objective of this research is to study the influence of the most significant machining parameters on wire deflection by carrying out three forms of analysis, namely, mathematical modeling, experimental modeling, and thermomechanical finite-element modeling. To analyze the wire stresses and wire lag, mathematical modeling is performed. To observe the wire deflection and the cutting forces, experimental modeling is achieved. To forecast the wire deflection and make a correlation between the experimental and computational works, thermomechanical finite-element modeling is accomplished.

2. Mathematical modeling

2.1. Wire stresses

The wire is subjected to different types of stresses such as direct stress due to the weight of the wire, bending stress due to the wire winds around the wire guides, and stresses that occur during starting and stopping of wire motion. The direct stress (σ_d) can be calculated using Equation (1) (Khurmi, 2000):

$$\sigma_d = \frac{w}{A} \tag{1}$$

where w is the weight of the wire and A is the cross-sectional area of the wire.

When a wire is stretched over a guide that would be tensile at the top and compressive on the bottom, bending stresses are created in the wire. The bending stress (σ_b) in the wire can be calculated using Equation (2), while the equivalent bending load (W_b) on the wire can be calculated using Equation (3) (Khurmi, 2000):

$$\sigma_b = \frac{E_r d_w}{D} \tag{2}$$

$$W_b = \sigma_b A \tag{3}$$

where E_r, is the wire elastic modulus, d_w is the wire diameter, and D is the wire guide diameter. It should be noticed that E_r is not the elastic modulus for the wire material but for the entire wire. It has been realized experimentally that E_r is equal to (3/8 E), where E is the wire material elastic modulus.

The wire has to be accelerated while starting and stopping. This generates additional stress (σ_a) and load (W_a) in the wire that can be calculated using Equations (4) and (5), respectively (Khurmi, 2000).

$$\sigma_a = \frac{W_a}{A} \tag{4}$$

$$W_a = \frac{w}{g} a \tag{5}$$

where a is the acceleration of the wire and g is the acceleration due to gravity. If the time (t_s) required to achieve a certain speed (v) is known, the value of 'a' may be calculated as (v/t_s).

2.2. Wire lag

Significant wire vibrations can be avoided by specifying acceptable pulse parameters. However, the presence of static wire deflection remains. The static deflection of a stretching wire guided at opposite ends by two-wire guides can be modeled mathematically with the following assumptions.

(1) The wire mass stretches evenly over its length.
(2) Between the wire guides, the axial tensile force is maintained at a constant level.
(3) In the dielectric medium, the viscous force resisting wire deflection is negligible.
(4) The troubling forces acting per wire unit length perpendicular to the axial force are constant between guides across the wire span.

When considering the hypothesis above, the wire bending or the static deflection of the stretched wire of length 'L' in a plane along the z-axis may be expressed as in Equation (6):

$$T \frac{d^2 D_f}{dz^2} = F_t \tag{6}$$

where T is the wire tension, D_f the wire deflection, and F_t is the force unit per workpiece thickness. Using MATLAB software in solving the above equation under the boundary conditions of $z = 0$, $D_f = 0$, and $z = \mathrm{L}$, $D_f = 0$, Equation (7) is obtained:

$$D_f = -\frac{F_t}{2T} z(L - z) \tag{7}$$

where z is the distance taken in the z-direction from the lower wire guide. A schematic diagram of wire deflection is shown in Fig. 2. If the total deflection 'D_f' of the wire is at z=(2 L/3+b), then D_f can be calculated using Equation (7). Equation (8) estimates the total deflection that can be obtained. The length 'b' illustrated in Fig. 2 is very small and can be neglected, as the workpiece thickness is very small compared with the center distance between the upper and lower wire guides:

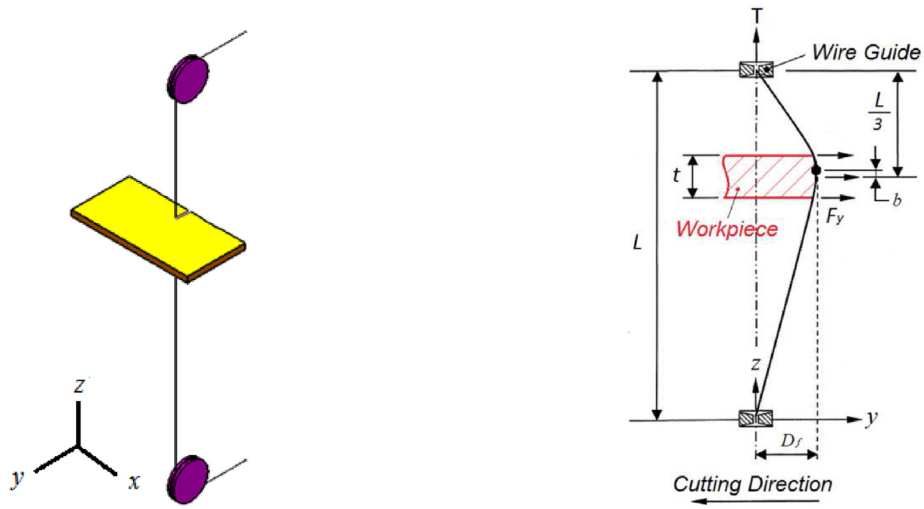


Fig. 2. Schematic diagram of the WEDM process during cutting.

$$D_f = -\frac{F_t}{2T}\left(\frac{2L}{3}+b\right)\left(\frac{L}{3}-b\right) \quad (8)$$

3. Experimental modeling

Wire vibration and deflection are increased under severe cutting conditions. Consequently, the cutting parameters are tuned so that the peak current and the pulse-on time are increased while the pulse-off time is decreased. Table 1 summarizes the machining conditions.

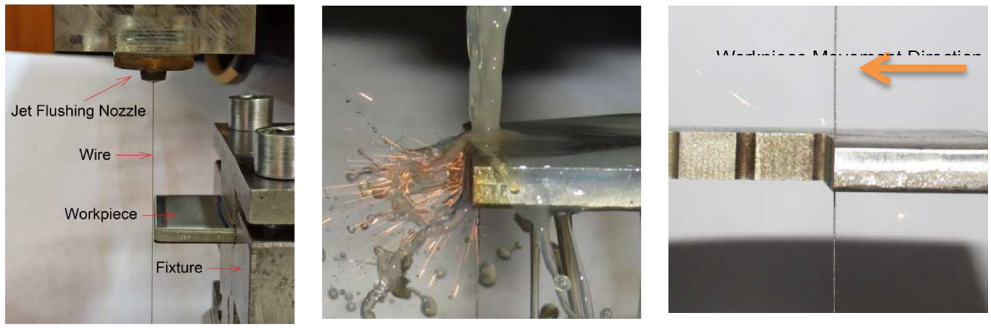
The experimental work is performed with and without a working fluid by substituting a dry air medium to allow discharging. The movement of the wire during machining is observed using a high-speed camera (*Canon PowerShot SX530 HS*). Fig. 3 shows the wire cutting during machining with and without a working fluid. Wire refraction is considered a problem that is occurred during cutting with a working fluid, which affects the wire deflection measurement. The used high-speed camera has solved this problem, as many shots can be taken per second, so many shots can be observed with little fluid flow.

According to Zhang et al. and Tomonori et al. (Zhang et al., 2014; Ebisu et al., 2018), deflection could only occur along the feed direction. Thus, the analysis of the deflection is only conducted in that direction, while it is neglected in the other directions. Accordingly, the camera is set to take shots in a direction perpendicular to the workpiece movement direction.

After taking many shots with the camera during machining, the wire deflection is measured with the aid of the *ImageJ Java-based image processing* program. Many images are selected to observe the wire deflection, and then *ImageJ* program is applied as shown in Fig. 4. First of all, a datum line is drawn on the selected image beginning from the upper side of the wire at its guideway. Second, the image is dragged into the program, where a scale is

Table 1. Machining conditions.

Thermal and mechanical properties of wire material	
Wire	Molybdenum (0.16 mm diameter)
Thermal conductivity	139 W/mK
Density	10,280 kg/m^3
Young's modulus	329 GPa
Poisson's ratio	0.31
Coefficient of thermal expansion	4.8×10^{-6}/°C
Inelastic heat fraction	0.9
Fraction of heat transferred to the wire	0.5
Specific heat	275 J/kgK
Thermal and mechanical properties of workpiece material	
Workpiece	AISI 304 Stainless Steel (5 mm thickness)
Young modulus	200 GPa
Poisson's ratio	0.3
Melting temperature	1399.85 °C
Specific heat	440 J/kgK
Density	7900 kg/m^3
Thermal conductivity	16.2 W/mK
Machining conditions (experimental and numerical)	
Machining length	5 mm in the y-direction
Wire tension	18.8 kgf
Working fluid	Tap water with anticorrosive
Center distance between wire guides	300 mm
Pulse-on time	45 μs
Pulse-off time	5 μs
Peak current	6A
Machining voltage	80—85 V



(a) (b) (c)

Fig. 3. (a) Machining setup, (b) cutting with working fluid, and (c) cutting without working fluid.

accomplished depending on the known workpiece thickness. More than one measurement is taken at the wire–workpiece interaction zone referenced to the datum line. Then the net deflection is estimated by averaging the resultant deflection values.

4. Thermomechanical finite-element analysis

To simulate the heating behavior of the wire and the associated displacement without jet flushing, a three-dimensional coupled temperature–displacement model is developed using ABAQUS software. The conditions for the performed thermomechanical finite-element analysis are mentioned in Table 1. The ABAQUS mesh generator is applied by assigning 660 elements of the C3D8RT type to the modeled wire under coupled temperature–displacement modeling. The mesh is kept finer at the contact area between the wire and the workpiece (at one-third of the wire length from the top). The assumptions of the simulations can be summarized as follows.

(1) The model is designed for a single spark.
(2) The heat is only transferred along the wire by conduction.
(3) The material of the wire is considered homogeneous and isotropic.
(4) The front region of the wire against the workpiece is the input source of heat.
(5) The heat generated during the spark is equally divided between the wire and the workpiece.

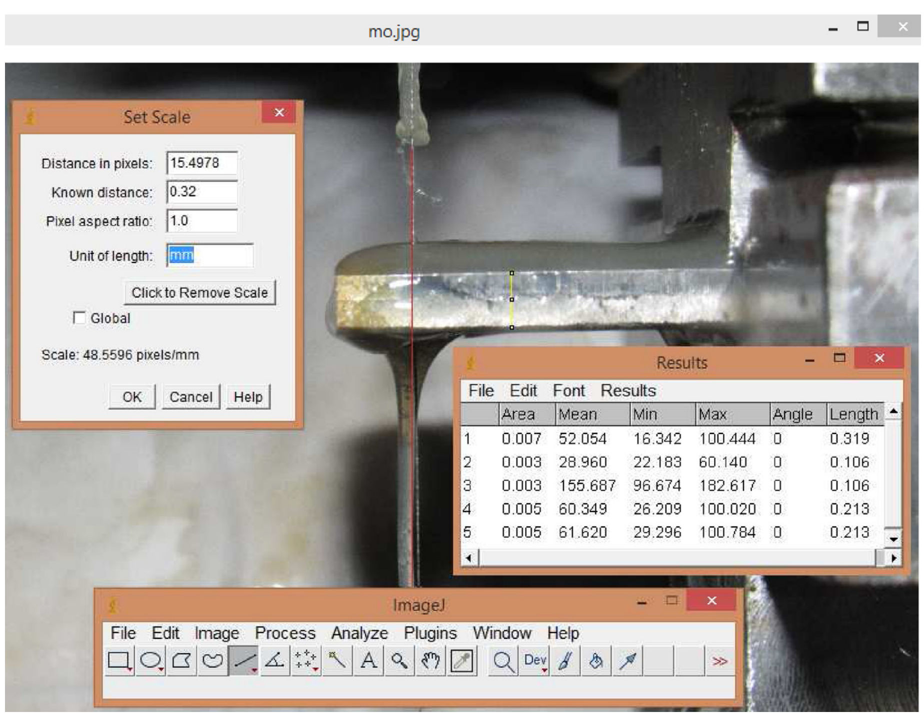


Fig. 4. Deflection measuring steps on ImageJ Java-based image processing program.

It is worth mentioning that the applied heat flux is centered at a distance of one-third of the wire length, which is 100 mm apart from the upper end of the wire. The length of the heat flux region is 5 mm, which is the same as the workpiece thickness. The heat flux is used as the heat input to the simulation where it could be calculated using Equation (9) (Quarto et al., 2020):

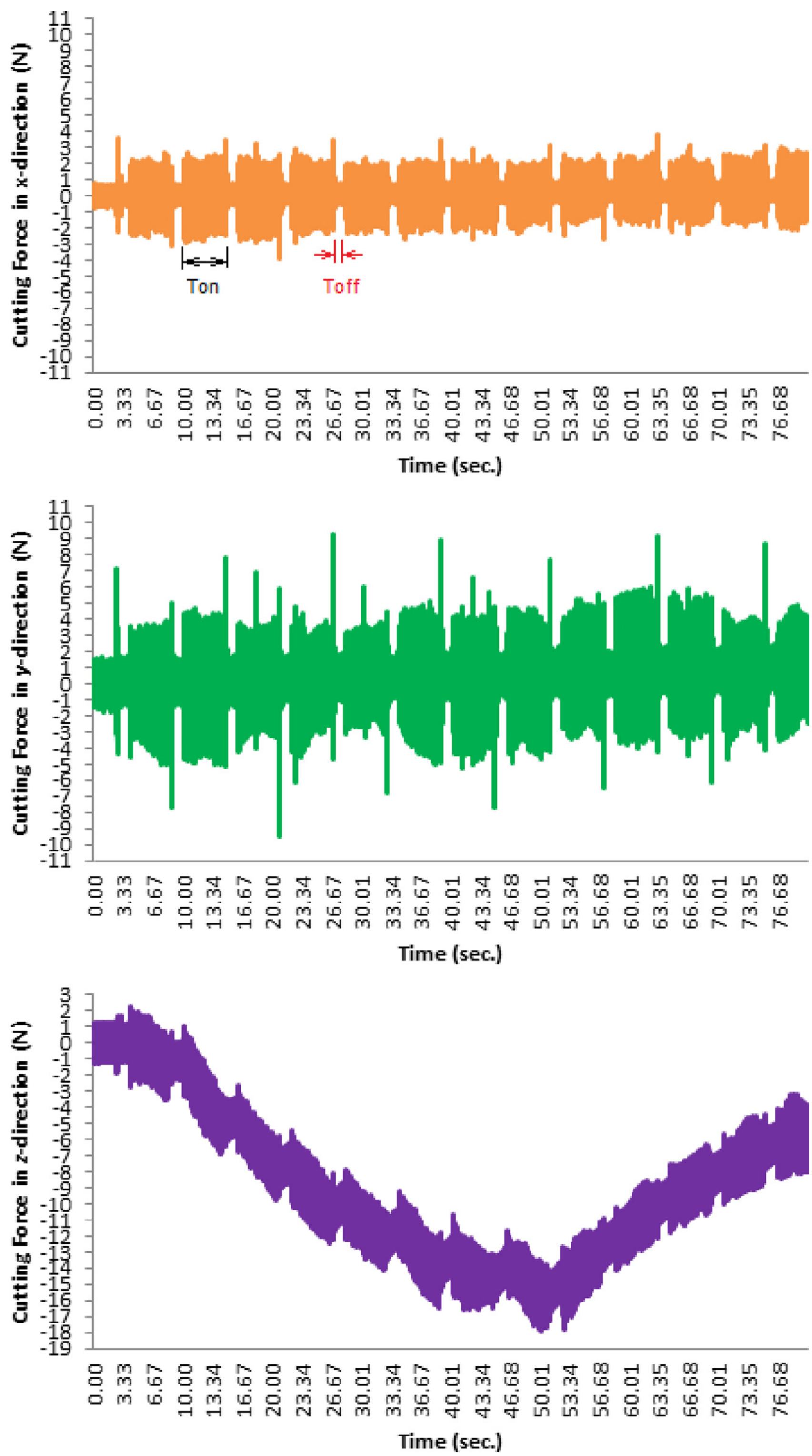


Fig. 5. The resultant cutting force curves in the three directions x, y, and z.

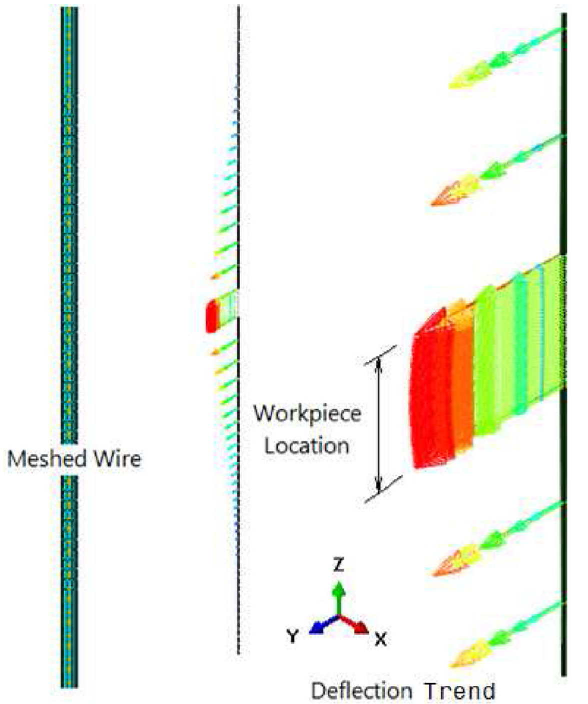


Fig. 6. Modeled wire deflection.

$$Q = \frac{F_a V I}{A_w} \tag{9}$$

where F_a is the fraction of heat transferred to the wire, V and I are the voltage and current during cutting, and A_w is the half surface area on which the heat flux is applied. According to the assumptions and the experimental data, a surface heat flux of about 200 is applied.

5. Results and discussions

During observing the deflection by the high-speed camera, the wire deflection increased at a shorter machining length and then it is decreased. The measurements revealed that the deflection of the wire is larger in the case of cutting without a working fluid compared to with a working fluid. The measured wire deflection with and without a working fluid is equivalent to 0.226 mm and 0.271 mm, respectively. In addition, the direction of the wire deflection is in the same cutting direction in the case of without a working fluid, while it is reversed in the case of a working fluid flow.

The cutting forces in the three directions (x, y, and z shown in Fig. 2) are measured during cutting by a Kistler-type 9257B dynamometer with a measuring range of -5–10 kN. Fig. 5 shows the resultant cutting force curves. The cutting force in the y-direction has the maximum amplitude compared with the other forces, owing to the blockage of the two workpiece sidewalls within the machined kerf. Hence, the resulting force in the y-direction is used to estimate the wire deflection according to the mathematical model using Equation (8). Accordingly, the resultant wire deflection is 0.266 mm. Also, based on the resultant curves, the trend of the cutting force that comes up and down in the z-direction ensures the presence of wire vibration and deflection during cutting.

Relating to the thermomechanical finite-element analysis, Fig. 6 shows the resultant wire deflection shape. It has the same trend as the experimental and the mathematical analyses. The modeled wire deflection value is equal to 0.268 mm.

Fig. 7 illustrates a comparison between the resultant wire deflection according to the three kinds of

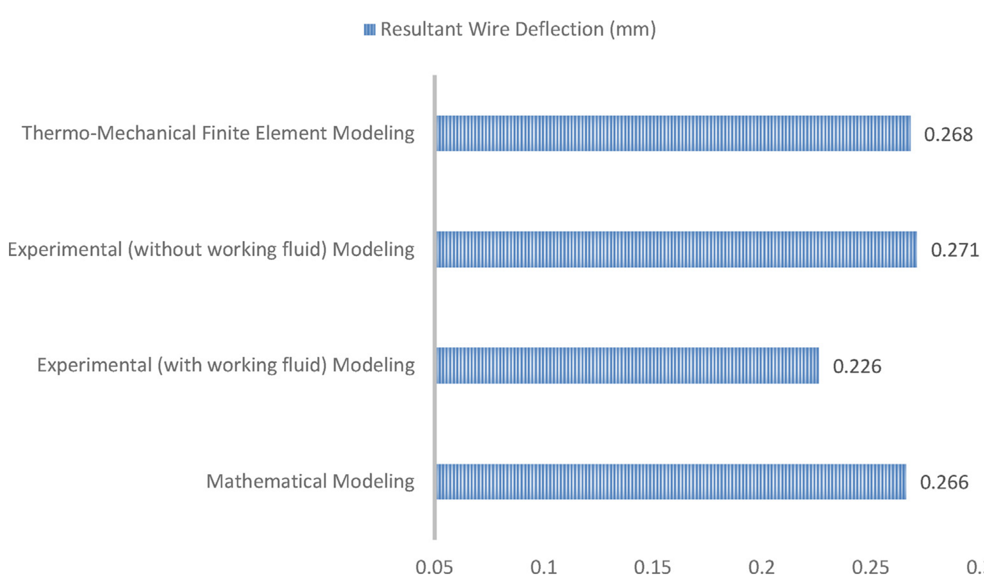


Fig. 7. The resultant wire deflection according to the three types of modeling.

modeling. The values are within the same range for all the modeling. The experimental model with a working fluid achieves the lowest deflection due to the effect of the fluid in reducing the frictional forces.

5.1. Conclusion

The current work seeks to study and determine the wire deflection during WEDM of AISI 304 stainless steel. Three types of modeling are performed to study the wire deflection phenomena. Mathematical modeling is performed to analyze the wire stresses and wire lag, while experimental modeling is achieved to observe the wire deflection and the cutting forces. The thermomechanical finite-element modeling is accomplished to forecast the wire deflection and make a correlation between the experimental and computational works. The result reveals that the obtained wire deflection increases at a shorter machining length then it is decreased. Also, it is concluded that the wire deflection is larger in the case of cutting without a working fluid compared to with a working fluid. In addition, the direction of the wire deflection is in the same cutting direction in the case of without a working fluid, while it is reversed in the case of a working fluid flow. The resultant wire deflection according to the mathematical, experimental (with and without a working fluid), and thermomechanical finite-element modelings are 0.266, 0.226, 0.271, and 0.268 mm, respectively. By estimating the obtained wire deflection from the three models, it is clear that the values are similar, which indicates the accuracy of the proposed models. The proposed strategies are effective in forecasting and reducing wire deflection, hence increasing the dimensional accuracy, productivity, and stability of the parts machined by WEDM.

Author credit statement

Sara A. El-Bahloul: Study conception or design of the work; Visualization; Data collection and tools; Data analysis and interpretation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Statistical analysis; Software; Supervision; Drafting the article; Critical revision of the article; Final approval of the version to be published. Mohamed G. Elkhateeb: Study conception or design of the work; Visualization; Data collection and tools; Data analysis and interpretation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Statistical analysis; Software; Supervision; Drafting the article; Critical revision of the article; Final approval of the version to be published.

Conflicts of interest

The authors declare no competing interests.

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