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Model prediction of angular error in wire-EDM taper-cutting

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ABSTRACT: *Taper-cutting is a common application of the wire electrical discharge machining (WEDM) process used for the production of parts with complex geometry such as extrusion dies in wear-resistant materials, cutting dies, etc. During cutting, the wire is subject to deformation, resulting in deviations in the inclination angle of machined parts. This fact causes dimensional errors and loss of tolerances that can lead to the rejection of high added-value tooling. Currently, WEDM machine manufacturers propose time-consuming experimental trial-and-error methodologies for the correction of the errors. To reduce the experimental load and to contribute a more general approach to the problem, two original models for the prediction of angular error in WEDM taper-cutting are presented here. Results show that part thickness and taper angle are the most influencing variables in the problem. Experimental validation of the proposed models shows that angular error can be reduced below 3′45″ in 75% of cases.*
Keywords *Wire EDM, Taper cutting, FEM, Angular error*

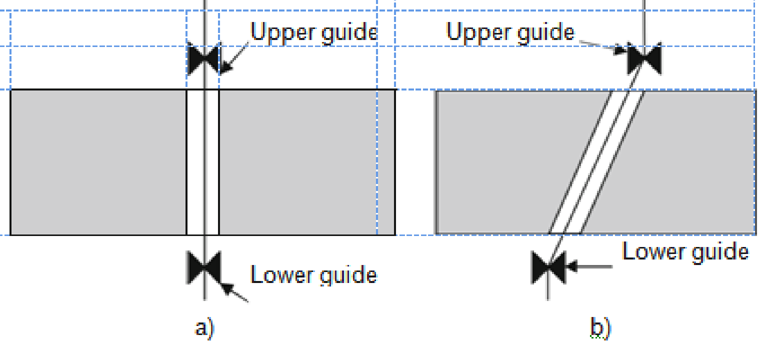
I. INTRODUCTION

In the wire electrical discharge machining (WEDM) process, a wire that follows a path programmed in the numerical control (NC) of the machine is used as electrode. This process is used to cut a geometry rather than to machine a cavity. The wire is subjected to axial mechanical stress in order to keep it straight during the cut with respect to the programmed path. Deionised water is used as dielectric fluid.

When vertical walls are required in the workpiece, the wire is kept vertical. In the case of taper-cutting, the objective is the generation of non-vertical ruled surfaces. This is done by applying a relative displacement between the upper and lower guides of the wire. In fact, the machine is equipped with four interpolated axes: X and Y for the horizontal movement of the machine table and U and V for the horizontal movement of the upper guide with respect to the lower guide. Thus, a certain inclination of the wire with respect to the vertical can be obtained. The maximum angle that can be cut depends upon part thickness, but values about 30° can be easily achieved. Figure 1 shows a schema of a taper-cutting operation.

In order to understand the problem of the loss of precision in taper-cutting, Fig. 2 shows the deformation of the wire when applying the relative displacement between the guides. If the wire had no stiffness, it would exactly adapt to the geometry of the guide. In this ideal case, the programmed angle would be α; this is the angle expected in the machined part. However, the fact that the wire has a certain value of stiffness is the reason for the deviation of the wire with respect to its ideal shape. Again in Fig. 2, the angle β represents the angular error induced by this effect.

Fig. 1 Wire EDM cutting. a Vertical cutting. b Taper cutting



The value of the error depends on aspects such as the distance between upper and lower guides, the stiffness of the wire, the geometry of the guides and the forces exerted during the cutting process, amongst other factors. As a final consequence, tolerances are lost in parts machined using this operation.

Research work dealing with the effect of the forces acting on the wire during the cutting process has been carried out by [1–4]. The forces are generated by the pressure gradients produced by gas bubbles originated during the discharge, the axial force imposed by the machine itself in order to keep the verticality of the wire, the hydraulic effects produced by dielectric flushing and the electrostatic and electrodynamic forces produced by the electrical discharges. These forces are, in general, variable in time and direction of application. Despite the research efforts carried out so far, existing models still lack generality and cannot be effectively validated (due to the difficulty in measuring the forces). This is why industrial application of these models is still very limited.

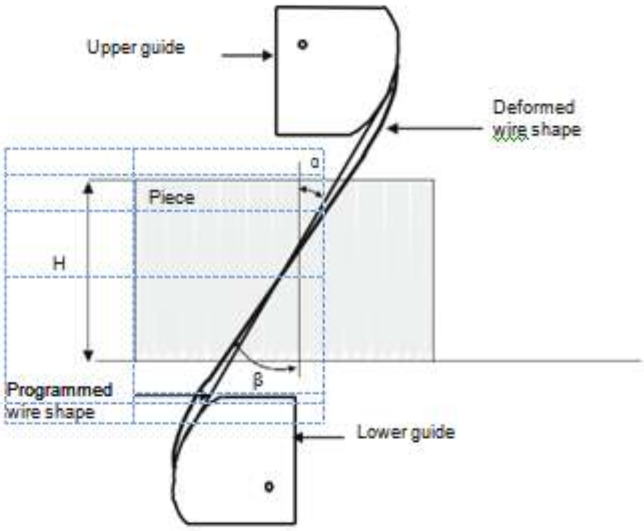


Fig. 2 Theoretical and actual location of the deformed wire

Modelling wire deformation in straight cutting has been

a classical research topic during the 1990s ([5–7]). The equation of movement of an elastic string subjected to an axial force has been used in many research works. Solving that equation is difficult because some of its terms are unknown. In order to simplify the problem, time depen-dency has been neglected, and the static component has been solved. Experimental modal analysis has also been used to predict the dynamic behaviour of the wire, as shown [8]. In a similar research line, [9] presented a novel approach basing on the forces acting in the actual process.

A very limited number of papers deal with the case of taper-cutting and with the loss of precision in this operation. During the last decade, some studies related to the computer-aided design definition of ruled surfaces ([10– 12]) have been published. More recently, [13] developed an analysis of material removal in taper-cutting and proposed a strategy for the optimisation of the efficiency of the process using discharge energy control techniques. In another work based on the analysis of pulse sequences under different regimes, [14] carried out an on-line adjustment of the axial force imposed by the machine on the wire in taper-cutting.

No doubt, probably the most interesting contribution to the study of the problem was given by the work by Kinoshita [15] that proposed a linear model of wire deformation neglecting the forces produced during the process. Excellent results were obtained by Kinoshita in the application of the model to wires of high yield strength and low elongation and with a guide geometry character-ised by large inner radii (5 mm). When the model is applied to the high elongation wires and the guides of small inner radii that are currently used (0.7 mm), important deviations are observed between theoretical predictions and experi-mental results.

An industrial solution used by some machine manu-facturers in order to improve the accuracy of taper-cutting is based on cutting test parts and then measuring the deviation between the programmed and the effectively machined angle. The value of the error is then used as input for the method described in the patent by [16]. Using this method, industrial parts with angular errors below 2′ can be obtained. However, the method is costly and time-consuming because it involves extensive experimentation.

There are some research which propose different methods to compensate the angular error in the taper-cutting, amongst which [16] should be mentioned. Howev-er, only [15] has developed a method to predict the angular error so far. In this paper, two original models for the prediction of angular error in WEDM taper-cutting are presented. The predicted error will be used for the compensation in the machined parts. In the first case, a regression equation is obtained by using design of experiment (DoE) techniques that include the effect of the EDM process. In the second case, a numerical model that estimates wire deformation due exclusively to the relative displacement of the guides (that is, process forces are not considered) has been developed. The model includes non-linear effects such as the friction between wire and guide, the plastic behaviour of the wire, the effect of stress-stiffening and the large displacements involved. This model provides the basis for future research work on optimisation of guide geometry, guide wear, development of new generation of wires, etc.

II. A DOE-BASED MODEL FOR THE PREDICTION ON ANGULAR ERROR IN WEDM TAPER-CUTTING

Design of experiment techniques can be used as a modelling tool in order to estimate the angular error as a function of EDM regime. Moreover, the method yields information about the influence of the different process variables on the error. The DoE is nowadays a common tool in industry for process optimisation, and different models are adapted to the different problems proposed as a function of the characteristics of the variables, its number and the precision required in the solution of the problem.

In this work, a multilevel design with quantitative variables has been selected. This approach permits deriving mathematical expressions that relate process variables to angular error. In this case, the so-called central composite rotatable design has been chosen [17]. It is based on a Hadamard matrix extended using the concept of star points and center points. Star points are the actual limit values of each variable in coded form. These points allow estimating the curvature, increasing the accuracy of the solution. The center points refer to the central value within the range of each variable and provide information about the standard deviation of the process.

2.1 Selection of the variables

The success of the model depends largely on the proper selection of the input variables. A previous selection of the most influencing variables is critical, since thus the number of experiments can be largely reduced.

The deviation of the wire during the WEDM process is dealing with the mechanical behaviour of the wire (static deformation) and the effect of the forces acting on the wire during the cutting process (dynamic deformation) [14].

The mechanical behaviour of the wire is related to its mechanical properties (Young Modulus, per cent elongation at rupture, ultimate strength, etc.) and to the geometrical definition of the problem defined by the distance between the upper and lower guides and the desired angle (supposing that the guide geometry remains invariable).

As it has been mentioned in Section 1, the forces acting on the wire are the electrostatic and electrodynamic forces, the hydraulic forces, the pressure gradients produced by gas bubbles originated during the discharge and the axial force imposed by the machine itself in order to keep the verticality of the wire.

According to the static and dynamic deformation of the wire, the following variables have been selected:

Part thickness (H) and wire inclination angle (α)

These variables are directly related to the geometrical definition of the problem, that is, they have a large influence on the mechanical behaviour of the wire. In this study, the mechanical properties of the wire have not been selected as input variable since one single type of wire has been used (standard wire). However, in case of applying another type of wire, a parallel study to that developed in this paper should be done.

Open-circuit voltage (U_0)

This value is related to the electric field responsible for ionisation of the gap and, therefore, for the electrostatic forces acting on the wire. U_0 can directly be programmed in the control of the WEDM machine.

Discharge energy (E)

Electrodynamic forces are directly related to the energy of the discharge. This parameter cannot be programmed in the control by the user. In order to obtain the value of E, statistical analysis of the voltage and current signals of the process must be carried out. In the tests, NI-6115 acquisition system has been used. E parameter can be finally calculated.

where U(t) is the voltage during the discharge, i(t) is the current during the discharge, and tp is the pulse duration.

This is the period between two consecutive discharges. From a mechanical point of view, it defines the frequency of application of the electrostatic and electrodynamic forces. t_0 can directly be programmed in the control of the WEDM machine.

The hydraulic forces related to the flushing conditions have been kept constant, since in taper-cutting it is advisable to maintain at a maximum both dielectric flow and pressure in order to get the best cleaning conditions for the gap. As far as the axial force imposed on the wire refers, the manufacturer recommends carrying out taper-cutting at an axial load equal to that used in vertical cutting, which is the reason why it has not been included as input variable.

The study here presented focuses on the 0.25-mm-diameter uncoated wire, CuZn 37. This is a wire of high yield strength, for which an axial load of 11.3 N is recommended.

The variables described, together with their range of variation, are collected in Table 1. The limits of the electrical machining parameters have been selected wide enough in order to cover the possibility of machining a large number of different workpiece materials, from the classical hardened steels used in the tooling industry to advanced materials such as boron carbide, used in applica-tions that require high wear resistance.

Since the number of variables is 5, a 16-test Hadamard matrix of resolution V must be built. This approach covers the main factors as well as the interactions between each two factors, but it neglects the possible interactions between three or more factors. The result is that the degree of influence of each variable, its curvature and the degree of interaction between different variables can be evaluated. The concept of interaction refers to the fact that the effect of one factor on the global response of the system depends on the level at which the rest of variables are.

The Hadamard matrix results in 32 EDM experiments. The geometry of the test parts for the experiments is shown in Fig. 3. The upper and lower surfaces are ground so that they can be used as a reference for the measurement of the angle. The experiments have been carried out on an ONA

Table 1 Variables of the design and range of variation

Variables	Range of variation
Thickness, H (mm)	10–80
Angle, α (°)	5–30
Open-circuit voltage, U_0 (V)	110–150
Off-time, t_o (μs)	5–80
Discharge energy, E (μJ)	2,500–6,000

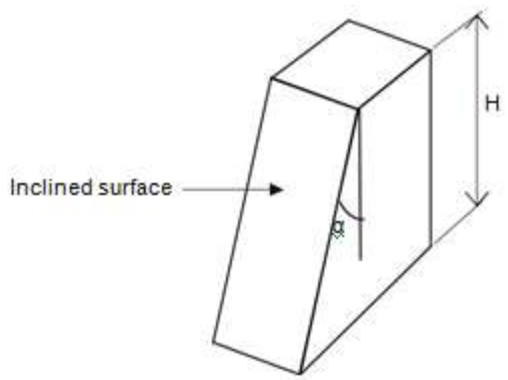


Fig. 3 Geometry of the test part

Prima E-250 WEDM machine, and material of test parts has been AISI D2 tool steel. Dimensional measurements have been carried out on a Zeiss 850 Coordinate Measuring Machine. The results of the angles measured in the machined parts and the values taken by each variable in the 32 tests can be found in Table 2.

2.2 Regression equation

The results of the experiments are then used to generate the regression equation. It will be a quadratic equation, and the coefficients are obtained from the complete Hadamard matrix. Then a signification test using the unidirectional t distribution is performed in order to estimate the degree of confidence of each coefficient through the study of the standard errors (SE). Any coefficient with a degree of signification below 90% will be removed from the equation, since its influence on the global response is small.

Figure 4 shows, in a logarithmic scale, the relative weight of each coefficient on the global response. The horizontal dotted line represents the limit value below which a coefficient must be removed from the response. Results prove that most of the response is due to the geometric configuration of the problem through the variable thickness and taper angle. Electrical variables must also be considered, but their influence is smaller than that of part geometry. Still smaller is the contribution of the interactions between variables.

The actual angle that will be obtained when machining a part with a given set of electrical parameters can be predicted.

Table 2 Set of tests of the DoE

Experiment no.	H (mm)	α (°)	t_0 (μs)	E (μJ)	U_0 (V)	Measured angle (°)
1	27.5	11°15′	23.75	5,125	140	11°49′24″
2	27.5	11°15′	61.25	3,375	140	11°52′20″
3	62.5	11°15′	61.25	5,125	140	11°34′18″
4	62.5	23°45′	61.25	3,375	140	24°22′36″
5	62.5	23°45′	61.25	5,125	120	24°22′30″
6	62.5	23°45′	23.75	5,125	140	24°18′30″
7	27.5	23°45′	61.25	3,375	120	24°48′30″
8	62.5	11°15′	23.75	3,375	140	11°34′28″
9	27.5	23°45′	61.25	5,125	140	24°46′41″
10	62.5	11°15′	61.25	3,375	120	11°34′3″
11	62.5	23°45′	23.75	3,375	120	24°18′30″
12	27.5	23°45′	23.75	3,375	140	24°42′50″
13	27.5	11°15′	61.25	5,125	120	11°48′15″
14	62.5	11°15′	23.75	5,125	120	11°31′27″
15	27.5	23°45′	23.75	5,125	120	24°41′8″
16	27.5	11°15′	23.75	3,375	120	11°49′41″
17	45	17°30′	42.5	4,250	110	18°3′17″
18	45	17°30′	42.5	4,250	150	18°3′52″
19	45	17°30′	5	4,250	130	18°6′22″
20	45	17°30′	80	4,250	130	18°12′
21	10	17°30′	42.5	4,250	130	18°46′15″
22	80	17°30′	42.5	4,250	130	17°53′
23	45	5°	42.5	4,250	130	5°12′7″
24	45	30°	42.5	4,250	130	30°52′40″
25	45	17°30′	42.5	2,500	130	18°5′39″
26	45	17°30′	42.5	6,000	130	18°4′3″
27	45	17°30′	42.5	4,250	130	18°7′35″
28	45	17°30′	42.5	4,250	130	18°8′14″
29	45	17°30′	42.5	4,250	130	18°8′55″
30	45	17°30′	42.5	4,250	130	18°6′6″
31	45	17°30′	42.5	4,250	130	18°7′20″
32	45	17°30′	42.5	4,250	130	18°6′59″

III. VALIDATION OF THE DOE MODEL

Equation 2 must be validated. In order to do so, a number of experiments in which the angle predicted by the equation and the angle effectively cut in industrial WEDM oper-ations can be compared.

With the aim of analysing the influence of the erosion parameters on the validation tests, two different regimes have been studied: tests using low-energy EDM regimes (LE), and tests using high-energy EDM regimes (HE).

Table 3 shows the EDM parameters used in both cases. The validation has been carried out in part thickness of 20, 40, 60 and 80 mm, with taper angles from 5° to 25° depending upon part thickness. The deviation between the angle predicted by the equation and the angle measured in the machined parts is used as index for the validation.

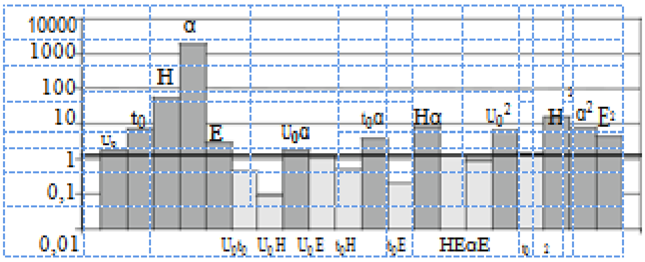
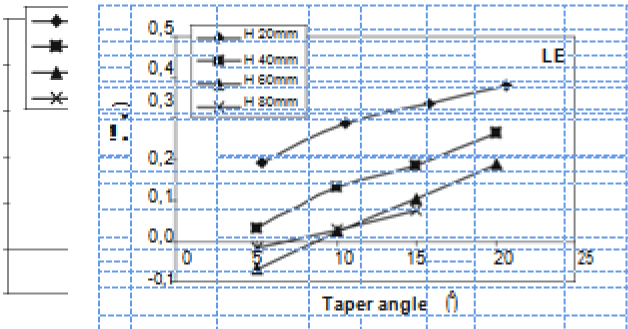


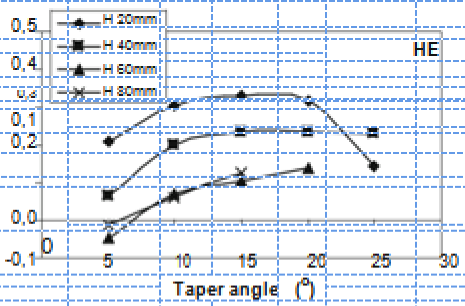
Fig. 4 Relative weight of the different coefficients

Table 3 EDM parameters in low-energy and high-energy regimes

Parameters	Angle		
	Up to 15°	20°	Up to 30°
t_{off} (μs) (HE)	5	5	5
t_{off} (μs) (LE)	15	20	25
U_0 (V)		110	
E (μJ) (HE)		4,500	
E (μJ) (LE)		3,500	



H (mm)	Nominal angle (°)	Experimental angle (°)
20	5	5°9'36"
	10	10°17'35"
	15	15°26'46"
	20	20°34'44"
40	10	10°11'13"
	15	15°18'25"
	20	20°22'26"
60	5	5°4'48"
	10	10°9'36"
	15	15°13'15"
	20	20°15'10"
80	5	5°2'52"
	10	10°8'46"
	15	15°12'14"



H (mm)	Nominal angle (°)	Experimental angle (°)
20	5	5°8'53"
	10	10°13'37"
	15	15°26'35"
	20	20°37'5"
40	5	5°3'43"
	10	10°7'1"
	20	20°22'41"
60	5	5°3'54"
	10	10°6'50"
	15	15°12'25"
	20	20°16'41"
80	5	5°3'4"
	10	10°6'29"
	15	15°8'35"

Fig. 5 Deviation between the angle predicted by the regres-sion equation and the angle measured in machined parts (low-energy and high-energy regimes)

Figure 5 shows the results obtained for both high- and low-energy EDM regimes. The values measured for the angles in the parts cut are shown in the tables included for the given part thickness and nominal angle.

In this case, it can be seen that the higher the part thickness is, the lower the deviation from the nominal angle is obtained. On the other hand, when maintaining the part thickness, the deviation rises as the angle does. This tendency takes place in both LE and HE regimes.

Regarding the deviation reached using the regression equation model, it must be mentioned that, in the case of the tests using low-energy EDM regimes, the maximum deviation is 22′ for the case of part thickness 20 mm and taper angle 20°, and the minimum deviation is 54″ for the case of part thickness 80 mm and taper angle 5°. In the tests using high-energy EDM regimes, the maximum deviation is 19′48″ for the case of part thickness 20 mm and taper angle 15°, and the minimum deviation is 50″ for the case of part thickness 80 mm and taper angle 5°.

At the sight of the results from the DoE model, most of the error can be attributed to the deformation of the wire produced only by the movement of the guides. In other words, the effect of the EDM regime on the error is limited. Thus, once selected, a specific wire whose mechanical properties are known and defined the geometry of the guides, it can be said that the angular error stems mainly from the geometrical definition of the problem.

However, the erosion regime cannot be neglected since the results seem to be slightly influenced by the load conditions applied over the wire during the process.

The fact that the actual angle can be theoretically predicted using Eq. 2 introduces a new advantage in the solution to the problem. From that equation, the angle that must be programmed in the machine in order to obtain a required angle in the machined part can be calculated. In order to do so, Eq. 2 can be rewritten in the following form:

0:024 a^2 þ ð0 :007 0:016 t$_0$ þ 0:033 H 6:422Þ a ¼
U$_0$ 18:128
006 0 006
angle þU t 0187H 0 01 E
Required$_2$ 0: 2 $_0$ þ : $_2$ 0 : þ :
þ 0:048
0:019 U$_0$ H 0:014 E

ð3Þ

where α is the angle that must be introduced in the NC of the machine if the Required angle must be obtained in the machined part. Thus, for a given required angle, the value of α can be extracted from Eq. 3. Table 4 collects the results obtained when cutting test parts in AISI D2 tool steel for different EDM regimes. The angular error obtained after applying this method is within the range from 1′54″ for the case of part thickness 80 mm and angle 19°, to 4′33″for the case of part thickness 40 mm and angle 24°.

When comparing these results with those from the industrial solution (explained in Section 1), it is shown that the regression equation provides slightly higher errors with far lower experimental cost.

As an example, when machining part thickness 60 mm with inclination angle 20°, the industrial solution gives a final deviation in machined part of 1′25″, whereas when applying the regression equation proposed, the deviation is 4′09″.

Finally, the results of the new procedure have been validated for the case of cutting an advanced material such as boron carbide. Tests in part thickness 20 and 30 mm have been carried out. Table 5 shows the results that show a degree of agreement between experimental and theoretical predictions similar to that obtained in the cutting of tool steel.

As a conclusion, it can be stated that the DoE-based model provides the user with an effective method for the prediction and correction of angular errors in WEDM taper-cutting.

Table 4 Results obtained from the measurement of the machined pieces (AISI D2) applying regression equation model

Thickness (mm)	Nominal angle (°)	Energy level	Real angle (°)
20	12	LE	12°3′31″
20	7	HE	6°57′6″
40	24	LE	24°4′33″
40	30	HE	30°2′52″
60	11	LE	11°4′30″
60	20	HE	20°4′9″
80	8	LE	8°2′36″
80	19	HE	19°1′54″

Table 5 Examples of validation of the regression equation

Thickness (mm)	Nominal angle (°)	Measured angle in WEDM tests (°)
20	6	6°5′28″
30	16	16°4′30″
30	27	27°4′13″

Workpiece material is boron carbide

IV. A NUMERICAL MODEL OF WIRE DEFORMATION IN TAPER-CUTTING

In Section 3, it has been shown that, even though there is a certain influence of the EDM regime on the angular error in taper-cutting, most of the deviation can be attributed to the geometry of the problem and to the mechanical properties of the wire.

Under this hypothesis, modelling the mechanical behav-iour of the wire neglecting the influence of the EDM regime can yield very valuable information about the problem. In fact, this was also the interesting approach used by [15]. However, with respect to the work by Kinoshita, further efforts must be carried out in the modelling approach especially in order to introduce the effect of non-linearities such as friction between wire and guide, plastic behaviour of the wire, large displacements, contact between wire and guide surfaces and the effect of stress-stiffening. In this case, numerical methods such as the finite-element method (FEM) are the optimal choice for modelling. Such a model can reduce largely the experi-mental load of research and place the bases for future research on the design of guides and new wire generations.

A FEM model of the problem requires characterisation of the mechanical characteristics of the wire material. These have been obtained from tensile tests and can be found in Table 6. Using these results, a bilinear model that considers elastic-plastic behaviour of the material and strain-harden-ing has been proposed.

Table 6 Mechanical characteristics of the wire CuZn37

Mechanical properties	CuZn37 wire
Tensile strength, σ_r (N/mm^2)	1,042
Yield strength, σ_f (N/mm^2)	940
Young modulus, E (N/mm^2)	100,000
Elongation, ε_r	2
Poisson coefficient, ν	0.33

4.1 Elements of the FEM model

Figure 6 shows the elements used in the different zones of the wire to build the 3D FEM model:

& Linear hexaedrons with plastic behaviour in the zones close to the contact wire guide

& Elastic beams in the zone of the wire far from the contact wire guide, where the behaviour is probably linear

& Shell elements in the linking surface between hexae-drons and beams

4.2 Load and boundary conditions

The symmetry of the problem can be used to reduce computational cost: half of the section of the wire can be simulated while avoiding the possibility of vertical dis-placement of the upper end of the wire. Then, a horizontal displacement is imposed to the lower end of the wire, so that the relative displacement between guides is simulated. Only half of the length of the wire is simulated, under the assumption that the behaviour is identical in the other half.

The fact of imposing a relative displacement between the ends of the wire leads to the introduction of the concept of follower load so that the axial force can be adequately considered. The value of that force depends on the friction between wire and guide and can be related to the vertical force and to the friction coefficient using Eq. 4,

$$\frac{T_s}{T_e} ¼ e^{ma} \qquad ð4Þ$$

where T_e is the axial force applied in vertical direction at the entrance of the guide, T_s is the axial force in the tapered

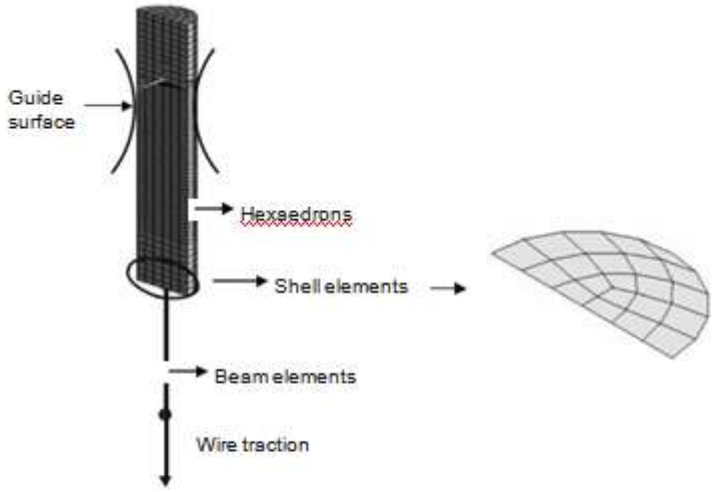


Fig. 6 Finite-element model of the mechanical behaviour of the wire zone, that is, at the exit of the guide, α is the contact angle between wire and guide, and μ is the friction coefficient.

The methodology for estimating the value of the friction coefficient can be found in [18].

For the definition of the contact wire guide, a rigid– flexible approach has been selected. The reason for this is the large difference between the hardness of the guide (sapphire, 1700HV) and that of the wire (brass, 120 HBN). The radius of the guide is 0.7 mm.

Stress-stiffening effects must be considered in those cases of structures in which bending stiffness is very small when compared with axial stiffness. This is, for instance, the case of thin wires as those used in WEDM. The stress-stiffening effect modifies the stiffness matrix of the model, and therefore, it must be included in the model.

Once the model is completely built, the following step is its validation by comparing theoretical predictions and experimental results, in a similar method as that used in Section 3 with the DoE-based model.

V. VALIDATION OF THE FEM MODEL

Validation of the model involves comparing the values of angle predicted numerically with those obtained from the cutting of parts in an industrial WEDM machine. The same experiments planned when validating the DoE-based model (see Table 3) have been carried out in this case. Simulated cases include part thickness from 20 to 80 mm and angles from 5° to 30°.

Figure 7 shows the results of deviation between theoretical predictions and experimental measurements corresponding both to high-energy and low-energy EDM regimes. Also, the values of angular deviation for the different part thickness and angles tested are included. Deviations are, in all the cases, higher than those obtained using the regression equation (Eq. 2). A reason for this may be found in the fact that the numerical model does not take into account the effect of the EDM regime. The maximum deviation is 28′30″ for the case of part thickness 20 mm and angle 10°, and the minimum deviation is 8′ for part thickness 80 mm and angle 15°.

To complete the validation of the FEM model, a set of tests parts in AISI D2 tool steel has been cut using different EDM regimes. Correction of the location of the guides has been performed using the methodology proposed by [16]. In this case, the angle used as input for correction is obtained from the FEM model. The results obtained are presented in Table 7. The deviations with respect to the programmed value of the angle range from 8″, in the case of parts of thickness 80 mm and angle 17°, to 4′52″ in the case of parts of thickness 40 mm and angle 28°.

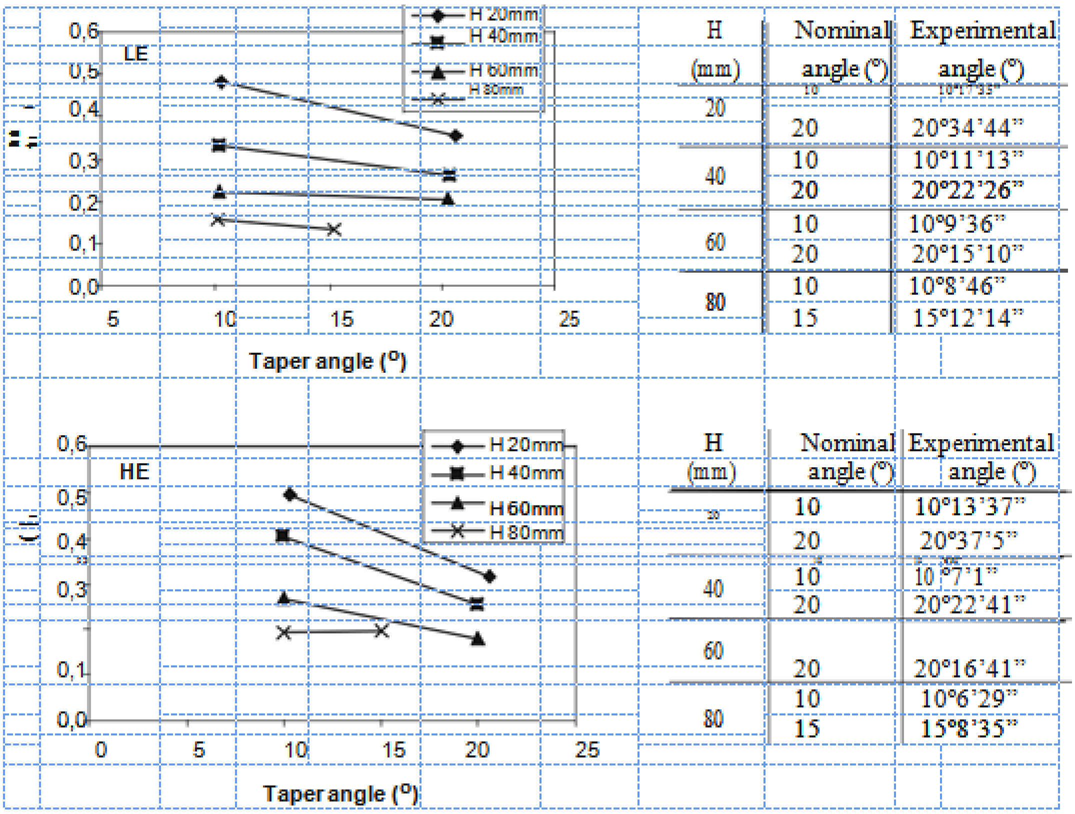


Fig. 7 Deviation between the angle predicted by the FEM model and the angle measured in machined parts (low-energy and high-energy regimes)

Comparing to the industrial solution (explained in Section 1), from the results obtained through the FEM model, slightly higher errors can be drawn. Furthermore, the FEM model reduces drastically the experimental load and contributes with a more general approach to the problem.

As an example, when machining part thickness 80 mm with inclination angle 10°, the industrial solution gives a final deviation in machined part of 18″, whereas when applying the FEM model the deviation is 3′47″.

Table 7 Results obtained from the measurement of the machined pieces (AISI D2) applying FEM model

Part thickness (mm)	Nominal taper angle (°)	Energy Level	Measured angle in WEDM tests (°)
20	9	LE	9°2′38″
20	24	HE	24°1′3″
40	12	LE	11°57′27″
40	28	HE	28°4′52″
60	8	LE	7°56′26″
60	22	HE	22°0′48″
80	10	LE	9°56′13″
80	17	HE	16°59′52″

VI. CONCLUSIONS

From the work carried out, the following conclusions can be drawn:

- ❖ A design of experiments methodology has been proposed to study the influence of WEDM process variables on the angular accuracy of taper-cutting operations. The influence of the variables related to the geometry of the problem, that is, part thickness and angle has been quantified.
- ❖ A quadratic regression equation that allows prediction of angular accuracy for a given EDM regime has been obtained. The equation can also be used to determine the angle that must be programmed in the NC of

the machine in order to obtain a required angle in the machined part. Using this method, the maximum angular deviation has been 4′33″.

- The mechanical behaviour of the wire, neglecting the influence of the EDM regime, has been studied using a finite-element model of the wire. From the model, the actual angle of the wire can be theoretically predicted, and then this value can be used to correct the location of the guides. Through this method, the maximum angular deviation reached in machined parts has been 4′52″.
- In 75% of results obtained from the two models proposed, the angular deviation is below 3′45″.
- When compared with industrial practice, based on trial-and-error experiments, the models proposed here are more general and permit a deeper insight into the scientific knowledge of the problem. In the case of the numerical model, the results set the bases for future research of new guide geometries and new generations of wires.

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