Int J Adv Manuf Technol (2009) 41:858–864
DOI 10.1007/s00170-008-1531-4

ORIGINAL ARTICLE

Using wire electrical discharge machining for improved corner cutting accuracy of thin parts

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Received: 29 December 2006 / Accepted: 15 April 2008 / Published online: 27 May 2008

Abstract The wire electrical discharge machining process (WEDM) allows one to achieved ruled surfaces along intricate contours in hard materials. When one intends to use such a machining process, one has to analyze both the magnitudes of the corners' radii and the corner's angles that are formed between adjoining surfaces. Some experimental research work carried out unveiled the systematic occurrence of machining errors when WEDM is used to obtain outside sharp corners, especially in small thickness workpieces. A permanent bending at the crest of sharp corners, which leads to a substantial deviation from the prescribed geometrical shape, was found. The deviation form depends on the magnetic properties of the workpiece material. The research was focused on establishing a means for characterizing this shape error. Moreover, the influence exerted by certain factors, such as the corner angle and the thickness of the workpiece on the above-mentioned machining error was quantified.

Keywords Wire electrical discharge machining · Accuracy · Corner · Shape error

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1 Introduction

Wire electrical discharge machining (WEDM) simply allows one to achieve ruled surfaces as a result of the process essentials: gradual generating of a notch along a prescribed path, using a thin wire travelling electrode that is stretched between two distinct points near the machining area. However, the latest improvements in WEDM allow for remarkable dimensional accuracy and smooth surface finishing in the manufacturing of components with intricate shapes. The material removal mechanism is independent of the material hardness. Sometimes, the process provides the best alternative, and the only means to machine at a suitable time and cost conductive, high strength, temperature resistive materials, including some modern composite materials [1–3].

The width of the kerf that can be achieved by WEDM, k, depends on the wire diameter, d_{WE}, and on the EDM overcut, s:

$$k = d_{WE} + 2 \cdot s \quad (1)$$

The *geometrical accuracy* could be defined as the deviation between the produced part and the constraints prescribed by the part design [4]. The forces acting on the wire are the main cause of the geometrical inaccuracy of the machined parts, and the efficiency and the accuracy of the process are limited by the risk of rupture, deflection and vibration of the wire, as well as by some other process parameters (the pulses voltage and shape, the viscosity of work liquid, the potential drop in the gap, etc.).

Among these forces, there are the hydraulic forces due to flushing, the electrostatic and electromagnetic forces inherent to the spark generation, the forces induced by the material removal mechanism, and the pulling force that straightens the wire.

In the case of corner cutting, the geometrical inaccuracy is mainly caused by the following:

1. The wire deflection phenomenon: in fact, the forces acting upon the wire pull it backwards causing it to bend. A tensile force is applied to the wire in order to compensate this effect, but it is not possible to completely avoid the wire deflection without breaking the wire.
2. The change of the direction of the wire's motion. This causes a change of the wire deflection that results from the external loads exerted on the wire. The forces due to the material removal process and to the flushing system also change their direction and magnitude, and the equilibrium of the cutting process is disturbed.
3. The intensification of the electric field in the neighbourhood of the corner crest. This causes the instability of the material removal rate.
4. The increase of material removal rate close to the corner crest due to the temperature rising up that is caused, not only by the above-mentioned intensification, but also because the generated heat is difficult to dissipate in the corner's section.

In most of the previous studies, the inaccuracy is considered as resulting from the wire deviation relative to the defined path. Three groups of corner angles are considered in the literature [1, 5]. A group with corners angles of more than 135°, a second group with angles between 30° and 135°, and a third group with angles smaller than 30°. The classification takes into account the main phenomena causing the inaccuracies. For the first group, the error is relatively small and is mostly due to the wire deflection, and for the third group the main cause is the intense sparking at the corner crest. As for the second group, both the wire deflection and the intense sparking are significant.

Several methods for the improvement of the geometrical corner accuracy have been studied in the past [6–13]. Some of these methods propose different strategies for correcting the programmed electrode path in an off-line or on-line manner. Other methods propose monitoring and controlling the on-line wire position by means of an optical sensor [9]. Furthermore, some of those studies propose path control strategies based on the fuzzy logic and expert systems. A different approach consists in changing the machining parameters, such as the feed rate and the pulse off-time at the corner's neighbourhood [10, 11].

According to Lin et al. [5], the *corner error* is defined as the loss of height, Δl, i.e., which is defined as the distance between the pick of the ideal corner and the intersection of the real corner counters with the bisector (see Fig. 1).

To increase the machining accuracy in taper-cut by wire electrical discharge machining, a guide of electrode wire can be used, so that locally sharp bending of wire not appear [14].

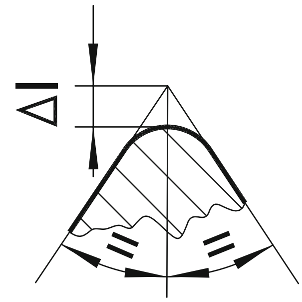


Fig. 1 WEDM of corner error

Daw et al. [15] noticed that the wire electrical discharge machining accuracy depends on the mechanical interaction during the machining process. They proposed and used measurement and acquisition system to improve the cutting precision by the using of suitable detection and control algorithms.

To achieve the desired accuracy of the surfaces made by the wire electrical discharge machining, Williams and Rajurkar [16] used deterministic and stochastic techniques to better understand the process mechanism and to improve the process results.

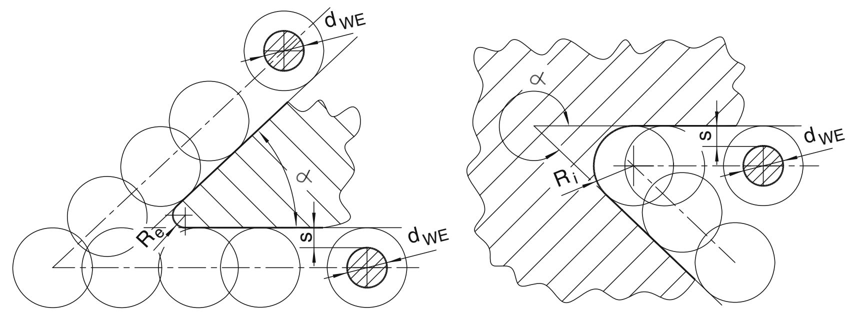
Hsue et al. [13, 17] achieved a geometry analysis of wire electrical discharge machining in corner cutting; they developed a mathematical model to estimate the material removal rate by considering wire deflection.

An experimental research based on the Taguchi method was developed by A. B. Puri and B. Bhattacharyya to study the influence exerted by the wire lag phenomenon on the geometrical accuracy during wire electrical discharge machining [10]. They succeeded to find optimum parametric setting for different machining situations.

Sanchez et al. [18] investigated the possibilities to use a computer-aided system for the optimization of the corner cutting accuracy of the wire electrical discharge machining process. The system was using a combination of the experimental knowledge and numerical simulations. A supplementary research led to the elaboration of software, taking into consideration the effect of friction to adequately model the cutting of the surfaces intersected at large angles [19]. Within a paper published in 2007, some aspects concerning the influence exerted by the cutting speed on the accuracy of wire electrical discharge machining corner cutting were emphasized [20]. The study proved that in the case of the corner geometry generated by the successive cuts (roughing and finishing), the corner accuracy optimization procedure has to consider the errors generated by the previous cuts.

Fuzhu et al. [21] proposed a simulation method for wire electrical discharge machining in corner cut of rough cutting, by taking into consideration the wire electrode

Fig. 2 WEDM of corners
a) inside radius b) outside radius



vibration due to the reaction force acting on the wire electrode during the machining process.

Another type of error at corner cutting of thin workpieces was found: the corner bending that occurs in WEDM outside corner cutting of thin workpieces. This type of error is analyzed in the present paper, and the obtained experimental data is used to achieve a simple mathematical expression with practical relevance.

The objective of this work was to emphasize the conditions in which surfaces characterized by sharpen corners and small corner radius size could be machined in workpieces of small thickness by the using of the wire electrical discharge machining.

2 Proposal and experimental observations

Like a number of other machining processes, WEDM cannot generate very sharp corners. The process performance depends on several parameters such as workpiece thickness, pulse on-time, pulse off-time, pulse peak current, open voltage, dielectric flushing pressure, wire axial mechanical tension, wire feed velocity, and diameter of the wire electrode. The research work has shown that, in addition, the minimum size of the corner radius also depends on the corner's angle, i.e., the size of the dihedral angle that is formed between each pair of adjacent machined surfaces.

By convention, *outside corners* have dihedral angles in the interval 0–180 degrees, and *inside corners* form angles larger than 180 degrees. *An outside radius*, R_e, and *an inside radius*, R_i, will correspond to those types of corners.

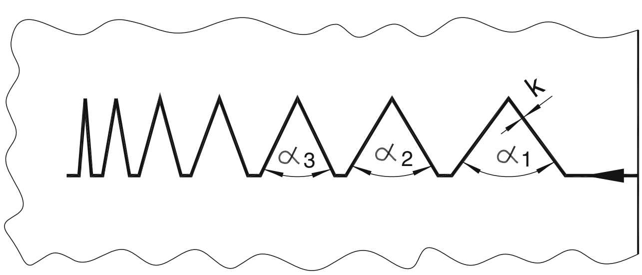


Fig. 3 Typical path of the machined kerf in the workpieces

Concerning to the trajectory of the wire electrode motion, there are different ways to generate inside and outside corners.

Figure 2 shows how to achieve inside and outside corners, respectively. In an *ideal case*, the minimum inside corner radius is equal to the wire offset value and the minimum outside corner radius is zero. The following relations hold:

$$R_i \geq s + \frac{d_{WE}}{2}, \tag{2}$$

$$R_e \geq 0, \tag{3}$$

where s is the gap size, i.e., the overcut.

In order to study the influence exerted by the magnitude of the corner angle on the minimum corner radius size, some tests were made with the wire electrode motion, as shown in Fig. 3.

A WEDM CNC machine was used, and the values for both the minimum outside and inside corner radii were measured, in a basis of no trajectory correction.

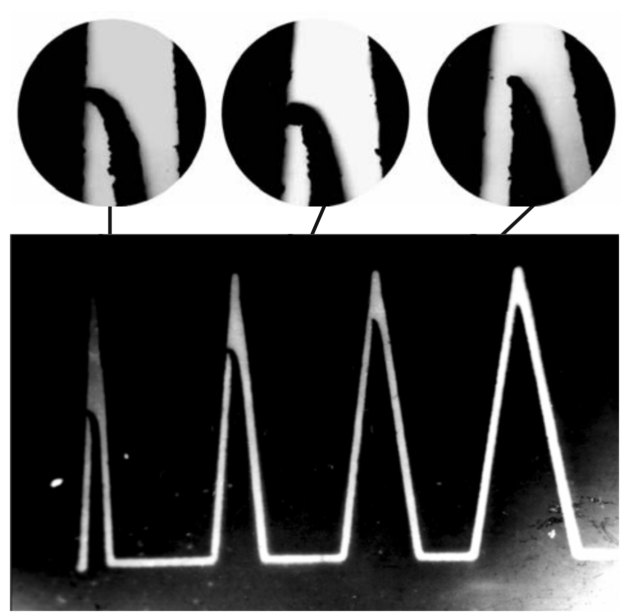


Fig. 4 Shape error in a steel workpiece

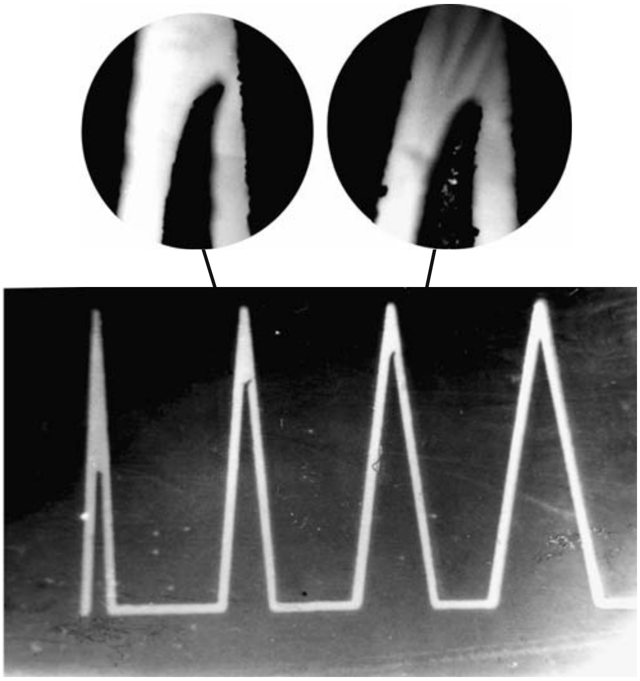


Fig. 5 Shape error in an aluminium workpiece

The experimental work has revealed an interesting aspect of thin, small corner angle workpieces. Essentially, the coming out of a permanent bending in this kind of outside corners were consistently observed; this means that a typical shape error has been found. Two photos of corners obtained during the experimental tests are shown in Figs. 4 and 5.

The tests were run on 1 mm thick specimens, made of steel and of aluminium alloy, using a 250 μm diameter copper wire electrode. The analysis of the photos showed a bending of the top of the corner in the direction of the wire electrode motion along the prescribed path for steel workpieces (Fig. 4), and in the opposite direction for aluminium alloy workpieces (Fig. 5). Moreover, the smaller are both the workpiece thickness and the angle α, the larger is the corner bending.

3 Discussion

The bending direction led to the assumption that it was generated by the electromagnetic forces developed during the electrical discharge machining process. Such forces are due to the interaction between the electric current that pass through the wire and the workpiece during the electrical discharge.

In fact, the wire electrode and the workpiece can be considered as being two parallel conductors through which electric current circulates. From a practical point of view, one can consider that the electromagnetic force developed during the electrical discharge is evenly distributed along both the electrode wire and the workpiece. The direction of the magnetic force that is generated depends on the magnetic properties of the workpiece material: attraction for ferromagnetic workpieces, repulsion for diamagnetic specimens.

The distributed electromagnetic force is given by the relation [12]:

$$q = \frac{\mu_0 \cdot \mu_r}{16} \cdot \frac{I_d^2}{s + d_{WE}/2} \cdot \Phi \qquad [N/m] \tag{4}$$

where μ_0 is the magnetic permissivity of the dielectric de-ionized water [N/A^2], μ_r the relative magnetic permissivity of the de-ionized water [dimensionless], I_d the discharge current [A], and Φ a dimensionless factor that reflects the increasing of the wire electric resistance due to the proximity effect.

The corner's permanent bending shown in Figs. 4 and 5 can be considered as resulting from an electromagnetic force that is perpendicular to the lateral surface of the forming corner (Fig. 6). The force moves due to the relative motion of the electrode wire, as long as the notch is being machined, and the formed corner behaves like a cantilever beam. The internal stress induced by the electromagnetic force goes beyond the yield stress near the top of the corner, where the beam section is very small, and the material undergoes a significant post-yield bending. Notice that the post-yield bending is made easier by the material softening that results from the heat up caused by the electrical discharges between wire-tool and the workpiece. Notice also that the heat dissipated by discharges is difficult to conduct away due to the sharp geometrical configuration of the corner.

The simplified drawing of Fig. 6 corresponds to the presence of an attraction force between the wire electrode and the workpiece, which is the case of ferromagnetic materials. The phenomenon is similar for diamagnetic

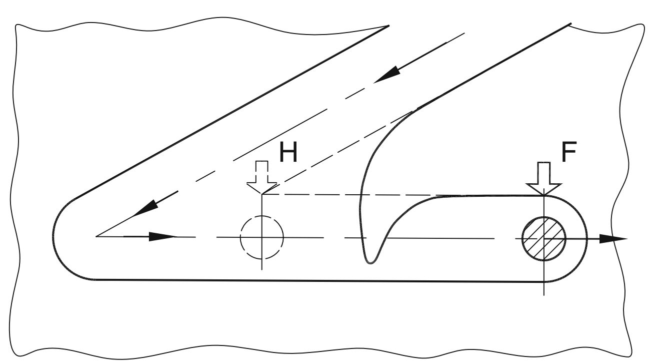


Fig. 6 Permanent outside corner bending as result of electromagnetic forces

materials, except that the post-yield bending has the opposed direction.

Thus, the post-yield corner bending is a typical machining error that occurs when producing small thickness, sharp, outside corners by using WEDM.

To evaluate the magnitude of this error, two dimensional characteristics are proposed: the displacement of the corner top in the horizontal direction, *n,* and the loss of height, Δl, as depicted in Fig. 7.

The displacement of the corner top in the horizontal direction, *n*, is measured along a course that is perpendicular to the theoretical symmetry axis of the corner, AD.

Concerning to the loss of height, there is a difference between the theoretical and the true "height" of the corner. In fact, the true height is smaller due to the post-yield corner bending. The associated *loss of height*, Δl, is measured along the theoretical symmetry axis, AD, and can be described by:

$$\Delta l = l_r - l_t \tag{5}$$

where l_r is the distance from point A to point B. Point A is located at the intersection of the true corner contour with the theoretical corner's symmetry axis AD (see Fig. 7), and point B is situated at the intersection of the external envelope of the electrode path with the above-mentioned symmetry axis. As for l_t, it is the distance between point B and the top of the corner if there was not post-yield bending.

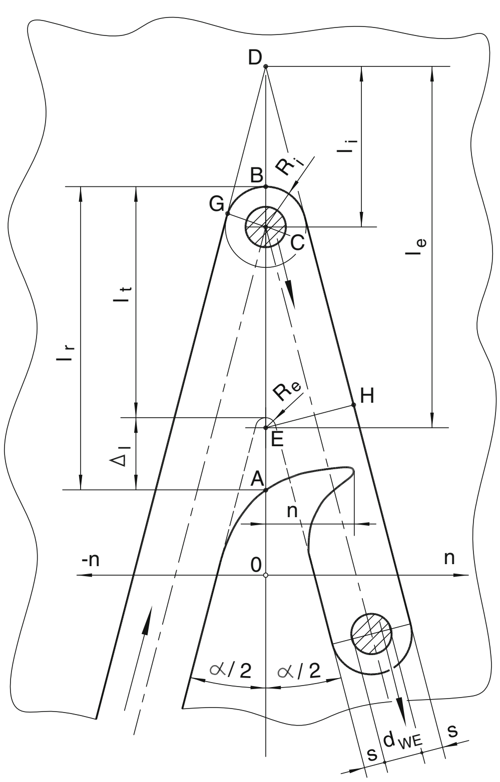


Fig. 7 Measurements used to assess the permanent outside corner bending

Both *n* and Δl were measured by means of a microscope, the latter in an indirect way. First, the distance the real distance between the piece and the scrap, l_r was directly measured. Then, the theoretical distance l_t was computed as follows.

Taking into account the geometric details, the theoretical distance l_t is defined by:

$$l_t = l_e - R_e - (l_i - R_i) \tag{6}$$

On the other hand, since DCG is a right triangle, it follows

$$\sin\frac{\alpha}{2} = \frac{R_i}{l_i} \tag{7}$$

In addition, because DEH is also a right triangle, the following relation can be written:

$$\sin\frac{\alpha}{2} = \frac{R_e + k}{l_e} \tag{8}$$

where α is the corner angle, l_i the distance between the cross-sectional centre C of the electrode at the theoretical top of the corner, and *D* the dihedral vertex; l_e is the distance between the curvature centre of the theoretical corner crest, E, and the dihedral vertex, *D*.

From Eqs. 7 and 8, one can find the expressions for l_i and l_e. Substituting l_i and l_e in Eq. 6 and using Eqs. 1, 2 and 3, one can write:

$$l_t = \frac{k}{2}\cdot\left(1 + \frac{1}{\sin\alpha/2}\right) \tag{9}$$

At last, Eq. (5) is used to compute the loss of height.

4 Mathematical modelling and evaluation

The aim of the experimental work was to study the influence exerted by the thickness, *h*, and the corner angle, α, on the sizes of both Δl and *n* of the workpiece. Keeping this in mind, one produces the corners following machining paths similar to the one that is shown in Fig. 3. Several workpieces made of two distinct materials were used, specifically an aluminium alloy (94% Al, 4% Cu, 0.45% Mg, 0.5% Mn, 0.5% Ni), and a carbon steel (0.45% C).

All the experiments were run on a WEDM machine type JAPAX L250 A, using the machine maker's recommended settings for the following parameters: pulse-on time (between 2 and 12 µs), pulse-off time (7 and 30 µs), open voltage (135 V and 160 V), wire feed rate (500 and 2500 mm/min), wire axial mechanical tension (0,250 and 1,075 Kgf), and dielectric flushing pressure (5 kg/cm^2).

The lengths n and l_r were measured using a Zeiss-Jena microscope type BK 70×70.

Distinct tests were run for the different magnitudes of the corner angle α (5, 10, 15, 20, 30 and 45 degrees) and of the workpiece thickness h (1, 3 and 8 mm). The wire electrode characteristics (copper, d_{WE}=0.2 mm), and the electric conductivity of the dielectric fluid were not changed during all the experimental tests.

The least squares fitting for n and Δl leaded to the following empirical relations valid for carbon steel workpieces:

$$\Delta l = 137931.2 \cdot h^{-0.68} \cdot \alpha^{-2.23} \quad (10)$$

with the coefficient of determination s=730381, and

$$n = 4286.6 \cdot h^{-1.35} \cdot \alpha^{-1.4} \quad (11)$$

with s=3041.

The procedure was repeated for aluminium alloy workpieces, with the following results:

$$\Delta l = 74641.4 \cdot h^{-1.26} \cdot \alpha^{-2.06} \quad (12)$$

with s=265540, and

$$n = -2860.5 \cdot h^{-1.16} \cdot \alpha^{-1.4} \quad (13)$$

with s=1435.

Figures 8 and 9 are based on the empirical Eqs. 10–12 and 13. Figure 8 shows the influence exerted by the corner angle α on the difference Δl, and Fig. 9 shows the influence exerted by the corner angle α on the permanent corner horizontal displacement, n, both for steel workpieces.

From Eqs. 10–12 and 13, one can notice that the corner angle α exerts a larger influence than the workpiece thickness h. It is also worth mentioning that the influence of the specimen thickness on the difference Δl is greater for the case of aluminium alloy than for the case of steel.

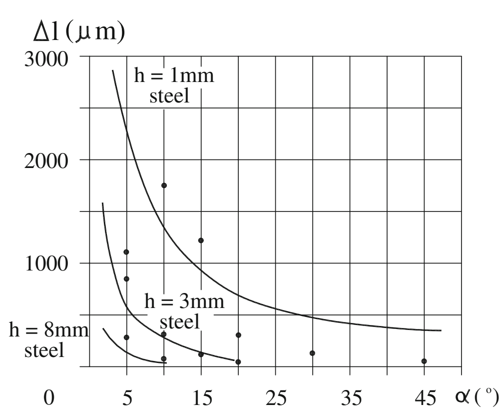


Fig. 8 Influence of the corner angle and workpiece thickness on the loss of height (carbon steel)

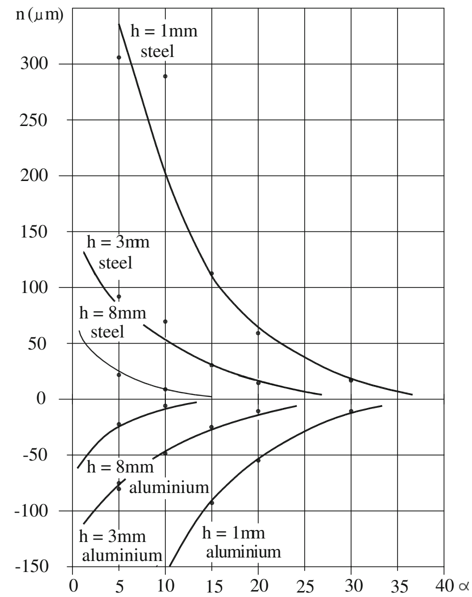


Fig. 9 Influence of the corner angle and workpiece thickness on the horizontal displacement of the corner (aluminium alloy and carbon steel)

5 Conclusions

There are research preoccupations concerning the WEDM corner cutting accuracy. The experimental work shows that the use of WEDM to obtain outside corners with small corner angle and small thickness is accompanied by a machining error having the shape of a post-yield bending.

In the case of ferromagnetic workpieces, outside corners are bent in the direction of the wire electrode movement along the prescribed path. For diamagnetic workpieces, the permanent bend has the opposite direction.

Empirical mathematical models valid for carbon steel and aluminium worpieces were established. For each workpiece material, the magnitude of the machining error is especially dependent on the corner angle, α, and the workpiece thickness, h. Therefore, when concurrently designing small thickness parts with sharp outside corners and the corresponding WEDM production process, one has to pay attention to the correction of the described machining errors.

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