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Study on Wire-EDM Taper Cutting Process: A Review

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Abstract - Wire-electro discharge machining (WEDM) has become an important non-traditional machining process, as it provides an effective solution for producing components made of difficult-to-machine materials like titanium, zirconium, etc., and intricate shapes, which are not possible by conventional machining methods. Taper-cutting is one of the most important application of wire electrical discharge machining (WEDM) process used for producing precise complex geometries with inclined surfaces in hard material parts. The wire is subjected to deformation during taper cutting operation leading to deviations in the angular dimensions and loss of tolerances in machined parts. As a result, the machined part losses its precision. Most of the work is done on straight cutting but some researchers have explored a number of ways to improve the accuracy of taper cutting process. The paper reports a review on the research relating to WEDM taper cutting process for improving and optimizing performance measures and reducing time and cost of manufacturing. The literature survey has revealed that a limited research has been conducted to obtain the optimal levels of machining parameters that yield the best machining quality in WEDM taper cutting process in machining of difficult to machine materials.

Keywords: Wire EDM, Tolerances, Taper Cutting, Cutting Speed, Angular Dimensions

I. INTRODUCTION

Wire electrical discharge machining (WEDM) is among the more widely known and applied non-traditional machining processes in industry today which demands high-speed cutting and high-precision machining to realize productivity and improved accuracy for manufacturing geometrically complex and hard material parts that are extremely difficult to machine by the main stream machining processes. It is a thermo- electrical process in which the material is eroded by a series of sparks between the work piece and the wire electrode (tool).WEDM process with a thin wire as an electrode transforms electrical energy to thermal energy for cutting materials. With this process, alloy steel, conductive ceramics and aerospace materials can be machined irrespective to their hardness and toughness. Furthermore, WEDM is capable of producing a fine, precise, corrosion and wear resistant surface. WEDM was first introduced to the manufacturing industry in the late 1960s. The development of the process was the result of seeking a technique to replace the machined electrode used in EDM.

During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the workpiece and the wire, eliminating the mechanical stresses during machining [1]. In addition, the WEDM process is able to machine exotic and high strength and temperature resistive (HSTR) materials and eliminate the geometrical changes occurring in the machining of heat-treated steels. WEDM machining is widely used in die making industries that need high precision accuracy in their products. The typical applications of the WEDM process include stamping dies, extrusion dies, wire drawing dies, etc. With WEDM, it is also possible to machine complicated shapes that cannot otherwise be achieved using traditional machining processes, such as turning, milling, and grinding [27].

The term taper-cutting is commonly used for WEDM operations aiming at generating parts with tapered profiles, for instance, tooling in which a draft angle is present. In this case the angle is achieved by applying a relative movement between the upper and the lower guides, as shown in Fig. 1. The maximum angle that can be obtained is a function of the workpiece thickness and the mechanical behaviour of the wire. Depending on the machine angles as high as ±30° can be cut in a workpiece of thickness 400mm, but this is an upper limit and the angle is normally limited for parts of high thickness [33].

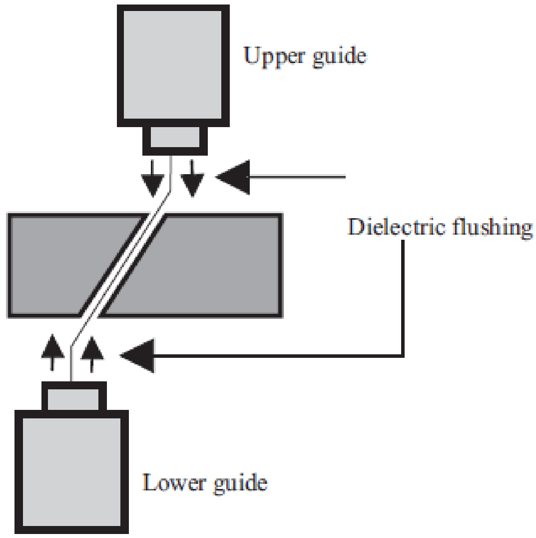

Fig.1 Relative displacement of upper and lower guides in WEDM taper-cutting [25].

II. BASIC PRINCIPLE OF WEDM PROCESS

The WEDM machine tool comprises of a main worktable (X-Y) on which the work piece is clamped; an auxiliary table (U-V) and wire drive mechanism. The main table moves along X and Y-axis and it is driven by the D.C servo motors. The travelling wire is continuously fed from wire feed spool and collected on take up spool which moves though the work piece and is supported under tension between a pair of wire guides located at the opposite sides of the work piece. The lower wire guide is stationary where as the upper wire guide, supported by the U-V table, can be displaced transversely along U and V-axis with respect to lower wire guide. The upper wire guide can also be positioned vertically along Z-axis by moving the quill.

A series of electrical pulses generated by the pulse generator unit is applied between the work piece and the travelling wire electrode, to cause the electro erosion of the work piece material. As the process proceeds, the X-Y controller displaces the worktable carrying the work piece transversely along a predetermined path programmed in the controller. While the machining operation is continuous, the machining zone is continuously flushed with water passing through the nozzle on both sides of work piece. Since water is used as a dielectric medium, it is very important that water does not ionize. Therefore, in order to prevent the ionization of water, an ion exchange resin is used in the dielectric distribution system to maintain the conductivity of water.

In order to produce taper machining, the wire electrode has to be tilted. This is achieved by displacing the upper wire guide (along U-V axis) with respect to the lower wire guide. The desired taper angle is achieved by simultaneous control of the movement of X-Y table and U-V table along their respective predetermined paths stored in the controller. The path information of X-Y table and U-V table is given to the controller in terms of linear and circular elements via NC program. Figure 2. exhibits the schematic diagram of the basic principle of WEDM process.

III. WEDM TAPER CUTTING PROCESS

The term taper-cutting is commonly used for WEDM operations aiming at generating parts with tapered profiles, for instance, tooling in which a draft angle is present [31]. 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.

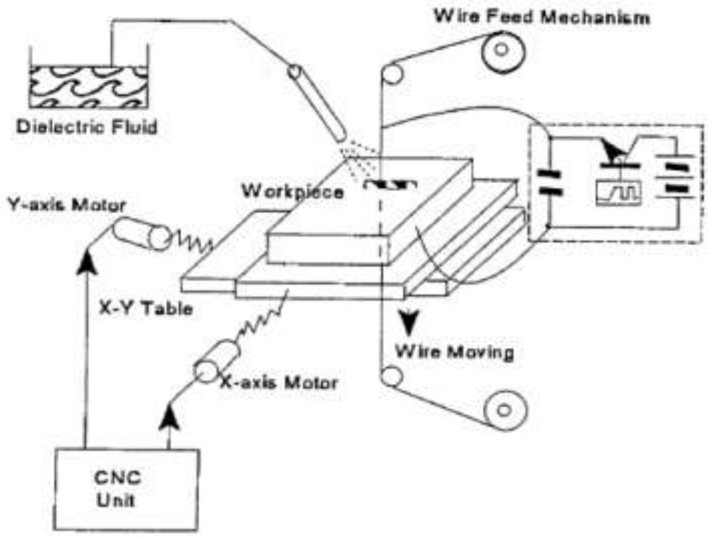

Fig. 2 Schematic Diagram of the Basic principle of WEDM process [22]

In order to understand the problem of the loss of precision in taper-cutting, Fig. 3 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 and the angle β represents the angular error induced by this effect. 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 [3].

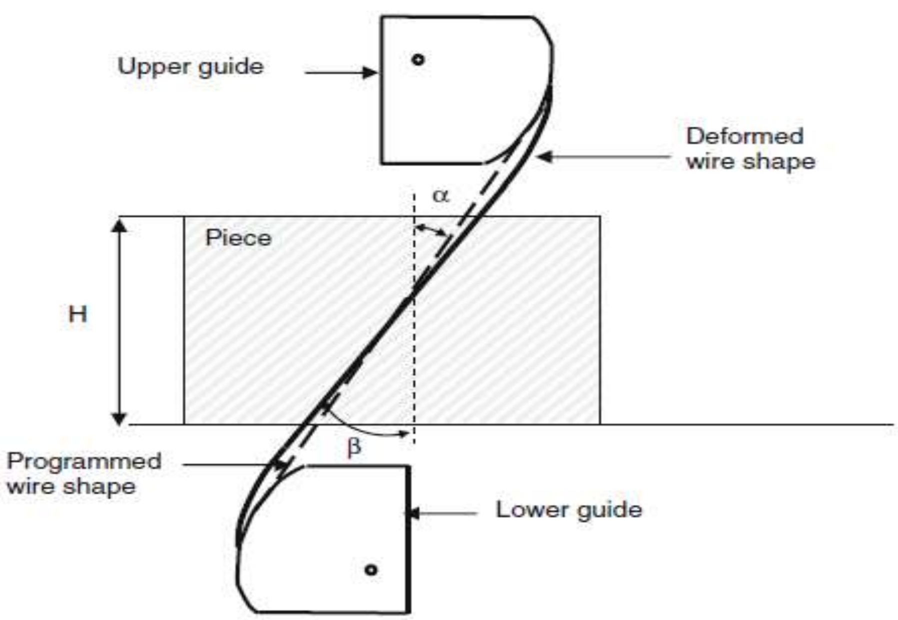

Fig. 3 Theoretical and actual location of the deformed wire [9].

For a better understanding of the causes of lack of accuracy, the mechanics of the process must be analysed. With the wire subjected to tensile stress, the deformation induced on it during the process depends on factors such as the cutting conditions, whether it is a roughing or a finishing cut, the geometry being machined and, of course, the mechanical properties of the wire. In the case of taper-cutting, the deformation caused by the rigidity of the wire when forced to generate a given angle is also of primary importance [31].

IV. LITERATURE REVIEW

Accuracy and modelling in WEDM are recognized [1] as key research lines for the next years, the development of precision and die industries not only requires more productivity, tolerances and dimensional accuracy but also demands complicated profiles with inclined or curved surfaces. Different authors [2-5] studied the effect of the forces acting on the wire during cutting process. N. Kinoshita et al. [2] studied the mechanical behavior of wire dynamically in process over a wide range of machining conditions and the difference between programmed path and produced profile was characterized. A new in process measuring method of the area of wire vibration in wire EDM has been developed and observed that for cutting accurate profile, it is very important to estimate the width of the groove which depends upon the behavior of electrode-wire.

According to [3-5] the mechanical forces are generated by the pressure gradients produced by gas bubbles originated during the discharge, the axial forces applied to straighten the wire, the hydraulic effects produced by dielectric flushing and the electrostatic forces acting on the wire 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.

Models related to wire deformation in straight cutting ware developed by [6-8]. D.F Daun et al. [7] focused on analysis of the wire vibration phenomenon by showing that the EDM wire behaves like a vibrating string and it was the wire EDM unprecision which was influenced by Physico-Mechanical interactions during EDM machining.
[9] carried experimental modal analysis which was used to predict the dynamic behaviour of the wire and similarly, [10] presented a novel approach basing on the forces acting in the actual process. The variation of the geometrical inaccuracy caused due to wire lag phenomenon with various machine control parameters in machining of die steel using WEDM has been investigated. Puri and Bhattacharyya [11] investigated the effect of wire vibration in EDM and found that the higher the thickness/ height of the work piece, the larger will be the maximum amplitude of the vibration for a given span of the wire guides and amplitude. Rajurkar and Wang [12] argued that the wire breakage is correlated to the sudden increase in sparking frequency. It was also found that their proposed monitoring and control system based on the online analysis of the sparking frequency and the real-time regulation of the pulse off-time affects the MRR.
Yan and Huang [13] presented a closed-loop wire tension control system for a wire-EDM machine to improve the machining accuracy. Dynamic models of the feed control apparatus and wire tension control apparatus are analyzed and derived. Beltrami and Dauw [14] monitored and controlled the wire position online by means of an optical sensor with a control algorithm enabling virtually any contour to be cut at a relatively high cutting speed.

Wang and Ravani [15] developed a computational method for numerical control (NC) of traveling wire electric discharge machining (EDM) operation from geometric representation of a desired cut profile in terms of its contours. Tool motion generation for wire cut EDM using a simple surface modeling scheme based on boundary profiles or contours was presented. Masanori Kunieda et al. [16] proposed the use of dry WEDM to eliminate the influence of electrodynamic and electrostatic forces, by conducting a new dry wire electrical discharge machining (dry-WEDM) method in a gas atmosphere without using dielectric liquid to improve the accuracy of finish cutting.

Some researchers focused on corner cutting process in EDM [17-21]. W.J Hsue et al. [17, 18] has presented an effective wire EDM corner cutting strategy with appropriate control and tension adjustment and introduced a concept of discharge contact angle and a geometrical analysis for both angular and arc corner cutting. By lowering the discharge power and increasing the wire tension, the straightness of wire is backed up around corner and the enhanced wire vibration is suppressed as well. Sanchez et al. [19] introduced a new approach to the improvement of the accuracy of WEDM operations involving corner cutting (sharp corner and small fillet radii) which involved the use of a hybrid system in which experimental knowledge and numerical simulation of the process allowed the user to select the optimum strategy for a given job. Sanchez et al. [20] discussed the influence of work thickness, corner radius and number of trim cuts on the accuracy of WEDM corner cutting of AISI D2 tool steel work material. It was found that wire lag was responsible for the back-wheel effect in corner cutting and deviation was larger in case of the test-piece with smaller corner radius. Dodun et al. [21] carried out research work concerning with the WEDM corner cutting accuracy. Empirical mathematical models valid for carbon steel and aluminium worpieces were established which revealed that for each workpiece material, the magnitude of the machining error is especially dependent on the corner angle, α, and the workpiece thickness (h). [22,23] studied surface integrity evolution from main cut, rough trim cut to finish trim cut in CH- and water-based dielectrics in WEDM. Evaluation of improvements in wire electrode properties for longer working time and utilization in wire EDM machining was done [24]. Development of sinking and wire electro discharge machining technology for two ceramics with a promising future (boron carbide and silicon infiltrated silicon carbide) was described by [25]. Formula to calculate the maximum inclination angle of ruling was introduced and coordinates of points on ruled surface have been obtained [26].

Research work related to vertical WEDM has been focused in the above mentioned papers with little or none attention paid on WEDM taper-cutting. As taper cutting is one of the most important applications of WEDM process, in the past years some of the research works dealing with this operation has been published. The problem of prediction of angular error in taper-cutting was initially proposed by Kinoshita et al. [27]. In programming of a tapered geometry it is observed that the actual wire shape (deformed) does not coincide with the theoretical (programmed) shape due to the stiffness of the wire as shown in the fig. 4 leading to angular error in the WEDM'ed part. The influence of wire stiffness is considered using the differential equation for the static deflection of an elastic beam that can be written as follows

$$\frac{d^2y}{dx^2} = \frac{T_W y(x) - F_A x - M_A}{EI} \quad (1)$$

where E is the Young modulus of the wire, I the momentum of inertia of the wire, TW is the axial force imposed on the wire by the machine, FA the normal force at point A and MA, the bending moment at point A.

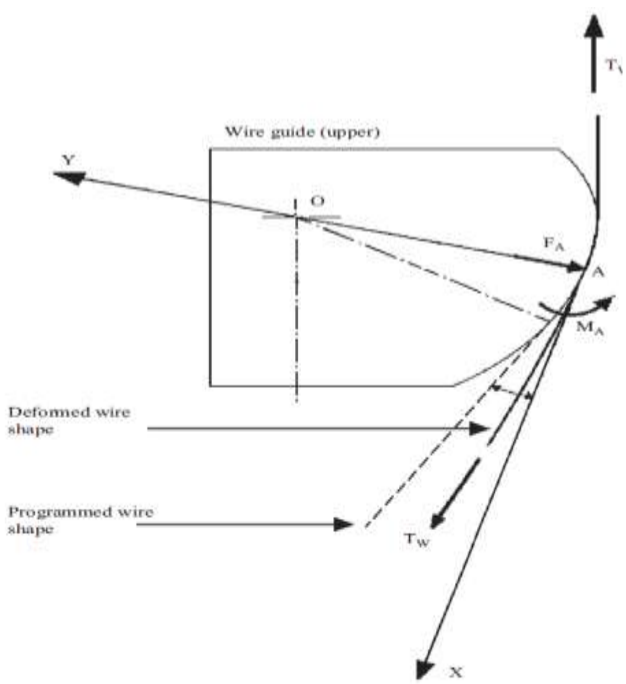

Fig. 4 Deformation of the wire in taper-cutting due to rigidity. Forces and momentum acting on the wire [27]

This approach is used for estimation of the angular error caused by the deformation of the wire, and from that theoretical value, corrections to the position of the guides can be introduced in the Numerical Control of the machine in order to balance the error [28]. This approach does not take account of the effect of EDM regime on the prediction of angular error which is also recognised by a recent patent [29], in which the position of guides is corrected using the data obtained from calibration carried out using precision tooling, and performed previous to cutting. Method of measuring taper angle in wire electric discharge machining apparatus and measuring tool was developed in patent [30]. The present invention relates to a wire electric discharge machining apparatus in which a wire electrode is vertically supported under tension between upper and lower wire guides. Theoretical model and inclined discharge angle concept for material removal analysis of tapering process in WEDM was developed and to improve the efficiency of the process a strategy including control of wire tension and discharge power was proposed by Huse and Su [31]. Sanchez et al. [32] presented computer simulation software for the analysis of error in wire EDM taper-cutting.

An approach for predicting the angular error in wire-EDM taper cutting on AISI D2 tool steel was presented by Sanchez et al. [33]. Two original models for the prediction of angular error in WEDM taper-cutting process are presented by Plaza et al. [34]. Nayak & Mahapatra [35] employed Taguchi's design of experiment for investigating the effect of various process parameters on angular error, surface roughness and cutting speed in wire electrical discharge machining process during taper cutting operation. As Taguchi method fails to solve multi objective optimization problems, utility concept has been explored to aggregate multiple responses (objective functions) into an equivalent quality index (single objective function). An on line adjustment of axial force exerted by the machine on the wire in WEDM taper cutting was carried out by Chiu et al. [36]. Most of the literatures have discussed more about straight cutting with less concentration towards taper cutting in WEDM involving limited work on optimization of process variables.

V. CONCLUSIONS

After a comprehensive study of the existing literature related to taper cutting operation in WED, the following conclusions can be mainly made

- Literature review reveals that the researchers have focused on straight cut and little attention is paid on taper cut in WEDM.
- A very limited number of studies deal with the effect of process parameters on angular error during taper cutting operation in WEDM.
- Multi-response optimization of WEDM process is another thrust area which has been given less attention in past studies.

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