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An industrial system for estimation of workpiece height in WEDM

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Abstract

The wire electrical-discharge machining process (WEDM) is a widely-used technology which can achieve the requirements needed by industry, such complex geometries and precision. Cutting process control in WEDM becomes essential in terms of surface finish and dimensional tolerances. When a cut is made in a variable workpiece thickness, the process becomes very unstable in the transition zone. The difference of energy related to the WEDM regime cannot be easily accommodated when changing to another thickness. In this work a study of the most important variables that take part in the process is presented. It has been found that the workpiece thickness determination can be accomplished from the analysis of the variable Gap error, which is built as a combination of Ionization time (Td) and Servo voltage (Servo). An industrial system has been developed to determine the workpiece thickness with less than 10% error in comparison with the nominal value of part thickness.

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Keywords: wire electric discharge machine (WEDM); process monitoring; stability; roughing process.

1. Introduction

Wire electrical-discharge machining (WEDM) is a widely-used process that allows the machining of materials of low machinability and extreme hardness, obtaining excellent surface finish (less than 0.2µm of average roughness, Ra) and very tight dimensional tolerances, in the order of micrometres. Its application is widespread in sectors such as mould and tooling, tool manufacturing and aeronautical industry, among others. In general, the components

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produced by EDM are characterized by a very high added-value, due to the complexity of this technology. The EDM process is a thermal nature machining method, in which each discharge carries out the removal, by melting and vaporizing, of a small amount of workpiece material whose dimensions are about a few micrometres. Therefore, process control is crucial to achieve the established demanding manufacturing requirements.

A detailed review of the state-of-the-art in conventional WEDM, points out that there are two trends aiming at obtaining the best performance of the process: on the one hand, the optimization of the process, through optimization of its main parameters, adjusting them to different wires and materials; on the other, process monitoring and control.

With regard to the first research line, note that one of the major existing problem must be faced down is mainly due to great number of influential variables involved in the process: so much so that a change in variable can destabilize the process, modifying important aspects such as surface finish or Material Removal Rate (MRR). That means a loss of performance, making it difficult to achieve the required part specifications [1, 2]. Process optimization involves using complex approaches due to the large number of parameters affecting WEDM performance [3, 4].

Traditionally, the selection of appropriate machining conditions for a particular application has been made through the experience and using conservative parameters in order to avoid possible instabilities during the cutting process, such as wire breakage [5, 6].

The use of modelling and optimization techniques has aimed at the definition of the optimum set of parameters that minimize surface roughness or maximize cutting speed, mainly [7, 8]. However, the industrial fact is that the process is so complex, and the technology of the machines evolves so fast, that this type of approaches is rarely used by machines manufacturers, and even less, by machine users.

Industrial solutions are focused on the on-line monitoring of process parameters and the rapid response to stochastic events. Scientific literature also deals with the problem of on-line adapting erosion parameters to the current conditions that present in the cutting zone. The introduction of intelligent machines is a key aspect in WEDM, since it is essential to become this process a reliable and autonomous operation. As an example, Sato et al. [9] presented an adaptive control for increasing the cutting speed. Subsequent to this study, there has been quite number of research works, dealing with aspects such as the development of optimal systems for monitoring voltage and current in real time [10], or the on-line classification of the types of discharges generated during the cutting process [11], among others. These monitoring and control systems have meant an important contribution to minimize the effect of instabilities in the performance of the WEDM process.

Many authors have led their research towards the study of the problem that arise when cutting workpieces of variable thickness. If there is a decrease in the workpiece thickness, keeping the cutting parameters constant, the number of discharges per unit thickness varies, which leads to wire breakage. Otherwise, if the thickness increases, that number of discharges per unit thickness decreases, causing thus a drop in productivity. Artificial neural network systems have been applied to the solution of this problem [12]. In [13, 14], researchers have chosen adaptive control techniques and online monitoring, developing a system which is able to estimate the thickness that is being cut, and thereof, makes an adjustment of the machining parameters in order to prevent wire breakage and maximize in this way the production.

The aim of this work is to develop an industrial system for estimating workpiece thickness in WEDM. The objective is that, at the sight of the value of some process-related parameters (that can be easily an instantaneously measured during cutting) automatic detection of workpiece height can be accomplished. Accordingly, it is possible to know what is the thickness value that is being cut at every moment and, in a further development, to automatically adjust the cutting parameters to their optimum value.

Thus, the methodology involves the analysis of the WEDM cutting process problems in the transition zone between two different thicknesses, the design and the obtaining of an experimental database, a preliminary analysis for the selection of appropriate variables that contribute to the transition behaviour, the establishment of a new variable that help to predict the new thickness and, finally, the development of the industrial application and the subsequent validation.

2. WEDM cutting process problems on variable thickness pieces

When a cut is made by WEDM a large number of factors must be considered, the most important being part material and its geometric features. Based on these conditions appropriate parameters are set in the machine with the purpose of optimizing the cutting process. In order to simplify and streamline the work that the user must do to introduce the value that has to take each of the cutting parameters, manufacturers of WEDM machines provide their customers with all those parameters. The parameters are collected for each type of workpiece material and its thickness and kind of wire (material, diameter, if it is coated or uncoated…).

When it comes to cutting a part of variable thickness, variations mainly in off-time and discharge energy must be taken into account. In the transition zone between two different thicknesses, the cutting process becomes very unstable. The excess of energy related to the WEDM regime for a higher thickness cannot be easily accommodated when changing to a smaller thickness, and wire breakage may occur. In the case of cuts with transitions to higher thickness the situation is just the opposite one. In this case, cutting speed is far below the expected one. Thus, so dependent on the energy of the discharge parameters such as Pulse off time (t_{off}) and the distance between wire and workpiece must be modified to suit the new cutting conditions.

3. Experimental Procedure

3.1. Test definition

The tests were performed on an ONA AX3 WEDM machine. The wire used for all these tests was an uncoated brass wire (CuZn37) 0.25mm diameter, with an ultimate strength of 900N/mm^2 and 1% elongation. The workpiece material utilized was typical steel for the manufacture of tools and tooling F-5211 (UNE), whose high carbon, chromium, molybdenum and vanadium containing, provide excellent wear resistance and good properties for quenching and tempering.

The characterization of the variables involved in the cutting process has been made with workpieces of varying thickness with the following ranges of variation: 150-125-100, 100-80 or 60-40-20, 125-40 and 150-60-20mm respectively, as it can be seen in the example, Fig. 1. With these ranges possible problems that may occur during cutting are considered, from those involving instability in the process to those that can produce wire breakage.

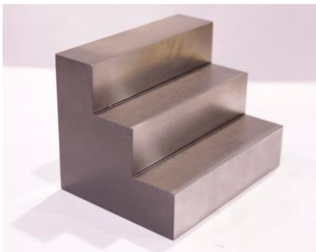

Fig. 1. Workpiece used for the variable characterization, with 60–40–20mm thickness variation.

All tests were performed for roughing conditions. These conditions characterized the process as the most energetic and, therefore, a cut in which major instabilities take place in the thickness exchange zone. WEDM regime corresponds to that of larger workpiece thickness.

As a first step a WEDM monitoring system has been developed. Through this system, the values taken by the variables that determine the cutting process for subsequent study are stored. The working capacity of the recording system is limited by the minimum sampling time that can work, which is 1ms.

The tests performed on the workpiece are carried out as a linear interpolation in one axis. Each test has been repeated five times to ensure repeatability of the results. Two set of tests have been carried out, which are characterized by a different phenomenon:

- A first series of tests along the constant thickness zone of the workpiece, so that the behaviour of the variables (electric discharges, ionization time, Gap error…) is characterized while the thickness does not vary throughout the cutting process.
- A second set of tests in which thickness suffers a variation, so that the behaviour of the variables are checked in these cases, consequently a relationship between these changes in the value of some variables and the thickness variation is obtained.

To characterize the behaviour of the variables in case of constant thickness the methodology used is the following: the workpiece to be cut is placed in WEDM machine, and one of the available thicknesses is selected in process parameters. The cut is made and the behaviour of the variables has been saved by the recording system implemented in the machine. The process is repeated for each of the selectable thickness of the WEDM machine, without changing the workpiece one. In Table 1 some examples of cutting parameters for different thicknesses are listed.

Table 1. Cutting parameters for 40–70–100mm thickness

Cutting parameters	40mm	70mm	100mm	Cutting parameters	40mm	70mm	100mm
Power rate	7.0	9.0	10.0	Dielectric pressure [bar]	17	17	17
Off time [µs]	9.0	12.0	13.0	Wire tension [kg]	1.2	1.2	1.2
Current intensity [A]	5.0	5.0	5.0	Wire speed [mm/min]	10	10	10
Open circuit voltage [V]	80	80	80	Offset [µm]	170	175	183
Servo voltage [V]	48	50	54				

Once all those cuts are made, a workpiece of different thickness is placed in the machine and the process is repeated, and so on until all parts of constant thickness have been cut.

The aim is to study the behaviour of the variables while there is an abrupt change in thickness of the workpiece, and linear interpolation is the simplest cutting case. The monitoring system starts the cutting process registration 2mm before the change in thickness occurs, along 4mm, recording also 2mm after the change in order to make the process stable again. This length is enough to characterize the behaviour of all the variables involved in the cutting process.

3.2. Data processing

The treatment of the data files collected during the cutting process and the analysis of the behaviour of the variables was performed using a computer system programmed on MATLAB® software. An efficient removal of noise component of the signal has applied from the library of functions. It has been displayed each of the variables versus time and position of the guides of WEDM machine. As it is shown in Fig. 2, original values of variable Sparks with high Ionization time versus time is represented in black, and the average value of it in red. The fall in the values of the curve is the thickness variation rendering.

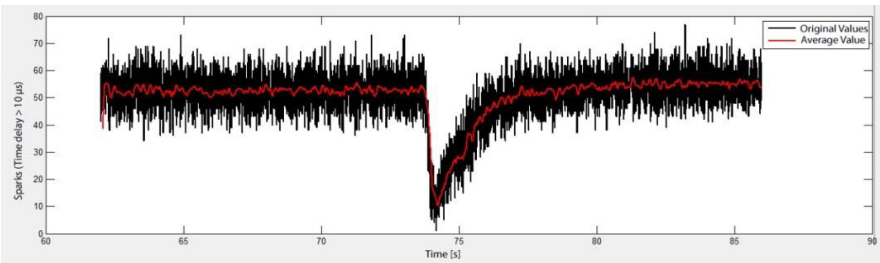

Fig. 2. Representation of original values of Sparks with high Ionization time (in black) and average values (in red) vs Time.

3.3. Variables processed

The most important collected variables during the cutting process are the following ones:

- Ionization time or Delay time (*Td*) is the time from which the machine generates a voltage pulse until the electric shock starts.
- Total time (*Ttotal*) is the real sampling time.
- Servo voltage (*Servo*) controls the distance between wire and workpiece. Higher values of it enlarge the discharge channel size, increases the ionization time and the *MRR* decreases. Otherwise, a drop in the value of this variable implies a decrease in wire-workpiece distance and, consequently, the cutting speed is increased. A compromise between the *MRR* and the wire breakage risk because of cleaning difficulty has to be reached.
- Number of electric discharges, which are classified according to the *Td*:
  - High ionization time (*Td* higher than 10 microseconds): are the most important due to the amount of material they can remove during the cutting process.
  - Medium ionization time (*Td* between 3 and 10 microseconds).
  - Low ionization time (*Td* lower than 3 microseconds).

The Percentage *Td* (*Td [%]*) is defined as the relation between *Td* captured by the recording system and the total time (*Ttotal* [µs]). In Fig. 3, as an example, the shape of filtered Percentage *Td* is shown, to the case of cutting a workpiece thicknesses 100-40mm where wire breakage occurs (a) and 40mm-20mm thickness variation without wire breakage (b). In both figures it is shown a fall in the value of *Td [%]* at point in which thickness variation occurs. In the first case the instability has been not overcome and wire breakage is represented with a fall in the variable, which drops to a null value. In the second one, it is shown the case in which the instability of thickness variation is overcome.

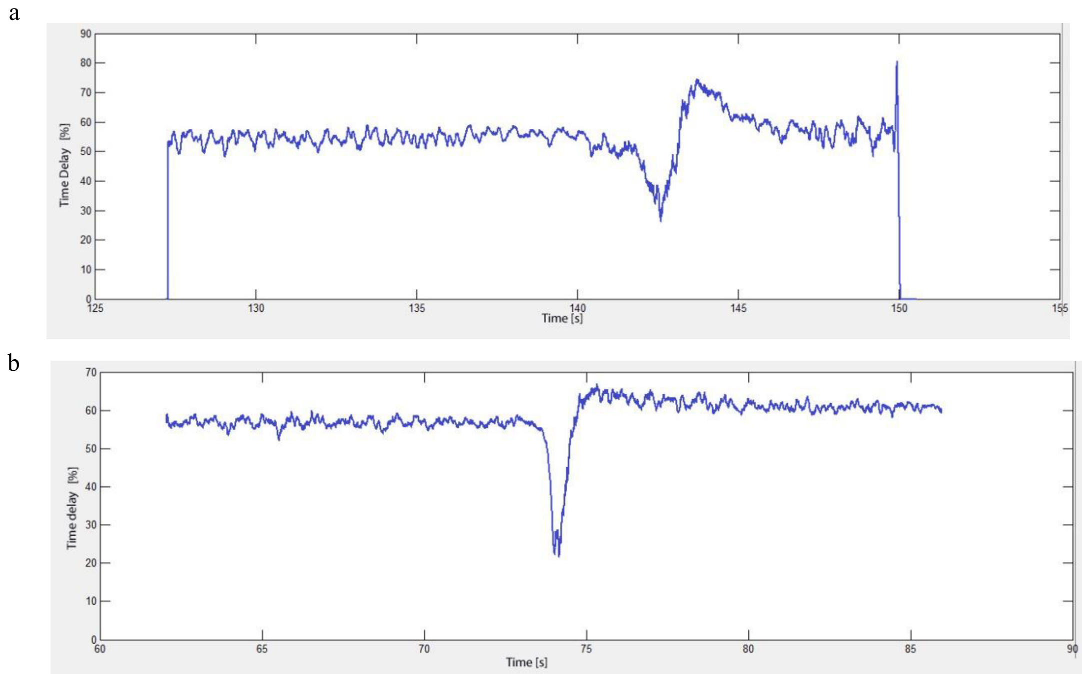

Fig. 3. Percentage of Ionization time (*Td [%]*) versus erosion time for a piece of (a) 100-40 mm with wire break; (b) 40-20 mm without wire breakage.

In order to measure the wire-workpiece distance, which can help to the workpiece thickness determination, a new variable called Gap error is defined:

$$Gap\_error = \frac{Td \cdot 1000}{Ttotal} - Servo10 \quad (1)$$

Thus, if the Gap error is positive the actual wire-workpiece spacing is bigger than the theoretical, which means that the wire is far from the workpiece. In this case, productivity falls. On the other hand, if the error gap is negative, this separation is less than the theoretical, and the wire is too close to the workpiece. This provokes a rise in the number of wire breakages.

4. Results and Discussion

Values taken by the variable Gap error vary depending on the actual thickness of the workpiece, but are also affected by the workpiece thickness value that is selected in the WEDM machine. Therefore, from this variable and knowing the selected thickness in the machine to perform the cut, which is a value imposed by the user for the cutting operation, the group of equations that determine the actual thickness of the workpiece are constructed according to the previously selected thickness value in the WEDM machine.

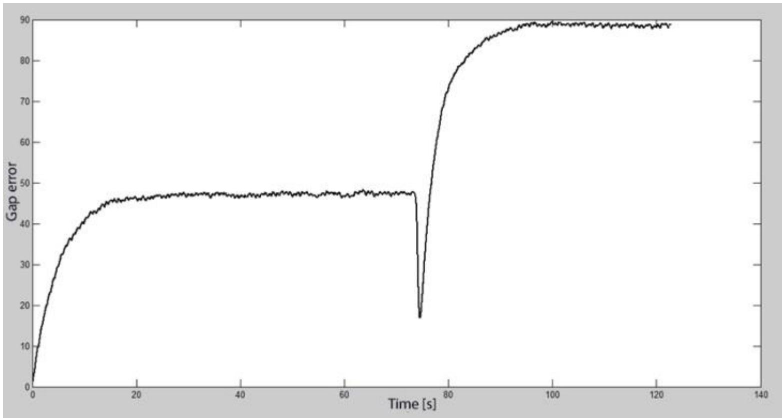

Fig. 4. Gap error vs Time in a test with 40-20mm thickness variation workpiece.

The behaviour of the variable Gap error is shown in Fig. 4, in the case of a cut of a sample with 40-20mm thicknesses. On the one hand, the regions where the value taken by the variable is constant is due to constant thickness areas of the workpiece, the left one to a value of 40mm and the right to a value of 20mm; on the other hand, the discontinuous area represents the thickness change. Firstly, a fall in its value occurs, which is physically interpreted as a decrease in the separation between the workpiece and the wire. Then, it grows very rapidly to around the new value corresponding to the thickness of the workpiece again.

As it has been mentioned before, there is a relationship between the variable Gap error and workpiece thickness, but it is influenced by the selected thickness value in the WEDM machine. This phenomenon is shown in the following illustration. Fig. 5a corresponds to the case of 40mm thick workpiece with a machine selecting thickness value of 150mm, whereas that Fig. 5b represents a situation in which the section of a 40mm thickness workpiece has been cut selecting in the WEDM machine a value of 60mm. It has been proved that, although in both cases the behaviour of the variable is similar, it is not stabilized around the same value. In the first case, the function is stabilized around a value of 35, while in the second the value at which tends is approximately 45. This difference allows the system, from the equations governing the behaviour of this variable for each thickness selected in the machine, what is the actual value of the workpiece thickness cut at any moment.

a b

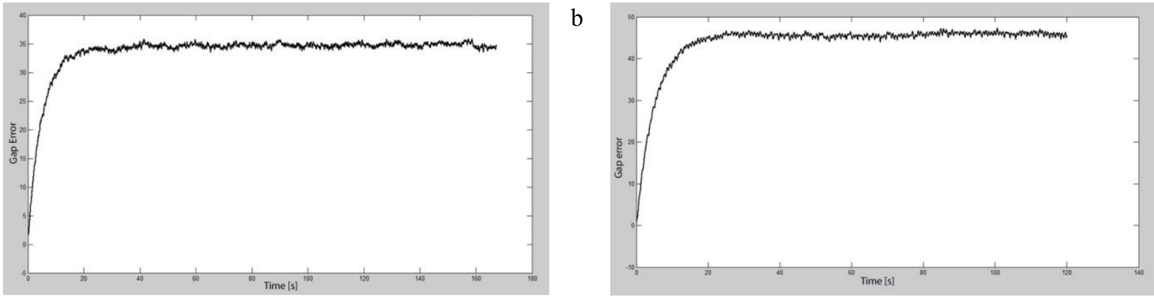

Fig. 5. Gap error behaviour in 40mm thickness workpiece cutting test with a selected thickness in the machine of (a) 150mm; (b) 60mm.

The data obtained are processed in order to acquire a representation of an equation of these points. Keeping constant the value of selected thickness in the machine, a relationship between the value of actual thickness of the workpiece and value taken by the variables that define the cutting process is obtained. In these cases, it was found that there is a direct relationship between the thickness and the Gap error.

In the following illustration, Fig. 6, the above mentioned relationship obtained is shown in case of selecting 150mm thickness in the WEDM machine. On the horizontal axis the value of the Gap error is represented; in the vertical axis the actual value of the thickness of the workpiece is shown. The software determines the equation that best fits the relationship of points obtained, and also the best conditioned solution.

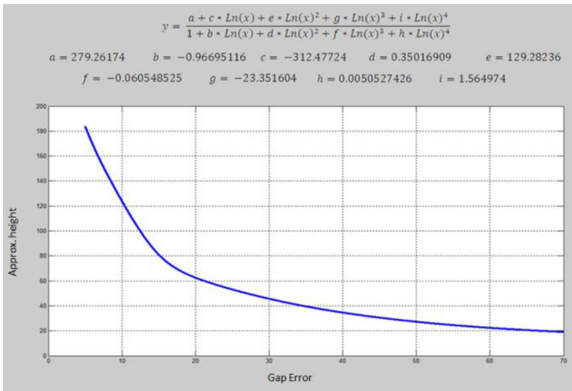

Fig. 6. Thickness determination curve in a workpiece with 40-20mm thickness variation.

Using this system it has been possible to determine the workpiece thickness with an error lower than 10%, as it is drawn in Fig. 7. Similarly, it has been found that the error increases as the variation thickness of the parts being cut on increases.

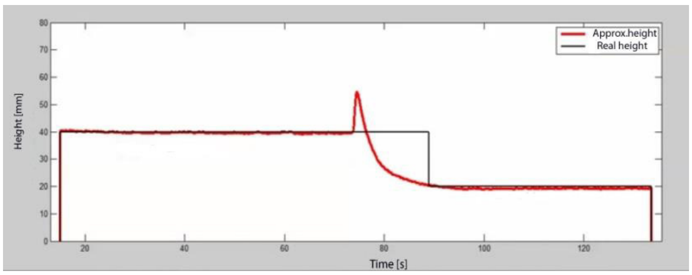

Fig. 7. Offline thickness determination curve in a workpiece with a 40-20mm thickness variation.

5. Conclusions

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

- Near the thickness variation zone and in cases where the wire breakage occurs, an abrupt deviation is observed in the values taken by the variables. Variables related to the number of electric discharges suffer a fall of between 15 and 20%, while the variable Gap error is reduced between 30 and 40%, being higher the reduction as the difference between defined thicknesses and thickness variation increases.
- A relationship between the variable Gap error (obtained from the Ionization time or Delay time (*Td*) and the Servo voltage (*Servo*)), the selected thickness in the machine numeric control and the nominal thickness has been found. From this nominal value it can be determined the actual thickness of the workpiece.
- The time required for the stabilization of the variable Gap error around the new value after an abrupt change in thickness may take up to 30 seconds, depending on the variation of it. That is, this value is the time it takes the system to establish the new thickness.
- The developed system is able to determine the workpiece thickness with less than 10% error in comparison with the nominal value of it.

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