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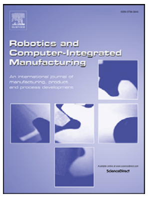

High-accuracy wire electrical discharge machining using artificial neural networks and optimization techniques

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ABSTRACT

For many industrial sectors, high-added value components are related to high accuracy manufacturing technologies. Wire Electrical Discharge Machining (WEDM) is an advanced non-conventional machining method commonly used in the production of precision components in extremely hard materials. The precision of the process depends largely on the deformation of the wire tool. Whilst theoretical models allow a scientific understanding of the causes of a lack of accuracy, they still lack the level of precision required to predict actual deviations in industrial products. In this work, we propose a way to predict the accuracy of components produced by WEMD by using an Elman-based Layer Recurrent Neural Network (LRNN). The results reveal that the average deviation between network predictions and actual components is below 6μm, which implies extremely good performance of the net. In a further step, an algorithm was proposed for designing wire paths of variable radius, so that the deviations in the machined parts can be corrected via software. By combining the predictions of the developed LRNN with the Simulated Annealing (SA) optimization technique, wire paths of variable radius can be designed, so that radial deviations due to wire deformations can be minimized. The results show that the new proposal is very efficient in those situations in which wire deformation is greatest. In other words, when the part radius is low and part height is large, the stiffness of the wire is reduced and the error of the part sharply increases. In these cases, the average deviation was reduced by as much as 80%, and the Coefficient of Variation (C_V) was decreased by 43%. The solution can be readily implemented on any existing WEDM machine.

1. Introduction

Wire Electrical Discharge Machining (WEDM) has become one of the most popular non-conventional processes due to its capacity for achieving tight tolerances and an excellent surface finish in very difficult-to-machine materials including hard tool steels, aerospace alloys, and conductive ceramics.

The material removal mechanism is based on the application of controlled electrical discharges in a dielectric medium (usually de-ionized water). Each single discharge removes a micro-crater from the workpiece in such a manner that a new surface is created on the component. By following the numerical control program, complex geometries can be effectively and accurately cut, regardless of the hardness of the material. For this reason, the application of this technique has become increasingly widespread in various areas of industry, including micro-manufacturing, tool manufacturing, and the aeronautical sector [1,2].

However, in order to meet the increasing dimensional requirements that are so often demanded by modern industry, several factors must be taken into account. It is well known that the vibration caused by the forces acting on the wire produce a lack of precision in the machined workpieces that affects dimensional accuracy, mainly in roughing cuts where high levels of discharge energy are used. These effects are more pronounced when geometries with changes in direction are cut, that is, corners and circles.

The literature contains a number of important research studies focused on understanding the causes of this problem. A common approach involves modeling the mechanical phenomena that produce deformations. Since the wire is subjected to several forces during the process, such as tensile stress, dielectric flow and forces related to electromagnetic conditions, some authors have focused their efforts on identifying their nature [3,4]. An example of this approach can be found in Tomura et al. [5]. In their work, the electromagnetic forces that are present during the process have been modeled using a two-dimensional finite element numerical simulation. The numerical results have then been compared with those obtained from experimental tests, indicating that electromagnetic force must be considered for an accurate simula-

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Glossary

α	angular position
C_V	coefficient of variation
$LW^{2,1}$	context layer weights
b_1	hidden layer biases
$LW^{2,1}$	hidden-Output layer weights
IW	input-hidden layer weights
$i(t)$	input to the net
i_{lim}	limit number of iterations
$MAPE$	Mean Absolute Percentage Error
$mMAPE$	mean of $MAPE$
μ	mean value of deviation of measuring points at plane j
D	number of delays in the feedback
i	number of iterations
HN	number of neurons in the hidden layer
R_m	objective function or solution matrix
R_{min}	objective radius
R_0	optimum value of the radius to be programmed in the NC code
b_2	output layer biases
$o(t)$	output of the Artificial Neural Network
$a_1(t)$	output of the hidden layer of the Artificial Neural Network
j	plane number
P	predicted value by the ANN
σ	standard deviation of measuring points at plane j
k	points of the dynamic evolution
e	square error of the coordinates
T	target value
t	time
H	workpiece height
Z	workpiece height position
ANN	Artificial Neural Network
BPNN	back-propagation Neural Network
BPTT	back-propagation through time
CMM	Coordinate Measuring Machine
LRNN	Layer-Recurrent Neural Network
MLP	Multi-Layer Perceptron
MRR	Material Removal Rate
NC	Numerical Control
PSO	Particle Swan Optimization
RBFN	Radial Basis Function Network
RNN	Recurrent Neural Network
SA	Simulated Annealing
WEDM	Wire Electrical Discharge Machining

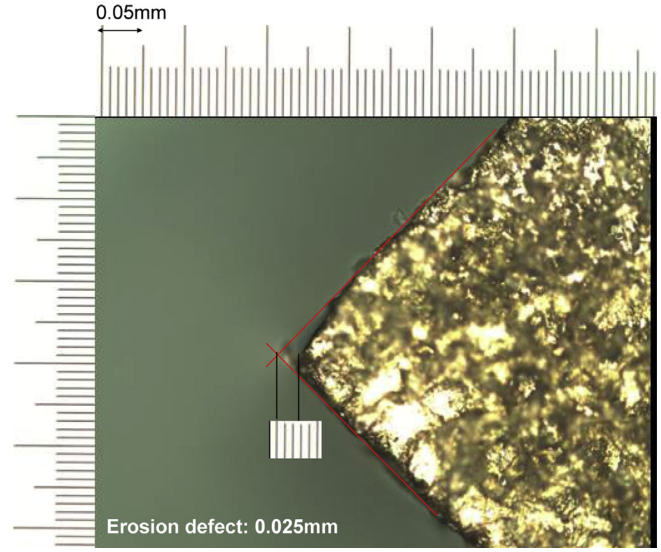

Fig. 1. Loss of accuracy in corner cutting: a fillet radius is produced instead of a sharp corner due to wire-lag in a 90° corner (part material AISI D2 tool steel).

tion. However, in order to predict process behavior other factors (i.e. forces or guide paths) must also be taken into account together with the electromagnetic component. Puri et al. [6] have developed a mathematical model to analyze wire-tool vibration, highlighting the relationship between amplitude of the vibration and variables such as density of spark, wire tension and workpiece thickness. Although it is clearly observed that minimization of wire vibration plays a fundamental role in improving accuracy in complex contours, practical application of this knowledge was not presented in their paper. In recent years there has also been an increase in the development of theoretical models. For instance, Chen et al. [7] have proposed a three-dimensional multi-physics coupling model (thermal model, electromagnetic field model and structural model) for analyzing and controlling wire vibration while cutting thin plates. Habib et al. [8] have recently developed a wire vibration model, finding that vibration amplitude and frequency depend mainly on wire tension and cutting direction. They noticed that, in a straight cut, amplitude is greater in the machining direction than in a perpendicular direction.

Whilst models of this sort undoubtedly contribute to the scientific understanding of the problem and help to form the basis for future technological developments, concordance between theoretical and experimental results is largely limited. This is primarily due to the high number of overlapped phenomena and unknown coefficients (for instance, modeling of damping effects, turbulences of dielectric flow, friction with guides, etc.).

The concept of wire-lag is commonly used as a component of wire vibration, because its effect is evident in corner cutting. Wire-lag can be described as the maximum deviation between the position of the guides and the amplitude of wire vibration, measured on the plane defined by the wire itself and the direction of movement. The effect of this phenomenon is particularly harmful where the profile to be cut exhibits direction changes, as in the example shown in Fig. 1.

Beltrami et al. [9] have monitored this effect using an optical sensor. On this basis, a control algorithm was developed enabling virtually any contour to be cut at high speed. Another interesting study attempted to predict the best WEDM parameter combination using Taguchi methods [10]. In a more recent study, Sarkar et al. [11] have proposed a model for wire-lag prediction based on the concept of gap force intensity. The results indicated that compensation is inversely proportional to the programmed radius.

The literature reveals the close relationship between wire-lag and loss of accuracy in corner cutting. Hsue et al. [12] have paid attention to the fundamentals of the geometrical relationship between wire diameter and part geometry by comparing the discharge-angle and the material removal rate. Sanchez et al. [13] have discussed, among others, the influence of work thickness and corner radius during the corner cutting process. The results have shown that improvements in accuracy can be achieved by limiting the cutting speed.

Corner cutting is, no doubt, a critical issue in relation to the accuracy of WEDM. The first attempts to address this problem using wire path modification can be found in Dekeyser et al. [14], who used this method in order to reduce the dimensional error by up to 50% in corners between 30° and 135°. Another way to improve corner cutting has been presented by Sanchez et al. [15], developing a computer-integrated system for error prediction and wire path modification. Han et al. [16] have carried out a corner error simulation based on the wire vibration analysis due to the reaction force acting on the wire, obtaining the optimum wire path from this simulation system. Other investigations include that