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AXIOMATIC DESIGN APPROACH TO THE DESIGN OF A DEVICE FOR WIRE ELECTRICAL DISCHARGE MACHINING

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ABSTRACT

This paper presents a few considerations concerning to product design. As an application, it focuses on the study of a device that was designed to improve the material removal process in wire electrical discharge machining. The main objective of the research is to assess the device in the light of the independence axiom of Axiomatic Design. The device was intended for the experimental study of the material removal process. The functional requirements concern essentially to the ability for changing the machining process input factors, the device adaptability to a specific machine tool and the usual economics, safety, reliability, and easy-to-repair requirements. The problem under analysis is focused on functional requirements and design parameters and the results show that the principles of axiomatic design are valid in the case of the designed device and highlighted some interesting aspects to be addressed in future research.

Keywords: axiomatic design, wire electrical discharge machining, wire electrode tool, wire travelling speed.

1 INTRODUCTION

The design process was divided by [Pahl, 1994] in four distinct phases: 1) *Formulation of the requirements*; 2) *Conceptual design*; 3) *Embodiment design* and 4) *Detail design*. Within each stage, the process could be presented as a flow diagram. The basic trends of embodiment design should be "clarity, simplicity and reliability". Moreover, some of the principles of embodiment design are as follows: principle of the division of tasks, principle of self-help, principle of force and energy transmission and principles of safety and reliability, but some times these principles are not easy to apply.

The researchers elaborated methodologies for systematization of the design process. Some of these methodologies are based on algorithms and others on diverse approaches that cannot be generalized. Each stage of the iterative process is based on the designer experience and intuition. Usually, the morphological approaches use a matrix to highlight all possible design options, from which the designer must choose the best one [Pahl, 1994], [Slătineanu *et al.*, 2011]. This last task could be problematic because one could pass aside the most suitable solutions.

The distinct possible solutions could be evaluated by using weighted factors for the technical or economical meanings. An overall evaluation of the design can be obtained through the relation [Pahl, 1994]:

$$W_j = \frac{\sum_{i=1}^{n} w_{ij}}{w_{\max} \cdot \sum_{i=1}^{n} g_i} \tag{1}$$

where: i is the number of evaluating criteria, j - the number of evaluated possible solutions, w_{ij} - the numerical evaluation value of the jth solution regarding to the ith criterion, w_{max} - the maximum value of the evaluation values and g_i the value of the element corresponding to the ith criterion.

Using such a methodology, the decision is based on exact data but it is still possible to obtain a solution that is not the best one. It is possible to have a solution with a high total value, but with one or more specific weak points, which is clearly worst than a different solution with an overall lower total value but with better distributed specific values for the different criteria.

Usually, in the industrial practice, the potential infinite number of different solutions is reduced to 2 or 3, which are analysed in the above-described manner, in order to select the best one.

Other authors present the design process as a problem of optimization, by considering all the existing constraints [Arora, 2004]. The process supposes the identification of a set of design variables, establishing an objective function to be optimized, as well as the constraint functions.

In [Suh, 1990] and [Suh, 2001], the design process was presented as a process with clear rules, design axioms (independence and information), corollaries, theorems and a methodology for decomposing the hierarchical structure, in order to obtain good designs. The approach represents a breakthrough in terms of design process based on scientific methods and evaluation of the solutions. The founder of axiomatic design proposes a general framework to assist in the decision-making at any instance of the designing process. The unique "zigzagging" process allow including the multiple design solutions into three basic categories (uncoupled, decoupled and coupled) and, in the end, to select the best alternative with the maximum probability of success [Suh, 1990].

The main objective of the research presented in the paper is to test if the principles specific to axiomatic design are valid in case of a device designed for activating the material removal process in wire electrical discharge machining.

2 WIRE ELECTRICAL DISCHARGHE MACHINING

The *wire electrical discharge machining* (WEDM) is used mainly in industry for obtaining accurate and intricate parts made of conductive materials, such as parts of dies and molds, parts of sintering presses, geared elements, profiles for cutting tools, etc.

WEDM takes advantage of thermodynamic, electromagnetic, hydrodynamic and electrodynamic phenomena. The material removal is caused by pulsating electrical discharges generated by a power supply at a frequency in the range of 20000-30000 Hz. The discharges occur between the electrodes that are formed by the workpiece and by a wire that plays the role of tool. The electrodes are separated by a thin layer of dielectric liquid and material is removed from both electrodes. Yet, the aim of the machining process is the material removal from the workpiece, the removal from the wire being an annoying wearing process that should be minimized. Due to the plasma channels that buildup between the anode and cathode, a part of the kinetic energy of the subatomic particles in motion is transformed in thermal energy; subsequently, the generated heat is distributed by conduction to the electrodes and to the dielectric fluid. The temperatures have values in the range of 8000-20000 °C. Because of such a high temperature, the process of melting and vaporization of the surface layers of the two electrodes is initiated. When the electric discharge is turned off, the plasma channels break down, the temperature suddenly decreases and the circulating dielectric fluid flushes the re-solidified particles of the electrodes in the form of microscopic debris.

WEDM allows manufacturing parts having various contours, and due to the machining scheme it makes it possible to obtain only ruled surfaces (Figure 1). The wire tool electrode travels from a reel to a take-up reel and the workpiece has numerical controlled movements in a plane perpendicular to the electrode axis. Some manufacturers of machine tools propose an additional controlled movement of the upper support of the wire guide, making it possible to obtain conical surfaces, or even ruled surfaces similar to conical surfaces.

The feeding motion of the wire electrode is required to compensate for the wear that is generated by the electrical discharges. In order to obtain intricate shapes with small fillet radii, one has to use wire electrodes with diameters in the range of 0.01 – 0.3 mm. The wire feed is also necessary to completely avoid the wire breakage due to the wear that occurs during the machining process.

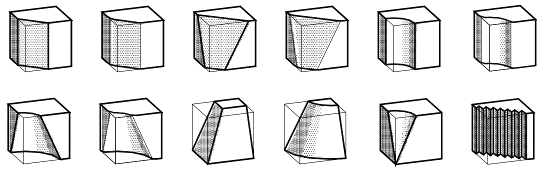

Figure 1. Example of WEDM ruled surfaces.

The typical WEDM technological characteristics are the cutting rate, the material removal rate, the accuracy, the surface roughness, and the thickness of the heat-affected zone. The current machine tools allow obtaining a feed rate of 300 mm^2/min for 50 mm thick steel plate workpieces, and of 750 mm^2/min for 150 mm thick aluminum plate workpieces [Patel and Vaghmare, 2013]. The machining accuracy and surface roughness are considered as corresponding to the current machining requirements. Due to the deionized water used as a dielectric fluid, which allows a certain anodic dissolving of the workpiece material, the surface roughness could reach values for the *Ra* parameter equal to or higher than 0.1 μm. The deviation from straightness could be less than 2 μm for a 100 mm thick workpiece and the slope of the machined surfaces is in range of ten seconds.

2.1 ACTIVATING THE WEDM PROCESS

It is widely accepted that WEDM is appropriate for manufacturing parts made of hard or extra-hard materials with high precision and shape complexity. However, most of the known literature is focussed on the problem of increasing the productivity in a condition of high cost and/or low accuracy [Boothroyd and Knight, 2006].

The main trends of research aiming at improving WEDM can be grouped in three classes: improving the machine tool architecture and constructive details, improving the technology by optimizing the operation input parameters and improving the activation of the material removal process.

Analyzing the first research direction, one can notice that the known literature mainly concerns to the limitations of the machine tool components (such as the dc power supply subsystem, the wire electrode tool, the dielectric fluid supply subsystem or the mechanical subsystem) [Dauw and Albert, 1992].

The second trend, which is specific to each machine tool, is based on establishing the best working conditions to accomplish certain criteria under some restrictions. Usually, the optimization criteria refer to maximizing the machining feed rate (expressed in mm/min), while minimizing both the surface roughness and the total specific machining cost [Dodun, 2000].

As for the activation of the material removal process, it could be achieved in various ways. Some researchers presented various approaches mostly based on overlapping the electrical discharge machining process while applying a magnetic field or using a high injection pressure of dielectric liquid. Other researchers referred to methods based on vibrating or extra movements of the tool electrode [Patel and Vaghmare, 2013]. In order to improve the overall machining consistency, the material removal rate and the performance, Ho *et al.* described a solution that uses an orbiting movement of the tool electrode around the workpiece [Ho *et al.*, 2004].

This additional motion of the tool electrode facilitates the material removal from the work zone, due to the easier penetration of the dielectric liquid in the work gap. In this way, a better evacuation of the eroded particles from the work gap is achieved.

3 CASE STUDY

The main goal of this paper was to test the appropriateness of the solution that was found for a device adaptable to the traveling wire tool electrode system of a Japax L250A machine from the point of view of axiomatic design (Figure 2). The *customer needs (CNs)* correspond to a device that must allow changes of the wire motion parameters, in order to optimize the process of material removal from the workpiece by wire electrical discharge machining. Thus, the top level *functional requirements (FRs)* are concerned to allowing the wire motion, as well as ensuring the adaptability of the device to the Japax wire travelling system and the usual economical, safety, reliability, and easy-to-repair requirements.

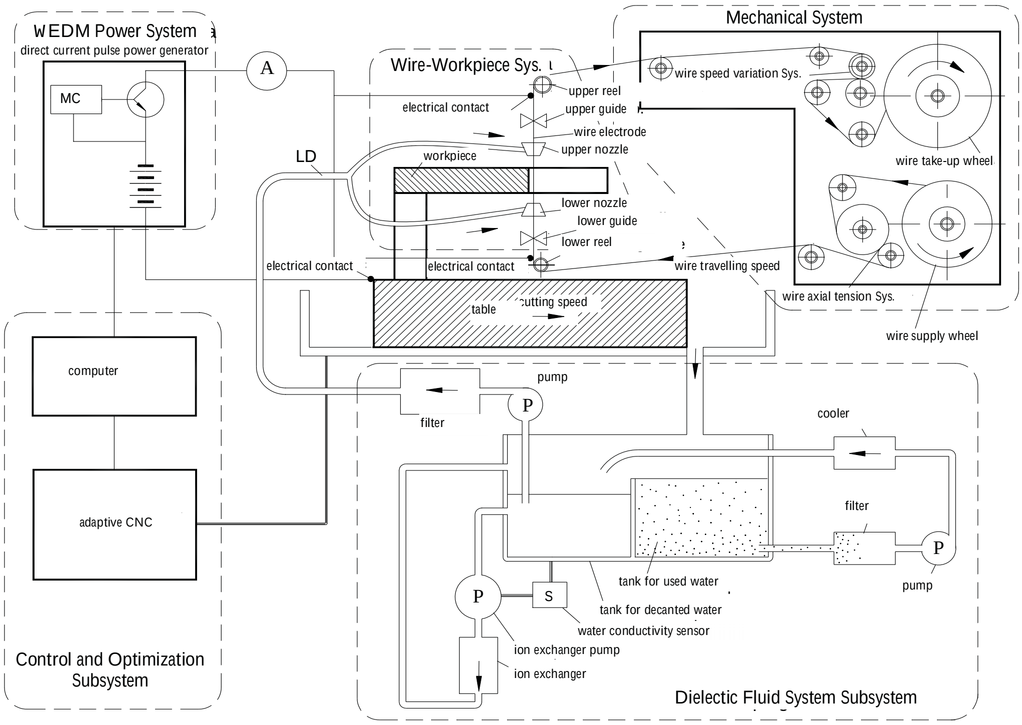

Figure 2. The wire electrical **discharge system**.

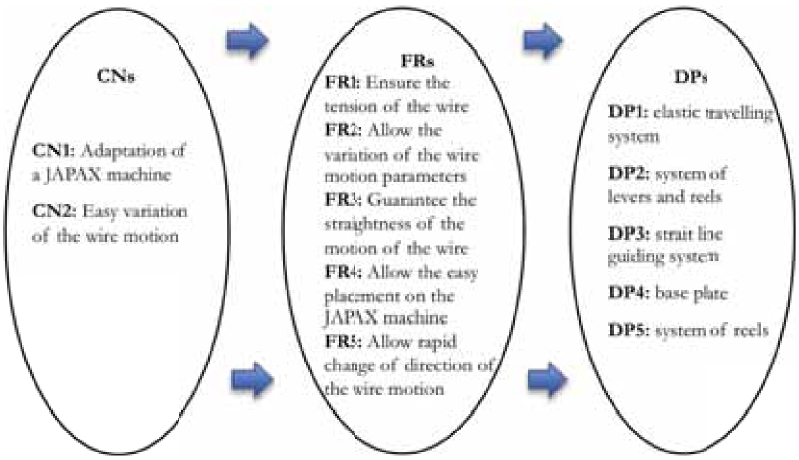

Figure 3. The design domains of the device for studying the wire electrical discharge process.

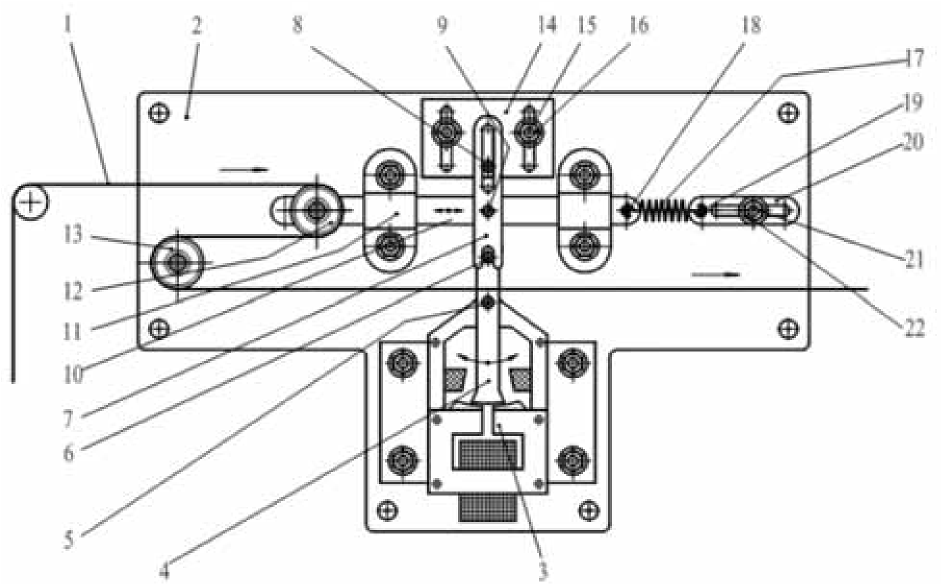

Figure 4. The structure of the device for studying the WEDM process.

Zigzagging was performed to establish the functional requirements and finding the design parameters and Figure 3 shows the top-level result of this process.

By loosely using the independence axiom, the mapping between the customer and the functional domain yielded to the following *functional requirements*:

FR1: Ensure the tension of the wire tool;

FR1.1: Provide tension in wire;

FR1.2: Allow the correct adjustment of the axial tension in wire;

FR2: Allow the variation of the wire motion parameters;

FR2.1: Ensure easy changing of excitation frequency;

FR2.2: Ensure easy changing of the wire vibration amplitude;

FR3: Guarantee the straightness of the motion of the wire;

FR3.1: Ensure the change of the initial reciprocating circular movement into a reciprocating rectilinear one;

FR3.2: Ensure the rectilinear displacement of the wire support;

FR3.3: Ensure the power source for performing the motion;

FR4: Allow the easy placement of the device on the electrode wire travelling subsystem of the JAPAXtype machine;

FR5: Allow rapid change of direction of the wire motion;

The constraints could be defined as:

C1: Ensure a high wear resistance;
C2: Ensure low energy consumption;
C3: Ensure a lightweight;
C4: Ensure a simple solution (minimum number of parts of the device);
C5: Ensure an easy manufacturing;
C6: Ensure safety in operation;
C7: Diminish the possibility of wire breakage;
C8: Ensure an easy access to wire tool electrode in case of breakage;
C9: Ensure a minimum cost of device.

The achieved *design parameters DPs* for those functional requirements are the following:

DP1: elastic travelling system

DP1.1: spring subsystem;

DP1.2: system of changing the tensioning force of the spring (groove, supporting plate, nut and threaded rod);

DP2: system of levers and reels;

DP2.1: electromagnetic subsystem (magnetic circuit, coil, frequency generator);

DP2.2: system of modifying the lengths of the levers (groove, pin, supporting plate, nut and threaded rod);

DP3: strait line guiding system;

DP3.1: mechanical levers;

DP3.2: guiding subsystem for the rectilinear motion;

DP3.3: electric power source;

DP4: base plate including the necessary components and its placing on the machine tool;

DP5: system of reels on which the wire travels.

	DP1	DP1.1	DP1.2	***DP2***	DP2.1	DP2.2	***DP3***	DP3.1	DP3.2	DP3.3	***DP4***	***DP5***
FR1	X											
FR1.1		X										
FR1.2			X									
FR2				X								
FR2.1					X							
FR2.2						X						
FR3							X					
FR3.1								X				
FR3.2									X			
FR3.3										X		
FR4											X	
FR5												X

Figure 5. The design matrix for the WEDM device.

The result of the zigzagging is presented in the matrix of Figure 5. The relationships between *FRs* and *DPs* are denoted by the letter *X*, and one might notice that the design is uncoupled.

4 THE ACCOMPLISHED SOLUTION

The embodiment of the solution introduced in the previous section is described here.

In order to ensure the variation between some pre-established limits for the speed of the wire tool electrode motion at any given frequency (or even to reverse the direction of the wire motion), the achieved device was based on the design parameters presented in Figure 4 [Dodun and Lungu, 2005].

The device includes a base plate 2 (design parameter DP4), on which there is an electromagnetic subsystem 3 (coil, magnetic circuit and frequency generator that generates the periodical motion of lever 4 around the axis of bolt 5 (design parameter DP2.1). Bolt 6, which is placed at the end of lever 4, generates the periodical rotation motion of lever 7 around the axis of bolt 8, which is fixed to the base plate 2. Bolt 9 (design parameter DP3.1) that links lever 7 and the prismatic bar 10 generates a rectilinear-alternative motion of bar 10 (design parameter DP3.2), which is guided by linear guides 11.

In order to adjust the amplitude of the rectilinear-alternative motion of bar 10, bolt 8 can be moved together with its supporting plate 14 along two grooves machined in plate 14. The required position of supporting plate 14 can be achieved by means of two cylindrical threaded end bars 15 and two matching nuts 16 (design parameter DP2.2). An electric power source and a frequency generator (which are not included in the schematic representation of Figure 4) are used to materialize design parameter DP3.3).

The wire tool electrode 1 travels on pulley 12, situated at the end of bar 10, and on pulley 13 (design parameter DP5), which axis is fixed on base plate 2. The rectilinear-alternative movement of bar 10 ensures conditions for the periodical change of the wire tool electrode travelling speed.

In order to create the tension force in the wire tool electrode, as well as to obtain a smooth motion of the squared bar 10, one used spring 17 (design parameter DP1.1), which has an end fixed on bolt 18 on the squared bar 10. The other end of spring 17 is fixed on bolt 19.

In order to easy modify the value of tension in the wire tool electrode by means of the spring tensioning, the bolt 17 could be moved with its supporting plates along a groove existing in the supporting plate 20 (design parameter DP1.2). The supporting plate 20 is fixed on the base plate 2 by means of a nut 21, found on the threaded end of the bar 22. This bar 22 passes through a groove existing in the supporting plate 20 and it is fixed on the base plate 20.

5 CONCLUSIONS

The wire electrical discharge machining process can be activated by providing an additional motion to the wire tool electrode. Axiomatic Design's independence axiom was used to evaluate a device that allows changing the translation speed of the wire between certain speed limits and with a specific frequency.

Specifically, a device that was designed some time ago to improve the performance of the Japax L250A wire electrical discharge machine was assessed in the light of the AD's independence axiom. The conclusion is that the device is a typical case of uncoupled design, a condition that can explain its good behavior in service**.** Retrospectively, one could say that the design of the presented solution would be much easier if the designers were aware of the AD's independence axiom.

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