Optimisation of electro-spark coating method

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Abstract. Application of wear resistant coatings on cutting tools in a technological process requires taking into account multiple factors. Optimisation of the hardening process presents one of the main steps that needs to be addressed. This paper describes a method of optimisation of the electro-spark coating (ESC) process. The performance of the process was chosen as the target function. A parametric function was defined based on the previously developed mathematical model of the process whereby the condition of the strong connection of coating material with the foundation was used. Another parametric function is a prerequisite for a suitable coating thickness. Additional limitations are the characteristics of the equipment for the reinforcement.

1. Introduction
Given the economically unstable situation in the world, the efficient use of available resources becomes a first priority. Minimising the cost of manufacturing new products leads to a significant increase in profits. [1] One of the tools to achieve profit growth is the introduction of lean manufacturing methods (Lean Production). The basic idea of lean production is to increase the efficiency of the producers within existing resources through the modernisation of all processes. [2] The first lean production practices have been applied by Toyota. The basic idea of this principle was the elimination of some losses in the existing technological process: loss of time and budget due to standby, overproduction, extra processing steps, unnecessary transportation, redundant inventory, and defective goods. [3]

Implementation of lean ideas in large-scale and mass production instantly brings significant profit to companies; however, it is a complicated task since one has to operate in the already running process.

One of means of increasing the wear resistance of the cutting tool is a method of electro-spark coating (ESC). The organisation of this method in the production environment for hardening of tools not only requires special equipment, but also optimisation of the process. This will reduce the operational time spent on resurfacing and the costs associated with it.

The process of ESC in the real environment is defined by the following parameters [4, 5, 6]:
1) the power of a pulse generator, \( W \);
2) the speed of an electrode, \( v \);
3) the thickness of a coating, \( h \).
2. Mathematical model of the process

To obtain a coating with a durable connection of the anode material (tool) with the cathode material (product), it is necessary to comply with a condition stating that the surface temperature of the cathode equals the melting temperature [7, 8]. Thus, this condition can be written as

$$T_M = \frac{q_0}{2\pi\lambda} \cdot F(k)$$

(1)

In this equation, the unknown variables are the intensity of the heat source, $q_0$, and the velocity of the source, which is the argument of function $F(k)$.

In [7], it was determined that the heating of the cathode is supplied from two sources, the total power of which is determined by the power pulse generator

$$q_2 + q_3 = q_0 = \eta \cdot \frac{W}{S_E}$$

(2)

where $\eta$ is the efficiency of the pulse generator; $\eta \approx 0.8$; $W$ is the discharge power determined by the type of a generator used in a particular case.

Equation (1) is the lower technical limit that is a function of equal temperatures which should provide a set of parameters: generator power $W$ and the velocity of the source $v$, which is taken into account by function $F(k)$.

The speed of the source determines the performance of the coating process and in the calculation of the optimal mode should be selected as large as practical. This expression ($v \rightarrow \text{max}$) will be the objective function for the system optimisation.

Equation (2) substituted into (2) yields

$$W = \frac{2\pi \cdot \lambda \cdot S_E \cdot T_M}{\eta \cdot F(k)}$$

(3)

To determine the third process parameter, the coating thickness, we assume that in a steady process of electro-spark alloying all the energy supplied to the anode (electrode) is spent on its partial melting and is transferred to the cathode. This assumption is fair since in a steady process electrode (anode) gives the heat to the cathode through the material as well as to the environment. The heat exchange with the environment is via air which is a poor conductor of the heat. According to authors of [4, 5], for most materials in normal conditions, in the most effective modes from the perspective of quality indicators and process performance values of the gain are high, that is, the thickness of the formed layer on the cathode is limited. The limited thickness of the formed layers on the cathode (product) in many cases hinders the practical use of ESC [9, 10, 11]. Therefore, the analysis of the factors determining such nature of the process and opportunities for targeted management become highly important.

3. Process optimization

Numerous experimental studies of electrode erosion (the anode) and the metal transfer to the product (cathode) allows to manifest that in the process of ESC the erosion and the release material of the anode do not stop with time, rather settling of the anode on the cathode slows down due to evaporation to the environment [12, 13, 14]. The limitation of the layer thickness can only be explained by considering the entire set of physical, chemical and mechanical effects on the surface of working electrodes. As ESC is associated with multiple-pulse thermal and mechanical effects on the material of the electrodes of phase and structural transformations in the generated layers [15, 16, 17], we can assume that these processes should determine the nature of the growth and limitation of the thickness of the applied layer.
Phase and structural transformations, heating and cooling of the surface layers of the electrode’s material under the influence of electric pulses lead to the formation of residual stresses of types I and II [15, 18, 19], characterising their ultimate irreversible stress state. Consequently, in real conditions of coating the whole complex of the processes occurring between the anode and cathode is determined by the law of energy conservation. Given the above-mentioned statements, it can be said with a small extent of error associated with the evaporation of materials into the environment (according to estimates of different authors [15, 20, 21], evaporation takes 3-5%) that the intensity of the heat flux of transferred energy is equal to

\[ q_3 = \eta \cdot \rho \cdot \frac{W}{S_E} = m_E \cdot L_{JE} \]  

(4)

This expression determines the melting rate (deposition) of the electrode material. The mass transferred per unit time of the electrode is determined by the product of the density and the volume:

\[ m_E = \rho_E \cdot d \cdot h \cdot \nu. \]  

(5)

Therefore, expression (4) can be represented as follows:

\[ \eta \cdot \rho \cdot \frac{4W}{\pi \cdot d^2} = \rho \cdot h \cdot d \cdot \nu \cdot L_{JE} \]  

(6)

Hence,

\[ W = \frac{\pi \cdot \rho \cdot L_{JE} \cdot d^3}{4 \cdot \eta \cdot \rho} \cdot h \cdot \nu \]  

(7)

This expression links the power generator of impulses in specific process conditions with the coating thickness and the speed of the anode.

The thickness of the coating is selected from experience, applied for various materials and operating conditions, it may be different, but one should keep in mind that the greater thickness of the coating, the more fragile the coating becomes. Therefore, most often the coating thickness of the cutting tool is taken from the range of 8-12 µm. The test tool in the production environment confirmed the validity of this statement. Coating thickness of 20 µm and more typically wears off due to chipping.

Given the equations above, the process of electro-spark alloying is described by the following system of equations:

\[ W = \frac{2\pi \cdot \lambda \cdot S_E \cdot T_M}{\eta \cdot F(k)} \]  

(8)

\[ W = \frac{\pi \cdot \rho \cdot L_{JE} \cdot d^3}{4 \cdot \eta \cdot \rho} \cdot h \cdot \nu \]  

(9)

\[ W \leq W_{\text{max}} \]  

(10)

\[ W \geq W_{\text{min}} \]  

(11)

Let us consider the example of applying a carbide coating (\( \rho = 5.37 \, \text{g}/\text{sm}^3, \, \lambda = 0.21 \, \text{W}/(\text{sm}^2 \cdot \text{ºC}), \, L_{JE} = 1.45 \cdot 10^7 \, \text{W}/(\text{g} \cdot \text{sec})) \) on the tool steel (melting temperature \( T_M = 1550 \, \text{ºC} \)) under the following conditions: \( a = 1, \, d = 2 \, \text{mm} \).
Characteristics of the electrode material are presented in Table 1.

**Table 1. Electrode properties.**

| The chemical composition of the electrode | Density, [g/sm³] | Hardness, [HRA] | σ, [kg/mm²] |
|------------------------------------------|-----------------|----------------|-------------|
| TiC-Cr3C2-10Ni                           | 5.37-5.38       | 92.5-93.0      | 90-100      |

For these conditions, $F(k)$ is satisfactorily approximated by the exponential function

$$ F(k) = \exp \left( -0.82 \frac{\nu}{2\omega} \right) $$  \hspace{1cm} (12)

Let us assume that the capacity of the plant is equal to $W=150$-400 Watts. Therefore, the solution of equations (8)-(11) can be represented by the plot in Figure 1.

**Figure 1.** Optimisation of electro-spark alloying of high speed steel by electrode made of the solid alloy.

Fig 1 depicts that the function based on equation (8) shows the values of the generator power $W = F(\nu)$ at which the temperature on a surface of the hardened product equals the melting temperature, that is, this function represents the lower limit in the optimisation system.

The function based on equation (9) shows that the maximum output power $W = F(\nu)$ that provides the required coating thickness, that is, this function represents an upper limit in the optimisation system.

Functions represented by equations (10) and (11) are additional constraints.
In Fig. 1, functions (8)-(11) selected area searched possible solutions, the optimal solution corresponds to a point in the delineated area with $v_{\text{max}}$. This point lies on a curve of equal temperature with a value of $v_{\text{opt}} \approx 0.39 \text{ sm/sec}$.

Therefore, for these conditions the coating technological process should be conducted on the optimal mode for the following parameters:

\[ v_{\text{opt}} \approx 0.39 \text{ sm/sec}; \; W = 400 \text{ W}; \; h = 12 \mu\text{m}. \]

Fig. 2 shows a photo of microsection of the sample after hardening at optimal conditions. The coating was applied using Elitron-22A. The figure shows that the coating has a relatively uniform structure without any breaks.

![Figure 2. Image of microsection of a sample of high speed steel with coating of microsection of a sample of high speed steel with coating (magnification ×1000).](image)

4. Conclusions

The paper presents the system of equations for the optimisation of the process where the objective function is the productivity. The lower limit is a function of equal temperatures ($\theta(x,y,t)=T_{\text{Me}}$, the melting point of the electrode). The upper limit is the required thickness of the coating. Additional limitations are the capabilities of the equipment.

The optimisation system was pilot-tested and it showed the uniformity and reliability of the applied layer.

The introduction of electro-spark coating on a cutting tool increases its wear resistance, is embedded in the concept of the lean production and leads to a decrease in tool wear.

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