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Investigations of Electro-Discharge Mechanical Machining of Manganese Cast Steels

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Abstract

This paper presents a study of the hybrid electro-discharge mechanical machining BEDMM (Brush Electro-Discharge Mechanical Machining) with the application of a rotary disk brush as a working electrode. The discussed method enables not only an effective machining with a material removal rate of up to 300 mm^3/min but also finishing (with the obtained roughness of Ra < 0.5 µm) of the surfaces of complex-shaped alloys with poor machinability. The analysis of the factors involved in the machining process indicates that its efficiency is determined by electrodischarge. The use of flexible working electrodes makes it possible to apply simple technological instrumentation and results in the simplicity of the process automation. The aim of the study was to obtain quantitative relationships between the parameters of brush electro discharge mechanical machining (BEDMM) and its effects. The presented experimental research results define the effect of the process input parameters on the performance and roughness of machined surfaces obtained for manganese cast steel.

Keywords: EDM, Flexible electrode, Cast steel, Machining efficiency, Roughness

1. Introduction

One of the problems connected with the machining of castings made of alloy cast steels is the significant wear of abrasive or cutting tools. These problems become particularly important during surface machining associated with the removal of the casting epidermis, remnants of the removed gating system, defects in shape such as dislocations, flashes, swells, casting surface defects such as folds, scars, pits, burn-ons, as well as cleaning welds [1-4]. These faults often cause the uneven distribution of machining allowance. Another reason for the conditions of the machining allowance removal being significantly difficult is the hardening of the austenitic cast steels due to cold work or surface improved parts [5-8]. These difficulties increase in the case of castings with complex macrogeometry as well as thin-walled or medium and large-sized castings. The conducted industrial study provided the basis for the selection of a material with particularly poor mechanical machinability – Hadfield L120G13T cast steel. The L120G13T is a manganese alloy cast steel with an austenitic structure and abrasion resistance. This cast steel is used in an oversaturated state. The austenitic structure of cast steel at ambient temperature is stabilized by the high content of manganese. The cast steel under study is used for components subjected to significant pressures, high bending loads under the conditions of the exposure to abrasive wear. These include castings exposed to impact loads and cold work such as jaws of breakers and crushers, crushers bars, railway crossing points, etc.

The main reason for the poor machinability of the cast steel under consideration is the increase in manganese austenite hardness caused by cold work generated during abrasive or cutting machining. Other factors impeding the processing of austenitic cast steels include:

- low thermal conductivity,
- high ductility and plasticity,
- significant adhesion tendency.

The high abrasion resistance resulting from the discussed properties of Hadfield type cast steels causes poor machinability by cutting and abrasive machining methods. The comparison of abrasive wear as a function of surface load for Hadfield manganese, chrome and carbon cast steels is illustrated in Figure 1.

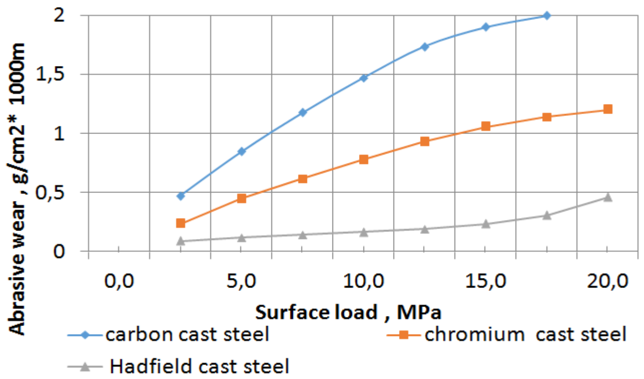

Fig. 1. Abrasive wear versus surface load for carbon, chromium and Hadfield manganese cast steels [9]

The presented graphs reveal that manganese castings are most abrasion resistant in the presented material group. Surface finishing of this kind of castings is usually conducted manually using electric or pneumatic tools by means of grinding wheels, usually with resin or rubber binders, strengthened with glass fabric or metal reinforcement [10]. Analyzing the possibilities of using the positive properties of brush tools, the authors suggests a hybrid electro-discharge mechanical treatment method combining several types of impact on a workpiece:

- mechanical,
- chemical,
- electro-discharge.

Owing to the synergy effect, the use of hybrid machining consisting in combining several types of treatment enables the increased material removal rate and extends the possibilities of processing manganese cast steels with poor machinability[11-13].

The authors predict that the use of flexible electrodes with a discrete structure (brush electrodes) in the electrical discharge machining will result in the generation of periodic electrical microdischarges at low values of the supply voltage (5 - 25 V) and non-fullcontact between the working electrode and the workpiece.

It is recommended that the process should take place in the presence of a weak electrolyte, which contributes to the formation of a passivation insulating layer on the workpiece surface.

Brush electro discharge mechanical machining (BEDMM) process is a way of machining complex surfaces made from hard-to-cut materials. During the BEDMM process, excess material removed from the machined surface by: electro-erosive, electro-chemical and mechanical processes. In this case working electrode (steel disk) and the workpiece are the parts of direct current circuit. The BEDMM process is different from the traditional EDM process and has the following features:

- application of DC generators,
- random character of energy of the electric discharges, the frequency and voltage,
- current flow during periodic contact between working elements (brush electrodes and the workpiece),
- elastic fit between the working electrode (steel disk) and the workpiece.

2. Characteristics of Electro-Discharge Mechanical Machining with Brush Electrodes

Electro-discharge mechanical machining with brush electrodes in an aqueous solution of sodium silicate is a form of electrical current conductive materials machining. The process can be aimed not only at removing significant machining allowances but also at providing the machined surface with a high degree of smoothness [14-17]. Since the machining of elements with large surface areas takes less time, the application of brush electrodes gives significant economic effects. By the appropriate selection of the machining parameters, the properties of the working electrode together with the type and properties of the machining fluid, it is possible to control the intensity of the phenomena in the machining zone to achieve the desired technological effects (material removal rate- MRR, geometric surface structure - GSS) [18-22]. The treatment can result in deburring together with deflashing and sharp edge smoothing without damaging the surface. During the electro-discharge mechanical machining an anode film is formed on the machined surface due to electrochemical processes in the aqueous solution medium of sodium silicate; the pressure of the working electrode wires and its relative movement on the machined surface cause its wear and create conditions for the initiation of electrical discharge. The removal of the material due to electric discharges causes a local anode depassivation, while electrochemical processes result in the reconstruction of the anode layer. These processes are repeated cyclically, resulting in the gradual removal of the successive material layers. The simplified mechanism of the electro-discharge mechanical machining described here is affected by numerous impacts that are hard to assess quantitatively [23-25]. Figure 2 shows the geometrical and kinematic parameters of the machining process. The following areas of the machined surface can be distinguished in the diagram:

I - surface before machining,
II - the area of the limited mechanical impact of the electrode,
III – machining area,
IV - machined surface.

Three basic types of impact can be distinguished as typical of machining process conditions: electrochemical (EC), electro-discharge (electrical impulse EI), mechanical (M), and their interactions[26-28].

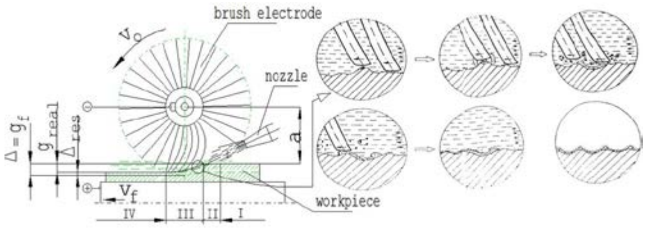

Fig. 2. Schematic diagram of electro-discharge mechanical machining (BEDMM), geometrical and kinematic parameters of the process, zones affected by the working electrode (WE) and by the surface being machined

In zone I the brush electrode does not come in contact with the machined surface, weak electrochemical effect occurring only in the immediate vicinity of the electrode have little impact on the final machining effect. In zone II the brush components also do not touch the machined surface, the only interactions that occur here are the electrochemical ones. Due to the shorter distance, the intensity of electrochemical processes is higher than in zone I. As a result of electrochemical impact (EC), a passive film composed mainly of SiO_2 is formed on the machined surface. It is of considerable significance because of the machining - the passivation film formation determines the correct course of the process. Zone III is the area of interactions characteristic of hybrid machining. In this area there occur effects accompanying electrochemical processes, spark discharges; the electrode components remain in contact with the machined surface exerting mechanical pressure on it - this is the area of effects typical of electro-discharge mechanical machining with the brush electrode. Zone IV, the EC impact is observed in vicinity of the working electrode (WE). In terms of the physics of phenomena in zone IV, there occur the same processes as in zone I. However, the final machining effect is different. The analysis of the experimental results indicates that, electrochemical anodic dissolution processes are inhibited rapidly. Their effects are limited to surface etching; as a result, the geometrical structure of the surface is modified.

3. Conditions and Methodology of Research

The aim of the study was to obtain quantitative relationships between the parameters of BEDMM machining and its effects. The study included determining the impact of the conditions on the machining rate and roughness of the surface. The tests were performed using a working liquid in the form of aqueous solution of sodium silicate (water glass) $Na_2SiO_3nH_2O$ with a specific density of 1.15 g/cm^3 and the initial temperature of T_{el} = 293 K. The experiment involved using 35x30x10 mm cuboid samples made of L120G13T wear-resistant manganese cast steel, quenched from 1340 K with cooling in water. Working electrodes in the form of brush disks with the following dimensions were applied in the research:

- outer diameter D_z = 160 mm,
- width of brush W = 30 mm,
- wire diameter d = 0.5 mm,
- material of wire steel S235,
- wire packing density G_R = 0.36.

The input factors selection was based on the analysis of preliminary study results and on the criterion of controlling them easily. Input factors and the ranges of their variability are presented in Table 1. The machining effects were assessed on the basis of:

- machining rate w_v, mm^3/min,
- surface roughness parameters Ra, Rv, µm.

Table 1.
Ranges of input factor variability

Input quantity	Symbol	Variability range		Units
		x_{kmin}	x_{kmax}	
supply voltage	U	8	16	V
disk rotational velocity	v_0	0.4	7.1	m/s
feed rate	v_f	12	36	mm/min
wire deflection value	Δ	0.4	1.2	mm

The investigation programme (DOE) was selected on the basis of modern experiment theory methods. The experiment that was conducted was planned in accordance with a static, determined, multifactor, rotatable design with PS/DS-λ repetitions. A five-level study programme and the norm range [-α, α] were adopted; α = 2, corresponding to the PS/DS-λ design stellar arms.

The statistical analysis of the obtained experimental study results was conducted according to standard procedures (standard deviation, approximation error). It included: the approximation of the study object function, the statistical verification of the approximating function adequacy and the statistical verification of the significance of the approximating function coefficients.

The geometric structure analysis after BEDMM were obtained using optical profilometer Talysurf CCI Lite, with Gaussian filter 0.8 mm (ISO 4287) and TalyMap Platinum software.

The analysis of the BEDMM (Brush Electro-Discharge Mechanical Machining) process shows that relations between the researched and resulting factors may be nonlinear and that interactions may occur. The lack of a theoretical model of the research object and the existence of an imperfect physical model resulted in attempts at approximation using numerous functions, the second-order polynomial with linear and quadratic components as well as interactions – i.e., the function typical of second order plans being the basic one.

4. Results and Discussions

The experiment and the research results analysis provided the relationships between the input (U, v_0, v_f,Δ) and output (w_v, Ra, Rv) process parameters. The analysis of the significance of the regression equations coefficients indicates that the value of the machining voltage is the most important parameter influencing the process rate and the obtained surface roughness. Due to the limited paper length, the most interesting relations between the output parameters and machining parameters are presented as function graphs (Figure 3 - 5). The effect of the circumferential velocity of the working electrode (v_0) and the supply voltage (U) on the machining rate (volumetric efficiency) (w_v), with other machining parameters being set, is illustrated in Figure 3. The graph analysis shows that the machining rate is significantly related to the supply voltage, as the value of the voltage increases, the process efficiency rises.

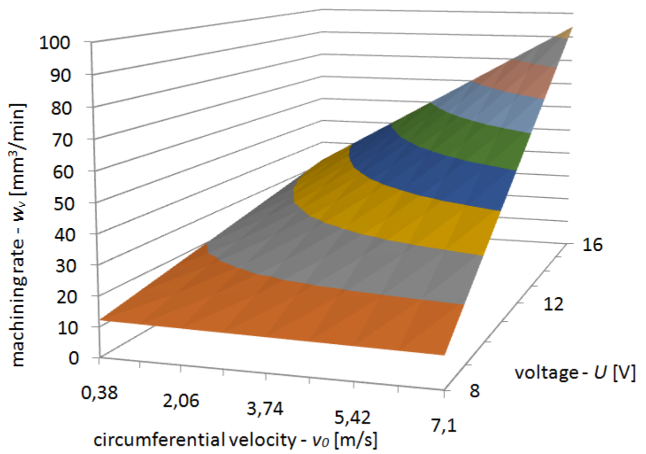

Fig. 3. Effect of circumferential velocity of working electrode – WE and voltage on machining rate - w_v. Process parameters: feed rate v_f = 24 mm/min, deflection of wires Δ = 0.8 mm, wire diameter d = 0.5 mm (for the central point of the experiment), the machined material – L120G13T cast steel

This effect can be explained by the fact that, as the voltage increases, the energy of electric discharge and the volume of eroded metal grow accordingly. Together with the voltage rise, the impact of the circumferential velocity of WE on the process efficiency grows. The increase in machining efficiency associated with a higher value of v_0 is especially visible for the upper voltage range. This relation can be explained by the increase in the mechanical impact of the ends of the brush elements on the metal that has become molten or softened due to the thermal effect.

Figure 4 shows the *Ra* parameter as the function of the electrode circumferential velocity and the supply voltage, for the set of deflection of wires values Δ = 0.8 mm and the feed rate v_f = 24 mm/min and the electrode wire diameter d = 0.5 mm. The analysis of the surface roughness graph indicates that this parameter significantly depends on the voltage. The rise in the value of the *Ra* parameter accompanying the increasing voltage can be explained by higher electrical discharge energy for higher voltages. In the area of low voltages, a slight decrease in roughness is noticed with the decrease in the circumferential velocity of WE. This relation can be explained by the increase of the role of mechanical impact on the roughness peaks under the conditions of low energy discharge. As far as the upper range of the applied voltages is concerned, it is noticed that the increase in the electrode circumferential velocity is accompanied by the rise in roughness.

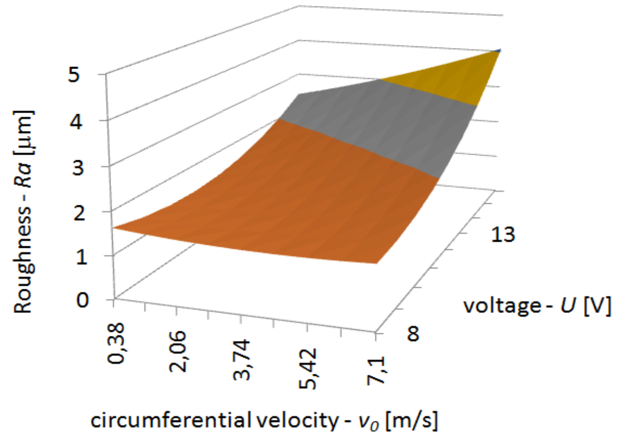

Fig. 4. Effect of the machining voltage and circumferential velocity of WE on the value of the *Ra* roughness. Process parameters for the central point of the experiment

The machining results in a surface with the *Ra* roughness ranging from 0.8 to 4.0 µm. The effect of the machining voltage and circumferential velocity on the maximum surface roughness profile *Rv* is shown in Figure 5. The analysis of the *Rv* parameter graph shows that its value depends to a large extent on the value of the machining voltage. The fact that value of the *Rv* parameter increases together with voltage can be explained by higher electrical discharge energy for higher voltages. In the low voltage range, a significant decrease in the maximum roughness is observed with the increasing of WE circumferential velocity.

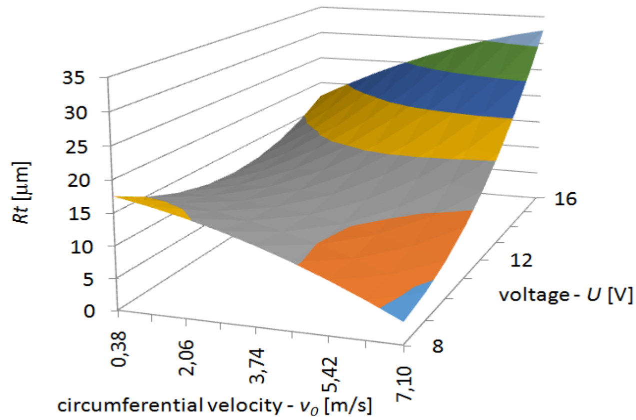

Fig. 5. Effect of voltage and circumferential velocity of WE on the *Rt* parameter. Process parameters for the central point of the experiment

This relation can be explained by the increase in the intensity of mechanical impact on the roughness peaks. Under the conditions of light energy discharge, the role of mechanical processes is reduced to the smoothing of the roughness peaks. For the upper range of the applied voltages, the increase in roughness accompanies the increasing electrode circumferential velocity. As a result of the treatment, a surface with a maximum roughness in the range (maximum profile valley depth) – *Rv* = 4 – 30 µm is obtained. The analysis of numerous profilograms shows that they are assymetrical. The depth of the profile depressions *Rv* is two to three times the height of the maximum profile peak height – *Rp* elevations.

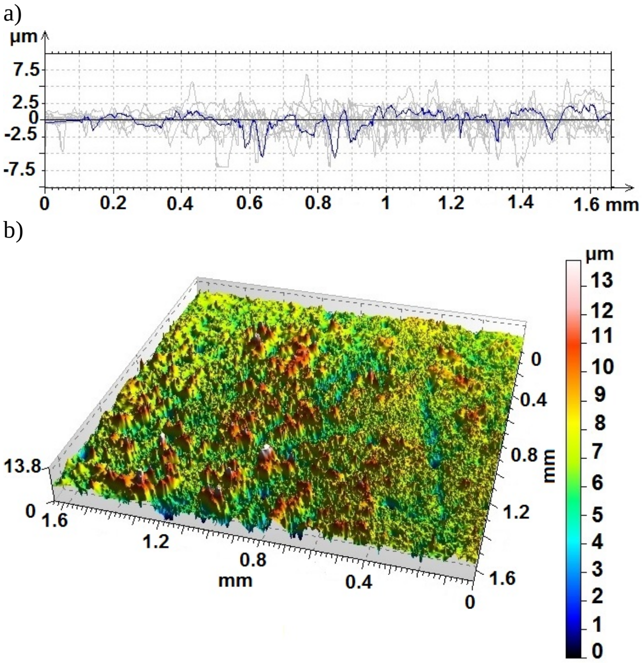

Fig. 6. Surface topography a) sample profilogram b) 3D profile map of a surface after BEDMM machining (repet. 150x); Process parameters: voltage U = 12 V, circumferential velocity of WE v_0 = 7.1 m/s, feed rate v_f = 24 mm/min, deflection of wires Δ = 0.8 mm, wire diameter d = 0.5 mm, the machined material – L120G13T cast steel

Figure 6a shows a sample profilogram of the surface after electro-discharge mechanical machining. Its assessment indicates that it is asymmetrical. It is possible to distinguish the basic structure resulting from the spark effect– its remnants are the depressions in the form of spherical bowls and the secondary structure visible on the roughness peaks – as a result of mechanical impact. The distribution of the roughness profile ordinates is highly favourable– characterized by flat peaks and lower roughness. Roughness studies were supplemented with scanning topography images of the surface – Figure 6b. Surface reconstruction from scanned data shows randomly distributed, overlapping craters, which indicates that, to a significant degree, the surface is shaped by electrospark discharge. The geometric surface structure (GSS) is of non-determined nature – typical of EDM. The surface sub-roughness is formed as a result of weak electrochemical interactions. The sample surface is matte duo to affect of the occurrence of electrochemical etching.

5. Conclusions

The effect of the machining voltage and the federate on the material removal rate for manganese cast steel (Hadfield L120G13T), show that the effectiveness of the material removal rate increases with an increase in the discharge energy. At a small voltage the plasma channel is very narrow and therefore the removal rate is low. In the case of a high voltage the removal rate is higher because of an increase in the discharge energy.

Technological research of the manganese cast steel demonstrates that the machining efficiency at U = 24 V, v_0 = 7.1 m/s, v_f = 36 mm/min, Δ = 1.2 mm is about 300 mm^3/min.

- Electro-discharge mechanical machining is an effective method of austenitic cast steels machining,
- In the range of low voltages the increased mechanical impact is associated with the rise in the circumferential velocity of the working electrode, which does not considerably affect the process efficiency but causes the decrease in the value of the *Ra* and *Rv* parameters,
- In the upper range of the applied voltages, increasing the mechanical impact associated with the growth of v_0 results in the rise in the machining efficiency and the increase of the *Ra* and *Rv* parameters,
- The use of “soft” machining parameters, mainly low voltage, enables the removal of small machining allowances e.g. in the case of objects of considerable size and with low stiffness,
- When high parameters are involved it permits high rate bulk machining of metals and their alloys with the use of the same technological devices.

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