PLASMA-ELECTROLYTE POLISHING OF LOW-ALLOY STEEL 16MnCrS5

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https://doi.org/10.37904/metal.2024.4891

Abstract

Surface treatment methods are often necessary to achieve the desired functionality of parts produced by conventional technologies. Plasma-electrolyte (ELP) technology is an advanced technology for surface treatment. It is based on the phenomena occurring between the metal surface and the electrolyte under DC voltage exceeding 150 V. The process can reduce the surface irregularities and polish the surface to a mirror gloss. The function of tool for reducing the initial roughness is taken over by an ionized steam-plasma envelope that surrounds the entire object during the process. The paper presents the results into polishing of 16MnCrS5 steel utilizing the ELP process. The case-hardened surface layer has demanded two-stage treatment. In each stage, electrolyte of a different chemical composition, concentration, and temperature, and process durations were applied. In the first stage, an electrolyte based on an aqueous solution of ammonium sulphates and chlorides reduced the initial roughness Ra of 0.34 µm more than 50 % within 120 seconds, but a dark coating was detected on surface. In the second stage, an electrolyte based on an aqueous solution of carbonates removed this coating and imparted the surface with a mirror gloss. The final roughness Ra reached value of 0.09 µm. The ELP treatment had a positive effect on the macroscopic character of the steel surface, achieving homogeneity and eliminating traces of grinding tool or other surface macro-unevenness (burrs) that disrupt the surface integrity.

Keywords: Plasma-electrolyte polishing**,** multistage process, surface roughness reducing, low-alloy manganese-chromium steel

1. INTRODUCTION

Components produced through conventional methods may not consistently meet the standards for their intended use. As a result, additional surface treatment is frequently required to achieve the desired condition. In the field of metallic materials treatment, plasma-electrolyte (ELP) technology has got to be known. This technology is based on phenomena that occur in the interface between the metal surface and the electrolyte under the DC voltage exceeding 150 V. The function of tool is performed by electrical discharges coming about between the machined surface and the electrolyte together with a vapour-plasma layer that is generated by these discharges and uniformly envelops the entire treated object.

The erosion, cleaning, and smoothing effect of electrical discharges between a metal surface and the electrolyte has been understood since the late 19th century. However, application in practice was limited until recently due to various reasons. Common low-voltage processes such as an electrolysis require the high current densities and, along with high energy consumption, are accompanied by unpredictable electrical discharges that put the pulse load on the power supply. A positive turn for electrolyte plasma technology has

brought about an understanding of phenomena that occur with most electrically conductive solutions at DC voltages exceeding 150 V. At this threshold, a continuous vapour-plasma layer forms on the treated surface, where the erosive effect of local discharges is applied, along with the cavitation action of intensely moving components of the envelope on the treated surface. This results in the smoothing of the surface irregularities with a significant reduction in roughness [1, 2].

In practice, the application of processes involving DC voltages exceeding 150 V was limited by the negative electrical resistance exhibited by the electrolytic circuit. This resistance meant that a decrease in voltage between the electrolyte and the treated surface will result in an increase in the intensity of the electric current, and conversely, an increase in voltage will cause a decrease in current intensity. When such a circuit is supplied by a conventional power supply based on transformer with rectifier, any random fluctuation in current or voltage will cause the oscillations in the system under which amplitudes of the electrical quantities are rising and attain values that usually cause the damage to the power supply. A significant advancement toward the commercial application of this technology has been working out the technical challenges regarding the impulse loaded power supply for electrolytic circuits with negative resistance through the capacity compensation of the inductive component of the internal resistance of the source [3]. A power supply with capacitive compensation of the inductive component is sufficient to rate for nominal output consumed by the electrolytic circuit with using commonly available commercial capacitors. This approach has been used for the ELP equipment with the power of 17 kW device developed at Faculty of Mechanical Engineering of STU in Bratislava.

The technology is characterized by highly effective cleaning capability. The object being cleaned can be connected to the negative or positive pole of the DC power supply. Connecting with negative polarity there is a higher cleaning effect, but the treated surface is heated intensively. Conversely, the anode process under which the treated electrically conductive object is connected to the positive pole of the supply and the negative pole to a working vessel with electrolyte is a more energy-efficient process and allows for achieving a mirror gloss on the surface while the heating of the treated surface reduces significantly. The technology can be applied to a wide range of metallic materials and especially, complex-shaped objects where the traditional machining processes are not effective.

The ELP technology offers numerous advantages over traditional electrochemical polishing processes. It utilizes environmentally safe inorganic salt solutions of low concentration instead of acids and toxic substances. These solutions are easy to prepare and yield long-lasting and consistent results, producing a mirror-like finish on the surface. When these solutions are used, iron and other alloying elements are typically bound in forms that are minimally soluble in working solutions [4-8].

The essential parameters of the ELP process that have influence on the final characteristics of the treated surface encompass the chemical composition and properties of the electrolyte (such as electrical conductivity, temperature, and concentration), working DC voltage, and process time. These parameters determine the current density on which depends the intensity of the material removal from the surface of the treated object. The process provides a range of options for selecting a working solution. For example, different types of one-component and mixed solutions of carbonates, sulphates, and chlorides can be used to attain mirror gloss and identify surface defects, with their dissociated components exhibiting minimal chemical reactivity with the material of the treated surface.

The paper presents the research results on the effect of parameters of the ELP anode process in a two-stage arrangement on the surface roughness (Ra) of cylindrical-shaped samples made of low-alloy manganese-chrome steel 16MnCrS5 in the case-hardening state, as well as the potential for achieving a mirror gloss.

2. EXPERIMENTAL METHODS

To investigate how technological factors affect the anode process of ELP technology in a two-stage setup, the study utilized 30 cylindrical samples composed of low-alloy manganese-chrome steel 16MnCrS5 (EN 1.7139)

with the chemical composition (wt. %): 0.16% C, 0.25% Si, 1.15% Mn, 0.95% Cr, 0.4% Cu, and 0.02 - 0.04% S after case-hardening and fine grinding (**Figure 1**).

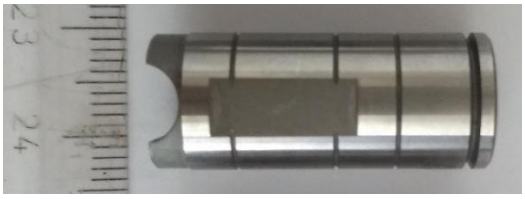

Figure 1 Cylindrical sample made from steel 16MnCrS5

The experimental equipment had a maximum power of 6 kW, with a working DC voltage ranging from 250 to 340 V and a maximum DC current up to 15 A. Each cylindrical sample had the surface area of 16 cm^2, with dimensions of ø 12 x 30 mm and a weight of about 20 g. Before the experiments and after each ELP operation, the samples were cleaned in 96% methanol under ultrasound, dried using warm air, and finally, weighed with the laboratory balances with an accuracy of 0.0001 g. The surface roughness (Ra) of the samples before and after each ELP application was measured by a contact roughness gauge, Taylor Hobson SURTRONIC 3+. Five measurements were taken for each sample, and the mean value as well as the standard deviation were computed.

The electrolyte-plasma polishing process consisted of two stages, each one involving two consecutive operations. Different chemical compositions and concentrations of electrolytes were used in each operation, along with varying electrolyte temperatures (80 or 85°C) and anode process durations (60, 120, and 180 seconds). In the first stage, the electrolyte composed of ammonium sulphate and ammonium chloride (ASC), designed for carbon steels to reduce surface roughness, was utilized, while the second stage employed a carbonate-based electrolyte to achieve a mirror gloss surface. The anode process achieved a current density of 0.14 A/cm^2 under a working DC voltage of 270 V and a DC current value of 6.5 A. To maintain the required working electrolyte temperature, accurate within ±1°C, the electrolyte was circulated through the cooling circuit of the ELP device. For a detailed overview of the ELP parameters, refer to Table 1.

Table 1 Parameters procesu ELP

Sample	**Electrolyte**	**Concentration of electrolyte** (wt %)	**Temperature of electrolyte** (°C)	**Process time** (sec)
	1. stage			
I	ammonium sulphate ammonium chloride (ASC)	4	80	60
II			80	120
III			80	180
IV			85	60
V			85	120
VI			85	180
	2. stage			
I	carbonate	4	85	60
II		4		120
III		4		180
IV		6		60
V		6		120
VI		6		180

3. RESULTS AND DISCUSSION

The initial surface roughness Ra of cylindrical samples (**Figure 1**) after case-hardening and fine grinding varied from 0.19 to 0.34 µm. The effectiveness of the electrolytes utilized in each stage, along with the effect of electrolyte's temperature and process time on dynamics of surface roughness reducing during the ELP

process, were evaluated on samples both before and after ELP processing. The influence of electrolyte concentration and temperature, as well as the duration of the ELP process, on the level of surface irregularity smoothing for samples Ra in individual operations P1 and P2 is presented in (**Figure 2**)for samples I-III and in (**Figure 3**) for samples IV-VI.

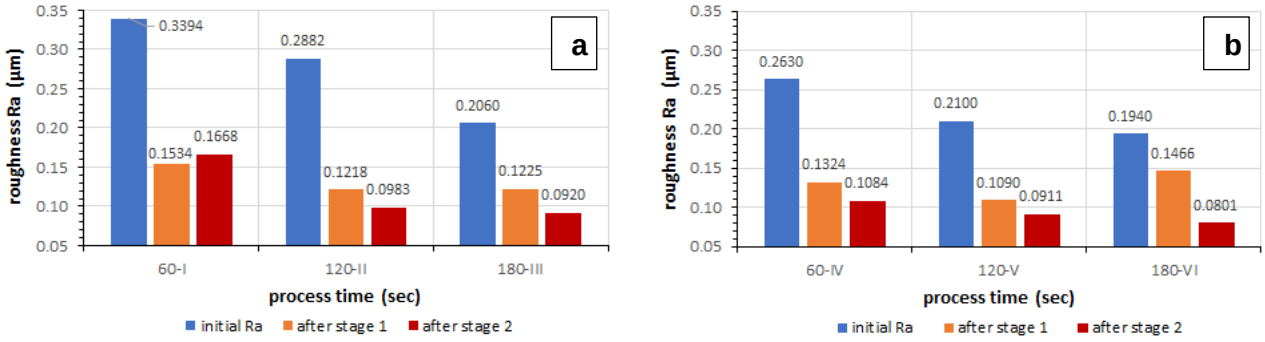

Figure 2 Changes in surface roughness Ra depending on the applied electrolyte and length of the ELP process **Table 1**: a- samples I – III, b- samples IV - VI

Based on the results obtained, it is evident that the ASC electrolyte that was developed for carbon steel processing and used in the first stage has led on average up to 50% reducing in the initial surface roughness Ra across the whole set of samples. When evaluating the impact of electrolyte's operating temperature employed at the first stage on intensity of roughness reduction, there was observed that an increase in the electrolyte working temperature results in a decrease in the intensity of roughness reduction. For set of samples of I - III, when the ASC electrolyte had a working temperature of 80°C, the surface roughness decreased on average by 54% i.e., from an average starting roughness Ra of 0.28 µm to a value Ra of 0.12 µm. Under the electrolyte of temperature of 85°C (samples IV - VI), an average decrease of 46% was observed, when the average starting roughness of 0.20 µm dropped to a value of 0.12 µm. These findings have pointed to that the thickness of the vapour-plasma envelope influences the final effect of the ELP process. An increase in electrolyte temperature causes the envelope expansion that results in decrease in current density and intensity of ongoing processes. Analysis of the effect of the ELP process time on surface smoothing revealed that for a given initial roughness, it is not necessary to prolong the process beyond 120 seconds, as longer times do not significantly improve the roughness. Rather the opposite, at the ASC electrolyte temperature of 80°C and a process time of 180 seconds, the surface roughness was reduced by only 45%.

In the second stage, a carbonate-based electrolyte was utilized at the constant operating temperature of 85°C with varying concentrations of electrolyte i.e., 4% for samples labelled I to III and 6% for samples from IV to VI. For the experiments, samples that had undergone the first stage were utilized without any additional treatment. Upon analysing the data presented in (**Figure 2**), there was observed the electrolyte used in the second stage is primarily designed for cleaning and polishing the surface rather than levelling unevenness through material removal. At the second stage, all samples have proven an average starting roughness Ra of 0.12 µm. Following the ELP process in a 4% carbonate-based electrolyte at the operating temperature of 85°C, the roughness of samples I - III decreased on average by 17% i.e., from a mean initial value of 0.12 µm to a value of 0.09 µm. The application of the 6% electrolyte caused a 20% reduction in roughness for samples of IV - VI, resulting in an average roughness comparable to that of samples I - III, i.e., 0.09 µm. When considering the impact of electrolyte concentration and the process time, the use of carbonate-based electrolyte did not have a significant effect on the roughness change. However, it changed the visual appearance of the treated objects surface that got a reflective, mirror gloss, contrasting with its original state or after processing during the first stage. The darkening of surface after the first stage, and the decline in appearance compared to that after fine grinding (**Figure 3**), resulted from the reaction of the electrolyte with the case-hardened layer with an

increased C content. Changes in the surface properties after fine grinding and application of electrolyte plasma technology are shown in (**Figure 3**).

Figure 3 The surface of 16MnCrS5 steel samples: a) initial state after fine grinding, b) after first stage (reduced roughness), c) after second stage (mirror gloss)

Figure 4 documents the influence of the ELP process on the macroscopic change at the surface of steel 16MnCrS5. The initial surface of steel after case-hardening and fine grinding, with a roughness of Ra 0.4 µm, revealing visible tool marks and other surface irregularities such as burns is presented in Figure 4a. In Figures 4b and 4c, the effect of electrolyte composition and concentration on the surface modification of the steel is shown. The surface treated in a carbonate-based electrolyte of 6% concentration exhibited traces after machining and uncovered grain boundaries, resulting in a roughness Ra of 0.3 µm. On the other hand, the surface treated in an electrolyte of 4% concentration based on ammonium sulphate and chloride showed no visible traces after machining, presenting a homogeneous surface with a roughness of Ra 0.15 µm.

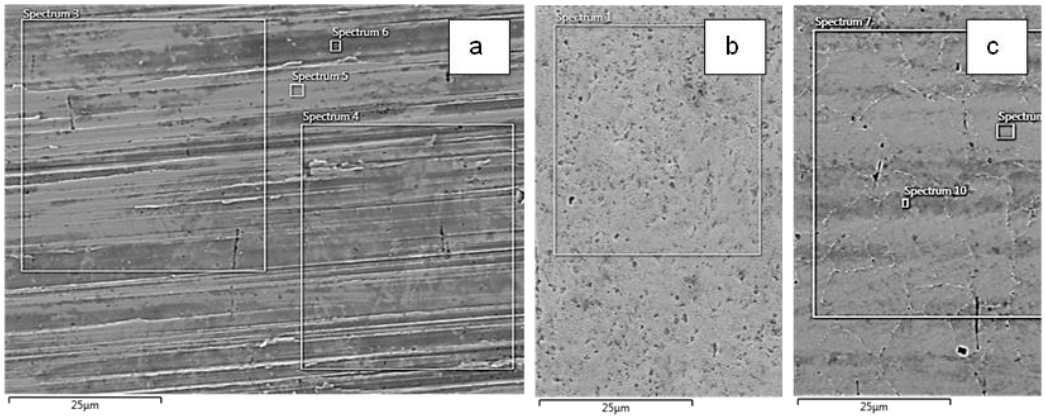

Figure 4 The surface of the 16MnCrS5 steel: a- after fine grinding (Ra 0.4 µm); b- after the ELP process (the 4% sulphate-chloride based electrolyte, 80°C, 60 seconds); c- after ELP process (6% carbonate-based electrolyte, 85°C, 60 seconds)

The analysis of weight loss data reveals only the minimal changes (Figure 5). Samples of I - III experienced an average weight decrease of 0.14 g or 0.7% after the first stage in the 80°C electrolyte, with the loss increasing over time. Elevating the electrolyte working temperature to 85°C has caused the average weight change of 0.12 g or 0.6% for samples IV - VI. The mass losses of the samples after the second stage of the ELP treatment were negligible at the level of thousandths of a gram. The weight losses have indicated that the ASC electrolyte used in the first stage contributed to smoothing the unevenness on the workpiece surface, while the electrolyte of the second stage assure surface cleaning and the attainment of a mirror gloss.

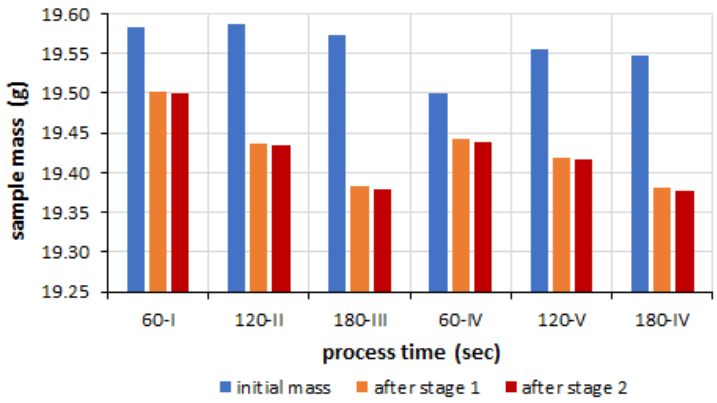

Figure 5 Changes in the weight of samples I-VI depending on electrolyte (Table 1) and ELP process time

4. CONCLUSION

The electrolyte plasma technology used in the anodizing process makes the surface smooth and creates a mirror-like gloss while minimizing surface heating. These capabilities were tested on objects made of low-alloy manganese-chrome steel 16MnCrS5 in the post-cementation state. Due to the presence of a cementing layer, a two-stage process was necessary, involving different electrolytes. The first stage utilized an electrolyte based on sulphates and ammonium chlorides, which reduced the initial roughness of Ra 0.28 µm by an average of 50% in 120 seconds but resulted in a darkening of the surface. The second stage involved a carbonate-based electrolyte, which not only removed the dark coating but produced a mirror gloss on the surface, resulting in a surface roughness of Ra 0.09 µm.

ACKNOWLEDGEMENTS

This work was supported by the Research and Development Agency under contract No. APVV-19-0559 and No. APVV-22-0580.

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