Methods of applying the reliability theory for the analysis of micro-arc oxidation process

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Abstract. To improve the handling of micro-arc oxidation (MAO) process in this paper, the analysis of factors influencing the properties and operating characteristics of MAO-coatings and their classification on the basis of methods of reliability and quality theory (cause-effect diagram and the relationship diagram) were done. The main factors influencing the MAO process were revealed and recommendations on the use of obtained results in theoretical and experimental studies were done.

1. Introduction
Micro-arc oxidation (MAO) technology exists since the 70-ies of XX century, but still here the handling of the MAO process and its automation remains the problem. Currently, this lack is eliminated by practicing the process. However, this approach is long and time-consuming, so the challenges of MAO process handling and the building of MAO automated systems are becoming increasingly real [1].

The main difficulty, with which the scientists face in solving these problems, is a large number of factors that affect properties of the MAO-coating (current density, anode and cathode currents ratio, MAO processing time, temperature and development of electrolyte, etc.) which directly affects the quality of the received product.

To eliminate these difficulties, it is advisable to systematize all factors according to the influence degree on the MAO process and identify the main ones. The similar systematization was proposed in the paper [2], but it is not sufficiently complete and does not take into account some interrelations. Reliability and quality theory methods, such as the cause-effect diagram (Ishikawa diagram) and the relationship diagram, on the other hand, can give a fairly exhaustive description of factors interrelations affecting the MAO process. All initial data to build these diagrams are set out in [3].

2. Cause-effect diagrams
Analysis of cause-effect diagram makes it possible to identify the main factors (reasons) that affect this coating property or one of its operation characteristics (quality parameters). In this work the Ishikawa diagrams were built for all quality parameters of MAO-coatings on aluminium and its alloys in silicate-alkaline electrolyte: microhardness, wear resistance, corrosion resistance, electrical strength, thermal conductivity (Figures 1 and 2) and also factors influencing each of them were identified.
Ishikawa diagram for the microhardness of the MAO-coatings is shown in Figure 1 (a). The stem charts the cause-effect relationship are shown by arrows, they are directed from cause to effect. For example, the arrow "workpiece surface finish - microhardness" indicates that the surface finish affects the microhardness, and not vice versa. If the arrow points in both directions, it means that the cause and effect have the same effect on each other. From Figure 1 we see that the microhardness of the
Figure 1(a, b, c, d). Cause-effect diagrams of MAO-coating quality parameters: (a) microhardness; (b) porosity; (c) electrical strength; (d) thickness.
Figure 2(a, b, c). Cause-effect diagrams of MAO-coating quality parameters: (a) corrosion resistance; (b) thermal conductivity; (c) wear resistance.

MAO-coating is influenced by the composition of the initial alloy and surface finish of sample, the liquid glass Na$_2$SiO$_3$ concentration in the electrolyte, current density, forming voltage, processing time and the electrolyte temperature. Factors that affect all the other properties of coatings and the quality parameters of the MAO process were identified (Table 1).

| Quality parameter/coating property | Influencing factors |
|-----------------------------------|---------------------|
| Microhardness                     | $j, t, T, Al$ content in the initial alloy, Na$_2$SiO$_3$ concentration, surface finish of the sample |
| Thickness, $h$                    | $j, t, T, I_k/I_a$, Al content in the initial alloy, Na$_2$SiO$_3$ and KOH concentration |
| Porosity                          | $j, t, T, f, h$, Na$_2$SiO$_3$ concentration, surface finish of the sample |
| Electric strength                 | $h$, porosity |
| Corrosion resistance              | $h$, porosity |
| Thermal conductivity              | $h$, porosity |
| Wear resistance                   | microhardness, porosity |

In Table 1, $j$ is the current density, $t$ is the treatment time, $T$ is the electrolyte temperature, $f$ is the current pulse frequency, $I_k/I_a$ is the ratio of the anode and cathode currents, and $h$ is the MAO coating thickness. If the quality parameter depends on the coating property (for example, the thermal conductivity depends on the thickness and porosity), then it automatically inherits all the causes of this property. Thus, the thermal conductivity (as well as the electrical strength and corrosion resistance) will depend on the current density $j$, the treatment time $t$ and the electrolyte temperature $T$, the current pulse frequency $f$, the anode and cathode currents ratio, the electrolyte composition (KOH and Na$_2$SiO$_3$ concentrations) and the initial alloy composition (aluminium percentage in it). It should be noted that the porosity in this case also depends on the thickness, but indirectly on the microdischarges power.
3. Relationships diagram

In accordance with Table 1, a diagram of factors influencing the MAO process with the properties of the coatings obtained and their quality parameters was constructed (Figure 3). The directions of the arrows were chosen on the same principle as for the Ishikawa diagrams. The relationships diagram makes it possible to identify the main influencing factors for the entire MAO process, and not just for a particular coating property or quality parameter.

When analyzing the relationships diagram, the following was found. All quality parameters are affected only by three MAO coating properties: microhardness, thickness and porosity, and microhardness only affects wear resistance. However, as follows from the Ishikawa diagrams, the intermediate reason for the "crystalline aluminium modifications content", which mainly determines microhardness, also holds for electrical strength and corrosion resistance.

All the factors of the MAO process, which can be divided into the parameters of the technological process and the initial alloy, the electrolyte composition and the external conditions, somehow influence the MAO-coatings properties. The main parameters of the MAO technological process are the current density and processing time. They are associated with all coatings properties, and also provide external conditions (temperature and electrolyte development). Forming voltage is also one of the main factors of the MAO process, but in many cases it affects the coating properties only indirectly, through the electrolyte temperature. The current pulses frequency only affects the porosity. The anode and cathode currents ratio affects thickness and porosity, but these coating properties determine all products quality parameters (wear resistance in part) with MAO-processing.

In the case of the initial alloy parameters, the following regularities can be distinguished. First, the higher the aluminium percentage in the material workpiece, the more high-quality MAO-coating on it is formed. Thus, products made of technical AD0 aluminium (99.8 % aluminium content) are best suited for MAO-processing, followed by AMg3 (94.9 % aluminium content) and duralumin D16.
(92.8 % aluminium content) [4]. This fact is explained by the one that in the aluminium alloys composition there are chemical elements that discourage the aluminium oxide formation, as a result of which the MAO-coating initial structure has a number of "weak" places, the electric breakdown occurs at lower voltage values, and the conditions for \( \gamma-\text{Al}_2\text{O}_3 - \alpha-\text{Al}_2\text{O}_3 \) phase transition are realized to a lesser voltage [3]. Secondly, the workpiece surface finish affects the microhardness and porosity differently: the higher the surface finish, the microhardness is greater and the porosity is less. This should be taken into account when planning the MAO process.

A special interest is the influence of external conditions (temperature and electrolyte development) on the MAO-coating properties. As can be seen from Figure 3, the electrolyte temperature affects all properties and, consequently, all the quality parameters of the MAO-coating. However, it, as well as the electrolyte development, depends on the current density and the processing time (and also on the forming voltage), and besides, the temperature and the electrolyte development are interdependent. It can be explained as follows (Figure 1 (a)). The electrolyte development is a decrease of the ions concentration in it, due to their inclusion in the structure of the MAO-coating. With increasing current density in microdischarge, the electrolyte is more impoverished by ions, its conductivity decreases [5], and the resistance and voltage drop increases, hence the power dissipated by the electrolyte increases, which leads to its heating. On the other hand, as the temperature of the electrolyte increases, the rate of chemical reactions increases, more molecules of the electrolyte dissociate into ions, and more of them are incorporated in the coating, which further increases the electrolyte temperature. Similarly, the external conditions are affected by the time of MAO-treatment.

The effect of the electrolyte composition is also ambiguous. In general, the concentration of substances forming the electrolyte is set once before the beginning of the MAO process and does not change during processing (this is true for KOH). At the same time, the concentration of technological liquid glass \( \text{Na}_2\text{SiO}_3 \), apparently, is a function of the current density, processing time and electrolyte temperature and determines its development, since silicate ions are incorporated into the coating [3]. In addition, this parameter can indirectly, through the electrolyte temperature, affect all MAO-coatings properties.

From the point of view of the MAO process mathematical description, the quality parameters can be represented as functions of several variables, the parameters of the technological process are independent variables, while the external conditions are also functions of these parameters. The parameters responsible for the composition and the initial alloy purity, as well as the concentration of alkali (KOH) in the electrolyte, can be represented in the form of constants, since they do not change during the MAO-process. Thus, for effective control of the MAO-process it is necessary to take into account the following regularities:

\[
T = F(j, t, U, _\text{f}) \\
C_{\text{Al}_{2}\text{O}_3} = F(j, t, T) \\
HV = F(j, t, P_{\text{Al}}, C_{\text{Na}_2\text{SiO}_3}, S) \\
h = F(j, t, I_{\text{f}}/I_{\text{a}}, P_{\text{Al}}, C_{\text{Na}_2\text{SiO}_3}, C_{\text{KOH}}) \\
P = F(j, t, f, I_{\text{f}}/I_{\text{a}}, P_{\text{Al}}, C_{\text{Na}_2\text{SiO}_3}, C_{\text{KOH}}, S) \\
E = F(h, P) \\
CR = F(h, P) \\
TC = F(h, P) \\
WR = F(HV, P) 
\]

where \( HV \) - microhardness;
\( h \) and \( P \) - the MAO-coating thickness and porosity, respectively;
\( E \) - electric strength;
\( CR \) - corrosion resistance;
TC - thermal conductivity;
WR - wear resistance;
U_f - forming voltage;
I_K/I_A - anode and cathode currents ratio;
C_{Na_2SiO_3} - liquid glass concentration in the electrolyte;
C_{KOH} = \text{const} - alkali concentration in the electrolyte;
p_{Al} = \text{const} - aluminium percentage in the initial alloy;
S = \text{const} - the workpiece surface finish.

Considering the fact that \( T \) and \( C_{Na_2SiO_3} \) are functions, we get:

\[
HV = F(j,t,U_f,p_{Al},S) \\
h = F(j,t,U_f,I_K/I_A,p_{Al},C_{KOH}) \\
P = F(j,t,U_f,I_K/I_A,f,p_{Al},C_{KOH},S) \\
E = F(h,P) \\
CR = F(h,P) \\
TC = F(h,P) \\
WR = F(HV,P)
\]  

From (2) it follows that the main parameters of the MAO process are the current density, the processing time, the forming voltage, the anode and cathode currents ratio, and the frequency of the current pulses. All other parameters either depend on the above, or are constants determined before the MAO process.

4. Conclusion

Thus, the methods of the reliability theory are presented by the informative way to search for cause-effect relationships in complex multifactor processes, such as MAO. Together with the quality control methods, they serve as the basis for the construction of the most common, primary mathematical models, as well as the hypothesis requiring experimental confirmation while studying factors affecting the quality of MAO-coatings.

References

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