Surface heating control during low-temperature plasma treatment

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Abstract. The main features of the process reflecting product surface heating during low-temperature plasma treatment have been established, and the necessity of managing this process has been substantiated. A control method has been developed that makes it possible to determine the moment of termination of the plasma effect on the product surface using a logistic curve as a data model on the temperature recorded outside the zone of thermal plasma effect (lagged temperature).

1. Introduction

Further efficiency increase of manufacturing processes for different-purpose parts necessitates taking into account factors that largely determine the actual state, and, therefore, the potential capabilities of technological equipment. Only their rational use will create conditions in which the efficiency can be brought to a new level.

Any modern equipment belongs to the class of complex systems, therefore, an a priori assessment of the state of the technological process implemented on it and the forecast of its changes are very difficult in practice. Feedbacks implemented in the equipment are local; they make it possible to control the main functional blocks but provide no information on the product quality. As a result, in most cases quality is assessed after the manufacturing process is completed. This means that in order to increase the equipment efficiency, it must have not only traditional (accuracy, reliability, speed) but also new properties, the main ones being the ability to readjust to changing external conditions and to adapt to assigned goals taking into account the actual state. In other words, the equipment must be self-organizing. As a result, the role of information technologies (first of all, digital) increases as a means of obtaining information and making decisions on self-organization based on the results of its processing, directly during the product manufacturing, i.e. in real time.

2. State of the issue

Information technologies used in various industries today can be divided into three groups:

- receiving and displaying information about the technological process parameters;
- receiving, processing and displaying the processed information about the technological process parameters;
- receiving and processing information about the technological process parameters with the subsequent use of the results obtained to affect its course.
Recently, technologies of the third group that focus on the use of automatic digital control systems capable of reproducing various principles of using the received and processed information, are being widely applied: disturbance control, deviation control, combined control, self-learning and self-organizing (adaptation) control. This makes it possible to increase the different-purpose equipment efficiency by improving the quality of control. The foregoing is also relevant for equipment that implements the method of low-temperature plasma processing of metal products in order to increase their reliability in terms of durability [1].

3. Methods
The main process in low-temperature plasma treatment is heating the product surface, as a result of which irreversible changes in the surface layer structure and properties occur. Analysis (using the nonparametric Kruskal-Wallis criterion based on the calculation of the Iman and Davenport $J_v$ statistics) of the data of experimental (including model) studies of the process of heating the surface of samples and real products of various materials and alloys [2, 3], during which the temperature outside the zone of thermal effect of the plasma (lag temperature) was recorded using a chromel-copel thermocouple with 1 Hz frequency and a 0.1°C accuracy, while the surface microhardness was measured with a PMT-3 device and its morphology was studied on a scanning electron microscope TESCAN \ MIRA LMU, made it possible to draw the following conclusions.

1. The lag temperature behavior is completely determined by the regularities of the processes in the plasma and reflects the course of the product surface heating process.

2. For each variant of processing conditions determined by a combination of operating parameter values, as well as physical and mechanical parameters, material chemical composition and their changes to varying degrees during the processing, there is an optimal time of plasma exposure to the surface (figure 1) which determines the moment when the exposure must be stopped, according to the criterion for obtaining the best results of surface layer structure and properties transformation (which corresponds to the maximum positive value of $J_v$ statistics).

![Figure 1](image1.png)

**Figure 1.** The results of assessing the significance of volumetric changes in the surface layer of 45 steel samples processed at different times with two operating parameter combinations: $J_v$ – tabular value of Iman and Davenport statistics.

3. It is not possible to visually determine the moment of heating termination from the lag temperature curve (figure 2); the only way to solve this problem is to use a model that describes data change patterns in the lag temperature signal, considered as dynamics time series.

The analysis materials were used as the basis for research related to the development of a method for controlling the process of product surface heating during low-temperature plasma treatment. The method development involved solving the following tasks: defining the type of model that flattens the lagged temperature signal data; estimation of model parameters and its verification based on the results of processing real data on the course of thermal processes; control algorithm development.
4. Results

The identification of the model type was carried out using an approach based on comparing the characteristics of changes in the increments of time series of lagged temperature values with the corresponding characteristics of growth curves [4]. The model was chosen from a number of alternative ones (straight line, parabolas of various degrees, exponentials, S-shaped curves), the increment change pattern of which was closest to the regularity of actual data increment change. The results showed that in all cases the best approximation was shown by the logistic curve belonging to the S-curve class:

\[
y_i = \frac{k}{1 + be^{-at}}. \tag{1}
\]

The quantities \(a\), \(b\) and \(k\) are the parameters of the curve.

From the standpoint of the main features of this curve, the change in the lagged temperature can be considered as an «avalanche-like» process with two tendencies determined by \(a\) and \(b\) values [5]: one tendency demonstrates the development acceleration, the other demonstrates deceleration (ie, a process in which growth depends, for the most part, on the level already reached), and «saturation» (ie, the asymptote \(k\) to which it tends), determined by the cumulative effect of heating processes, thermal conductivity and heat transfer. At the same time, various kinds of restrictions do not have a significant effect on the change. However, taking into account the practical orientation of the study, it is more expedient to consider the entire cycle of lagged temperature change as a single (special) type of trend with complex variable properties and a constant direction of change (in this case, upward). This will make it possible to calculate the entire trajectory of the heating process as early as at the first stage, and to determine the moment of its termination after the heating rate transition from accelerated to decelerated, caused, firstly, by the imbalance between the heat conduction and heat transfer processes due to intensified radiation from the surface, and secondly, by the melt layer formation on the product surface. The foregoing means that determining the heating termination moment is, in fact, a procedure for predicting the lagged temperature values using a model, therefore, in addition to verification, it requires searching for conditions that ensure the maximum forecast reliability.

Verification of the model, the parameters of which were estimated by the three-sum method [4], showed that the average value of the relative error in the lag temperature curve calculation does not exceed 4%.
The condition search for a reliable prediction consisted in determining the minimum amount of required data in the array of lagged temperature values. The implemented search procedure involved a sequential decrease in points in the arrays (according to which the model parameters were estimated and the moments of the heating rate transition from accelerated to decelerated were determined) from their initial number until the relative error value in determining the moment began to exceed the admissible limit value for which the error was obtained during the model verification. The arrays of errors formed in this way were approximated by second-order polynomials (with more than 99% accuracy) and using their equations we calculated the array volumes that provide the specified accuracy of determining the transition moment of the heating rate from accelerated to decelerated: from 300 to 320 points. This means that it takes about 5 minutes just to register the minimum required amount of data, while the moment of the heating rate transition from accelerated to decelerated can occur (e.g., for soft materials) already in 2.5 ... 3.5 minutes after the processing starts. Consequently, for the practical use of the model, it is necessary to increase the frequency of lag temperature value recording at least by a factor of 2.5. This will make it possible to obtain the required amount of data within 2 minutes after the start of processing. Also, the forecast reliability can be increased through the use of more accurate methods for estimating the model parameters, in particular, based on obtaining regression dependences for the growth rates of lagged temperature values.

![Graphs](image)

**Figure 3.** Variations in the values of the model parameters (1): (a), (b) – parameter $a$ when processing HG012 hard alloy samples (a) and copper samples (b); (c), (d) – parameter $b$ when processing hard alloy samples with TiN coating (c) and 1.4878 steel samples (d).

At the same time, it was found during the proposed procedure that the values of the model parameters (1) during the product heating behave alike regardless of the material. In particular, the parameter $a$, being in the positive region, at first decreases rather quickly from the maximum to the minimum value, and then starts to increase slowly (figure 3(a)), or, being in the region of negative values, it increases...
up to the transition to the region of positive values (figure 3(b)). The parameter \(b\), after passing the singular point (minimum or zero) by the parameter \(a\), at a certain moment of time abruptly changes its sign, and then starts to decrease in the region of positive values (figure 3(c), 3(d)). The moment of abrupt change in parameter \(b\) corresponds to the point of change in the heating rate. This means that it is possible to replace the procedure for the behavior of the lagged temperature predicted values with the procedure for analyzing the behavior of the model parameter current values. To do this, it is enough to consequently fix:
- sign change or minimum value of the parameter \(a\);
- sign change of the parameter \(b\);
- two- or three-time (in a row) decrease in the value of parameter \(b\) or its insignificant change, i.e. change not exceeding the value of the specified permissible error (for example, 5 ... 10%).

The implementation of this sequence provides, firstly, the possibility to increase the accuracy of identification of the heating termination moment through the use of different decision-making rules, and secondly, higher protection against various interferences arising during the lagged temperature real curve formation. The need to increase the lagged temperature value registration frequency is also eliminated.

The results of the study were used as the basis for the development of an algorithm for controlling the heating process of the product. Its practical implementation was carried out by machining a 10 mm cutter diameter, made of a TiAlN coated carbide alloy. Initially, it was processed without the heating process control for 15 minutes, which ensured the 37.63 GPa/μm compaction of the surface layer of the working part and, as a result, its hardness increase by 34.9%. The analysis of the lag temperature values array recorded during the treatment showed that the processing should have been carried out for 15.5 minutes. Further work of the cutter in real production conditions made it possible to manufacture parts from 1.4031 steel with 48 ... 52 HRC hardness with internal roughing and finishing workpieces on Hision VNC 1000L vertical machining center for 4 hours. After that, the cutter was reground and re-processed with the heating time control, which was 14.5 minutes, providing the following quality parameter values: the working part surface layer compaction 49.42 GPa/μm, hardness increase by 44.4%, operating time under similar conditions 4.5 hours. The result turned out to be better than when machining without control, which is quite natural, since it was obtained under conditions of a change (as a rule, for the worse) in the initial material properties after operation and tool regrinding, which were reflected in its heating curve and were formalized in the algorithm. In this regard the algorithm can be embedded in the software of the control system of the equipment for low-temperature plasma treatment, implementing its self-organization possibilities in practice.

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