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Advanced systems for heat treatment controlling of electrical furnaces

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Abstract. This paper presents a modern electric heat treatment which has implemented an electric furnace control system through thermoregulatory with PID control laws. An important aspect is the development of a mathematical model for controlling electrical heating systems for heat treatments based on mathematical modelling to predict the mechanical properties and structure of the play resulting from heat treatment. Validation of the experimental research of heat treatment designed by the mathematical model for predicting mechanical properties and structure of the finished part and model for controlling electrical heating system based on PID adjustment algorithms consists in structural analysis to determine the chemical composition, structural analysis by light microscopy, electron microscopy SEM and EDX quantitative analysis, determination of hardness alloys and physical and mechanical of the turbine blades component of a plasma torch on hydrogen made of heat-treated steel.

1. Introduction

The way to achieve a modern heating system for thermal treatments equipped with equipment for automatic control of the thermal processes in order to improve the mechanical and structural properties of the heat treated parts, which is determined by the need of obtaining low manufacturing costs and a level higher quality [1-6]. The main problem with the management of the heat treatment furnaces is to control the temperature in the furnace so that it evolves after the profile imposed by the technologist [1, 2, 4, 7, 8]. Thermal treatment processes can be accurately modeled with transfer functions for dead-time first order elements. PID algorithms are sometimes successfully implemented in the control of such machines but dead time has unfavorable adjusting effects, the best adjustment can be made using a one-step predictive algorithm. PID-type regulation having a simple structure and being easy to assign is one of the first control strategies used and has the widest applicability in industrial process control, the main feature of PID-type regulation is that it is very little dependent on accurate modeling of the process [7, 9-11].

2. Material and method

Technological multivariable system consists in an electric furnace heat treatment with two different temperature zones, maximum temperature of 1200 °C with total power of 1.6 kW / zones with digital temperature control (figure 1).
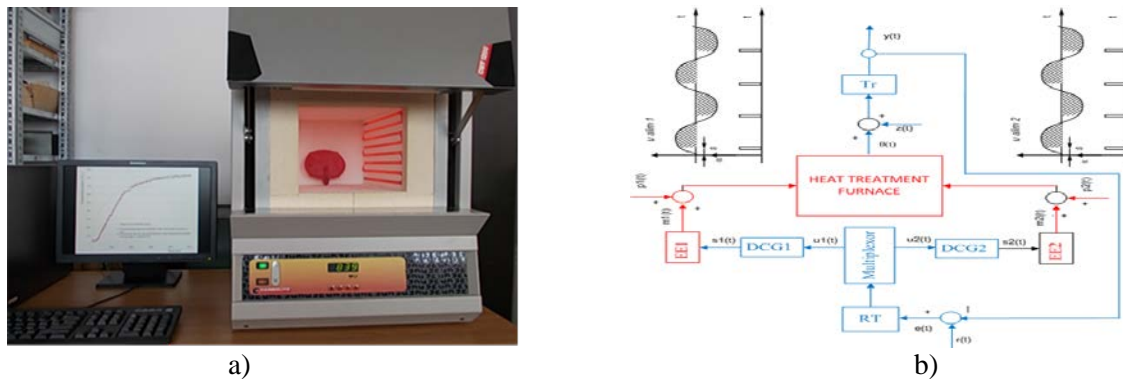
| a) | b) |

Figure 1. The multivariable heat treatment system with thermoregulatory controlled PID
a) heat treatment system   b) block diagram for furnace control

The mathematical model for designing the command system for heat treatment furnace involves the following steps:

- mathematical characterization of the behavior of the controlled heat treatment furnace and acting on its exterior sizes depending on operating mode, setting goals adjustment determined by the type of furnace process management;
- choice of method design involves optimizing parameter values agree, establish criteria for the selection and award regulators and determining optimal control algorithms;
- identification experimental model driven process, identification is performed online in safe working condition without piece inside the furnace, as input data becomes available through measurement;
- simulating the control structure of the heat treatment furnace using the Simulink package;
- test design and analysis of algorithms, possibility of achieving implementation, the optimal choice of equipment that ensures a precise implementation of the algorithm of management;
- mathematical modelling to predict the microstructure and mechanical properties of steel depending on the brand, size and number of semi batch, mechanical properties and quality of the piece prior to heating for optimal heat treatment diagram setting;
- finite element analysis of the evolution in time of the temperature and heat flow of the piece subjected to heat treatment conducted in the furnace with thermostatic controlled PID;
- implementing the heat treatment furnace control structures and tracking simulated time evolution of track parameters;
- validation solution by analysing the performance of the entire control system implemented allows the furnace if necessary redesign or adjustment parameters for the operating agreement.

Thermal treatment processes are modeled according to the control algorithms used, for the PID type control it is often used a one-time deceleration transfer function (f.d.t.) model with dead time and for predictive regulation on one step ARX model [1, 2, 7, 10, 11].

Both models are obtained experimentally by applying test signals to the input element of the furnace temperature probe assembly and by properly processing the output signals.

The transfer function is obtained for the processes described by the models:

$$G_f(s) = \frac{k_f}{(1 + sT_{f1})(1 + sT_{f2})} e^{-sL} \tag{1}$$

The grant procedure is based on simplifying process poles with regulator zeros, resulting in an open-circuit transfer function dependent only on the dead time L.

Knowing that G_d (s) = G_f (s) GR (s), by applying the Haalman method for the process transfer function (1) a PID regulator can be given [5, 6, 8]:

$$\frac{k_f}{(1 + sT_{f1})(1 + sT_{f2})} e^{-sL} k_R \frac{s^2 T_d T_i + s T_i + 1}{s T_i} = \frac{2}{3Ls} e^{-sL} \tag{2}$$

The simplification of process poles immediately leads to finding regulator time constants:

$$T_i = T_{f1} + T_{f2}, T_d = \frac{T_{f1}T_{f2}}{T_{f1} + T_{f2}} \tag{3}$$

and then to the calculation of the proportionality factor with the formula:

$$k_R = \frac{2\left(T_{f_1} + T_{f_2}\right)}{3Lk_f} \tag{4}$$

The mathematical model was obtained by parametric identification using Matlab-Simulink software platform with following diagram (figure 3).
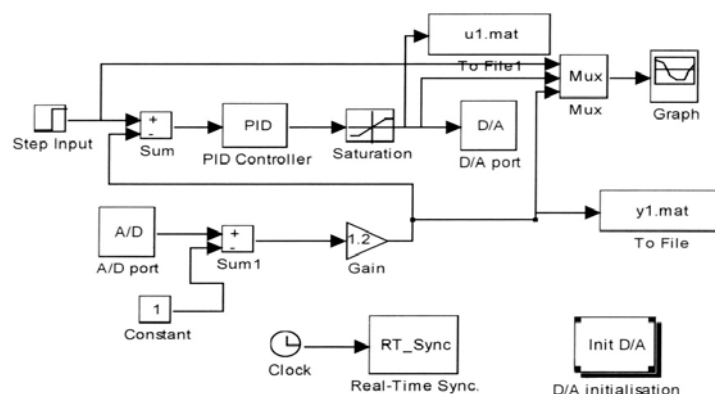

Figure 2. Real-time simulink diagram for implementing a PID regulator [6, 8].

Temperature control in most heat treatment processes is accomplished using PID regulators, considering an estimated off-line of the order I with dead time of form (1).

3. Results and discussions

Experimental validation of the results was made by applying a heat treatment to normalize a turbine blades component of a plasma torch on hydrogen made of heat-treated steel C45-RO1.0503, normalizing heat treatment has the effect of changing their structure and tenacity. The technological parameters were determined with expert software based on mathematical model for predicting mechanical properties and structural piece heat treated. Technological characteristics for normalizing heat treatment: $Ac_1=713,20$ $[^0C]$, $Ac_3=787,24$ $[^0C]$, $Ms=331,72$ $[^0C]$, heating temperature = 841 $[^0C]$, heating time = 5040 [sec], maintaining the temperature = 1048 [sec], cooling conditions air [7, 11, 12].

Figures 3 and 4 shows the experimental results, taken from data acquisition board installed in the electric furnace control system for the treatment of normalization, heating diagram calculated with classical algorithms and the actual temperature of the furnace resulting in following predictive PID control algorithm shown by thermocouples placed in the furnace vault.
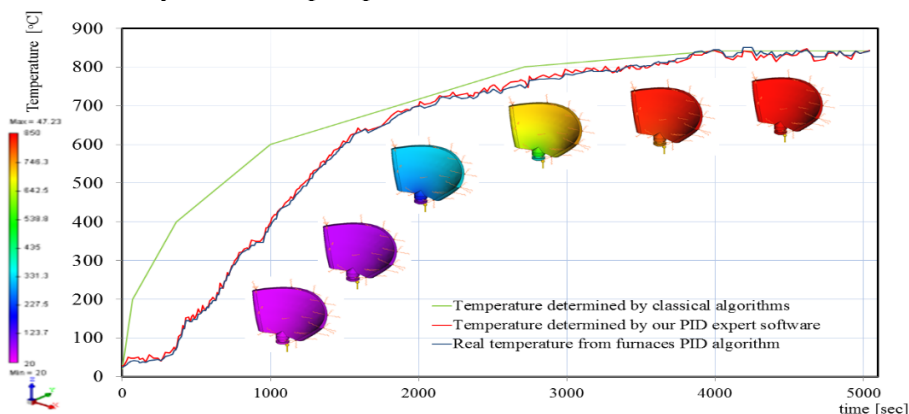

Figure 3. Normalizing heat treatment applied to piece in furnace with PID control system.
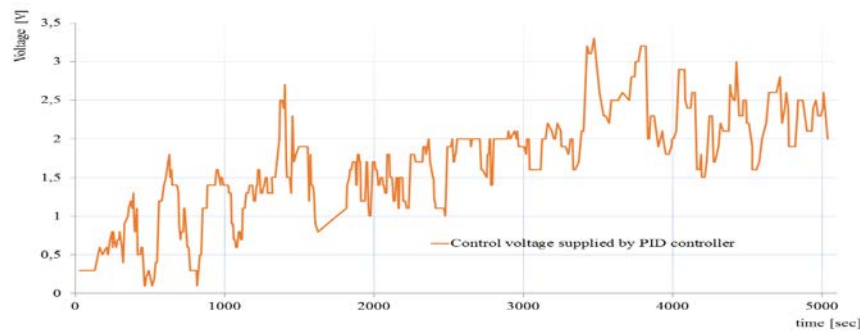
Figure 4. Treatment of normalization - control voltage provided by PID controller

The studies presented below relate to finite element analysis of the evolution in time of the temperature and heat flux normalization piece subjected to heat treatment conducted in the furnace with thermoregulatory controlled PID (figure 5).
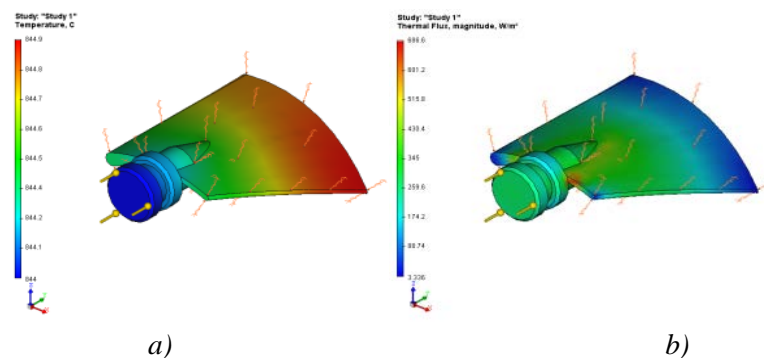

a)   *b)*

Figure 5. Temperature and heat flux magnitude normalization piece in furnace PID system
a) temperature, b) heat flux magnitude

From the results obtained by adjusting the electric furnace where it is found that traditional regulation is respected diagram heat treatment required with an accuracy of $\pm$ 10 ^{0}C acceptable for some types of heat treatment and grades of steel (alloy steel and low alloy) this type of control in turn has an adverse effect on the heating elements resulting in premature wear and a decrease in heating performance. When adjusting the PID controller tuning accuracy is $\pm$ 3 ^{0}C good for most conventional heat treatment diagrams, this setting determines not strain heating elements extending their operating results are influenced by the choice of the operating point and disturbance but is observed to improve performance when using conventional control relay.

In figure 6 are shown images of secondary electrons obtained by electronic microscopy Scanning Electron Microscopy (SEM) Vega Tescan LMH II, working - 46 High using detector type LFD (Large Field Detector), acceleration voltage electron beam used was 30 kV, and working distance was 15 mm.

EDAX (Energy Dispersive X- Ray Analysis) analysis was performed on the sample surface layer to highlight its chemical composition is observed the presence of chemical elements Fe, C, Mn, S, Si and O_2 in different proportions corresponding to the chemical composition of steel C45-RO1.0503.

If the heat treatment classical distribution of chemical elements in the sample material is uneven, pearlite is found in large islands scattered, surrounded by large areas consisting of ferrite.

In samples of heat treated blades in furnace control system based on PID algorithm shows that iron is observed following elemental analysis is found uniformly distributed in the base material as can be seen in the distribution map. Carbon is present in the iron alloy, uniformly distributed, but is observed uniformly dispersed islands alloys thereof chemical compounds with Mn, S and Si.

The manganese is in the form of large islands uniformly dispersed in the mass of base material.

Sulfur is a small scale and appears in different alloys with Fe, Mn, C, uniformly dispersed in the base material. Silicon is insignificant and appears only as an alloying element to the base material.

If the heat treatment temperature sensitive heat treatment furnace realized ordered thermostatic control systems with PID structure material consists of fine pearlite crystalline grains uniformly distributed in the ferrite matrix, the mechanical properties are superior parts have a high resistance to mechanical wear and high toughness.

 Determination of chemical composition by EDAX spectrometry (figure 6) allowed a comparative analysis of the distribution of chemical elements in samples of material palettes microcell reveals the fact that if the heat-treatment furnace control system based on PID algorithm is more uniform dispersion of chemical elements relative to the treated samples heat in microwave classic control system that allows the conversion of a higher percentage of austenite perlite dispersed to obtain uniform fine structure that leads to an improvement of the mechanical properties of the part.
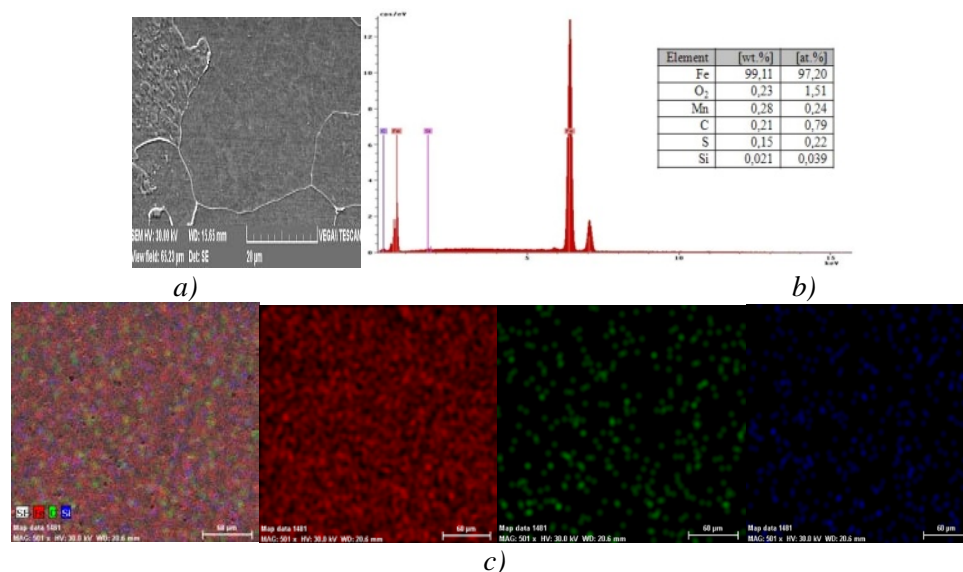

Element	[wt.%]	[at.%]
Fe	99,11	97,20
O₂	0,23	1,51
Mn	0,28	0,24
C	0,21	0,79
S	0,15	0,22
Si	0,021	0,039

a)   *b)*

c)

Figure 6. SEM and EDAX for turbine blades component of a plasma torch made of heat-treated steel C45-RO1.0503 with control system based on PID algorithm
a) SEM image, b) EDAX elemental chemical analysis, c) the distribution map of chemical elements all elements (Fe, C, Si) map, Fe map, C map and Si map

Microstructure blade material heat treated in heat treatment furnace is controlled with conventional systems composed of ferrite single phase crystalline grains which have flat and pearlite grains which are a mixture of two phases and presented in embossed steel microstructure is typical of overheating, identifies separation of the ferrite around the precipitates, the structure is unsuitable from the point of view of mechanical properties.

Material microstructure of heat-treated blade heat treatment furnace with thermostatic controlled temperature sensitive PID consists of ferrite and pearlite evenly distributed, perlite transformation of austenite made islands shaped ferrite embedded in the table, this determines superior mechanical properties. From the analysis of samples by electron microscopy SEM shows that if the heat treatment of pearlite grains are coarse classic uniformly distributed in the ferrite matrix therefore blade material's mechanical properties are reduced, the piece has a good running low, low durability and low mechanical strength. If the heat treatment temperature sensitive heat treatment furnace realized ordered thermostatic control systems with PID structure material consists of fine pearlite crystalline grains uniformly distributed in the ferrite matrix, the mechanical properties are superior parts have a high resistance to mechanical wear and high toughness.

4. Conclusions

The central objective of the research is to design and implement a management system for electric furnaces advanced mathematical modelling management system furnaces for heat-sensitive treatments based on algorithms evolve in order to increase the mechanical properties and structural parts heat treated and reducing the percentage of reboot due to classical technologies. Heat treatment processes can be modeled accurately with transfer functions for elements with stroke-order retarders, PID algorithms are implemented successfully in the control of such equipment but time is detrimental to the setting retarder. The main directions of continuation of the scientific researches are the development of mathematical models for the design and control of electrical heating systems for thermal treatments based on the prediction of mechanical properties and the structure of the workpiece resulting from thermal treatment by the diversification of databases in the field of alloyed steels.

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