PI Control of Laboratory Furnace for Annealing of Amorphous Alloys Cores

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Abstract:
There are presented theoretical and practical aspects of automatic control of resistive furnace for thermal annealing of magnetic cores made of amorphous alloys. Process of annealing requires specific conditions both from the point of view of temperature and its changes. Solutions presented in the paper create possibility for low value of error as well as fast achievement of set value.

Keywords: *PI controller, resistive furnace, temperature control.*

1. Introduction

New soft magnetic materials – amorphous alloys based on iron, nickel and cobalt gives new possibilities for design of inductive components [1], magnetic field sensors [2], magneto-mechatronic sensors [3], and heat transportation devices [4]. However, production of amorphous alloys cores requires precise thermal relaxation (core's annealing) [5]. This process is usually realized in 1 hour in argon protective atmosphere in order to avoid quick corrosion of cores surface. The relaxation improves cores magnetic permeability and reduces its coercive force.

Thermal relaxation in amorphous alloys, if performed correctly, enables fabrication cores with relative permeability magnitude greater than $2 \cdot 10^6$. This makes the amorphous alloys one of the best magnetic materials, with highest magnetic permeability.

This paper describes a control system for resistive furnace for annealing of amorphous alloys cores in the laboratory of Institute of Metrology and Biomedical Engineering, Warsaw University of Technology.

2. The furnace, measurement system and control system equipment

The thermal relaxation process of cores is realized in a small laboratory resistive furnace which mass is approximately 3 kg. The furnace has canal winding, installed in chamotte corpus covered by thermal isolation with mineral wool. Inside the furnace there is a long quartz pipe with 40 mm diameter, which is filled by argon with pressure slightly higher than atmosphere pressure during the relaxation stage. Argon atmosphere protects the core during relaxation process.

The relaxation process begins with heating the furnace to the relaxation temperature. Then, there is inserted capsule with room temperature having inside the annealed core and it is heated in the furnace during required time in the relaxation temperature. The temperature of amorphous alloys cores relaxation is equal to 345ºC and the relaxation time is equal to 60 minutes. When the relaxation is finished the capsule is taken out of the furnace and it is cooled inside the cold part of the quartz pipe. Therefore, also cooling in argon protective atmosphere is performed.

The controlled output signals are the furnace temperature measured by thermocouple type K and then the capsule temperature measured by thermocouple type J. Thermocouples are connected with temperature transducers AR-580 of Apar firm. Temperature measured range is from 0 to 500ºC and transducers output range is voltage from 0 to 10 V. Both sensors have linear characteristics.

The furnace is powered by pulse wide modulation power controller EJ1P50E of Carlo Gavazzi firm. Control output of the controller is voltage from 0 to 10 V and full pulse control period is 3 sec.

The furnace, temperature transducers and power controller are connected with PC computer by data acquisition card NI-USB-6361 of National Instruments firm.

The control of the furnace temperature is realized by computer controller implemented on the connected PC computer. The controller program was prepared using the LabView software and implementing the PI controller.

Block diagram of the laboratory furnace for annealing of amorphous alloys cores with measurement and control system is presented in Fig. 1, and the furnace laboratory stand is shown in Fig. 2, where 1 – capsule with core, 2 – furnace, 3 – quartz pipe, 4 – temperature transducer, 5 – argon inlet, 6 – data acquisition card and 7 – PWM power controller.

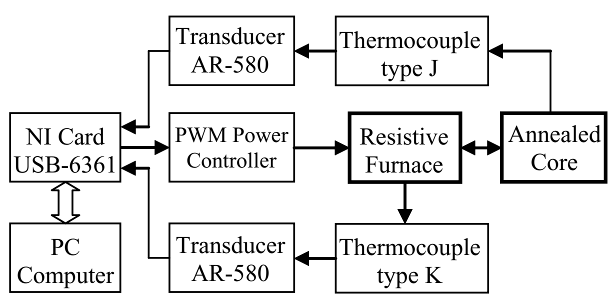

Fig. 1. Block diagram of the installation for annealing of amorphous magnetic cores

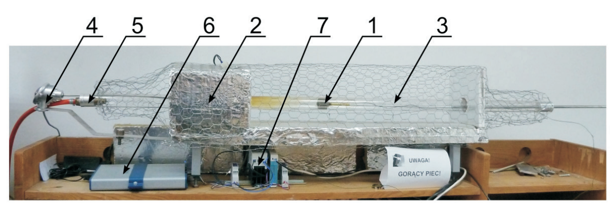

Fig. 2. Laboratory stand of furnace for cores annealing

3. Requirements of the control process

As mentioned before, the controlled process consists of (i) heating stage of the empty furnace and (ii) core relaxation stage in the relaxation temperature. The control input is a voltage of power controller and the output signal is in the first stage temperature inside the quartz pipe and in the second stage the annealed core temperature.

For the furnace heating stage it is only required relatively short heating time and limitation of control input magnitude and change speed because of furnace properties, step response time for the furnace is approximately 3 hours.

Then, for the annealing stage it is required
1. annealing temperature equal to 345ºC,
2. annealing temperature errors should be less than ±5ºC,
3. time of core heating from temperature 320ºC to 345ºC no longer than 15 min,
4. no overshoots in the core heating stage to 345º C.

The third requirement is rather important since usually annealing process starts in temperature 320ºC and if core stay too long in the annealing temperature but less than required annealing temperature its properties are different to the required ones.

4. Identification of control plant

Model of the furnace has been calculated based on step response of the furnace for change of voltage of power controller from 0 to 0.7 V in the form

$$G(s) = \frac{k}{Ts+1} e^{-T_0 s} \qquad (1)$$

where k is model gain, T time constant and T_0 time delay.

In the identification we have found the following values of the parameters

$$k = 500\ [\text{ºC/V}], \quad T = 3450\ [\text{sec}], \quad T_0 = 840\ [\text{sec}]$$

In Fig. 3 there are presented response of the furnace and response of the model. It is easy to see that the calculated model is quite good.

It should be however noted that because relatively big mass of the capsule with core (0.25 kg) with respect to mass of the furnace (3 kg) insertion of the core in room temperature approximately 22ºC into warm furnace with temperature 345ºC really influent temperature of the furnace.

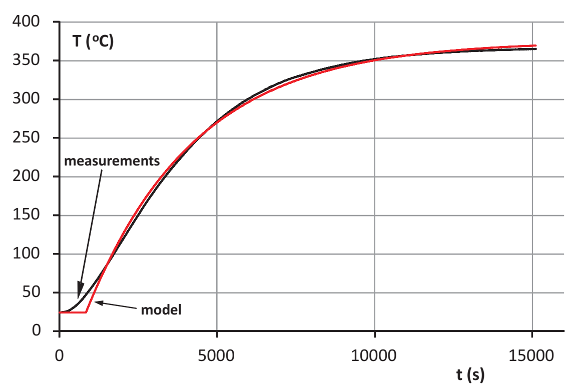

Fig. 3. Furnace step response: measured temperature and model response

5. Control algorithm

Accordingly to the requirements indicated in Section 3, two stages of the process were identified: heating stage and annealing stage. Considering step response time for the furnace (which is approximately 3 hours) two control algorithms were proposed:
1. linear control of the furnace heating stage, and
2. linear control for annealing of the core with nonlinear phase after insertion of capsule with core into the furnace.

In both cases we have used PI linear controller

$$R(s) = k_P \left(1 + \frac{1}{T_I s}\right) \qquad (2)$$

Settings of the controller were chosen based on the calculated model (1) of the furnace. Calculating the settings in such a way that overshooting of the process is equal to zero, $\varkappa = 0$, one obtains [6]

$$k_P = 0.6 \frac{T}{kT_0} = 0.0049, \quad T_I = 0.8T_0 + 0.5T = 2397\ (\text{s})$$

Next, we have modeled control system [Fig. 4] with PI controller and calculated settings.

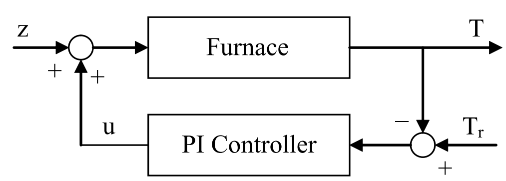

Fig. 4. Block diagram of furnace temperature control system, T – furnace temperature, u – control input voltage, Tr – reference temperature, z – disturbance

Unfortunately, in the contradiction to setting base we have obtained small overshooting for step change reference temperature *Tr*, Fig. 5. However, overshooting for the disturbance which modeled insertion of capsule with core into the furnace was quite small. Therefore, we have decided to apply for control of the furnace the PI controller with calculated settings.

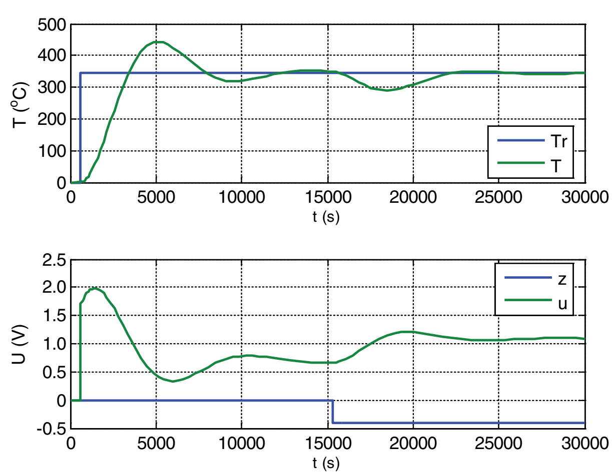

Fig. 5. Furnace model control response with PI controller

PI controller has been used for control of the furnace and core temperature for (i) shortening of the furnace heating and (ii) control of the furnace heating after insertion of the capsule with core and (iii) control of the core temperature in the annealing process.

The nonlinear phase of control algorithm after insertion of the capsule with core into furnace was as follows:

1. before insertion of the capsule with core automatic control was changed into manual control with constant control input voltage,
2. after insertion of the capsule into furnace there was added one triangle control input impulse with magnitude 0.6 V and time 600 sec (10 min) to constant control input; the triangle input was designed based on practical experiments and in the control process it was automatically generated by the controller software LabView,
3. after the triangle impulse the control was changed from manual mode into automatic mode with PI controller with calculated settings but also with annealing core temperature as the controlled output signal.

In the control we do not use PID controller because in the control system we have quick measurement disturbances which generate quite big control input changes calculated by PID controller since derivative action D of PID controller implemented in the software has big dynamic derivative gain.

6. Experimental results

Designed control system has been applied for control of the furnace for annealing of cores in the Institute of Metrology and Biomedical Engineering of Warsaw University Technology. In Fig. 6 there are presented temperature of the furnace, temperature of the core and control input voltage obtained by PI controller and triangle impulse in the insertion of capsule with core into the furnace. Controller settings were as we calculated before.

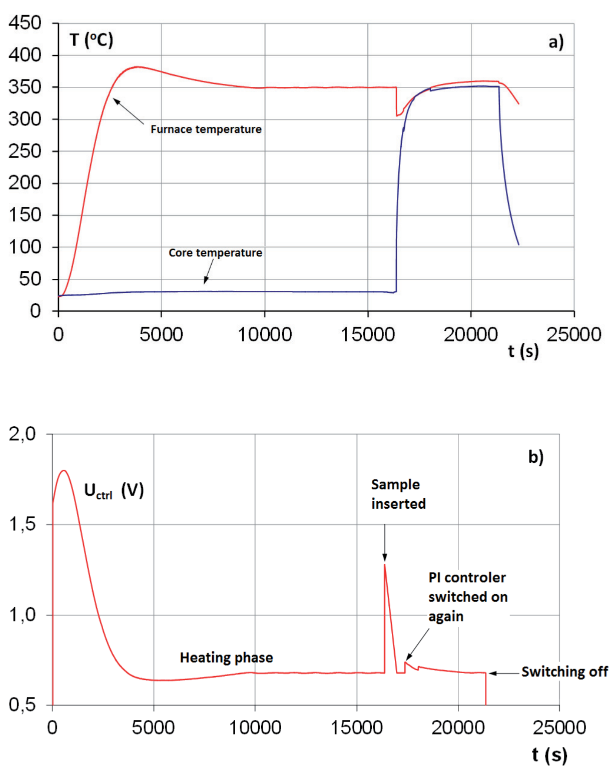

Fig. 6. Heating and annealing process with PI controller and triangle impulse control input: a) furnace and core temperature b) control input voltage

It is interesting to note that the core temperature is lower than the furnace temperature in the annealing process.

In the annealing process we have obtained maximal core temperature error 2ºC. The core heating time from 320ºC to 345ºC was 12 min, less than it was maximal allowed value 15 min and annealing time in temperature equal to 345ºC was 60 min.

7. Concluding remarks

Proposed PI control system allows conducting annealing process according to requirements – quickly and in the required temperature without overshooting and without presence of operator, operator action was only required for short time in the moment of insertion of capsule with core into furnace.

In laboratory conditions the proposed control system has shorten the annealing time about 70% comparing with annealing process in the manual mode and also improved quality of the annealing because less annealing temperature errors. Moreover, the annealing was automatic and no operator assistance was required.

Presently we work on improving the automatic annealing process and shortening assistance of the operator.

The research on magnetic cores was founded in 2010-2012 as a research project.

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