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Thermocouple Dynamic Errors Correction for Instantaneous Temperature Measurements in Induction Heating

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Abstract- The most commonly used thermometer to measure high temperatures in metallurgy is the thermocouple, but because of its long response time it can be used mainly for measuring time-averaged temperatures. Research on steel wire patenting using inductive heating required instantaneous temperature values. Pyrometers or thermographic cameras could be used, however they are generally expensive, and temperature measurements are not always reliable due to differing emissivities. In described case expensive infrared thermometers could be replaced by cheap thermocouple provided that dynamic errors were corrected. Correction algorithm would not increase the total cost of the measuring system as no additional hardware is required. Correction algorithm was implemented in LabVIEW. The time constant was determined experimentally. Experiments were carried out to examine improvement in response time of thermocouple with correction algorithm.
Keywords: thermocouple dynamic errors, correction algorithm, steel wire patenting, inductive heating.

I. Introduction

Problem presented is a part of research on steel wire patenting using inductive heating. Patenting is a process of isothermal hardening which is performed in order to obtain specific mechanical properties of wire such as tensile strength, torsion and the ability to be drawn. At a glance, the process involves austenitizing at high temperature between 870 °C and 920 °C and quenching at 450-550 °C [1]. Wires are usually heated in continuous furnaces heated with gas or mazout, and then cooled in lead bath. There is however little information on the properties of wire patented using electrical inductive heating. Induction heating is energy efficient, productive, precise, clean and easily controllable. Constructions of induction heating devices are safe for operators and environment. Therefore the use of induction heating in the process of wire patenting would be beneficial both in terms of wire properties as it allows precise controlling of heating parameters and because of the ecological purity of the process. The test stand was built to study the influence of inductor current frequency and type of inductor on the heating efficiency, the speed of temperature rising and the temperature field distribution along the heated wire.

The production efficiency requires high heating rate. There are heated wires of small diameter (2.2 - 3.5 mm), which requires the research on the shaping of the magnetic field, which would allow heating of load with such a small diameter within required short time. The production effective heating time is about 3 s. With such a short heating time, an important factor in the research are the dynamic properties of the temperature sensor.

Most often in the metallurgy for measurements of temperatures of specified order there are used thermocouples for contact measurements and pyrometers for non-contact ones.

Pyrometer gives fast response, but as non-contact measurement it is related with the possibility of large errors. The main error source is improperly defined emissivity of measured object. In practice emissivity is determined experimentally by measuring the temperature accurately by thermocouple. However, even then the element surface may be slightly inhomogeneous, and hence the emissivity can vary greatly. Another source of the pyrometer measurement errors in the case described, is a small diameter of the wire, which is connected with difficulties in obtaining the same measurement conditions - slight displacement of the measuring spot is associated with a large change in the angle between pyrometer and measured surface.

Thermocouple measurement under the conditions described is associated with too long time constant, which can be larger than the total heating time. In the first approach it completely disqualifies this method of measurement in the presented case. On the other hand, thermocouple measurement is very cheap and accurate in static conditions. It was therefore decided to check whether good enough results can be achieved by implementing correction algorithm into measuring chain. Software dynamic correction algorithm was used and its efficacy examined.

II. Dynamic error correction algorithm

For the experiments in the test stand unshielded K-type thermocouple was used. Such temperature sensor is a first-order system and is governed by the first-order ordinary differential equation

$$\tau \frac{dT_y(t)}{dt} + T_y(t) = T_x(t), \tag{1}$$

where $T_y(t)$ is the response of the system (the output, temperature indicated by thermocouple) to forcing function $T_x(t)$ (the input, temperature of patented wire), τ is the time constant for the system.
The time constant τ depends in fact not only on the properties of thermocouple itself (for example dimensions and material constants of sheathed thermocouple), but also on properties of conditioning circuit, especially commonly used low-pass filter.

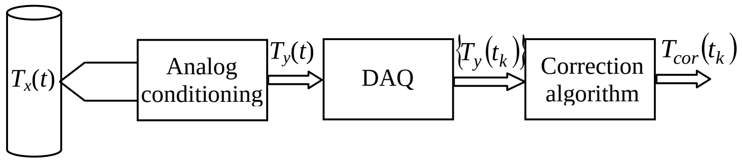

Figure 1. Thermocouple measuring chain

Figure 1 presents the considered thermocouple measuring chain. It contains three kinds of processing: analog described by (1), analog-to-digital performed in DAQ board that consists of sampling and quantization and finally digital correction algorithm. It is assumed that measured quantity $T_x(t)$ varies in time which causes dynamic errors arising in analog part of the chain. These errors can be decreased using a correction algorithm. The rests of not corrected dynamic errors influence the accuracy of results at the output of the measuring chain, therefore they should be taken into account while final uncertainty is estimated [2][7-11].
Results $T_{\mathrm{cor}}(t_k)$ at the output are estimates of instantaneous values of the input quantity $T_x(t)$ at the moments $t_k = kT_d$, where T_d is the sampling period, k is the number of the sampling moment, $k = 0,1,\ldots$ The results are obtained on the basis of the quantized samples sequence $\{\tilde{T}_y(t_k)\}$ of the analog part output value $T_y(t)$. These samples are processed by a dynamic correction algorithm which is built on the basis of the dynamic properties model of the analog part.
For the first-order system dynamic correction algorithm is [2][11]

$$T_{\mathrm{cor}}(t_k) = \frac{1}{\psi_1}\left[\tilde{T}_y(t_{k+1}) - \varphi_{11}\tilde{T}_y(t_k)\right], \tag{2}$$

where

$$\varphi_{11} = e^{-\frac{T_d}{\tau}}, \ \psi_1 = 1 - e^{-\frac{T_d}{\tau}}. \tag{3}$$

III. Description of the test stand

In order to check the properties of measuring chain with described correction algorithm the test stand was prepared as presented in figure 2. Temperature was measured by unshielded K-type thermocouple, connected to IPAQ-L converter [12] which converts thermocouple voltage to 4-20mA current. The current was measured by data acquisition card NI USB 6009 and then measured signal was processed by program implemented in LabVIEW [13].
A step change in temperature to examine the dynamic response of a thermocouple was obtained by moving it from a room temperature to melted tin.
Second channel of DAQ board was used to determine exact moment of thermocouple dipping.
Algorithm described by (2) and (3) was implemented in LabVIEW.

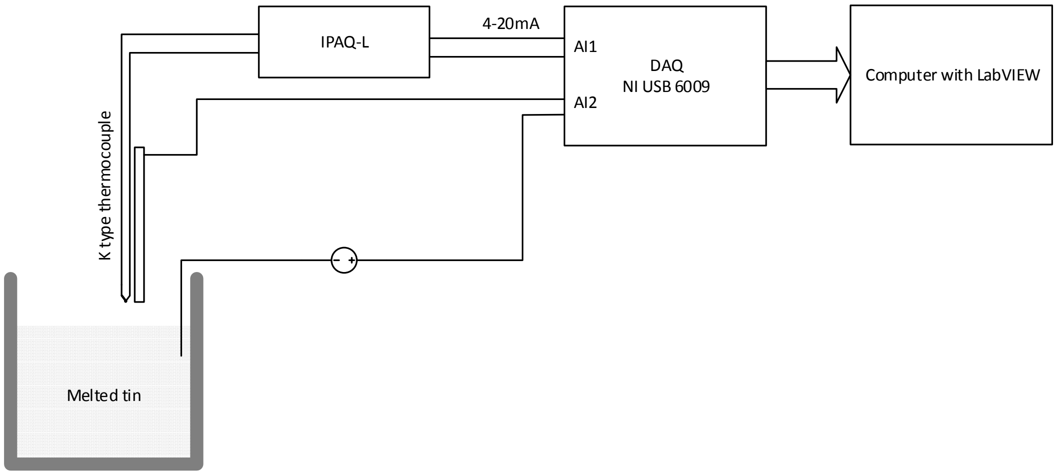

Figure 2. The test stand to check the properties of measuring chain

IV. Identification of the dynamic properties of the object

Dynamic parameters of the measuring chain were not analyzed on the basis of analytical equations. It was about the maximum simplification of the procedure for practical applications. The whole part of the measuring chain up to the correction algorithm was interpreted as a black box and its dynamic parameters were determined experimentally. Step response was easiest to implement in practice. The experiment was carried out in such way that thermocouple was immersed in the molten tin. The ambient temperature changed rapidly from room temperature to the molten tin temperature. The moment of immersion, which is the moment of temperature step change, was determined using the second measurement channel of DAQ board. Exemplary temperature curve is shown in figure 3.

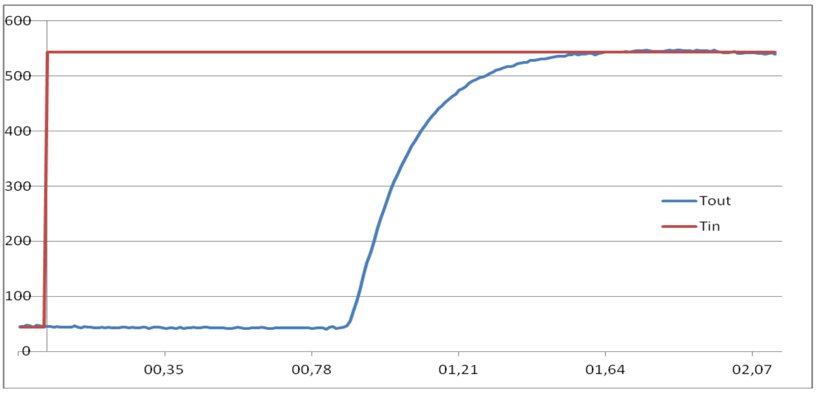

Figure 3. Thermocouple measuring chain step response

Basing on the waveforms measured it was assumed that the measuring chain can be modeled by two transducers: converter generating delay T_0, and the dynamic converter. For unshielded thermocouple it is assumed the first order dynamic model. Other measuring chain elements have also dynamic properties, but it was assumed, that first order model is sufficient for the whole chain.
Basing on experimental results time delay is T_0=0,88s.
The time constant of first order dynamic converter was determined using approximate method with assumption, that the converter is the ideal one. Time constant was determined using dependence

$$\tau = \frac{\tau_{0,5}}{\ln 2}, \tag{4}$$

where τ is the time constant, $\tau_{0,5}$ is the moment in time when thermocouple indicates the half of real temperature value.
Experiments allowed to measure $\tau_{0,5}$ = 0,12s, therefore τ = 0,17s.

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V. Random errors

Dynamic error correction algorithms amplify random errors. This amplification is dependent on sampling period T_d. The smaller T_d, the bigger random errors amplification. On the other hand T_d cannot be too long as it would decrease measurement resolution in time domain. As it was described in introduction the aim of measurements is the heating time to achieve the desired temperature.

Tables 1, 2 and 3 show the influence of measuring chain parameters on random errors amplification.

Noise in directly obtained results were too large and correction algorithm amplified it to an unacceptable level (row 1 and 5 in table 1). So noise filtering is necessary. But most filters makes dynamics worse.

In first step capabilities of DAQ device were used. Its maximum sampling rate for two channels is 24 kS/s. It is far enough for performed temperature measurements, so the temperature was measured with frequency f_{DAQ} which was N times assumed frequency for correction algorithm f_p

$$f_p = \frac{1}{T_p} = \frac{f_{DAQ}}{N} \; . \tag{5}$$

From subsequent portions of N samples arithmetic mean was calculated. In this way, results were obtained with the period of T_p and partially eliminated random errors (filter 2 in figure 5). Such filter does not change dynamic properties of measuring chain, but it requires faster sampling. Results in table 1 and 2 show that efficacy of such filtering depends of course on N, but also on T_p. With growing f_p more and more random errors pass through the filter as they have lower frequencies then f_p.

For higher f_p typical smoothing filter is necessary. There was used moving average with rectangular window (filter 1 in figure 4). Such filter changes of course dynamic properties of measuring chain, therefore new identification of dynamic properties of measuring chain was performed, as described in chapter IV.

Time constant of measuring chain with digital smoothing filter was determined as τ = 0,36s.

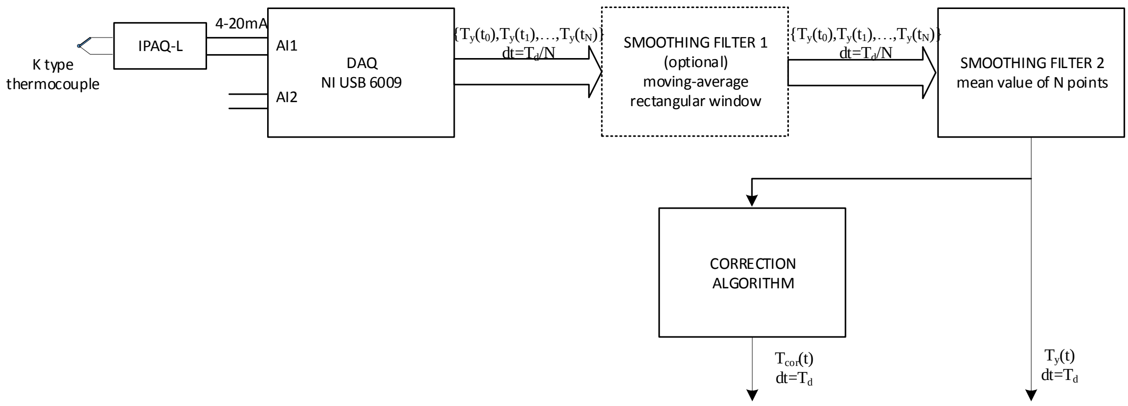

Figure 4. Thermocouple measuring chain with digital smoothing filters

Table 1 Noise amplification by correction algorithm.
Influence of N on noise standard deviation.
Only filter 2 used, filter 1 inactive. N=1 means that filter 1 is also inactive.
σ_{Ty}-noise standard deviation on input of correction algorithm
σ_{Tcor} -noise standard deviation on output of correction algorithm

No	$f_{DAQ}=N/T_p$	N	T_p	σ_{Ty}	σ_{Tcor}
	Hz		s	K	K
1	10	1	0,1	0,97	2,36
2	100	10	0,1	0,32	0,76
3	1000	100	0,1	0,10	0,24
4	10000	1000	0,1	0,02	0,04
5	100	1	0,01	0,97	23,98
6	1000	10	0,01	0,36	8,43
7	10000	100	0,01	0,07	2,18

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Table 2 Noise amplification by correction algorithm.
Influence of N and T_p on noise standard deviation.
Only filter 2 used, filter 1 inactive.
σ_{Ty}-noise standard deviation on input of correction algorithm
σ_{Tcor} -noise standard deviation on output of correction algorithm

No	$f_{DAQ}=N/T_p$	N	T_p	σ_{Ty}	σ_{Tcor}
	Hz		s	K	K
1	10000	100	0,01	0,17	2,51
2	10000	200	0,02	0,11	0,43
3	10000	300	0,03	0,08	0,36
4	10000	500	0,05	0,14	0,20
5	10000	750	0,075	0,16	0,18
6	10000	1000	0,1	0,02	0,04

Table 3 Noise amplification by correction algorithm.
Influence of N on noise standard deviation.
Both filter 1 and filter 2 used.
σ_{Ty}-noise standard deviation on input of correction algorithm
σ_{Tcor} -noise standard deviation on output of correction algorithm

No	$f_{DAQ}=N/T_p$	N	T_p	σ_{Ty}	σ_{Tcor}
	Hz		s	K	K
1	100	1	0,01	0,08	0,10
2	1000	10	0,01	0,12	0,21
3	10000	100	0,01	0,11	0,25
4	24000	240	0,01	0,01	0,36
5	10	1	0,1	0,04	0,04
6	100	10	0,1	0,07	0,07
7	1000	100	0,1	0,16	0,18
8	10000	1000	0,1	0,07	0,09
9	24000	2400	0,1	0,04	0,05

VI. Performance of measuring chain with correction algorithm.

Dynamic parameters were identified and noise reduced, so performance of the whole measuring chain was tested. Figures 5 and 6 present the system response to unitary jump. T_{cor} is a temperature calculated by dynamic error correction algorithm. $T_{cor\text{-}del}$ is temperature T_{cor} shifted in time to correct delay T_0. Performance of system was tested for different combinations of T_p and filtration – exemplary graph is in figure 7.

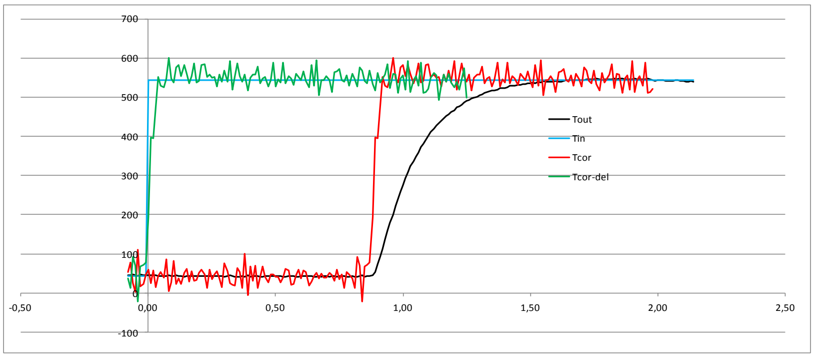

Figure 5. Graph of signals before and after correction; T_d=0,01s, no noise filter

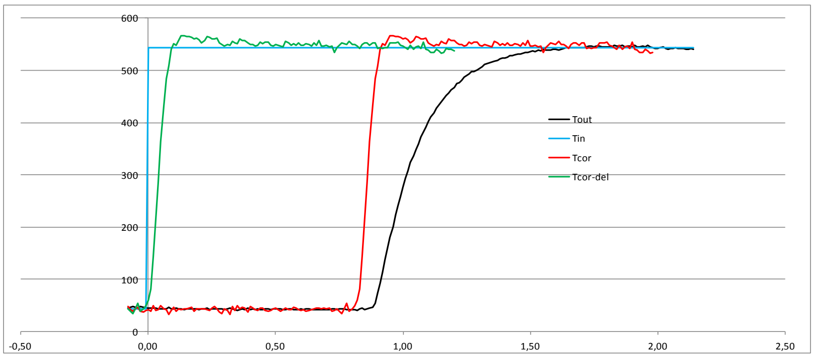

Figure 6. Graph of signals before and after correction; T_d=0,06s, no noise filter

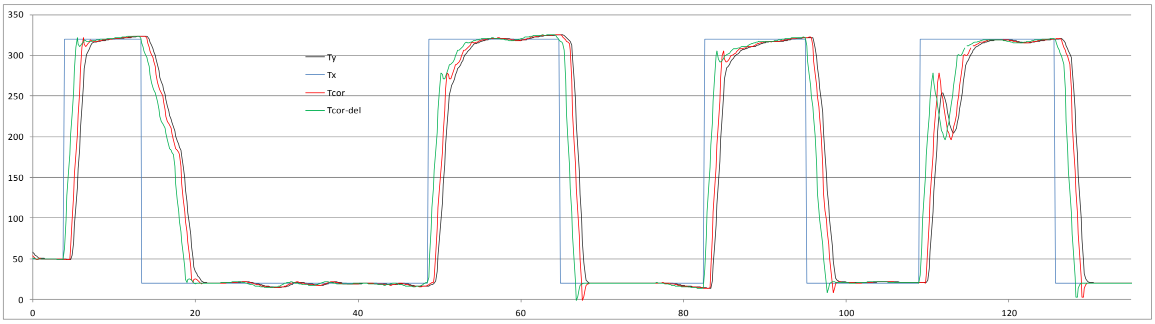

Figure 7. Graph of signals before and after correction; T_d=0,16s, smoothing filter I and II

Finally system was used to determine the time of induction heating of thin rods to the desired temperature, as mentioned in the introduction. Exemplary heating curve is shown in Figure 8. In this particular case, a small diameter rod resulted in a small magnetic coupling and heating was relatively slow.

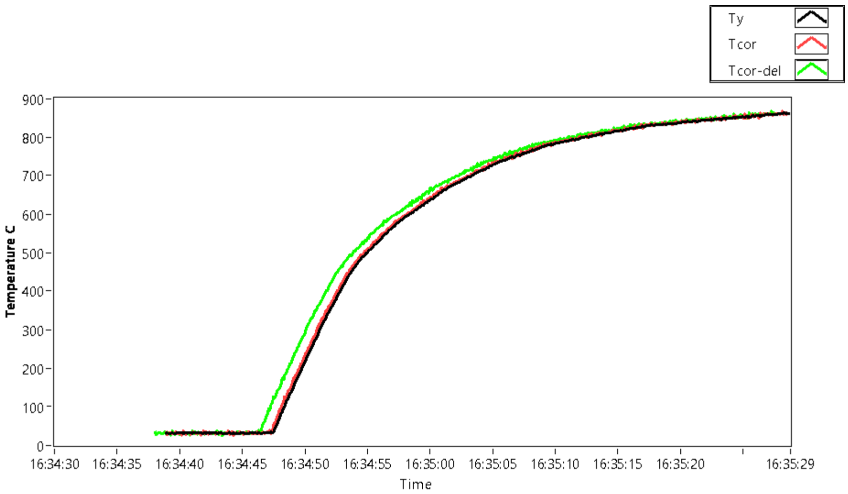

Figure 8. Heating curve of thin rods with induction heater, rod diameter 2,2mm, power *P*=7,3 kW, *f*=61,0 kHz; T_d=0,1s, no noise filter.

VII. Conclusions

The most commonly used thermometer to measure high temperatures in metallurgy is the thermocouple because of its low cost and wide experience in its application. But because of its long response time it can be used mainly for measuring time-averaged temperatures. When instantaneous temperature is needed because transient phenomenon is to be observed, other thermometers can be applied such as pyrometers or thermographic camera. However, they are generally expensive, temperature measurements are hindered by differing emissivities and reflections from other surfaces so thermography measurements are not as accurate as contact methods. In many

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cases expensive infrared thermometers could be replaced by cheap thermocouple if its dynamic properties were corrected. Correction algorithm would not increase much the total cost of the measuring system as no additional hardware is required.

Results presented in the paper show that because of the delay T_0 measuring chain with correction can be used for research, but harder for controlling. However, despite imperfections, it makes possible such measurements that are impossible to achieve another way. Presented research of induction heating of steel wires in the patenting process can be used as an example. As may be seen in Figure 9 it is not possible to measure the temperature inside the inductor with the pyrometer.

Dynamic error correction algorithms amplify random errors, there may therefore be necessary the filtering and the optimum between noise and dynamic properties must be found. This is especially important for measurements during induction heating, which itself adds noise to thermocouple measurements [3][4].

Influence of the algorithm to errors and measurement uncertainty can be also tested through simulations [5][6], making it much easier to carry out experiments.

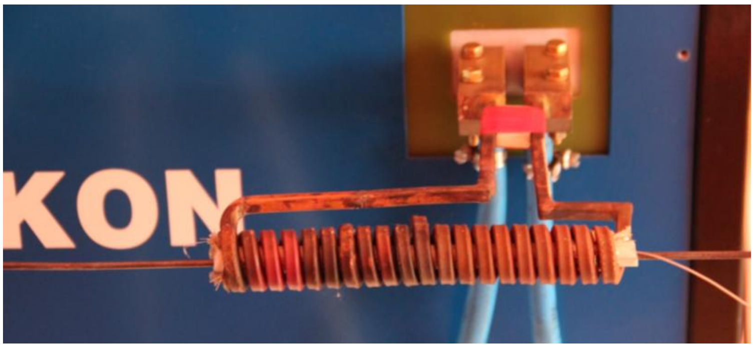

Figure 9. Exemplary inductor used in research of induction heating of steel wires in the patenting process. It is possible to measure the temperature inside the inductor with thermocouple, not with pyrometer

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