TEMPERATURE MEASUREMENT WITH THERMOCOUPLE PROBES

Balonová K., Vajsábel M., Kopunec T., Rosolowska R., Barbolyas B.

Institute of automation, measurement and applied informatics, Faculty of Mechanical Engineering,

Slovak University of Technology in Bratislava, Námestie slobody 17, 812 31 Bratislava 1

Abstract

To obtain information about the current temperature in the ongoing technological process the thermocouples are often used in technical practice. Thermocouple is a type of an electric thermometer that utilizes the Seebecks phenomenon. He says that the temperature difference, between the ends of two by the ends connected conductors, causes the rise of a thermoelectric voltage at these wires.

The MATLAB & SIMULINK software system is widespread used in currently academic and engineering practice, due to its extensive possibilities in the field of modeling, control, data acquisition and analysis of the measured signals.

Article is presenting the method for temperature measurement of a casting technological process. Measurement was carried out on the casting/mold interface by using eleven thermocouples probes. An introduction describes the basic operation principle of a thermocouple. Furthermore it's describes a method for recording and visualization of measured data by using of MATLAB additional module SIMULINK. Shows the temperature profile measured at the casting/mold interface, by casting in the mold cavity.

1 Introduction

Sensors are an essential element of all technical means for measuring and collecting information from control systems. They are key parts, which determine the properties and activities of the entire system. Sensitive part of the sensor is an element, which is affected by a measured variable of the external environment. This causes a generating of physical, chemical and mechanical or fluid measureable change on sensor.

The measurement is linked to testing of each technological or production process necessarily. The thermocouples are widely used for temperature measurement in technical practice. Thermocouple consists of two conductive metal wires of different chemical composition, connected at each end to a closed circuit. Sensitive part of thermocouple sensor is the point of common connection of two metal wires. When sensitive part of sensor is heated, the thermoelectric voltage is generated in closed circuit, figure 1. This phenomenon was discovered by Thomas Seebeck in 1821. This article is aim to design of measurement experiment by using thermocouple probes and software MATLAB & Simulink. Software MATLAB & Simulink allows to users make various corrections before itself measurement, this property is crucial for reduce of overall uncertainty of the whole measurement process [2].

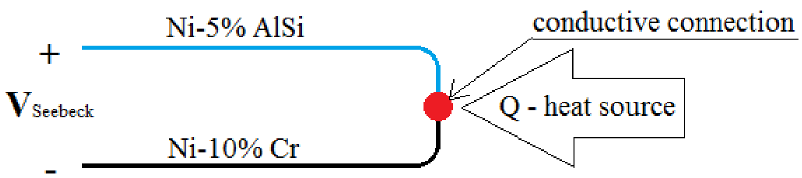

Figure 1: Seebecks voltage generating scheme [1].

Thermoelectric voltage dependence on temperature is non-linear, but for a small interval can be linearized and expressed by equation (1). For commonly used thermocouples, such as J, K, T, R and S are known tables of functional dependences of temperature and thermoelectric voltage. Measured temperature is accurately determined by the polynomial equation (2) and tabulated values of a_i coefficient [1].

$$U_{te} = \alpha \cdot \Delta T \quad (1)$$

$$\mathrm{t} = \sum_{\mathrm{i=0}}^{\mathrm{n}} a_i U_{te}^{i} \quad (2)$$

where:

U_{te} $[V]$ - thermoelectric voltage generated by a thermocouple,

α - proportionality constant (Seebecks coefficient - value is changed with a temperature),

ΔT $[^\circ C]$ - the temperature difference at both ends of the circuit,

t $[^\circ C]$ - unknown temperature,

a_i - coefficient derived for the specified type of thermocouple,

n - polynomial degree.

Metal wires for thermocouple was choiced in regard to specific requirements for measurement. These requirements are sensitivity, linear dependence of voltage to temperature, resistance to corrosion and mechanical damage and resistance to high temperature. Another requirement for thermocouples is perfect metal joint. Very significant is also a temporal stability of material by high temperatures. Some dependencies like as resistance to corrosion and chemical effects are usually normalized for specified temperature range. It have to take into account these parasitic effects by evaluating of measured data:

- error of the measuring device,
- errors caused by temperature,
- thermocouple material contractions.

Essential effects measurement by thermocouples are these:

- imperfect contact or poor heat conduction of thermocouple (immersion is insufficient),
- temperature changes caused by time and spatial distribution of temperature ,
- time and spatial inhomogeneity of bath,
- temperature change in comparative connection,
- parasitic thermoelectric voltage by using of extension or compensating cable,
- cable or multipositon switch of sensing zones,
- electromagnetic interference,
- mechanic tension and deformation,
- inhomogeneity,
- oxidization,
- effects of impurities of alloys,
- resistance of insulation.

These sensors are linked with other special, extensions and compensation cables usually. This is necessary in order to avoid of parasitic voltage at the indexed end points, which can effect required signal. Indexed end point is often a terminal block, which is placed near to evaluation unit. Other connection can be realized by metallic (cooper) cable, alternatively copper connectors.

2 Technical devices used by measurement

Testing was done on experimental foundry mold, which is located at Institute of Automation, Measurement and Applied informatics. Foundry mold is cross shaped, figure 2. Basic dimensions of mold are 450x105x550 mm. For data acquisition was used measurement card Advantech AD622 and Humusoft PCI-1710. In body of mold are evenly placed thermocouples type K from OMEGA, figure 3. Thermocouple probes was used for temperature measurement by casting into the mold cavity at mold / cast interface, temperature of liquid cast and cooling itself namely. Thermocouples are placed at bottom part of foundry mold, it is a best contact place with a melt. Measured connection to obtain information about actual information of melt was realized via thermocouple probe casing. Temperature of liquid cast was 650°C.

In the figure 2 is shown a scheme of thermocouple layout, along with other active elements of foundry mold. To secure the position of the mold cover was used screws, placed in top part of mold. Thermocouples used for temperature measurement 3 is shown in the figure 3. It is a standard thermoelectric sensor by Omega company.

Material used for casting is aluminum alloy Al-Si7. For melting of Al-Si7 was used ceramic induction furnace Rohde. This furnace has satisfactory controllable progress curves of temperature. Temperature for melting aluminum was set on 750°C.

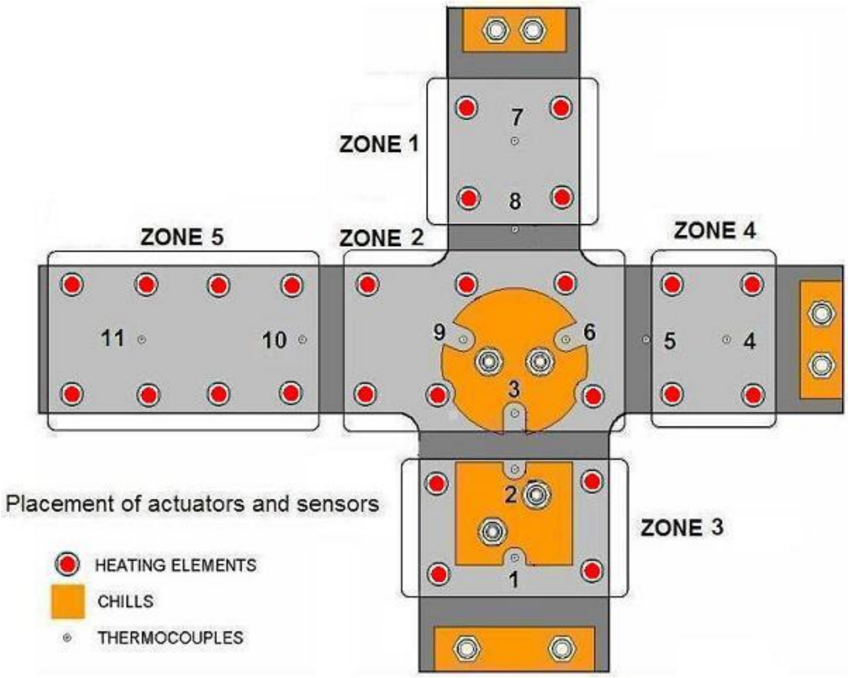

Figure 2: Thermocouples sensing elements, cooling and heating elements located on body of foundry mold [3].

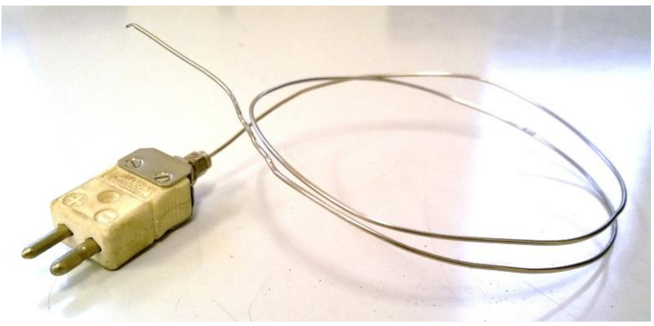

Figure 3: Thermocouple type K, Omega mold [9].

3 Evaluation of the measurement

Measuring was realized in laboratory conditions of Institute of Automation and Measurement. Aluminum alloy was melted in furnace at the first phase of an measured experiment. Melting itself and getting to temperature 750°C took about 5 hours. After achieved desired temperature was started signal acquisition from thermocouple probes installed on foundry mold. Measured was a voltage signal in principle. Transformation to temperature signal was realized by using Simulink scheme shown in the figure 5.

The second phase of an experiment is a filling the cavity of mold. It started after 220 seconds after running up signal acquisition. Melted alloy was given into mold trough an chimney of mold, figure 4. Filling of mold itself took about 30 seconds. Cooling of melted alloy is a fast process in environment with an ambient temperature, which was about 23°C, so the filling have to be fast and precise. Mold cavity was filled up three times in row in one measurement period.

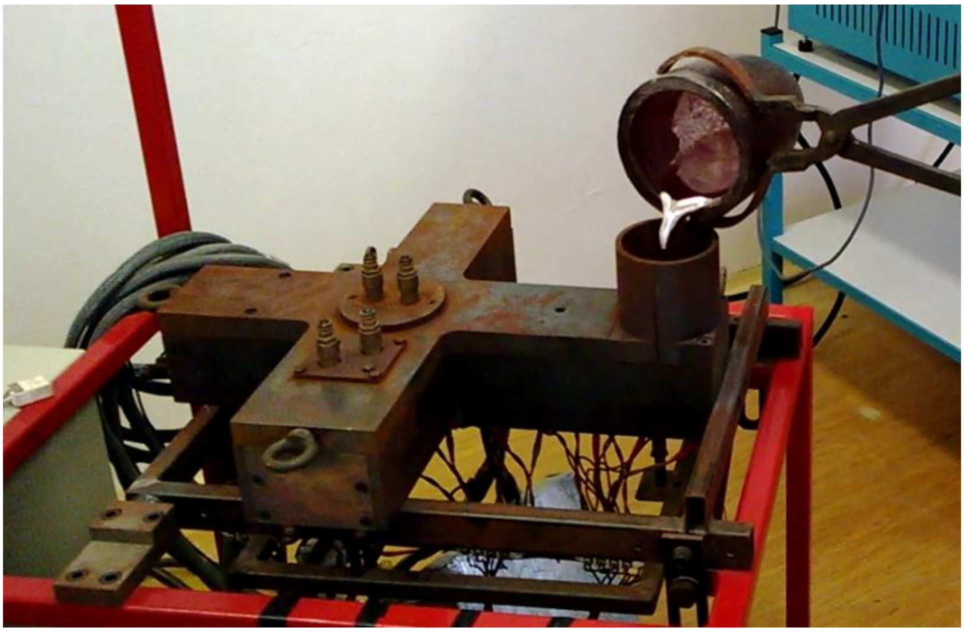

Figure 4: Filling the cavity of foundry mold.

Output temperature signal progress is shown on figure 7. Measured temperature progress is given by matrix of discrete values of temperature in time with sampling time 5 seconds. Output of thermocouples is measureable voltage signal as has been said, so transformation to values of temperature is secured by designed multiplying polynomial blocks in Simulink. It is a way to conversion measured voltage values in discrete time steps into temperature.

Graphical user interface of Simulink was used for creating scheme of measurement, resp. process data acquisition, figure 5. This scheme consists of four essential blocks. Block of measurement card Advantech PCI-1710 for receiving data into MATLAB. There are scope blocks for displaying course of measured signal. Block of subsystem „Thermocouples - In 1 out1“, which contains a set of 11 function blocks of transformation inputting voltage signals into temperature signal, figure 6. These blocks contains polynomial function (8), which is crucial for precise measurement of temperature by using of thermocouples. On mold 11 thermocouples is installed, so in scheme is 11 function blocks. Polynomial function is the sixth order, which is specified by manufacturer. The possibility of specification of polynomial function and appropriate constant directly in measurement scheme is a great advantage of MATLAB & Simulink. All values of measured variable are stored at Workspace of MATLAB and entire content of Workspace can be store in binary file with .mat extension.

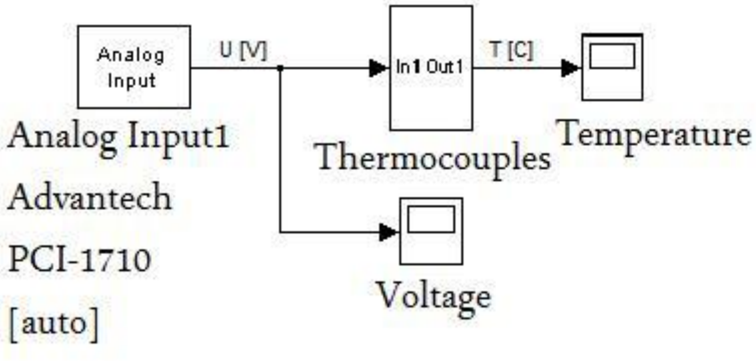

Figure 5: Temperature measurement scheme in Simulink.

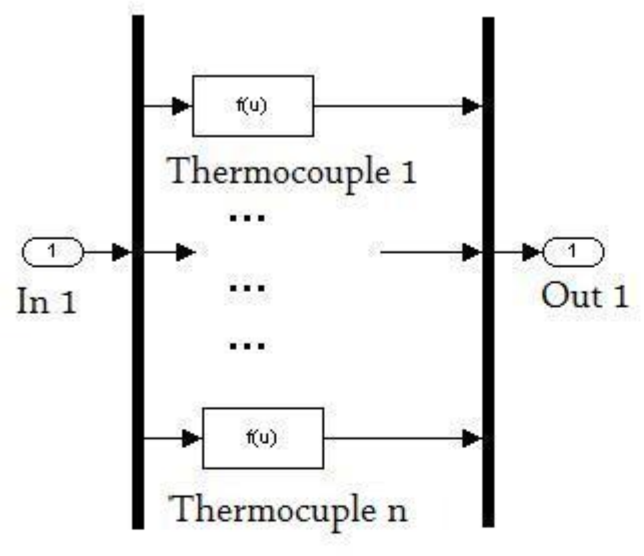

Figure 6: Scheme of subsystem - Thermocouples.

More measured variables are interesting in commonly praxis often. Relation between these variables can be expressed like equation (3). In this case it is function:

$$t = b_0 p^0 + \cdots + \mathrm{b}_n p^n \tag{3}$$

where:

$t\,[^\circ\mathrm{C}]$ - temperature,

$b_{0\ldots n}$ - parameters of the polynomial,

$p_{0\ldots n}$ - degree polynomial.

The overall uncertainty of output variable can be expressed by equation (4).

$$\boldsymbol{U} = \left(\boldsymbol{A}^T \boldsymbol{U}^{-1}{}_{(\Delta)} \boldsymbol{A}\right)^{-1} \boldsymbol{A}^T \boldsymbol{U}^{-1}{}_{(\Delta)} \boldsymbol{b} \tag{4}$$

where:

$\boldsymbol{U}$ - the resulting uncertainty,

$\boldsymbol{U}_{(\Delta)}$ - covariance matrix,

$\boldsymbol{A}$ - matrix of experiment plan,

$\boldsymbol{b}$ - vector of polynomial parameters.

Covariance matrix is specified as (5):

$$\boldsymbol{U}_{(\Delta)} = \begin{pmatrix} u^2(x_1) & u(x_1,x_2) & \dots & u(x_1,x_m) \\ u(x_2,x_1) & u^2(x_2) & \dots & u(x_2,x_m) \\ \vdots & \vdots & \ddots & \vdots \\ u(x_m,x_1) & u(x_m,x_2) & \dots & u^2(x_m) \end{pmatrix} \tag{5}$$

where:

$\boldsymbol{U}_{(\Delta)}$ - covariance matrix,

$u(x_{1...m})$ - standard uncertainty of estimation of input variable,

$u(x_i, x_j)$ - covariance between the estimates.

Matrix of sensitivity coefficients (6) can be created by partial derivative of model (3), according to each of variables and look like this:

$$\boldsymbol{A} = \begin{pmatrix} 1 & p_1 & p_1^2 & \cdots & p_1^n \\ 1 & p_2 & p_2^2 & \dots & p_2^n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & p_m & p_m^2 & \dots & p_m^n \end{pmatrix} \tag{6}$$

where:

$\boldsymbol{A}$ - matrix of experiment of plan,

p_m^n - polynomial sensing coefficients,

Vector of polynomial parameters (7) is following

$$\boldsymbol{b} = \begin{pmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{pmatrix} \tag{7}$$

where:

$\boldsymbol{b}$ - vector polynomial parameters,

$b_{0...n}$ - polynomial parameters are for i=1, ..., n.

Polynomial (8) is specified by manufacturer of thermocouple as a function, which can be used for transform measured thermoelectric voltage to temperature. In case that this polynomial is not specified by manufacturer, it can be find by calibration. This specific polynomial is given by equation (8).

$$f(p) = -0{,}0014p^6 + 0{,}0482p^5 - 0{,}6312p^4 + 3{,}8080p^3 - 10{,}756p^2 + 109{,}79p^{-0{,}0411} \quad (8)$$

where:

$f(p)$ - polynomial of thermocouple,

p - parameter of polynomial.

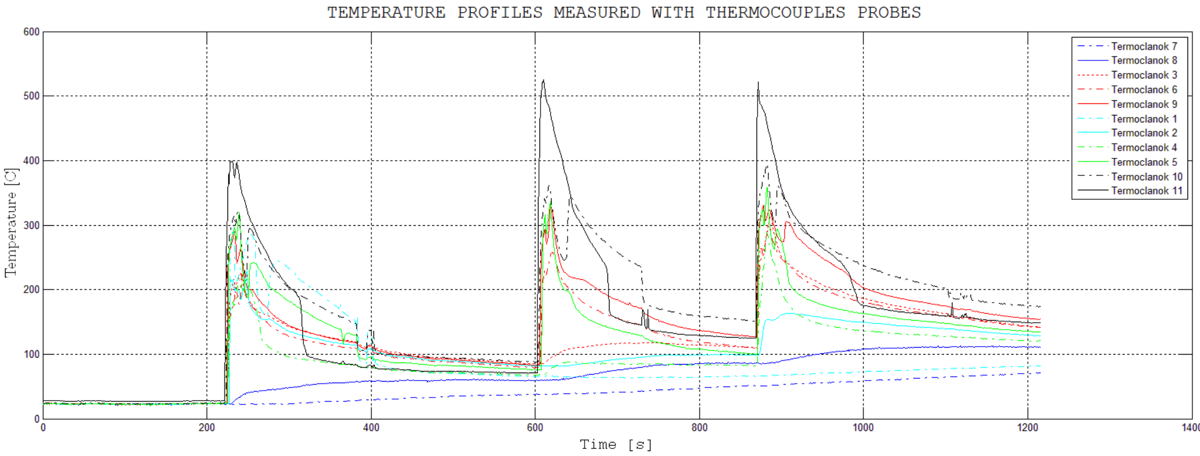

Figure 7: Temperature profiles measured by 11 thermocouples.

Values of temperature measured by thermocouple probes are shown in the figure 7. Measurement started at time $t = 0\text{s}$. The first dose of melted aluminum has been cast in the mold cavity at time $t = 220s$. The ambient temperature was $T = 23^\circ\text{C}$. Temperature of mold was before the first casting equal to the ambient temperature. Temperature of mold increased rapidly to $T = 400^\circ\text{C}$ after casting of melted aluminum into mold cavity. Thermocouple probe has the most fast response, because it is located in location of the first contact of melted aluminum with mold. The first cast was removed from mold in time $t = 380\text{s}$.

The second casting has been done in time $t = 600\text{s}$, temperature of mold was effected by previous casting, because of that temperature maximum increased up to $T = 520^\circ\text{C}$. The second cast was removed from mold cavity in time $T = 650^\circ\text{C}$.

The third casting has been done at time $t = 880\text{s}$. Temperature of mold before the third casting was $T = 150^\circ\text{C}$. This temperature is an temperature inertia effect of previous casting. Mold reach temperature maximum $T = 530^\circ C$. Cast was removed in time $t = 950\text{s}$.

Experiment of temperature measurement and period dose casting took time $t = 1250\text{s}$. After each casting has been taken some time for solidification of cast and free cooling. Visual check of cast has been done after removing solidified cast from mold cavity.

4 Results

The article describe method of a temperature measurement on experimental foundry mold by using a set of thermocouple probes. Temperature measurement has been done by casting into the mold cavity. At the start is described basic physical principle of thermocouple functionality. Measurement circuit consist of device as these: thermocouple probes, measurement cards Humusoft AD-622 and Advantech PCI-1710, cables, control computer and software MATLAB & Simulink. For displaying and evaluating data collected by experiment has been used MATLAB & Simulink. Aim of this paper is to present the measurement of temperature by using of thermoelectric sensors in continuous casting.

Output temperature profiles recorded during the casting and solidification in mold cavity are shown in the figure 7. It might be argued that the results that were found in the continuous casting of aluminum into the cavity are affected by heating the mold cavity. This is due to the fact that the mold was not able to cool down to ambient temperature before started a new cast of aluminum. Therefore the initial temperature of mold was increased for every followed castings. Where is the limit of mold heating can be interesting to find out in the future, for secure stable temperature of mold.

The advantage of thermoelectric sensor is that, it is convenient for contact measurement of high temperature object. It has relatively simple structure and it is an affordable device for measurement.

The resulting uncertainty of K thermocouple is 0,182 °C, for measuring range.

Acknowledgement

The authors would like to take this opportunity to thank to grant agency for their support in writing the following article. Specifically, the grant projects APVV 1/0120/12, a VEGA 0090-10.

References

[1] V. Chudý, R. Palenčár, E. Kureková, M. Halaj. Meranie technických veličín. Vydavateľstvo STU v Bratislave, Bratislava, 1999.
[2] M. Vlček. Modelovanie a identifikácia teplotných polí zlievarenskej formy. 21th Annual Conference Proceedings, Zborník príspevkov 21. ročníka konferencie Technical Computing Bratislava 2013.
[3] P. Buček. Mechatronická zlievarenská forma ako systém s rozloženými parametrami, Dizertačná práca. Bratislava, 2010.
[4] L. Stanček. Technológia I, Zlievanie. Vydavateľstvo STU v Bratislave, Bratislava, 2006.
[5] P. Noga. Modelovanie a riadenie procesov zlievania ako systémov s rozloženými parametrami, Dizertačná práca. Bratislava, 2011.
[6] Hruška, F. Senzory. Fizikálne pricípi, úpravy signáů, praktické požití, Univerzita Tomeše Bati ve Zlíně, Zlín, 2011, ISBN 978-80-7454-096-7
[7] R. Palenčár, J. M. Ruiz, I. Janiga, A. Horníková. Štatistické metódy v metrologických a skúšobných laboratóriách, Vydalo Grafické štúdiu Ing. P. Juriga a Ľ. Fulu v Bratislave, Bratislava 2001, ISBN 80-968449-3-8
[8] MATLAB & Simulink User Guide,
[9] Omega Termocouples. User Guide. Dostupné z: http://www.omegaeng.cz/prodinfo/thermocouples.html

---

Katarína Balonová
katarina.balonova@stuba.sk

Michal Vajsábel
michal.vajsabel@stuba.sk

Tomáš Kopunec
tomas.kopunec@stuba.sk

Romana Rosolowska
romana.rosolowska@stuba.sk

Boris Barbolyas
boris.barbolyas@stuba.sk