The effect of the assumed thermophysical properties of steel on the heat transfer calculation result in contact phenomena

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Abstract
The article presents a model of heat transfer between two solid surfaces remaining in contact under the effect of the force applied. The presented results were obtained from the authors’ own studies conducted with the application of a new method of determining the heat flux transferred between these surfaces. The method consists of two stages: the experiment and numerical calculations. The experimental tests include temperature measurements in specific points in two samples remaining in contact with each other. The numerical part uses the inverse solution and the finite element method for the calculation of the heat flux on the contact surface.

An analysis was performed on the effect of the steel grade used in the tests on the result of heat transfer determination in contact phenomena. The calculations were conducted with the application of proprietary software using the inverse method integrated with FEM.

Keywords: heat transfer, inverse method, solid surface contact

1. Introduction
Heat transfer between objects remaining in contact occurs in the process of the plastic forming and treatment of metals during continuous casting of steel and many others. In all of the mentioned production technologies, heat transport is a phenomenon which determines the course of the process and ensures failure-free operation. It has an effect on obtaining a product with the initially assumed properties.

Direct identification and determination of the boundary conditions in metallurgical processes are complicated to realize. This problem can be solved with the construction of a mathematical model of the applied technology, as well as measurements performed on an experimental stand and numerical methods in order to determine the desired boundary condition. A verification of the properness of the proposed model has to be carried out by means of values which are easily measurable in industrial processes (Furmański & Wiśniewski, 2002; Yovanovich, 2005). Heat transport can run according to three mechanisms: conduction, convection, and radiation. Due to the complexity of the contact and the type

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of medium occurring during the process, for general cases, all the mentioned phenomena are possible to take place simultaneously. The basis for the determination of the temperature field in solid bodies is a differential equation of heat conduction. In the contact of two solid bodies, heat transfer occurs in the case of both an ideal and non-ideal contact between the bodies (Furmański & Wiśniewski, 2002; Poński et al., 2013; Wiśniewski & Wiśniewski, 2010). The heat conduction on both sides of the ideal contact surface of two solid bodies is described by Fourier’s law. The heat transfer from the surface of the first body by the surface of the second body proceeds freely (Fig. 1). The surface temperatures of both bodies taking part in the process are equal:

\[ T_{s_1} = T_{s_2} \]  

where:
\( T_{s_1} \) – sample 1 surface temperature [K],
\( T_{s_2} \) – sample 2 surface temperature [K].

According to the law of energy conservation, there is an equality of the density of the heat flux flowing to the surface of the first body and that flowing from the surface of the second body:

\[ q_s = -\lambda_1 \left( \frac{\partial T_{s_1}}{\partial n} \right) = -\lambda_2 \left( \frac{\partial T_{s_2}}{\partial n} \right) \]  

where:
\( q_s \) – heat flux density [W/m²],
\( \lambda_1 \) – thermal conductivity coefficient for sample 1 [W/(m·K)],
\( \lambda_2 \) – thermal conductivity coefficient for sample 2 [W/(m·K)],
\( \frac{\partial T_{s_1}}{\partial n} \) – derivative in the temperature direction normal to the surface for sample 1,
\( \frac{\partial T_{s_2}}{\partial n} \) – derivative in the temperature direction normal to the surface for sample 2.

Under real conditions, obtaining ideally smooth surfaces is impossible. In effect, the contact of the bodies takes place on a limited surface, which is caused by their roughness. A result of the lack of ideal contact is thermal contact resistance occurring between the surfaces (Fig. 1b). Its value depends on the surface irregularity of the bodies in contact, the unit pressures exerted on the surfaces, the type of medium between the surfaces (gas or liquid) and the temperature on the contact surface. The temperature difference formed in the contact area is called the temperature fault:

\[ \Delta T = T_{s_1} - T_{s_2} = R_s q_s \]  

where \( R_s \) – thermal contact resistance [W/(m²·K)].

The coefficient of heat transfer through the contact surface is defined as the converse of thermal heat resistance:

\[ h_s = \frac{1}{R_s} = \frac{q_s}{\Delta T} \]  

where \( h_s \) – coefficient of heat transfer through the contact surface [W/(m²·K)].

The density of heat flux exchanged between the surfaces of the bodies in contact can be expressed with an equation similar to Newton’s law for convection (5):

\[ q_s = h_s (T_{s_1} - T_{s_2}) \]  

The heat transferred by the contact resistance must flow in and out of the contact surface by heat conduction. The heat transport between surfaces in the case of non-ideal contact, separated by thermal contact resistance, can be described by the transformed Fourier equation (6), which gives a double equation of the boundary conditions for an imperfect contact:

\[ q_s = -\lambda_1 \left( \frac{\partial T_{s_1}}{\partial n} \right) = -\lambda_2 \left( \frac{\partial T_{s_2}}{\partial n} \right) = h_s (T_{s_1} - T_{s_2}) \]  

Fig. 1. Temperature distribution on two surfaces in: a) ideal contact; b) real contact (Wiśniewski & Wiśniewski, 2010)
The available literature makes it possible to divide the models describing the heat transfer in the contact between bodies into two groups (Furmański et al., 2008; Madhusudana, 2014; Yovanovich, 2005). The models in micro-scale, which describe the basic heat transfer mechanisms and the corresponding unit resistances, distinguish between:

- heat conduction in the contact area of surface irregularities – resistance $R_\text{ps}$;
- heat conduction in the fluid present in the gaps between the surfaces – resistance $R_\text{pp}$;
- radiation between the walls surrounding the spaces formed between the contact points (in the case when the fluid possesses the right properties) – resistance $R_\text{r}$.

![Fig. 2. Thermal contact resistance for a real contact – micro (a) and macro model (b)](image)

The effects of the assumed thermophysical properties of steel on the heat transfer calculation result...
atmosphere of argon, which counteracted surface oxidation during heating. In the measurements, two samples were used: “Hot” made of steel C45 (1.0503), which was heated in the furnace, and “Cold” made of steel WNL (1.2713), which was placed outside the furnace and held at room temperature. The “Hot” sample, after reaching the required temperature, was removed from the furnace and pressed with the assumed force down to the “Cold” sample at constant pressure. Both samples were 20 mm high and 20 mm in diameter. In each sample, in its axis, a type K thermocouple was mounted, 0.5 mm in diameter. The temperature sensors were fixed at the distances: 2 mm (T_{C1}), 4 mm (T_{C2}) and 6 mm (T_{C3}) from the head for the Cold sample and 2 mm (T_{H1}) and 4 mm (T_{H2}) from the head for the Hot sample. The measurements were made for the initial temperatures of the Hot sample, 1100°C, and the pressures of 10 MPa, 20 MPa. A full description of the test stand and the experiment is available in the literature (Rywotycki et al., 2015).

The course of the experiment can be divided into a few stages. They are as follows:

1. Removing the Hot sample from the heating furnace (0–7.5 seconds) – cooling of the Hot sample in air, while the Cold sample remains protected with the insulation shield.
2. Removing of the insulation shield placed over the Cold sample – the Cold sample heats up as a result of heat transfer through radiation (7.5–9.0 seconds).
3. Contact of the sample – the main measurement, in which the heat transfer takes place as a result of direct contact of the samples’ surfaces. The time of the contact is 30 seconds (9.0–39.0 seconds).

The temperature changes were recorded with a frequency of 10 Hz. The recorded measurement results for the sample made of steel 1.2713 are presented in the following diagrams (Fig. 5). Increasing pressure leads to the higher temperature of the Cold sample. Thermocouples that were closer to the surface of the sample registered higher temperatures.
2.2. Numerical calculations

The numerical part applies the inverse solution and the finite element method for the calculation of the heat flux and the value of heat transfer coefficient for the contact surface (Rywołt et al., 2015). The temperature field in the samples was determined by means of an axi-symmetric solution of the heat conduction problem. The schematic diagram of the boundary conditions and the applied finite element mesh is shown in Figure 6. The calculations were made with the use of the proprietary computer program developed at the Faculty of Heat Engineering and Environmental Protection of the AGH University of Science and Technology in Krakow.

![Fig. 5. The temperature distribution in time: a) pressure 10 MPa; b) pressure 20 MPa](image)

The boundary conditions on the surfaces were given in the form of a heat flux according to the denotations in Figure 6. On the side surface of the samples, the heat transfer takes place by way of convection \( h_{\text{conv}} \) and radiation \( h_{\text{rad}} \). The value of heat transfer coefficient for the side surface was determined from:

\[
h_{\text{ss}} = h_{\text{rad}} + h_{\text{conv}}
\]

where:

\[
h_{\text{conv}} = \frac{Nu \cdot \lambda}{z} \quad \text{(8)}
\]

\( Nu \) – Nusselt number \([-]\),
\( \lambda \) – air thermal conductivity \([\text{W/(m} \cdot \text{K)}])
\( z \) – characteristic length \([\text{m}]\).
The value of the Nusselt number was determined from the following equations (Wiśniewski & Wiśniewski, 2010):

\[
Ra < 500 \quad Nu = 1.18 Ra^{1/3}
\]

\[
500 \leq Ra < 2 \cdot 10^7 \quad Nu = 0.54 Ra^{1/3}
\]

\[
2 \cdot 10^7 \leq Ra < 10^{13} \quad Nu = 0.135 Ra^{1/3}
\]  

(9)

The coefficient of heat transfer through radiation equals (Malinowski, 2001):

\[
h_{rad} = \left(1.2 - 0.52 \frac{T_d}{1000}\right) \cdot 5.675 \cdot 10^8 \frac{T_d^4 - T_a^4}{T_d - T_a}
\]  

(10)

For the bottom surface being in contact with the handle of the testing machine, the heat transfer coefficient determined in an empirical way was applied (Malinowski et al., 1994):

\[
h_b = 300 \left(1 + \frac{\tau}{30}\right)
\]  

(11)

where \(\tau\) – time [s].

3. Effect of the steel grade on the inverse solution accuracy

The output parameters, the heat flux value, identified based on the inverse solution, are determined in an indirect manner. The errors in all the physical quantities present in the model affect the accuracy of the determination of the resulting parameter. The data used in the calculations were assumed on the basis of the literature as well as the measurements performed on the test station. The value of each initial parameter is burdened with the error of its determination, resulting from the method used to determine the given parameter. These errors affect the accuracy and uncertainty of the inverse solution for the heat conduction equation. During the performed calculations, an analysis was made of the effect of the steel grade on the result of the numerical calculations. It was assumed that the sample was made of three grades of steel which differ in their thermophysical properties. In the numerical tests, “Cold” samples of three steel grades were used – 1.2713, 1.2063 and 1.1735. Sample “Hot” which was used in physical test was heated in the furnace. It was the source of heat for this test. The full description of the numerical calculation for both samples is available in the literature (Rywotycki, 2017).

The thermophysical parameters of the materials were used in the function of temperature. The values of these parameters are presented in diagrams (Figs. 7–9) (Falkus, 2012; Telejko, 2001), while the chemical composition is shown in Table 1.
The effect of the assumed thermophysical properties of steel on the heat transfer calculation result

Table 1. Chemical composition of steel

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2713</td>
<td>0.50–0.60</td>
<td>0.15–0.40</td>
<td>0.50–0.80</td>
<td>Max 0.030</td>
<td>Max 0.030</td>
<td>0.50–0.80</td>
<td>0.15–0.25</td>
<td>–</td>
<td>1.40–1.80</td>
<td>–</td>
</tr>
<tr>
<td>1.2063</td>
<td>1.30–1.45</td>
<td>0.15–0.40</td>
<td>0.40–0.70</td>
<td>Max 0.030</td>
<td>Max 0.030</td>
<td>1.30–1.65</td>
<td>Max 0.20</td>
<td>0.10–0.16</td>
<td>Max 0.35</td>
<td>–</td>
</tr>
<tr>
<td>1.7335</td>
<td>0.08–0.18</td>
<td>Max 0.35</td>
<td>0.40–1.00</td>
<td>Max 0.025</td>
<td>Max 0.01</td>
<td>0.70–1.15</td>
<td>0.40–0.60</td>
<td>–</td>
<td>–</td>
<td>Max 0.30</td>
</tr>
</tbody>
</table>

The results of the numerical calculations are presented in Figure 10. The calculation results made it possible to determine the heat flux in all examined cases for the three grades of steel. Figure 10 shows the changes in the heat flux in time, where we can see that an increase in pressure also increases the heat flux. Steel 1.2063 has the lowest value of thermal conductivity and specific heat. These differences reduce the heat flux obtained in the performed numerical calculations. The other two steels are characterized by a higher value of these two thermophysical parameters. The results of numerical calculations for two steel grades – 1.7335 and 1.2063 were compared with the 1.2713 steel for which the experiment was carried out. A sample made of this steel grade was used as a reference model in numerical calculations. The calculation error (Tab. 2) in the scope of the analysed changes in the thermophysical parameters resulting from the steel grade used in the tests remains at an acceptable level. The big differences in the initial parameters refer mainly to the heat conduction coefficient. The parameters differ not only in the values but also the character of the changes in the function of temperature. The change in the value of thermophysical properties causes a proportional shift of the curves observed in the diagrams, without a change in their character (Fig. 10). The change in the thermophysical parameters related to the steel grade is at a level low enough for its effect on the inverse solution accuracy to enable a statement that the elaborated methodology is an effective tool in the examination of the heat transfer processes in contact phenomena.

Table 2. Errors of the solution compared to the assumed boundary condition model for steel 1.2713

<table>
<thead>
<tr>
<th>Steel</th>
<th>$p = 10$ MPa</th>
<th>$p = 20$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average absolute error of heat flux [W/m$^2$]</td>
<td>average relative error of heat flux [%]</td>
</tr>
<tr>
<td>1.2063</td>
<td>58 464</td>
<td>9.6</td>
</tr>
<tr>
<td>1.7335</td>
<td>10 597</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Fig. 10. Heat flux as a function of time: a) pressure 10 MPa; b) pressure 20 MPa
4. Conclusions

The phenomenon of heat transfer plays an important role in many industrial processes. The temperature fields of the solid bodies participating in the heat transfer are described by means of a heat conduction equation. The heat flux transferred between the surfaces of the bodies in contact depends on various parameters, of which the most important are: temperature, time, and pressure force. However, the initial parameters, that is the value of heat flux identified based on the inverse solution, are determined in an indirect manner. The errors of all the physical quantities present in the model affect the accuracy of the determination of the desired parameter. As a result of the performed analysis of the effect of the steel grade on the accuracy of the inverse solution, it has been demonstrated that this effect is at an acceptable level for this scope of changes in the values of the thermophysical parameters. It is not more than 10% when calculations are made with the use of a different grade of steel than the actual steel used in the experiment on the test bench. On the basis of the conducted analyses, it can be stated that the developed methodology is an effective tool in the study of the heat transfer processes in contact phenomena which accompany the description of heat transfer in many industrial processes.

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References

Rywotycki, M. (2017). Wymiana ciepła w warunkach kontaktu narzędzia i materiału w wysokotemperaturowych procesach metalurgicznych. Wydawnictwa AGH.