COMPUTER METHODS IN MATERIALS SCIENCE

2020, vol. 20, no. 4, 165–172
https://doi.org/10.7494/cmms.2020.4.0738

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:

$$T_{s1} = T_{s2} \tag{1}$$

where:
T_{s1} – sample 1 surface temperature [K],
T_{s2} – 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:

$$q_s = -\lambda_1 \left(\frac{\partial T_1}{\partial n} \right) = -\lambda_2 \left(\frac{\partial T_2}{\partial n} \right) \tag{2}$$

where:
q_s – heat flux density [W/m^2],
λ_1 – thermal conductivity coefficient for sample 1 [W/(m·K)],
λ_2 – thermal conductivity coefficient for sample 2 [W/(m·K)],
$\frac{\partial T_1}{\partial n}$ – derivative in the temperature direction normal to the surface for sample 1,
$\frac{\partial T_2}{\partial n}$ – 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:

$$\Delta T = T_{s1} - T_{s2} = R_s q_s \tag{3}$$

where R_s – thermal contact resistance [W/(m^2·K)].

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

$$h_s = \frac{1}{R_s} = \frac{q_s}{\Delta T} \tag{4}$$

where h_s – coefficient of heat transfer through the contact surface [W/(m^2·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):

$$q_s = h_s (T_{s1} - T_{s2}) \tag{5}$$

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:

$$q_s = -\lambda_1 \left(\frac{\partial T_1}{\partial n} \right) = -\lambda_2 \left(\frac{\partial T_2}{\partial n} \right) = h_s (T_{s1} - T_{s2}) \tag{6}$$

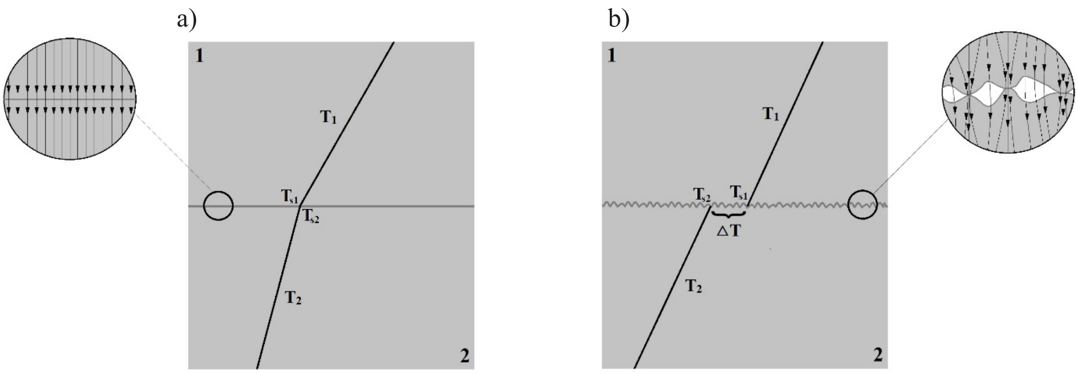

Fig. 1. Temperature distribution on two surfaces in: a) ideal contact; b) real contact (Wiśniewski & Wiśniewski, 2010)

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_{ps};
- heat conduction in the fluid present in the gaps between the surfaces – resistance R_{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_r.

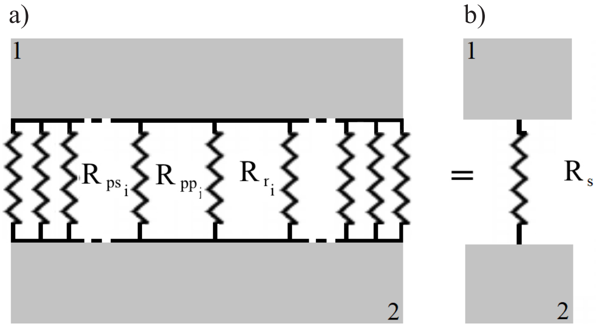

Fig. 2. Thermal contact resistance for a real contact – micro (a) and macro model (b)

The models which are practically applied in engineering calculations related to the description of the heat transfer in the contact between two surfaces are those which describe the heat transfer in a macro scale. In such a case, a micro model (Fig. 2) with a large number of elementary heat transfer mechanisms is replaced by one global thermal contact resistance R_s. Such an approach makes it possible to construct heat transfer models which can be applied in numerical calculations with the use of both commercial and proprietary programs.

An analysis of the literature in the field of heat transport makes it possible to compile the applied heat transfer models with contact in the previous studies. Several methods of identifying heat transfer conditions in processes have been described. They can be divided according to: time variability, the number of bodies, and the algorithm used (Furmański & Wiśniewski, 2002; Rosochowska et al., 2004; Rywotycki et al., 2016; Zhao, 2015).

In the work (Fang et al., 2018), a rough surface of contact materials was modelled. The numerical calculations were performed for two cases, i.e., a contact of aluminium samples and a contact of stainless steel samples. The real topography of the contact of solid bodies was considered in the article (Ren et al., 2021), where the roughness of composite samples was measured by means of a microscope. The case referred to the steady-state of heat conduction, with no internal heat sources. The method was based on a measurement of one-dimensional heat flux in the steady-state. The temperature profiles of the contact samples and the contact surface temperatures were obtained through extrapolation of the measured temperatures. The heat transfer coefficient for stainless steel has been determined in an earlier study (Feng et al., 2020). The thermal contact resistance between the two samples in contact was determined through a measurement of the temperature difference of their surfaces and the heat flux. The aim of one work (Panagouli et al., 2020) was to examine the effect of the roughness of surfaces in contact on the thermal contact resistance. The calculations referred to the detection of abnormalities at micro and macro scales. The problem was simplified through the assumption of surfaces with non-elastic properties. The mechanical and thermal aspect of the issue was solved by means of the finite element method.

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, 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. In this article, control tests were performed to assess the influence of thermophysical properties on the value of the heat flux.

2. A method of identifying heat transfer in contact phenomena

The method of determining the heat transfer coefficient in high-temperature contact phenomena consists of two parts:

1. Experiment – consisting of measurements of the temperature changes in specific points in two samples in contact.
2. Numerical calculations – applying the reciprocal solution of the heat conduction equation and the finite element method.

2.1. Measurements on an experimental stand

The arrangement of the experimental stand is shown in both a photograph and a diagram (Fig. 3 and 4). The furnace in which the sample was heated had a protective 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).

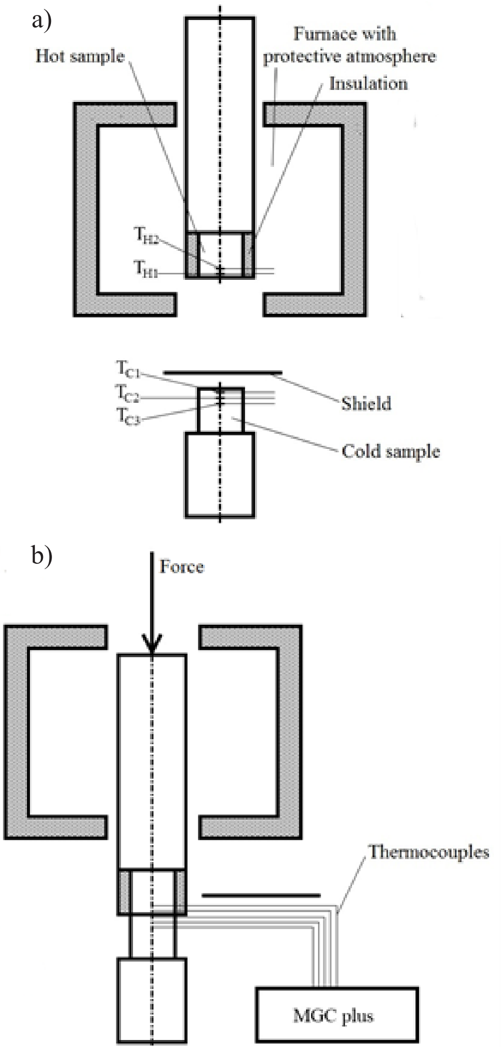

Fig. 3. Schematic diagram of the experiment: a) the heating of a sample in the furnace; b) the positions of samples during the test

a)

b)

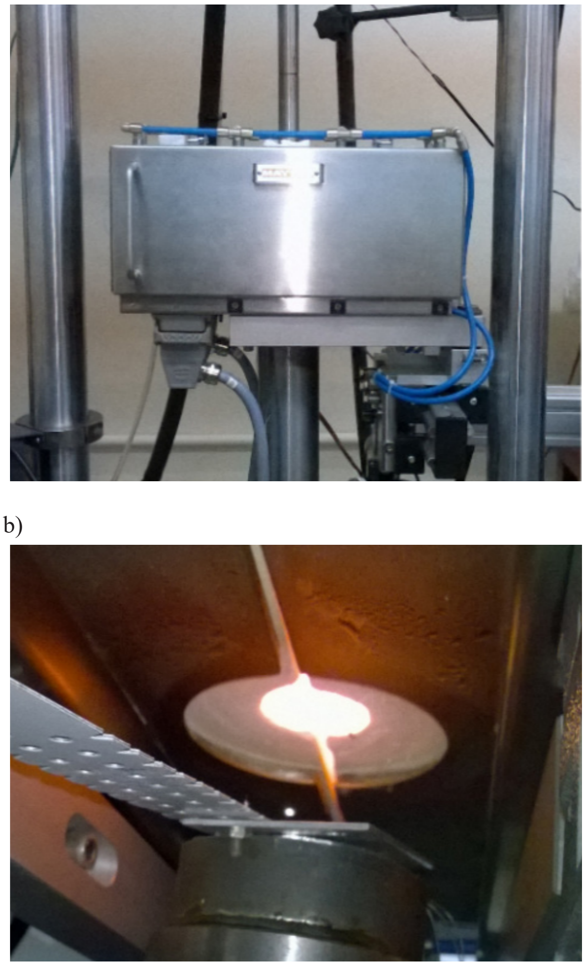

Fig. 4. View of the measurement station: a) heating furnace; b) cold sample protected with a thermal shield

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.

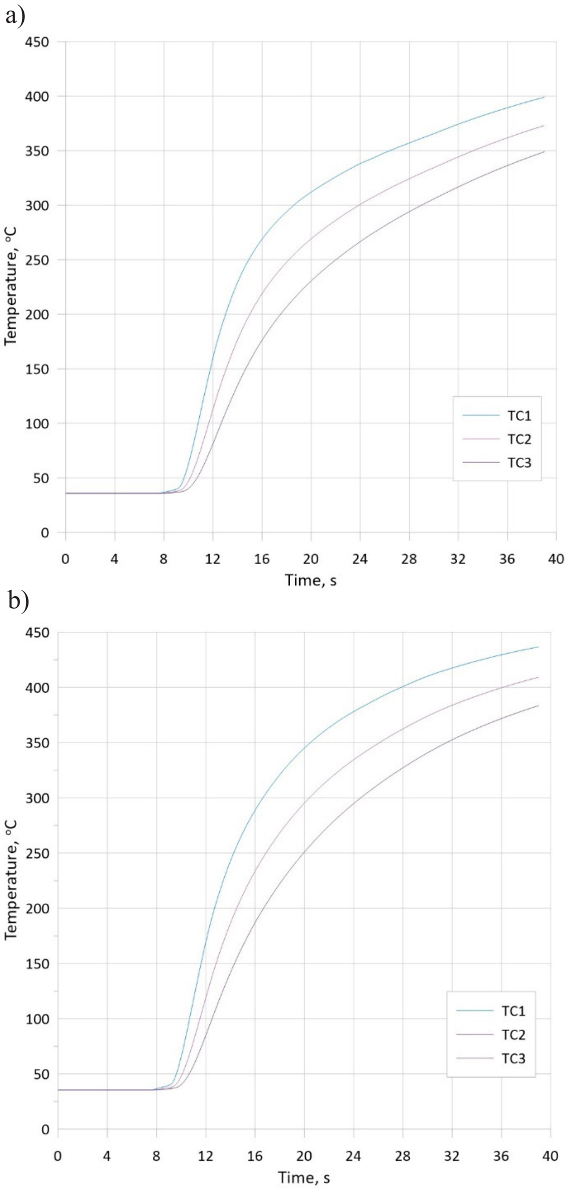

Fig. 5. The temperature distribution in time:
a) pressure 10 MPa; b) pressure 20 MPa

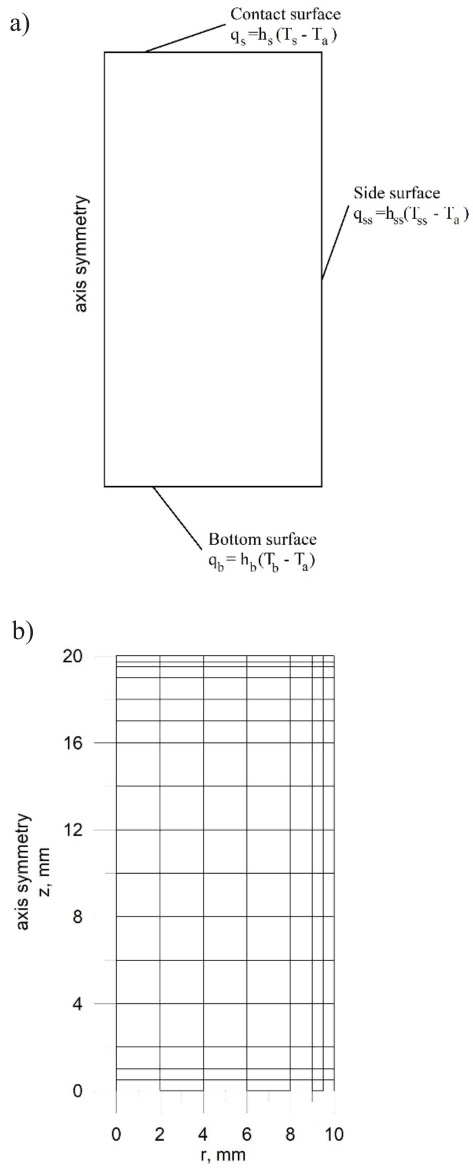

Fig. 6. Schematic diagram of boundary conditions (a) and finite element mesh (b)

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 (Rywotycki 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.

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_{con}) and radiation (h_{rad}). The value of heat transfer coefficient for the side surface was determined from:

$$h_{ss} = h_{rad} + h_{con} \tag{7}$$

where:

$$h_{con} = \frac{Nu \cdot \lambda}{z} \tag{8}$$

Nu – Nusselt number [–],
λ – air thermal conductivity [W/(m·K)],
z – characteristic length [m].

The value of the Nusselt number was determined from the following equations (Wiśniewski & Wiśniewski, 2010):

$$\begin{aligned} &Ra < 500 && Nu = 1.18 Ra^{\frac{1}{8}} \\ &500 \le Ra < 2 \cdot 10^7 && Nu = 0.54 Ra^{\frac{1}{4}} \\ &2 \cdot 10^7 \le Ra < 10^{13} && Nu = 0.135 Ra^{\frac{1}{3}} \end{aligned} \tag{9}$$

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

$$h_{rad} = \left(1.2 - 0.52 \frac{T_{ss}}{1000}\right) \cdot 5.675 \cdot 10^{-8} \frac{T_{ss}^4 - T_a^4}{T_{ss} - T_a} \tag{10}$$

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):

$$h_b = 300 \cdot \left(1 + \frac{\tau}{30}\right) \tag{11}$$

where τ – 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.

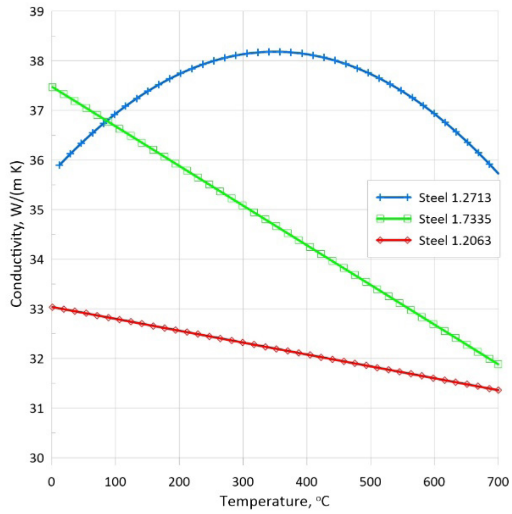

Fig. 7. Heat conduction coefficient as a function of temperature for of the steels analyzed

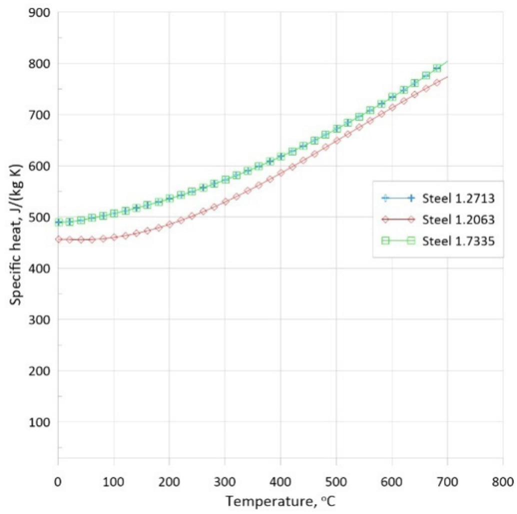

Fig. 8. Specific heat as a function of temperature for of the steels analyzed

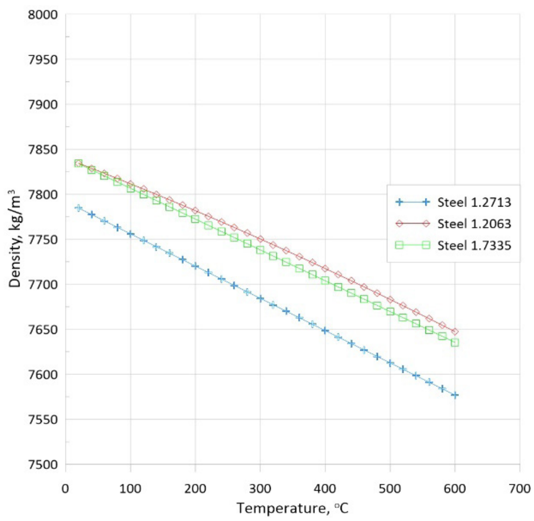

Fig. 9. Density as a function of temperature for of the steels analyzed

Table 1. Chemical composition of steel

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

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.

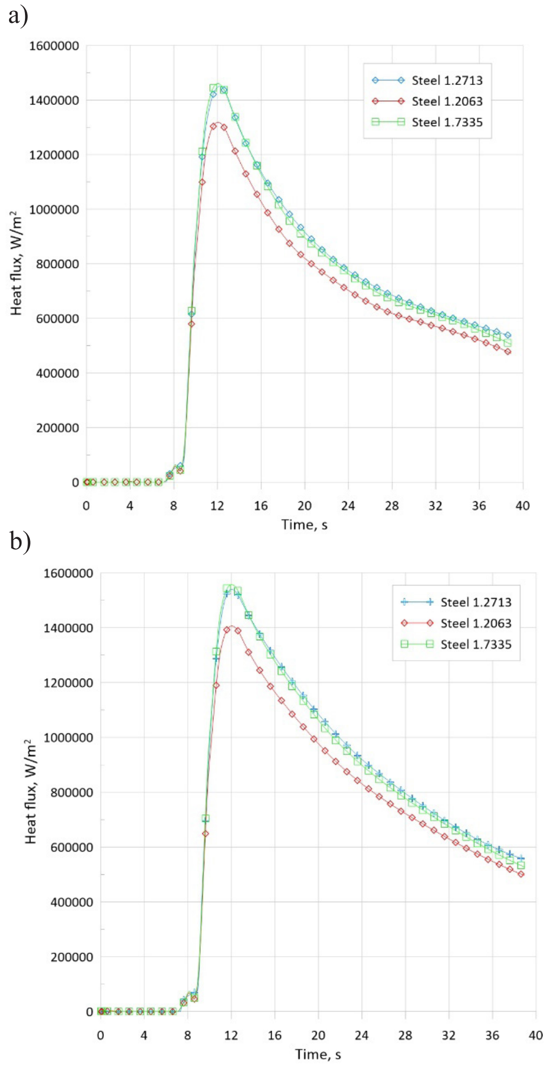

Fig. 10. Heat flux as a function of time: a) pressure 10 MPa; b) pressure 20 MPa

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

Steel	p = 10 MPa		p = 20 MPa	
	average absolute error of heat flux [W/m^2]	average relative error of heat flux [%]	average absolute error of heat flux [W/m^2]	average relative error of heat flux [%]
1.2063	58 464	9.6	65 200	9.7
1.7335	10 597	2.6	13 585	3.0

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.

Acknowledgments

The study was performed as part of the regular activity of the AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, Work No. 16.16.110.663.

References

Falkus, J. (Ed.) (2012). *Modelowanie procesu ciągłego odlewania stali. Monografia*. Wydawnictwo Naukowe Instytutu Technologii Eksploatacji – Państwowy Instytut Badawczy.

Fang, W.-Z., Gou J.-J., Chen, L., & Tao, W.-Q. (2018). A multi-block lattice Boltzmann method for the thermal contact resistance at the interface of two solids. *Applied Thermal Engineering*, *138*, 122–132.

Feng, B., Tu, J., Zhang, Y.-H., Fan, L.-W., & Yu, Z.-T. (2020). An improved steady-state method for measuring the thermal contact resistance and bulk thermal conductivity of thin-walled materials having a sub-millimeter thickness. *Applied Thermal Engineering*, *171*, 114931.

Furmański, P., & Wiśniewski, T.S. (2002) *Thermal Contact Resistance and Other Thermal Phenomena at Solid-Solid Interface.* Institute of Head Engineering – Warsaw University of Technology.

Furmański, P., Wiśniewski, T.S., & Banaszek, J. (2008). *Thermal Contact Resistance and Other Thermal Phenomena at Solid-Solid Interface* (Wyd. 2). Institute of Heat Engineering – Warsaw University of Technology.

Madhusudana, C.V. (2014). *Thermal Contact Conductance*. Springer.

Malinowski, Z. (2001). Analysis of temperature fields in the tools during forging of axially symmetrical parts. *Archives of Metallurgy*, *46*(1), 93–118.

Malinowski, Z., Lenard, J.G., & Davies, M.E. (1994). A study of heat-transfer coefficient as a function of temperature and pressure. *Journal of Materials Processing Technology*, *41*(2), 125–142.

Panagouli, O.K., Margaronis, K., & Tsotoulidou, V. (2020). A multiscale model for thermal contact conductance of rough surfaces under low applied pressure. *International Journal of Solids and Structures*, *200–201*, 106–118.

Poński, M., Paluszyński, J., & Dubała, K. (2013). Modele przepływu ciepła w ciałach stałych. *Zeszyty Naukowe Politechniki Częstochowskiej. Budownictwo*, *19*(169), 129–134.

Ren, X.-J., Dai, Y.-J., Gou J.-J., & Tao, W.-Q. (2021). Numerical study on thermal contact resistance of 8-harness satin woven pierced composite. *International Journal of Thermal Sciences*, *159*, 106584.

Rosochowska, M., Chodnikiewicz, K., & Balendra, R. (2004). A new method of measuring thermal contact conductance. *Journal of Materials Processing Technology*, *145*(2), 207–214.

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

Rywotycki, M., Malinowski, Z., Szajding, A., Sołek, K., Falkus, J., & Miłkowska-Piszczek, K. (2015). *Identification of heat flux at solid to solid interface.* In A.J. Nowak, J. Banaszek, B. Šarler (Eds.), *Numerical Heat Transfer 2015. Eurotherm Seminar 109, Gliwice–Warsaw, Poland. September 13–16 2015 – book of abstracts* (pp. 267–276). Institute of Thermal Technology, Silesian University of Technology, Institute of Heat Engineering, Warsaw University of Technology.

Rywotycki, M., Malinowski, Z., Szajding, A., Falkus, J., Sołek, K., & Miłkowska-Piszczek, K. (2016). Wymiana ciepła przy przeróbce plastycznej metali – porównanie modeli. *Hutnik. Wiadomości Hutnicze*, *83*(1), 13–17.

Telejko, T. (2001). Analiza porównawcza wybranych formuł do obliczania przewodności cieplnej stali. *Hutnik. Wiadomości Hutnicze*, *68*(11), 418–423.

Wiśniewski, S., & Wiśniewski, T.S. (2010). *Wymiana ciepła* (Wyd. 6). Wydawnictwa Naukowo-Techniczne.

Yovanovich, M.M. (2005) Four decades of research on thermal contact, gap, and joint resistance in microelectronics. *IEEE Transactions on Components and Packaging Technologies*, *28*(2), 182–206.

Zhao, K., Wang, B., Chang, Y., Tang, X., & Yan, J. (2015). Comparison of the methods for calculating the interfacial heat transfer coefficient in hot stamping. *Applied Thermal Engineering*, *79*, 17–26.