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THE HEAT TRANSFER PROCESS BETWEEN TWO BODIES WITH A LARGE TEMPERATURE DIFFERENCE

Heat transport when two surfaces of solids come into contact is an important phenomenon in many metallurgical processes. Determining the boundary conditions of heat transfer allows to obtain the correct solutions of the heat conduction equation. The paper presents models for determining the heat transfer coefficient between steel materials in contact. Experimental tests were carried out to measure the temperature changes of the contacting samples made of steel S235 (1.0038) and steel 15HM (1.7335) under the pressure of 10, 15 and 20 MPa. There was a large temperature difference between the samples. The results of the experiment were compared with numerically calculated temperatures and the value of the heat transfer coefficient was determined at different pressure values depending on the time.

Keywords: heat transfer coefficient; thermal conductivity; inverse solution; steel

1. Introduction

The heat transfer coefficient at the contact of two solid surfaces is desirable in modeling metallurgical processes. The heat exchange between the bodies in contact occurs in the processes of plastic processing of metals, hot stamping of sheet metal and during continuous casting of steel. In all these production technologies, heat transport is a phenomenon that determines the correct course of the process and ensures failure-free operation. The production of structural parts with the assumed properties using heated tools requires a thorough knowledge of the heat transfer phenomena at the contact surfaces of working bodies [1,2]. It is well known that when two solid surfaces are pressed together, the interface includes both point contacts and air gaps. The contact surfaces are never perfectly flat and the actual contact area is only a small fraction of the nominal area. Lack of perfect contact results in thermal contact resistance between the surfaces. The contact heat transfer coefficient is defined as the reciprocal of the thermal contact resistance. Its value between the metals in contact depends on many factors, such as: temperature, pressure, contact time, contact surface morphology, the presence of scale and many others [3-5]. The contact state of the contact surface should be carefully determined in order to investigate the phenomenon of contact heat conduction. Current research can provide only a few qualitative explanations and cannot effectively characterize the state of contact between contact surfaces [1,3,6-8].

The determination of the input parameters, and in particular the direct identification and determination of the boundary conditions in metallurgical processes, is complicated to implement. Boundary conditions are difficult to determine experimentally. This problem can be solved by constructing a mathematical model of the technology used, performing measurements on an experimental stand and using numerical methods to determine the boundary condition sought. The correctness of the proposed models must be checked with the help of easily measurable values in industrial processes. These include temperature, which can be used in reverse methods to determine the heat transfer coefficient [9-11].

In this study, the models for determining the heat transfer coefficient in the contact of two solids were analyzed. The temperature changes of two cylindrical steel samples in contact were experimentally measured. The HOT sample with an initial temperature of 1200°C was pressed against the COLD sample with different pressure forces: 10, 15 and 20 MPa. Using the inverse method and the finite element method, the values of the heat transfer coefficient were determined and the temperature values measured at individual points were compared with the temperatures determined by the calculation method for the COLD sample.

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2. Determination of the heat transfer coefficient

The available literature allows to divide the models describing heat transfer in contact with bodies into two groups. The first one covers the issues defining the constant average value of the heat transfer coefficient. On the other hand, the models of the second group describe the variable value of this coefficient as a function of the surface temperature at constant pressure or variable pressure at constant temperature. Failure to take into account the influence of pressures at a constant value of the heat transfer coefficient in the numerical calculations results in the lack of precise results of the temperature field in high-temperature processes. Adjusting the results obtained in the research part to the results obtained with numerical methods allows to determine the correct value of the heat transfer coefficient sought. Below are presented examples from the literature for determining the heat transfer coefficient between steel samples in contact phenomena and the model used by the Authors.

2.1. Literature examples of models for determining the heat transfer coefficient between bodies in contact

In their work, Biao et al. [12] conducted tests for stainless steel. The thermal contact resistance between two samples in contact was determined by measuring the difference in surface temperatures and the heat flow. The samples were in the form of coaxial cylindrical objects with the same cross-sectional areas. The temperature gradient was perpendicular to the contact surface. The samples were placed between the heat source and the heat absorber. Thermal insulation was used on the experimental stand to avoid circumferential heat dissipation and to maintain steady state one-dimensional heat conduction between the heat source and the heat absorber. Thus, the heat transfer coefficient could be estimated by the Eq. (1):

$$h = \frac{q_1'' + q_2''}{2(T_{c2} - T_{c1})} = \frac{q_1'' + q_2''}{2\Delta T_c} \tag{1}$$

where T_{c1} is the temperature of the upper surface of the cooled sample, T_{c2} is temperature of the lower surface of the heated sample, and q_1'' and q_2'' are the heat flux density flowing, respectively, in front of the lower and upper samples. The experiment carried out by Biao et al. was based on stacking thin-walled samples and measuring the total thickness of a given variation. It allowed to determine the total heat transfer coefficient from the Eq. (2):

$$h_{tot} = h_{s,tot} + h_{c,tot} + 2h_c' \tag{2}$$

where $h_{s,tot}$ is the total heat transfer coefficient of the thin-walled sample, $h_{c,tot}$ is the total heat transfer coefficient between the samples, and h_c' is the heat transfer coefficient between the heat source / absorber. The applied methodology for determining the thermal conductivity was verified using the laser pulse method and the thermal properties analyzer. The maximum discrepancy of the obtained results was quite good, it amounted to a maximum of 13%.

The work of Mosayebidorcheh & Gorji-Bandpa [13] concerned the analysis of the temperature distribution of the band in the process of continuous steel casting. The thermal boundary conditions were determined using local and surface averaged heat transfer coefficients in the secondary cooling zones. The calculations were performed using the finite volume method for the two- and three-dimensional model of temperature and thickness distribution of steel. The simulation results were confirmed by industrial measurements. Due to the complex nature of the continuous casting of steel, assumptions were made according to which Eq. (3) could be derived:

$$\rho c_p \left(\frac{\partial T}{\partial t} + V_{cast} \frac{\partial T}{\partial z} \right) = \\ = \frac{\partial}{\partial x}\left(\lambda_{eff}(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda_{eff}(T) \frac{\partial T}{\partial y} \right) + \dot{q} \tag{3}$$

where λ_{eff} is the effective thermal conductivity, and $\dot{q}$ is the heat generated by solidification. The left side of Eq. (3) describes the temperature variation of the steel and the energy conservation of the cast steel. The first two terms on the right side of the Eq. (3) describe the transverse heat conduction in the x and y directions. The last term of the Eq. (3) describes the heat generated during the solidification process. The variable $\dot{q}$ in the equation is a function of the solid steel fraction and increases with increasing solid fraction, which can be represented by Eq. (4):

$$\dot{q} = \Delta h \left(\frac{\partial (f_s \rho)}{\partial t} + V_{cast} \frac{\partial (f_s \rho)}{\partial z} \right) \tag{4}$$

where Δh is the latent heat.

2.2. Inverse solution for the heat conduction equation

The mathematical model for the heat conduction coefficient determination uses the inverse solution for the heat conduction equation and the finite element method to calculate the heat flux on the contact surface. The frontal surface for which the value of the heat transfer coefficient is sought exchanges heat as a result of contact with the other body. Boundary conditions were set in the form of heat flux density for a solid in the form of a cylinder [14]. The boundary condition on the side surface of the sample was determined by Eq. (5):

$$q_{ss} = h_{ss}(T_{ss} - T_a) \tag{5}$$

where T_a is the reference temperature, and T_{ss} is the side surface temperature of the sample. The boundary condition on the lower surface of the sample was given by Eq. (6):

$$q_b = h_b(T_b - T_a) \tag{6}$$

where T_b is the temperature of the lower surface of the sample. The last boundary condition on the contact surface was defined as the heat flux density Eq. (7) as a time dependent function:

$$q_s = h_s(\tau)(T_s - T_a) \tag{7}$$

where h_s is the heat transfer coefficient through the contact, and T_s is the contact surface temperature.

The inverse solution of the heat conduction equation uses the BFGS variation method, the effectiveness and precision of which was developed by Liu [15]. The value of the heat transfer coefficient in time is approximated by the general form of the function. The final result is obtained by using a specific form of this function. Obtaining the assumed accuracy of the solution is possible as a result of minimizing the objective function defined by the equation Eq. 8 [16]:

$$E(p_i) = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[\frac{t_{ij}^{\exp}(\tau) - t_{ij}^{inv}(\tau)}{t_{ij}^{\exp}(\tau)}\right]^2 \tag{8}$$

where p_i is the vector of the unknown parameters, $t_{ij}^{\exp}$ is the sample temperature measured by the sensor i at time τ_j, and t_{ij}^{inv} is the temperature obtained from the inverse calculation result at point i and time τ_j. Derivatives of the error norm with respect to unknown parameters p_i were determined numerically in the form of finite differences of the first derivative, which is given by the Eq. 9:

$$\frac{\partial E(p_i)}{\partial p_j} \approx \frac{E(p_i + \Delta p_j) - E(p_i)}{\Delta p_j} \tag{9}$$

where the approximate expression of the first derivative was used increment $\Delta p_j = |p_j| \cdot 10^{-6}$.

3. Experimental

Determination of the heat transfer coefficient between two bodies with a large temperature difference began with the measurements on the experimental stand. The experiment consisted in measuring temperature changes at specific points in two samples in contact. The layout of the experimental stand is shown in Fig. 1. The measurements were made of samples from two different grades of steel. The HOT sample was made of S235 (1.0038) steel, and the COLD sample was made of 15HM (1.7335) steel. Both samples were cylindrical, 30 mm high and 16 mm in diameter. Based on the results of previous measurements the Rywotycki et al. work [16], the samples dimensions were reduced due to the difficulty of making holes for thermocouples. The HOT sample was wrapped with a 3 mm layer of high temperature insulation wool. In the axis of each sample, 0,5 mm holes were drilled and then thermocouples with a diameter of 0,5 mm were inserted into them. N-type thermocouples in the HOT sample, K-type thermocouples in the COLD sample. The furnace in which the HOT sample was heated had a protective atmosphere of argon to prevent oxidation of the sample surface during heating. The sample was heated to a temperature of 1200°C and then it was subjected to pressures of 10, 15, 20 MPa. The COLD sample was kept at room temperature throughout the experiment. The course of the experiment can be divided into three stages:

1) The HOT sample exits the furnace and is cooled in the air. During this time, the COLD sample is obscured by an insulating screen.
2) The insulating screen above the COLD sample is removed and the sample heats up as a result of heat exchange by radiation.
3) The samples HOT and COLD are brought into contact. The actual measurement is in progress, in which the heat exchange takes place as a result of direct contact of the surfaces of the samples.

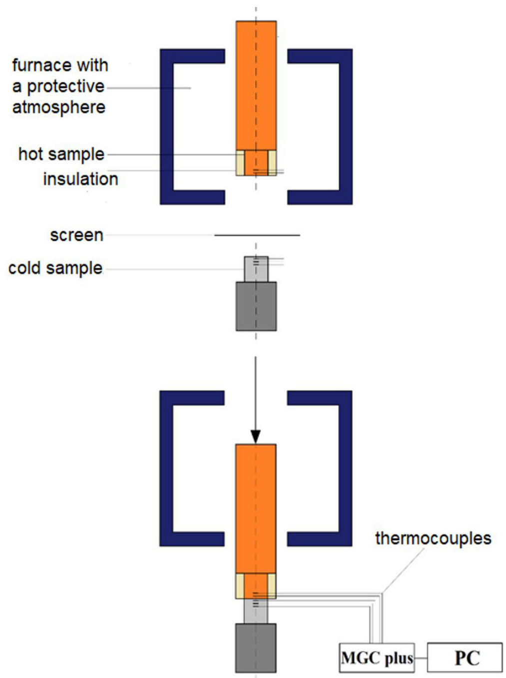

Fig. 1. Schematic diagram of the experiment

4. Results

The temperature changes from the experiment were recorded with a frequency of 10 Hz. The recorded measurement results are presented in Fig. 2. The values measured with thermocouples (TC) allow to trace the nature of temperature changes in the COLD sample during the experiment. With time, the dynamics of temperature changes decreases. Increasing the pressure applied to the COLD sample results in obtaining higher temperatures.

The computational part uses the inverse solution and the finite element method to calculate the value of the heat transfer coefficient on the COLD sample surface. Calculations were made using Eqs. (5)-(9). The temperature field in the samples was determined by means of an axi-symmetric solution of the heat conduction problem. 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. 2 shows the comparison of the experimentally measured temperatures

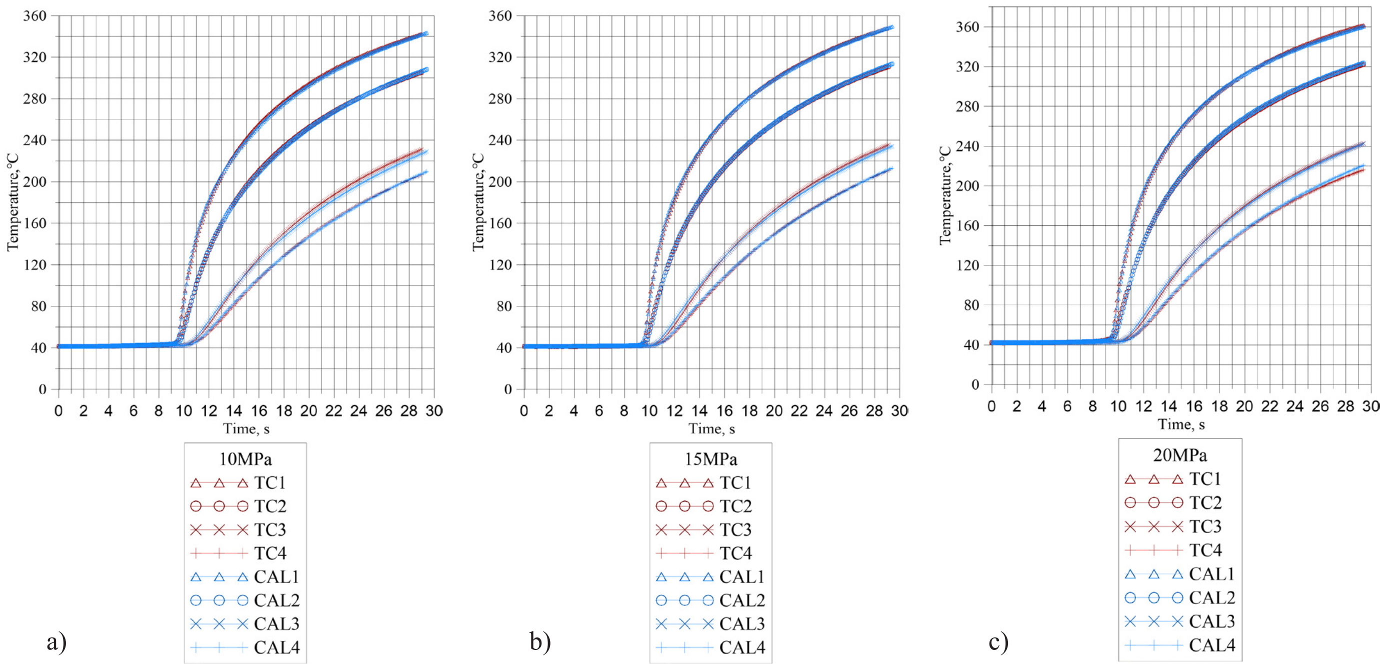

Fig. 2. Summary of measured (TC) and calculated (CAL) temperatures at individual points for different pressure forces: a) 10 MPa, b) 15 MPa, c) 20 MPa

(TC) and the temperatures obtained as a result of the calculations (CAL). It can be seen that in the case of pressures of 10, 15 and 20 MPa applied to the COLD sample, the course of changes in temperatures measured at specific points is consistent with the calculated temperatures.

The results of the heat flux density calculations determined from the inverse solution allow to determine the changes of heat fluxes exchanged between samples at different pressures. The value of the obtained heat transfer coefficient is strongly dependent on the value of the applied pressure during the process, as shown in Fig. 3. The increase in the applied pressure causes less abrupt changes in the value of the heat transfer coefficient. It is related to the lack of changes in the actual contact surface. In this and the experiment described by Rywotycki et al. [16] and others, a very high speed of pressure increase was used. As shown in Fig. 3, the rapid increase in the heat transfer coefficient took place within about 1 second. The nature of the curves slope in the graph is caused by the cooling of the HOT sample, which is due to the heat transfer mechanism.

The heat transfer dynamics is specific only to the sample system used in the experiment and cannot be generalized to other cases. In the case of a different size of samples, the obtained distribution of the heat transfer coefficient in time will not be correct. A better solution for presenting the results is to provide the calculated value distribution as a function of a parameter that is not directly related to the experiment specificity. It may be the sample surface temperature. The visualization of the heat flux density value depending on the surface temperature, as in Fig. 4,

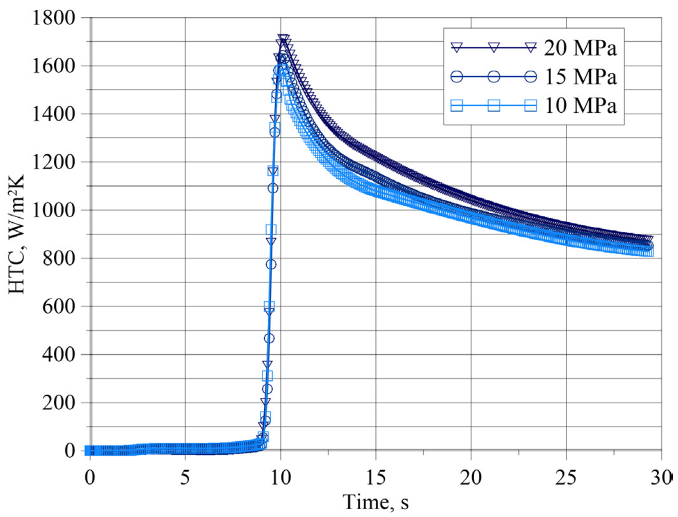

Fig. 3. The value of heat transfer coefficient as a function of time for different pressure forces

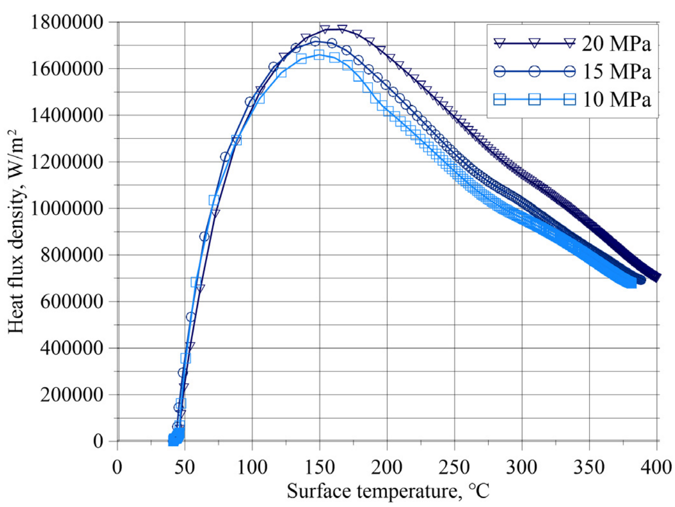

Fig. 4. The value of heat flux density as a function of surface temperature for different pressure forces

allows the obtained solution to be used for various sizes bodies. The increase in pressure applied to the COLD sample causes an increase in the heat flux exchanged between the surfaces. The maximum value of the heat flux occurs at a temperature of 150-160°C, depending on the pressure value.

5. Conclusions

Heat transfer in contact with solids is a common phenomenon in industrial processes. Determining the boundary conditions and their direct identification are difficult to implement, but necessary to obtain a correct solution of the temperature field. In order to solve this problem, models of the phenomenon are used, which require the performance of experimental tests on the stand and the use of numerical methods. The verification of models must be based on typical and easy-to-measure quantities in industrial processes. Temperature is such a quantity.

In this study, the heat transfer at the contact of two solids with a large temperature difference was investigated experimentally and computationally. As a result, the heat transfer coefficients from time for different pressure forces were determined. Along with the increase in the pressing force, the changes in the value of the heat transfer coefficient decreased over time, which resulted from the deformation of the surface layer of the contacting samples. The greater the value of the applied force increased the COLD sample temperature at the end of the process. The calculated temperature changes in the points compared to the measured temperatures mostly converged. On the basis of the obtained results, it is not possible to unequivocally state the correctness of the obtained solution. For this it is necessary to carry out the same calculations for the HOT sample.

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