The investigations described in the paper were related to the determination of the characteristics of a cylinder in the heat treatment to the temperature of 550 °C. The paper describes the design and principle of operation of the test stand. When preparing the experimental research, the authors included different forms of heat flow and their influence on the uneven cylinder heating. A forced flow of gas has been analyzed along with its impact on the heat flow in the tested cylinder. The investigations discussed in this paper aimed at finding the cross-section of the cylinder in which the heat conductance could be limited to radial direction. Distribution of temperatures has been analyzed during the heating process on the entire length of the cylinder. The results obtained in the experimental research will constitute a basis for the calculations of temperature distribution inside the cylinder during the heat treatment with the use of the inverse problem method.

Keywords: heat treatment, nitriding, heating of cylinders, flow of heat inside the furnace

1. INTRODUCTION

When carrying out a heat treatment, engineers aim at applying the highest possible heating rates to ensure the highest possible efficiency of the process avoiding the excess of the admissible thermal stresses. The users of furnaces also aim at filling the furnace with the maximum possible input, which is impactful on
its heating by increasing the heat flow resistance. In thermal-chemical processing such as carbonizing and nitriding, the control of the heating rate in the final stage of the process is important because this rate is decisive of the growth of the diffusive layer [8]. In thermal and thermal-chemical processing radiation has a significant share in the process of heat exchange. This causes problems with the measurement of temperature on the surface of the processed element [9, 12]. In such cases, the temperature of the edge can be determined from solving an inverse problem based on the measurement of temperature at points located inside the elements near the edge, on which the course of temperature is unknown [1, 11]. The analysis of the temperature measurement in solids and gases, including the ways of thermocouple fitting, has been presented in [11]. Some methods of solving a one-dimensional inverse problem of the distribution of fields of temperatures in cylinders have been presented in [3, 5, 6, 7] and for the cylindrical layer, in [2]. The analysis of the heat flow in industrial furnaces based on the mathematical models considering radiation has been described in [9, 10]. The paper presents the results of experimental research of a heat treatment of a cylinder. The distribution of temperature of the cylinder on its length during the heating process has been analyzed.

2. RESEARCH STAND

The tests of the cylinder heating process were performed in a VTR PP furnace (Fig. 1). This is a horizontal load type chamber furnace. The furnace is adapted for operation in an intermittent mode.

Fig. 1. The heating furnace
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The schematics of the furnace have been shown in Fig. 2. The wall of the working chamber of the furnace is cylindrical. The furnace is equipped with a cylindrical partition that, together with the wall of the working chamber, forms a channel in which the flowing gas heats up. The furnace has three heating zones, located every 120° on the circumference. Two of the zones are located symmetrically at the bottom of the working chamber. The third heating zone is located in the upper part. The measurement system of the furnace allows reading the temperature of the furnace and its input (10 thermocouples), percentage composition of the gases and pressure during the process. The heating and annealing temperature has been set according to the thermocouple measuring the temperature of the gas in the furnace. This thermocouple is fitted in the shield and put in the working space of the furnace (Fig. 3).

The investigations of the heating of a cylinder were carried out in the nitrogen atmosphere. The axis of the fan is not in line with the axis of the furnace. The direction of the gas flow has been marked with arrows. The furnace has a form of a return chamber (Fig. 2), in which the gas is sucked by the fan (Fig. 4) and then pushed through the ring-shaped return channel (Fig. 3) between the outer and inner walls of the furnace. The gas changes its flow direction at the doors. For the purpose of the research it has been assumed that the heat flow during heating of the cylinder is done through radiation of the furnace chamber walls as well as the gas surrounding the cylinder. The heat flow is also realized through forced convection of gas, whose flow is forced by the fan. The heated cylinder was placed so that its axis ran between the axis of the furnace chamber and the axis of the fan in a vertical plain. This solution aimed at ensuring optimum conditions on the circumference of the cylinder for the heat flow density to remain close to constant.

Fig. 2. Diagram of the furnace with the input and gas flow marked with blue arrow
The subject of the research was the determination of the temperature distribution inside a steel cylinder of a diameter \( D = 110 \text{ mm} \) and length \( L = 530 \text{ mm} \). During preliminary research, a heating to the temperature of \( T_{\text{max}} = 550 \degree \text{C} \) was carried out. The heating rate was assumed at 5 \( \degree \text{C/min} \). The fan speed was 50\% of its maximum speed of 2800 \( \text{rpm} \). The heating time from ambient temperature \( T_{\text{amb}} = 16.4 \degree \text{C} \) to maximum temperature of the process \( T_{\text{max}} = 550 \degree \text{C} \) was 23,160 seconds (6h 26`). The cylinder was placed in the furnace chamber in such a fashion as to minimize the heat flow in the supporting elements.
For the measurement of the cylinder temperature, nickel – chromium – nickel K type thermocouples were used. The holes for the thermocouples were made perpendicularly to the lateral surface of the cylinder, along its radius. The holes were of the diameter of 1.6 mm and depth of 4.5 mm. The location of the holes and numbering of the thermocouples in the cylinder have been shown in figures 4 and 5.

Thermocouples from T1 to T8 were placed in the cylinder and thermocouple T9 was located near the cylinder surface in the furnace atmosphere. The temperature of the gas was also measured with the thermocouple marked T_retorty that is a fixed component of the furnace and is covered with a pipe, as shown in Fig. 3. Insulation plates were fitted on the cylinder mounts (Fig. 4) to reduce the heat transfer through these surfaces.

3. RESULTS

The temperature values measured during the experiment for different measurement points (T_retorty, T1 – T9, Fig. 5) have been shown in Fig. 6.
Fig. 6. Temperature distribution in time for the thermocouples placed in the cylinder

The changes in the dimensionless temperature on the length of the cylinder for the times from 1000 s to 20 000 s every 1000 s have been shown in figures 7–10. After 4000 s we may observe a faster heating of the cylinder ends. On the cylinder side where the gas flew in, the intensification of heat exchange might have been caused by a thin wall layer and insufficient insulation. Greater heat exchange at the point where the gas flew out was caused by the detachment of the wall layer due to turbulence generated by the fan rotor. Uneven heating of the cylinder along its length resulted in the appearance of an axial component of the heat flow direction.

Fig. 7. Dimensionless temperatures along the cylinder axis for the heating times $t = 1000$ s, $t = 2000$ s, $t = 3000$ s, $t = 4000$ s and $t = 5000$ s
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Fig. 8. Dimensionless temperatures along the cylinder axis for the heating times $t = 6000$ s and $t = 7000$ s

Fig. 9. Dimensionless temperatures along the cylinder axis for the heating times $t = 8000$ s and $t = 9000$ s
4. CALCULATION MODEL OF HEATING OF CYLINDERS

The lines of temperature distribution for the heating times from 5000 s to 14 000 s have their minimum for approx. 320 mm, which is 0.6 of the length of the heated cylinder. In this area it was assumed that the lowest temperature gradient occurs along the axis of the cylinder, hence the smallest axial heat flow. Radiation models are burdened with significant error. To eliminate this error, the tests were performed so that the heat exchange analysis in the subsequent stage of the research would be carried out using the inverse problem method.

The process of heating of the investigated element can be described with a non-linear non-stationary equation of heat conductance in a limited area $\Omega$ [5]

$$\rho(T)c(T)\frac{\partial T}{\partial t} = \text{div} \left( \lambda(T) \text{grad}T \right), \quad t > 0, \quad (r,\varphi,z) \in \Omega \quad (1)$$

In the determined cross-section of the cylinder, in which the heat flow can be limited to radial direction, in equation (1) we may consider assumption $\frac{\partial T}{\partial z} = 0$. For a symmetric field of temperature we have $\frac{\partial T}{\partial \varphi} = 0$, hence equation (1) becomes a one-dimensional equation. Equation (1) can be reduced to a simpler form by applying the Kirchhoff’s substitution [4]
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\[ \mathcal{G} = \frac{1}{\lambda_0} \int_{T_e}^{T} \lambda(u) du = \frac{1}{\lambda_0} \int_{T_0}^{T} \lambda(u) du \]  

(2)

We obtain the following [4]

\[ \frac{1}{a \left( \mathcal{G}(T(r, \tau)) \right)} \frac{\partial \mathcal{G}(r, \tau)}{\partial \tau} = \Delta \mathcal{G}(r, \tau) \]  

(3)

where \( \Delta \) – Laplace operator, \( a \) – coefficient of temperature stabilization. The Kirchhoff’s substitution results in a shift of the linearity from under the operator of divergence in (1) to implicit function located in the denominator of the left side of the equation (3). In equations (1) and (3) the dependence of the heat conductance coefficient \( \lambda \) and specific heat \( c \) on the temperature have been considered. Based on the above assumptions and based on the inverse problem software [5] was developed serving the purpose of determining the temperature on the edge of the cylinder heated in a furnace designed for thermal and thermal-chemical treatment.

5. CONCLUSIONS

Based on the analysis described in the paper, in the cross-section in 0.6 L of the cylinder holes will be made for further stages of the experimental research. It will cover the analysis of heating in thermal and thermal-chemical processes. Temperature distributions and substitute coefficients of heat transfer will be determined using the inverse problem method.

REFERENCES


ANALIZA PROCESU NAGRZEWANIA WALCA

Streszczenie

Przedstawione w pracy badania dotyczą wyznaczenia charakterystyki nagrzewania walca w procesie obróbki cieplnej do temperatury 550 °C. W pracy opisano budowę i sposób działania stanowiska badawczego. W przygotowaniu badań eksperymentalnych uwzględniono różne formy przepływu ciepła oraz ich wpływ na nierównomierny proces nagrzewania walca. Przeprowadzono analizę przepływu gazu i jego wpływ na proces przepływu ciepła w piecu. Badania przedstawione w pracy miały na celu znalezienie przekroju walca, w którym przewodzenie ciepła może ograniczyć do kierunku promieniowego. Analizie poddano rozkłady temperatury na długości walca w procesie nagrzewania. Wyniki badań eksperymentalnych stanowią dane do obliczeń rozkładów temperatury w walce podczas procesów obróbki cieplnej z zastosowaniem metod zagadnienia odwrotnej.

Słowa kluczowe: obróbka cieplna, azotowanie, nagrzewanie geometrii walcowych, przepływ ciepła w piecu do obróbki cieplnej