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PROCESS CHECK OF ANNEALING PROCESS OF COILED SHEETS BY INDIRECT MEASUREMENT

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The contribution deals with a possibility of increasing quality production and decreasing costs in annealing furnaces by process check of annealing temperatures. The lowest temperature of annealed coiled sheets is very important. The information about this inner temperature is unknown during annealing. It is possible to obtain this information by indirect measurement. The indirect measurement uses two types of mathematical models. In this paper, the structure of both models and its verification is described.

Key words: sheet, annealing process, indirect measurement, mathematical models, verification

INTRODUCTION

Low carbon steel is the most common form of steel as it provides material properties that are acceptable for many applications. One way of establishing required material properties is heat treatment. The various heat treatment processes are annealing, normalizing, hardening, tempering, and surface hardening. It involves heating a material to above its recrystallization temperature, maintaining a suitable temperature, and then cooling. Heat increases the rate of diffusion [1-3] by providing the energy needed to break bonds. The high temperatures at which annealing occurs serve to accelerate this process. The temperature range for process annealing ranges from 260 °C to 760 °C, depending on the alloy in question. Usually, the annealing regimes are determined experimentally for specific carbon steel [4]. Here it is necessary to emphasize that today in steelworks the parameters of batch (diameters, heights, weight, quality,…) change very frequently. Then for each new kind of coiled sheet it is necessary to determine a new annealing regime. The second problem is checking these temperature regimes during annealing. Usually, only the temperature of annealing atmosphere is measured. However, the quality of annealing is given by minimal inner temperature in the steel coil which should be attained during hold time. The main objectives of this study are to investigate the nondestructive methods for measurement of temperatures inside the coiled sheet.

DIRECT MEASUREMENT OF TEMPERATURES

In this study a set of coiled sheets have been used, the density is 7,15 g/cm^3, where the chemical composition is in wt % (0,039 % C, 0,012 % Si, 0,265 % Mn, 0,006 % P, 0,013 % Cr, 0,014 % Ni, 0,03 % Cu, 0,005 % S, 0,057 % Al, 0,003 % N) and geometrical parameters are given in Table 1.

Table 1 **Dimensions of coiled sheets**

Coiled sheet	Height / mm	Full diameter / mm	Inner diameter / mm
1	1 400	2 010	600
2	1 400	1 990	600
3	1 400	2 020	600

The process of annealing consists of three stages (heating, holding and slow cooling) and the annealing regime is shown in Figure 1. Of course, this regime is valid for the annealing atmosphere under the cover. The investigated coiled sheets are stored on the stand of Bell furnace on top of each other.

63 thermocouples of type K were used, which are connected to a temperature module AT660.6. The measuring system consisted of the computer and a PLC with eight temperature modules 3AT660.6 (B&R 2005). Each module was enabled to combine with eight thermocouples. The communication between the PLC and

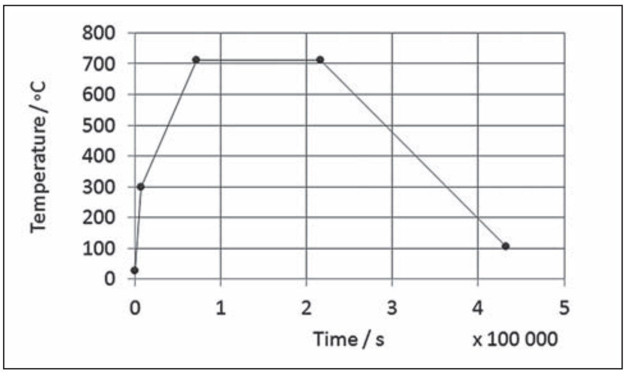

Figure 1 Annealing regime

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the computer was realized by a serial line (RS 232). The initialization of measurement, its control, data processing including data records was done by software application from the computer. Temperatures were measured on the surface, at the center of each steel coil and also the temperatures of annealing atmosphere. The temperature of annealing atmosphere (Ta) is measured under standard working conditions only. The thermocouple is placed between the coil and annealing cover. The location of measurement points in the coil space (Ta – T_{38}) is shown in Figure 2.

DEVELOPMENT OF INDIRECT MEASUREMENT OF TEMPERATURES

New methods of measurement, process control in various industry fields [5-6], including metallurgy are being developed at present [7-10].

In annealing of coiled sheets, from the standpoint of quality, it is necessary to know the temperature inside the coil because at that place the temperatures are the lowest during annealing. Of course, permanent direct inner temperature measurement is unrealizable in the production process. A workaround appears to be taking indirect measurements [10, 11]. Two methods of indirect measurement have been developed.

The first one is based on mathematical modelling of heat conduction through coiled sheet provided that its surface temperature t_s is directly measured during annealing. The initial temperature in the coil equals t_0 for time τ = 0. When the heating runs τ > 0, the boundary

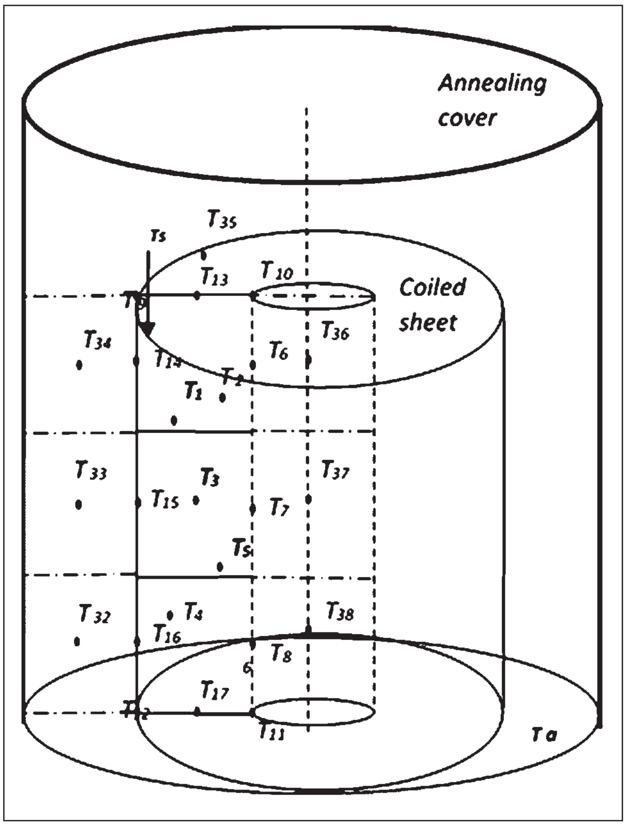

Figure 2 The scheme of thermocouple positions in coil space

conditions on coil surface is subjected to surface temperature (ts). In the unsteady-state heat conduction, the governing equation and boundary conditions could be expressed as shown below. The dynamic process of the heat conduction is given by Fourier partial equation (1) for rectangle with dimension d x h.

$$\frac{\partial t}{\partial \tau} \cdot c(t) \cdot \rho = \frac{\partial\left(\lambda(t) \cdot \frac{\partial t}{\partial x}\right)}{\partial x} + \frac{\partial\left(\lambda(t) \cdot \frac{\partial t}{\partial y}\right)}{\partial y} \qquad (1)$$

Where λ – heat conductivity of annealed coil / W×m^{-1} ×K^{-1}, c – heat capacity of annealed coil / J×kg^{-1} ×K^{-1}, ρ – density of annealed coil / kg ×m^{-3}, t – temperature / °C, x – horizontal axis /m, y – vertical axis /m, τ – time /s.

The measured surface temperatures are used for determining boundary conditions of first type by (2-5).

$$t(x,0,\tau) = ts_1(\tau) \quad for \quad x \in \langle 0, d \rangle \qquad (2)$$

$$t(x,h,\tau) = ts_2(\tau) \quad for \quad x \in \langle 0, d \rangle \qquad (3)$$

$$t(0,y,\tau) = ts_3(\tau) \quad for \quad y \in \langle 0, h \rangle \qquad (4)$$

$$t(d,y,\tau) = ts_4(\tau) \quad for \quad y \in \langle 0, h \rangle \qquad (5)$$

Where d is the width of annular area of coil / m, h is the height of coil / m.

The functions ts_i (2-5) for i = 1, … , 4 were obtained from measured temperatures on the surfaces of coil (see Figure 2).

Mathematical model given by (1) – (5) was solved by elementary energy balance method with different heat conductivity because there are lacunae between convolutions of annealed coils. Seeing that the batch is anisotropic (unequal size of the gaps between single spire), the method was adjusted so that it was possible to determine heat conductivity in the direction of axis *x*. The values of heat conductivity as function of temperature and chemical composition were adjusted in numerical solution [10] according to formula (6)

$$\lambda_{ef} = \frac{d_s + d_g}{\frac{d_s}{\lambda_o} + \frac{d_g}{\lambda_p}} \qquad (6)$$

where λ_{ef} is the thermal conductivity for the steel layer and gas gap / W×m^{-1}×K^{-1}, λ_0 is thermal conductivity of the steel as function of temperature and composition / W×m^{-1}×K^{-1}, λ_p is thermal conductivity of infilling gas / W×m^{-1}×K^{-1}, d_s is the average thickness of the coil's sheet / m, d_g is the average thickness of the coil's gaps /m.

In the direction of axis *y* the values of heat conductivity were used in dependence on chemical composition and temperature of the annealed coil. The average thickness of the coil's gaps has been determined according to relationship (7)

$$d_g = \frac{d - N d_s}{N - 1} \qquad (7)$$

where N is the number of convolutes in coil.

The behavior of calculated temperatures according to mathematical model (1) – (7) and directly measured

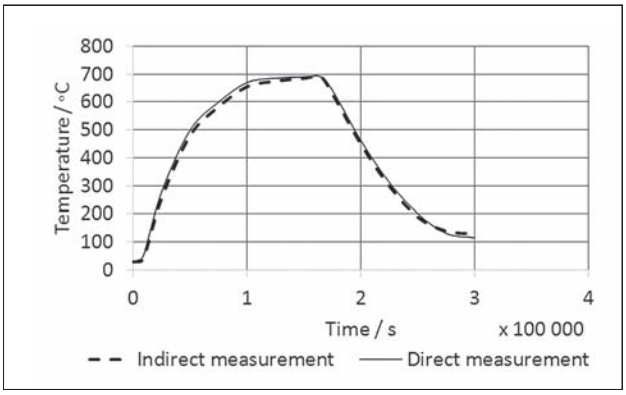

Figure 3 Comparison of directly and indirectly measured temperature in point T_3 for coiled sheet 1

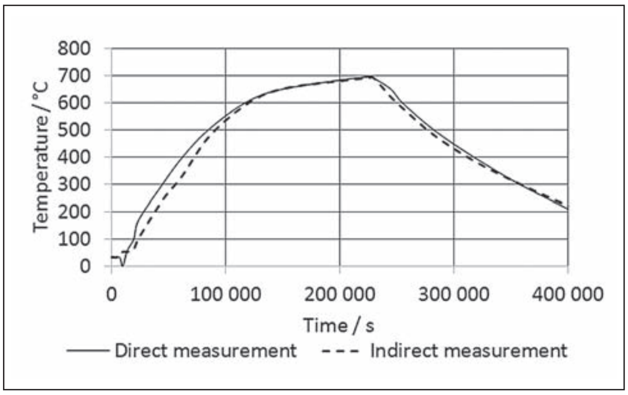

Figure 4 Comparison of directly and indirectly measured inner temperature in point T_1 for coiled sheet 2

temperatures in the first coil is shown in Figure 3. In other words, the inner temperature is obtained by software which is based on mathematical model (1) – (7). This software has carried out so called indirect measurement of inner temperatures. The lowest temperature has been measured during the entire holding stage of annealing at the center. The position of thermocouples is designated as T_3 in Figure 2.

In the first stage a model was created for indirect measurement of inner temperatures if surface temperatures of coils (ts_i) are directly measured. A disadvantage of this method is the need of thermocouples for surface temperature measurement, and that the location of these thermocouples must be in close contact with coil surfaces and also that their destruction can occur during replacement of annealing cover. Therefore, another approach was developed for elimination of this disadvantage.

The second variant has been designed with the aim to indirectly measure surface temperatures of each coil. The following differential models for indirect measurement of surface temperatures of coils were considered.

$$ts_{ij}[k] = a_{0ij} + a_{1ij} \cdot t_a[k] \quad (8)$$

$$ts_{ij}[k] = a_{0ij} + a_{1ij} \cdot t_a[k] + a_{2ij} \cdot t_a^{2}[k] \quad (9)$$

$$ts_{ij}[k] = a_{0ij} + a_{1ij} \cdot t_a[k] + a_{2_{ij}} \cdot t_a^{-1}[k] \quad (10)$$

$$ts_{ij}[k] = a_{0ij} + a_{1ij} \cdot t_a[k] + a_{2ij} \cdot t_a^{2}[k] + a_{3ij} \cdot t_a^{3}[k] \quad (11)$$

$$ts_{ij}[k+1] = a_{0ij} + a_{1ij} \cdot T_a[k+1] + a_{2ij} \cdot T_a[k] + a_{3ij} \cdot T_a^{2}[k] \quad (12)$$

$$ts_{ij}[k+1] = a_{0ij} + a_{1ij} \cdot t_a[k+1] + a_{2ij} \cdot t_a^{2}[k+1] + a_{3ij} \cdot t_a[k] + a_{4ij} \cdot t_a^{2}[k] \quad (13)$$

where ts_{ij} are calculated surface temperatures / °C, i is the index of surface point in coil j, k is the time step / -, t_a is measured temperature of annealing atmosphere (see thermocouple position Ta in Figure 2) / °C, a_0, a_1, a_2, a_3, a_4 are coefficients / -.

The matrix coefficients $\boldsymbol{a}$ in the models (8) – (13) for indirect measurement of surface temperatures were calculated by using the least square methods. The square of deviations between measured and model surface temperature [10] was minimized. The best results for indirect measurement of surface temperatures were reached by differential model (11) from the standpoint of accuracy. Then at each time step the model (11) calculating surface temperatures and these data are inputs for model (1) – (7) which calculates inner temperatures in coils. It is fundamental for indirect measurement of inner temperatures in coils during annealing process.

The behavior of directly and indirectly measured inner temperature inside the coil is shown in Figures 4 – 5 for the second coiled sheet because in this coil the inner temperatures were the lowest in comparison with other coils.

By comparing Figures 4 and 5 it is apparent, that the lowest temperature according to direct and indirect measurement is in the coil center (position T_3) again. Of course, the second variant of indirect measurement is less accurate than the first variant. The average relative deviation for temperature T_3, which is the closest to the coolest spot in the coil is 5,28% during the entire cycle. It should be emphasized that during the temperature equalization stage (holding stage) the model yielded continually lower temperature than that directly measured. It means that in the case of its usage for indirect measurement the quality of heating is always maintained (the temperature of recrystallization is reached).

In order to reach the recrystallization temperature in the entire load, the temperature at the coolest spot must reach the so-called cold-spot temperature (see Figure 5)

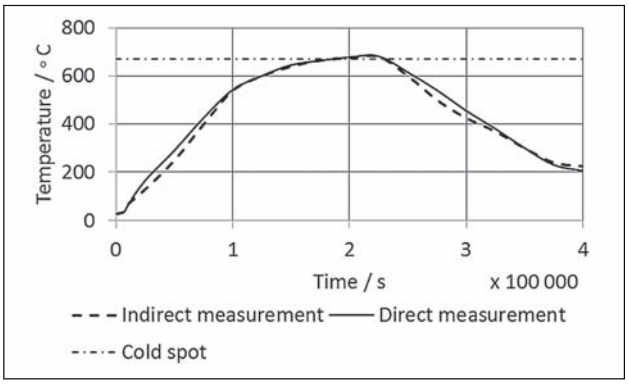

Figure 5 Comparison of directly and indirectly measured inner temperature in point T_3 for coiled sheet 2

which, in this mode was 670 °C. If the system of indirect measurement was used then the period of holding could be reduced by 3,6 hours in this annealing cycle.

CONCLUSIONS

The model of indirect measurement of inner temperatures enables to find out information about the lowest temperature inside of annealing coils in real time. The contribution of indirect measurement of inner temperatures during their annealing in bell furnaces can be analyzed from the viewpoint of quality of production and economy. From the viewpoint of quality the main contribution is the guarantee of the coils reaching the recrystallization temperature at the coldest spot. The economic merit can be determined on the basis of reducing the holding time (increase in productivity of annealing operation and saving heating gas).

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Note: The responsible translator for English language is Ladislav Pivka, Košice, Slovakia