Journal of Engineering Physics and Thermophysics, Vol. 68, No. 1, 1995

DEVELOPMENT OF A METHOD OF HEAT TREATMENT OF METALS IN SOAKING PITS IN THE BAR-ROLLING SHOP OF THE BELARUSIAN METALLURGICAL WORKS

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UDC 621.1.0.18

The problem of constructing a method for heat treatment of metals in soaking pits is considered and solved. Procedures of optimum heating and cooling of blanks are presented. Results of numerical calculations are given.

At the Belarusian Metallurgical Works there are soaking pits intended for heating and controlled cooling of rolled alloyed steels.

The purpose of heat treatment is to prevent defects (flakes and cracks) and to soften metals to the level admitting machining. The heat treatment should result in a metal lattice of the blank that would ensure required properties of ready workpieces.

Experimental studies have revealed substantial deviations of the work of the programmer and the automatic control system from preset operation, which, in turn, increases the amount of gas spent in the production process. This has led to the need to develop mathematical models and algorithms for determining optimum processes.

The heat treatment process consists of the following stages:

heating of blanks to soaking temperatures for a prescribed time;

soaking of metal at a controlled temperature;

cooling of blanks to temperatures of delivery at a preset rate.

In the present work the above set of problems is solved in succession.

The scheme of charging a pit for controlled cooling with internal recirculation of gases and the locations of control thermocouples are shown in Fig. 1. Experiments revealed an insignificant temperature drop over the cross section of blanks, and therefore the problem of heating in the pit is presented in the form [1, 2]:

$$\frac{dT_g}{dt} = A_1 U - A_2 T_g - A_3 (T_g - T) , \quad \frac{dT}{dt} = \mu (T_g - T) , \tag{1}$$

$$T_g (0) = T_{g0} , \quad T (0) = T_0 , \quad T (t_k) = T_k . \tag{2}$$

The gas flow rate is prescribed by [2]

$$I = \int_0^{t_k} U \, dt . \tag{3}$$

It is assumed that $t_k > t_{\min}$ and $A_3 > A_2$:

$$U_h \le U (t) \le U_k . \tag{4}$$

Using results of [3–5], it is possible to show that optimum heating of metal to soaking temperatures has three intervals of constancy of the gas flow rate.

Belarusian State Polytechnic Academy, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 1, pp. 117-122. Original article submitted March 29, 1993.

 1062-0125/95/6801-0110$12.50 ©1995 Plenum Publishing Corporation

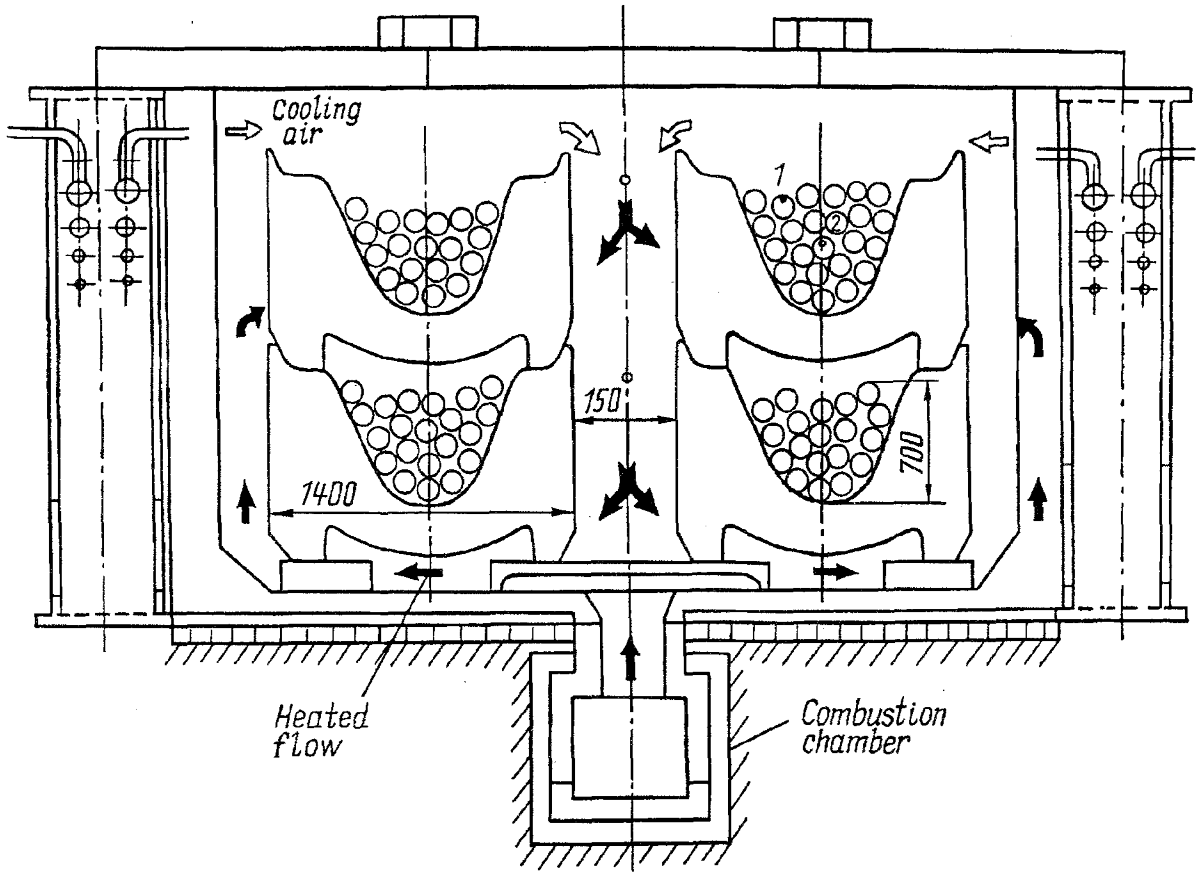

Fig. 1. Schematic of charging a controlled cooling pit: 1) upper surface of the pile; 2) center of the pile.

Our next task is to investigate the following problems:

1. If maximum temperature nonuniformity over the pile ΔP is prescribed, it is necessary to determine the minimum soaking time in order that the temperature nonuniformity over the pile be at most ΔP by the end of soaking and a minimum gas flow rate be ensured.

2. It is necessary to determine the changes in the temperature of the working space of the pit and in the gas flow rate that would ensure the above conditions of heating.

The first problem will be considered now. Since, on the one hand, during soaking the temperature of the working space should be equal to the soaking temperature T_s and, on the other, by the time t_k (the time of the end of optimization) $T_g(t_k) > T_s$, initially the temperature of the working space should be decreased to T_s. From the condition of stability of refractories in the pit we have the following restriction

$$\frac{dT_g}{dt} \geq V,$$

where $V < 0$ is a constant the prescribing the maximum rate of decrease of the temperature of the working space in 1 h of cooling. From the conditions of stability of the lining $V = -30^{\circ}\mathrm{C/h}$ is adopted. It is also clear that if the metal is cooled at the maximum rate, i.e.,

$$\frac{dT_g}{dt} = V, \tag{5}$$

then the gas flow rate and the cooling time t_c will be minimum. The cooling time t_c will be found now.

From Eq. (5) we have

$$T_g(t) = V(t - t_k) + T_g(t_k), \tag{6}$$

where $T_g(t_k)$ is the temperature of the working space at the end of heating. Next, the following relation will be written:

$$T_g(t_c) = T_s,$$

whence

$$t_c = \frac{T_s - T_g(t_k)}{V} + t_k. \tag{7}$$

In this stage the gas flow rate U_c and the temperature of the metal T_c are found from the relations

$$A_1 U - A_2 [V(t - t_k) + T_g(t_k)] - A_3 [V(t - t_k) + T_g(t_k) - T)] = V,$$

$$\frac{dT}{dt} = \mu [V(t - t_k) + T_g(t_k) - T)], \quad t_k < t \le t_c;$$

the temperatures $T_g(t_k)$ and $T(t_k)$ are specified. We obtain

$$T_c(t) = \left[T(t_k) - T_g(t_k) + \frac{V}{\mu} \right] \exp(-\mu(t - t_k)) +$$

$$+ V(t - t_k) + T_g(t_k) - \frac{V}{\mu},$$

$$U_c(t) = [V + A_2 T_g(t) + A_3 (T_g - T)]/A_1, \quad t_k < t \le t_c.$$

It should be noted that the temperature of the working space is determined by relation (6), and the time t_c by Eq. (7).

Thus, it is necessary to provide that the temperature of the working space be equal to the control temperature. Since soaking starts from the cooling time t_c, in view of Eq. (1) and the initial conditions at the time $t = t_c$, we obtain relations for determining the gas flow rate $U_s(t)$, the temperature of the working space $T_{g.s}(t)$, and the temperature of the metal $T_s(t)$ for the soaking time:

$$T_{g.s}(t) = T_s, \quad A_1 U(t) - A_2 T_s - A_3 (T_s - T) = 0, \quad \frac{dT}{dt} = \mu (T_s - T),$$

$$t_c < t \le t_s, \quad T(t_c) = T_c(t_c),$$

whence

$$T_s(t) = [T(t_c) - T_s] \exp(-\mu(t - T_c)) + T_s,$$

$$U_s(t) = \frac{A_2}{A_1} T_s + \frac{A_3}{A_1} (T_s - T_s(t)), \quad t_c < t \le t_s.$$

The optimum condition for heating will be denoted by $\overline{U}(t)$, $t \in [0, t_k]$. In this case the gas flow rate $\tilde{U}(t)$, $t \in [0, t_s]$ will be specified on the basis of the relation

$$\tilde{U}(t) = \begin{cases} \overline{U}(t), & 0 \le t \le t_k, \\ U_c(t), & t_k < t \le t_c, \\ U_s(t), & t_c < t \le t_s. \end{cases} \tag{8}$$

Using conditions (2) and changing the coefficient μ: $\Delta\overline{P}(t_c) = |T(t_s) - T_h(t_s)|$, where $T(t_s)$ and $T_h(t_s)$ are the temperatures of the metal obtained by solving of the equations ($T_h(t)$ is the temperature at the center of the pile of blanks), we determine from Eq. (1)

$$\frac{dT_g}{dt} = A_1\tilde{U} - A_2T_g - A_3(T_g - T), \quad \frac{dT}{dt} = \mu(T_g - T),$$

$$\frac{dT_h}{dt} = \bar{\mu}(T_g - T_h), \quad 0 < t \le t_s,$$

with the initial conditions

$$T_g(0) = T_{g_0}, \quad T(0) = T_0, \quad T_h(0) = T_0$$

(it is assumed that all the blanks have the same initial temperature). Here $\bar{\mu}$ is a positive constant that characterizes the dynamics of the heating process at the center of the pile of blanks. Then, the minimum soaking time is the minimum time $\bar{t}_s$ when

$$\Delta\bar{P}(\bar{t}_s) \le \Delta P. \tag{9}$$

Here ΔP is the specified admissible nonuniformity of the temperature over the pile.

Thus, we have Eq. (9), and the soaking time will be determined after the minimum root of the equation has been found. In particular, Eq. (9) can be solved using the method of division of the segment $[t_c, t_0]$ into two parts. Here t_0 is the time that *a priori* provides soaking with the nonuniformity ΔP over the pile (ΔP is a rather large value).

Then, the process requires cooling of the metal to the temperature T_n: $T_n < T(\bar{t}_s)$, $T_n < T_h(\bar{t}_s)$ with prescribed nonuniformity of the temperature over the pile ΔP_0 at the end of the process. Now, we will determine the shortest cooling time of the pile to the temperature T_n. With saving of gas in view, from the conditions of stability of the lining we will write as before

$$\frac{dT_g}{dt} = V$$

until the time $\hat{t}$ at which the temperature of gas cooling T_n that is suitable for this operating condition becomes equal to T_n. We find

$$\bar{t}_s < t \le \hat{t}, \quad T_g(t) = V(t - t_s) + T_g(\bar{t}_s), \quad T(t) = \left[T(\bar{t}_s) - T_s + \frac{V}{\mu}\right] \times$$

$$\times \exp(-\mu(t - \bar{t}_s)) + V(t - \bar{t}_s) + T_s - \frac{V}{\mu},$$

$$U(t) = [V + A_2T_g(t) + A_3(T_g - T)]/A_1, \quad \hat{t} = \frac{T_n - T_g(\bar{t}_s)}{V} = \bar{t}_s.$$

Then, we find the minimum time t_1 that provides the temperature of the pile T_n with an error of at most ΔP_0. In this stage the calculation formulas have the form

$$T_g(t) = T_n, \quad A_1U(t) - A_2T_n - A_3(T_n - T) = 0,$$

$$\frac{dT}{dt} = \mu(T_n - T), \quad \hat{t} < t \le t_1, \quad \frac{dT_h}{dt} = \bar{\mu}(T_n - T_h);$$

where $T(\hat{t})$ and $T_h(\hat{t})$ are prescribed.

Thus, the process is divided into a number of stages:

(a) optimum heating to the temperature of the metal $T_k = T_s$: $0 \le t \le t_k$;

(b) cooling of the medium to the soaking temperature T_s: $t_k < t \le t_c$;

(c) soaking at a temperature of the medium equal to T_s: $t_c < t \le t_s$;

(d) cooling of the medium to the temperature of metal discharge T_n: $\bar{t}_s < t \le \hat{t}$;

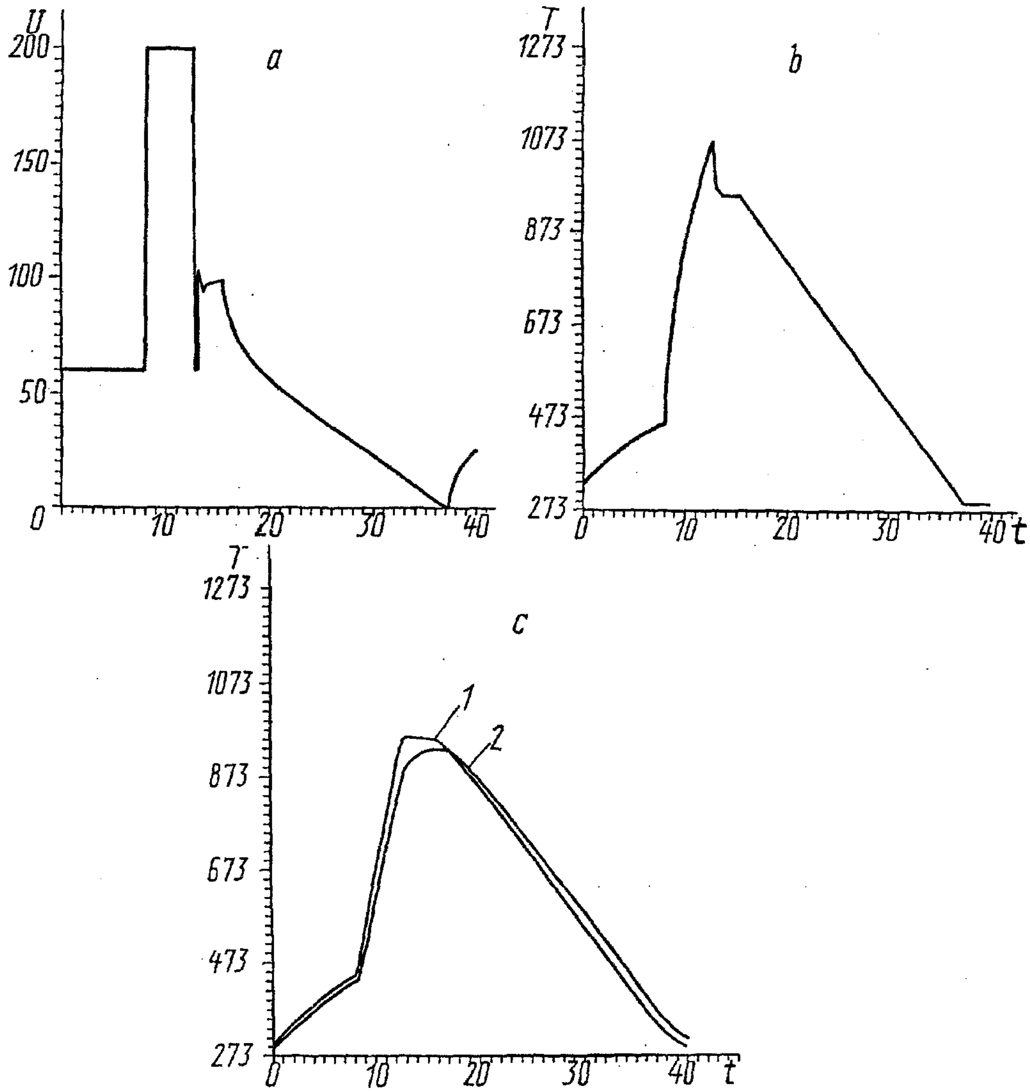

Fig. 2. Plot of changes in the gas flow rate (a), the temperature of the medium (b), and the temperature of the metal in the pit. U, m^3/h; T, K; t, h.

(e) soaking at a temperature of the medium equal to T_n: $\hat{t} < t \le t_1$.

A PC program has been developed that covers stages (a) to (e).

The following procedure for heating of metal has been calculated: heating of the metal to the soaking temperature 680°C for 13 h and cooling to the temperature 20°C at the rate 30°C/h.

The coefficients are obtained in the experiments. They are as follows:

$$A_1 = 6.11\ {}^{\circ}\mathrm{C/h}, \quad A_2 = 0.638\ \ 1/\mathrm{h}, \quad A_3 = 3.45\ \ 1/\mathrm{h},$$

$$\mu = 0.65\ \ 1/\mathrm{h}, \quad \bar{\mu} = 0.464\ \ 1/\mathrm{h}, \quad t_k = 13\ \ \mathrm{h}, \quad T_0 = 20\ {}^{\circ}\mathrm{C}, \quad T_{g_0} = 50\ {}^{\circ}\mathrm{C}, \quad U_h = 60\ \ \mathrm{m^3/h},$$

$$U_k = 200\ \ \mathrm{m^3/h}, \quad V = -\ 30\ {}^{\circ}\mathrm{C/h}, \quad \Delta P = 10\ {}^{\circ}\mathrm{C}.$$

$$\Delta P_0 = 10\ {}^{\circ}\mathrm{C}, \quad T_s = 680\ {}^{\circ}\mathrm{C}, \quad T_n = 20\ {}^{\circ}\mathrm{C}.$$

The total time of the process is 40.02 h and the total amount of gas spent in the process is 2537 m^3.

The gas flow rates and the temperature of the medium are shown in Fig. 2a, b and the temperatures of the most (1) and least (2) heated blanks in the pile are shown in Fig. 2c.

Thus, an algorithm has been constructed for calculating the optimum heat treatment of metal in a pit that ensures satisfaction of the main process requirements. Results of the work have been used by the Belarusian Metallurgical Works and have allowed a substantial decrease in the amount of gas spent in the process.

NOTATION

t, time; T_g, $T(t)$, temperatures of the heating medium and the metal, respectively; $U(t)$, gas flow rate at the time t; t_k, time of heating of the metal to the soaking temperature; μ, A_1, A_2, A_3, positive constants characterizing the dynamics of the heating process; U_h, U_k, minimum and maximum gas flow rates; $t_{\min}$, minimum time of heating of the metal to the temperature T_k.

REFERENCES

1. G. V. Trubitsyn and G. V. Sotnikov, Izv. VUZov, Chyorn. Metallurg., No. 12, 103-107 (1983).
2. A. G. Butkovskii, S. A. Malyi, and Yu. N. Andreev, Control of Heating of Metal [in Russian], Moscow (1981).
3. F. M. Babushkin, V. B. Kovalevskii, and O. Yu. Sedyako, Inzh.-Fiz. Zh., **61**, No. 2, 199-203 (1991).
4. V. B. Kovalevskii and V. I. Panasyuk, Avtomatika, No. 4, 23-29 (1992).
5. V. I. Timoshpol'skii, A. B. Steblov, V. B. Kovalevskii, et al., Technology of Metallurgical Mini-Works [in Russian], Minsk (1992).