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The Design of In-Line Temperature Control Systems for Bar Mills

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Abstract: This study presents a workable, cost-effective proposal for eliminating the thermal distortions observed during production of rolled steel bars in billet mills. Manipulation of the temperature distributions in the workpiece to produce the desired shape of the final product was achieved through control of the heat supplied to a thermal housing designed for installation on the cooling bed to enhance homogenization of the heat flow across the dimensions of the product as it cools down from the final rolling temperature of about 900°C. The control system matches the changes in the operation of the rolls by introducing the concept of residence time the effect of which was the ultimate homogenization of the product temperature and elimination of the internal stresses.

Key words: Control system design, thermal housing, spatial heat flow, temperature distributions, temperature control

INTRODUCTION

Control of heat flow in a bar mill of unknown transfer functions is reported in our research findings for Delta Steel Rolling mill at Aladja, Warri, Nigeria. Bar mills operate in continuous mode to produce light sections. Steel billets delivered from the re-heating furnace are rolled from stand to stand through the several roll-stand passes that make up the mill train. Each roll stand is 2 high and the barrels of the rolls are profiled obviously because of the design to produce a vast configuration of sections ranging from circular to asymmetrical shapes such as channels, U- and I-beams, T-sections and angled bars. The rolling process is a complex phenomenon with a large amount of uncertainties in terms of pressure and temperature distributions in the workpiece, as well as spread of the material in the roll gap during the deformation. Consequently, control of the internal stress and temperature distributions responsible for the shape of the final product poses a problem of considerable interest to the operators of the plant.

Efficient management of the rolling process requires proper selection of the best values of the operating parameters, taking into account the various economic and technological constraints. Typically, the number of these parameters and constraints can be very large, thus rendering the mill amenable to irrecoverable losses if drastic control measures are not incorporated.

In general, rolled steel is said to have a good dimensional tolerance if it is free from thermal distortion effects on exit from the cooling bed and after any subsequent cutting into sections. Distortion of rolled steel is generally caused by differential thermal expansion (Spivakov *et al*., 1983) due to non-uniform heat distributions, inhomogeneity in the metallurgy of the workpiece, non-uniform lubrication of the moving parts and physical characteristics of the rolls namely, roll wear, roll deflection and roll thermal camber.

Steel bars are rolled in the temperature range 1000-900°C, the workpiece being pre-heated initially to a higher temperature of about 1200°C to allow for the losses due to water quenching effects in the roll gaps. It is noted (Yu and Sang, 2007; Yang and Lu, 1986) that the precise pre-heat temperature and the pattern of distribution of heat in the workpiece are unclear for a given material composition of the steel. This is a serious shortcoming in the operation of the plant because the increase in the resistance to deformation imparted to the workpiece by relatively slight reductions in temperature can result directly in significant variations in the power required for rolling, because it is the ease with which hot steel can be made to flow plastically in the desired directions in the roll gaps.

Temperature control, which is a common phenomenon in hot rolling process, refers to control of the internal stress distribution in the rolled steel so that

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sections will lie flat on a flat surface when the temperature has attained the ambient value. In bar mills, the product arrives on the cooling bed at a temperature of about 700°C after it had been cut, at the pendulum shear station some 200 m upstream the mill train, to the required final length. These bars are fairly long (about 66 m) and in most cases, are so badly warped on the cooling bed that skin-pass rolling in the straightening machine often produces no appreciable effects. The mill is thus saddled with a two-pronged temperature-dependent problems:

- Continual roll breakages, which are caused in part by cyclic thermal stresses set up by non-uniform cooling of the rolls during rolling and the asymmetrical torques called into play when deforming billets of varying temperature values.
- Shape distortion of the rolled steel especially in thin sections (≤6 mm), which leads to a high rate of product reject at the dispatch stand of the cooling bed. The thermal stresses are due to uncontrolled cooling of the workpiece from the final rolling temperature of about 700°C to the ambient value. The critical elasto-plastic temperature range (600-300°C), adversely affects the shape of the final product. It has been observed (Pedersen, 1999) that a temperature gradient even as low as 10°C mm^{-1} across the product dimensions is capable of producing a stress gradient of 2.3 kgf mm^{-2} in a normal carbon steel of coefficient of linear expansion of 11×10^{-6} and Young's Modulus of 21×10^{3} kgf mm^{-1}. This value is, on its own, large enough to generate permanent distortion in the product during uncontrolled cooling.

Because of uncontrolled cooling, poor dimensional tolerance of the final product causes large recycle streams of scrapped rolled steel to be generated at the cooling bed of the mill. The transient heat flow in a rolling process must therefore be subjected to rigorous control in order that the customers' requirements may be met at minimum possible cost. Any variation in the thermal condition of the workpiece from an optimal level will correspondingly affect the effectiveness of heat extraction strategy, giving rise to a number of problems. Obinabo (1991) shows that these thermal stresses were not fully relaxed before the product arrived on the cooling bed and could therefore be the major cause of these defects.

In this study, an in-line temperature control system is proposed for eliminating these effects by homogenizing the temperature distributions in the workpiece in the mill train as it cools down from the rolling temperature of about 900°C to the ambient value.

CHARACTERISTIC THERMAL DISTORTIONS IN ROLLED BARS

One of the causes of thermal stresses in hot-rolled steel is non-uniform cooling. As the temperature of the workpiece approaches the ambient value, the fibres of the steel contract. In a continuous body this contraction cannot generally proceed freely and stresses due to the cooling are set up. These stresses are influenced principally by the temperature and material composition of the steel. In this study, measurements are made of typical shape distortions associated with steel rolling in bar mills. Here, we refer to sideway bowing of the workpiece as camber defect and upward bowing as banana or turn up defect.

General data:

Profile:	Angled bars.
Product length:	66 m.
Length of the cooling bed:	72 m.
Distance apart between two products on the cooling bed:	20 mm.
Product resident time on the cooling bed:	30 min.
Number of products sampled:	50
Mode of sampling:	Random.
Other information:	Forced convection fans and water sprays were installed underneath the cooling bed.

Camber defects: The locations on the product where these defects predominate as well as their dimensions are indicated as follows:

Average number of camber in each bar:	3.
Average locations of these defects along each bar:	Both ends and approximately half way along the length of the bars.
Average difference in lengths between the outer and inner fibres of the cambered sections:	0.05 m.
Average chord length of camber:	Varies randomly from 4-22 m
Average deviation from straightness:	0.23 m

Turn up (banana) defects: These defects are visible only at both ends of the rolled product and are manifested each time the product is cut into sections during cooling on the bed. There are analogies associated with this defect: the burning of a match stick at one end, for example, causes large temperature differential to be set up between any two adjacent sections along the length of the stick. Consequently, the burning match stick curls up and breaks. Another analogy is to do with the emerging metallic chip during cutting on a lathe machine. In this operation, the chip curls upwards away from the cutting tool. A corrective action to keep the chip straight as it cools down from the temperature of the cutting interface would require some restraining action. When this action is in place, the chip would subsequently remain perfectly straight when the ambient temperature is attained.

The turn-up (*banana*) shape defect in the rolled steel is thermally induced and aggravated by the cutting action before the workpiece is allowed to cool down to the ambient temperature. The pendulum-shearing machine normally located at the exit of the last finishing stand of the mill train cuts the product to its final lengths. The location of the shearer and the timing of the cutting action are such that the induced stresses due to deformation in the roll gaps are not allowed sufficient time to relax.

THE HEAT FLOW CONTROL PROBLEM

A model of thermal housing for temperature homogenization of the workpiece in the mill is proposed here for application to our model. A pneumatic control system which uses air as the control medium (Obinabo, 1991) and which finds considerable application in the process control field is proposed because of its reliability. The operation of a pneumatic controller is based on flapper-nozzle principles and is similar to the operation of a leakage-free, spring-controlled piston, using bellows as a transducer for converting the pneumatic pressure to mechanical motion. The exchange of heat between the workpiece and the housing is defined mathematically as follows:

$$q = c\left(\theta_h - \theta_s\right) \qquad (1)$$

where, c is a constant of proportionality, θ_h is the temperature of the housing and θ_s is the temperature of the sample. The thermal housing eliminates the high degree of distortion experienced during production of all profiles in the mill by regulating the interstand temperature as the workpiece cools down from the rolling temperature of 900°C on the cooling bed. The rate of heat accumulation in the sample is defined as follows:

$$C(\theta_h - \theta_S) \ = \ k\frac{d\theta_s}{dt}$$

from which a simple exponential lag was obtained as follows:

$$\frac{\theta_s}{\theta_h} \ = \ \frac{1}{1 + \tau s} \qquad (2)$$

where, τ = (K/C) is the time constant of the system and s = (d/dt) the Laplace variable. Now let q represent the pressure in the bellows and A the surface area. Taking moment about the pivot gives (Obinabo, 1991):

$$k(x - y)a = Aqb \qquad (3)$$

where, k is the spring stiffness. Also *x* is proportional to the temperature setting θ_i. Hence, the following was obtained

$$x = k_i\,\theta_i \qquad (4)$$

If the volume of the bellows were denoted by V, then we may write as follows

$$\begin{aligned} &q = f(\theta_S, V) \\ \text{or} \quad &q = k_1\theta_S \ - \ k_2 V \end{aligned} \qquad (5)$$

where, $k_1 = (\partial q/\partial\theta)$ and $k_2 = (\partial q/\partial v)$ represent small disturbing changes in the process parameters (θ_s and V) required to operate the bellows. The negative sign in the equation arises because the pressure *q* decreases as the volume increases. The equations of motion were obtained for the linkage as follows:

$$v \ = \ -k_3 z \qquad (6)$$

and

$$\frac{z}{y} = \frac{b}{a} \qquad (7)$$

Eliminating x and q from Eq. 3-7 yields the following:

$$akk_i\theta_i \ - \ kay \ = \ Abk_1\theta_S \ + \ \frac{Ab^2 K_2 K_3 y}{a} \qquad (8)$$

if c represents the opening of the flapper and r the distance swept when the response of the system is measured, the following equation would result:

$$r = \left(\frac{c + b}{a}\right)y \qquad (9)$$

From Eq. 8-9,

$$akk_i\theta_i \ - \ Abk_1\theta_S \ = \ \frac{Ab^2 K_2 K_3 y}{a} \qquad (10)$$

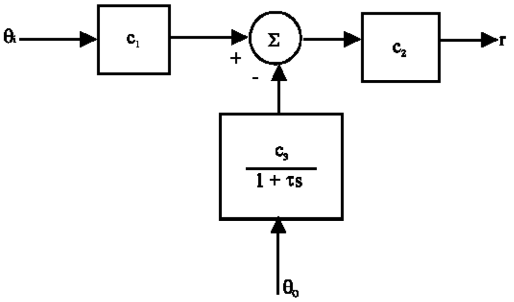

Fig. 1: Representation of the heat flow process in the thermal housing

For negligible disturbance input to the system, Eq. (2) and (10) gave the block diagram shown in Fig. 1, where,

$$c_1 = kk_1a, c_2 = \frac{c+b}{Ab^2K_2K_3 + ka^2}, c_3 = Abk_1$$

With zero input to the system (i.e. $\theta_i = 0$) the following was obtained:

$$\frac{r}{\theta_o} = \frac{c_2\,c_3}{1+\tau s} \tag{11}$$

Thus, with the input dial fixed, $\theta_i = 0$. Consequently, Fig. 1 becomes reduced to Fig. 2.

At steady state, s = 0 so that Eq. (11) becomes

$$\frac{r}{\theta_o} = c_2\,c_3 \tag{12}$$

From the plot of the average data obtained from the monitoring of the cooling samples (Obinabo, 1991), θ and r were obtained as 800°C and 27 cm, respectively. Thus $C_2C_3 = 0.034$ cm /°C. With introduction of a controller $G_c(s)$ in the forward path of the control loop, the overall open-loop transfer function becomes:

$$G(s)H(s) = \frac{c_2\,c_3}{1+\tau s}.G_c(s) \tag{13}$$

where, C_2C_3 is the system gain constant and $G_c(s)$ the proportional controller given by K_P. The output from the measuring sensor in the feedback loop is compared with the set point. The feedback element H(s) was given by:

$$H(s) = k_s \tag{14}$$

The closed-loop transfer function for the system was obtained as:

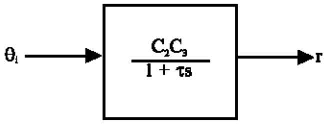

Fig. 2: Representation of Fig. 1 when $\theta_i = 0$

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{\frac{c_2c_3}{1+\tau s}k_p}{1+\frac{c_2c_3}{1+\tau s}k_pk_s} = \frac{c_2c_3k_p}{1+\tau s + c_2c_3k_pk_s}$$

giving

$$\frac{d\theta_o(s)}{dt} = \frac{\theta_i(s)c_2c_3k_p - \theta_o(s)\left(1+c_2c_3k_pk_s\right)}{\tau}$$

$$\text{or } dt = \frac{\tau}{\theta_iC_3C_pkp - \theta_O\ (s)\ (1+C_2C_3K_pK_s)}..\,d\theta_o\ (s) \tag{15}$$

Integrating both sides of (15) yields:

$$t = -\frac{\tau}{1+C_2C_3K_PK_s}$$
$$\text{In}[\theta_i(s)C_2C_3K_P - \theta_O(s)(1 + C_2C_3K_PK_S)] + C$$

where, C is the constant of integration. The initial condition was $\theta_O(s) = 0$ when t = 0

This gave

$$C = \frac{\tau}{1+C_2C_3K_PK_s}\ \text{In}(\theta_i(s)C_2C_3K_P)$$

So that

$$t = -\frac{t}{1+C_2C_3K_PK_{sS}}\ \ln(\theta_i(s)C_2C_3K_P$$
$$-\theta_O(s)(1 + C_2C_3K_PK_S)) - \ln\left(\theta_ic_2c_3k_p\right)$$

This was simplified to:

$$-\frac{1+c_2c_3k_p.t}{\tau} = \frac{\ln\theta_i(s)c_2c_3k_p - \theta_o(s)\left(1+c_2c_3k_pk_s\right)}{\theta_i(s)c_2c_3k_p}$$

from which the following was obtained:

$$\theta_o(s) = \frac{\theta_i(s)c_2c_3k_p}{1+c_2c_3k_pk_s}\left(1-e^{-\frac{t}{T}}\right) \quad (16)$$

Where,

$$T = \frac{\theta_i(s)c_2\,c_3\,k_p}{1+c_2c_3k_pk_s}$$

represents the time constant, that is, the time taken by the heat input to the thermal housing to build up to 63.2% of the pre-set value. The output temperature θ_0 (s) is the temperature of the housing.

DESIGN OF THE THERMAL HOUSING

Much of the early work on shape control in rolling mills was directed to cold strip plants (Wilmotte, 1983) for which off-line models were developed to give linear relationship between the total roll crown (assumed parabolic) required to produce a product with a zero parabolic component of shape and roll force. These off-line models are essentially algebraic expressions derived for the deflection of the work rolls caused by the deformation process in the roll gap. An expression for the heat generated in the gap enable the thermal camber, against the roll force, to be obtained. More recently, very little effort has been directed towards controlling the mismatch due primarily to the inter-relationship between shape, crown and gauge defects (Linchesky, 1983).

In bar mills, control of this defect is attempted from the point of view of interstand temperature control. Ershaw (1978) and Gertsev *et al.* (1982) considered the effects of water cooling spray headers installed within the finishing passes of the mill train. To obtain the required accuracy in achieving and regulating the temperature of the product; the installation was composed of 4 independently controlled sections, each of which was sited in one of the inter-spaces between the roll stands. Each section consists of a tank of water for direct strip cooling from above and bottom cooling headers. The water for each section was fed through a fast acting shut-off valve and fed into the bottom header through a manual valve which was used to control the ratio of water consumption on either side. The effect of this form of control was that during rolling at constant speed, the finishing temperature was reduced by 30-45°C from the front to the tail end of the strip, thus reducing considerably the curling-up defects of the 2 ends. Unfortunately, these headers appear to be bulky and something of a hazard in the event of a cobble occurring in production line.

Now from the results obtained so far in this study, we were able to show (Obinabo, 1991) that a suitable in-line thermal housing for bar mills should be one involving an arrangement capable of conserving heat and ensuring constant temperature distribution in the workpiece. This strategy encourages extraction of heat at a uniform rate from the surfaces of the workpiece especially at low rolling speeds as the workpiece exits the last finishing stand. This has been achieved elsewhere (Ostapenko *et al.*, 1988) by using un-insulated aluminum reflecting covers installed in the mill train.

In this study, our proposal is based on a housing that makes use of black insulating surface. The benefit of this is that a complete enclosure of insulating panels rapidly reaches operating temperatures of approximately 1000°C whereas, by contrast, reflectors reach equilibrium temperatures of approximately 700°C. The fully enclosed system is thus considered to represent a high efficiency passive type insulation system capable of reducing the temperature differential, between any 2 points on a workpiece, from 60°C over a 10 m length to near zero, which improves temperature uniformity in the mill train with improved shape and gauge control. A special feature of the insulating surface is that it has a fast heat-up rate and is capable of remaining hot between bars if high efficiency, graded insulation and a thin, high temperature alloy membrane is used to act as a transient heat store.

Furthermore, a refractory-lined mill maintained at a constant and uniform temperature by means of a multiple-zone gas burner system has been investigated by Obinabo (1991) for a bar mill where appropriate infrastructures were in place for regular and uninterrupted supply of natural gas to the plant. It was observed that a refractory-lined thermal housing maintained at a sufficiently high temperature offers the possibility of accurately controlling the temperature of the workpiece at entry to the finishing train and thus for the finishing train and thus for achieving correct rolling temperature at the last finishing stand, in the preferred range 870-880°C for low carbon steels, without recourse to adjusting the speed of the train. Another benefit of the housing is that it provides a means of raising the back-end temperature of the work-piece to within 10°C of the front-to-end temperature. This follows primarily from the fact that the entry speed of the work-space into the housing is higher than the speed at exit from the housing. The residence time of the back-end of the bar will consequently be longer than that of the front-end.

Although, the shape control models described in the literature contain considerable detail, all of them apply to both cold and hot strip mills. Treatment of rolling in bar mills seems to have been ignored. Also, no analytical control model exists in the literature for the rolling temperature distribution. The factors affecting process control in bar mills are so much more complex than those applicable to strip mills that quantitative study of the process problems is hardly available in the existing literature. In particular, there has been very little, if any, of theoretical study made of rolling through profiled-rolls (Obinabo and Chijioke, 1991). Most of the knowledge is that of catalogued experimental experience and observation.

TWO TERM CONTROLLER DESIGN

The traditional process controllers used extensively in industry employs proportional-plus-integral control algorithms to take advantage of the fast transient behaviour of proportional control and the off-set free steady state behaviour of integral control. A two-term proportional-plus-integral control is achieved by modifying the pneumatic control system proposed in (Obinabo, 1991) to include a flapper-nozzle arrangement. Subsequently, a closed-loop control scheme defining the problem is represented in Fig. 3 from which the open loop transfer function for the system is as follows:

$$G(s) = \frac{C_2C_3}{1+\tau s}\left(K_c\left(1+\frac{1}{T_is}\right)\right) \qquad (17)$$

where, C_2C_3 represents the system gain constant. K_c is the controller proportional gain constant and T_i the controller integral gain.

The transfer function of the controller given by:

$$\left(K_C\left(1+\frac{1}{T_is}\right)\right)$$

Equation 17, is the ratio of the manipulated variable U(t) to the error signal e(t) and is expressed as follows:

$$\frac{U(t)}{E(t)} = \left(K_C\left(1+\frac{1}{T_is}\right)\right)$$

(16.0)

$$U(t) = K_c\left(e(t) + (t) + \frac{1}{T_i}\int_0^i e(t)dt\right) \qquad (18)$$

In discreet terms, Eq. (18) becomes:

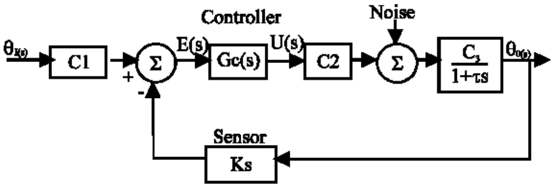

Fig. 3: Schematic of the closed loop heat flow problem

$$U_t = K_c\left(e_t + \frac{T_s}{T_i}; \sum_{i=0}^{i} e_i\right) \qquad (19)$$

and subsequently

$$U_t = U_t\left(e_{t-1} = K_c\left(e_t - e_{t-1} + \frac{T_s}{T_i}e_t\right)\right) \qquad (20)$$

where, T_s is the sampling time interval.
On Z-transformation,

$$Z\left(e(t\pm n)T_s\right) = Z^{\pm n}F(Z) \qquad (21)$$

Equation (20) now becomes:

$$U(z) = z^{-1}U(z) = K_e\left(F(Z) - z^{-1}F(z) + \frac{T_s}{T_i}F(z)\right) \qquad (22)$$

On rearrangement, the following is obtained:

$$\frac{U(z)}{F(z)} = D(z) = \frac{z(d_0Z + d_1\ )}{z-1} \qquad (23)$$

where,

$$d_0 = K_c\left(1+\frac{T_s}{T_i}\right);\ d_1 = -K_c$$

From Eq. (20), the discrete control law for the process becomes

$$\begin{aligned} U_t &= K_c\left(e_t\left(1+\frac{T_s}{T_i}\right) - e_{t-1}\right) + u_{t-1} \\ &= d_oe_t + d_1e_{t-1} + U_{t-1} \end{aligned} \qquad (24)$$

Implementation of a conventional controller involves selection of numerical values of the constants defining the controller. Control of the problem based on Eq. (23) can be readily implemented provided that the integral gain T_i, the proportional action gain K_c and the sampling time T_s can be selected to give the response θ_I within the design criteria.

For a dynamic process represented by a first order lag, it is shown that "Integral of Time and Absolute Error (ITAE)" criterion enables the parameter values of the open loop transfer function to be computed from the two-term controller as follows:

$$K_C = \frac{0.586}{K_p}\left(\frac{T_s}{\tau}\right)-0.916 \tag{25}$$

$$T_i = \frac{\tau}{1.03 - 0.165\left(\frac{T_s}{\tau}\right)} \tag{26}$$

For A sampling time of 1.0 min, the numerical value of these controller parameters are computed from Eq. (25) and (26) as:

$$K_c = \frac{0.586}{0.034}\left(\frac{1}{5.1}\right)^{0.916} = 0.30$$

$$T_i = \frac{5.1}{1.03 - 0.165\left(\frac{1}{5.1}\right)} = 5.1$$

where, K_p (= C_2C_3) is the system gain constant. These results enable the value for d_0 and d_1, which are the terms defining the two-term control law, to be computed as follows:

$$d_0 = 0.3\left(1+\frac{1}{5.1}\right) = 0.40; d_1 = -0.30$$

These values should be made available to the process engineer for start up of the plant and should constitute a necessary datum with which to tune the controller once the plant is on-line.

PRODUCT RESIDENCE TIME IN THE HOUSING

The product residence time in the housing is related to the period of energy transfer between the housing and the enclosed steel product undergoing temperature homogenisation process. The time is here defined as a function of the spatial distribution of heat in the dimensions of the workpiece. If the heat flux into the product through all the surfaces is even and if all the surfaces of the product are of equal dimensions, then the following expression holds for all steel products of similar metallurgical constitutions.

$$\theta(x,0) = a_o + a_2x^2 + a_4x^4 \tag{27}$$

where, the coefficients a's are determined from the boundary conditions and *x* is the spatial extent in any dimension of the workpiece. Differentiating this function with respect to time t gives:

$$\frac{d\theta}{dt} = 2a_2x\frac{dx}{dt} + 4a_4x^3\frac{dx}{dt} \tag{28}$$

from which

$$t = \int \frac{d\theta}{\left(2a_ox\frac{dx}{dt} + 4a_4x^3\frac{dx}{dt}\right)} + C_1 \tag{29}$$

$$= \int \frac{d\theta}{\frac{f_1(\theta)}{2a_2x + 4a_4x^3}\left(4a_4x^3 + 2a_2x\right)} + C_1 \tag{30}$$

$$= \int \frac{d\theta}{f_1(\theta)} + C_1 \tag{31}$$

Where,

$$f_1(\theta) = \frac{d\theta}{dt}$$

Similarly, in the other dimension, this function is defined as:

$$t = \int \frac{d\theta}{f_2(\theta)} + C_2 \tag{32}$$

The research referred to in this chapter reports these temperature-time curves for the two different planes of the workpiece considered and establishes the temperature profile as one of exponential decay given by the expression 1 + A exp(-Bt), where A and B were determined experimentally as 33.16 and 0,013, respectively. This enables the residence time of the workpiece in the housing to be expressed generally as

$$t = \int \frac{d\theta}{f(\theta)} + C$$

or, precisely

$$t = \int \frac{d\theta}{1 + A\exp(-Bt)} + C$$

Since, the intention of the housing was to ensure gradual and uniform cooling of the workpiece from the rolling temperature of 750°C to the ambient value the limits of integration were chosen as these values so that the above result,

$$t = \int \frac{d\theta}{1+Ae^{-Bt}} + C$$

becomes

$$\frac{dt}{d\theta} = \frac{1}{1+Ae^{-Bt}}$$

from which we obtain

$$\theta_2 - \theta_1 = \int_0^t \left(1+Ae^{-Bt}\right)dt.$$

This expression enables the temperature homogenising time of the workpiece in the housing to be computed as 12.5 min, which is the time constant of the system's transient response. The residence time is the sum of this amount and the settling time of 60 min also obtained for the steel samples cooling from the temperature of 750°C to the ambient value of the housing. This gives the overall time as 72.5 min. The relevance of this result in this study is to enable the production rate in the mill to be tuned to match this time factor in order to synchronise the processes which otherwise would result in accumulation of the product at the entry of the housing.

DISCUSSION

The magnitude of the temperature gradient along the length of the workpiece during the rolling sequence depends on the geometrical dimensions entering the intermediate and finishing stands of the mill train and on the ratio of the exit speed of a preceding stand to the entry speed of the next stand (Gertsev *et al*., 1982). Without a temperature gradient as the workpiece exits the furnace and with constant rolling speeds at the roll stands, each point along the length of the workpiece will enter the first stand at the same temperature. However, with a temperature gradient (either run-up or run-down) of the workpiece from the furnace, the temperature difference can be eliminated at entry to the first stand by adjusting the rolling speed so that the entry speed is, respectively smaller or greater than the exit speed from the furnace.

The factors that affect the exit speed of the workpiece from the reheating furnace and subsequently the temperature difference between the head and tail ends of the workpiece, have been identified in the study as the manually controlled operation of the pinch roll and the finite time delay at the first pendulum shear station located between the pinch roll and the first roughing stand. The discretion of the operator is often called into play in this adjustment to minimise the total heat loss from the workpiece in this part of the mill. On the average, the speed of the workpiece measured between the furnace and the first roll stand varies from 0.24-0.67 ms^{-1}. This wide range is sufficient to cause temperature difference between the head and tail ends of the workpiece. The delay (or time lapse) at the pendulum shear station, though measured in seconds, has a significant contribution to the problem; it causes the part of the billet still in the furnace to remain there for the duration of this delay. Thus temperature differential becomes introduced intermittently along the workpiece. The DC drives for the roll stands are not robust enough to respond appropriately to both the temperature changes of the deforming billets and the rolling speed; they cannot therefore on their own operate to adjust these parameters to the required levels. A control system is therefore required to match these changes to the operation of the rolls. Such control action is incorporated in the thermal housing mechanism proposed in this study the effect of which is the ultimate homogenization of the product temperature and elimination of the internal stresses.

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