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On the Experimental Investigation of Spatial Heat Flow During Air-cooling of Rectangular Cross-sectional Bars Rolled from RST 37-2 Steel

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Abstract: This study presents the results of an experimental investigation to determine the temperature and spatial heat flow during air-cooling of rectangular cross-sectional bars rolled from RST 37-2 steel. It was postulated that if these gradients could be determined for a simulated model, information could be obtained to validate the mathematical formulations of the problem by estimating the temperature profiles in the workpiece for subsequent control of shape distortions caused by the observed thermal effects. This study presents a novel approach for estimating the temperature distributions during air cooling of the workpiece from the rolling temperature of about 900°C to the ambient value and shows that for a workpiece of homogeneous metallurgical constitution air-cooling produces non-uniform temperature distributions that can be modelled mathematically to a good accuracy. The study provides a basis for controlling the rate of heat removal during interstand cooling of the rolled steel.

Key words: Spatial heat flow, temperature distributions, thermal effects

INTRODUCTION

In general, temperature is one of the most important parameters that govern the behaviour of steel during rolling processes (Yu and Sang, 2007; Spivakov *et al.*, 1983). Inaccurate estimation of its values will, among others, lead to errors in the estimated rolling load and hence the dimensional tolerance of the final product. An accurate knowledge of the temperatures and their variations especially in the transverse dimensions of the workpiece is therefore, a prerequisite for quantitative correlation between them and the shapes distortion effects observed during air cooling of the final product.

Rolling of steel bars appears to be particularly subject to a 2-pronged problem namely: (a) continual roll breakages which are caused, in part at least by excessive differential thermal expansions and by asymmetric torques called into play, during the rolling and (b) shape distortion of the final product especially in flat and angled bars (Stevens, 1971). The induced thermal stresses, due from poorly controlled temperature distributions, may not have fully relaxed before the bars arrive at the cooling bed and could therefore be the source of this problem. While, item (a) has, in general, been fairly well discussed by a number of authors (Yu and Sang, 2007; Stevens, 1971; Mihalow, 1982), item (b) although economically very consequential, has been given so far a very scant treatment, a fact that no doubt reflects the complexity of the problem.

In bar mills, warping is the major shape distortion observed during air cooling of the finished products. This is attributable to a number of factors, notably non-uniform temperature distributions (Sheppard, 1976). Samarasekera (1982) observes that thermal distortions not associated with restraint on free expansion of the product, such as distortions of bars on the cooling bed of a hot mill, may depend not only on the imposed thermal field, but on the steel properties and the geometry of the product. At present, the shape of a hot strip is corrected by means of a leveler in skin-pass rolling after the actual rolling operation (Iwawaki *et al.*, 1976). In bar mills, this is achieved by passing the cold products through straightening machines. It has been reported (Iwawaki *et al.*, 1976) however, that the internal stress distributions in the steel products may be varied by the work in these straightening operations, producing both desirable and adverse results. Experienced in bar mills has also shown that a large quantity of rectangular and angular cross-sectional products are so badly distorted already on the cooling bed that skin-pass rolling in the straightening machine is not possible at the stage.

The temperature at which steel is rolled in bar mills falls within the range 1000 and 900°C, the billets being preheated initially to a higher temperature (of about 1200°C) to prepare them for the subsequent stages of deformation and reduction in the roll gaps. In spite of this the precise preheat temperature and the pattern of heat distribution in the workpiece are as yet unclear (Yang and Lu, 1986). This is a serious shortcoming because the increase of the resistance to deformation imparted to a steel sample by relatively slight reductions in temperature results directly in significant increase in the power required for rolling, because it is a reduction of the ease with which the hot steel can be made to flow plastically in the desired directions. Chelyshev *et al.* (1971) confirm there is a significant influence by non-uniform heating on the distribution of deformation across the sample.

In this study, the temperature and spatial heat flow distributions in flat bars of rectangular cross section rolled from RST 37-2 steel were determined, the aim being to demonstrate first, the nature and reasons for the distributions and secondly develop a control strategy that will improve their uniformisation as the product cools down from the final rolling temperature of 900°C to the ambient value.

MATERIALS AND METHODS

Experimental basis: The novel and most important aspect of the investigation was the confinement of the test samples to static cooling at instantaneous times (0.0-50.0 sec) from the termination of the movement of the workpiece in the mill train. The study complements the mathematical formulation of the heat flow problem reported elsewhere (Obinabo, 2008) from estimates of the temperature profiles in the transverse dimensions of the samples.

The test bench (Obinabo and Chijioke, 1991) consists of an arrangement for thermocouple elements to be movable from point to point of the sample and connected between this and the monitoring recorders via a reference junction. The main components of the apparatus are the muffle furnace, digital multimeters and the thermocouple elements. All have been described earlier (Obinabo and Chijioke, 1991) in detail.

The test samples: The material of the samples investigated is designated RST 37-2, the nominal chemical composition and the mechanical properties of which are shown in Table 1 and 2, respectively.

Table 1: Norminal composition of rse 37-2 steel

C	Si	Mn	P	S	Cu	Cr	Ni
0.14	0.20	0.53	0.027	0.006	0.008	0.03	0.03

Table 2: Mechanical properties of rst 37-2 rectangular bars

Yields stress (Mnm^{-2})	Tensile stress (Mnm^{-2})	Elongation (Mnm^{-2})
330	440	12

Method of sample preparation: The method employed in the preparation of the samples involved use of a powered hacksaw to cut several 110 mm lengths of the test pieces from 70×6 mm rectangular cross sectional bars of RST 37-2 steel. Subsequently, grids of points were mapped out on the width and thickness surfaces of the samples using scribing blocks and set squares. Thus, each sample surface bore several test points located symmetrically with respect to its axes, 60 points in the case of the width surface, are as shown in Fig. 1. Subsequently, the points were each center-punched and drilled, on a verticals drilling machine, to depth of 3.0 mm and width of 3.0 mm approximately. This was to ensure easy identification of the points for connection with the thermocouple elements after the samples had been pre-heated in the furnace. These drill-bit dimples also provide thermally good housing contact for the thermocouple elements during the measurements.

Procedure: Test samples were charged into the muffle furnace, the interior of which was preheated to a temperature of about 900°C. Samples were left in the furnace for one and a half hours during which they attained the temperature of the furnace and were also able to soak and homogenize at this temperature. The same furnace was used to preheat the thermocouple elements so as to ensure the same temperature of the thermocouples and samples at the beginning of each measurement. On removal from the furnace, the

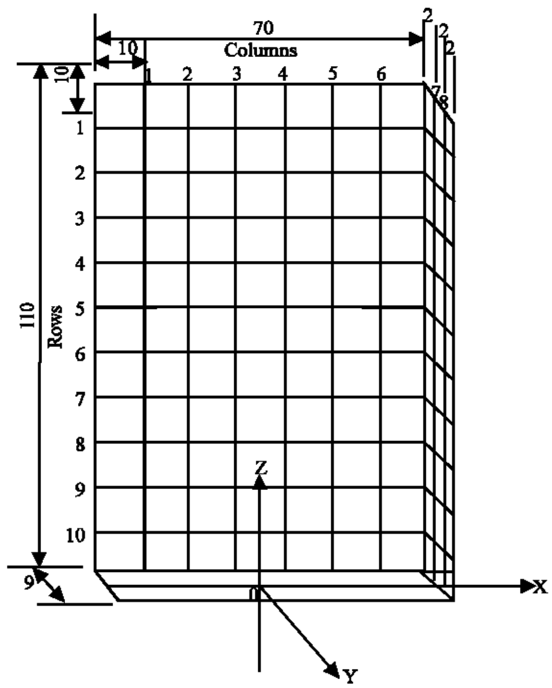

Fig. 1: Geometrical model of the bar sample

thermocouple elements were quickly placed in contact with the samples at the points of interest in the drill-bit dimples and the air cooling of the samples were monitored with the aid of a stop watch.

RESULTS

Monitoring of the surface temperature profiles on the grid points of the samples (Fig. 1) was not without difficulties. For accurate monitoring, non-contact pyrometric method was considered inadequate in view of its shortcomings (Al Alawi and Sparling, 1982). It has also been reported elsewhere (Afejuku, 1974) that the temperature distributions across a heated surface can be measured fairly accurately using several thermocouple elements at even spacing on the surface in question. However, the work reported by this author covers very low temperature values in the range 19°C (ambient) to 40°C and makes no mention of the problems likely to be encountered in a hostile environment such as one involving very high temperatures.

The monitoring procedure reported in this study involves acquisition of temperature data on several test samples more or less simultaneously at only 2 points per sample. The effects of monitoring several points on the samples, 2 at a time, were that the initial temperatures as shown by the first points on the plotted graphs differ form one another by an amount that can be related to the variations in the temperature of 2 different locations in the heating furnace. These variations are believed to be contributed to by the relative positions of the test samples in the furnace during heating. The muffle furnace used for the experiment was not designed to give a truly uniform temperature distribution in the chamber. The heating element which was a resistance wire wound onto a refractory former was about one-fifth the length of the furnace chamber. The furnace bore 2 of these at the rear inner end of the chamber, about 200 mm above the furnace floor, thereby causing the variation in temperature between the inner and outer apartments of the chamber as shown by the values recorded in Table 3.

The differences between the temperatures of the innermost and the outermost sections of the furnace are as follows: Left side (1102-953) = 149°C, centre of the furnace (1063-949) = 114°C and right side (1100-957) = 143°C. The implication of these temperature variations in the furnace is that the initial temperatures of the samples depend on the location they occupy in the furnace during heating. The furnace pre-set temperature level at the time of measurement was 1100°C and this value was attained by the furnace before the measurements. The difficulties encountered in this investigation concerns simultaneous monitoring of the several points on the test samples. The method of approach reported in this research was tried as a better alternative, all care being taken to ensure reproducibility of the results.

Table 3: Data showing temperature variations in the muffle furance

Section of furnace	Temperature (°C) Left side	Mid-way from the sides	Right side
Inner section	1102	1063	1100
Middle section	1082	1025	1082
Outer section	953	949	957

The atmosphere of the muffle furnace used for heating the steel samples was uncontrollable. Consequently, what appeared as appreciable scaling was observed on the entire surfaces of the samples on removal from the furnace. Additionally, scaling occurred during air cooling and, as expected, this was more serious when the samples had to be cooled from higher temperatures. The scale thicknesses were measured and a maximum value of 0.75 mm was obtained. The average cooling rates of the various points on the sample were found to lie between 1.034 and 1.041°C per sec over the 900-550°C temperature range. The points nearest to the edge surfaces of the sample were expected to cool faster than those close to the middle because of their proximately to these surfaces. This is confirmed in the experimental data. The effects of the oxide thickness were not investigated further since it was difficult to control and measure. In particular, the scales were observed to break away during the static air-cooling, presumably due to thermal stresses. It may be of practical interest to quantify the effects of the scale thickness by carrying out air cooling tests on materials with adherent oxide layers of different thicknesses. The effects of these scales may even explain the presence of the scatter in the plots. However, such data were not available and since this study was mainly concerned with the establishment of the temperature profiles, detailed analysis of these effects was not considered important. The time-dependent cooling curves for the discrete points on the surfaces of the samples considered are similar. The average initial slope was obtained from the plots as -2.6°C sec^{-1}, while the response time constant was obtained as 5.1 min (Obinabo and Chijioke, 1991). From the method of determining transient heat flux rates by experimentally measuring the temperature time slope (Eckert *et al.*, 1996; Scott, 1976) of the material, the following is defined.

$$\frac{\theta-\theta_f}{\theta_o-\theta_f} = \exp\left(-\frac{h\,A_s}{\rho_s c_{ps} v_s}.t\right) \qquad (1)$$

Where:

θ	=	Measured temperature value.
θ_o	=	Initial temperature (at time = 0).
θ_f	=	Ambient fluid temperature.
p^s	=	Density of the sample.
V_s	=	Volume of the sample.
c_{ps}	=	Specific heat capacity of he sample.
A_s	=	Area of the sample.
h	=	Time.
h	=	Surface heat transfer coefficient of the material.

Taking the natural logarithm of both sides of Eq. (1) yields

$$\ln(\theta - \theta_f) = A - \frac{hA_s}{\rho_s c_{ps} v_s}.t \qquad (2)$$

where:

$$A = (\theta_o - \theta_f)$$

The plots of in $(\theta-\theta_f)$ against time for all the points on the cross sections of the sample considered are presented and Fig. 2-5 are typical plots obtained for the X-Z and Y-Z planes of the sample. For all the points, the cooling gradients are superimposed in Fig. 2 for the X-Z plane and in Fig. 3 for the Y-Z plane. In Fig. 3, the upper and lower bounds of the points were estimated from which the mean values were plotted to represent the cooling profile of the width surface. The slope of this graph was found to be 1.01 °C sec^{-1}. For the Y-Z plane, this value was found

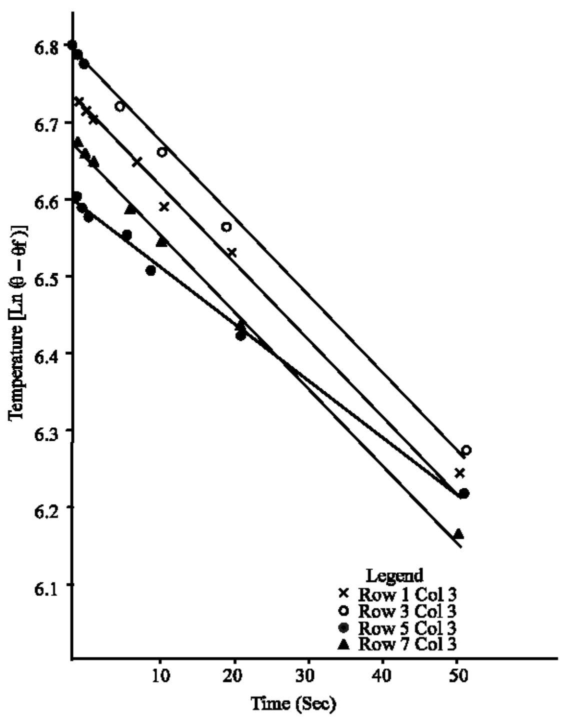

Fig. 2: Typical cooling gradients obtained for discrete points on the X-Z plane of the test sample

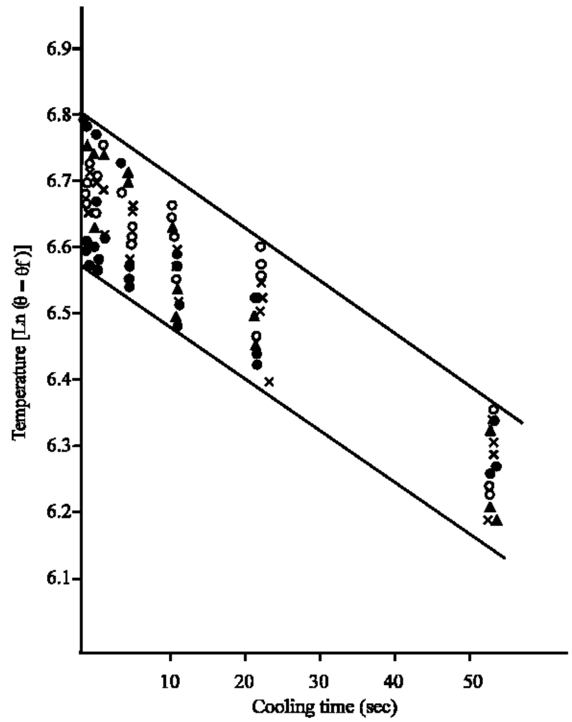

Fig. 3: Average cooling gradients obtained for discrete points on the X-Z plane of the test sample

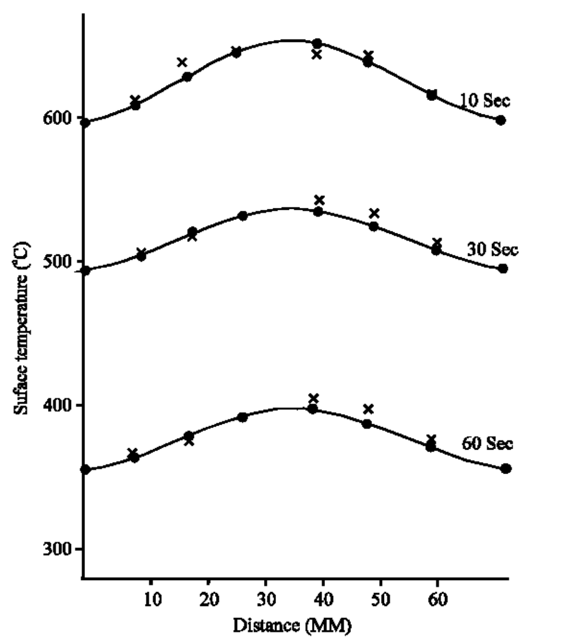

Fig. 4: Average cooling gradient for discrete points on the X-Z plane

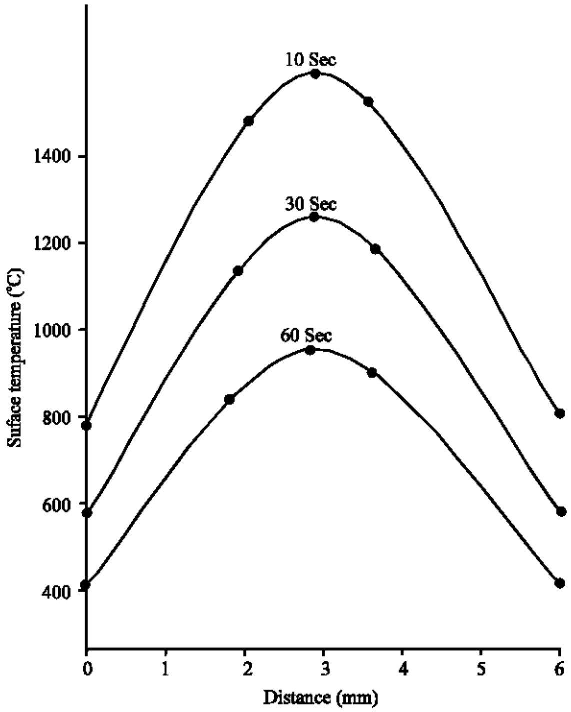

Fig. 5: Average cooling gradient for discrete points on the Y-Z plane

tabulated as shown in Table 4 and 5, respectively. Form these tables, the average cooling gradient of the sample to be steeper by as much as 0.02°C sec^{-1}. The slopes and intercepts obtained from the cooling curves of the discrete points on these planes of the sample were was computed as 1.035°C sec^{-1}. Equating this value to the second term on the right hand side of Eq 1 enabled the surface heat flux of the steel grade to be determined test samples during cooling were estimated by from the material constants of the sample. The spatial distributions of the heat flow across the flatsurface of the considering the instantaneous temperature of the sample measured at the discrete points on the surfaces. Typical profiles for the 2 planes of the sample are as shown in Fig. 4 and 5.

To obtain reasonably good estimates of the temperature distribution during the air cooling, a simplified method based on the computed average times was used. The information so generated was used to obtain the empirical model of the spatial distribution of heat on the sample. For the cooling profiles of the individual points on the sample, the temperature at any time was taken as the mean value of the temperature readings for each pair of points symmetrically placed across the longitudinal centre line of the sample. In this case, the fitted curve was derived by modifying the surface heat flux equation for a body cooling in air (Hills, 1969) given by:

Table 4: Data on the cooling rates of the monitored points on the X-Z plane

	Interceprs-(°C) slope (in brackets-°C sec^{-1}.)			
Row/cols	1	3	5	7
1	804 (1.04)	821 (1.04)	796 (1.03)	821 (1.03)
2	846 (1.04)	854 (1.03)	850 (104)	880 (104)
3	845 (1.04)	898 (1.03)	791 (104)	796 (1.03)
4	833 (1.04)	804 (1.04)	833 (1.04)	833 (1.03)
5	804 (1.03)	804 (1.03)	773 (1.04)	854 (1.03)
6	825 (1.03)	889 (1.03)	825 (1.03)	854 (1.04)

Table 5: Data on the cooling rates of the monitoredpoints on the Y-Z plane

	Intercepts-°C slope (in brackets-°C sec^{-1}.)			
Row/cols	1	3	5	7
7	837 (1.04)	889 (1.04)	925 (1.04)	829 (104)
8	880 (1.04)	846 (1.03)	880 (104)	863 (104)

$$q = -\left(\sigma F\left(\theta^4 - \theta_A{}^4\right) + h\left(\theta - \theta_A\right)\right) \tag{3}$$

Where:

- θ_A = Ambient temperature.
- θ = Measured surface temperature.
- σ = Stefan-Boltzman constant.
- F = Shape factor accounting for the geometry of the surfaces of the workpiece radiating heat.

The following result was obtained:

$$q' = -a\theta_o + a\theta_s + b\left(\theta_s + 273\right)^4 \tag{4}$$

where, θ_O, θ_S were ambient and surface temperatures, respectively and a was constant given by the surface heat transfer coefficient of the sample.

$$b = 5.67 \times 10^{11} \times \varepsilon kN\,m^{-2} \tag{5}$$

ε was the emissivity of the material of the sample.

Using the value of 0.84 predicted by for the emissivity of mild steel, a value of 4.76×10^{11} was computed from Eq 5 for the constant b. Writing q as Ae^{Bt} θ where, A and B were computed from the available data (Obinabo and Chijioke, 1991) as 33.16 and 0.013, respectively and substituting for both time and the corresponding measured surface temperature of the sample, Eq. 4 gave the value of 0.03 for the constant a. From the analysis, the best fit appeared to be given by a curve whose equation is:

$$q = 0.9 + 33.16 \exp(-0.013\tau)\,\theta_S + 4.76\times10^{-11}(\theta_S + 273)^4 \quad (6)$$

where, q is measured in KW m^{-2}, θ_S in °C and θ_O equals 30°C τ is time. The corresponding temperature profile models found for the specimens are:

$$\begin{aligned}\theta_x &= a_O + a_2 x^2 + a_4 x^4 \\ \theta_y &= b_O + b_1 y + b_2 y^2\end{aligned} \quad (7)$$

where the values of the *a* and b coefficients vary with the interstand position of the sample.

DISCUSSION

The monitoring procedure reported here involved acquisition of temperature data on several test samples more or less simultaneously at each pair of points. In consequence, the initial temperatures as shown by the first points on the graphs (Obinabo and Chijioke, 1991) differ from one another by an amount (roughly 35°C) that can be related to the variations in the temperatures of 2 different locations used in the heating furnace (Table 3). The variations were therefore believed to be contributed to by the relative positions of the samples in the furnace during heating. The muffle furnace used in this study was not designed to give a highly uniform temperature distribution in the chamber. In addition, the atmosphere of the furnace was not controllable. Frequently what appeared as severe scaling was observed on the entire surfaces of the samples on removal from the furnace. Additionally, scaling occurred during air cooling and as expected, this was more serious when the cooling was from higher temperatures. The scales were observed to break away subsequently during the static air cooling, presumably due to increased differential thermal stressing. The scale thickness was measured and a maximum value of 0.75 mm was obtained; but the effects of the oxide thickness were not investigated further. It was difficult to control and measure and since this investigation was mainly concerned with establishment of temperature profiles, detailed analysis of these other effects were not considered relevant. Nevertheless, it may be of practical interest to quantify them by carrying out air cooling tests on materials with adherent oxide layers of different, precisely measured thicknesses.

The average cooling rates of the various points on the sample were found to lie between 1.034 and 1.041°C sec^{-1} over the 900-550°C temperature range. The expectation that portions of the samples nearest to the edge surface cool faster than those close to the middle, is supported by experimental data (Obinabo and Chijioke, 1991). The plots of the temperature distributions obtained for the X-Z plane of the sample show no significant difference in the cooling of the points on this plane. This confirms the homogeneity of the material and characteristics of the sample. It was also noted that there was little or no asymmetry in the spatial distribution of the heat flow across the sample as was expected because the bounding surfaces of this plane was equally free of constraints. In addition, the thickness of the oxide scales formed on the surfaces was approximately the same for the points monitored-a further confirmation of thermal symmetry. The importance of symmetry of temperature distribution is that it simplifies considerably the derivation of the modelling equations, allows computation carried out on a quarter section of the sample to represent the whole and confirm absence of unevenness in the temperature profile which could otherwise give rise to effects like buckling.

The plots obtained for the time-dependent profiles of the heat flow in the Y-Z plane of the sample do not portray basic departure from the general features observed in the case of the X-Z plane. However, by virtue of the manner in which the samples were positioned (surface-wise) on the cooling platform, the rate of cooling of the X-Z surface in contact with the platform was expected to be different from that of the opposite surface. Asymmetry in temperature was thus introduced between the top and bottom boundaries of the Y-Z faces, giving rise to asymmetrical Y-Z distributions, unlike the X-Z distributions. The temperature profiles indicate that the cooling rates on the Y-Z plane were slightly higher than those recorded for the X-Z plane. An average value of 1.04°C sec^{-1} was obtained for the Y-Z plane. The resulting spatial distributions of the heat flux on the sample were determined directly from these temperature data at the instantaneous times of 10, 30 and 60 sec after cooling had commenced, using techniques reported earlier by Obinabo (2008) and which were based on a rigorous mathematical formulation and digital computer solutions.

Relating these results to the situation in bar mills, the asymmetry of the temperature distribution in the edge (Y-Z) dimension of the workpiece was expected to be appreciable and the magnitude was likely to be a larger multiple of that expected from the experimental investigation, because of the differences in dimensions and in processing between the test samples and the rolling mill products (Obinabo and Chijioke, 1991). It is worth noting also that on the cooling bed of the mill, the top surface of the bars were open to free air streams while the other surfaces rested on racks and were partially enclosed by the basement and by adjacent bars; the basement of bar mills houses a network of mechanical linkages that operate to transport the static bars sideways on the cooling bed, to the point of dispatch to the straightening machine. No provision exists in the mills for quick evacuation of the accumulated heat from the basement. Although, the temperature due from this accumulated heat was not found to be as high as that of the bars themselves, the fact that the air in the basement was somewhat still, especially when all the positions were taken up on the cooling bed, was likely to present a situation whereby, a large temperature differential was established between the top and bottom surfaces which become distributed, randomly rather than regularly, along the lengths of the bars. The result was non-uniform stressing of the form observed and discussed by Obinabo and Chijioke (1991).

CONCLUSION

The experimental work reported in this study has presented a fairly novel approach for estimating the spatial distribution of temperature and the heat flow during air cooling of flat bar samples rolled from RST 37-2 steel. It is shown that for a flat steel bar of homogeneous material composition, air cooling in the mill will be asymmetrically distributed across the edge dimensions, which contrasts with the distribution across the width surfaces. Homogenization of the temperature distributions in the workpiece was by means of in-line thermal housing proposed for controlled air cooling on the cooling bed.

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