ASPECTS REGARDING THE HEATING TECHNOLOGY OF THE STEEL BILLETS IN VIEW OF ROLLING PROCESS

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Abstract

The heating process of alloyed and high alloyed steel billets and ingots in view of processing by rolling presents some difficulties due to important differences of temperature occurred on their section. These temperature differences are generating internal thermal stresses, which make more difficult the plastic deformation process, and if their values exceed the tensile strength they can even lead to the destruction of the finished product. The thermal stresses are mostly due to poor correlation of heating process of the billets in typical furnaces for rolling mills with mechanical and thermal characteristics of the heated material.

The work intends to analyse a number of cases that could occur during heating process in view of plastic deformation and to establish correlations between the thermal regimes, the properties of metallic material and furnace output so that an optimum be reached. Some correlations between parameters of the semi-finished product (size, tensile strength, thermal conductivity, heat capacity), of thermal regime (temperatures during the heating, speed and duration of heating) and of thermal aggregate are established.

1. THEORETICAL CONSIDERATIONS

The heating process of alloyed and high alloyed steel billets and ingots in view of processing by plastic deformation by rolling presents some difficulties due to important differences of temperature occurred on their section. These temperature differences are generating internal thermal stresses that make more difficult the plastic deformation process and if their value exceeds the tensile strength they can even lead to the destruction of the finished product.

Having in view these aspects, a theoretical and experimental study of the mechanism of thermal stresses generation and determination of critical thermal values is imposed. The obtained results contribute to establish the principles of remodelling of the heating furnace.

1.1 Billets with circular section

Because the thermal flow is not uniform, in the upper and bottom part of the billet the distribution of temperature is asymmetric. If initial temperature ($\theta_0$) is the same on whole semi-finished product, one part of it is heated with speed $w_1$ and another part with speed $w_2$. Subject to temperature on the upper, respectively the bottom part and to the heating time temperature differences are:

- for the upper part of the billet:

$$\Delta \theta_1 = \theta_{s1} - \theta_{ws} = \frac{w_1 - w_2}{2} \tau + \frac{w_1 + w_2}{2} \frac{R^2}{4a}$$

(1)

- for the bottom part:

$$\Delta \theta_2 = \theta_{s2} - \theta_{ws} = \frac{w_2 - w_1}{2} \tau + \frac{w_1 + w_2}{2} \frac{R^2}{4a}$$

(2)
a: thermal diffusivity of the steel
R: radius of the billet
To represent variation of thermal stresses in the round billet it is used the Bessel functions[1].
Noting with “R” the cylinder radius and with “r” the current radius:
a) for \( r = R \) stresses at the surface are:
\[
\sigma_{ig} = \sigma_{ax} = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \left[ \nu \cdot \varphi_{\,1} \cdot J_{n_1}(n_1 R) \right]\]  
(3)
where \( J_{n_1}(n_1 R) \) is Bessel function
b) for \( r=0 \), on cylinder axis:
\[
\sigma_{r ax} = \sigma_{ig} = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \left[ \nu \cdot \varphi_{\,1} \right]\]  
(4)
c) for whole section of the round billet, if heating is symmetrical (\( \Delta \theta_1 = \Delta \theta_2 \)):
\[
\sigma_{s} = \sigma_{r} = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \left[ \nu \cdot \varphi_{\,1} \cdot \frac{2 J_{n_1}(n_1 R)}{n_1 R} \right]\]  
(5)

### 1.2 Billets with rectangular section

For the billets with rectangular section with the thickness \( X \), the admitted thermal stresses reported to (x) and respectively (y) axis, could be determined by the equation:
\[
\sigma_{x} = \sigma_{y} = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \cdot f \left[ \frac{a \cdot \tau}{X^2}, \frac{\alpha \cdot X}{\lambda}, \frac{x}{X} \right]\]  
(6)
and in case of a thermal difference \( \Delta \theta_0 \) at the initial heating moment:
\[
\sigma_{x} = \sigma_{y} = (\Delta \theta - 0,7 \Delta \theta_0) \cdot f \left[ \frac{a \cdot \tau}{X^2}, \frac{\alpha \cdot X}{\lambda}, \frac{x}{X} \right]\]  
(7)

Maximum stress (absolute value) at the surface of the billet is given by the equation:
\[
\sigma = \frac{\beta \cdot E}{1 - \nu} \cdot \frac{w \cdot X^2}{3a} = \frac{\beta \cdot E}{1 - \nu} \cdot \frac{2}{3} \Delta \theta = 0,95 \beta \cdot E \cdot \Delta \theta\]  
(8)
where “a” is thermal diffusivity of the material.

It is proposed the following formula for the calculation of the thermal stresses:
-thermal stresses on axial and tangential direction in the axis of the semi-finished product:
\[
\sigma_{s ax} = \sigma_{s ys} = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \left[ \nu \cdot \varphi_{\,1} \right] = \frac{\beta \cdot E}{1 - \nu} \cdot \Delta \theta \cdot \frac{\theta_{e} - \theta_{m0}}{\theta_{e} - \theta_{m0}}\]  
(9)
where: \( \theta_c \): furnace temperature
\( \theta_{m0} \): temperature in the centre of the semi-finished product
\( \theta_{m0} \): initial temperature of the semi-finished product
-thermal stresses on axial and tangential direction at the surface of semi-finished product:
\[
\sigma_{s x s} = \sigma_{s y s} = \frac{\beta \cdot E}{1 - \nu} \Delta \theta \left[ \nu \cdot \varphi_{\,1} \cdot \cos(n_1 X) \right] = \frac{\beta \cdot E}{1 - \nu} \Delta \theta \cdot \frac{\theta_{e} - \theta_{m0}}{\theta_{e} - \theta_{m0}}\]  
(10)
where \( \theta_{ms} \) is the temperature at the surface of semi-finished product (its value is determined subject to upper or lower surface).
Distribution of stresses on whole surface of the semi-finished product:

\[
\sigma_m = \frac{\beta \cdot E}{1 - \nu} \Delta \theta | v_1 \cdot \phi_1 \cdot \sin(n_1 \cdot X) | = \frac{\beta \cdot E}{1 - \nu} \Delta \theta \cdot \frac{\theta_f - \theta_{i}}{\theta_f - \theta_{inf}}
\]

where \( \theta_{inf} \) is the final temperature of the semi-finished product (billet).

2. TEMPERATURE UNIFORMITY AND THE THERMAL STRESSES

Choosing different experimental thermal regimes of the furnaces there were simulate many situations which can appear in case of heating of the billets in view of plastic deformation by rolling. The cases of the thermal regimes of the furnace together with the disposal mode of the samples and the quality of the steel have led to a number of 126 experimental cases. Variation of thermal stress in relation with temperature is presented based on above equations (figure 1 and figure 2).

![Figure 1: Variation of the thermal stress (\( \sigma_{real} \)) in function of the sample’s temperature for bearing steel in case of \( \theta_c=700^\circ C \) (centre of the sample)](image)

Figure 1 shows variation of thermal stresses subject to sample temperature (\( \Phi=65\text{mm} \)) for the case when furnace temperature when introducing the sample is 700°C and then increase to 920°C, and figure 2 represents the case of heating at higher temperatures of the furnace (1280°C) of a sample of same diameter, maximal values used also in real cases when heating in continuous furnaces for rolling mills.

The heating mode (the disposal mode) of billets in the furnace that give the biggest value of the ratio between the heated surface and the mass unity of the body \((m^2/kg)\), leads for a certain intensity of the thermal flow, to a minimum value of the thermal stresses.

The values of the thermal source influence the heating intensity of the billet and by this the value of the thermal stresses. Therefore, the value of the furnace's temperature must be
correlated with the thermal resistance considered on the direction of the thermal flow and the maximal admitted value of the thermal stress. To prevent the material cracking, it is imposed that the value of the thermal stresses should be lower than the cracking resistance of the metal at the heating temperature. This is the basic to justify the heating method of the metallic bodies in the continuous furnace for rolling mills.

A correlation between the elements of the thermal regime of the furnace and the optimum values of the consumption of the furnace is necessary.

So, the non-uniformity of the temperature in the section of the billet, $\Delta \theta$, will be:

$$\Delta \theta = k_1 \cdot \frac{S \cdot c \cdot \rho \cdot w_i}{\lambda}$$

$k_1$, function depending on the form section of the billet and on the disposal mode on the hearth of the furnace [3];
- $S$ is the equivalent surface of heat exchange [3], [4];
- $c$: thermal capacity
- $\lambda$: thermal conductivity
- $\rho$: density of the material

The output of the furnace can be established using the equation:

$$P = \frac{m \cdot n \cdot \Delta \theta}{T \cdot k_2 \cdot (\theta_j - \theta_i)}$$

“$T$” - “specific time of internal heating - STIH” [6, 7]

$k_2$, the function of heating time [7]

The heating speed will be practically determinate by the equation:
\[ w_i = \frac{\lambda \alpha_{r+c} (\theta_i - \theta_j)}{k_i S \cdot c \cdot \rho \Delta I \left( T \cdot k_z (\theta_f - \theta_i) \right)} \]  \hspace{1cm} (14)

where \( \alpha_{r+c} \) is the complex coefficient of heat exchange by radiation and convection.

Equation (14) shows the complexity of the factors that influence the heating speed of the billet.

3. ANALYSIS AND INTERPRETATION OF EXPERIMENTAL DATA

Using the experimental data, we can remark how different modalities of the thermal regime of the furnace influence the variation of temperature in the section of the billet, and by these, the thermal stresses. An example is presented in figure 3.

![Figure 3](image)

**Figure 3** Recorded temperature in case of sample D8 for a 70mm rectangular billet

We remark a quickly rapprochement of the temperature of the lower surface of the sample to the temperature of the centre. The maximum difference of temperature is obtained for the section corresponding to the difference between the upper surface and the centre of the sample; it results that the maximum value of the thermal stress will be recorded for the zone between the upper surface and the centre of the sample (respectively of the billet).

The variation of the thermal stress in function of the billet temperature is given by a polynomial equation with the general form (there are considerate for calculation the real value in the centre of the sample and not a medium value on the section):

\[ \sigma_{real} = \sigma_0 + \kappa_1 \cdot \theta + \kappa_2 \cdot \theta^2 + \kappa_3 \cdot \theta^3 + \kappa_4 \cdot \theta^4 \]  \hspace{1cm} (15)

Analysing the values of \( \sigma_0 \), it was established [8] that it corresponds to an initial value of the thermal stress, which appears in the material in the first 0.1÷2.0 minutes from the beginning of the heating process. The sign “+” or “−” for the values of \( \sigma_0 \), shows the way the thermal stress acts (compression for “−”, elongation for “+”). In case when we reheat a billet, the
value of $\sigma_0$ represents the residual stress in the material due to any precedent thermotechnological process. The value of $\sigma_0$ does not represent the cracking resistance of the material, but the true value of the thermal stress generated in the material, for specific heating conditions, at the beginning of heating process.

4. THE POSSIBILITY TO TRANSFER THE EXPERIMENTAL RESULTS TO PRACTICAL CASES OF HEATING

In figure 3 are presented, as an example, the registered temperatures in the billet for an experimental case.

To analyse the possibility to transfer the results to practical cases it is necessary to establish the ratio between the mass of the billet and the participant surface to heat exchange by radiation.

Therefore, it is established “the functions of transfer” with the following forms:

- for the billets with circular section:
  $$\mathcal{R}_c = \frac{d_1 \cdot \rho_1 \cdot k_{1-2}}{d_2 \cdot \rho_2 \cdot k_{1-1}}$$
  (16)

- for the billets with rectangular sections:
  $$\mathcal{R}_r = \frac{a_1 \cdot \rho_1 \cdot f_2 \cdot k_{1-2}}{a_2 \cdot \rho_2 \cdot f_1 \cdot k_{1-1}}$$
  (17)

$d_1, d_2, a_1, a_2, f_1, f_2$ are data which refer to the dimensions of the heated metal $k_{1-2}, k_{1-1}$ functions that refer to the “equivalent surface of heat exchange”.

To exemplify, figure 4 shows, the obtainable temperatures in a billet with a diameter of 300mm if it will be loaded at the 860°C temperature of the furnace and the thermal regime of the furnace recommended to not surpassing the admissible values for thermal stresses.

Figure 4: Establishing of the admitted temperature of the furnace, function of $\Delta \theta_{\text{admis}}$ (maxim) and the of the billet dimensions ($\Phi=300\text{mm}, \theta_c=860\degree\text{C}$)
5. CONCLUSIONS

The obtained results regarding the thermal stresses contribute at the re-modelling of the general form of the design of the furnace. From this, we present the aspect that refers to the re-modelling of the furnace vault.

The curve of temperature variation the length of the furnace (or in function of heating time) determined on the basis of the researches regarding the maximum admissible thermal stresses, depends on the maximum admitted temperature of the furnace (figure 5).

If a various range of steel with different thermal properties is heated in the furnace, it is recommended to establish the curve of the vault for the most unfavourable case.

Figure 5: Establishing of max. admitted temperature of the furnace in function of $\Delta \theta_{\text{admis}}$ (maxim) and the thickness of the billet $\Phi=300\text{mm}$

Figure 6: Example of the establishing of the curve of the vault in the case when the temperature at the entrance in the furnace is $750^\circ \text{C}$
Starting from the diagrams that show the variation of maximum admitted temperature of the furnace it is possible to realise the aspect of the vault of a walking beam furnace, represented in figure 6. In section, this vault is plane.

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