THE CURRENT STAGE OF THE RESEARCH ABOUT THE THERMAL SHOCK INSIDE THE WARM ROLLING CYLINDERS

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Key words: thermic, shock, rolling

Abstract

Thermic shocks in rolling cylinders are usually produced in the beginning of the rolling process, when some compulsory conditions are subdued, especially when the rolling cylinders are not correctly warmed up and the initial temperature in the production plants during the cold season are low – such conditions are meant for a correct use of the stands. This paper work is going to describe the current stage of the research about the thermal shock during the industrial rolling in case of the plane plates – it is true for the industrial processing cylinders, too.

1. Introduction

Thermal shocks represent a particular feature of the thermal tensions produced inside the warm rolling cylinders. These features are highlighted when the rolling of the rolling mill stands are not warm at the beginning of the process, and the environment temperature inside the production plants during the cold season is rather low. This paper work is going to describe the current stage of the research about the thermal shock during the industrial rolling in case of the plane plates – it is true for the industrial processing cylinders, too. This paper work presents the approximate calculation of the parameters of the thermal shock who could be determined only if we know the values of the thermal tensions inside the warm rolling cylinders.

2. The current stage of the research

The study of the thermal shocks described by S.S. Manson in his work "Thermal stress and low – cycle fatigue" [6], that analyses the way the thermal shock (within the plane plates) occurs. In case of the rolling cylinders, the segments of these section – near the calibres belt, could be compared to the circular plane plates, and their dimensions are determined, meanwhile the study of the thermal shocks could be extended to these areas. Any calculations for determining the thermal tensions within the plane plates, in case of less studied thermal shocks, are referred to in many publications about this subject [1], [2]; and the tensions are mathematically calculated through approximative methods.

3. Determining the parametres of the thermal shock through approximate methods

During the first stage, in case of problems referring to the plane plates, we must determine the variations of temperatures inside the plates during time τ, referring to the environmental temperature.

If we presume that the material of the cylinders is homogenous, we could say that the relation (1) for determining the specific tension (adimensional) – we also know it as the theory of the thermal-resilience [6].

$$\sigma^* \cong \frac{T_{cp} - T}{T_0} \quad (1)$$

- where: T_{cp}- average temperature of the plate thickness; T- temperature to the point where we determine the tension; T_0 - innitial temperature, which is uniformly within the plate, if we calculate it according to the environment.

Physically speaking, σ^* - we could consider an average amongst the tensions that stress the plate and the tensions that occur when the warmth transfer between the plate and the environment is stopped. The formula to determine σ^* is comprised in the relation (2):

$$\sigma^* = \frac{\sigma \cdot (1 - \mu)}{E \cdot \alpha_0} \quad (2)$$

- where: σ - the tension within the plate; μ - the value of transversal lines; E - resilience module; α_0 – the value of thermal dilatation.

In order to determine the tensions on the surface of the plate and on the surface of the cylinder calibres belt, we have to determine the average temperature within the plate and the temperature on the surface of the plate, and of the belt. The problem of the temperature is carefully studied by specific literature, and the solution to that is a finite row. In fig. 1, we refer to the results of some calculations made according to the method of substitution, according to [6] – in order to obtain the exact values for the rows, in case of temperatures and the relation amongst the tensions.

This solution, according to fig. 1, there are three important variables: specific tensions σ^*, Biot criterion and Fourier criterion.

Biot criterion refers to the relation: $Bi = \frac{a \cdot h}{k}$

- where: a = ½ of the plate thickness; h – thermal diffusivity value; k – material thermal conductivity value*; h – thermal difusivity value that represents the quantity of warmth transmitted by a surface plate segment, through the difference between the temperatures on the surface and the environment (0^oC).

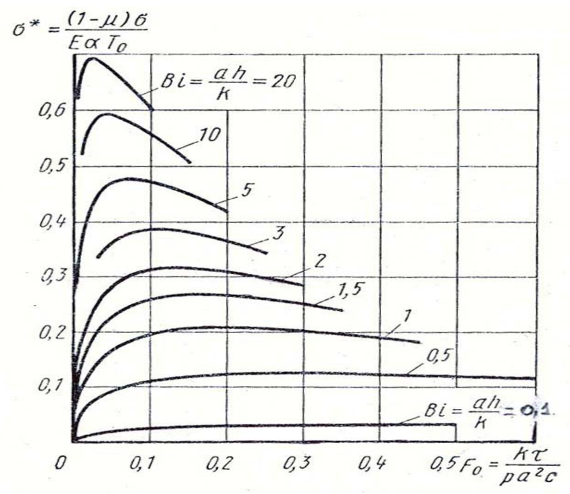

Fig. 1 Dependency amongst specific tensions (adimensional) on the surface of a plane plate and the adimensional-time

Variables a, h and k, are usually used in order to solve the relation in a complete way; it is the result of the calculation method of the difderential equation. Thus, considering the matter in a general way, it's not important to know the separate values of the a, h and k variables, but to know the resulting value of the Bi criterion – the parametre of the warmth transfer.

Fourier - Fo criterion also called the specific time (adimensional) is determined due to the relation (3).

$$Fo = \frac{k \cdot \tau}{\rho \cdot c \cdot a^2} \qquad (3)$$

- where: k - material thermal conductivity value, and of the cylinder; τ - time; ρ - material density; c – specific warmth; a =1/2 of the plate thickness.

Fig. 1 describes all specific tensions according to the specific time (adimensional), according to different values of the Fourier – Fo criterion. This graphic design highlights the principle of general sollution for thermal tensions on a plane plate.

The highest tensions on the surface of the plate are analytically determined in the work paper number [1] and [4]. For instance, after [6] we study the specific tensions for low values of Bi, where the first two elements of the row could be excluded. Thus, the highest tensions are determined as such: we consider them if the tension derivate relation is equal to 0, after a certain time. Fig. 2 describes the variation of the specific tension according to the values of Bi.

According to the tensions' variation of the Bi criterion, they are liniar in case of low values of Bi, and reach to high values in case of Bi high values – they tend to reach 1, there si a curve asymptote – the value of $\sigma^*_{\max}$.

In order to get a new and more accesible formula in order to determine the specific tensions σ^*, according to [2] and using some general hypothesis, in order to get a more simple and precise formula. In order to perform that, it represented ther distribution of the warmth within the surface of the plane plate - fig. 3.

According to the graphic analysis described in the fig. 3, the vertical dotted line refers to the middle of the plane plate, subject to our study about the thermal shock; meanwhile the vertical lines represent the surface of such plates. Temperature is represented on the ordinate line and the thickness of the plate is represented on the abscissa line.

The spreading of the temperature within the thickness of the plate in different moments in time - τ_{0}, τ_{1}, τ_{2}, τ_{3}, after the plate has been warmed up suddenly (symilar to warming up the belts inside the core of deformation and cooled off suddenly, in the area of the spray of water for cooling them off), it is produced by the curves PQ, P`Q`.

These curves must comply with two limit conditions:

- the first condition is to be a tangential line to a curve in the middle of the plate and it must be horizontal; because the centre of the plate, represented by a dotted line, is symmetrical, the warmth on this symmetrical axis cannot be spread, and the tangential line to the spreading curve of the temperature is a horizontal line.

- the second limit condition requires that the curves angle to the surface of the plane plate must correspond to the value of the thermal difusivity which is equivalent to the tangential line to the distribution curves of the temperature on the surface of the plate at one point, which represents the temperature of the environment – to $0^{o}C$.

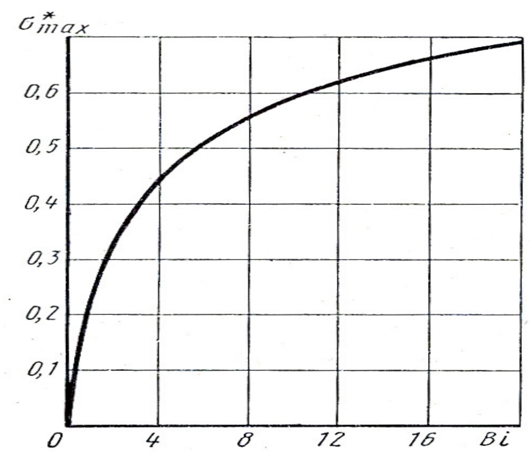

Fig. 2 Description of the specific tensions according to the values of Bi criterion, determined by analytical calculation, [6]

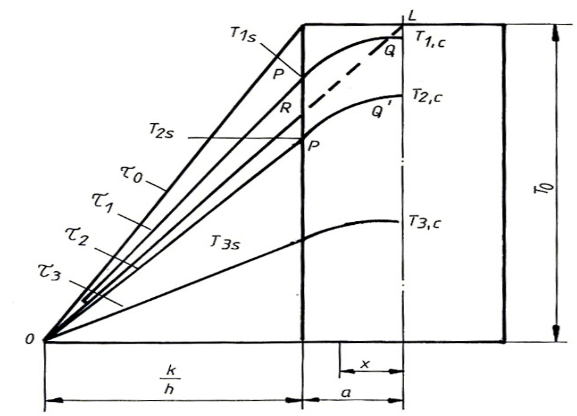

Fig. 3 Distribution of the tenperature within the plane plate, in case of thermal shocks [2]

The temperature distribution curves must also comply with the differential equation and use some values, so that the final result should be equal to the values rquired by the dependency curves σ^{*} and Bi, analytically calculated; for instance, they should have the following direction:

We should admit that in order to have relation (4), for the temperature curve, we have:

$$T = T_{2c} - M \cdot \left(\frac{\chi}{a}\right)^{n} \qquad (4)$$

- where: T_{2c} - the temperature in the middle of the plate, when the tension on the surface is the highest, but it is not determined yet; M şi n – determined constant values, according to all required theoretical results.

When n > 1, this equation does automately comply with the first limit condition, the tangential line to the curve is horizontally, thorugh χ = 0. If the second limit condition is complied with, on the surface of the plate, we can write down the relation (5).

$$k \cdot \left(\frac{dT}{d\chi} \right)_a = h \cdot T_{2S} \tag{5}$$

- *where:* T_{2S} – surface temperature, when the tension has the highest values. In this situation, the second limit condition is complied by the relation (6).

$$M = \frac{Bi \cdot T_{2c}}{Bi + n} \tag{6}$$

If we consider the relations (1), (4) şi (6), we can obtain the specific tension -σ^*, determined according to the equation (7).

$$\sigma^*_{\max} = \frac{T_{2c}}{T_0} \cdot \frac{n}{n+1} \cdot \frac{Bi}{Bi+n} \tag{7}$$

And if we note with $R = \frac{n \cdot T_{2c}}{T_0 \cdot (n+1)}$, relation (7) could be written down as follows:

$$\frac{1}{\sigma^*_{\max}} = \frac{1}{R} + \frac{n}{R} \cdot \frac{1}{Bi} \tag{8}$$

Relation (8) – the graphic of the variation $1/\sigma^*_{\max}$, function of 1/Bi, is a straight line that is represented in fig.4, according to [1], where in order to determine the dependency line we have used the following values of $\sigma^*_{\max}$ and Bi, represented in fig. 2.

For the values 1/Bi > 0,2 or Bi < 5, the graphic is a straight line, and the equation is according to the relation (9).

$$\frac{1}{\sigma^*_{\max}} = 1{,}5 + \frac{3{,}25}{Bi} \tag{9}$$

Based on the analysis of the dependency amongst the values $1/\sigma^*_{\max}$ and 1/Bi represented in Fig. 4 the result is the gap 1/Bi < 0,2, and Bi > 5, and the curve is deviated by the straight lower line and it reaches the limit value σ^*=1,0 for 1/Bi =0, then the relation (9) has been corrected and we have obtained a precise calculation formula (10).

$$\frac{1}{\sigma^*_{\max}} = 1{,}5 + \frac{3{,}25}{Bi} - 0{,}5 \cdot e^{-16/Bi} \tag{10}$$

In work paper [4], we described that relation (10) could contain an error of at most 5%, when Bi = 20. In practical Bi < 20, then we can admit that the relation (10) is highly precise. Nevertheless, Cheng proposes another method for calculating the highest specific tensions - $\sigma^*_{\max}$ for values like 5 < Bi < 20; we use a simple formula (11), written for engineering calculations,

$$\frac{1}{\sigma^*_{\max}} = 1{,}0 + \frac{3{,}25}{Bi^{2/3}} \tag{11}$$

and for the values 0 < Bi < 5 we still use relation (9), and we have used all the values according to Bi criterion.

The work paper [2] contains a formula for calculating the specific tensions obtained by Buesem, which is more simple and uses an original procedure, due to the analysis of temperature distribution presented in fig. 3. He has considered that the specific tension corresponds to the dotted line RL, when the temperature is reaching the highest value. Then, he has determined the specific surface tensions by using two values for Bi and then he has written the relation (12),

$$\frac{1}{\sigma^*_{\max}} = 1{,}0 + \frac{4}{Bi} \tag{12}$$

We can see that the formula is almost the same with relation (9).

- 1- analytically calculated curved, described in fig. 2; 2 - curved calculated according to a simple formula (9); 3 - curve calculated according to formula (12).

Fig.5 represents the graphic comparison amongst the results of the specific tensions $\sigma^*_{\max}$, according to Bi criterion, which are analytically calculated according to fig. 2, - curve 1; according to the simple frormula (9) - curve 2; and according to Buesem formula (12) – curve 3.

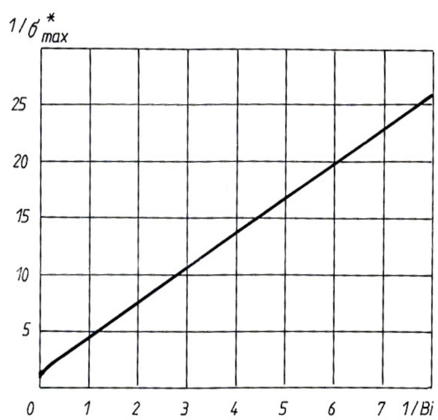

Fig. 4 Dependency relation between $1/\sigma^*_{\max}$ and 1/Bi

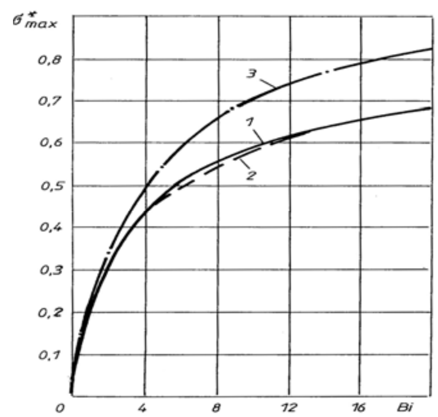

Fig. 5 Results of the specific tension calculation $\sigma^*_{\max}$, according to Bi criterion

The approximation formulas for determining the specific tensions $\sigma^*_{\max}$ could be used for comparing the highest tensions within the materials whose physical features correspond to them. For most of Bi values, in real situations of the themal difusivity values h (α_T) and of thermal conductivity k, (λ) are not high, so that the addition element 1,5, from relation (9), used for enginnering calculations, could be elliminated. In this case, equation (9) could be reformulated and written as expression (13).

$$\frac{1}{\sigma^*_{\max}} = \frac{3{,}25}{Bi} \tag{13}$$

$$T_0 = \frac{k \cdot \sigma_{mx}}{E \cdot \alpha} \cdot \frac{3{,}25 \cdot (1-\mu)}{a \cdot h} \tag{14}$$

For destroying $\sigma^*_{\max} = \sigma_R$, relation (14) could be the following:

$$T_0 = \frac{k \cdot \sigma_R}{E \cdot \alpha} \cdot \frac{3{,}25 \cdot (1-\mu)}{a \cdot h} \tag{15}$$

This last equation allows us to see that according to the thermal difusivity value, the highest thermal shock that stresses a plane whose thickness reaches "2a", and the belt of the rolling cylinder which is proportional with the factor $\frac{k \cdot \sigma_R}{E \cdot \alpha}$, which is identified with a **parametre of the thermal shock** who enables the cutting of the rolling cylinder and depends on the features of the material.

We should mention that this parametre is highlighted by this fact in paper [3], and in the works of other authors.

If we refer to relation (10), we could see that the value 3,25/Bi could be neglected in case the Bi values are really high, and the result is $\sigma^*_{\max}$=1. The relation (16) could be determined according to that.

$$\sigma_{\max} = \frac{E \cdot \alpha \cdot T_0}{1-\mu} \tag{16}$$

The product α T_0 of relation (16) represents the highest comprimation of the material caused by low temperatures, until it reaches value T_0, in case of free movement. If the movement is not enabled then, α T_0 represents the plastic deformation that occurs under such conditions. If we multiply the deformation with factor $E/(1-\mu)$, we determine the tension who is going to influence two different directions, which are perpendicular on each other, in order to compensate any movement caused by the temperature. In case of rolling cylinders, such tension influences are produced on the sides of the calibres' belts. If Bi is very high, we could get the criterion about material deformation according to relation (16), as following:

$$T_{0\max} = \frac{\sigma_R}{E \cdot \alpha} \cdot (1-\mu) \tag{17}$$

Factor $\frac{\sigma_R}{E \cdot \alpha}$ is called **material criterion**, which is different than the thermal shock parametre $\frac{k \cdot \sigma_R}{E \cdot \alpha}$, because it lacks the value of thermal conductivity k(λ). We have to understand that under such conditions, thermal conductivity could not be so high, but the decrease of the temperature that could stress the material is porportional to $\frac{\sigma_R}{E \cdot \alpha}$.

4. Result interpretation:

According to the elements presented in sub-point 3, physically speaking the results of the study about thermal shock, using approximate methods that could be explained in the following:

- if Bi values are very high, then the values of *h* and *k* are also high or smaller than "a" values.

- if "a" value is high, the first layer could be cooled off down to the environmental temperature, faster then the core of the rolling cylinder belt, so that the core should keep a certain specific temperature. In this case, the first layers of the belt could not be contracted

because they should change their shape to the inside of the belt, and that is not possible in case of such big body. Thus, comprimation is fully and completely fulfilled and the tension $\frac{E \cdot \alpha \cdot T_0}{1-\mu}$ occurs, apart from the action of thermal difusivity. In case of high values, the difusivity value h(α_T), the results are the same.
- if the surface of the belt of the rolling cylinder are cooled off down to environmental temperature earlier than the core, there is a complete contraction and there are tensions that do not depend on the thermal conductivity k(λ).
- in case of a lower thermal conductivity, only the first layers could react to thermal shock, and the other parts of the belt keep their innitial temperature, which produces another complete contraction because of the deformation caused by compression and the tension does not depend on the exact value k(λ), if they have very low values.

There are two parametres of the thermal shock for two limit values of Bi criterion; $\frac{k \cdot \sigma_R}{E \cdot \alpha}$ and $\frac{\sigma_R}{E \cdot \alpha}$, and they are necessary for the study of thermal shocks inside warm rolling cylinders, for we could make some calculations if we know the values of thermal tensions inside the rolling cylinders.

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