Technical Sciences
Academy of Romania
www.jesi.astr.ro

D. Chemical Engineering, Materials Science and Engineering, Natural Resources

The theory and practice of heating quality steel ingots

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Abstract: In the process of hot–metal working under the pressure, the heating of the metallic material has a decisive influence upon the quality of the resulted products. On choosing the heating method it has to be taken into account the properties of the metallic material and the kind of its further processing. A performing method for establishing the heating regime of quality steel is proposed. This method is based on the mathematical theory of thermal conductivity and takes into account the nature of steel and the technological processing factors. The analytical determination of the thermal stress is based on the theory of elasticity. Therefore, in order to solve the heat transmission's equations, the obtained results do not correspond, in sufficient measure, with practical data. These results may be considered only as a first approximation that requires to be corrected using the experimental data. It is not intended the examination of different kinds of stress that appear in the steels' heating processes. Is mentioned only that the thermal stress are dangerous in the case of steels with low plasticity and heterogeneous structure, in the presence of the non-metallic inclusions, gas bubbles, films, segregations, holes in the crystalline network etc. The steel's inhomogeneity will result in uneven distribution of the stress, and sometimes, at concentration of the tension in certain parts of the ingots. At heating of these ingots, it is possible to the destruction of the integrity, if the stress value becomes comparable with the limit of the resistance, before the temperature from the central part exceed the limit of elasticity ($500\text{-}550^0$C). It is known that the steel have sufficient elasticity till the interval $500\text{-}550^0$C, over which, practically, can be found in the plastic status. Therefore, thermal stress should be taken into consideration in the heating process, in the interval of $0\text{-}500^0$C, especially in the case of steels with low plasticity. The size and the repartition of the thermal stress depend on the heating conditions, thermophysical and mechanical properties of the steel, the shape and size of the ingots. The work proposes to determine the thermal stress depending on the heating speed, on the basis of the parameters resulting from the experimental research, in order to optimize the heating of the austenitic stainless steel ingots.

Keywords: heating regime, steel ingots, temperatures, thermal stress.

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1. Introduction

In the process of hot–metal working under the pressure, the heating of the metallic material has a decisive influence upon the quality of the resulted products. On choosing the heating method it has to be taken into account the properties of the metallic material and the kind of its further processing. Thus, the ingots' heating requests a higher attention and care then the semiproducts' heating, which is explained by the particularities of the structure and the casted metallic material which is more predisposed to defect formation during the process of hot–metal working [1,2].

The main factors that condition the influence of heating upon the quality are: the temperature and the uniformity of heating, the heating speed and the state of the furnace's atmosphere. Summarizing all these, it is necessary to notice that the heating temperature and the uniformity of the heating are the most important factors and may be even more important than the speed or duration of heating [3,4].

The problem of the influence of the heating regime upon the quality gets a special importance for steel with a high content of the carbon and the alloy ones. Due to the diversity the composition, their heating technology is more complicated and more responsible than that for mild steel or those with a medium content of carbon [5,6,7].

Indeed, steel with a high content of carbon and alloy ones possess a series of particularities that burden and delay the processes of heating, which are [8,9,10]:

- they have lower thermal conductivity and temperature coefficients;
- they are more sensitive to factors that provokes spoiling of the metallic material: overheating and burning, formation of the thermal stress and cracks, etc.;
- during working they are more resistant to deformation and they have closer limits for hot–working temperatures, requiring a higher uniformity of the heating in thickness, on the perimeter and in length [11,12,13].

2. Content

The method proposed in the paper, based on the mathematical theory of thermal conductivity and the theory of the heating regime, allows to establish the heating regime taken into account the steel properties, their conduct upon the heating and during the hot–metal working, the tension and more other factors.

It is known from the practice of heating quality and high–grade steel that destruction of the ingot integrity is possible if the value of the thermal stress becomes comparable with the resistance limit before the temperature of the central part overtakes the perfect elasticity.

The paper compares some practical obtained data from industrial research with data from theoretical methods of computation, with the aim of optimizing the heating technology.

Industrial quality steel ingots underwent heating in deep furnaces (figure 1), recording the dynamics of thermal parameters (figure 2) on heating with different heating speeds.
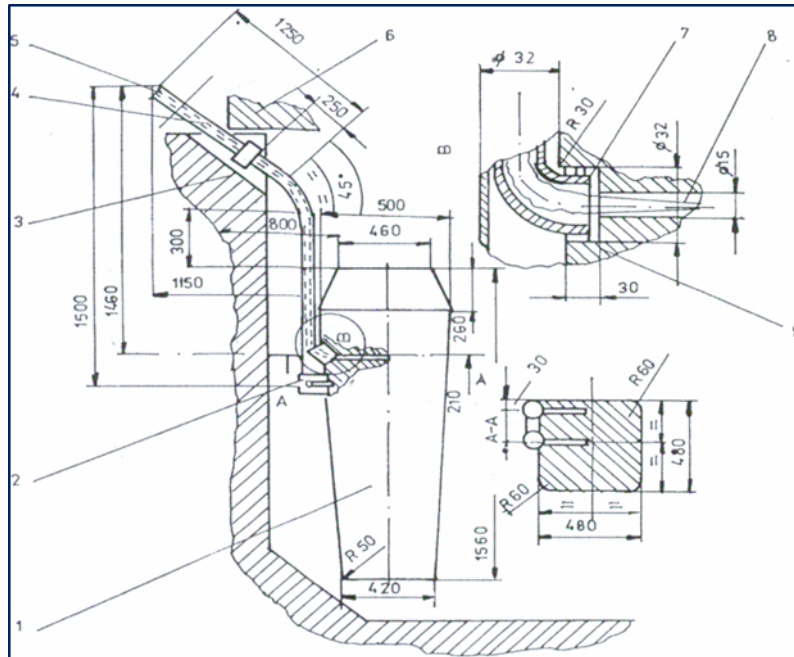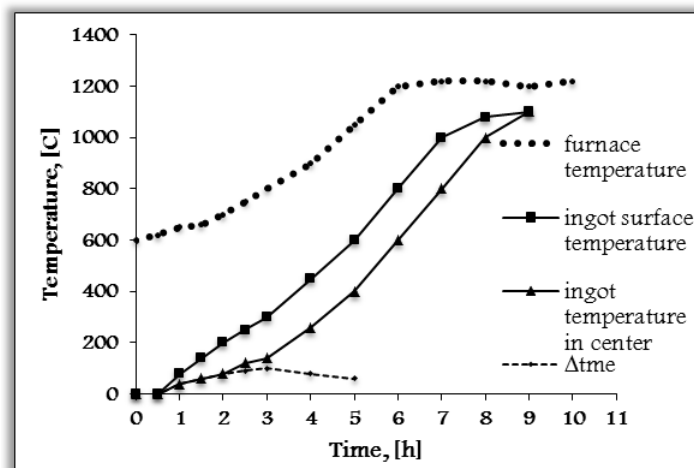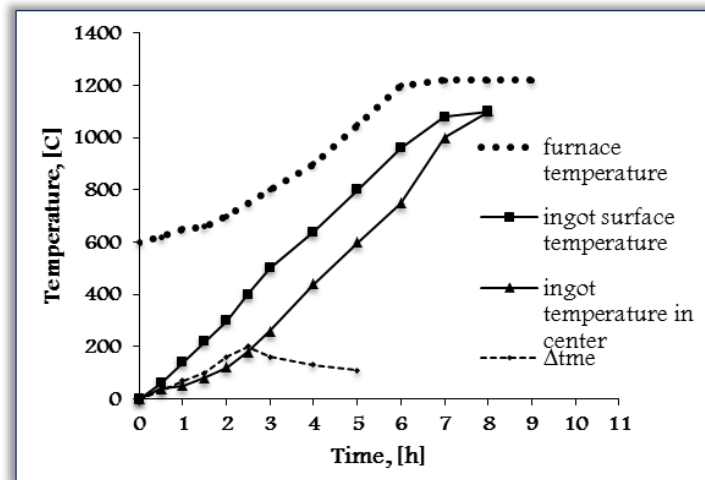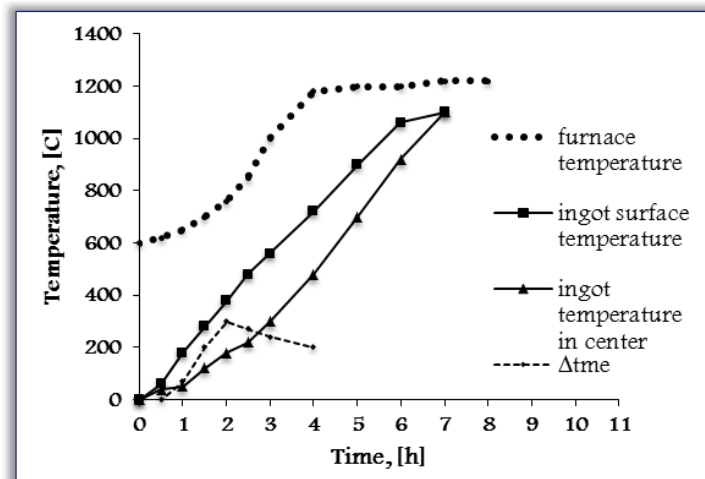

Figure 1. Installing of thermal torques for measurement of the ingot's temperature
1 – ingot; 2 – thermocouple's spiral coil for cooling; 3 – furnace's wall; 4 – thermocouple's sheath; 5 – thermocouple's electrodes; 6 – furnace's ceiling; 7 –thermocouple's connection sheath; 8 – ingot's core thermocouple electrodes; 9 – ingot's hole for the thermocouple.

a)

b)

c)

Figure 2. Experiments with different heating speeds, seeking the optimum ingot heating
a) heating speeds at 60 C/h; b) heating speeds at 80 C/h; c) heating speeds at 100 C/h

The determination of existing stress depending on the heating speed applied, which upon working might cause quality decreasement, has been studied, based on the following computation theories:
- in conditions of changing surface;
- linear variation of surface temperature;
- considering the experimental–stated temperature gradient.

Explanations of computations:

λ–thermal conductivity coefficient, $(W/mK)10^{-3}$; c_p – heat capacity, J/kgK; γ– weight capacity, kg/m^3; E – elastic modulus, daN/mm^2; β– linear dilatation

coefficient, $^0C^{-1}$; ν– Poisson's coefficient (for steel = 0.3); a – temperature diffusivity coefficient, m^2/h; τ– time, h; t_s – ingot surface temperature, ^0C; Δt_m – maximum temperature gradient on section, ^0C; R – ingot radius approximated to a cylinder, m; r – distance from ingot axis to its surface, m; c – heating speed, $^0C/h$.
Applying the first theory – in conditions of changing surface, which in fact is also the most frequent case in industrial practice, tension values will be:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{c_m \cdot R^2}{8a}\left(1 - \frac{2 \cdot r^2}{R^2}\right) + \frac{\beta \cdot E}{1-\nu} \cdot \frac{R^2}{a} \cdot \sum_{n-1}^{\infty} \frac{2}{\mu_n^4} - \mu_n \cdot \frac{I_0\left(\mu_n \frac{r}{R}\right)}{I_1 \mu_n} \cdot A_n \quad (1)$$

in which:

$$A_n = C_1 e^{-\mu_n^2 \frac{a\tau}{R^2}} + (C_2 - C_1)e^{-\mu_n^2 \frac{a(\tau-\tau_1)}{R^2}} + ...$$

Introducing in relation (1) the value for A_n it becomes:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{c_m \cdot R^2}{8a}\left(1 - \frac{2 \cdot r^2}{R^2}\right) + \frac{\beta \cdot E}{1-\nu} \cdot \frac{R^2}{a} \cdot \sum_{n-1}^{\infty} \frac{2}{\mu_n^4} - \mu_n \cdot \frac{I_0\left(\mu_n \frac{r}{R}\right)}{I_1 \mu_n} \cdot C_1 e^{-\mu_n^2 \frac{a\tau}{R^2}} + \quad (2)$$
$$+ (C_2 - C_1)e^{-\mu_n^2 \frac{a(\tau-\tau_1)}{R^2}} + ...$$

Accomplishing the computations with relation (2) requires the consideration of a great number of terms infinite series. For simplification, the respective infinite series are approximated with the functions $\left(\frac{a\tau}{R^2}; \frac{r}{R}\right)$.

Thus, the relation (2) becomes:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{R^2}{a}\left\{\frac{c_m}{8}\left(1 - \frac{2r^2}{R^2}\right) + C_1 f' + [(C_2 - C_1)f'' + (C_3 - C_2)f''' + ...]\right\} \quad (3)$$

in which: c_m – represent the heating speed in period m;

$c_p, \gamma, \lambda, \beta, E, a \left(a = \frac{\lambda}{c_p \gamma}\right)$ – represents coefficients which depends by steel's nature, having different values at temperature variations.
For the coefficients employed in the relations, table 1 values are beginning used.

The value of the introduced $f\left(\frac{a\tau}{R^2}; \frac{r}{R}\right)$ functions depend on the heating time (τ) and the distance from the center of the ingot to the surface, approximated with (r), the results of the computations being for an easier utilization, processed as a nomogram (figure 3). Because quality steel has a low thermal conductivity in the size of industrial ingots and requires long times of preheating, the computation of stress in condition of changing surface had been accomplished with the relation (3) in the interval 0 – 500^0C, applying three heating speeds: 60, 80 and 100$^0C/h$ using

the parameters from table 1, and for the functions $\left(\dfrac{a\tau}{R^2};\dfrac{r}{R}\right)$ the nomogram from figure 3. The resulted stresses dependent on the heating temperature are show in table 2.

Table 1. Value of the employed coefficients depending on the temperature

$t\,^0C$	0	100	200	300	400	500	600	700	800	900	1000
λ [W/mK 10^{-3}]	15.9	16.3	17.2	18.4	20.1	21.7	23.8	25.6	26.7	26.7	28.0
γ [10^3Kg/m^3]	7.92	7.98	7.84	7.80	7.75	7.71	7.66	7.66	7.56	7.51	7.46
c_p [J/kgK]	-	0.502	0.511	0.523	0.527	0.536	0.544	0.548	0.557	0.561	0.561
E [10^3N/ mm^2]	196.2	190.0	180.5	175.0	156.9	151.1	145.2	–	126.5	–	–
β x10^{-6} [K^{-1}]	-	14.8	16.5	17.1	17.6	18.0	18.4	18.8	19.0	19.2	19.4

Table 2. Value of the thermal stress depending on the speed and the heating temperature

$t_c\,^0C$	100	200	300	400	500
$v\,^0C$	Value of the thermal stress σ_z, N/mm^2				
60	110	139.5	131.4	114.1	92.7
80	160.9	200.0	191.5	166.3	135.7
100	203.7	257.5	242.0	211.2	171.2

In the second variant, considering that the ingot's surface temperature varies linear, the heating is achieved with constant t_0 temperature and the heating speed is uniform. Then, temperature distribution on ingot section will be:

$$t = t_0 + C\tau + \frac{CR^2}{4a}\left(\frac{r^2}{R^2}-1\right) + \frac{CR^2}{a}\cdot\sum_{n=1}^{\infty}\frac{2}{\mu_n^3 I_1(\mu_n)}I_0\left(\mu_n\frac{r}{R}\right)\cdot e^{-\mu_n^2\frac{a\tau}{R^2}} \qquad (4)$$

or writing down the sums of the infinite series with $f\left(\dfrac{a\tau}{R^2};\dfrac{r}{R}\right)$ it is obtained:

$$t = t_0 + C\tau + \frac{CR^2}{4a}\left(\frac{r^2}{R^2}-1\right) + \frac{CR^2}{a}\cdot f\left(\frac{a\tau}{R^2};\frac{r}{R}\right) \qquad (5)$$

Thermal tension for this variant are begin calculated with the relation:

$$\sigma_z = \varepsilon_z E + \frac{\beta\cdot E}{1-\nu}\cdot\left(-t + \frac{2\nu}{R^2}\cdot\int_0^R t_r dr\right) \qquad (6)$$

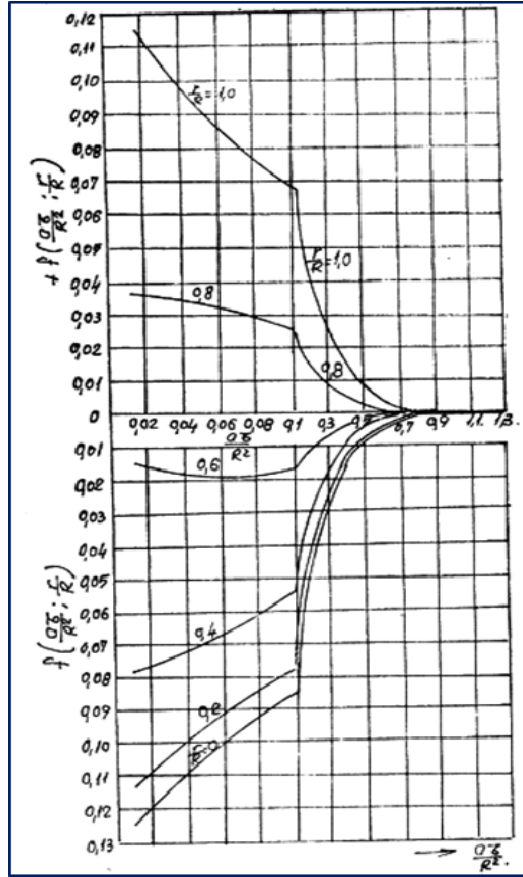in which ε_z stands for axial deformation.

Figure 3. Nomogram traced for function $f\left(\dfrac{a\tau}{R^2};\dfrac{r}{R}\right)$ for determination

of thermal stress in quality steel ingot [8]

If in the previous relation it is introduced the value of t and integration is accomplished, it results:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{CR^2}{a} \cdot \left\{ \frac{1}{8}\left(1 - \frac{2r^2}{R^2}\right) + \sum_{n=1}^{\infty} \frac{2}{\mu_n^4}\left[2 - \mu_n \frac{I_0\left(\mu_n \frac{r}{R}\right)}{I_1(\mu_n)}\right] \cdot e^{-\mu_n^2 \frac{a\tau}{R^2}} \right\} \qquad (7)$$

and replacing the infinite series with the $f\left(\dfrac{a\tau}{R^2};\dfrac{r}{R}\right)$ function, it is obtained the

computation relation for the thermal stress in the ingot when its surface temperature varies linear:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{CR^2}{a} \cdot \left[\frac{1}{8}\left(1 - \frac{2r^2}{R^2}\right) + f\left(\frac{a\tau}{R^2}; \frac{r}{R}\right) \right] \tag{8}$$

For the same speeds and heating temperatures, results stress given in table 3.

Table 3. Value of the thermal stress depending on the speed and temperature
when the ingot's temperature varies linear

$t_c \, ^0C$	100	200	300	400	500
$v \, ^0C$	Value of the thermal stress σ_z, N/mm^2
60	137.0	132.0	113.0	109.0	92.7
80	204.0	191.0	161.5	159.2	132.5
100	250.2	241,2	209.0	197.1	175.9

If the third case is being considered, when it is experimentally known the temperature gradient on the ingot section, the resulted stress will record the values from table 4, which are mostly close to real.

Table 4. Value of thermal stress, considering the maximum temperature gradient Δt_m
on the ingot's surface

v	\multicolumn{5}{c}{60}	\multicolumn{5}{c}{80}	\multicolumn{5}{c}{100}
t_c	100	200	300	400	500	100	200	300	400	500	100	200	300	400	500
Δt_m	125	102	107	99	97	200	204	200	170	159	272	270	269	262	254
σ_z	253	216	228	195	164	405	430	427	335	269	540	574	566	517	431

v – heating speed [^{0}C/h]; t_c [^{0}C]; Δt_m [^{0}C]; σ_z [N/mm^2]

But the temperature gradient (Δt_m) can be also established analytically with the relation:

$$\Delta t_m = \frac{CR^2}{4a} \tag{9}$$

Introducing this value in relation (8) it is obtained the computation formula for the thermal stress that comes into being in any spot on the ingot's section:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{CR^2}{8a} \cdot \left(1 - \frac{2r^2}{R^2}\right) = \frac{\beta \cdot E}{1-\nu} \cdot \frac{\Delta t_m}{2} \cdot \left(1 - \frac{2r^2}{R^2}\right) \tag{10}$$

If the stress determination is made for the core of the ingot, relation (10) becomes:

$$\sigma_z = \frac{\beta \cdot E}{1-\nu} \cdot \frac{\Delta t_m}{2} \tag{11}$$

Thermal stress resulted by using the three methods studies above, depending on the experimentally applied heating speed, are presented in figure 4.
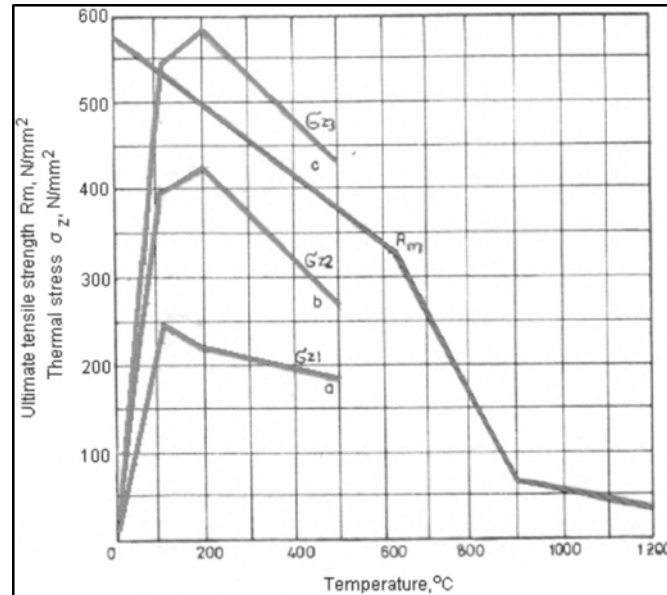
Figure 4. Thermal stress resulted by using the different heating speeds

Comparing the obtained results, it is noticed that when using the experimentally measured temperature gradient (Δt_m) on the ingot's section it is recorded values close to the R_m hot breaking limit if the heating speed is 80^0C/h (figure 4, curve b) when the thermal stress reach 420 N/mm^2 and the ingot's surface temperature record 200^0C. If, for the specific quality steel is applied a heating speed of 100^0C/h (curve c) it results in the destruction of the ingot's integrity with the appearance of internal fissures due to the fact that $\sigma_z > R_m$.

3. CONCLUSIONS

The work has proposed to determine the thermal stress depending on the heating speed, on the basis of the parameters resulting from the experimental research, in order to optimize the heating of the austenitic stainless steel ingots.
The steel ingots cracking during the heating is caused by the thermal stresses whose value are comparable with their limit of resistance, before that the temperature in the center of them exceed the limit of elasticity (500-550^0C).
If the temperature variation in the mass of ingot can be experimental determined, the thermal stress can be valued than by analytical way.
The determination of the thermal stress depending on the heating speed is performed, more frequently, by the following methods:
– considering a changeable surface conditions;
– considering that the temperature's linear variation on the surface;
– considering an experimentally determined difference of temperature.

The calculation of the thermal stress, in terms of changeable surface conditions, it has been performed on the experimental ingot heating within 0-500^{0}C, by applying the three heating speeds (60, 80 and 100^{0}C/h) using the relations (1), (2) and (3). If it is considered that the ingot's temperature on the surface varies linear, the heating is performed with constant temperature, the heating speed being uniform. The temperature distribution on the ingot's section, in these heating conditions, is given by the relations (4) and (5).

For the determination of the thermal stress in the conditions of the temperature's linear variation at the surface of the ingot, the relations (6), (7) and (8) are used.

If the third case is analyzed, when the temperature difference on the section of the ingot is experimentally knows, the thermal stress can be calculated as close as possible to reality.

By comparing the results obtained by the three methods in the calculation of the thermal stress, it is noted that in the case of use the difference temperature per section (Δtm) shall be recorded the maximum values. For heating with a speed of 80^{0}C/h (figure 4), thermal stress to reach values about the 420 daN/mm^2, when the surface temperature records 200^{0}C. If, for the studied steel, has applied a heating speed of 100^{0}C/h (figure 4) will occurs the destruction of the ingot's integrity.

In conclusion, the method based on the use of the maximum difference temperature in the ingot's section, by which it shall take into account, to the greatest extent possible, the influence of the heating technological factors, is easier for the technological calculations and have a greater safety factor for the industrial practice.

The method applied in the present research, based on the use of the maximal temperature gradient on the ingot's section considers best the influence of the heating technological factors comparatively to the other studied methods. This method is easier and presents safety for industrial practice, leading to the improvement of the quality of rolled steel by avoiding thermal stress.

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