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# The influence of rolling technological factors on the quality of reinforcing steel

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**Abstract.** The research conducted under industrial conditions deals with the influence of chemical composition factors and rolling technological factors on the mechanical properties of alloy steel for constructions.

Determining the influence of technological rolling factors on mechanical characteristics was a difficult problem due to the lack of research equipment for measuring with sufficient accuracy in operating conditions the temperature of the laminate and the dependence of this factor on the whole complex of other technological parameters. The completion of the study required the extension of research in the field of equipment construction to measure the temperature of small laminates and the cooling rate to meet the requirements of current practice.

Following the research carried out in industrial conditions, the contribution brought on the qualitative characteristics of the experienced reinforcing steel is specified, depending on the technological factors of the process.

**Keywords:** reinforced concrete, tenacity, brittle tear, thermal hardening, weldability.

## 1. Introduction

In order to be suitable as a building material, low-alloy steels of high technical strength must have characteristics and properties that allow the consumer to achieve savings through their proper use [1,2]. These steels need to be much stronger and in many cases more tenacious than structural carbon steels. It must also be sufficiently ductile, formable, weldable [3,4,5] and easy to process by the usual workshop methods. In addition, they are often required to have a higher

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corrosion resistance [6,7], so that an element of this steel with a small cross-section has a service life equal to that of an element with a higher cross-section of structural carbon steel, or, in the case of equal section, the service life of the low-alloy steel element to be longer.

The first property, superior strength is common to these steels. The other properties taken individually or as a whole appear or not in the various steels of this group depending on their composition. In reinforced concrete constructions, welded metal and mechanical constructions, it was passed to elaboration and rolling of steels with improved strength characteristics such as PC 52 reinforcing steel (SR 438-1: 2012).

Also, parallel to the level of characteristics achieved for this steel, the sensitivity to overheating was studied for the structural alloy steels 15Co8 and 18MoCN13, rolled under similar conditions.

## 2. Industrial experiments

The qualitative characteristics of rolled steels are determined both by their nature (chemical composition) and by the technological conditions of the technological process.

In order to obtain by rolling of a fine structure, which ensures high constancy of the quality characteristics, it is recommended to reduce the temperature at the end of rolling, which causes the specific energy of deformation to increase, and the time during which the laminated material is above the critical recrystallization temperature to reduce.

From the research carried out in industrial conditions, the influence of the chemical composition on the quality characteristics is highlighted, but to a lesser extent that of the technological factors. These tests were the basis for the introduction of the new reinforcing steel grade PC52.

Determining the influence of the technological parameters on the quality characteristics required an intensive research activity in order to build the equipment for measuring the temperature of small-sized rolled steel and the cooling speed that would meet the requirements of current practice.

The technical characteristics of the pyrometer made are: maximum error 1%, resolution time 1s, minimum aiming diameter – 6 mm recommend its use for research and production purposes.

The program established for the rolling research of PC52 steel grade with a diameter of 20 mm aimed to make the end-of-rolling temperature range as wide as possible, and the distribution of samples number over the entire temperature range to be as uniform as possible. Also, in the conditions of the existence of temperature variations along the length of the rolled profile, it is necessary to have the certainty of knowing the temperature in the portion from which the sample is cut.

For this purpose, it was necessary to install optical pyrometers at the exit from the first and last rolling stand to measure the temperatures at the beginning and end of rolling process (the first pyrometer with a measurement range of 1000-1250°C, and the second one of 850-1100°C).

The values corresponding to the upper limit of the temperature range were obtained by heating the propulsion furnace to 1320°C; exceeding this temperature leads to technological deficiencies such as: sticking of billets, burning of the material, etc.

The values of the lower limit of the tested temperature range were obtained by reducing the furnace temperature to 1250°C, and in some cases by removing the end of the billet from the furnace, over a length of about 2 m, for 20-45 seconds. In this way the end of the billet loses temperature, reaching minimum values of 1050°C, which allows the realization of a range for end-of-rolling temperatures between 900 and 1000°C.

The fact that in the rolling stand the laminate moves at a constant speed (0.4 m/s in the first rolling stand, 12 m/s in the last rolling stand) allows the temperature-time diagram to transform into a temperature-length diagram (Fig. 1, 2 and 3).

During the experiments, the radiation pyrometers installed at the exit of the rolled steel from the first rolling stand (fig. 1.a) and from the last rolling stand (fig. 1.b) noticed that the heating along the length is uneven. The uneven heating of the billets along the length is due to the radiation of the furnace walls, which produces an additional heating of the ends of the billet, making its temperature higher than the middle. Incorrect adjustment of the burners in the equalization zone also causes local temperature rises. These non-uniformities in some cases reach values of about 100°C

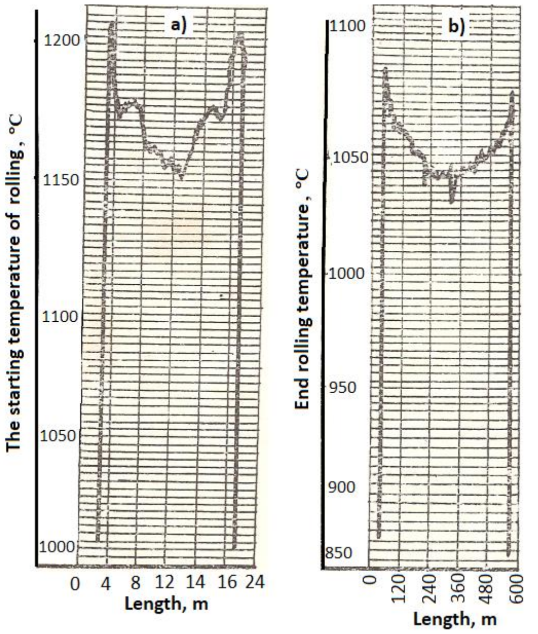


Fig. 1. Uneven heating along the length, detected by the radiation pyrometers mounted at the exit of the rolled steel: a – from the first rolling stand; b – from the last rolling stand.

As seen, temperature non-uniformities were also intentionally created at the ends of some billets to expand the investigated temperature range (fig.2, a,b). From a practical point of view, the uneven heating of billets can have an influence both on the mechanical characteristics variation of the rolled steel along the length, to the extent of their dependence on the temperature at the end of rolling, and on the plasticity of the metal (burrs appear along the length of the rolled steel in the portions with lower temperature).

With the help of the temperature-length diagram, during the experiments, the portions with temperature differences were located along the length of the billet, which, by adjusting the burners, ended up being adjusted to the minimum (fig. 3, a,b).

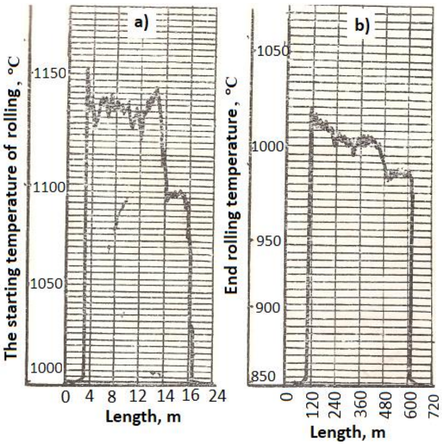


Fig. 2. Temperature non-uniformities created at the ends of some billets to expand the investigated temperature range: a – at the exit from the first rolling stand; b – at the exit from the last rolling stand.

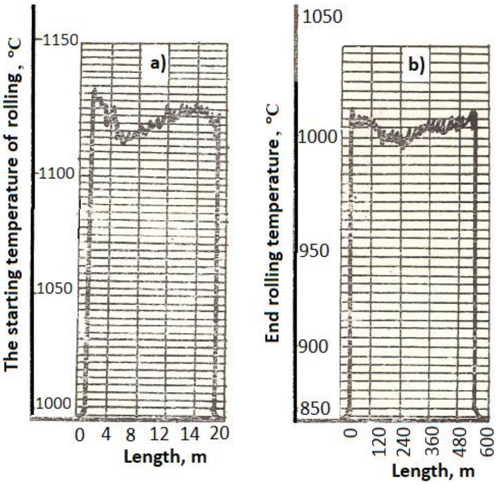


Fig. 3. Uniformization of temperature during heating by means of length-temperature diagrams: a – at the exit from the first rolling stand; b – at the exit from the last rolling stand.

The knowledge of these non-uniformities through the interpretation of the temperature-length diagrams, had the effect of improving the heating process, and the widening of the temperature range necessary for experimentation was subsequently ensured only by reducing the temperature at the end of the billet, keeping the furnace temperature constant.

Metallic and metallographic characteristics were determined on 500 mm long samples cut from the end of rolled bars and numbered. For each sample, the chemical analysis was carried out, determining the content of C, Mn, Si, the mechanical characteristics $R_m$, $R_{p0,2}$, $A_5$, KCU 300/2 as well as the metallographic analysis of the structure resulting from rolling, in the longitudinal section of the samples.

In order to avoid errors caused by segregations or superficial decarburization, the samples needed for chemical analysis were collected from holes transversely made in the ends of the samples that were subjected to traction. The chemical composition of the experimental samples resulting from the current production fell within narrow limits compared to the norms. The statistical analysis shows the variations of the chemical composition compared to the average values (Table 1). As in the case of chemical composition, the range of variation of mechanical characteristics is reduced (Table 2).

Table 1.

| **Chemical composition** | **Average value, %** | **Standard deviation, %** | **Relative error, %** |
|---|---|---|---|
| C | 0.19 | 0.02 | 10,5 |
| Mn | 1.500 | 0.120 | 8 |
| Si | 0.033 | 0.033 | 10 |

Table 2.

| **Mechanical characteristics** | **Average value** | **Standard deviation** | **Relative error** |
|---|---|---|---|
| Tensile strength $R_m$ | 580.9 N/mm$^2$ | 19.5 N/mm$^2$ | ±3.2 |
| Yield strength $R_{p0,2}$ | 366.6 N/mm$^2$ | 16.7 N/mm$^2$ | ±4.5 |
| Elongation $A_5$ | 29.58 % | 3.73% | ±12.6 |
| Resilience KCU 300/2 | 17.16 daJ/cm$^2$ | 3.11 daJ/cm$^2$ | ±18.3 |

As can be seen from these data, the smallest variations show the tensile strength, and the largest the resilience. In order to establish the dependence between the final rolling temperature and the mechanical characteristics, it is first necessary to know the effect of the chemical composition, then the effect of the temperature can be established by difference. Through the statistical-mathematical processing of the data with the help of the electronic computer, the equations that determine the mechanical characteristics of the samples according to the chemical composition were obtained. These equations are of the form:

$$y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{k=1}^{3}\sum_{j=1}^{3} a_{kj} x_k x_j \tag{1}$$

in which:

$a_{kj} x_k x_j = a_{jk} x_j x_k$, so they can group

and:

$$x_1 = \%C; \quad x_2 = \%Mn; \quad x_3 = \%Si.$$

In addition to the influence of the chemical composition, similar equations were obtained to estimate the influence of the end of rolling temperature:

$$y = b_0 + \sum_{i=1}^{4} b_i x_i + \sum_{k=1}^{4}\sum_{j=1}^{4} a_{kj} x_k x_j \tag{2}$$

in which:

$a_{kj} x_k x_j = a_{jk} x_j x_k$, so in this case too they can group

and:

$$x_1 = \%C; \quad x_2 = \%Mn; \quad x_3 = \%Si \quad x_4 = T_f.$$

$T_f$ - end of rolling temperature.

The equations obtained in this way are more accurate as they allow the assessment of the degree of influence of the temperature at the end of rolling on the mechanical characteristics.

By introducing this new variable $x_4 = T_f$ in all equations, the correlation factor increased, as can be seen from the comparative data presented in Table 3.

Table 3.

| **Correlated parameter** | **Correlation factor as a function of chemical composition** | **Correlation factor as a function of chemical composition and $T_f$** |
|---|---|---|
| $R_m$ | 0.67 | 0.78 |
| $R_{p0,2}$ | 0.33 | 0.522 |
| $A_5$ | 0.513 | 0.522 |
| KCU 300/2 | 0.473 | 0.675 |

The quantitative determination of the mechanical characteristics variation according to the temperatures at the end of rolling was done by deriving equations (2) resulting in equations of the form:

$$\frac{d_y}{d_T} = c_0 + \sum_{i=1}^{4} c_i x_i \tag{3}$$

Using equation (3), the following quantitative variations are obtained for the mechanical characteristics:

$$\frac{d_{Rm}}{d_T} = -0.3\ \frac{N \cdot mm^{-2}}{°C};$$

$$\frac{d_{Rp0,2}}{d_T} = -0.5\ \frac{N \cdot mm^{-2}}{°C};$$

$$\frac{d_{A5}}{d_T} = \frac{0.004\%}{°C}\ ;$$

$$\frac{d_{KCU300/2}}{d_T} = 0.185\ \frac{daJ \cdot cm^{-2}}{°C}$$

These values indicate the degree of influence of the end-of-rolling temperature on the mechanical characteristics, a fact that is also reflected by the dynamics of the growth of the correlation coefficients of the equations.

The increase of the correlation coefficient of equation (2) from 0.67 to 0.78, by introducing the variable $x_4 = T_f$ and the existence of an average growth factor of the tensile strength with $-0.3$ , confirms the existence of this influence.

The metallographic analysis was performed for each sample in order to correlate the thermal parameters with the mechanical characteristics and the structure obtained after rolling.

The dependence between end-of-rolling temperatures and the structure of steel PC52, Φ 20mm (figure 4) was established by careful and repeated observation of the metallographic samples that were classified into three representative groups (a, b and c) for the temperature range between 900 and 1000°C, forming a comparative scale.

The examination of these microstructures obtained at different temperatures at the end of rolling shows that, at temperatures of approximately 900°C, the structure is pearlitic-ferrite (figure 4,a), with ferrite and pearlite being arranged in thin parallel rows. As temperatures increase, the thickness of the parallel layers of ferrite and pearlite increases concomitantly with grain growth. At the same time, a weakening of the arrangement in rows of the structure is observed. At temperatures of 950°C (figure 4,b), the parallel rows structure disappears, and ferrite and pearlite become compact, with greatly increased dimensions.

a) b) c)

Fig. 4. The influence of the end-of-rolling temperature on the metallographic structure of steel PC52, Φ 20mm: a – at a temperature of approx. $900^0$C; b – at $950^0$C; c – at $1000^0$C.

With further increase in temperature, austenitic grain growth makes the existing cooling rate no longer able to precipitate pro-eutectoid ferrite at the grain boundary. Some of the ferrite will precipitate inside the pearlite grains as fine elongated grains (Widmanstatten). Around the temperature of 1000°C (figure 4,c) the pro-eutectoid ferrite almost disappears, all the ferrite precipitated inside very large pearlitic grains.

Attempts to establish the dependence of the end-of-rolling temperatures and the structure of PC52 steel show that the change in grain size after deformation causes the change in yield strength and toughness.

Probably the most effective means of grain size control is to adjust the cooling intensity of the bar immediately after rolling. In this case, the change in the structure of the steel is closely related to the adjustment of cooling [8,9,10]. The influence of plastic deformation on the grain size is removed by the effect of the end-rolling temperature, so that the newly formed grain tends to grow undesirably if it is not subjected to rapid cooling. For this purpose, tests were carried out to indicate the influence of the cooling rate on the mechanical characteristics of the researched structural steel.

In order to keep the chemical composition as homogeneous as possible, 50 samples with a length of 300 mm were cut from the same PC52 Φ 20mm laminated steel bar. Grouped by 5, the samples were heated up to the value corresponding to the end of rolling temperature (≈900°C), and the cooling from this temperature was carried out in different environments: free air (to determine the conditions of similarity with the cooling that takes place on the factory cooling bed), water, oil, sprayed water, compressed air, sprayed water and compressed air and cooling together with the furnace. The cooling rate for each medium was obtained by recording the cooling curves. The temperature was measured with a contact thermocouple whose end was previously glued to the contact surface.

In table 4 it is given, depending on the nature of the experimented environment, the achieved cooling rate and the value obtained for the tensile strength.

Table 4.

| **The cooling environment** | **Cooling rate °C/s** | **Tensile strength $R_m$, N/mm$^2$** |
|---|---|---|
| Water | - | 1100 |
| Oil | 106 | 760 |
| Sprayed water | 16 | 580 |
| Compressed air | 4.0 | 540 |
| Air | 2.5 | 520 |
| Cooling in the furnace | 0.028 | 472 |

Analyzing the results, it can be seen that by varying the cooling rate, the tensile strength of this steel changed between 470 N/mm$^2$ in the case of cooling in the furnace and 1100 N/mm$^2$ in the case of cooling in water. So, it results that the physico-chemical characteristics of the finished product can be influenced to a great extent, by applying the appropriate cooling rate after lamination.

## 3. Austenitic grain growth kinetics in reinforcing steel

From the specialized literature, as well as from the interpretation of the experimental data, it follows that the austenitic grain size is dependent on the temperature at which the austenising is carried out [11,12,13,14]. To determine the size of the austenitic grain in steels, the austenising temperatures are established by standards and generally vary within tight limits, depending on the steel grade, the duration of maintenance at the austenising temperature, being 8 hours for the carburizing method and 3 hours for the other methods.

When determining the kinetics of austenitic grain growth, the holding times at the austenising temperature and the austenising temperatures are not standardized, they can be fixed according to the temperature range considered as representative and according to the thickness of the parts to be analyzed.

In the research works, 10 minutes is considered as the time required for austenising for samples with dimensions of about 5 mm; in the case of our determinations for samples with a diameter of 10 mm, the holding time was 30 minutes, sufficient for the formation of the austenitic grain. At an extension of the holding time up to 2 hours, no changes in the austenitic grain size were observed in relation to the time of 30 minutes.

The dependence of the austenitic grain size on temperature is all the greater the higher the percentage of carbon, and in the case of high temperatures (over 930°C) the increase in the degree of carbon diffusion can lead to essential distortions regarding the austenitic grain size.

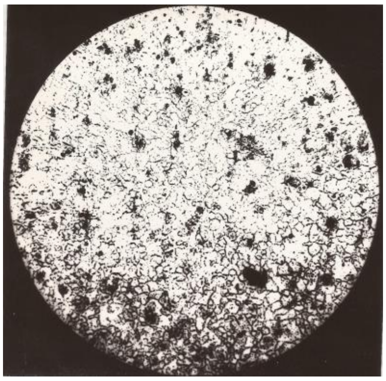
For the mentioned reason, the oxidation method was used by introducing an air current directed on the surface of the austenising sample (heated in an argon atmosphere). After removing the oxide layer and polishing the sample, the attack was done with the Villela reagent.

The kinetics of austenitic grain growth in PC52 low-alloy reinforcing steel at elevated temperatures was studied in comparison with the kinetics of two structural alloy steels 15Co8 and 18MoCN13 heated under similar conditions. Table 5 shows the scores determined for different temperatures at the analyzed grades, and the microstructures for the samples analyzed at 950°C, 1150°C and 1350°C are included in figures 5, 6 and 7.

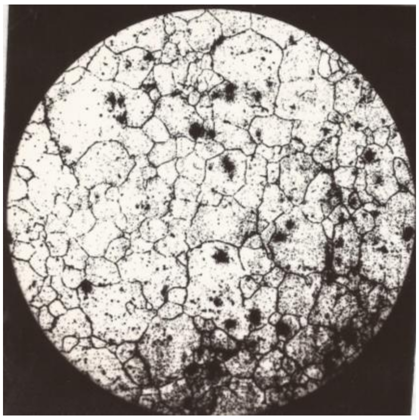
Table 5.

| **Grade** | **Austenising temperature, °C** | | | | | |
|---|---|---|---|---|---|---|
| | **870** | **950** | **1050** | **1150** | **1250** | **1350** |
| PC52 | 9 | 8 | 6 | 5 | 3 | 1 |
| 15Co8 | 7 | 7 | 7 | 7 | 6 | 2 |
| 18MoCN13 | 10 | 9 | 9 | 8 | 6 | 4 |

It is generally observed that at temperature increases up to 1150°C, an excessive size of the austenitic grain size is not obtained, a fact less valid for temperatures above 1150°C, an area in which the increases become accentuated. It is worth noting that even with concrete steel PC52, which shows significant increases at the temperature of 1350°C, at the temperature of 1150°C the grain size is score 5, so in general much lower than those reported in the literature.



Austenising temperature of 950□C
(Scale: 100:1)

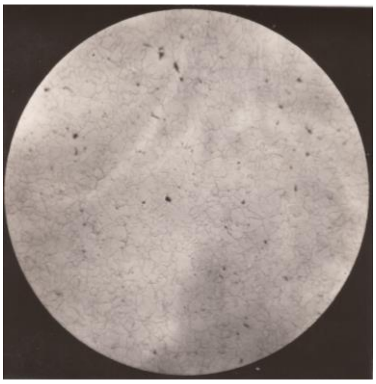


Austenising temperature of 1150□C
(Scale: 100:1)

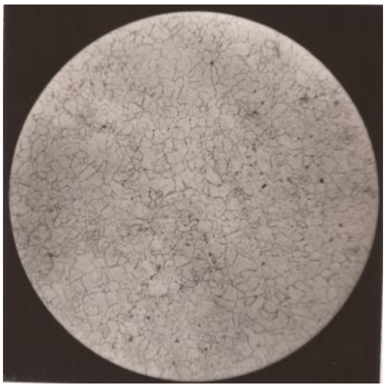
Austenising temperature of 1350□C
(Scale: 100:1)

Fig. 5. Characteristic microstructures for the PC52 reinforcing alloy steel.

As expected, the 18MoCN13 steel has the highest resistance to austenitic grain growth due to the alloying with molybdenum, an element that raises the grain growth temperature. Since the normal forging temperatures are located in areas below the temperature of 1150°C, and the quenching temperatures for the studied grades do not exceed 890°C, it can be appreciated that the three steel grades have a high stability regarding the austenitic grain growth tendency.



Austenising temperature of 950°C
(Scale: 100:1)



Austenising temperature of 1150°C
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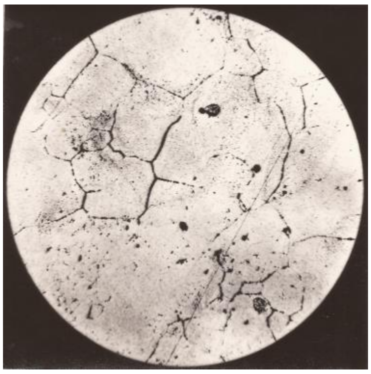
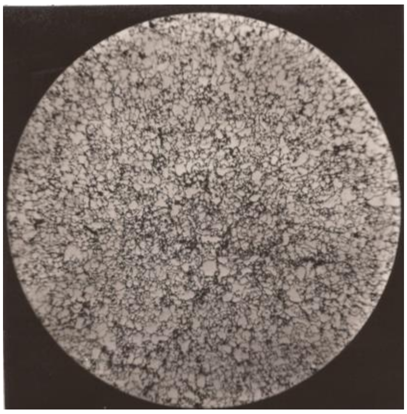
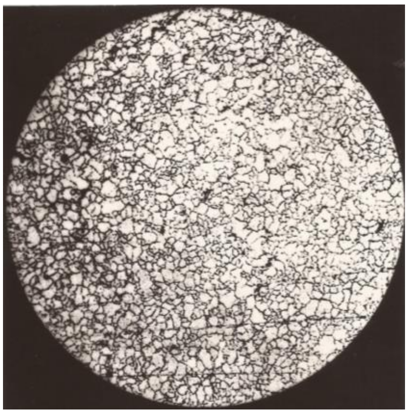


Austenising temperature of 1350°C
(Scale: 100:1)

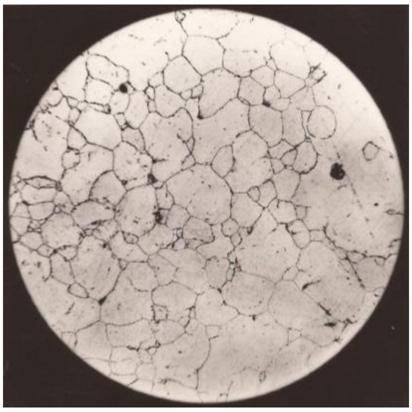
Fig. 6. Characteristic microstructures for the 15Co8 structural alloy steel.



Austenising temperature of 950°C
(Scale: 100:1)



Austenising temperature of 1150°C
(Scale: 100:1)



Austenising temperature of 1350°C
(Scale: 100:1)

Fig. 7. Characteristic microstructures for the 18MoCN13 structural alloy steel

## Conclusions

Using the temperature-length diagrams, recorded with the pyrometer built for experimentation (maximum error 1%, resolution time 1s, minimum aiming diameter 6 mm), improvements were made to the heating process by equalizing the temperature of the billets along the length and the quality level of the finished products, by achieving the constancy of the quality characteristics to the extent of their dependence on the variation of the thermal parameters.

Through the research carried out in the rolling of reinforcing steel, the degree of influence of the technological factors, especially the temperature at the end of rolling and the cooling rate after rolling on the mechanical characteristics was determined and the dependence between the end of rolling temperature and the metallographic structure was comparatively established. Among the researched technological parameters, it follows that the cooling speed after lamination has a very decisive role in guaranteeing the quality characteristics.

The strength characteristics of reinforcing steel PC52 improve with increasing cooling rate starting from austenising temperature. The impossibility of the appearance of hard structures, even in the case of energetic cooling, eliminates the danger of embrittlement of this steel. In normal industrial conditions, reinforcing steel PC52, rolled in the form of a periodic profile, cools in the range of transformation temperatures at speeds of 5°C/s, presenting a pearlitic-ferrite structure in rows. Increasing the cooling rate to 25°C/s in the transformation area leads to the appearance of sorbite in the structure in addition to ferrite and pearlite, and the arrangement of the grains in rows disappears. Increasing the cooling rate to 25°C/s is still lower than the rate at which martensite appears and contributes to the improvement of the strength and toughness characteristics of this steel. From the point of view of stability to overheating, the analyzed steels exhibit great stability at high temperatures, pronounced increases in austenitic grain size being evident only in the range of temperatures above 1200°C.

## REFERENCES

[1] Kingkam W. et. al., *Hot deformation behavior of high strength low alloy steel by thermo mechanical simulator and finite element method,* The 2nd International Conference on Materials Engineering and Nanotechnology IOP Publishing, IOP Conf. Series: Materials Science and Engineering 205, 2017.

[2] Ilca I., Miloştean D., *Improving the manufacturing technology of structural steels*, Journal of Engineering Sciences and Innovation, 4, **3**, 2019, p. 273-284.

[3] Huixia Zhang et.al., *Investigation on Stress Corrosion Cracking Behavior of Welded High Strength Low Alloy Steel in Seawater Containing Various Dissolved Oxygen Concentrations,* Int. J. Electrochem. Sci., **8**, 2013, p.1262-1273.

[4] Illescas S, et. al., *Study of the mechanical properties of low carbon content HSLA steels,* Revista de Metalurgia, **45**, 6, 2009, p. 424-431.

[5] Burca M. s.a., *Technological aspects of the self-shielding tubular wire welding of overlap joining on reinforcing steel, Annals of the University of Oradea,* Fascicle of Management and Technological Engineering, 3, 2014.

[6] Skobir D. A., *High-strength low-alloy (HSLA) steels,* Materials and technology, **45**, 4, 2011, p. 295–301.

[7] Ilca I., Miloştean D., *The deformability and thermal treatment for the low alloyed Romanian steel of high resistance*, Journal of Engineering Sciences and Innovation, **3**, 2, 2018, p. 141-154, AGIR Publishing House, ISSN-L2537 – 320X (on-line version).

[8] Ilca I., *The theory and practice of heating quality steel ingots,* Journal of Engineering Science and Innovation, **1**, 1, 2016, p. 120-130.

[9] Ilca I., *The determination of the gradient and thermal stresses for the heating of type 18-10 stainless steel ingots*, Journal of Engineering Science and Innovation, **2**, 2, 2017, p. 58-74

[10] Ilca I., Bistrian D., *Contributions to the ingots' heating study in industrial furnaces*, Journal of Engineering Sciences and Innovation, **5**, 3, 2020, p. 205-220.

[11] Yue C., Zhang L., Liao S. et al., *Kinetic Analysis of the Austenite Grain Growth in GCr15 Steel*. J. of Materi Eng and Perform, **19**, 2010, p.112–115.

[12] Fanyun Meng et al., *Growth behavior and kinetics of austenite grain in low-carbon high-strength steel with copper,* Mater. Res. Express 8, 2021.

[13] Jaromir Moravec, *Determination of Grain Growth Kinetics and Assessment of Welding Effect on Properties of S700MC Steel in the HAZ of Welded Joints*, Metals 2019, 9, 707.

[14] Dong Xu, *A new study on the growth behavior of austenite grains during heating processes,* SCIENTIFIC RepoRts | 7: 3968 | DOI:10.1038/s41598-017-4371-8, 2022.