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Improving the manufacturing technology of structural steels

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Abstract. The industrial research investigates the influence of chemical composition and rolling technological factors on the mechanical properties of structural alloyed steel.
Determination of the influence of the rolling technological factors on the mechanical characteristics was a difficult problem due to the lack of the research equipment for measuring with sufficient precision, under exploitation conditions, of the rolled product temperature and due to the dependence of this factor on the entire complex of the other technological parameters. The completion of the study required the expansion of research into the construction of equipment for measuring the temperature of small-sized rolled products and the cooling rate, to meet the requirements of current practice.
The research carried out under industrial conditions specifies the contribution brought on the qualitative characteristics of the studied structural steel, according to the technological factors of the process.

Keywords: reinforced concrete, toughness, embrittlement cracking, thermal hardening, weldability.

1. Introduction

In reinforced concrete constructions, welded metallic and mechanical constructions, the OB37 steel grade is widely used. In order to reduce metal consumption in this area, new steel grades with enhanced strength properties have been assimilated.
As a result of these requirements, OB37M2 and OB37M3 steel grades were produced and rolled, together with the increase the share of PC52 steel.
The qualitative changes, compared to steel OB37 (SR 438-1:2012) consist in:

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- The OB37M2 steel grade has a manganese content limit increased to 0.5-0.75%, and the guaranteed yield strength presents a contribution of 20N/mm^2 to OB37 steel grade, and allows for metal savings in the construction industry;
- The OB37M3 steel grade is a low manganese alloyed steel (0.7-1.2%), which ensures a minimum yield strength of 280N/mm^2 and a high toughness, being suitable for construction of particular importance.

2. Content

In industrial practice it has been noticed that for carbon steel intended to reinforcing steel periodic profile, as well as for the low alloyed constructional steel (PC52), with increasing the size of the finished rolled product (ϕ>20mm), results in a worsening of the mechanical characteristics of strength and plasticity [1], while increasing the sensitivity to embrittlement cracking.

By applying after rolling of the thermal hardening treatment, which consists of an accelerated cooling followed by tempering, high strength properties can be obtained [2] by keeping plasticity and weldability at an adequate level [3].

By studying the temperature variation along the length of the rolled bars, through the recorded diagrams from figures 1 and 2, improvements were made to the heating process in the propulsion furnaces, ensuring a uniform temperature by the billet length and the quality level of the finished rolled bars, as well as a constancy of the mechanical properties to the extent of their dependence on the variation of the thermal parameters.

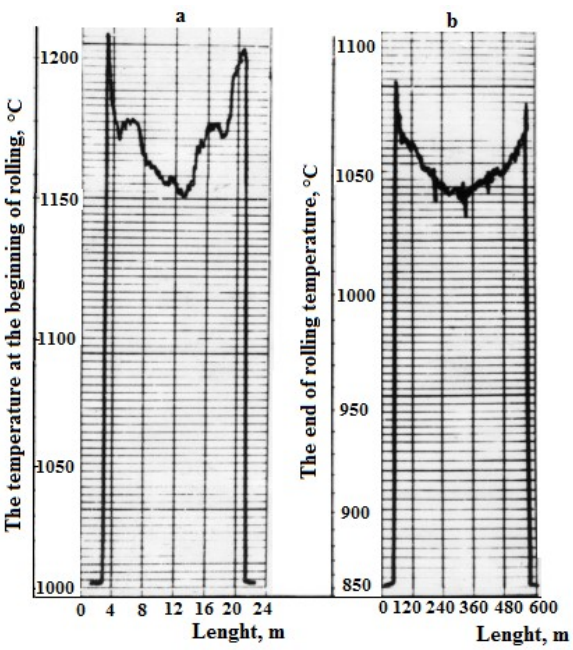


Fig. 1. Temperature variation over the length of the rolled bar:
a - recorded at the first cage; b - recorded at the last cage.

Thus, by determining the chemical composition, metallographic structure and mechanical characteristics, and by measuring the end of rolling temperature (T_f) during the process, data was obtained that by mathematical processing using electronic technique led to relations of the form:

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

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

where $a_{kj} x_k x_j = a_{jk} x_j x_k$

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

By derivation of the equations (2) were obtained relations of the type:

$$\frac{dy}{dT} = c_0 + \sum_{i=1}^{4} c_i x_i \qquad (3)$$

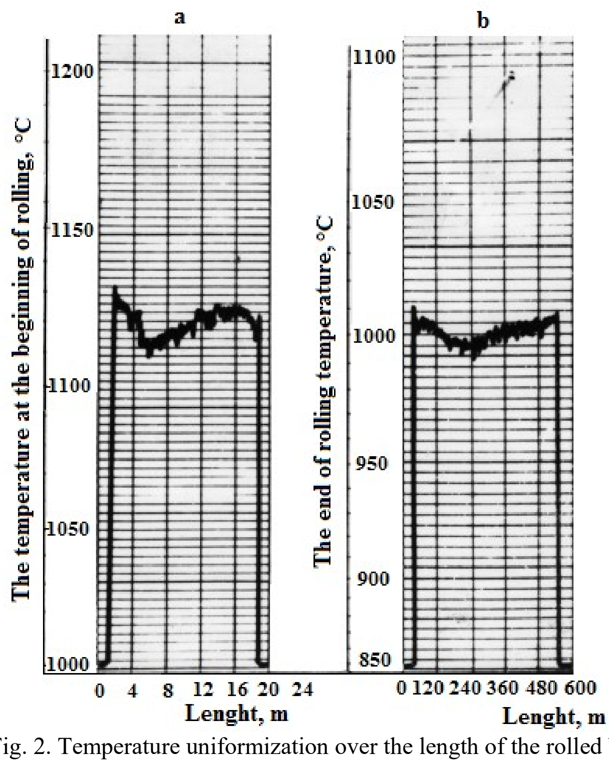


Fig. 2. Temperature uniformization over the length of the rolled bar:
a - recorded at the first cage; b - recorded at the last cage;

These relations (3) show quantitatively, the meaning and the degree of influence of the set of factors: chemical composition and the end of rolling temperature, on each of the mechanical properties of the obtained product. Through the research made at rolling of structural alloyed steel, was determined the degree of influence of the technological factors (especially the end of rolling temperature and the cooling rate after rolling) on the mechanical characteristics. The influence of cooling conditions on the mechanical characteristics was studied, taking as a basis the usual cooling under the conditions of the existing technological process.

Without influencing this time the end of rolling temperature that has been framed within the established technological process limits, and taking as a base the qualitative level of the mechanical characteristics achieved under ordinary cooling conditions after rolling, was studied the influence of the cooling conditions on cooling bed of the rolling line on the mechanical properties of the finished profiles, including the periodic profile for reinforcing steel grades OB37M2, OB37M3 and PC52.

2.1. Influence of cooling rate after rolling on the mechanical properties

The chemical composition of the OB37M2 steel grade does not allow an essential modification of its mechanical properties by hardening and tempering. Since, the decomposition of austenite in the structure of this steel can only occur in ferrite and perlite [4,5], the only possibility of influencing its characteristics remains grain modification. The size of the ferrite grain depends mainly on the size of the austenitic grain from which it precipitated.

In order to reduce the ferritic grain to the soft steels a normalization is generally made, consisting in the austenitization of the steel at temperatures slightly over Ac_3, followed by cooling at a sufficiently large rate to prevent the ferritic grain growth after precipitation.

Immediately after rolling the steel microstructure is made of fine austenitic grains due to the mechanical action of plastic deformation. Through a heat treatment consisting of a controlled cooling immediately after rolling, the growth of austenitic grain can be prevented and thus the resultant ferrite-perlite structure is also fine.

On the industrial platform, experiments were carried out to determine the possibilities for improving the mechanical properties of steel OB37M2 ϕ16mm. Researching these possibilities on the reheated samples after lamination does not fully elucidate the advantages of directing cooling after rolling, but still gives an indicative image.

For the experiments, samples of OB37M2 ϕ16mm steel with identical chemical composition (cut from the same bar) were taken, on the surface of which the Rh-RhPt thermocouples were bonded.

Samples temperature was recorded during cooling by the recording potentiometer on the diagram of which the sample cooling curve was automatically plotted. From the slope of the cooling curves (temperature-time curve) the cooling rates were determined. The samples were heated to 900°C for austenitization and then cooled at different speeds. The range of cooling rates between 0.05 to 200°C/s was obtained by cooling in the following media:

- 0.05 - 1°C/s - cooling in the furnace, respectively in thermo-insulating material;
- 1 - 6°C/s - cooling in the open air and compressed air;
- 6 - 25°C/s - cooling in sprayed water with compressed air;
- 25 - 90°C/s - oil cooling;
- 90 - 200°C/s - cooling in water at different temperatures.

After cooling, the samples were subjected to tensile test determining the strength characteristics, the yield strength and the tensile strength ($R_{p0,2}$ and R_m) as well as the plasticity characteristics, percent elongation and percent reduction of area (A_5 and Z). The resulting values are shown in table 1 and plotted in figure 3, as compared to the tensile strength of PC52 steel samples of the same size, cooled under identical conditions (table 2 and R_m curve for PC52 in figure 3).

Table 1. Strength and plasticity properties obtained after cooling of OB37M2 steel grade in different cooling media

No.	**Strength properties**		**Plasticity properties**		***Cooling rate v_r, °C/s***	***Cooling media***
	$Rp_{0,2}$ N/mm²	**Rm N/mm²**	**A_5 %**	**Z %**		
1	-	*410*	*35.0*	*66.94*	*4.76*	*air*
2	*252*	*400*	*37.2*	*66.21*	*5.0*	*air*
3	*242*	*398*	*33.9*	*68.36*	*3.8*	*air*
4	*240*	*400*	*32.5*	*68.36*	*4.3*	*air*
5	*252*	*406*	*33.8*	*64.75*	*3.6*	*air*
6	*296*	*392*	*38.0*	*69.06*	*3.4*	*air*
7	*293*	*408*	*39.0*	*65.48*	*4.8*	*air*
8	*291*	*420*	*36.6*	*64.00*	*5.5*	*air*
9	*268*	*373*	*38.2*	*67.65*	*3.3*	*air*
10	*252*	*398*	*33.1*	*66.21*	*4.0*	*water + air*
11	*289*	*395*	*34.7*	*68.36*	*3.4*	*water + air*
12	*385*	*456*	*27.2*	*61.00*	*20.0*	*water + air*
13	*293*	*453*	*23.2*	*61.72*	*20.0*	*water + air*
14	*249*	*437*	*32.5*	*62.60*	*18.0*	*water + air*
15	*286*	*434*	*27.5*	*84.85*	*12.5*	*water + air*
16	*298*	*437*	*34.7*	*62.60*	*12.5*	*water + air*
17	*286*	*440*	*31.0*	*62.60*	*11.0*	*water + air*
18	*290*	*437*	*32.0*	*62.60*	*12.0*	*water + air*
19	*299*	*467*	*27.2*	*64.00*	*45.0*	*oil*
20	*358*	*490*	*26.5*	*64.745*	*50.0*	*oil*
21	*433*	*480*	*28.5*	*62.48*	*66.0*	*oil*
22	*348*	*480*	*23.7*	*66.21*	*50.0*	*oil*
23	*239*	*380*	*36.0*	*62.48*	*0.05*	*furnace*
24	*333*	*498*	*31.3*	*64.748*	*100.0*	*hot water*
25	*373*	*506*	*26.0*	*63.24*	*100.0*	*hot water*
26	*318*	*483*	*27.0*	*64.748*	*100.0*	*hot water*
27	*445*	*570*	*23.0*	*60.36*	*200.0*	*cold water*
28	*451*	*578*	*21.2*	*60.36*	*200.0*	*cold water*
29	*451*	*566*	*16.5*	*60.90*	*200.0*	*cold water*
30	*413*	*520*	*22.0*	*58.75*	*100.0*	*cold water*
31	*287*	*393*	*37.3*	*64.75*	-	*in coil*

Figure 3 shows the dependence between the strength characteristics obtained with the cooling rate achieved in different media and it is noticed that the yield strength ($R_{p0,2}$) and the tensile strength (R_m) register an insignificant increase in the speed range below 10°C/s. At speeds above 10°C/s the growth trend is uniform and quite accentuated with the increase in cooling speed.
The plasticity characteristics, percent elongation and percent reduction of area (A_5 and Z) remain constant at cooling speed up to 10°C/s, then decrease evenly with increasing cooling speed. Improved strength properties are obtained due to the modification of the metallographic structure according to the applied cooling speed (fig.4). Samples cooled at speeds below 1°C/s have a large ferrite-perlite structure (fig.4a), which explains their relatively low strength.

Table 2. The strength properties of PC52 steel after cooling in different cooling media

Cooling media	***Cooling rate*** **v_r, °C/s**	***Tensile strength *,*** **R_m, N/mm²**
Water	-	1100
Oil	106	760
Sprayed water	16	580
Compressed air	4.0	540
Air	2.5	520
Cooling in the oven	0.028	470

* the tensile strength value represents the arithmetic mean of the results obtained by cooling in each medium of 5 steel samples from PC52 ϕ16 steel grade

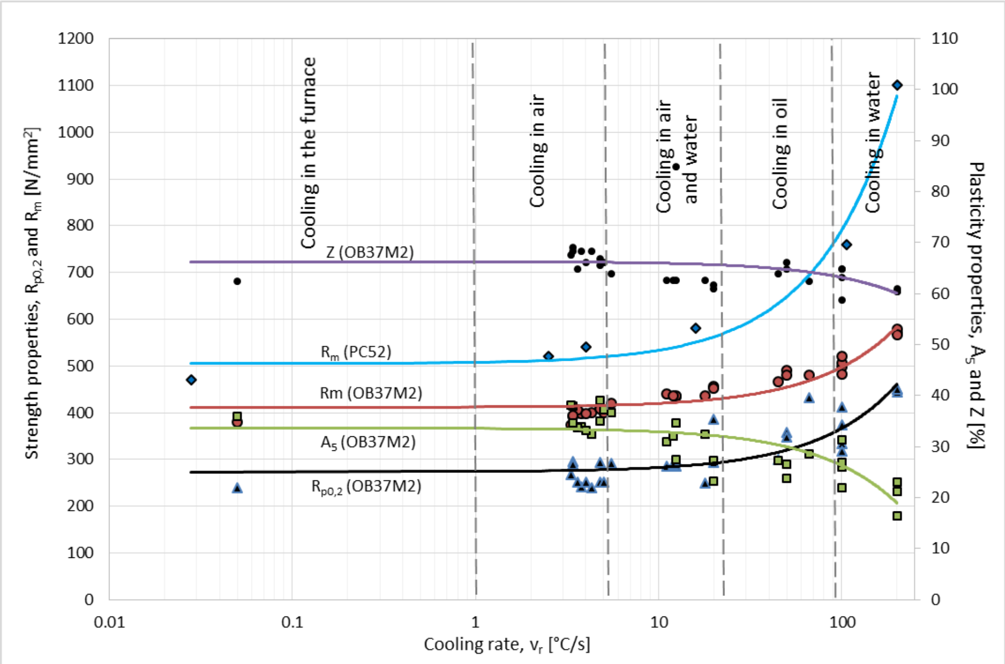
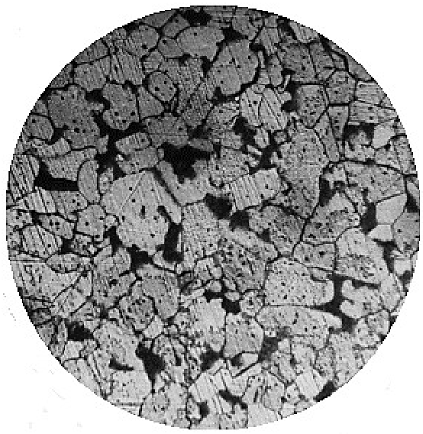
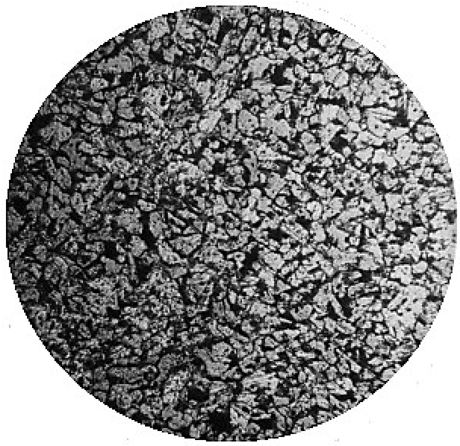


Fig. 3. Influence of cooling rate achieved in different cooling media on the strength properties of OB37M2 and PC52 steel grades

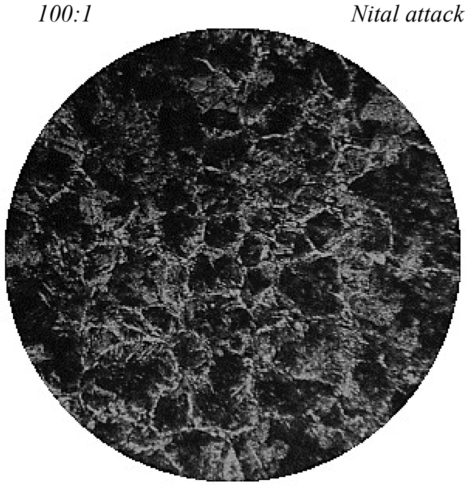
At speeds of approx. 10°C/s the ferrite-perlite structure becomes finer and the perlite network is discontinuous (fig. 4.b).
The samples cooled at speeds corresponding to the maximum values of the variation range, at which have been obtained the highest resistance characteristics [6,7], have a very fine ferritic structure and the perlite is not distributed in network so explaining the existing strength characteristics (fig. 4.c).



a) $v_r < 1°C/s$;
Nital attack 2%   100:1



b) $v_r \sim 10°C/s$;
Nital attack 2%   100:1



c) $v_r > 100°C/s$;
Nital attack 2%   100:1

Fig. 4. Influence of cooling rate on the microstructure of OB37M2 steel.

The results of these experiments prove that OB37M2 steel grade offers the possibility of raising its strength properties if is achieved an energetic cooling after austenitisation. The impossibility of hard structures appearance eliminates the risk of embrittlement for this steel. In the case of controlled cooling after rolling, it is possible to improve the strength characteristics even with less energetic cooling.

The possibility of obtaining the quantitative effect of the cooling rate influence on the mechanical characteristics under the conditions of the current industrial production, by applying immediately after rolling the cooling in the described media, is limited by a whole series of technological and constructive considerations.

Therefore, in order to determine the possible contribution to be achieved by intensifying the cooling of the rolled products on the cooling bed under normal technological flow conditions, controlled cooling experiments with PC52 ϕ16mm steel grade were performed compared to the experiments previously performed (fig.3, R_m curve for steel PC52 ϕ16mm).

Since accelerating cooling of the laminate over the entire length would involve changing the entire cooling bed, in these experiments, the acceleration of cooling affected only a portion of approx. 1.5 m of the laminate length.

The additional cooling system (fig.5) can spray water over a 1.5 m of the cooling bed length. The sprayer consists of a ϕ25 mm pipe with holes of ϕ5 mm on the generator, spaced 10 mm apart. The pipe was provided with valves for debit and concentration regulating of the sprayed water. The cooling capacity of the installation was estimated by comparing the laminate cooling rates in the normal cooling portion with the zone from the additional cooling installation.

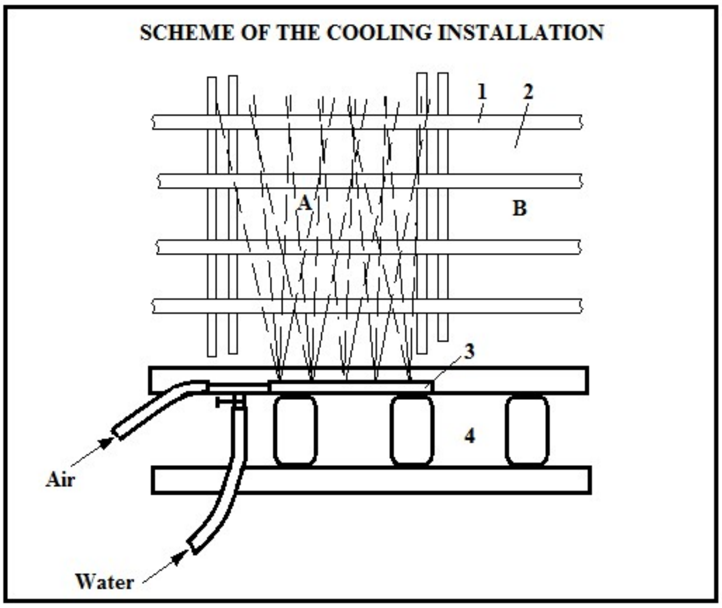


Fig. 5. Location of the spraying system on the cooling bed
1 - rolled bars; 2 - cooling bed; 3 - spraying pipe; 4 - the roller track;
A - energetic cooled region (25°C/s); B - normally cooled region (5°C/s).

To determine the cooling rate on the laminate surface, Rh-RhPt thermocouples were bonded, which plotted the cooling charts from figure 6.

The cooling rate was determined from the temperature-time curve slope at point t=750°C. The cooling system provides a range of speeds between 5°C/s curve B (no additional cooling) and 25°C/s curve A (cooling at maximum system capacity).
The cooling bed electrical installations are not capsulated, so can be damaged due to excessive moisture. For this reason, the idea of using a water jet as a cooler was dropped. Sprayed water has a higher cooling capacity than compressed air and evaporates rapidly, does not endanger the operation of the electrical equipment. The maximum cooling speed of 25°C/s is limited by optimal evaporation conditions.

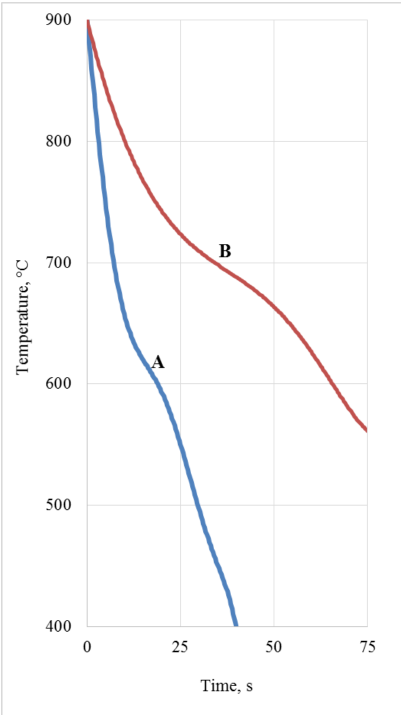
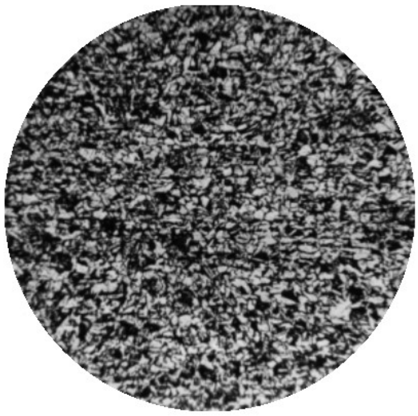


Fig. 6. Diagram of cooling speeds realized industrial:
A - forced cooled laminate; B - ordinary cooled laminate.

The effect of accelerating cooling was assessed by comparing the sample characteristics from the forced cooling portion, with control samples taken from the same bar but from the normally cooled part.
For the two samples having the same chemical composition, the differences between their strength properties can be attributed exclusively to the effect of cooling.
The quantitative determination of the characteristics caused by the acceleration of the cooling was done on a number of 20 bars.
The changes that increasing cooling speed causes in the metallographic structure are emphasized by comparing the microstructure of a forced cooled sample (A) with the microstructure of the normally cooled control sample (B) of figure 7.

The microstructure examination of figure 7 shows that the normally cooled samples show a larger grain size, with precisely defined grains to which is still retained the structure in rows characteristic at deformation by rolling. Forced cooled samples, in addition to a finer structure where ferrite and pearlite grains are no longer placed in rows, also have sorbitic formations. To explain these structural changes, the experimentally determined cooling curves of figure 7 were plotted on the TTT diagram from figure 8 (transposed to a logarithmic scale).

A (25°C/s)
Nital attack 2% *100:1*



B (5°C/s)
Nital attack 2% *100:1*

Fig. 7. Microstructure of PC52 steel, cooled at different speeds.

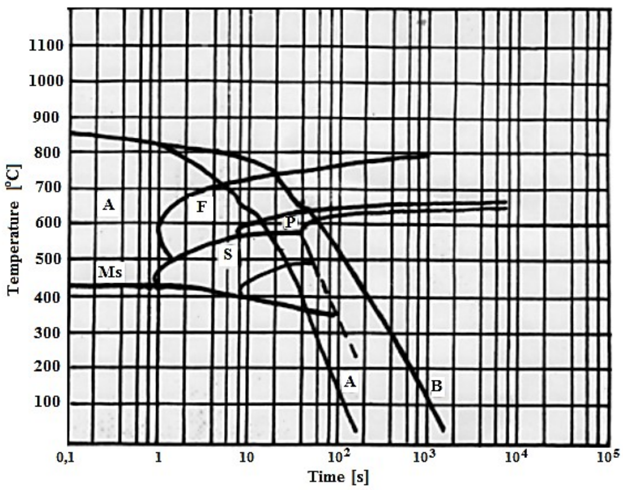


Fig. 8. TTT diagram for PC52 steel.

If the normal cooling rate process (curve B) is followed, it is found that only the ferritic and perlite fields are crossed. This shows that during the austenitic cooling after precipitation of the proeutectoid ferrite is completely transformed into perlite.

In the case of high-speed cooling (A), the cooling curve intersects the ferritic and perlite fields but also the sorbitic one. Consequently, austenite will not be able to fully transform into ferrite and perlite, but some of it will transform into sorbite. Also, at these cooling rates, the proeutectoid ferrite will not have time to diffuse to the edge of the austenitic grain, but will precipitate inside, fragmenting it. For these reasons, ferrite and perlite grains from accelerated cooled samples will have a less accurate contour than normal cooled samples.

Table 3 shows the values resulting from the tensile test of normal (B) and accelerated (A) cooled samples. It is observed that the acceleration of cooling causes an average increase of the yield strength $R_{p0.2}$ of 12.6N/mm^2, which represents a relative increase of 3.6%. At the same time, the tensile strength R_m also increases with 9.8N/mm^2, so a relative increase of 1.84%. Percent elongation A_5 shows a large scattering, both at forced and normally cooled samples, with a mean increase of only 0.53%.

Table 3. Strength characteristics for normal (B) and accelerated (A) cooled samples

No.	$Rp_{0,2}$ (B) N/mm²	$Rp_{0,2}$ (A) N/mm²	Rm (B) N/mm²	Rm (A) N/mm²	A_5 (B) %	A_5 (A) %
1	361	378	548	555	35.7	34.9
2	368	384	551	564	33.8	34.4
3	342	357	541	543	36.2	28.9
4	362	375	549	552	35.0	36.2
5	354	362	536	549	35.0	37.5
6	360	375	549	556	35.0	36.0
7	362	375	553	560	35.1	36.2
8	352	362	540	544	39.2	29.4
9	348	360	539	545	36.1	35.2
10	370	372	545	550	37.8	36.2
11	367	369	550	556	37.4	32.5
12	350	362	546	548	37.5	33.6
13	342	360	544	546	42.0	35.0
14	342	358	538	548	36.2	33.0
15	344	359	546	549	36.2	35.0
16	346	360	538	542	34.4	35.0
17	358	359	544	561	36.2	32.2
18	358	359	536	555	36.2	34.4
19	347	360	542	546	36.2	35.7
20	343	367	533	548	35.0	36.2

3. Conclusions

The technology currently applied for the production and rolling of structural steel generally ensures the prescribed mechanical characteristics, with some exceptions for rolled products ≥ 30mm.

Compared to the achieved level of strength properties, under unchanged technological conditions, have been studied for the OB37M2 and PC52 steel grades the improvement in strength performance by varying the cooling rate after rolling

in a wider range. Has resulted the improvement of strength characteristics for OB37M2 steel with the increase of the cooling rate starting from the austenitizing temperature. Also the impossibility of hard structures appearance, even in the case of energetic cooling, eliminates the risk of embrittlement for this steel.
Under standard industrial conditions, PC52 reinforcement steel, rolled in the form of a periodic profile is cooled in the transformation temperatures range of 5°C/s, presenting a ferrite-perlite structure in rows. Increasing the cooling rate to 25°C/s in the transformation field, leads to the appearance in the structure of ferrite, perlite and also sorbite, and the structure in rows of the grains disappears. Increasing the cooling rate to 25°C/s is still inferior to the velocity at which martensite occurs and contributes to improving the strength and tenacity characteristics of this steel.

References

[1] Achamyeleh T., Şahin Y., *Investigation of Mechanical Properties of Ribbed Reinforcement Steel Bars: A Case Study on Ethiopian Construction* Industry, International Journal of Steel Structures, 2019, https://doi.org/10.1007/s13296-019-00236-0
[2] Daramola O.O., Adewuyi B.O. and Oladele I.O., *Effects of Heat Treatment on the Mechanical Properties of Rolled Medium Carbon Steel*, Journal of Minerals & Materials Characterization & Engineering, **9**(8), 2010, p. 693-708.
[3] Ashish Vermaa, Pravin Kumar Singhb, *Influence of Heat Treatment on Mechanical Properties of Aisi1040 Steel*, OSR Journal of Mechanical and Civil Engineering **10**(2), 2013, p. 32-38.
[4] Gaude-Fugarolas D., Bhadeshia H. K. D. H., *A model for austenitisation of hypoeutectoid steels*, Journal of Materials Science, **38**, 2003, p.1195-1201.
[5] A. Ray, et.al, *Microstructure and Properties of Thermomechanically Strengthened Reinforcement Bars: A Comparative Assessment of Plain-Carbon and Low-Alloy Steel Grades,* JMEPEG 6, 1997, p. 335-343.
[6] Ali A. Hmud, Hamid M. Mahan, Abdaljabar S. Jomah, *Effect of Cooling Media and Tempering Temperature on the Mechanical Properties of Reinforcement Steel*, International Journal of Applied Engineering Research, **13**(6), 2018, p. 3979-3987.
[7] Ilca I., Miloştean D., *Research on the effect of thermomechanical treatment applied on low alloy steel for construction*, Annals of Faculty Engineering Hunedoara – International Journal of Engineering, **XIV** (4), 2016, p. 147-150.