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THERMAL STRENGTHENING OF THE LOW-CARBON STEEL STRIP

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The results of research of microstructure and mechanical properties of the strips cross-section 45x6 and 30x8 mm from low carbon steel in hot-rolling condition and after accelerated cooling of different intensity and schemes of the coolers movement in the cooling chambers are shown. Regimes that provide the high level of steel's strength with the smallest changing of the mechanical properties by the length of the rolled strip were defined.

Key words: *thermal strengthening, steel, mechanical properties*

Toplinsko očvršćivanje trake niskougljičnog čelika. U radu su prikazani rezultati istraživanja mikrostrukture i mehaničkih svojstava traka od niskougljičnog čelika poprečnog presjeka 45x6 i 30x8 mm u toplovaljanom stanju i nakon ubrzanog hlađenja različitog intenziteta i shema kretanja u rashladnoj komori. Definirani su postupci koji osiguravaju visoku čvrstoću čelika uz najmanje promjene mehamčkih svostava cijelom duljinom valjane trake.

Ključne riječi: *toplinsko očvršćivanje, čelik, mehanička svojstva*

INTRODUCTION

Some research works [1-7] demonstrate that even fine-grained structure and increase in steel mechanic properties can be achieved in two ways:

- introduction of the powerful carbide forming elements and micro alloying additions during steel making in combination with strict cycles of plastic deformation and braking of austenite recrystallisation at the expense of it;
- rolled stock cooling for reducing the temperature at the end of rolling and a controlled after deformation cooling, impeding recrystallisation.

The main advantage of the second method is an economy of alloying elements and a possibility of increasing performance characteristics of low-carbon steels.

The main condition of realization of the technological process of thermal strengthening is working-out of coolers providing intensive rolled stock cooling combined with its hydro-transportation on the site where the coolers have been installed at the rolling speed up to 20 m/s.

The properties of the rolled steel after the thermal strengthening are defined by the condition of its structure. It has been shown in many researches that with rolled wire and reinforcing steel cooling a heterogeneous structure with martensite tempering on the surface and perlite-ferrite core is formed [6, 8-9]. With the rectangular cross-section of rolled steel the unevenness of the distribution of structural components must appear not only in the center of the section but also along its perimeter because its quite clear that the flank cooling goes quicker than that of the central part.

EXPERIMENTAL DETAILS

The research was conducted with the strip rolled low-carbon steel, cross-section 45x6 mm (0.29 - 0.30 % C; 0.69-0.74 % Mn; 0.09-0.15 % Si) and 30x8 mm (0.27 % C; 0.73 % Mn; 0.27 % Si). The strips were cooled in the continuous water flow in the wire-type chambers after rolling in the rolling mill.

The analysis of the current line of cooling devices for the small-sort rolled steel in the mill flow found out their faults, which were taken into consideration, while creating a device of the updated construction. The device, which is designed for these purposes, consists of cooling chambers, a unit of water sprayers in the chambers and branches for exhaust water escape. Sprayers units are designed in the way as to provide the best contact of the flow and the rolled steel and water mixing, and the velocity component of the flow which is perpendicular to the surface being cooled increases. In the sprayer the water is separately

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sprayed on the upper and lower surfaces of the strip, which, in some way, gives the possibility of regulating the intensity of its cooling along the cross-section. The cross-section of the cooling chamber is designed like a rectangle. In the bottom of the chamber the channels are made by which the water goes without any difficulties along the whole length of the chamber, and thereby the intensive cooling of the lower surface of the rolled steel is provided. In the chambers like this water from closed channels after cooling the lower surface of the strip doesn't go up as the result of convection and doesn't wash the flanks of the stripe. It promotes a more even distribution of cooling of the strip along the cross-section. The cooling chamber is made of the two parts: the box and the lid, which are tied with special devices; it provides a better hermetically sealing of the inner part of the cooling chamber. For excessive pressure escape which appears in the chamber while entering the front part of the strip the values are designed on its lid by using of which the part of water is dumped in case the pressure in the chamber is exceedingly high and the cooling goes less intensively which promotes forming even characteristics along the length of the strip. The cooling plant can be assembled up to 12 m long from the separate units which are tied with each other as well as with sprayers by means of the flange connection.

The cooling device was placed between the cleaning cage and the freezing chamber. The track of active cooling was 8.5 - 11 m, water pressure at the entrance to the sprayer - 1.5 - 1.8 MPa, water usage - 100 mł/h, its temperature - 20 - 30 °C. The temperature at the end of the deformation didn't exceed 1150 °C. The velocity of the rolling was regulated (from 5.9 till 6.7 m/s) and consequently, the duration of the cooling (from 1.3 till 2.0 s).

RESULTS AND DISCUSSION

The maximum intensity of the cooling is reached under the conditions of counterflow along the entire device. The researches of the mechanical properties of the metal have shown that the increasing of cooling duration promotes the strengthening, but it provokes the worsening of the plasticity. For example, the stripe of cross-section 46x5 mm (0.30 % C; 0.69 % Mn; 0.09 % Si), which has cooled for 1.3 and 1.5 s, had the following properties in its middle respectively: the tensile strength to the repture was 770-800 and 970-1000 N/mm^2; the specific elongation - 20 and 16 %. Under the same conditions of the cooling the strip of cross-section 30x8 mm was described with such indices: 800-850 and 1050-1100 N/mm^2; 20 and 15 % respectively. The hot-rolled strip of the steel of the same melt had lower indices of the durability: R_m = 585 N/mm^2 and R_m = 600 N/mm^2 (A = 32 %).

Along the entire length the stripe had the same mechanical properties except for the front part with the length of about 5 - 6 m. On entering cooling chamber the strip blocked its cross-section which caused spasmodic short-term rise of pressure inside the chamber and intensive mixing of liquid flow. With all this the cooling ability of the liquid intensified very steeply, which led to the overcooling and considerable strengthening of the front part of the strip in comparison with the middle part. The strip of cross-section 45x6 mm had the level of durability overfall and reached in particular cases ~ 400 - 500 N/mm^2, and the strip of cross-section 30x8 mm had a less considerable overfall: 100-150 N/mm^2. Such a significant difference was caused by the ratio of the stripe sizes to the chamber in the cross-sections. The cooling chamber is designed in the form of the rectangle with the sizes of 55x12 mm. The difference in vertical sizes of the strips is inconsiderable and horizontal sizes of the cross-section 45x6 mm are closer to the size of the chamber, that's why the strip in a higher degree blocks the chamber causing more barriers in a liquid flow and consequently in a higher degree increases its cooling ability. Such an overfall is caused by uneven cooling of the strip along its length.

The hardness measurment along the width of the strip proved a higher cooling degree of the flanks in comparison with the central parts: 275-290 HB and 200 HB respectively in the stripe of cross-section 46x5 mm in the middle of the strip. Under the same hardness of the flanks of the stripe as in the middle, its central part has a higher level of hardness: 255 - 290 HB. And it makes the front part of the stripe different.

Upon switching on the cooling part of the plant the rolled steel is being strengthened in a lower degree because of the lower heat irradiation ratio. However, the effect of more stable mechanical properties of the rolled steel is reached. The experiment in the cooling plant was held to study the influence of the location scheme of uniflow and counterflow devices on the character of strengthening along the length of the stripe where length of uniflow cooling composed 0; 0.25; 0.55 of the entire length of the cooling track. Besides, as one way more, the uniflow cooling device has been set directly at the exit of the metal from the rollers or behind the conterflow device at the distance of 3 m from the rollers. The results of the research are presented in the Table 1.

Upon being put into operation the uniflow section worsened the cooling ability of the plant. For example, the replacement of the counterflow section II with the length of 2.5 m for the uniflow section brought about a fall of durability level of the rolled steel, but at the same time the difference between the durabilities of the front part of the strip and its middle decreased. With the increasing of the length of uniflow devices the durability characteristics decreased even in a higher degree, but the distribution of the mechanical properties along the length of the strip almost couldn't be seen.

Table 1. **A change in mechanical characteristics along the length of the strip under different schemes of uni-and counter-flow cooling***

Tablica 1. **Promjena mehaničkih svojstava duljinom trake i različite sheme hlađenja u - smjeru kretanja i smjeru suprotnom od smjera kretanja**

Cross-section [mm]	The velocity of rolling [m/s]	The location sheme of the section**	R_m [N/mm^2]	$R_{p0.2}$ [N/mm^2]	A [%]
45x6	6.7	I i II (→) + III (←)	627-625 / 625	451-460 / 440	18.0
		I (→) + II i III (←)	700-663 / 657	638-463 / 460	16.3
		I i III (←) + II (→)	800-725 / 725	623-580 / 580	17.0
		I i III (←)	1300-992 / 900	1188-742 / 756	13.0
	5.9	I i III (←) + II (→)	860-830 / 800	715-660 / 620	14.0
	6.7	hot-rolling condition	554	369	35.0
30x8	6.7	I i III (←)	970 / 825	766 / 660	20.0
	5.9	I i III (←)	1180 / 1070	1050 / 920	15.0
	6.7	hot-rolling condition	600	410	32.0

*The values of R_m and $R_{p0.2}$ at distance of 1 and 5 m of the beginning of the rolled strip are presented in numerator; and their values in the middle of the rolled steel are in denominator;
**Uniflow and counterflow

The stripe in its cross-section had a complex lamellar structure. On the surface of the strip of cross-section 45x6 mm having been cooled a counterflow for 1.3 s a thin layer (0.4 - 0.5 mm) of tempered martensite appeared (Figure 1.a). The central zone which was 4.5 mm along the height of the stripe (Figure 1.c) was composed of perlitr grains surrounded by continuous ferrite net.

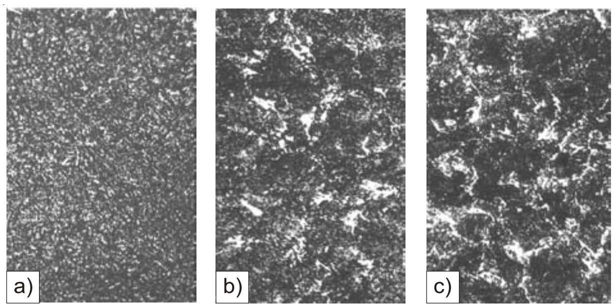

Figure 1. **The structure of the strip, cross-section 45x6 mm, made of low-carbon steel after the accelerated cooling in the mill flow: a) the section adjoining the upper and lower parts of the strip; b) transitional layer; c) central part of the cross-section of the strip. Magnification x400**

Slika 1. **Struktura trake presjeka 45x6 mm napravljene od niskougljičnog čelika nakon ubrzanog hlađenja u prolazu kroz valjački stan: a) granični presjek gornjeg i donjeg dijela trake, b) prijelazni sloj, c) centralni dio presjeka trake. Povećanje 400 puta**

The perlite-ferrite ratio in central zone was P:F=70:30. The perlite component becomes more disperse while moving from the centre to the edges. The ferrite net was getting thinner and in transition layer became very thin, even torn (P:F=95:5). The flanks of the strip were cooled more intensively. The thickness of tempered martensite layer on the flanks of the strip was about 4 mm. The transition layer had the width of 4.8 mm and was of bainite structure (Figure 1.b) and then the ferrite-perlite structure was formed. The front part of the stripe had ferrite-perlite core. The entire cross-section was composed of martensite and bainite transformation products. It shows that the front part of the strip was cooled more intensively. Hot-rolled strip made of steel taken from the same melt had ferrite-perlite structure along the entire cross-section (Figure 2.). The increase in duration of cooling up to 1.7 s led to widening of martensite layer from the flanks till 7.5 mm. Perlite transformation was entirely brought down. Austenite of the central zone was involved in bainite transformation.

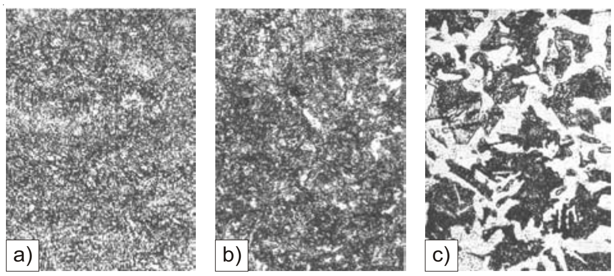

Figure 2. **The structure of the strip, cross-section of 45x6 mm, made of low-carbon steel in hot-rolled condition: a) buttend of the strip (the edge); b) transitional layer (4-8 mm of the buttend); c) central part. Magnification x400**

Slika 2. **Struktura presjeka trake 45x46 mm napravljene od niskougljičnog čelika u toplo valjanom stanju: a) tupo zavareni kraj trake (rub), b) prijelazni sloj: (4 - 8 mm od tupo zavarenog kraja); c) središnji dio. Povećanje 400 puta**

A change in geometrical sizes of the strip-rolled steel leads to a change in the ratio between layers with different structure after thermal strengthening. For example, while cooling a strip, cross-section 30x8 mm, for 1.2 s a martensite layer on the upper and the lower surfaces was thinner but it was also wider (6 mm). The width of the bainite zone increased as well, but a zone of perlite-ferrite structure decreased and was 14.4 mm. The availability of layers was observed in the structure of rolled steel under the conditions of uniflow cooling as well, however the sizes of layer of strengthening phases decreased.

CONCLUSIONS

1. Thermal strengthening in the mill flow gives a chance of getting the strip-rolled steel which has strengthened

surface composed of martensite and bainite structure and high plasticity of ferrite-perlite core.

2. The strengthening layer is spread unevenly along the perimeter of the rolled steel. The formation character of the structure and its spreading along the cross-section depends on intensity of cooling and the ratio of the width of the strip to its thickness.

3. Strengthening degree and distribution of durability properties along the cross-section depend on cooling scheme. The least disperron of properties along the length of the strip (60 N/mm^2) at sufficiently high level of tensile strength to the rupture R_m = 800 N/mm^2 is reached by cooling under the following scheme: counterflow-uniflow-counter-flow.

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