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INFLUENCE OF COOLING INTENSITY ON THE STRUCTURE FORMATION IN STRIPE STEEL BY THERMOMECHANICAL TREATMENT

V. Goryany*#, T. Khlyntseva, I. Mamuzic*** and V. Radsinsky*****

*Institute for Applied Materials Technology University of Duisburg -Essen,
Campus Duisburg, Germany
**National Metallurgical Academy of Ukraine, Dnepropetrovsk, Ukraine
***Faculty of Metallurgy, University of Zagreb, Sisak, Croatia

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Abstract

The results of research of microstructure of the strips from low carbon steel 45x6 and 30x8 mm in hot-rolling condition and after accelerated cooling of different intencity and schemes of the coolers movement in the cooling chambers are shown. 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 stripe to its thickness. 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.

Keywords: thermal srtengthening, steel, mechanical properties

1. Introduction

The properties of the rolled steel after the thermal strengthening are defined by the condition of it's structure. It has been shown in many researches that

[#] ***Corresponding author:*** *goryany@t-online.de*

with rolled wire and reinforcing steel cooling a heterogeneous structure with martensite tempering on the surface and perlite-ferrite core is formed [1-5]. With the rectangular cross-section of rolled steel the unevenness of the distribution of structural components must appear not only to the center of the section but also along it's perimeter because it's quite clear that the flank cooling goes quicker than that of the central part. For identifying the character of a temperature change in cross-section of the stripe rolled steel a cooling kinetics for rolled steel of rectangular cross-section has been calculated.

2. Experimental

The amount of heat, the metal emits into the environment, is defined by the equation:

$$dQ = \alpha \cdot F \cdot \Delta t \cdot d\tau,$$

where: α - heat irradiation ratio; Δt - temperature gradient, i.e. exceeding of the surface temperature above cooling medium temperature; F - the area of the surface of the body; τ – time.

We can see from the equation above that under other equal conditions the cooling intensity is defined by heat irradiation ratio α. It is not physical constant, typical for particular substance and depends on a large number of factors such as geometrical form and rizes of the body, physical conditions of washing medium, it's direction and velocity, temperature. Since heat irradiation ratio changes along the length of cooling chamber, and besides, is defined by the character of the motion of the liquid, it's temperature, velocity and pressure in the chamber as well, different values of α have been set: from 5000 till 20 000 $W/m^2 \cdot K$, taking it as average, which corresponds to real cooling velocities of the stripe rolled steel in the continuous water flow in the closed chamber.

Temperature distribution along the cross-section of the stripe and it's change with the time have been obtained from the heat conductivity equation:

$$\frac{\partial t}{\partial \tau} = \alpha \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right)$$

with the starting conditions t_o = 1100°C with $\tau = 0$ and boundary conditions dt/dx=-1/(λ/α). The selected equation is valid when *a* (thermal diffusivity coefficient) is constant. As if thermal diffusivity coefficient is the function of the temperature (a=λ/c · ρ), and the dependence of it to the temperature is weak; so in the researched interval of temperatures the changing of this value is to neglect.

Equation was solved for the rectangular cross-section bar.

The research was conducted with the stripe rolled low-carbon steel, cros-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 stripes were cooled in the continuous water flow in the wire-type chambers after rolling in the rolling-mill.

From the curves of temperature distribution and it's change with time in point's, which are located on the axes of cross-section of the stripes, (cross-section 45x6 and 30x8 mm) on Fig.1, it can be seen that the flanks of stripes with the width of about 3-5 mm are cooled much quicker, than the central parts, but the most intensively it takes place only in the first moment.

The same picture can be seen and along the thickness of the stripe. With the maximum possible on the rollong-mill length of track of active cooling, time of cooling process mustn't enceed 1.5-1,6 s. During this time the surface layers of the stripes with cross-section 30x8 and 45x6 mm under all set values of α are cooled down to the temperature below temperature of martensitic transformations beginning and the central parts - down to ~ 650-450 °C.

After leaving the cooling plant the rolled steel keeps on cooling in fresh air; heat irradiation ration drops very quickly. Thanks to the high temperature of the central parts and low temperature of the surface, the heat from the core spreads to surface layers very quickly and heats them. With the same duration of the process, the more intensive water cooling is, the lower the heating temperature of the surface is, and this, in its turn, is defined by the heat irradiation ratio.

In order to show up the influence of the cooling intensity on structure-forming, the curves, which were describing the cooling velocity under different diagram of low-carbon steel. It gave a chance of defining a temperature interval of phase transformations in the points of cross-sections of stripes starting from axis of symmetry and going to the edges with the step of

1.5 mm. Central parts of the stripe are cooled evently in time: at the velocity of ~250 K/s. On the surface and the areas, adjoining to flanks, the cooling velocity is very high in the first moment (~1200 K/s), but it goes down gradually and by the end of the cooling it is ~ 50 K/s.

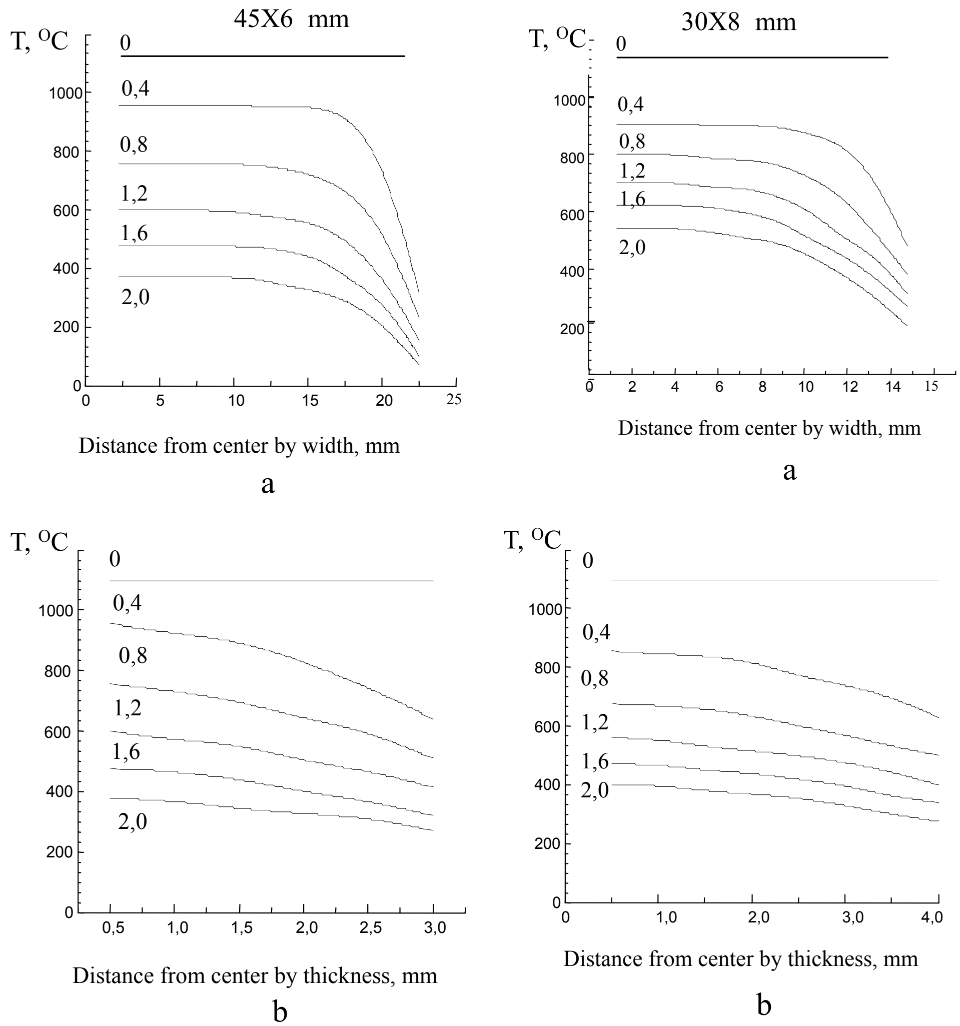


Fig. 1. Temperature distribution along the width (a) and thickness (b) of stripe rolled steel (cross-section 45x6 and 30x8 mm) under accelerated cooling [α = 10 kW/m$^2\cdot$k]; figeres near the curves - time since the beginning of the transformation, s; a - distance from the centre considering the width; b - distance from the centre considering the thickness.

Analysis of distribution of the structural components along the cross-section of the stripe with cross-section 30x8 mm, found out that with the heat irradiation ratio of 7 kW/m$^2 \cdot$K , the strengthening phases martensite and bainite can be obtained only in the thin layer next to the surface with width of 3.0-3.5 mm in the flanks (Fig. 2, A), which is not enough for the considerable strengthening of the rolled steel.

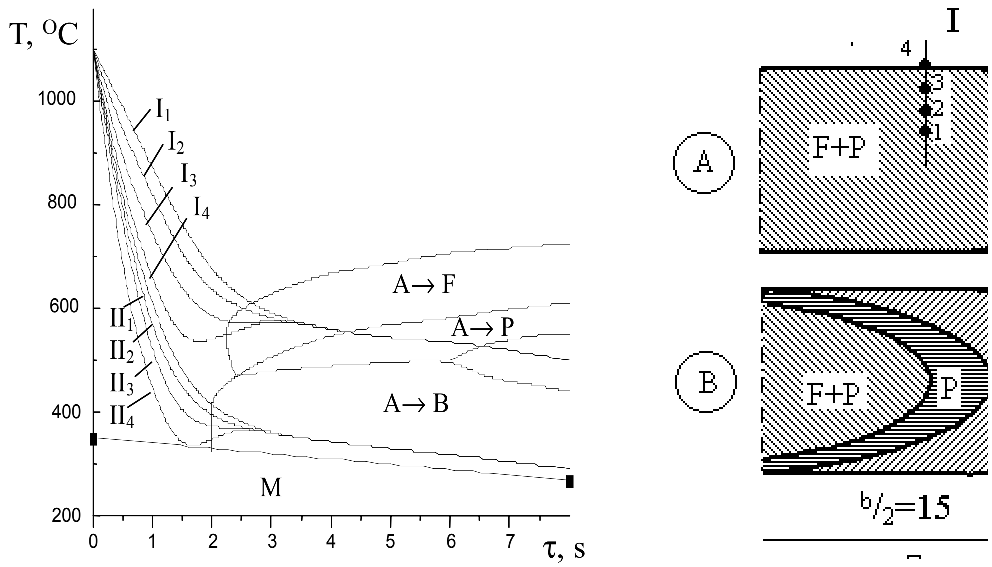


Fig. 2. The scheme of stripe rolled steel structure forming with the cross-section 30x8 mm with different cooling intensities (according to the results of the calculation): A - heat irradiations ratio α = 7 kW/m^{2}K ; B - α = 10 kW/m^{2}K

The required strengthening effect can be achieved only with increasing the time of cooling up to 2 s, which is possible under decreasing the velocity of roling down to 5 m/s. Under the lower cooling intensity [α = 5 kW/m^{2}K] the perlite-ferrite structure is formed around the entire section, i.e. the hot-rolled condition remains.

With the increasing of cooling intensity up to α = 10 kW/m^{2}K, the share of high-durable phase in the structure of the cooled metal is going up. In the surfase layers with the width of about 1 mm along the entire perimeter there is a probable formation of bainite and martensite. The width of the flanks with the structures of martensite and bainite can reach ~ 5 mm. A higher level of durability characteristics of rolled steel must correspond to such a distribution of structural components.

The stripe with cross-section 45x6 mm can be strengthened under α = 7 kW/m^{2}K and τ = 1.6 s (Fig. 3). Combination of martensite and bainite in surface layers and perlite-ferrite core has to provide high durability and sufficient flexibility.

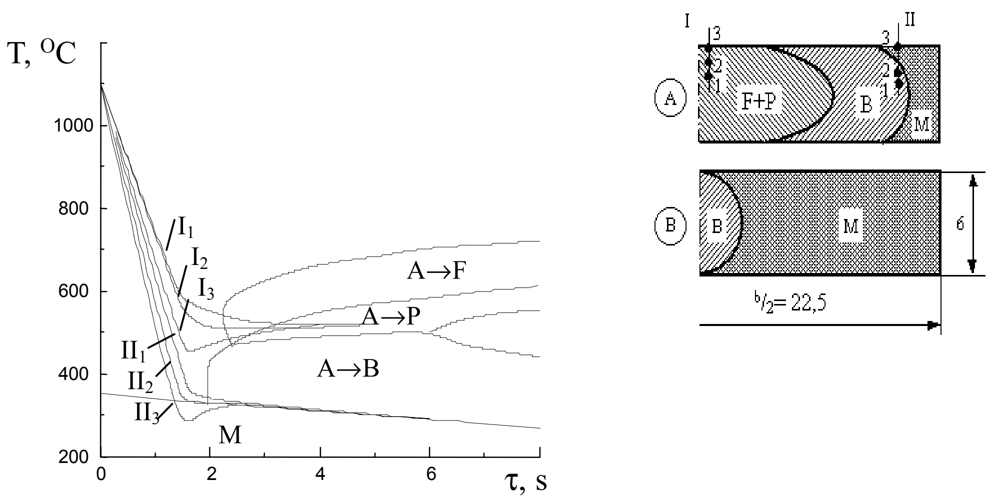


Fig.3. The scheme of stripe rolled steel structure forming with the cross-section 45x6 mm with different cooling intensities (according to the results of the calculation): A - heat irradiations ratio α = 7 kW/m^{2}K; B - α = 10 kW/m^{2}K .

A more intensive coolong [α = 10 *kW/m^{2}K*] for 1.6 s can lead to obtaining of martensite in the surface layers and bainite in the central part of the cross-section. This kind of structure is undesirable because of bad flexibility of its components. The required combination of structural components under α =

10 kW/m^{2}K can be obtained with descreasing the time of cooling to 1.2-1.3 s. With the more intensive cooling [α = 20 kW/m^{2}K] in the stripes of both sizes a martensite-bainite structure is formed the bainite area in it composes only ~ 25% of the total area of the cross-section of the stripe.

Thus, it has been found out, that the more the ratio of the stripe width to its thickness is in the more degree the unevennes of the distribution of the strengthening phases is expressed and consequently the mechanical properties along the width of the stripe. The required structural condition of stripe rolled steel can be achieved under α = 7-10 kW/m$^{2}\cdot$K .

The calculated conditions were tested while cooling rolled steel in a continuous water flow in closed chambers.

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 considera-tion, 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 into the chambers and branches for exhaust water escape. Sprayers units are designed the way 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 sprayed on the upper and lower surfaces of the stripe, 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 as a rectangle. In the bottom of the chamber the channels are made by which the water goes without any difficulties along the while 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 stripe 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 stripe along the cross-section. The cooling chamber is made of the two parte: the box and the lid, which are tied with special devides; it provides a better hermetization of the inner part of the cooling chamber. For exessive pressure escape which appears in the chamber while entering the front part of the stripe the values were designed on its lid using which the part of water is dumped in case the pressure in the chamber is exceedingly high and the cooling goes less intensively and this promotes forming even characteris-tics along the length of the stripe. The cooling plant can be assembled up to

12 m long from the separate units, which are tied with each other themselves 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 m^3/h, its temperature - 20-30 °C. The temperature of 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).

3. Results and discussion

Accelerated cooling of the rolled stock in the rolling mill as such the interrupted hardening. The cooling velocity of the surface layer secures hardening to martensite, but the core is still hot. After finishing the intensive cooling the rolled stock continues cooling on the air. During that time balancing of the temperature on the cross-section takes place. That leads to the surface martensite harded layers are high-temperature tempered. The temperature of the self-tempering layers is as low, as high the intensity or duration of the cooling in chamber is.

The maximum intensity of the cooling is reached under the conditions of contraflow along the entire device. The researches of the mechanical properties of the metal have shown that the accelerated cooling of the stripe 45x6 mm (0,30 % C; 0,69 % Mn; 0,09 % Si) during 1,3 s leads to the intensing to till 770-800 N/mm^2, i. e. strength growth compared to the hot-rolled elongation is 185-215 N/mm^2, but specific elongation sinks till 20 % (in hot-rolled condition $\delta = 32$ %). Growth of the cooling intensity to 1,5 s assist the strength properties improvement 970-1000 n/mm^2 ($\Delta R_m \sim 385 - 415 N/mm^2$) and lowers the specific elongation to16 %.

The hardness measurement along the width of the stripe of cross-section 45x6 mm in the middle of the stripe shows the high cooling degree in the side compared to the center: 275-290 HB and 200 HB.

By the same cooling increasing of cooling duration promotes the strengthening, but it provokes the worsening of the plasticity. For example, the stripe of cross-section 45x6 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 stripe 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 stripe 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 exept for the front part with the length of about 5-6 m. On entering cooling chamber the stripe 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 stripe in comparison with the middle part. The stripe of cross-section 45x6 mm had the level of durability overfall and reached in particular cases ~ 400–500 N/mm^2, and the stripe 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-section. The cooling chamber is designed in the form of the rectangle with the sizes of 55x12 mm. The difference in vertical sizes of the stripes is uncosiderable and horizontal sizes of the cross-section 45x6 mm are closer to the size of the chamber that's why the stripe in a higher degree blocks the chamber causing more barriers in a liquid flow and it consequently in a higher degree increases its cooling ability. Such an overfall is causes by uneven cooling of the stripe along its length.

The forehead of the stripe shows more difference by the strength of the middle situating nearly to the strength of the side and is: 255-290 N/mm^2.

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 contraflow 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 more way, the uniflow cooling devise has been set directly at the exit of the metal from the rollers or behind the contraflow device at the distance of 3 m from the rollers. The results of the research are presented in the Table 1.

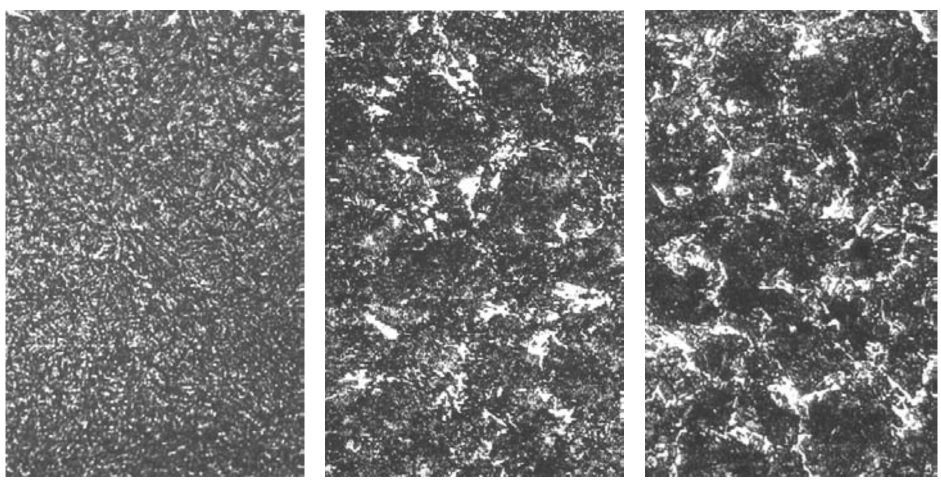
*Table 1. Change in mechanical characteristics along the length of the stripe under different schemes of uni-and contraflow cooling**

Cross-section, mm	The velocity of 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 (←)	$\frac{627-625}{625}$	$\frac{451-460}{440}$	18,0
		I (→) + II i III (←)	$\frac{700-663}{657}$	$\frac{638-463}{460}$	16,3
		I i III (←) + II (→)	$\frac{800-725}{725}$	$\frac{623-580}{580}$	17,0
		I i III (←)	$\frac{1300-992}{900}$	$\frac{1188-742}{756}$	13,0
	5,9	I i III (←) + II (→)	$\frac{860-830}{800}$	$\frac{715-660}{620}$	14,0
	6,7	hot-rolled condition	554	369	35,0
30x8	6,7	I i III (←)	$\frac{970}{825}$	$\frac{766}{660}$	20,0
	5,9	I i III (←)	$\frac{1180}{1070}$	$\frac{1050}{920}$	15,0
	6,7	hot-rolled 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 stripe are presented in numerator; and their values in the middle of the rolled steel are in denominator; **Uniflow (→) and contraflow (←)

Upon being put into operation the uniflow section worsened the cooling ability of the plant. For example, the replacement of the contraflow 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 stripe 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 stripe almost couldn't be seen.

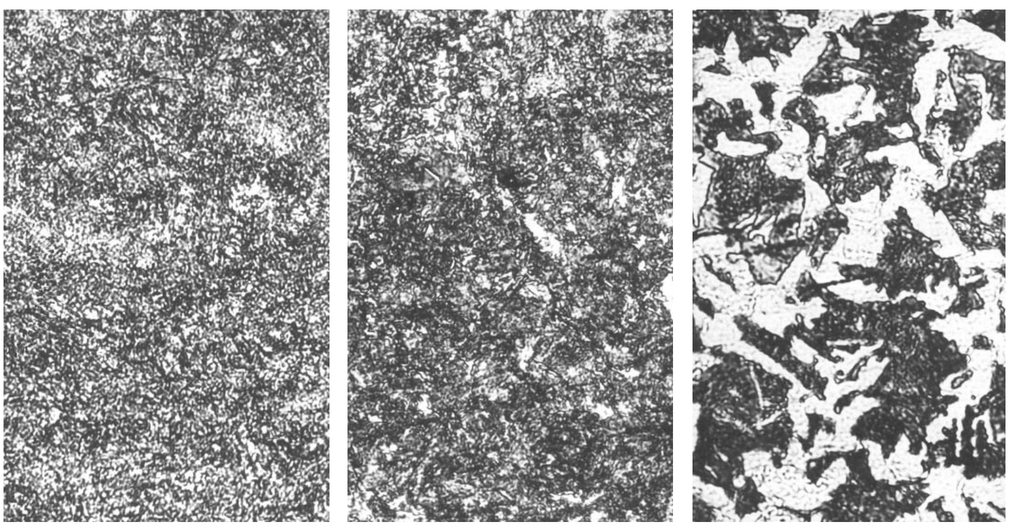
The stripe in its cross-section had a complex lamellar structure. On the surface of the stripe of cross-section 45x6 mm having been cooled a contraflow for 1.3 *s* a thin layer (0.4-0.5 mm) of tempered martensite appeared (Fig. 4 a). The central zone which was 4.5 mm along the height of the stripe (Fig. 4 c) was composed of perlit grains surrounded by continuous ferrite net.



a) b) c)

Fig. 4. The structure of the stripe of cross-section 45x6 mm made of low-carbon steel after the accelerated cooling in the mill flow: a - the section, adjaining the upper and lower parts of the stripe; b - tran sitional layer; c - central part of the cross-section of the stripe. Enlargement 400:1

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 stripe were cooled more intensively. The thickness of tempered martensite layer on the flanks of the stripe was about 4 mm. The transition layer had the width of 4.8 mm and was of bainite structure (Fig. 4 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 stripe was cooled more intensively. Hot-rolled stripe made of steel taked from the same melt had ferrite-perlite structure along the entire cross-section (Fig. 5). The incresse 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 beinite transformation.



a) b) c)

Fig. 5. The structure of the stripe of cross-section of 45x6 mm made of low-carbon steel in hot-rolled condition: a - buttend of the stripe (the edge); b - transitional layer (4-8 mm of the buttend); c - central part. Enlargement 400:1

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

The study of the structure and its comparison with the calculated one with different values of heat abstraction coefficient α has shown that under contraflow cooling of the stripe in the designed device the heat irradiation ratio reaches ~10 kW/m^2K on average. Under the conditions of mainly uniflow cooling the intensity goes down. The heat irradiation ratio makes 5-7 kW/m^2K.

4. Conclusions

1. Thermal strengthening in the mill flow gives a chance of getting the stripe 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 stripe to its thickness.
3. Strengthening degree and distribution of durability properties along the cross-section depend on cooling scheme. The least dispersedness of properties along the length of the stripe (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 such kind of scheme: contraflow-uniflow-contra-flow.

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