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Industrial Testing of the Advanced Technology of Cold Continuous Rolling of Strips

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According to the results of calculation and industrial tests rolling process with preliminary rewinding of the strip at 180° with the withdrawal of thickened (internal) coil of the hot-rolled coil to the external coil of the hot-rolled coil, increasing the product yield, was suggested.

Keywords: ROLLING, CONTINUOUS MILL, STRIP, THICKNESS, REWIND, FRONT END, BOTTOM END, THE LONGITUDINAL GROW-BACK

Introduction

Increase Strip rolling in the cold condition is performed in the presence of transient processes, during which the speed of the rolls is much smaller than in a steady process at their maximum speed. These transient processes are known to include rolling of strips with welding seams as well as rolling of end sections. Strip speed in finishing stand of five-stand mills with endless rolling during rolling the bottom end is v_5 = 4-5 m/sec, and in four-stand mills of individual coil rolling - $v_ч \leq 1.0$ m/sec.

Methodology

Front and bottom ends are rolled at threading speed in the mills of individual coil rolling. Moreover, when the front end of the strip is passing through the mill, housing screws are lowered according the productimeter as follows (continuous cold mill НСХП 1680), mm: stand № 1 0.7-1.0; № 2 0.5; № 3 0.3. After outgoing the front end of the strip outgoing from the finishing stand (№ 4) the housing screws return to the zero position for rolling in the steady process, and after the gripping the front end by the coiler rolling speed increases to a maximum (v_y).

The mill begins to stop at the moment when there are 5-6 coils left on the decoiler and during the bottom end passing through the stands №1 and № 2 the housing screws are lowered (according to the productimeter) to 0.7-1.1 mm and 0.5-0.9 mm, respectively, depending on the thickness of the rolled strip. The scheme of rolling speed mode in НСХП 1700 (1680) is presented in Figure 1 where L_{fe} - length of the front end of the rolled strip during threading; L_{be} - length of the bottom end of the rolled strip during slowing down the of the mill; L_d and L_c – strip length between the stand № 1 and in the decoiler and in the coiler respectively; L_{ac}, L_{sl} - strip length during the periods of acceleration and slowing down, respectively; v_{fe},v_s, v_{be}, v_x - rolling speed, respectively, when threading the front end of the strip in the coiler, maximum in the steady process, with the release of the bottom end and the speed corresponding to the intensive change of friction coefficient (for v_x < 5 m/sec friction coefficient increases significantly with decreasing rolling speed).

Changing speed mode in the process of rolling the strip has a definite effect on all parameters of the deformation of the metal. Thus, the reduction of the rolling speed causes an increase in friction coefficient, rolling force and strip thickness [1-3]. Therefore the thickness of the strip in the end parts is always greater than in the steady process.

During threading the front end into the mill the strip is affected by only the back tension, and with the release of the bottom end from the stands the strip is affected by only front tension. Degree of the impact of the front and back tension on the stress state of the metal in the deformation varies [1, 3-5], what accounts for some differences in the thickness of the front and bottom ends. In addition, the thickness of the bottom end of the hot rolled strip (semi-finished rolled stock), as a rule, is larger than the thickness of the front end, and this congenital longitudinal grow-back makes an impact on increasing the thickness of the bottom end the cold strip. Below the evaluation of the influence of these factors on increase of the thickness of the bottom end is represented.

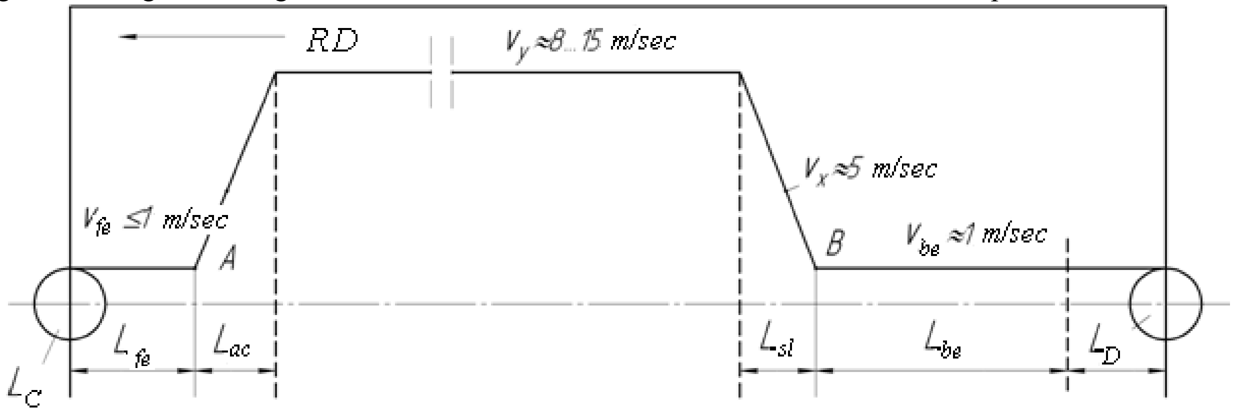

Figure 1. Diagram of the rolling speed mode in the finishing stand НСХП

Results and Discussion

Using previously developed and tested according to practical data calculation models [2, 6-9], the values of the friction coefficient, flow stress of the metal, length of the contact arc are determined taking into account elastic deformation of rolls and the strip, average normal contact stress and rolling force. The increase of the strip thickness in any rolling process compared to the baseline was calculated using the formula [3, 4]

$$\delta h_S = \frac{P_i - P_b}{M_S - \dfrac{\partial P}{\partial h}}, \quad (1)$$

where δh_S - increase of the strip thickness (longitudinal grow-back); P_b - rolling power in the basic mode (with minimum rolling power along the length of the strip in a steady process); P_i - rolling power in any other process; M_S - stand rigidity modulus; $\frac{\partial P}{\partial h}$ - current stand rigidity modulus.

In the case of determining increasing δh_S relative to the basic (minimum) strip thickness h_b (with minimum rolling power), it is acceptable to take $\partial P / \partial h = -\delta M_S$ (δM_S - increase of the rigidity modulus of the strip in the *i*-th process relative to the basic rigidity modulus). We determine parameter δM_S from the condition (if $M_{Si} > M_b$) [7, 8]

$$\delta M_S = M_{Si} - M_{Sb}, \quad (2)$$

where M_{Sb} and M_{Si} - rigidity modules of the strip in the i-th process (e.g., during the release of the bottom end from the mill).

Rigidity modules will be determined according to the method [3]:

$$M_{Sb} = \varphi_b \cdot P_b / \Delta h_b; \; M_{Si} = \phi_i \cdot P_i / \Delta h_i, \quad (3)$$

$$\varphi_i = [0.6 + 2.25(\varepsilon - 0.1)^2](0.6 + 0.45 f \sqrt{R/H}) \cdot (0.55 + 1.5 \cdot \varepsilon),$$

where Δh_b and Δh_i - reduction in thickness in the basic and the i-th modes; φ_i - coefficient; ε - relative reduction in thickness; f - friction coefficient; R – radius of the hard rolls.

The formula for calculation φ_i is obtained from the data from [3].

Taking into account expressions (1) and (2), we obtain

$$\delta h_S = \frac{P_i - P_b}{M_C + \delta M_S}. \quad (4)$$

The average normal contact stress taking into account various degrees of influence of the front and back stresses was calculated considering the size of zones of lag and slippage from the formulae [2, 5, 9]

$$p_{av} = \sigma_\Phi \left[\xi_0 \left(1 - \frac{\gamma}{\alpha}\right) + \xi_1 \frac{\gamma}{\alpha} + C_H \cdot f_S \cdot l_C / h_{av} \right]; (5)$$

$$\frac{\gamma}{\alpha} = \frac{2 f_S \sqrt{\frac{R_C}{h}} \cdot arctg \sqrt{\frac{\Delta h}{h}} - l\,\mathrm{n}\left(1 + \frac{\Delta h}{h}\right) - \frac{\sigma_0}{\sigma_\Phi} + \frac{\sigma_1}{\sigma_\Phi}}{4 f_S \cdot l_C / h_{av}}, \ (6)$$

where σ_Φ - deformation resistance; l_C and R_C - contact arc length and radius of the rolls considering the influence of elastic deformation of rolls and the strip; h and Δh - respectively, strip thickness after rolling and reduction in thickness; f_S - friction index; h_{av} - average strip thickness in the deformation zone; α and γ - contact and critical section angles, respectively; C_H - coefficient taking into account the intensity of the contact friction influence; ξ_0 and ξ_1 - coefficients taking into account the influence of the front and back tension, respectively

$$\xi_0 = 1 - \frac{\sigma_0}{\sigma_\Phi}; \quad \xi_1 = 1 - \frac{\sigma_1}{\sigma_\Phi},$$

where σ_0 and σ_1 - front and back tension, respectively.

Calculations were performed for the conditions of rolling the strip 0,9×1250 mm of steel 08кп in НСХП 1680 at JSC "Zaporizhstal" (without additional reduction in thickness of ends). Thickness of hot-rolled semi-finished rolled stock at the basic length is equal to H = 2.7 mm, and the tension stress $\sigma_S = \sigma_B$ = 150 N/mm^2. Back tension in front of stand №1 was assumed to be equal σ_0 = 20 N/mm^2, and front tension behind stand №4 σ_1 = 40 N/mm^2.

Rolling speed in the stand № 4 during threading and release of the ends was assumed to be $v_{fe} = v_{be}$ = 1.0 m/sec. In all calculations, the thickness of the front end of the hot-rolled semi-finished rolled stock was taken equal to that of the basic length of the semi-finished rolled stock H_{fe} = H = 2.7 mm and the thickness of the bottom end of the hot-rolled semi-finished rolled stock varied in the H_{be} = 2.5-3.0 mm imitating increase of the strip thickness in the wide-strip rolling mill. Taken initial parameters allow us to estimate the influence of rolling speed and of the strip thickness of end sections of hot-rolled semi-finished rolled stock on the increase of their thickness.

The calculated rolling parameters are presented in Table 1 and Figure 2. It follows from Table 1, during rolling in the steady process friction coefficient from first to last (finishing) stand reduces considerably, the average normal contact stress p_{av} varies in the range $p_{av} \approx$ 667,05-820,61 N/mm^2 due to the simultaneous influence of the meta hardening, reducing the friction coefficient, metal heating and increasing strain rate. Rolling power of the stand № 1 to № 4 decreases by reducing the length of the contact arc, and the rigidity modulus of the strip increases due to the hardening of the metal. Changing the strip thickness corresponds to the actual inrerroller (fixed) gap in the stands The thickness of the strip in the steady process, for evaluating of which increasing of the strip thickness of end sections was taken for the basic one during the grow-back δh_S = 0 (Table 1 presents data for the bottom end part of the strip (except δh_{SF})).

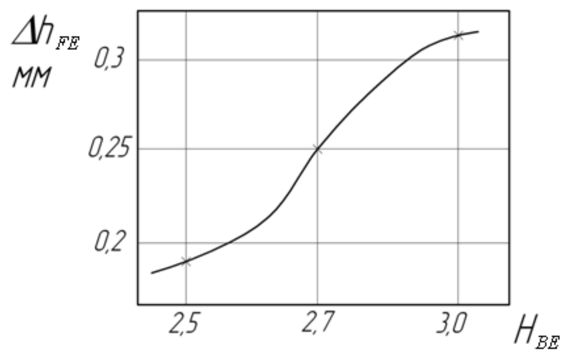

Figure 2. Dependence of influence of the strip thickness of the bottom end of the hot-rolled semi-finished rolled stock H_{be} (H_{fe} = const) on the increase of strip thickness in the bottom end after stand № 4

During rolling end parts the rolling power increases significantly in all the stands of the mill that causes an increase in elastic deformation of rolls and stands, as well as increase of the strip thickness in the front (δh_{SF}) and bottom (δh_{SB}) end sections. The calculations revealed that for the same thickness along the entire length of the hot-rolled semi-finished rolled stock (H = H_{SF} = H_{SB} = 2.7 mm) increase of the strip thickness in the front and bottom end sections are approximately the same (δh_{SF} = 0.250 mm, δh_{SB} = 0.238 mm). This

Table 1. Calculation of the strip deformation parameters taking into account the heating and deformation rate of the metal in the 4-stand cold rolling mill 1680, strip 08кп 2.7-0.9x1200

Stand numb	v, m/sec	h, mm	Δh, mm	δh_S, mm	f	p_{av}, N/mm²	P, MN	M_{fi} MN·mm,	l_c, mm	γ/α
Steady process (basic value)										
1	4.63	1.75	0.95	0	0.081	667.05	14.50	11.61	17.72	0.388
2	6.23	1.3	0.45	0	0.069	820.61	14.30	18.88	14.47	0.297
3	7.94	1.02	0.28	0	0.053	766.25	11.32	20.69	12.27	0.385
4	9	0.9	0.12	0	0.049	794.15	9.35	32.13	9.93	0.377
Front end thickness H_{fe} = 2.7 mm (v_4 = 1.2 m/sec)										
1	0.62	2.04	0.66	0.292	0.226	1021.82	20.21	28.65	16.51	0.426
2	0.83	1.581	0.459	0.283	0.097	923.04	16.11	21.42	14.96	0.300
3	1.06	1.3	0.280	0.280	0.075	891.01	13.48	24.67	12.84	0.367
4	1.2	1.150	0.150	0.250	0.089	980.38	12.54	41.67	10.72	0.419
Bottom end thickness H_{be} = 2.5 mm (v_4 = 1.2 m/sec)										
1	0.62	1.896	0.604	0.146	0.227	940.29	17.14	27.05	15.10	0.456
2	0.83	1.480	0.414	0.180	0.097	919.55	15.74	23.24	14.02	0.377
3	1.06	1.222	0.26	0.202	0.076	901.67	13.20	26.44	12.17	0.474
4	1.2	1.093	0.129	0.193	0.087	1068.05	13.74	52.64	10.71	0.470
Bottom end thickness H_{be} = 2.7 mm (v_4 = 1.2 m/sec)										
1	0.62	1.99	0.71	0.240	0.218	941.37	18.39	24.94	16.16	0.447
2	0.83	1.558	0.432	0.256	0.095	923.60	16.13	22.25	14.29	0.375
3	1.06	1.28	0.278	0.260	0.075	892.25	13.34	24.75	12.43	0.472
4	1.2	1.14	0.14	0.240	0.086	1058.10	13.86	48.52	10.91	0.468
Bottom end thickness H_{be} = 3.0 mm (v_4 = 1.2 m/sec)										
1	0.62	2.136	0.864	0.386	0.209	933.39	19.83	22.31	17.55	0.438
2	0.83	1.674	0.461	0.374	0.092	915.79	16.39	20.55	14.65	0.375
3	1.06	1.375	0.299	0.355	0.073	873.58	13.34	22.47	12.69	0.472
4	1.2	1.219	0.155	0.319	0.086	1032.93	13.84	43.14	11.16	0.465

shows the insignificant effect of the direction of the impact of tension stresses on the end parts. Obviously, this should be explained by absence of consideration metal hardening when calculating the p_{av}. In practical conditions the influence of the front and back tensions, can be more noticeable.

From the calculated data it follows that strip thickness of the bottom end of hot-rolled semi-finished rolled stock has a significant effect on the increase of the bottom end thickness. Thus the increase of the semi-finished rolled stock thickness in the back end (H_{be}) from 2.5 to 3.0 mm leads to an increase in the bottom end thickness in the finished strip in 0.126 mm. Analysis of the calculated data shows that the greatest impact on the value of the increase of end sections has the absence of end section tensions and less end thickening of the hot-rolled semi-finished rolled stock.

However, apart from the factors considered by the average thickness of the end sections rolled with $v_X \le 1$m/sec are affected by the differences of their rolling conditions at different length of the front and back end sections (Figure 1). It follows from Table. 1 that with equal thicknesses of the front and bottom ends ($H_{fe} = H_{be} = 2.7$ mm), the thickening in the front end is greater than in the bottom one ($\delta h_{SF} = 0.25$ mm, $\delta h_{SB} = 0.24$ mm). Such supposedly discrepancy to the well-known views on the formation of longitudinal grow-back is due to the fact that the front end is subjected to tension during threading into the mill in the first stand which equals $\sigma_0 = 20$ N/mm², and the bottom end of the strip in the first stand is affected by the front tension during the release from the mill and it is equal to $\sigma_1 = 150$ N/mm², what is much larger than back tension stress. In this case the strip thickness of in the front end was $h_{1F} = 2.04$ mm and the bottom one $h_{1B} = 1.99$ mm, what as a result determined a greater increase of the thickness of the strip in the front end.

As mentioned above, the length of front and back sections, rolled when threading and production of strips are different.

Define the length of the front and bottom ends of the finished strip, rolled at low speed (Figure 1). For the mill 1700 we have (m)

$L_c \approx 6.5$; $L_d \approx (6.0 \cdot 2.7)/0.9 = 18$; $L_{fe} \approx 6.0$.

Strip length (L_{be}) coming out of from the mill stand № 4 with the release at the speed equals to v_{be}

$$L_{be} = \frac{H+h}{2 \cdot h} \cdot L_m ,$$

where H and h - thickness of the hot-rolled semi-finished rolled stock and finished strip, respectively; L_m - distance between the axes of the first and finishing stands (for the mill 1700 $L_m \approx$ 16 m).

Then, the total length of the front end of during threading (L_F) and the bottom end during the release (L_B) ($L_{ac} \approx L_{sl}$) equals (H = 2.7 mm, h = 0.9 mm)

$$L_F = L_c + L_{fe} = 6.5 + 6.0 = 12.5 \text{ m};$$

$$L_B = L_d + L_{be} \cong 18 + \frac{2.7+0.9}{2 \cdot 0.9} \cdot 16 = 50 \text{ м},$$ where

L_F - total length of the front end of the finished strip, rolled at speed v_{fe}; L_B - total length of the bottom end of the finished rolled strip at speed v_{fe} ($v_{fe} = v_{be} \approx 1.0$ m/sec).

Thus, the length of the the bottom end of the strip, rolled in the finishing stand at low speed ($v_{be} \leq 1.0$ m/sec) is four times larger than that of the front end of the strip. In the areas of acceleration (L_{ac}) and slowing (L_{sl}) the average thickness of the strip is about the same. It is known (as above), that during rolling at small speeds ($v_{be}(v_{fe}) < 5$ m/sec) (**Figure 1**) as compared with rolling at speed v_y friction coefficient, rolling power, strip thickness and, therefore, longitudinal grow-back (increasing of thickness of the end sections of the strip) increase significantly.

During rolling a long bottom end deformation conditions worsen further owing to the fact that the thickness of the hot rolled strip is 0.1-0.3 mm larger than the thickness in the middle of the strip length and thicker than in the front end. When threading the strip into the coiler, the length of the end of the strip, rolled at a reduced speed (v_{fe}) is significantly smaller than the length of the bottom end of the strip, rolled in the period of its release from the mill. Therefore, technological process, in which the thickened bottom end of the hot rolled strip will be rolled as the front (threading) end of the strip, is more efficient and advisable. This process can be realized if the hot rolled coil is rewound before and after etching with the withdrawal of the thickened (internal) coil to the external coil of the hot rolled coil.

In this case, the thickened end of the hot rolled strip will be the threading one and about 37 m from 50 m of the thickened section of the hot rolled strip in the steady process will be rolled at maximum speed with less impact on the process of deformation of the surface friction. Reduction of the rolling power in this area compared with the power of rolling during its release at $v_{be} \leq 1.0$ m/sec will provide reduction in the actual strip thickness and increase of the yield product.

One way of rewinding hot rolled coil in the intermediate rewinding unit (4-6 in **Figure 3**) is shown in Figure 3 [10]. From the continuous-pickling unit (CPU), 1 hot rolled etched strip is fed to the coiling machine 2 for the formation of the roll, which is transported by a conveyor 3 to the uncoiler 4, from which the strip is rewinded by draw rollers 5 to the coiler 6 in a new roll with re-formation of its bottom end from the internal to the outer (external) coil; then a newly formed roll is rolled via transmitters 7,8 and rotary device 9 is mounted into the decoiler 10 in front of the mill and rolled according to the known variable deformation-speed mode in the rolling mill 11 by winding the strip into the coiler 12 and the subsequent taking away from the mill with the remover 13.

Industrial testing (In conducting the experimental rolling participated eng. Pchela N.I.) of the new process was performed in the continuous cold mill 1680 at JSC "Zaporizhstal". During testing of new technology rewinding of hot-rolled coils was carried out (at this stage without further reduction of strip thickness) on the reversing mill 1680. After rewinding of three coils they were rolled in the continuous cold mill 1680 in the current mode with threading the bottom end (external coil) in the coiler of the hot rolled strip.

In the same period batch-produced rolls (without rewinding) of the same metal smelting were rolled. The results of rolling are shown in **Figure 4** and **Table 2** (the table data were obtained from the computer of parameter recording of the rolling performed in the continuous cold mill 1680 at JSC "Zaporizhstal"). As can be seen in Figure 4a (batch-produced rolling), the front end of the strip is somewhat larger (in $\delta h_S \approx 0.06$ mm) than the nominal thickness ($h \approx 0.9$ mm). In the steady rolling process some parts were rolled to minus. In the bottom end of the strip the ~5 m long part was rolled to minus, and then the ~4 m long strip part its thickness increases by 0.37 mm higher than the nominal thickness.

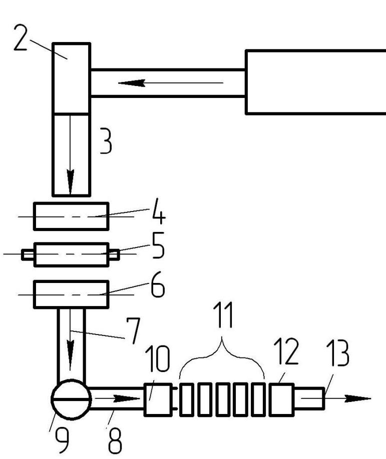

Figure 3. Scheme of processing hot rolled strip prior to cold rolling: 1 - continuous-pickling unit (CPU); 2 - coiling machine; 3 – transporter; 4 – decoiler; 5 - draw rollers; 6 – coiler;7,8 – transmitters; 9 - rotary device; 10 – decoiler; 11 - rolling mill; 12 – coiler; 13 - remover

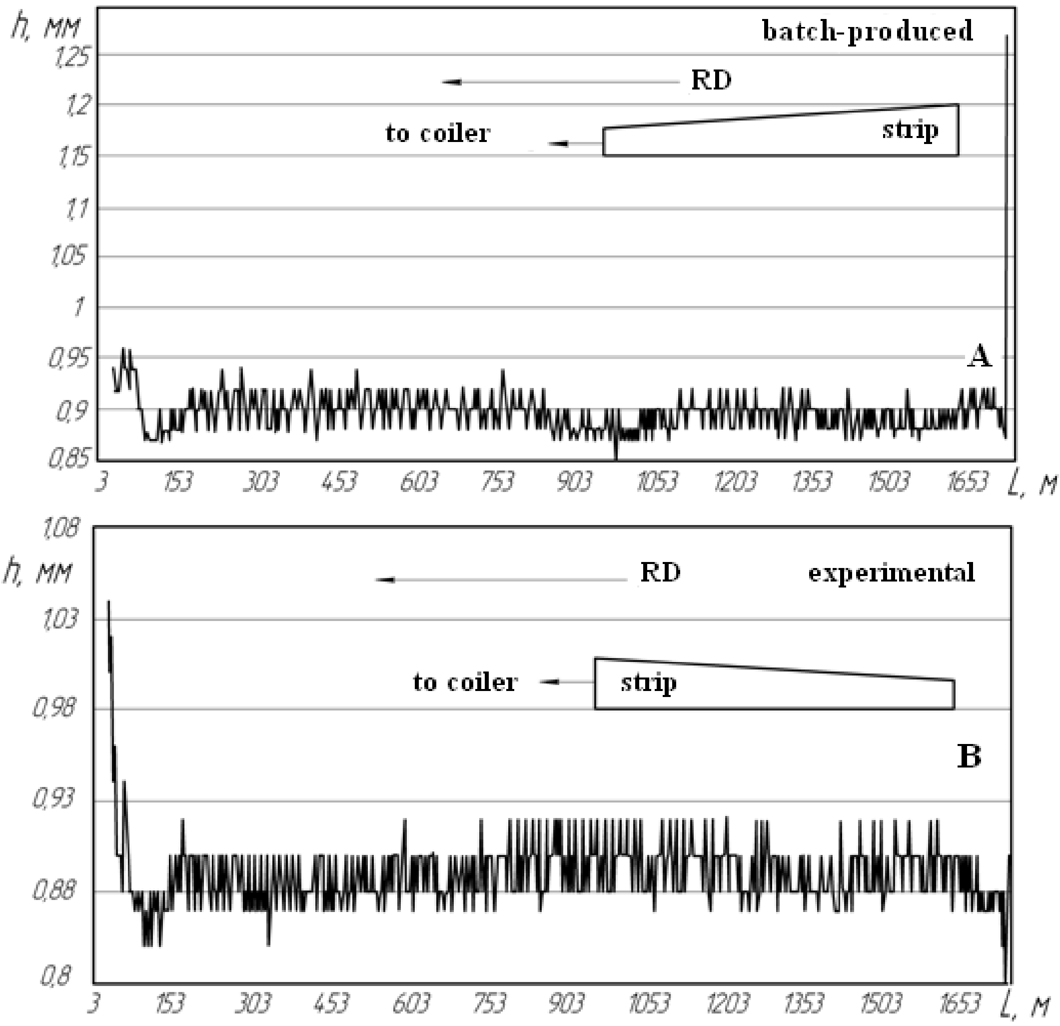

Figure 4. Profilogram of the thickness along the length of the strip 0.9×1000 mm (08кп): a - batch-produced rolling, b - a new technology with roll rewinding (RD - rolling direction)

Table 2. Parameters of rolling strips 0.9x1000 mm (08кп, 1211527, August 8, 2011) according to batch-produced and experimental (with rewinding) in the continuous cold mill 1680

Coil number	Average thickness	Meters without thickness gauge	Accuracy class	Defective products, m		Physical weight	Total strip length, m	% of yield product	Yield product increase, %	Note
				-	+					
5550	0889	24	AT	21	19	11.06	1527	95.57	-	batch-produced
5551	0.898	27	AT	0	19	11.66	1594	96.91	-	
5552	0.901	29	AT	0	21	11.70	1594	96.58	-	
5553	0.891	16	AT	16	19	11.59	1597	96.64	0.92	Experimental
5554	0.893	21	AT	3	13	11.57	1592	97.58		
5555	0.894	24	AT	0	5	11.25	1546	98.04		
5556	0.885	32	AT	0	13	11.14	1546	96.86	-	batch-produced
Average parameters										
-	0.893	28	-	5.25	18.0	11.39	1565	96.47	-	batch-produced
-	0.893	20.3	-	6.32	12.7	11.47	1578	97.39	0.92	Experimental

The nature of the profilogram changes in the experimental coil (**Figure 4b**). In the experimental coil (**Figure 4b**) the nature of the profilograms changes. In this process, the front end of the strip was rolled with thickening $\delta h_S = 0.14$ mm versus nominal (h = 0.9 mm). In the steady process strip thickness is within $h \approx 0.9$ mm, but the bottom end on the length of ~18 m was rolled in the minus tolerance field (h = 0.87 mm). Thus, the total reduction in thickness of the end sections during rolling the experimental coil was

$$\delta h_{SR} = 0.06+0.37-0.14+0.1 = 0.3 \text{ mm}.$$

Conclusions

The suggested process provides a decrease in the strip grow-back - reducing the thickened end sections This is achieved by decreasing the influence of external friction in the front end, as well as reduction of the temperature wedge of hot-rolled semi-finished rolled stock. Positive results of the improved process are confirmed by computer registration of the basic parameters of rolling batch-produced and experimental coils. As it follows from the averaged data:

- The number of meters rolled without measuring the thickness makes 20 against 28 meters (batch-produced);
- Defective products in thickness decreased from 23.2 to 19.0 m;
- The total length of the strip within tolerances (yield products) increased from 1565 to 1578 m;
- The number of metal yield increased from 96.5 to 97.4%.

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Промышленные испытания усовершенствованной технологии холодной непрерывной прокатки полос

Николаев В.А., Васильев А.Г.,Путноки А.Ю., Николенко А.Г., Васильев А.А.

По результатам выполненных расчетов и промышленных экспериментов предложен технологический процесс прокатки с предварительной перемоткой полосы на 180° с выводом утолщенного (внутреннего) витка горячекатаного рулона на внешний виток горячекатаного рулона, обеспечивающий увеличение выхода годной продукции.