DOI 10.1007/s11015-018-0635-9
Metallurgist, Vol. 62, Nos. 1–2, May, 2018 (Russian Original Nos. 1–2, January–February, 2018)

A STUDY OF THE PARAMETERS FOR HOT STRAIGHTENING OF THICK STEEL PLATES ON A ROLLER STRAIGHTENING MACHINE

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UDC 621.982

We examine the parameters for hot straightening of steel plates, taking into account deformation of the metal on the rollers during alternating bend process, as well as the temperature and strain rate. The calculations showed that deformation, temperature, and strain rate have a significant impact on the bending moments and the straightening force; these must be taken into account in the design and operation of roller straighteners. The approach used for straightening steel plates is used to calculate the operating parameters of plate straightening machines.
Keywords: *hot straightening steel plates, roller straightener, alternate bending, bending moment, straightening power.*

In today's competitive manufacturing environment, it is extremely important to improve metallurgical production quality, especially for high-demand products such as thick steel plate.

Despite the success of modern science and manufacturing in improving the flatness of steel plate, several new, stricter quality standards for rolled-metal stock have made it necessary to develop and implement the efficient technology.

Domestic hot-rolled thick steel plate production is currently most advanced at the following mills: the 2350, 4500, and 5000 mills at the Magnitogorsk Metallurgical Combine (MMK); the 2800/1700 and 5000 mills at the Izhora Metallurgical Plant, Severstal; the 5000 mill at the Vyksa Metallurgical Plant; the 2300/1700 mill at the Chelyabinsk Metallurgical Combine; and others. The MMK 5000 mill produces hot-rolled plate with thickness 8–100 mm and widths of 1500–4800 mm from carbon steel, low-alloy steel, and alloy steel; the Severstal 5000 mill (manufactured by Izhora Metallurgical Plant) produces plate with thickness 70 mm and maximum width 4800 mm from F500W high-strength steel; the Vyksa Metallurgical Plant 5000 mill produces plate with thickness 40–80 mm and maximum widths of 4800 mm. All these mills are equipped with plate straighteners.

When straightening steel plate, the primary difficulties involve determining the mean deformation stress during hot straightening operations (which reduces the calculation accuracy of bending moment and torque calculations for modernization of plate straighteners) as well as determining the geometric parameters of the plate being straightened. The purpose of this paper is to develop techniques for calculating the aforementioned parameters when straightening plates on a roller straightening machine (RSM).

In Russia, the primary standard for thick steel plate is GOST 19903-2015. However, many metallurgical firms in Russia produce plate to Eurostandard EN 10029-91 and US standard ASTM A6/A6M-91. Under GOST 19903-74, the maximum deviations from flatness are 5, 8, 10, and 12 mm over a 1 meter baseline. Under Eurostandard EN 10029-91 and US

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Translated from Metallurg, No. 2, pp. 42–45, February, 2018. Original article submitted March 7, 2017.

standard ASTM A6/A6M-91, flatness is measured over the full width of the plate and over a 4000 mm baseline along the long axis of the plate. Under Eurostandard EN 10029-91, the normal flatness N of a class varies from 5 mm to 8 mm, depending on plate thickness [1].

In hot rolling shops, plate is commonly straightened while hot. Hot straightening of plate is performed as the temperature decreases from the temperature at the end of the rolling process (850–900°C) to a temperature of 100–500°C [2]. This is accomplished by feeding the plate from the last stand of the rolling mill via a roller table to a roller straightening machine.

In hot forming, the mean strain resistance is determined using the method of thermomechanical coefficients [3]:

$$\sigma_{SC} = \sigma_0 k_\varepsilon k_u k_t, \tag{1}$$

where σ_0 is the basic yield strength; and k_ε, k_u, and k_t are coefficients that take into account the amount of deformation, the deformation rate, and the temperature at which the deformation occurs.

Under the method described in [3], the coefficients k_ε, k_u, and k_t for each metal or alloy are determined using graphs of the functions $k_\varepsilon = f(\varepsilon)$, $k_u = f(u)$, and $k_t = f(t)$.

The mean strain resistance for 45 steel may be calculated using the equation [4]

$$\sigma_{SC} = A_1\sigma_0(10\varepsilon)^{A2}\, u^{A3}(T/1000)^{-A3}, \tag{2}$$

where $\sigma_0 = 88$ MPa is the basic yield stress of the metal obtained for $\varepsilon = 0.1$, $u = 1.0$ sec^{-1}, $T = 1000$°C, $A_1 = 1.0$, $A_2 = 0.173$, $A_3 = 1.143$, and $A_4 = 3.05$.

When the plate is straightened using an RSM, the relative deformation can be written as

$$\varepsilon = z(1/r_0 - 1/r), \tag{3}$$

where z is the vertical distance from the neutral axis of the plate cross-section to the fiber under consideration, r_0 is the initial radius of the section of plate prior to straightening, and r is the bending radius of the sheet on the rollers.

The rate of plastic deformation during straightening $u = \varepsilon/t$ (t is the time required to straighten the plate in the RSM). The time required to straighten the plate $t = m/v_p$ (m is the spacing between RSM rollers, and v_p is the linear straightening speed).

Practical experience in straightening is known to cause the plastic deformation rate for the straightening process to vary from 0.01 sec^{-1} to 1.2 sec^{-1}. When a deformed section of a rectangular cross-section plate is straightened in an RSM, the plastic bending moment is given by the formula

$$M_{\text{pl}} = \frac{Bh^2}{4}\frac{2}{(\varepsilon^*)^2}\int_0^{\varepsilon^*}\sigma\varepsilon\, d\varepsilon, \tag{4}$$

where B and h are the width and thickness of the plate; ε^* is the relative deformation of the extreme fibers in the transverse section of the plate; and σ is the stress, which varies over the vertical cross section of the plate.

If the quantities σ and ε in Eq. (4) are represented in the form of mean values σ^* and ε^*, the latter equation may be written in the form

$$M_{\text{pl}} = \frac{Bh^2}{4}\frac{2}{(\varepsilon^*)^2}\int_0^{\varepsilon^*}\sigma\varepsilon\, d\varepsilon = W_S\sigma^*_{SC}, \tag{5}$$

where $W_S = Bh^2/4$ is the drag torque for a plate of rectangular cross-section, and σ^*_{SC} is the yield strength of the plate.

The total torque due to the RSM tractive force $M_{\Sigma\text{tor}}$ is the sum of the following torques: the torque $M_{\text{tor}(1)}$ from bending the sheet over the rollers, the torque $M_{\text{tor}(2)}$ required to overcome roller friction against the surface of the plate, and the torque $M_{\text{tor}(3)}$ required to overcome friction in the trunnions for the non-driven rollers [5, 6].

The torque required to overcome roller friction against the surface of the plate is given by

$$M_{\text{tor}(2)} = Pf_1(2v/D), \tag{6}$$

TABLE 1. Relative Bending Radii for Plate

r_0^*/h	Value of r/h			
	10 steel	20 steel	30 steel	45 steel
5	200	152	120	95
10	250	192	159	130
25	294	233	196	167
50	312	250	213	185
100	322	256	222	196
200	332	263	227	200

where f_1 is the coefficient of rolling friction for the rollers against the surface of the plate, v is the linear straightening speed, and D is the roller diameter. For hot straightening, the coefficient of rolling friction f_1 = 1.0–1.5 mm [1].

The torque required to overcome friction in the trunnions for the non-driven rollers is given by the formula

$$M_{\text{tor(3)}} = \sum_1^n P_i f_2 \frac{D}{2} \omega, \tag{7}$$

where P_i is the straightening force for the ith roller, f_2 is the coefficient of sliding friction for the roller trunnions in the bearings, and ω is the roller angular rotation velocity.

The RSM electric motor power is determined as follows:

$$N = M_{\Sigma\text{tor}} v / 102 D\eta, \tag{8}$$

where $M_{\Sigma\text{tor}} = M_{\text{tor(1)}} + M_{\text{tor(2)}} + M_{\text{tor(3)}}$ is the total torque, and η is the efficiency of the motor used in the machine.

The straightening force is given by the formula

$$P = 2M_{\text{pl}}/m. \tag{9}$$

We then rewrite Eq. (3) in slightly different form:

$$\varepsilon^* = \frac{h}{2}\left(\frac{1}{r_0^* h} + \frac{1}{rh}\right) = \frac{1}{2}\left(\frac{1}{r_0^*} + \frac{1}{r}\right), \tag{10}$$

where r_0^* is the initial radius of the plate prior to straightening, and r is the bending radius of the sheet on the rollers.

Table 1 lists experimental values of r/h for specific values of r_0/h for plate made from 10 steel, 20 steel, and 45 steel [5].

Table 1 can be used to determine the values of r/h if we know the relative initial radius of a section of plate prior to straightening r_0/h. Equation (10) was used together with the quantities r_0/h and r/h to determine the relative deformation at the second roller ε_2^*. The deformation at the third (ε_3^*) and subsequent RSM rollers was determined in a similar manner.

Table 2 lists the calculated bending torques for 45-steel plate as a function of deformation speed (u) and temperature.

In Table 2, $M_{2\text{pl}}$–$M_{10\text{pl}}$ are the plastic bending torques at RSM rollers 2, 3, ..., 10 calculated using Eq. (4).

Analysis of the results in Table 2 revealed the following:

1) the bending torque each roller increase with increasing temperature from 20 to 300°C, and then decrease as the temperature increases to 500°C. If the data in Table 2 are used to graph the bending torque as a function of temperature, the resulting graphs will appear to be similar to those for strain resistance as a function of temperature [3];

2) higher deformation speeds mean larger bending torques on all rollers;

3) the bending torques decrease from roller No. 2 through roller No. 10 as the plate passes through the RSM.

TABLE 2. Calculated Torques for Straightening 45-Steel Plate for Various Deformation Temperatures and Speeds on a 10-Roller Straightening Machine (h = 20 mm, B = 2000 mm)

Temperature, °C	M_{2pl}, N·m	M_{3pl}, N·m	M_{4pl}, N·m	M_{5pl}, N·m	M_{6pl}, N·m	M_{7pl}, N·m	M_{8pl}, N·m	M_{9pl}, N·m	M_{10pl}, N·m
$u = 6.0 \cdot 10^{-2}$ sec^{-1}									
20	466	440	415	336	155	145	120	110	98
300	990	820	720	620	340	300	280	260	250
500	420	380	340	286	101	98	98	85	80
$u = 6.0$ sec^{-1}									
20	625	550	495	364	195	175	140	130	125
300	1080	960	780	660	405	380	350	320	310
500	545	500	470	315	182	150	130	110	100

The calculation presented above is for hot straightening of thick steel plate (45 steel) after rolling on the 2300/1700 combination mill at the Chelyabinsk Metallurgical Combine, with the straightening machine immediately following the 2300 stand group. The technical specifications of the 2300 mill roller straightening machine are as follows:

Plate width, mm	800–2100
Plate thickness, mm	6–20
Straightening speed, m/sec	2
Number of straightening rollers	7
Diameter of straightening rollers, mm	400
Length of straightening rollers, mm	2300
Roller spacing, mm	410
Diameter of supporting rollers, mm	400

For a 45 steel plate with relative initial radius $r_0^* = 10.0$ (see Table 1), we obtain a relative plate bending radius $r^* = 130$. Substituting these values into Eq. (10), we obtain

$$\varepsilon^* = 1/2\,(1/r_0^* + 1/r) = 0.053. \tag{11}$$

The calculated plate straightening parameters at 400°C obtained from Eqs. (3), (4), (9), and (10) are listed in Table 3.

Analysis of the data provided for 45 steel in Table 3 indicated that ε^* decreases from 0.053 to 0.0029, the deformation rate u decreases from 0.106 sec^{-1} to 0.006 sec^{-1}, the bending torque M decreases from $104 \cdot 10^3$ to $40 \cdot 10^3$ N·m, and the straightening force decreases from 650.0 to 310.0 kN from roller No. 2 to roller No. 10.

In addition, the improved plate straightening quality in hot straightening compared with cold straightening is due to enhanced structural modification of the metal throughout the entire cross section. The plate has improved surface quality because the combination of alternating bends and cooling removes the scale.

The straightening efficiency of the ten-roller straightening machine for 45-steel plate (h = 20 mm, B = 2000 mm) was determined using the formula

$$\mathrm{E} = \frac{1/r_0 - 1/r_1}{1/r_0} 100, \%. \tag{12}$$

The straightening parameters for the 45-steel plate are listed in Table 4.

The data in Table 4 imply that the parameter A lies within the range 20.0 to 40.0 mm and the parameter l lies within the range 800 to 1000 mm; after straightening, A lies within the range 4.0 to 10.0 mm, and l lies within the range 800 to 1000 mm; the straightening efficiency is therefore 75–86.0%.

TABLE 3. Calculated Straightening Parameters for 45-Steel Plate (h = 20 mm, B = 2000 mm)

Roller	Parameter			
	ε^*	u, sec^{-1}	M, N·m	P, kN
No. 2	0.053	0.106	$104 \cdot 10^3$	650.0
No. 3	0.041	0.09	$98 \cdot 10^3$	61.2
No. 4	0.037	0.075	$90 \cdot 10^3$	562.0
No. 5	0.022	0.044	$80 \cdot 10^3$	500.0
No. 6	0.0049	0.011	$70 \cdot 10^3$	437.6
No. 7	0.0044	0.011	$604 \cdot 10^3$	409.0
No. 8	0.0039	0.009	$55 \cdot 10^3$	389.2
No. 9	0.0032	0.008	$50 \cdot 10^3$	350.0
No. 10	0.0029	0.006	$40 \cdot 10^3$	310.0

TABLE 4. Straightening Parameters for 45-Steel Plate (h = 20 mm, B = 2000 mm)

Before straightening			After straightening			Efficiency, %
A_0, mm	l_0, mm	$1/r_0$	A_i, mm	l_i, mm	$1/r_i$	
20.0	800	0.00025	4.0	800	0.00005	80.0
30.0	900	0.00029	6.0	900	0.000039	86.0
40.0	1000	0.00032	10.0	1000	0.000080	75.0
A is the defect height. and l is the defect length.						

Conclusion

1. We performed a theoretical study of the process for hot straightening of steel plate via alternate bending of metal over rollers, taking temperature and bending speed into account, and also determining the parameters for this process.

2. The calculations performed for this paper indicate that temperature and bending speed have a substantial impact on bending torque and straightening force, which must be taken into account in the design and operation of RSMs.

3. The calculations showed that for a 45-steel plate (h = 20 mm, B = 2000 mm) straightened on a roller straightening machine, ε^* decreases from 0,053 to 0,0049, the bending speed u increases from 0,106 to 0,011 sec^{-1}, the bending torque M decreases from $104 \cdot 10^3$ to $70 \cdot 10^3$ N·m, and the straightening force decreases from 650 to 437.6 kN.

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