Analysis of geometrical parameters of hot-rolled rolling

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Abstract. The shape of cross-sectional profile is the most important characteristic of the quality of hot rolled steel, because it is accurately reproduced after subsequent cold rolling and thereby has a significant effect on the flatness of cold rolled strips. Traditional method to evaluating the accuracy of cross-sectional profile by geometric dimensions is the least squares approximation of hot-rolled strip thickness by second order polynomial. A number of parameters that characterize the macro-features of hot-rolled strips' profile are found from the obtained second order parabola coefficients; this is wedge, convexity, displacement, coefficient of determination and the recently introduced saddle-shape coefficient, showing the presence of edge thickenings. Edge thickenings are formed due to wear of the work rolls in the areas corresponding to the edges of the rolled strips. An analysis of the existing geometrical parameters of the cross-sectional profile of the hot-rolled strips showed that with their help in some cases it is practically impossible to predict the flatness of cold-rolled strips. Analysis of the flatness of cold-rolled strips has identified four specific classes of cross-sectional profiles of hot rolled strips that have a significant effect on the shape of cold-rolled strips, and three of them negatively affect the flatness of cold rolled strips. Profiles with a concave middle and (or) near-edge areas lead to waviness, pike-shaped profiles cause warping.

1. Introduction

The peculiarities of the cross-section profile of hot-rolled strips have a significant influence on a flatness of cold-rolled strips, rolled from this semifinished rolled product [1–36]. Such peculiarities of the cross-section profile of hot-rolled strips, as increased (reduced) the convexity and wedging, are associated with changes in the deflection of the rolls’ axes and (or) flattening of the working roller in contact with the strip. Other peculiarities, such as the local thickening, relate to the defects in the cross-section profile and are associated with uneven deterioration of the working rollers during the hot rolling [1–4]. These defects lead to uneven specific tension across the width of the cold-rolled strips, which leads to a violation of their flatness. Various methods are used to prevent the appearance of strips’ non-flatness during rolling and to eliminate it after rolling [5–16, 21, 22].

On the continuous broadband mill 2000 of the hot-rolled shop by PJSC “NLMK” (Lipetsk), the cross-section profile is measured with the profilometer (Radiometrie–312). The construction of the measuring matrix of the device allows us to measure the thickness of the strip in the direction of the width with a discreteness of 5 mm. A set of such measurements, recorded in the database of technological parameters of the mill’s automated control system is called a scan. During the rolling process, the profilometer generates from 40 to 200 such scans for each strip. It is convenient to record the measurement results of a single strip in the form of the matrix $H$:
where \( h_{sc}^{l,j} \) is the value of the strip thickness of the \( l \)-th scan measured by the \( j \)-th measuring camera; \( q \) is the number of measured scans; \( p \) is the number of involved measuring cameras of the profilometer.

The values of the resulting cross-section profile \( H[x_i] \) are obtained by averaging the matrix \( H \) over the columns:

\[
\begin{align*}
H &= \left[ \begin{array}{cccc}
 h_{sc}^{11} & h_{sc}^{12} & \ldots & h_{sc}^{1p} \\
 h_{sc}^{21} & h_{sc}^{22} & \ldots & h_{sc}^{2p} \\
 \vdots & \vdots & \ddots & \vdots \\
 h_{sc}^{q1} & h_{sc}^{q2} & \ldots & h_{sc}^{qp} 
\end{array} \right],
\end{align*}
\]

2. Geometric parameters of cross-section profile of hot-rolled strips

The cross-section profile, with the exception of 40 mm on the side of each edge, is approximated by a polynomial, in this case a quadratic parabola [17, 19]:

\[
h(x) = a + bx + cx^2,
\]

where \( h(x) \) is the approximate width of the strip; \( a \), \( b \) and \( c \) are the coefficients, found by the least squares method (LSM); \( x \) is the relative coordinate of the strip’s width, reduced to the interval \([-1, 1]\):

\[
x = \frac{2x_{\text{fact}}}{B},
\]

where \( x_{\text{fact}} \) is the absolute coordinate for the strip’s width; \( B \) is the strip’s width, except for 40 mm from each edge.

The obtained coefficients \( a \), \( b \) and \( c \) are used to calculate the convexity \( P \), wedging \( W \) and convexity’s displacement \( S \). A schematic representation of parameters of the cross-section profile is shown in Figure 1.

![Figure 1. Real cross-section profile of hot-rolled strip and parameters of its estimation.](image)

According to [18], the model’s equation can be conveniently rewritten as:
\[ h(x) = h(0) - \frac{W}{2}x - Px^2, \]

where \( h(0) \) is the thickness in the middle of the strip’s width.

The parameters \( P, W \) and \( S \) are redundant. Each of these parameters can be expressed as a ratio of the other two. For example, the convexity’s displacement \( S \) can be expressed through the values of the wedging \( W \) and convexity \( P \) in the form:

\[ S = \frac{WB}{8P}. \]

Figure 2. Example of approximation of real cross-section profiles of the same size: \( a \) – with edge thickening; \( b \) – without edge thickening.

3. The determination’s and saddle’s coefficients
The coefficient of determination \( R^2 \) [6] is used as a criterion that shows the degree of proximity of the actual cross-section profile to the approximating parabola.

The closer the value of the determination coefficient is to one, the more accurately the approximating parabola describes the actual cross-section profile of the hot rolled rolling.

The parameter \( R^2 \) is calculated using the formula [20]:
\[
R^2 = 1 - \frac{\sum_{i=1}^{m} (H[x_i] - h[x_i])^2}{\sum_{i=1}^{m} (H[x_i] - \bar{H})^2}, \quad \bar{H} = \frac{\sum_{i=1}^{m} H[x_i]}{m},
\]

where \(H[x_i]\) is the actual value of the profile thickness at point \(x_i\), \(h[x_i]\) is the calculated value for the approximating parabola, \(x_i\) is relative coordinate for the strip’s width at point \(i\), \(m\) is a number of measurements of the cross-section profile with the exception of 40 mm on the side of each edge.

However, not always close to the unit \(R^2\) indicates a high quality of hot-rolled rolling [25]. Analysis of the results of rolling of the cold-rolled strips with close the values of the determination coefficients and parameters \(P\), \(W\) and \(S\) (that do not exceed the regulated values) showed that if one of these strips has a violation of flatness, then its cross-section profile has a characteristic saddle shape. Figure 2 shows us the real profiles of the hot-rolled stock of the same standard size with the edge thickening (Figure 2, \(a\)) and without the edge thickening (Figure 2, \(b\)), which have the same determination’s coefficient.

Therefore, the authors [26] have developed an additional criterion for estimating the size of the edge thickenings – the saddle coefficient \(K_S\):

\[
K_S = \frac{\sum_{i=1}^{m} (H[x_i] - h[x_i]) \cdot |x_i|}{\sum_{i=1}^{m} (H[x_i] - \bar{H}) \cdot |x_i|}.
\]

If the cross-section profile has no the edge’s thickening, the \(K_S\) values are negative. As the edge’s thickening increases, the value of \(K_S\) increases towards positive values.

4. Characteristic cross-section’s profiles of hot-rolled strips

It is established that there are four characteristic classes of the cross-section profiles of the hot-rolled rolling strips (Figure 3).

![Figure 3. Characteristic shape of cross-section profiles of hot-rolled strips: \(a\) – without edge thickening (class 1); \(b\) – with a peak-shaped convex of the middle (class 2); \(c\) – with edge thickening (class 3); \(d\) – concave profile with edge thickening (class 4).](image)

The best flatness indicators of the finished strips are achieved by a cold rolling of the hot-rolled strips, having the convex parabolic profiles of its cross-section (Figure 3, \(a\)). The cross-section profiles, characterized by a peak-shaped convex of their middle part (Figure 3, \(b\)), lead to the appearance of a central bulge. The saddle-shaped (Figure 3, \(c\)) and (or) concave (Figure 3, \(d\)) profile’s shape of the hot-rolled rolling causes an edge undulation in the cold-rolled strip.

For the hot-rolled strips with the cross-section profiles of classes \(b\), \(c\) and \(d\), it is necessary to adjust the cold rolling modes to ensure the given flatness. Thus, there is a necessity to supplement the known
parameters of the cross-section profile of the hot-rolled strips with a new parameter, describing its class.

5. Conclusions
Analysis of existing geometric parameters of the cross-section profile of the hot-rolled strips has shown that in some cases it is almost impossible to make a prediction of the flatness of the cold-rolled strips. The features of the cross-section profile of the hot-rolled strips make it necessary to take into account the shape of the contour of their cross-section’s profile.

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