Statistical Regression Analysis of Breakages in Cold Rolling

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Abstract: The maximum probability of strip’s breakage during the cold rolling is observed when the values of edge wedge are greater than 150 microns and the saddle coefficient is less than −0.075 and greater than 0.050. It is also shown that there is a pronounced synergistic effect of influence of combination of the saddle coefficient and the edge wedge on the breakage of the strip. When the edge wedge is reduced below 50 microns, the saddle coefficient ceases to affect the breakage of the strip during the cold rolling. At the same time, when the edge wedge is higher than 160 microns, the breakage is minimal with the saddle coefficient in the range from 0 to 0.025.

1. Introduction
The strip breakage during processing on the continuous cold rolling mill leads to significant losses: unplanned downtime, associated with the elimination of the consequences of breaks, the increased consumption of metal of the working and support rolls due to the injuries.

One of the main reasons for the strips’ breaks during the rolling is the presence of the defects on the hot-rolled blank. These can be either the edge’s defects or defects in the shape of the cross-section profile of the hot-rolled strip. If the edge’s defects can be detected either visually or by the specialized automated surface quality control systems for the rolled strips, then the defects in the cross-section profile cause the strip to lose its flat shape during the subsequent cold rolling. In turn, the flatness of the cold-rolled strip leads to the need for the additional technological leveling operations [1–33], which increase the production cost.

2. Criteria for evaluation of defects of strip’s profile
To detect defects in the cross-section profile of a hot-rolled strip, a criterion for evaluating their criticality for the subsequent cold rolling is required.
In order to formalize the estimation of the parameters of the cross-section profile of the hot-rolled strips, their parabolic approximation is usually used [12] and such parameters as, for example, the convexity \( P \) and the wedge shape \( W \) are calculated (figure 1).

The parameters, that characterize the cross-section profile, include the determination coefficient:

\[
R^2 = 1 - \frac{\sum_j \left[ H_{wc}^j - f(x_j) \right]^2}{\sum_j \left[ H_{wc} - H_m \right]^2},
\]  

(1)

where \( R^2 \) is the coefficient of determination, \( H_{wc} \) is averaged across the width of the thickness of the strip, \( H_{wc} \) is the measured value of strip thickness at \( j \)-th point in width, \( x_j \) is the coordinate of the
measured point (the distance between the measured point of the profile and middle of the band), 
\[ f(x) = ax^2 + bx + c \] is the approximating parabola of the measured cross-sectional profile, whose 
coefficients are determined by least squares.

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

The determination coefficient of the cross-section profile is a value that characterizes the share 
of dispersion of the actual profile, that is due to its parabolic approximation; in other words, it 
shows how close the actual cross-section profile is to the parabolic approximation. Quite often, 
there are the cases when the cross-section profiles of the hot-rolled strips with different deviations 
from the approximating parabola have similar, and sometimes identical, values of the 
determination coefficient.

One of the alternative criteria, for evaluating the quality of the strip’s cross-section profile, to 
the determination coefficient is the saddle coefficient \( K_s \) [13]. This value is intended to 
characterize the cross-section profile with the edge thickenings.

The saddle coefficient, as well as the determination coefficient, characterizes the deviation of 
the real cross-section profile from the approximating parabola, describing an increase in the 
contribution to its value of deviations with an increase in the distance from the strip’s center to its 
edges:

\[
K_s = \frac{\sum_i \left[ H_{m_i} - f(x_i) \right] \cdot |x_i|}{\sum_i \left[ H_{m_i} - H_m \right] \cdot |x_i|}.
\] (2)

The integral character of the saddle coefficient allows us to characterize the stability of other 
parameters of the cross-section profile. For example, the deviation of the saddle coefficient from 
zero is associated with an increase in the mean square deviation of the convexity of the cross-
section profile. This important feature of the saddle coefficient allows you to reduce the number 
of factors and thus to simplify the regression mathematical model.

Another parameter for the quality of the cross-section profile of the strip is the value of the 
edge-boundary wedge \( W_m \), which characterizes the difference in thickness within 40 mm from the 
edge of the strip.

3. Model for predicting the probability of strip’s break

We apply the above parameters of the strip’s cross-section profile in probability forecast model of 
breakage at the cold rolling.

Based on the results of experiments, we obtain the following binary logistic regression [23] of 
the forecast probability of breakage as a function of the saddle coefficient and the edge-boundary 
wedge:


\[ P_{\text{break}} = \frac{e^Y}{1 + e^Y}, \quad (3) \]

\[ Y = -3.402 - 6.91 K_s + 0.0282 W_r - 411 K_s^2 - 0.000429 W_r^2 - 0.0483 K_s W_r + \]
\[ + 4093 K_s^3 + 0.000002 W_r^3 + 4.13 K_s^2 W_r + 56866 K_s^4, \quad (4) \]

where \( P_{\text{break}} \) is the probability of strip’s break.

The presented model has the adequacy property, since: first, the model explains half of all breaks in the cold rolling mill (the determination coefficient of the obtained regression model is \( R_m^2 = 48.9 \% \)); secondly, the acceptable accuracy of the regression model is provided by a small number of the significant factors, since the value of the adjusted determination coefficient (\( R_{m, \text{adj}}^2 = 43.1 \% \)) is comparable to the value of the determination coefficient (48.9\%) [24].

The determination coefficient of model is calculated using the formula:

\[ R_m^2 = 1 - \frac{\sum (P_{\text{fact}}^j - P_{\text{break}}^j)^2}{\sum (P_{\text{fact}}^j - P_{\text{fact}})^2}. \quad (5) \]

The adjusted determination coefficient is calculated as follows:

\[ R_{m, \text{adj}}^2 = 1 - (1 - R_m^2) \frac{n-1}{n-k}, \quad (6) \]

where \( P_{\text{break}}^j \) is the probability of breakage of the \( j \)-strip in model, \( P_{\text{fact}}^j \) is the indication of breakage of the \( j \)-th strip (0 – no break, 1 – break), \( P_{\text{fact}} \) is the share strips with the breaks from the total number of analyzed strips, \( n \) is the total number of analyzed strips, \( k \) is number of factors in the regression model.

These properties allow us to use the developed regression model in the technological process to predict the probability of strip’s breakage during the cold rolling.

![Figure 2](image)

**Figure 2.** Dependence of probability of strip breakage on saddle coefficient of the maximum and minimum values of edge wedge.
4. Statistical testing of hypotheses
To analyze the significance of factors in the regression model, we use the method of statistical hypothesis testing [25]. Null hypothesis: the factor does not have a significant impact. An alternative hypothesis: the analyzed factor in the regression model has a significant impact on the probability of breakage during the cold rolling of the hot-rolled strip. The $P$-criterion is the probability that the null hypothesis is correct. We accept that the null hypothesis is rejected, when the $P$-criterion is less than 0.05. The sense of the $P$-criterion is the probability that the regression model is the result of coincidence of the random fluctuations of factors and has no the real physical regularities:

$$P_{value} = p_1 + p_2,$$

(7)

where $P_{value}$ is the $P$-criterion, $p_1$ is the probability that the average of the first sample is part of the second sample, $p_2$ is the probability that the average of the second sample is part of the first sample.

5. Conclusions
The parameters of the cross-section profile of the hot-rolled strip (the saddle coefficient and the edge wedge) can be used to predict the probability of the strip’s breakage during the cold rolling. At the values of the edge wedge below 50 microns, the probability of breaking the hot-rolled strip during the cold rolling is significantly reduced (see figure 2). At the values of the saddle coefficient in the range from 0 to 0.025, the probability of breakage of the hot-rolled strip during the cold rolling is significantly reduced.

The breakage of the hot-rolled strip during the cold rolling is influenced by the saddle coefficient and the edge wedge in an interrelation to each other. The maximum probability of breakage is observed when the edge wedge values are greater than 150 microns and the saddle coefficient is less than $-0.075$ and greater than $0.050$.

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