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Metal Flow and Defect Development in Rough Rolling on a Universal Rail Mill

A. A. Umanskii[a], *, A. B. Yur'ev[a], **, and L. V. Dumova[a], ***

[a] *Siberian State Industrial University, Novokuznetsk, Russia*

**e- mail: umanskii@bk.ru*

***e- mail: rector@sibsiu.ru*

****e- mail: doumova@bk.ru*

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Abstract—The metal flow and rolling of billet defects in the roughing stands of a universal rail mill are analyzed on a laboratory system. For box grooves and grooves of trapezium and horizontal trapezium types, the extension of the surface layers is found to be nonuniform in terms of width and length. Likewise, the extension in rolling is nonuniform over the billet cross section. In deformation, the extension is greatest in surface zones adjacent to the end of the billet. The nonuniformity of the extension over the cross section depends on the dimensional ratio (shape) of the deformation zone according to a power law. The removal of surface defects depends significantly on the extension and also on the configuration and orientation of the defects. The defect dimensions have no significant influence on their ease of erasure. Defects in the direction of rolling at the edges of the billet are most thoroughly eliminated (in terms of depth and width), while transverse defects are least effectively removed. With increase in the extension, any defect will be more thoroughly removed. Close to the lateral edges of the billet, the width (aperture) of transverse and inclined defects is increased. Longitudinal defects are further opened on the end sections of the billet. Analogously to surface defects, internal defects are more effectively removed as the extension increases. The degree to which they are removed is less than for surface defects. Defects in the middle of the sampler are least affected by rolling. The degree of their removal is inversely proportional to the distance from the surface. Regression equations may be written for the influence of the position and orientation of the defects and the extension in rolling on the degree of removal of internal and surface defects. They may be used in practice to predict the quality of the final product with variation in the rolling conditions.

Keywords: billet defects, defect modification, rollers, grooves, universal rail mill, roughing stands, deformation, metal flow

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INTRODUCTION

In rolling, the product quality must correspond to the stand requirements, including those relating to surface and internal defects. Research has shown that optimal rolling conditions not only minimize the risk of defects in deformation but also facilitate the removal of defects at the surface of the initial billet [1–5] and improve the elimination of internal pores and cavities [6–16].

Analysis of these results indicates that the ease of defect elimination depends on numerous parameters, including the total reduction in rolling; the dimensions of the grooves employed; the number of times the workpiece is tipped in rolling; and the configuration, orientation, shape, and dimensions of the initial defects. The information regarding the influence of these factors on the formation and erasure of defects is often contradictory. For example, defect removal is better when using groove systems that alternate 45° and 90° tipping, according to [2]; however, a system of rhombus–square grooves with 90° tipping after each pass is recommended for defect removal in [3].

Note that there has been practically no research on defect removal in universal rail mills; a few studies relate to linear rail mills [17–19].

In rail mills, despite the complex rail cross section, the initial stage of deformation includes numerous passes in simple groves (box grooves). This may be attributed to the considerable dimensions of the billet cross section, which, in turn, is associated with the need for deep processing of the metal so as to improve its internal structure. (Total reduction of at least 9.5 is recommended [20].)

The standard procedure for rail production in universal rail mills (Fig. 1) calls for six out of the total 15 passes in box grooves [21–23]. The deformation in such grooves is considerable. After rolling in box grooves, the remainder of the process employs trape-

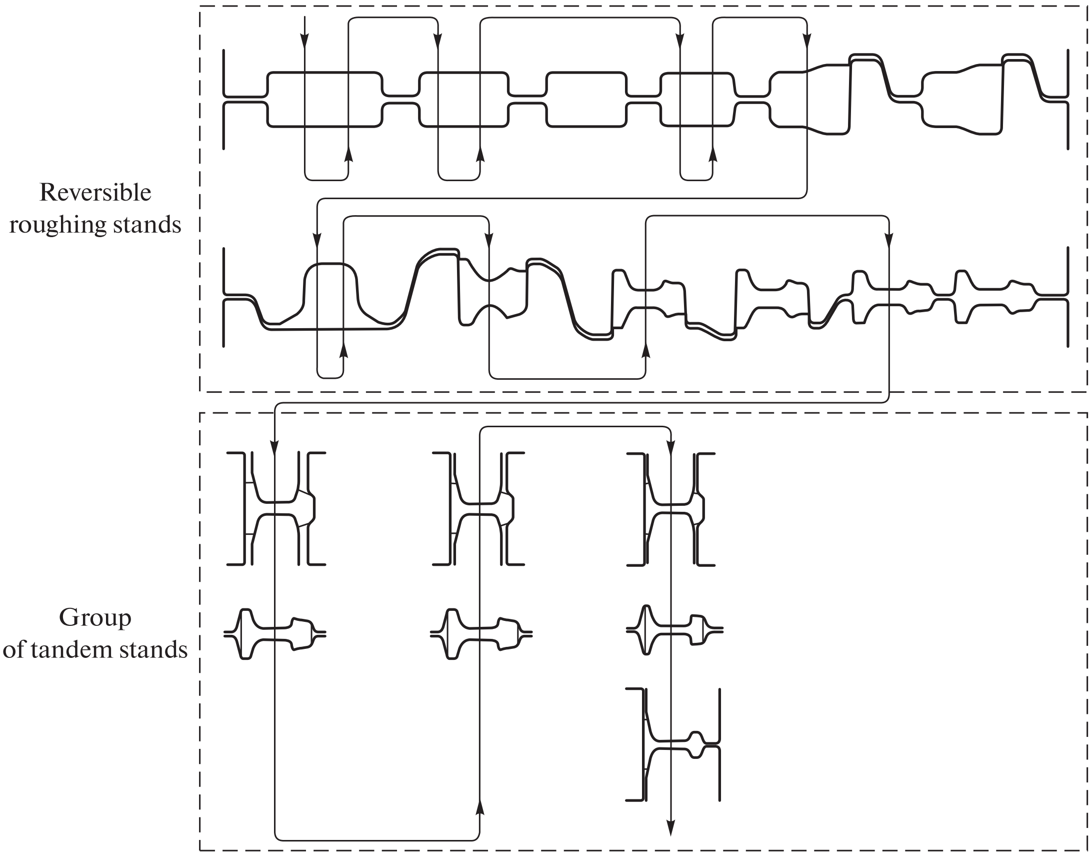

Fig. 1. Standard groove configuration for a universal rail mill.

zium grooves and horizontal trapezium grooves, which basically ensure transition to the rail configuration [24]. About three passes are recommended for such grooves; again, the deformation is considerable. Then the billet is rolled in the rail grooves of the roughing standards (three passes), and subsequently transferred to the continuous group of universal stands (tandem mill), where three passes take care of the final shaping [25, 26]. In the rail grooves of the roughing stands and the universal grooves of the tandem mill, the reduction is considerably less than in simple grooves. From this perspective, it is important to optimize the deformation in the first grooves, as confirmed in [17–19].

There is a pressing need to study the transformation of surface and internal billet defects in the initial stages of rail rolling.

EXPERIMENTAL METHOD

We use a Duo-80 laboratory rolling mill to investigate the metal flow and the modification of the defects in box grooves and grooves of trapezium and horizontal trapezium types. We consider lead samples. Their cross section (30 × 36 mm) corresponds in a 1 : 10 ratio to the dimensions of continuous-cast billet used in rail production on the universal rail mill at EVRAZ ZSMK.

Lead is chosen because its plastic properties at room temperature are similar to those of steel at the hot-rolling temperatures. Note that, although lead is not a multicomponent alloy, in contrast to steel, its use in determining the general laws of metal flow in rolling (including the associated defect modification) yields results applicable to the industrial production of steel profiles on existing mills, as confirmed by extensive research [2, 4].

To investigate metal flow, we use samples cut into equal sections along the longitudinal axis. A coordinate grid with 5- and 2-mm increments is applied to its faces. These sections are then attached by means of Wood's metal.

To determine the laws describing the transformation of surface defects in rolling, we use samples to which defects have previously been applied: cracks of depth 1.0 and 1.5 mm and width 0.5 and 1.0 mm with different orientations to the rolling axis (longitudinal, transverse, and inclined at 15°, 30°, and 45°). The defects are at different distances from the edges of the billet and its ends. The modification of the internal defects is investigated on samples in which holes (diameter 1.0 and 1.5 mm) have preliminarily been made; the holes are oriented along the rolling axis and at different distances from the sample surface and its lateral faces.

The samples are rolled in three box grooves and grooves of trapezium and horizontal trapezium types, simulating the grooves in the roughing cells of the universal rail mill at EVRAZ ZSMK, to a scale of 1 : 10. The deformation varies, with relative strain in the range 0.05–0.25. This range covers (with a slight safety margin) the actual variation in the deformation for rolling in such grooves (0.07–0.21) on industrial and universal rail mills.

In the experiment, we investigate the influence of the following parameters on the defect modification in rolling: the defect position (distance from the edges of the billet and the ends for surface defects; and the distance from the surface and the lateral faces for internal defects); the defect dimensions; its orientation relative to the rolling axis (for surface defects); and the reduction.

To assess the removal of surface defects, we introduce the corresponding ratios

$$K_H = \frac{H_0}{H_1}; \tag{1}$$

$$K_B = \frac{B_0}{B_1}, \tag{2}$$

where H_0 and H_1 are the defect depths before and after rolling; and B_0 and B_1 are the defect widths before and after rolling.

The removal of internal defects is assessed by the ratio

$$K_{\text{int}} = \frac{S_{\text{d}(0)}}{S_{\text{d}(1)}}, \tag{3}$$

where $S_{\text{d}(0)}$ and $S_{\text{d}(1)}$ are the defect areas before and after rolling.

RESULTS AND DISCUSSION

In the experiments on metal in box grooves with an applied coordinate grid on the samples, we find that the extension of the surface layers in contact with the rollers varies nonuniformly over the sample length and width (Fig. 2a). The deformation is greatest in the zone adjacent to the end of the billet. In particular, considerable motion is seen in the section near the rear end of the billet.

We may explain this nonuniformity in that the deformation in the sections of surface near the end of the billet is not restrained by adjacent zones. In addition, the extension at the rear end of the billet is greater than at the front end on account of the different flow rates in and opposed to the direction of metal motion.

Note that the length of the sections with the greatest longitudinal deformation of the surface layers is about 15% of the sample length after rolling. In these sections, the reduction is greater at the center of the sample than at the lateral edges and is distributed symmetrically with respect to the vertical groove axis. The nonuniform distribution of the longitudinal reduction over the width of the surface layer is explained in that,

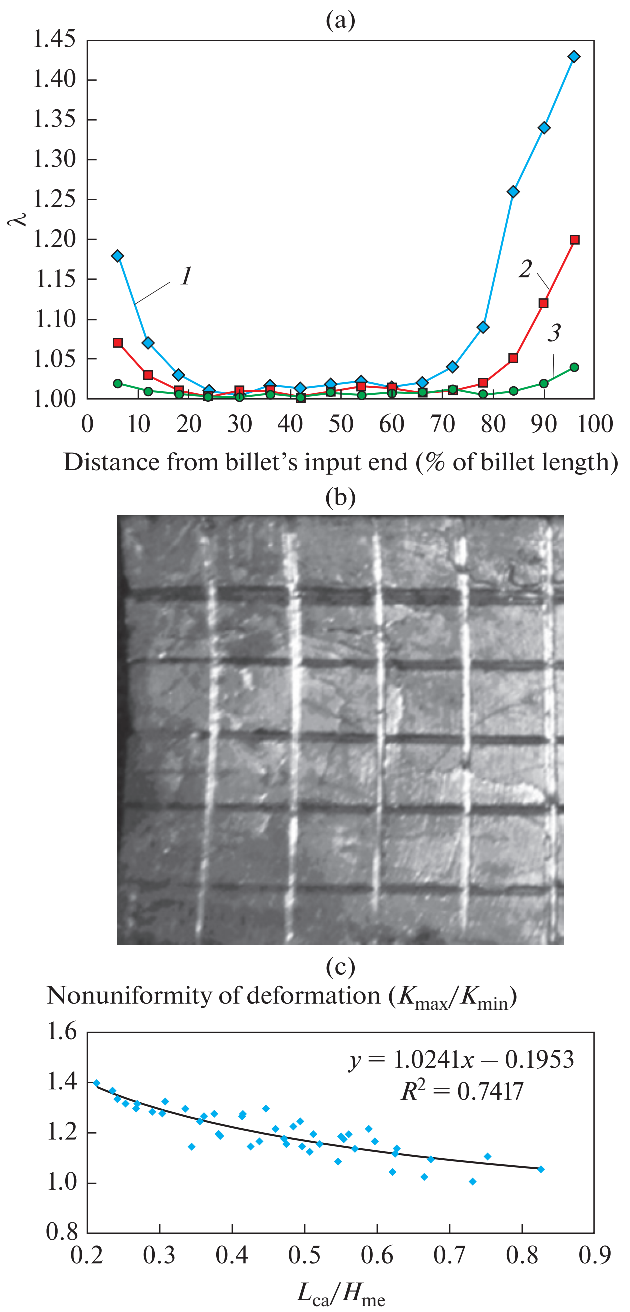

Fig. 2. Metal flow on rolling in box grooves of the roughing stands in a universal rail mill: (a) distribution of the extension λ within the billet; (b) shape of the billet end after deformation; (c) dependence of the nonuniformity of the deformation over the billet cross section on the shape of the deformation zone (its dimensional ratio L_{ca}/h_{me}): (*1*, *2*) surface layer at center and at lateral edge, respectively; (*3*) axial layer.

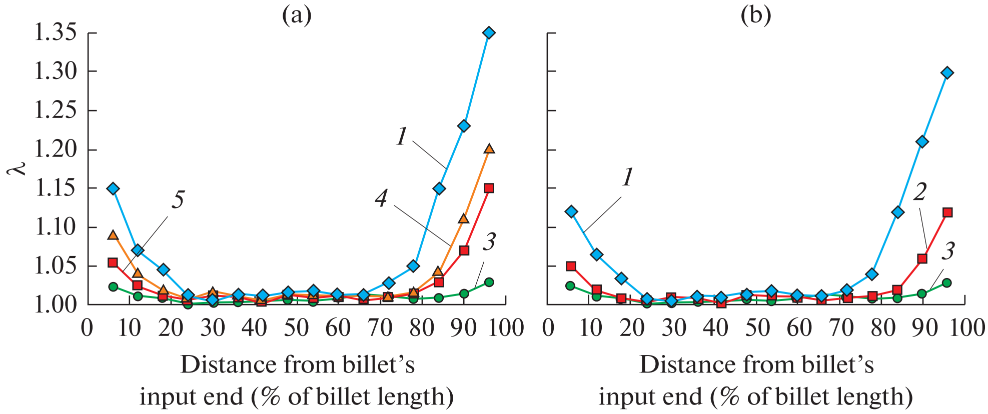

Fig. 3. Distribution of the extension λ within the billet on rolling in horizontal trapezium grooves (a) and trapezium grooves (b) in the roughing stands of a universal rail mill: (*1*) surface layer at center; (*2*, *4*, *5*) surface layer at lateral edges, floor, and roof; (*3*) axial layer.

close to the lateral edges, some of the metal is involved in sample expansion, since transverse flow is energetically preferable to longitudinal flow.

The reduction of the surface layers considerably exceeds that of the axial layers. Consequently, the ends of the sample after deformation deviate considerably from flatness (Fig. 2b). The distribution of the reduction over the billet cross section is largely determined by the shape of the deformation zone: that is, the ratio L_{ca}/h_{me}, where L_{ca} is the length of the capture arc; and h_{me} is the mean strip height before and after rolling (Fig. 2c). The dependence of the nonuniformity in the deformation on the ratio L_{ca}/h_{me} corresponds to a power law.

The results may be explained in terms of the change in the strain of different layers as a function of the ratio L_{ca}/h_{me} (the shape of the deformation zone). The penetration depth of the deformation and its relative value in the axial zone increase with increase in L_{ca}/h_{me}. When $L_{ca}/h_{me} < 0.3$, the axial zone does not undergo plastic deformation (but only elastic deformation). As a result, there is practically no longitudinal strain in the axial zone after rolling. When $L_{ca}/h_{me} = 0.3–0.5$, the axial zone undergoes forced plastic deformation (extension). However, the deformation in this case does not cover the entire billet; as a result, the changes are considerably less in the axial layers than in the surface layers. When $L_{ca}/h_{me} = 0.5–1.5$, the deformation penetrates over the whole depth of the billet, but, as before, is more intense in the surface layers than in the axial zone. Uniform deformation in the axial and surface layers is seen when $L_{ca}/h_{me} = 1.5$. At larger values, the axial layers are deformed more intensely than the surface layers.

In the experiments, L_{ca}/h_{me} = 0.21–0.83. That explains why the extension/reduction is greater at the surface layer than in the axial layer in all cases.

The metal flow when rolling in a groove of horizontal trapezium type is generally analogous to that for a box groove, except the distribution of the deformation over the faces in contact with the rollers. That may be attributed to the asymmetry of the horizontal trapezium groove with respect to the vertical axis, in contrast to the box groove. Correspondingly, the deformation is nonuniform over the billet width. As we see in Fig. 3a, for a horizontal trapezium groove, the extension of the surface layers within the groove corresponding to the future base of the profile (the right side of the groove in Fig. 1) is less than that at the point where the future roof of the profile is formed (left side in Fig. 1).

For a groove of trapezium type, no nonuniformity of the deformation in the surface layers is seen over the width of the contact faces (Fig. 3b). That may be attributed to the symmetry groove with respect to the vertical axis and the symmetry of the billet entering the groove.

Turning to the removal of defects, we find that the decrease in defect size on rolling is significantly determined by the position and orientation of the defects, for all types of grooves.

It is universally the case that the removal of longitudinal defects is greatest, while the removal of defects transverse to the rolling axis is least (Figs. 4a and 4b); this is especially true of the change in defect width (Fig. 4b). The explanation is that, with constraints on the billet broadening in the grooves, the longitudinal extension is greater than the transverse extension. This interpretation is confirmed by the opening of transverse and inclined defects observed close to the lateral edges of the billet (Fig. 4c). The defects inclined to the rolling axis are intermediate in terms of their ease of removal. In quantitative terms, the difference in the degree of defect removal is small.

We also find that the decrease in depth of longitudinal defects at the edges of the billet is 1.04–

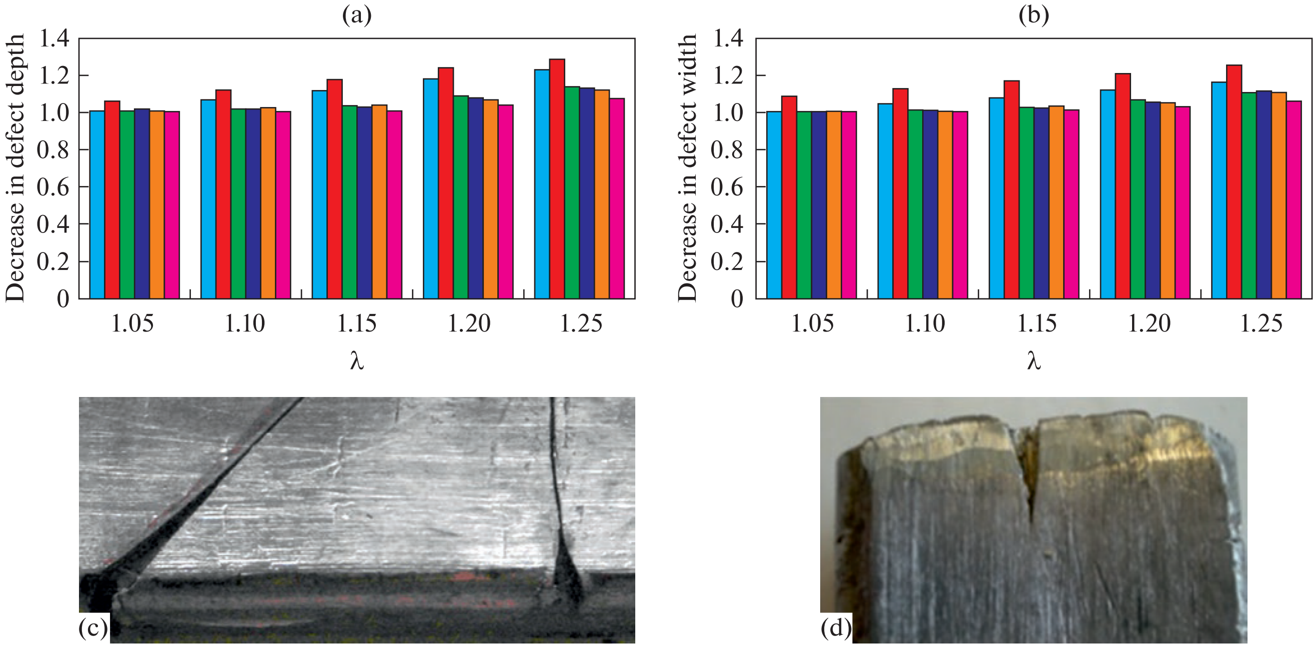

Fig. 4. Removal of billet's surface defects in box grooves and grooves of trapezium and horizontal trapezium type for the roughing stands in a universal rail mill: (a) decrease in defect depth; (b) decrease in defect width; (c) closing of inclined and transverse defects close to the lateral edge after rolling; (d) closure of longitudinal defect close to end of billet after rolling. Types of defects: longitudinal defects at the center ( ) and lateral edges ( ); defects inclined at 15° ( ), 30° ( ), and 45° ( )); and transverse defects ( ).

1.09 times that for defects in the center of the face in contact with the rollers (Fig. 4a). That is consistent with the laboratory results in [27] and the industrial data in [28, 29]. The explanation is that the stress–strain state of the metal in the surface zone close to the groove's vertical axis is less favorable [30]. The degree of defect removal does not seem to depend on the distance from the vertical axis; that may be attributed to the considerable width of the zone with an unfavorable stress–strain state, which covers around 70% of the width for box groves [30]. As a result, more favorable conditions for defect erasure are only created in the immediate vicinity of the groove's lateral faces.

The decrease in defect width is not significantly different for longitudinal defects at the center of the billet's contact face and at its edge (Fig. 4b). Note that, near the ends of the billet, the defects open. (In other words, their width increases.) This is obviously due to the absence of external constraints for such zones (Fig. 4d).

With increase in the extension in rolling, the removal of defects is better, regardless of their position and orientation, except in the case of defects close to the end of lateral edges of the billet (when opening of the defects is observed). The influence of the strain on the defect removal is linear.

Analysis of the results indicates that the initial depth and width of surface defects within the given range (depth 1.0–1.5 mm, width 0.5–1.0 mm) has no considerable influence on their removal. This is because, even with minimal L_{ca}/h_{me}, the penetration depth of the deformation greatly exceeds the defect depth. The modeling results indicate that the penetration depth is around 30% of the sample before rolling.

Analysis of the experimental data yields multiple regression equations between the strain when rolling in box grooves (no less than 1.05) and the degree of defect removal for surface defects:

— for longitudinal defects in the center of the billet face

$$K_H = 1.102\lambda - 0.143; \quad K_B = 0.781\lambda + 0.189; \qquad (3)$$

— for longitudinal defects close to the billet's lateral edges

$$K_H = 1.161\lambda - 0.156; \quad K_B = 0.839\lambda + 0.206; \qquad (4)$$

— for defects inclined at 15°–45° to the rolling axis

$$K_H = 0.589\lambda + 0.388; \quad K_B = 0.516\lambda + 0.461; \qquad (5)$$

— for defects perpendicular to rolling (transverse defects)

$$K_H = 0.371\lambda + 0.613; \quad K_B = 0.302\lambda + 0.685. \qquad (6)$$

Here λ is the degree of extension (strain).

The influence of λ and the initial dimensions of the internal defects on their removal is analogous: increase in λ is associated with greater defect removal, while the defect size has no significant influence. In studying the influence of the position on the removal of internal defects, we find that the degree of removal declines linearly on moving from the surface to the center of the sample (Fig. 4). As already shown, that is associated with nonuniform deformation over the billet cross section. (The surface layers are deformed more intensely than central layers.) Note also that the absolute degree of removal of internal defects is markedly lower than that of surface defects. That may also be attributed to nonuniform deformation over the billet cross section. The regression equation relating the degree of removal of internal defects to their position and λ (when λ is no less than 1.05) takes the form

$$K_{\text{int}} = 0.329 + 0.703\lambda - 0.13\frac{h_{\text{de}}}{h_0}.$$

Here h_{de} is the distance from the surface along the longitudinal axis of the defect, mm; and h_0 is the strip height before deformation, mm.

CONCLUSIONS

We have studied the deformation in the initial stage of rail rolling on a laboratory system.

Considerable nonuniformity is seen in the extension of the surface layers over the billet length and width and also over the billet cross section: the deformation is greatest in surface zones adjacent to the ends of the billet. A power law may be used to describe how the nonuniformity in the deformation over the billet cross section depends on the shape of the deformation zone (its dimensional ratio).

The removal of surface defects depends significantly on the deformation per pass and also on the configuration and orientation of the defects. Defects in the direction of rolling at the edges of the billet are most thoroughly eliminated (in terms of depth and width), while transverse defects are least effectively removed. With increase in the deformation, any defect will be more thoroughly removed.

The degree to which internal defects are removed depends on their position: it is inversely proportional to the distance from the surface. Increase in the strain increases the ease of removal of the defects, regardless of their position.

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