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Analysis of strip edge cracks during cold rolling of thin strip

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Abstract: In this paper, the mechanics of strip edge cracks and its propagation has been studied, and the effects of strip edge drop and stress intensity factor (SIF) on edge crack defections during cold rolling of thin strip have been discussed. An experimental investigation was presented into the effect of strip edge drop on edge cracks during cold rolling of thin strip. The edge crack increases significantly due to more inhomogeneous deformation and work hardening at the strip edge. The effective stress intensity factor range is important as it represents the major physical cause of the crack propagation. The efficiency and reliability of the SIF analytical model has been demonstrated in the study. The proposed method for predicting strip edge crack is helpful in producing defect-free products and providing an understanding of the mechanics of edge crack propagation in cold rolling of thin strip.

Key words: strip edge crack; edge drop; mechanism; SIF; thin strip

1 Introduction

Cold rolling is one of the essential elements in the manufacturing of plate, and sheet products of steel and its alloys. One of the important problems in improving the quality of rolled strips is to ensure that the surface of the cold rolled product is free of defects. Edge cracking which formed mainly at the sides of a rolled product is a commonly observed phenomenon in the cold rolling process. Subsequent edge trimming of the cracked material leads to significant productivity loss. A method of dealing with these defects is of considerable interest because the cost to industry in terms of lost time and materials is essentially proportional to percentage of materials being rejected. The evolution of edge cracking during rolling is complicated, depending on rolling conditions, and mechanical properties of the rolled strip. It is necessary to provide sufficient information about the edge crack mechanisms relevant to the rolling process.

Researchers have carried out some studies on crack propagation. Ervasti and Stahlberg[1] proposed the transversal cracks in the hot rolling of steel slabs. Thomson and Burman[2] reported edge cracking in hot-rolled Al-Mg alloys. The surface oxide fracture in cold aluminium rolling was also presented[3]. Dodd and Boddington[4] carried out the research on the causes of edge cracking in cold rolling. Tvergaar *et al.* [5] reported edge cracks in plastically deforming surface grains. Furthermore, stress intensity factor was introduced to crack research[6,7]. However, there were few reports about the edge crack during cold rolling of thin strip, especially with stress intensity factor solution (SIF). The SIF characterizes the crack tip condition, and its concept has been proven to be an effective tool for crack growth analysis.

For thin strip rolling, the edge crack is a key issue the researchers and manufacturers concern. Sutcliffe *et al.* [8,9] developed a model for thin strip and foil rolling, and carried out the experimental measurements of load and strip profile during thin strip rolling. Jiang *et al.* [10,11] reported the research on mechanics of roll edge contact and analysis of cold rolling on thin strip. Liu and Lee[12] proposed the mathematical model with influence function method for thin strip rolling and temper rolling process. Gratacos *et al.* [13] and Farzin *et al.* [14] used finite element models to analyze the strip rolling, and to improve the simulation accuracy of the strip shape and profile. Some researchers[15-17] carried out the study on friction and lubrication of cold rolling. For edge drop, Han *et al*[18] and Tateno *et al*[19] proposed some methods to control and reduce the edge drop in cold rolling. The edge drop on cold strip mill is a result of transverse material flow near the strip edge. The area of transverse material flow depends on the number of rolling passes as well as the total reduction. A great displacement will occur for these sections that move closer to the strip edge leading to thinning of the strip edge. Edge drop is one of the significant problems in cold rolling of steels. At present, there is not much work about the research on edge drop. For thinner strip, the edge drop identification and elimination have not been effectively identified.

In this study, the cause of edge crack formation in cold rolling is presented, and the simplified SIF solution is proposed to calculate the stress intensity factor around the edge crack tip during cold strip rolling. In order to determine the influences of rolling conditions on strip edge drop, an experimental simulation was carried out. The relationship between the strip edge drop and edge cracks is discussed. Mechanism and rolling parameters which affect the edge cracks are analysed.

2 Edge crack and SIF in cold strip rolling

2.1 Edge crack analysis

During cold rolling of thin strip, cracks initiate at grain boundaries after critical deformation due to inhomogeneous deformation and attendant large secondary tensile stresses. There are some causes which affect the formation and propagation of edge crack, including material ductility, inhomogeneous deformation with an uneven edge profile, and transverse variation of stresses. Edge cracking in cold rolling is firstly manifested as small cracks that may propagate across the strip in subsequent passes, and propagate through the areas where there is a concentration of high energy boundaries. The edge crack occurs when the longitudinal tensile stress at the strip edge, and the stress obtained from the stress-strain curve are equal at the same value of strain. Edge cracking in cold rolling has been attributed to secondary tensile stresses induced at the strip surfaces by inhomogeneous deformation. Fig. 1 (a) shows the thin strip rolling with edge cracks.

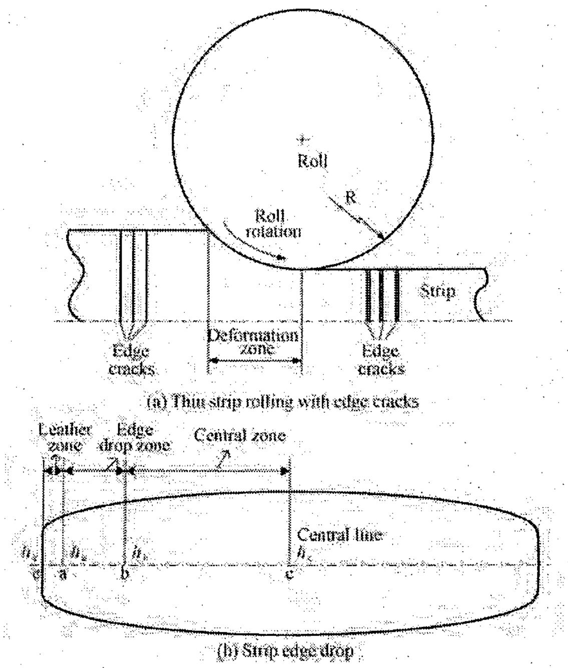


Fig. 1 Thin strip rolling with edge cracks (a) and strip edge drop (b)

The edge crack enters the deformation zone may become wide when the front edge of the crack moves into contact with the roll, and then the widened crack angle may decrease. The longitudinal stress in the crack develops as the crack approaches the deformation zone due to elastic stretching of the strip surface. The high hydrostatic pressure that is associated with the roll/strip contact surface. At the exit, the crack angle is slightly increased again. Because the back edge of the crack is still in contact with the roll, and its movement is retarded because of friction and the strip edge drop (Fig. 1(b)). As a result, the edge crack will be opening, closure and opening again.

The edge-crack specimen geometry is shown Fig. 2. As the strip is thin, and it can be taken as a plane stress state, $\sigma_z = 0, \tau_{xz} = \tau_{yz} = 0$, and $\sigma_x, \sigma_y, \tau_{xy}$ are applied on the sample planes. Under the normal stress, the crack tip is open, and the propagation direction is perpendicular to the stress as the applied stress is perpendicular to the crack plane. The maximum longitudinal stress in the rolled strip occurs during the contact of the roll and thin strip. The stress concentration around the strip edge significantly affects the edge crack extension and accelerates the edge crack propagation.

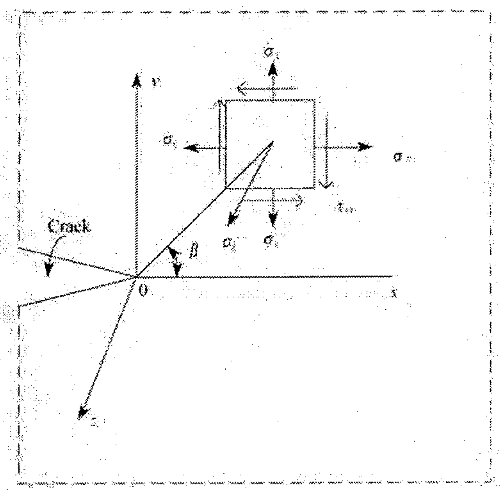


Fig. 2 Stress sketch near crack tip

2.2 Stress Intensity Factor (SIF)

The stress intensity factor (SIF) is a basis of the crack and describes the stress state at the crack tip. The stress intensity factor depends on the size and geometry of the crack, as well as the geometry of the component, the applied load and boundary conditions. The K-value was calculated by using Eq. (1) considering the finite specimen size correlation factor $Y(a/w)$, where a and w are the crack length and specimen width of the specimen, respectively.

$$K = Y(a/w)\sigma\sqrt{\pi a} \tag{1}$$

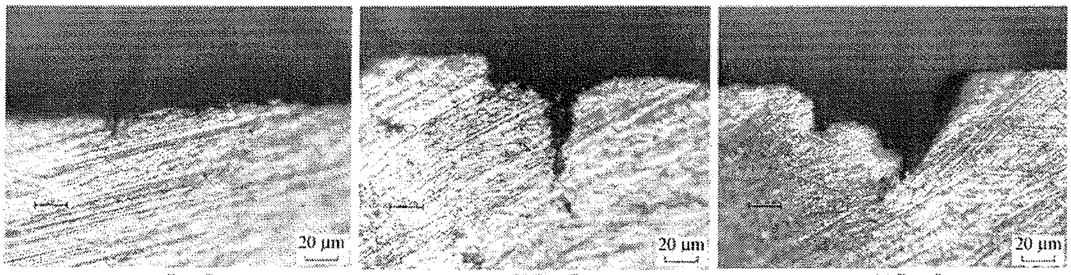
where $Y(a/w)$ is required to account for the geometry, stress distribution and boundary *conditions*, σ the nominal stress, a the crack depth, w the strip width. The geometric function obtained with the Boundary Collocation Method[20] can be shown as

$$Y = 1.988[0.026\,778(0.427\,103 + a/w)^{-2.738\,95} + 0.265\,14a/w + 0.724\,75]/\beta(1 - a/w)^{3/2} \quad (2)$$

where the thin strip is taken into account, and β is chosen as a ratio coefficient, $0 < \beta \leq 1$.

3 Results and discussion

During cold rolling of thin strip, the edge cracks occur with the rolling passes. Fig. 3 shows that the edge cracks of thin strip when the reduction (rolling passes) increases, in particular, the strip edge cracks increases significantly when the reduction is over 80%.



(a) Pass 5 (b) Pass 7 (c) Pass 9

Fig. 3 Effect of rolling passes on strip edge crack

3.1 Effect of strip edge drop on edge cracks

Research has found that the strip edge drop has an effect on edge cracks. In order to identify the effect, the rolling experiments were carried out. The diameters of the work roll and backup roll are 63 and 228 mm, respectively, and the roll barrel length of the work roll and backup roll is 254 mm. The initial crowns of the work roll and backup roll are zero. Oil lubricant was applied to the surface of the strip before rolling, and the low carbon steel was selected as a rolled material. In practical thin strip rolling, the upper and lower work rolls may have a local residual deformation beyond the edges of the strip if the strip is ultra thin, and there is no work roll bending system applied. The work roll edge contact force between the upper and lower work rolls will change with the rolling conditions and affect the work roll life[10]. In addition, the real contact area between two work-rolls changes with rolling conditions. Therefore, the research of edge drop is more complicated.

There are many factors affecting the strip edge drop, including the entry thickness, reduction, and resistance of deformation, front and back tension, and the bending force of the work roll. The strip edge drop can be controlled by changing the work roll crown, the work roll edge rigidity, and the pressure distribution on the work roll. It can be evaluated by the edge drop ratio ψ, as follows

$$\psi = \frac{h_b - h_a}{h_b} \times 100\% \quad (3)$$

where h_a and h_b are the strip thicknesses at distances a and b from the strip edge (Fig. 1 (b)), respectively. Normally, the values of a and b vary depending on the width of the cold rolled strip.

When the strip width is 100 mm, the effect of the strip thickness on the edge drop under certain reduction is shown in Fig. 4. It can be seen that the strip edge drop becomes larger with an increase of strip thickness. If the flow resistance decreases, the metal will flow to the centre. If the width is small, the edge drop becomes larger (Fig. 5). Edge drop is caused by elasticity deformation of roll system during cold rolling, and three dimensional deformation of metal. For thin strip rolling, the strip thickness is very thin, and the ratio of width and thickness is an important factor which influences the strip edge drop.

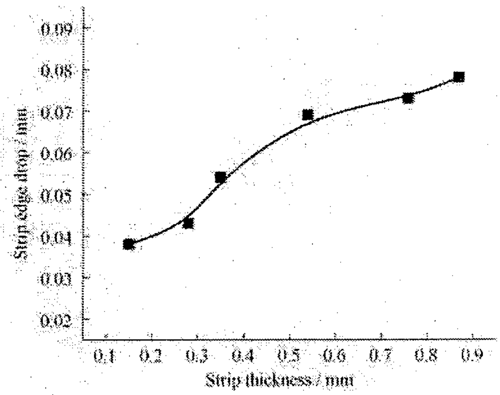


Fig. 4 Effect of strip thickness on edge drop

The coefficient of friction is reduced as the rolling speed and the reduction increase. At low reduction, all lubricants work well (and give similar friction). The friction coefficient along the strip width is not a constant due to the change along the strip width of operating parameters, *i. e.* the rolling force, reduction and rolling speed etc[10]. The transverse friction has significant influence on the rolling mechanics and strip shape and profile. For the variation of the transverse friction, the strip edge drop is significantly affected. Fig. 6 shows the effect of friction coefficient on strip edge drop. It can be seen that when the friction coefficient increases, the edge drop increases. Therefore, reducing friction coefficient is beneficial to reduce the edge drop, and to improve the productivity.

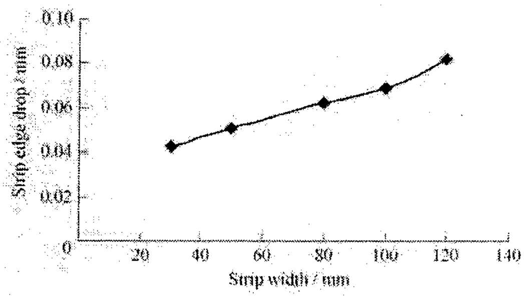


Fig. 5 Effect of strip width on edge drop

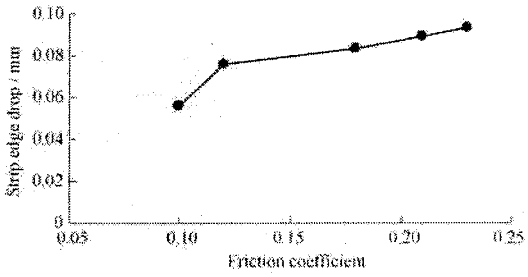


Fig. 6 Effect of friction coefficient on strip edge drop

Given in Fig. 7 is the effect of strip edge drop on edge cracks. It can be seen that the strip edge cracks increases with an increase of the edge drop, as well as the increase of edge cracks with reduction.

3.2 Effect of SIF on edge cracks

The SIF is determined in the study, and the solution is given for the evolution of the edge cracks during cold rolling of thin strip . The variation of geometric

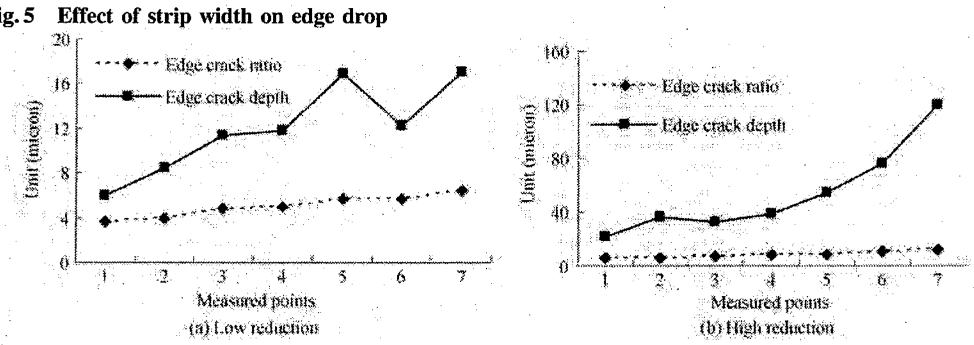


Fig. 7 Effect of strip edge drop on edge cracks

function Y with the edge crack depth is shown in Fig. 8. It can be seen that the value of geometric function Y increases with crack depth. The coefficient increases significantly when the edge crack depth reaches 5 mm. Fig. 9 shows the relationship between the SIF and crack growth. It can be seen that the crack growth increases with an increase of SIF. When the crack growth changes from 0.5 to 2.5 mm, the SIF increases from 43 MPa · $m^{1/2}$ to around 66 MPa · $m^{1/2}$. Therefore, the SIF can determine the strip edge crack propagation during cold rolling of thin strip.

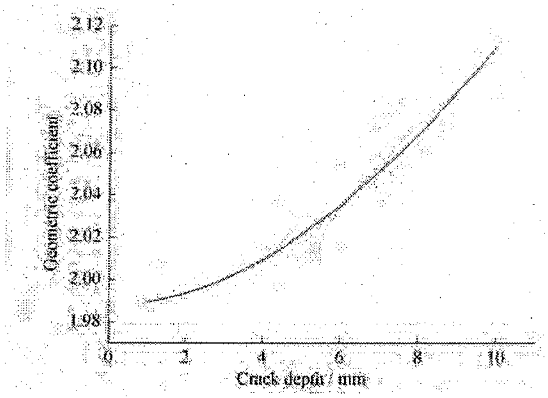


Fig. 8 Effect of crack depth on geometric function *Y*

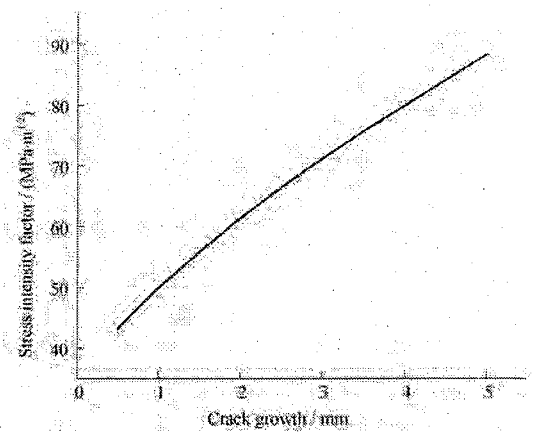


Fig. 9 Relationship between the crack propagation and SIF

4 Conclusions

The mechanics of strip edge cracks and its propagation have been studied, and the effects of strip edge drop and stress intensity factor (SIF) on edge crack defections during cold rolling of thin strip have been presented. With the increase of reduction, friction coefficient and strip entry thickness, the strip edge drop is significant. The edge drop reduces with low reduction, and it increases gradually with an increase of friction coefficient. The strip edge cracks increase with an increase of the strip edge drop. The edge crack increases significantly due to more inhomogeneous deformation and work hardening at strip edges. The geometric function value increases with the crack depth, and the crack growth increases with an increase of SIF. The presented approach for predicting edge cracks is helpful in producing defect-free products in thin strip rolling, and provides an understanding of the mechanism of edge crack propagation.

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