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Abstract
The behavior of transversal cracks on the surface of the slab corner during vertical and horizontal (V-H) rolling process with flat vertical roll and groove vertical roll was simulated by explicit dynamic finite element method. The closure and growth of crack and the contact pressure on surfaces of the crack in contacting zone between slab and roll during rolling process were analyzed. The results showed that during vertical rolling process, when the groove vertical roll is used, the maximum contact pressure on surfaces of the crack is 115 MPa, and the closure of crack is stable; when the flat vertical roll is used, the maximum contact pressure on surfaces of the crack is 70 MPa, and it fluctuates greatly. During horizontal rolling process, when groove vertical roll is used, the contact pressure becomes zero which may accelerate the growth of crack; when flat vertical roll is used, there is still contact pressure. The calculated results are in good agreement with the results of test. © 2006 Central Iron and Steel Research Institute.

Keywords
rolling, h, v, during, process, corner, behavior, slab, crack, transversal

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Behavior of Transversal Crack on Slab Corner During V-H Rolling Process

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Abstract: The behavior of transversal cracks on the surface of the slab corner during vertical and horizontal (V-H) rolling process with flat vertical roll and groove vertical roll was simulated by explicit dynamic finite element method. The closure and growth of crack and the contact pressure on surfaces of the crack in contacting zone between slab and roll during rolling process were analyzed. The results showed that during vertical rolling process, when the groove vertical roll is used, the maximum contact pressure on surfaces of the crack is 115 MPa, and the closure of crack is stable; when the flat vertical roll is used, the maximum contact pressure on surfaces of the crack is 70 MPa, and it fluctuates greatly. During horizontal rolling process, when groove vertical roll is used, the contact pressure becomes zero which may accelerate the growth of crack; when flat vertical roll is used, there is still contact pressure. The calculated results are in good agreement with the results of test.

Key words: slab; crack; V-H rolling process; FEM

V-H (vertical and horizontal) rolling process is often used to accomplish width reduction and width control during rough rolling process of hot slab, during which the transversal cracks may occur at the corner of some kinds of steel slabs (silicon steel, stainless steel, automobile sheet, and so on) under the influence of the casting slab quality and deformation conditions and so on. If the cracks aren't closed well during multi-pass V-H rolling process, they will grow during subsequent rolling process, which will heavily affect the quality and yield of the product. Analysis to the closure and growth of these kinds of transversal cracks during multi-pass V-H rolling process with the method of numerical simulation will be a significant way to display the regularity of the behavior of cracks, which will be helpful to control the quality of the product.

Researchers widely applied finite element method to resolve the problems that occur duing V-H rolling[1-5]. For example, an incremental visco-plastic model developed by David C et al[1] assumed a dog-bone shape as the function of friction; LIU Hui et al[2] analyzed the effect of edger share on the slab profile with explicit dynamic FEM; the whole V-H rolling process has also been studied by XIONG Shang-wu et al[3,4] and Chung W K et al[5], in which simulation was conducted during one pass without considering the effect of slab deformation of previous pass to next pass. However, there was no report about the research of behavior of the transversal cracks at the slab corner so far.

The main process of updating geometric method is using final configuration of previous pass V_t to take the place of the beginning configuration V_0, and subsequently taking that as beginning configuration of next pass V'_0 to conduct the following analysis, which proved that single pass rolling model is used to solve multi-pass rolling process.

In present study, the multi-pass V-H rolling process with flat vertical roll and groove vertical roll were respectively simulated by LS-DYNA. The closure and growth of the crack and the contact pressure of surfaces of crack in the deformation zone of vertical rolling and horizontal rolling were re-

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searched. Meanwhile, tests with lead have been done in laboratory, and the calculated results are in good agreement with the test results.

1 FEM Simulation

1.1 Computation conditions

The six passes [V_1-H_1-V_2-H_2-V_3-H_3 (V=vertical rolling; H=horizontal rolling)] of V-H rolling were simulated, and the specifications are as follows: (1) diameter of horizontal roll is 1 150 mm; (2) vertical roll of 980 mm in diameter employs flat vertical roll and groove vertical rolls respectively, and (3) the dimensions of the groove vertical roll are shown in Fig. 1. The deformation of rolls is neglected and the rolls are regarded as rigid. The dimension of initial profile of slab is 1 200 mm×250 mm. For the slab, bilinear isotropic hardening material model was adopted, and the main chemical composition of slab is (mass percent, %): C 0.18, Si 0.32, and Mn 0.82. The yield stress σ at high temperature is related to true strain ε, true strain rate $\dot{\varepsilon}$, and deformation temperature T. During this simulation, the yield stress is calculated by the Eqn. (1).

$$\sigma = A\varepsilon^{B}\dot{\varepsilon}^{CT+D}e^{FT} \quad (1)$$

where A, B, C, D, F are constant.

The transversal crack employs "V" shape crack, and one basic assumption is that the cracks do not propagate for the steel considered. The width of initial crack is 2 mm, and the depth on both the top surface and the side surface is 20 mm, as shown in Fig. 2. During the rolling process, the draft in vertical rolling in every pass is 50 mm, and the draft in horizontal rolling is 10 mm. The friction coefficient is 0.3.

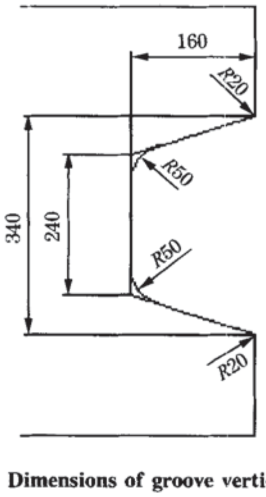


Fig. 1 Dimensions of groove vertical roll

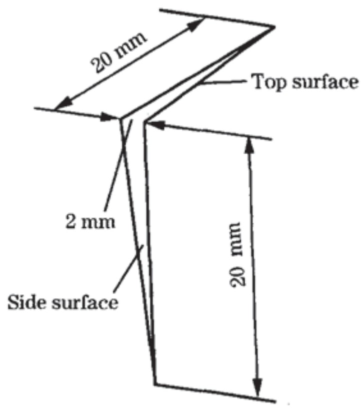


Fig. 2 Dimensions of "V" shape crack

1.2 Construction of model

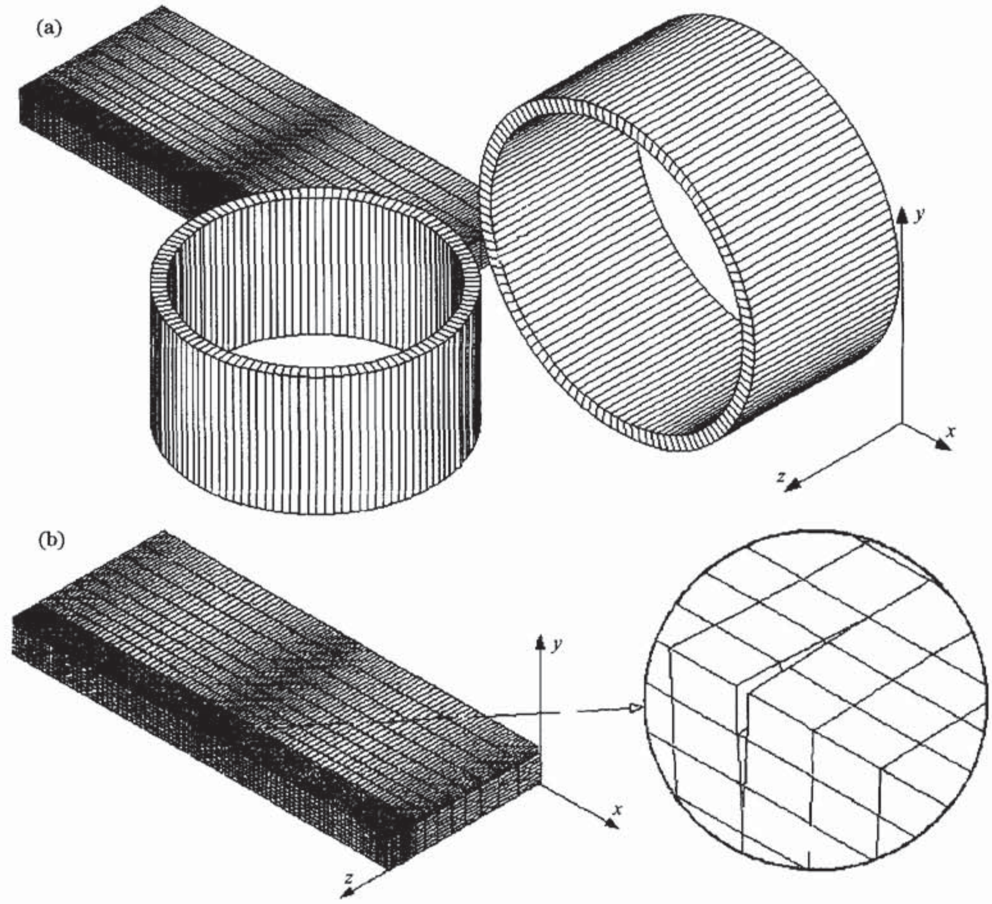
Owing to the symmetry of slab and rolls, 1/4 geometric model of slab and rolls are included in the simulation. It just refines the element near the slab margin where the deformation assembled. The whole model is dispersed with 8 nodes and hexahedral elements. The boundary conditions are as follows: the displacement of nodes on the bottom surface of the slab along y direction is zero, and the displacement of nodes on the center face of the slab along z direction is zero as well. The angular velocities of the vertical roll and the horizontal roll are invariable. The slab enters the vertical roll with an initial velocity which is a little less than the velocity of roll and exists on the horizontal roll under the frictional force. The meshing and geometric model of the V-H rolling process with flat vertical roll is shown in Fig. 3. At the same time, the rolling models of the second pass and the third pass were obtained by updating geometry, modifying material attribution, boundary conditions, and loads, which made the simulation of the rolling process continuous and true and saved the resource of computer.

2 Results and Discussion

2.1 FEM result analysis

During rolling process, self contact might occur on the surfaces of crack, for which contact pressure will consequently exist on the surfaces. It is of much significance to analyze the change of the contact pressure during rolling process while studying the regularity of the closure and growth of the crack.

Fig. 4 (a) shows the change regularity of contact pressure on the surfaces of the transversal crack



(a) V-H rolling model; (b) Slab with crack

Fig. 3 Geometric model and meshing

on the slab corner during vertical rolling when flat vertical roll is used in V-H rolling process. Fig. 4 (b) shows the distribution of σ_x along x direction in deformation zone during vertical rolling when flat vertical roll is used. It is clear that the contact pressure whose maximum value is 70 MPa has two big fluctuations when crack passes through the vertical roll, and at the slab corner, there are two tension stress zones along the contacting arc between the slab and the roll, which is consistent with the regularity of contact pressure. If the cracks aren't closed well, they may grow again under the influence of the tension stress. Meanwhile, at the exit of roll, there is compression stress which contributes to the crack closure and the contact pressure increase.

Fig. 5 (a) shows the change of contact pressure

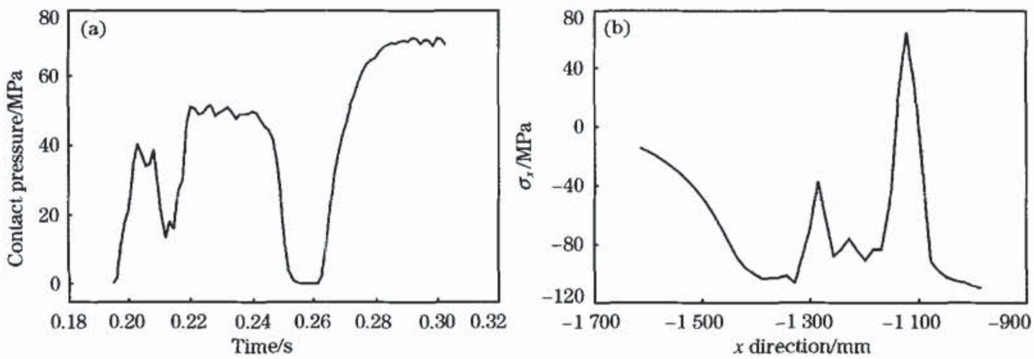


Fig. 4 Vertical rolling process using flat vertical roll

on the surfaces of the transversal crack on slab corner during vertical rolling when groove vertical roll is used during V-H rolling process. Fig. 5 (b) shows the distribution of σ_x along x direction in deformation zone during vertical rolling when groove vertical roll is used. It is clear that the contact pressure whose maximum value is 115 MPa is stable when the crack passes through the vertical roll, and the compression stress exists at the slab corner along the contacting arc between the slab and the roll which is consistent with the regularity of the contact pressure. Since tension stress doesn't exist in the contracting arc zone, the vertical rolling is helpful for the closure of the cracks when groove vertical roll is used.

Fig. 6 (a) shows the change of the contact pressure on the surfaces of the transversal crack on slab corner during horizontal rolling when flat vertical roll is used during V-H rolling process. Fig. 6 (b) shows the distribution of σ_x along x direction in deformation zone during horizontal rolling when flat vertical roll is used. It can be seen that the contact pressure whose value at the exit is 25 MPa has two big fluctuations when crack passes through the horizontal roll which is similar to Fig. 4. Furthermore, at the slab corner, there are two tension stress zones along the contacting arc between the slab and the roll which is consistent with the regularity of the contact pressure. For the presence of the tension stress, if the cracks don't close well, they may grow again. Meanwhile, at the exit of roll, there is compression stress which makes the crack close and also causes the contact pressure to increase.

Fig. 7 (a) shows the change of the contact pressure on the surfaces of the transversal crack on slab corner during horizontal rolling when groove vertical roll is used during V-H rolling process. Fig. 7 (b) shows the distribution of σ_x along x direction in deformation zone during horizontal rolling when groove vertical roll is used. It is obvious that the contact pressure becomes zero when crack passes through the horizontal roll, and at the slab corner, there is tension stress whose maximum value is 125 MPa along the contacting arc between slab and roll which

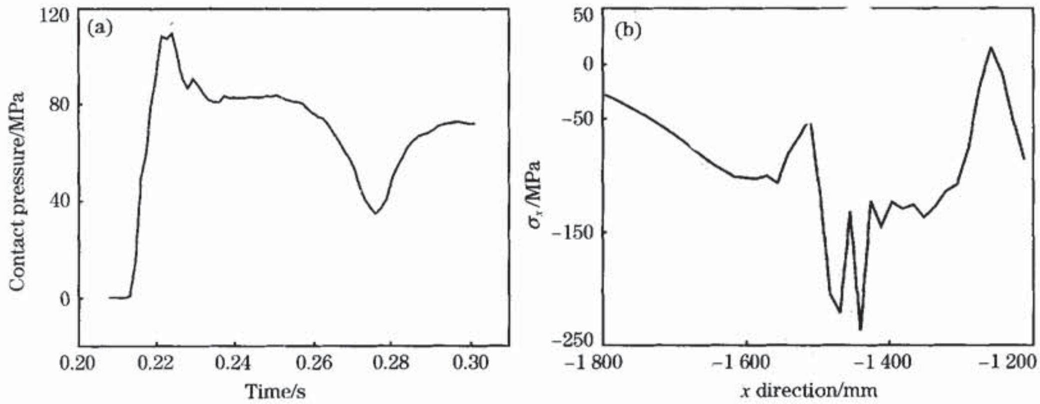


Fig. 5 Vertical rolling process using groove vertical roll

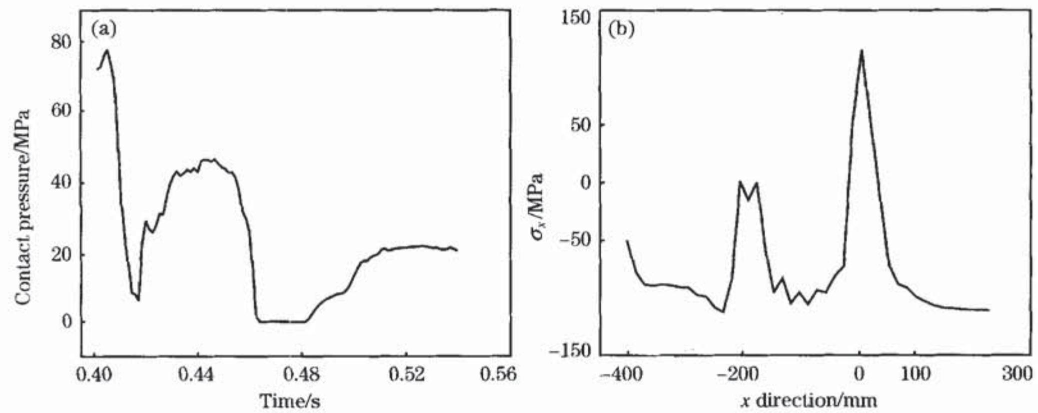


Fig. 6 Horizontal rolling process using flat vertical roll

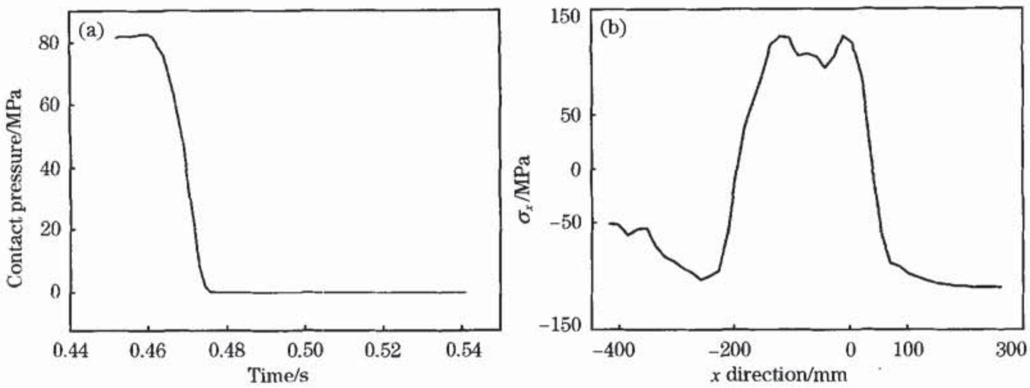


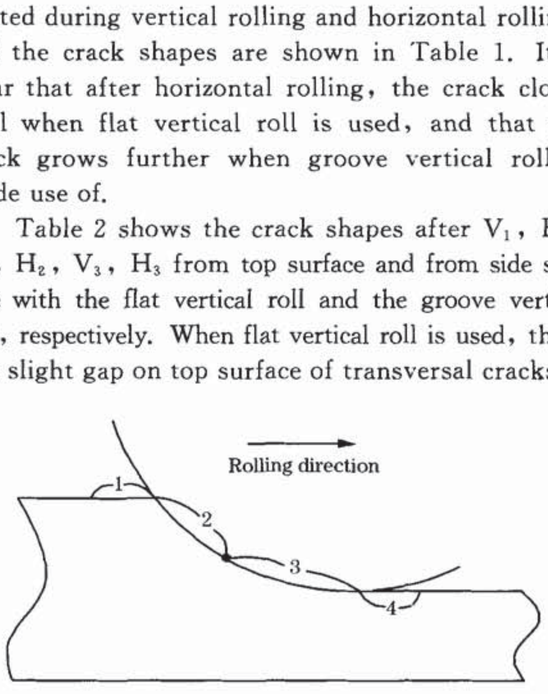
Fig. 7 Horizontal rolling process using groove vertical roll

is consistent with the regularity of the contact pressure. Due to the above-mentioned reason, the cracks may grow further during horizontal rolling if groove vertical roll is used.

It can be seen from above analysis that in the contacting zone between slab and roll, the closure and growth of crack may fluctuate greatly, from closure to growth, then to closure, then to growth and so on. The deformation zones may be divided into four parts, namely, entry, zone of slippage on the entry side, zone of slippage on the delivery side, and exit, as shown in Fig. 8.

Further research of crack deformation is conducted during vertical rolling and horizontal rolling, and the crack shapes are shown in Table 1. It is clear that after horizontal rolling, the crack closes well when flat vertical roll is used, and that the crack grows further when groove vertical roll is made use of.

Table 2 shows the crack shapes after V_1, H_1, V_2, H_2, V_3, H_3 from top surface and from side surface with the flat vertical roll and the groove vertical roll, respectively. When flat vertical roll is used, there is a slight gap on top surface of transversal cracks of



1—Entry; 2—Zone of slippage on entry side;
3—Zone of slippage on delivery side; 4—Exit

Fig. 8 Crack shape intercepting dislocation

slab corner, but it is closed well on side surface after vertical rolling. After horizontal rolling, slight openings may be seen on the side surface of the transversal cracks of slab corner surface, but closed well on the top surface. When groove vertical roll is used, the side surfaces of the crack on the surface of the slab corner close well but the top surface has little openings after vertical rolling. After horizontal rolling, the transversal crack on slab corner surface opens with different degrees, and at the same pass, the width of crack on side surface is bigger than that on top surface. It is observed that the crack is closed with the increase in rolling pass.

It can be observed that not only the flat vertical roll but also the groove vertical roll is helpful to the closure of crack on slab corner during vertical rolling. However, the deformation of cracks is different with the shape change of the vertical roll after horizontal rolling. It is further observed that the shape of the crack is not just from "V" shape to "Y" shape during V-H rolling process, and the whole crack has a slight leaning during the rolling process.

Results of further analysis of the transversal cracks on the surface of slab corner conducted are shown in Fig. 9. Fig. 9 (a) shows the change conditions of the slab crack width during multi-pass V-H rolling process, from which it can be found that the crack gradually closes with the increase in the rolling pass. Fig. 9 (b) shows the change conditions of the slab crack depth along y direction, from which it can be found that the crack depth is shortened with the usage of shape vertical roll and the crack depth is increased with the usage of plain-barreled vertical roll. Fig. 9 (c) shows the change conditions of the crack depth along z direction, from which the crack depth increase can be observed and can also be noted that the

Table 1 Crack shape during V_1 and H_1 rolling process

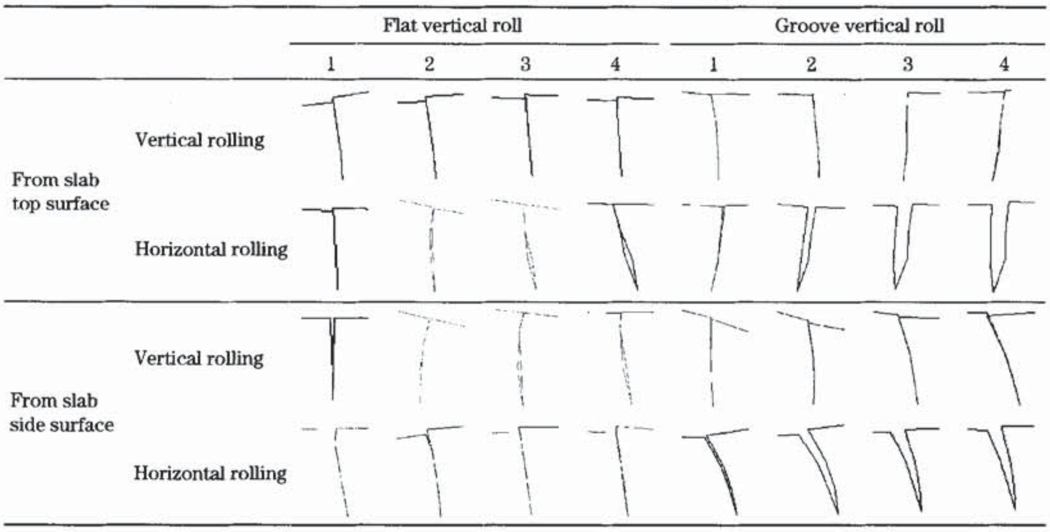
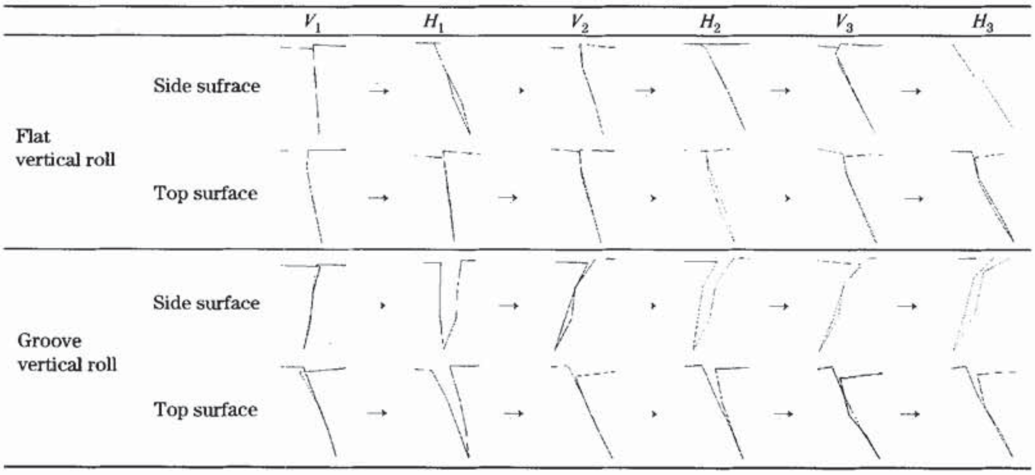


Table 2 Crack shape after V_1, H_1, V_2, H_2, V_3, H_3 by FEM results



Note: arrow shows the rolling direction.

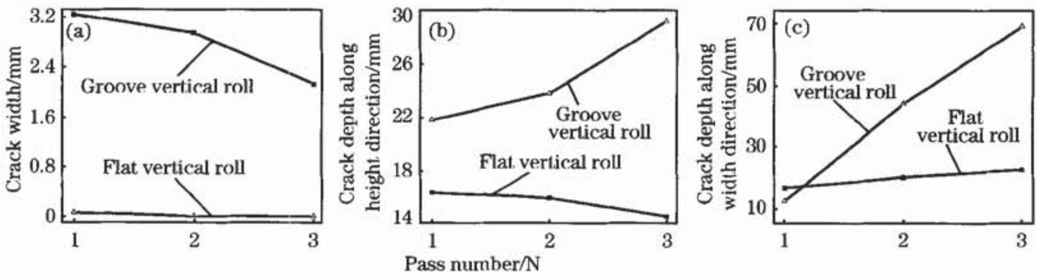


Fig. 9 Change of crack width and crack height

crack depth increased much more with the usage of plain-barreled vertical roll.

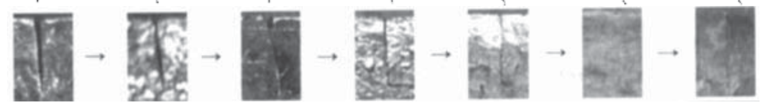
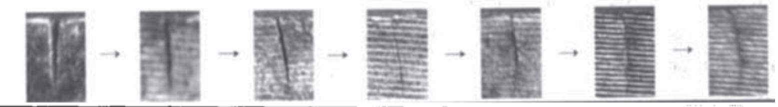
2.2 Experimental

In order to prove that the explicit dynamic FEM and updating geometric method can be well used to analyze crack closure and growth during multi-passes of V-H rolling process, the experiment of multi-pass of V-H rolling with lead and with flat vertical roll has been conducted in laboratory. ϕ300 mm rolling mill and ϕ180 mm rolling mill were adopted respectively during vertical rolling and horizontal roll-

ing. The rolling speed is 200 mm · s^{-1}. The dimension of specimens profile is 120 mm×25 mm. In order to research the deformation of the crack, "V" shape cracks are notched at the slab corner, where the width of crack is 0.5 mm, the depths on top surface and side surface are 5 mm, according to V_1-H_1-V_2-H_2-V_3-H_3 rolling process, the draft of vertical rolling in each pass is 5 mm, and the draft of horizontal rolling is 1 mm. The photos of crack shape of each pass from slab top surface and side surface are obtained by close focus digital camera.

From Table 3, it is clear that the calculated results are in good agreement with the actually measured results, which proves that finite element method and updating geometric method can be used to analyze the tendency of the deformation of the crack.

Table 3 Crack development direction according to FEM results and test results

		Initial → V_1 → H_1 → V_2 → H_2 → V_3 → H_3
From slab top surface	FEM results	
	Test results	
From slab side surface	FEM results	
	Test results	

Note: Arrow shows the rolling direction.

3 Conclusions

(1) During vertical rolling, when groove vertical roll is used, the maximum contact pressure of transversal crack on slab corner is 115 MPa and the contact pressure is stable in deformation zone; when flat vertical roll is used, the maximum contact pressure of transversal crack on slab corner is 70 MPa and there are two fluctuations in deformation zone.

(2) During horizontal rolling, when groove vertical roll is used, the contact pressure becomes zero and the crack may grow further; and when flat vertical roll is used, there is still contact pressure.

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