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Formation Mechanism of Voids around Hard Inclusion during Hot Rolling Processes

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Abstract: To investigate the mechanism by which voids form around hard inclusions, the deformations of a plastic slab with hard and soft inclusions that form inside it during the hot rolling process have been simulated with a finite element method. By comparing plastic strain distributions, the relative displacements of contact surfaces, and the deformations between hard and soft inclusions have preceded analysis of the formation mechanism of these voids. The variations of strain measurements between the matrix and hard inclusions cause relative displacement of their contact surfaces. Therefore, voids occur at the front and rear of the hard inclusions. Trials on the slab deformations using a titanium ball instead of the soft inclusion inside the slab during the hot rolling process are conducted. The simulated shapes of the soft inclusions with different reductions mostly agree with the experimental results.

Keywords: plastic deformation, inclusion, relative displacement, void

Introduction

Macro-inclusions are embedded in steel matrices. During the hot rolling process, voids occur between the matrix and the hard inclusions, causing deformities within the hard inclusions. This causes the quality of the steel to be markedly reduced by the voids around these hard inclusions [1–6].

Numerous studies [1, 7–10] on behavior of these inclusions during the rolling process have been published. These studies focused mainly on size measurements of the inclusions after rolling to determine their relative plasticity. However, the studies could not provide an accurate interpretation of the mechanism of this void formation.

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Recently, the deformation behavior of inclusions during the rolling processes has been studied using finite element methods. Ervasti et al. [11] found that the voids were likely to form close to the area where hard particles existed, and the formation risk of the voids could be reduced by using rollers of larger diameter. The deformation behavior of hard Al_2O_3 and soft MnS inclusions, along with the process by which varying defects caused by inclusions' cracking under stress, were investigated by Zhang [12]. Nagayama et al. [13] analyzed the deformation of non-homogeneous materials using a rigid-plastic finite element model. Yu et al. [14] investigated the deformation behaviors of the inclusions of varying sizes of stainless steel “trips” during multi-pass cold rolling, and that study showed that the reduced size of any hard inclusion reduced inclusion deformation. The formation of voids surrounding an inclusion was simulated by Luo [15] using a finite element method; in that case, the temperature profoundly affected the voids' width. The influence caused by process parameters, such as roller interface reduction, as well as the rolling temperature upon the deformation of inclusions were analyzed by Luo [16] using a previously developed rigid-viscoplastic finite element model. The simulation results showed that high temperatures, low roller speed and low reduction could increase the relative plasticity index of inclusions. Hwang [17] simulated void generation and development around the inclusion inside the sheet during the rolling processes. The simulated results showed that the void length in front of the inclusion was larger than the void length in the rear of the inclusion under varying rolling conditions.

This research provides valuable information regarding inclusions' deformation during the rolling processes. However, the formation mechanism of voids around the hard inclusions was inadequately studied regarding the analysis of the plastic strain distribution of the inclusion and matrix. Also, some of the simulation results lack verification with specific experimental results.

This work aims to explore the issue of the mechanism by which plastic voids deform the matrix, as well as to analyze the hot rolling process by utilizing finite element

model simulation. This process is also for the analysis of two types of inclusions, one which is softer and the other harder than the steel matrix. By using this model, the comparisons of plastic strain distributions, the relative displacements of the contact surfaces, and the deformations between the hard and soft inclusions have been made available to assist in the analysis of the formation mechanism of the voids. Furthermore, analysis on the deformation of the slab using a titanium ball instead of the soft inclusion inside it during the hot rolling process is included herein to verify the model.

Input data

The inclusions are assumed to be spherical. Generally, inclusions occur at the 1/4 thickness position from the inner-arc during the continuous casting process [18]. Therefore the inclusions are located at the 1/2L, 1/4H, and 1/2D positions of the slab in this model. The input data is shown in Tables 1–3. Table 4 shows the nominal chemical composition of the matrix steel.

Table 1: Input data.

Roller radius (mm)	150
Roll velocity (mm/sec)	200
Inclusion size (μm)	100
Position of inclusion from inner-arc	(1/2 L, 1/4H, 1/2D)
Slab thickness H (mm)	100
Slab length L (mm)	200
Slab width W (mm)	100
Roll temperature (°C)	950

Table 2: Flow stress.

Parameters	Matrix	Hard Inclusion	Soft Inclusion
Flow stress, MPa	46.5	500	40

Table 3: Rolling schedules.

Pass number	0	1	2	3	4	5	6
Rolling reduction (mm)	0	10	10	10	10	10	10
Total rolling reduction (mm)	0	10	20	30	40	50	60

Table 4: Nominal chemical composition of the matrix steel (wt%).

C	Si	Mn	P	S
0.7	0.2	0.45	0.03	0.02

Simulation

The simulation uses commercially available ABAQUS/Explicit software. The method analysis is based on elasto-plastic formulation [19].

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p \quad (1)$$

From Hooke's law:

$$d\varepsilon_{ij}^e = \frac{1-2\mu}{3E} \delta_{ij} d\sigma_{kk} + \frac{1+\mu}{E} dS_{ij} \quad (2)$$

From the Levy–Mises and the Prandtl–Reuss plasticity flow theories:

$$d\varepsilon_{ij}^p = \alpha d\lambda S_{ij} \quad (3)$$

Therefore,

$$d\varepsilon_{ij} = \frac{1-2\mu}{3E} \delta_{ij} d\sigma_{kk} + \frac{1+\mu}{E} dS_{ij} + \alpha d\lambda S_{ij} \quad (4)$$

where ε_{ij} is total strain, ε_{ij}^e is elastic strain, ε_{ij}^p is plastic strain, σ_{kk} is average stress, E is elastic modulus, μ is Poisson's ratio, S_{ij} is the stress deviator, α is a plasticity index, plastic state: $\alpha = 1$, elastic state: $\alpha = 0$. The elastic–plastic strain complies with the Von Mises criterion.

The volume of the inclusion is about 1×10^{-14} the total volume of the slab. The mesh model required to approximate the inclusion is too fine for the scope of this work, and it would also require too much computing time. To solve this problem, Figure 1 shows a new method by which to construct a finite element model of the slab's plastic deformation with an inclusion inside of it during the hot rolling processes. From Figure 1(a), a

Figure 1: A finite element model is established using a new method.

finite model for slab deformation during the hot rolling process has been constructed. The slab is broken into 128,000 four-node elements, each with the same dimensions ($2.5\text{ mm} \times 2.5\text{ mm} \times 2.5\text{ mm}$) in this model. From Figure 1(b), a micro-model ($2.5\text{ mm} \times 2.5\text{ mm} \times 2.5\text{ mm}$) which consists of tetrahedral elements with the inclusion constructed inside of it. The micro-model has been constructed in halves in order to maintain its symmetry. From Figure 1(c), the volume history and the plastic strain history which is shown in Figure 2 of the macro-element at the position of $1/4$ thickness from the inner-arc of the slab during the hot rolling process are stored and then applied to the micro-model with the inclusion inside it.

Some assumptions regarding the model are as follows:

1. The roller is rigid, and the sheet with its inclusion is made of elasto-plastic material.
2. The properties of the sheet and its inclusion are isotropic.
3. Any cohesion between the sheet and the inclusion is not considered.
4. The temperature of the steel and its inclusion remains unchanged during the hot rolling processes.

The constant friction factor between the roller and sheet is 0.2, and the constant friction factor between the steel and inclusion is 0.5.

Figure 2: Plastic macro-element strain data at the $1/4$ thickness position from the inner-arc of the slab.

Simulation results and discussion

Plastic strain distributions within the hard inclusion

The plastic strain distributions of the hard inclusion with different reductions are shown in Figure 3(A–f). Figure 3 shows that the hard inclusion becomes deformed as it changes initially from a sphere to an elliptical shape. This occurs gradually as the voids develop from the front and move to the rear of the hard inclusion during the hot rolling process. The plastic strain found at the center of the inclusion is greater than that at the edge of the hard inclusion. Therefore the plastic strain of the hard inclusion begins at the center. The plastic strain of the matrix around the hard inclusion, especially close to the top and bottom of the hard inclusion, is greater than that of the strain on the hard inclusion. This is because the flow stress of the hard inclusion is greater than that of the matrix. The plastic strain of the hard inclusion is less than that of the matrix under the same load.

The plastic strain distributions of the soft inclusion are shown in Figure 4(A–f). The plastic strain distributions of the soft inclusion following the pass numbers 1–6. The plastic strain of the matrix around the soft inclusion is almost equal to that of the soft inclusion. Additionally, no voids appear around the soft inclusion during the hot rolling processes. The plastic strain of the soft inclusion is almost equal to that of the matrix, which is not near the hard inclusion. The plastic strains of the matrix and soft inclusion both increase with a larger reduction. The flow stress of the matrix is greater than that of the soft inclusion. The plastic strain of the soft inclusion should be greater than that of the matrix under the same load. However, the soft inclusion is surrounded by the matrix, and this limited space prevents increased deformation of the soft inclusion. Therefore the plastic strains of the soft inclusion and matrix are equal. This limited space causes the plastic strain of the soft inclusion to be less than that of the matrix.

Comparison of plastic strain distribution and deformation

Comparison of plastic strain

Figure 5 shows that the sum of the plastic strains of the inclusions and of the matrix all increase as the reduction

Figure 3: Plastic strain distributions of the hard inclusion at 800°C with the following reductions: a) 10 mm; b) 20 mm; c) 30 mm; d) 40 mm; e) 50 mm; f) 60 mm.

Figure 4: Plastic strain distribution of the soft inclusion after the following reductions at 800°C: a) 10 mm; b) 20 mm; c) 30 mm; d) 40 mm; e) 50 mm; f) 60 mm.

Figure 5: Plastic strain of inclusions and matrix after different reductions.

increases. The sum of the plastic strains of the top and bottom of the hard inclusion and the matrix close to the top and bottom of the hard inclusion is about two times greater than that of the soft inclusion. Therefore, the plastic strain on the area between the contact surfaces is nearly equal to that strain of the matrix, which is not close to the hard inclusion.

Comparison of deformation of inclusions

Figure 6(a, b) shows the deformation behaviors of the hard and soft inclusions during the rolling process, respectively. As the reduction increases, the hard and soft inclusions both become longer and flatter. The soft inclusion is both flatter and longer than the hard inclusions with the same reduction. The lengths of the soft and hard inclusions at 60% reduction are approximately 142.2 μm and 148.6 μm , respectively. This is because the

flow stress of the hard inclusion is greater than that of soft inclusion. The deformation of the hard inclusion is smaller than that of the soft inclusion with the same load, which supports their deformation.

Mechanism of void formation

The volume of the matrix and inclusions remains nearly unchanged during the plastic deformation. When the matrix and inclusion are squeezed along the thickness of the slab during the rolling processes, they become longer in the direction of the rolling during the hot rolling processes, the plastic strain of the matrix around the hard inclusion, especially close to its top and bottom is greater than that of the hard inclusion. Therefore the increased length in the rolling direction of the matrix is greater than that of the hard inclusion. Figure 8 shows the length change between the tow points on the contact surface during the rolling processes. a and b are the lengths between the tow points on the contact surface of the hard inclusion before and after rolling, respectively. c is the length between the tow points on the contact surface of the matrix after rolling, so $c > b > a$.

Figure 7 also shows that A and B are the two points on the contact surfaces of the matrix and hard inclusion, respectively. A is close to B. The larger change of the length of the matrix close to the top and bottom of the hard inclusion produces the horizontal displacement of L_2 of A to be greater than that of L_1 of B. The vertical displacements H_1 and H_2 are also different. The value and direction of displacement S_1 of A are both different from that of S_2 of B during the rolling processes in Figure 8. Therefore voids occur between the hard inclusion and matrix. During the hot rolling process, the plastic strain of the matrix around the soft inclusion is almost equal to that of the soft inclusion. The displacements of the matrix and the inclusion are the same. Therefore no voids occur

Figure 6: The plastic deformation of inclusions with different rolling number: a) hard inclusion; b) soft inclusion.

Figure 7: The length before and after rolling: a) before rolling; b) after rolling.

Figure 8: The displacements of A and B: a) A; b) B.

Figure 9: The displacements of A and B during the rolling process.

around the soft inclusion during the hot rolling process. Figure 9 shows the displacements produced by points A and B during the rolling process.

Experimental verification for the finite element model

Table 5 shows the flow stresses [20] of the inclusion and titanium at 950 °C. The two flow stresses are almost the same. Figure 10 shows that when a titanium ball with a

Table 5: Flow stress.

Parameters	Ti	Inclusion
Flow stress, MPa	41	46.5

0.5 mm diameter rather than the inclusion is implanted in the slab at the position of 1/4 thickness.

The rolling temperature is 950 °C. The sizes of the slabs and roller and the rolling schedules of the experiment remained the same throughout the simulation.

The simulated and experimental results are shown in Table 6. The simulated shapes of the soft inclusion with different reductions are in good agreement with the experimental results.

Conclusions

The plastic deformation of the slab with the inclusions inside it during the hot rolling processes has been analyzed using finite element methodology. The following conclusions may be drawn from the analysis:

From the comparison of plastic deformation between the soft and hard inclusions during the hot rolling process, it was found that the strain produced by the plastic upon the matrix close to the top and bottom of the inclusion is greater than that of the inclusion when the flow stress of the inclusion is greater than that of the matrix. This difference of the plastic strain between the matrix and the inclusion produces the relative displacement between their contact surfaces. Therefore voids occur at the front and rear of the inclusion. The reduction of the number of inclusions, which are harder than the matrix steel, and also which exist within the molten steel, is beneficial for decreasing the effects of the voids on the overall quality of the rolled steel.

Figure 10: Experimental route.

Table 6: Experimental and simulated results.

Rolling number	Simulated results	Experimental results
3		
4		
5		
6		

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