Abstract

Recently it is required that non-metallic inclusion, which is fracture origin in forming process, should be harmless because ductility of high strength steel must be ensured. Non-metallic inclusion is observed in the form of composite inclusion. In this study, the influences of flow stress ratio of inclusion versus matrix steel and composite inclusion ratio on deformation behavior of inclusion were investigated analytically. It was found that the aspect ratio of inclusion would be determined by flow stress ratio and composite inclusion ratio. The result indicated that the aspect ratio of inclusion after compression could be estimated by average flow stress ratio and composite inclusion ratio.

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1. Introduction

Recently it is required that non-metallic inclusion should be harmless for high strength steel. Because L.Luyckxit et al. (1970) demonstrated inclusion is fracture origin in forming process. Non-metallic inclusion is observed in the
form of composite inclusion i.e. hard phase is covered with soft phase. Sasabe (2010) reported it has been achieved to produce carbon steel containing 10 ppm or less sulfur in large quantities. Concerning high strength steel sheet, however, it is needed to be more harmless inclusions from the viewpoint of the shape control because fracture is caused by elongated inclusions, which were deformed in hot rolling processes. Sven Ekerot (1974) studied relation between deformability index (i.e. the ratio of strains between inclusion and matrix) and steel composition experimentally. R.Maiti and E.B.Hawbolt (1985) investigated shape of inclusion after hot-rolling by additional material such as calcic treatment. However, it is difficult to elucidate the effects of parameters on the deformation behavior of non-metallic inclusions experimentally because many factors must be considered e.g. geometric shape of inclusion, process condition, and materials properties. Luo and Ståhlberg (2002) analyzed deformation behavior of non-metallic inclusions in plate rolling process under different rolling temperature, friction and rolling schedule by finite element simulation (FE simulation). Hai-liang Yua et al. (2009) were investigated effect of initial inclusion geometry analytically. In the papers above, the research on the deformation of inclusion under various inclusion positions, shapes and process were carried out analytically. However deformation of inclusion would be affected by many parameters. In this study, we focused on flow stress ratio of inclusion versus matrix steel and composite inclusion ratio, the influences on deformation behavior of inclusion were investigated. As foundational step, we studied the influences on deformation behavior of inclusion in uniaxial compressive stress state.

**Nomenclature**

- \( F \)  
  flow stress
- \( \varepsilon \)  
  strain
- \( \dot{\varepsilon} \)  
  strain rate
- \( C \)  
  carbon composition %
- \( T \)  
  heating temperature
- \( a \)  
  aspect ratio of inclusion, \( a=w/h \); Fig. 4 (b)
- \( \sigma_{\text{ave.}} \)  
  average flow stress
- \( R \)  
  average flow stress ratio, \( R=\frac{\sigma_{\text{ave.include}}}{\sigma_{\text{ave.steel}}} \)
- \( r_{\text{MnS}} \)  
  radius of MnS
- \( r_{\text{Al}_2\text{O}_3} \)  
  radius of Al\(_2\)O\(_3\)

**2. Identification of analytical condition**

In this chapter, experimental results and FE simulation results of uniaxial axis compression were compared. Determination of appropriate boundary condition and validation of analysis model were investigated.

**2.1. Experimental condition**

Uniaxial compression test for steel containing MnS (compound of manganese and sulfur) was conducted. The amount of 500g sample, which has composition shown in Table 1, was melted at argon (Ar) atmosphere. Casted samples were machined into cylindrical specimen (\( d=8 \text{ mm}, \ h=12 \text{ mm} \)). Heat treatment and compressive condition was shown in Fig. 1. Scanning electron microscope (SEM) observation was conducted in 0.65mm\(^2\)×33 fields at cross section near compression axis. Surface of specimen was provided electrolytic polishing by SPEED method (Selective Potentiostatic Etching by Electrolytic Dissolution method) as pre-treatment. 10% acetylacetone - 1% tetramethylammonium - methanol was used as electrolyte. Quantity of electrolysis charge was 100C / 0.65mm\(^2\).
Table 1. Material composition (%).

| C     | Si | Mn | P   | S   | Al | N   | Observed inclusion |
|-------|----|----|-----|-----|----|-----|-------------------|
| 0.041 | 0.48 | 0.74 | 0.062 | 0.0066 | 0.019 | 0.0015 | Al₂O₃, MnS |

Fig. 1. Heat treatment and compressive condition.

2.2. Analysis condition

Analysis condition was shown in Table 2. The commercial software DEFORM-2D was used as a simulation code. Thermal coupled calculation was not considered since the experiment was conducted by using high-frequency induction heating method to keep isothermal state. Analysis model outline was shown in Fig. 2. The inclusion was modeled at the center of cylindrical steel matrix as a spherical shape, which has a diameter of 5 μm. Steel matrix was modeled as cylindrical shape (d=0.1 mm, h=0.2 mm), and this geometry was defined with consideration of stress state of actual experimental specimen. Namely, analytical model showed almost the same stress state of full size cylindrical model (d=8 mm, h=12 mm).

The flow stress of matrix steel was extrapolated by Misaka’s equation as shown in Eq. (1).

\[
F = \varepsilon^{0.21} \cdot \dot{\varepsilon}^{0.13} \cdot \exp(0.126 - 1.75C + 0.594C^2 + \frac{2851 + 2968C - 1120C^2}{T}) \text{ kgf/m}^2
\]  

(1)

where, \( T=1373K, \dot{\varepsilon}=10/\text{sec}, C=0.04\% \) in actual experiment. Thus the flow stress was calculated as \( F=122\varepsilon^{0.21} \). The inclusion material properties were quoted from the reference of Misaka et al. (1967-8). Young’s modulus for MnS
was \(E = 15\text{GPa},\) Poisson’s ratio was \(\nu = 0.25,\) and yield stress was \(\gamma = 33\text{MPa}.\) After yield point, flow stress was presumed as constant, i.e. inclusion was modeled perfect elastoplasticity. Boundary condition between inclusion and matrix steel was supposed as shear frictional coefficient \(m = 1\) (fixed). To represent uniaxial stress state, the frictional condition between tool and steel was assumed \(m = 0.\)

| Analysis Condition.                                                                 |                                                                 |
|-----------------------------------------------------------------------------------|-----------------------------------------------------------------|
| **Geometric model**                                                               | Axi-symmetric problem, 1/4 model                                |
| **Material**                                                                      |                                                                 |
| steel                                                                             | Rigid plastic body                                              |
| MnS                                                                                | Elasto plastic body                                             |
| die                                                                                | Rigid body                                                      |
| **Compressive ratio**                                                             | 80%                                                             |

2.3. Results and discussion

The change of inclusion shape obtained from SEM observation is shown in Fig. 3. It was observed composite inclusion i.e. \(\text{Al}_2\text{O}_3\) is covered with MnS. Single MnS inclusion was elongated after 80% compression as shown in Fig. 3 (b). Aspect ratio of this elongated inclusion was calculated as 24. Meanwhile in the FE analysis, final inclusion shape was evaluated by aspect ratio \(a,\) which is defined as \(w / h\) (as shown in Fig. 4). Aspect ratio was calculated 25 by FE simulation. Validation of analysis model was demonstrated since the analytical result showed good agreement with experimental result.

![SEM image of inclusion before and after compression](image1.png)

Fig. 3. SEM image of inclusion before and after compression.

![Definition of aspect ratio in FE analysis](image2.png)

Fig. 4. Definition of aspect ratio in FE analysis.

3. Relation between aspect ratio and average flow stress ratio

We assumed that aspect ratio of inclusion is changed by flow stress of steel or inclusion. In this chapter, the influence of flow stress on final aspect ratio of inclusion was investigated.
3.1. Analysis condition

Average flow stress ratio $R$ was defined as index, which indicates the difference of strength between steel and inclusion. $R$ is defined as a value that the average flow stress of inclusion was divided by average flow stress of steel. Average flow stress $\sigma_{\text{ave.}}$ is defined as Eq. (2). This parameter means that inclusion is soft or hard i.e. $R < 1$: soft inclusion, $R > 1$: hard inclusion. It was assumed the existence of only single inclusion.

$$\sigma_{\text{ave.}} = \frac{1}{\varepsilon} \int_{0}^{\varepsilon} F(\varepsilon, \varepsilon) d\varepsilon$$  \hspace{1cm} (2)

3.2. Results and discussion

Relation between aspect ratio of inclusion $a$ and average flow stress ratio $R$ is shown in Fig. 5. It was found that aspect ratio is defined uniquely when flow stress of inclusion or steel is changed. Furthermore, in case of large flow stress of inclusion compared to matrix, namely inclusion is hard phase, the inclusion almost never deform during matrix deformation. The result indicated that the aspect ratio of inclusion after compression could be estimated by average flow stress ratio.

![Fig. 5. Relation between average flow stress ratio and compression ratio.](image)

4. Relation between aspect ratio and composite inclusion ratio

Non-metallic inclusion is observed in the form of composite inclusion i.e. hard phase is covered with soft phase in Fig. 3(a). In this chapter, the relation between aspect ratio and composite inclusion ratio was investigated.

4.1. Analysis condition

Outline of composite inclusion model is shown in Fig. 6. Model size and boundary condition were used value given in 2.2 section. Composite ratio of soft and hard inclusion was changed as 0–100%. Final composite inclusion shape was evaluated by aspect ratio, which is defined as $w/h$ (as shown in Fig. 6).

![Fig. 6. Definition of aspect ratio and image of composite inclusion.](image)
4.2. Results and discussion

Relation between aspect ratio and composite inclusion ratio is shown in Fig. 7. Aspect ratio was defined by soft inclusion (MnS) ratio. The variation of the aspect ratio became drastic with increase of soft inclusion ratio.

Fig. 7. Relation between aspect ratio and composite inclusion ratio.

5. Conclusion

(1) It was found that aspect ratio is defined uniquely when flow stress of inclusion or steel is changed. It was indicated that aspect ratio of inclusion after compression could be estimated by average flow stress ratio.

(2) Aspect ratio was defined by soft inclusion ratio. When soft inclusion ratio is high, difference of aspect ratio before and after compression is large.

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