Modeling the Behavior of Inclusions 
in Plastic Deformation of Steels 

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Doctoral Thesis

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Abstract

This doctoral thesis presents a modeling method for demonstrating the behavior of inclusions and their surrounding matrix during plastic deformation of steels.

Inclusions are inescapable components of all steels. More knowledge about their behavior in processes such as rolling and forging is necessary for carrying out the forming processes in a more proper way so that the properties of the final product are improved. This work is focussed on deformation of inclusions together with void formation at the inclusion-matrix interface. The topic of the work is analyzed by different FE-codes.

The relative plasticity index is considered as an important measure for describing the deformability of inclusions. The index could be analyzed quantitatively, enabling a deeper understanding of the deformation mechanisms. The working temperature is found to be an important process parameter. This is very clear when the deformation of silicate inclusions in a low-carbon steel is studied during hot rolling. Here a narrow transition temperature region exists, meaning that the inclusion behaves as non-plastic at lower temperatures and as plastic at higher. The results are in agreement with experiments published by other authors.

Regarding void formation, the simulations have been carried out by utilizing an interfacial debonding criterion. The difference in yield stress between the matrix and the inclusion is one common reason for void initiation and propagation. During large compressive deformation the evolution of voids goes through a sequence of shapes, from convex with two cusps to concave with three cusps together with self-welding lines. It is concluded that the formation of voids is always associated with a large relative sliding between the inclusion and the matrix.

In order to study the local behavior of the material close to inclusions during hot rolling a mesomechanical approach is used. Uncoupled macro- and micro- models have been developed. By means of the macro-model, the stress-strain history throughout each sub-volume of the steel is evaluated. The stress components or velocity fields are recorded with respect to time as history data. No consideration is taken to the existence of inclusions. The micro-model, which includes both inclusion and steel matrix, utilizes the stress components or the velocity fields from the macro-model as boundary conditions.

Keywords: Inclusion; Steel; Plastic deformation; Void; Rolling; Forging; Finite Element; Mesomechanical approach.
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Dissertation

This dissertation contains a summary and the following papers:


Paper D  C. Luo, Evolution of voids close to an inclusion in hot deformation of metals, accepted for publication in *Computational Materials Science*, 2001


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1. Introduction

Non-metallic inclusions in steels have been the subject of much study during the last half century. This interest originates from observations that the performance of steels can be strongly influenced by inclusions.

Controlling inclusions in steel is closely connected with the concept of ‘clean steel’. Cleanliness of steel can be considered as a low content of non-metallic inclusions, mainly oxide and sulfide inclusions. The idea of ‘clean steel’ often includes special requirements to the inclusions with respect to their composition, morphology, type, size and distribution in the liquid steel, in the solidified ingot and in the final product. The aims of the metallurgist are to eliminate undesirable inclusions and control the nature and distribution of the remainder. Metalworking plays an important role in the production of steel products. This work is a part of a project called “Precision Processing of Clean Steel – for Hardened Components”, which is launched by the Swedish Foundation for Strategic Research.

A lot of work has been done regarding the nature and performance of inclusions during plastic working of steels. In fact, inclusions are inescapable components. Their composition, morphology, size, and distribution can be controlled and monitored, but they can never be totally eliminated. Steel with inclusions is microscopically inhomogeneous and can be theoretically treated as a composite. For the understanding and quantitative analysis of steel with inclusions it is useful to consider the matrix with inclusions as a system, as illustrated in Fig. 1. A matrix/inclusion system comprises three components: A matrix, an inclusion, the inclusion-matrix interface. The main features of output of the system involve plastic deformation and fracture of the inclusion and the surrounding matrix, void formation close to the inclusion, the characteristics of the final inclusions and the matrix environment where the inclusions are located. The goal of the system is to control the inclusions and to optimize the properties of the final product. The matrix/inclusion system in the micro-level is looked upon as a sub-system within the workpiece, which is one component of the workpiece/tool system in the macro-level, as shown in Fig. 2. Although the inclusions can be explored by means of modern microscope, it is still a hard and difficult job to measure and investigate them at arbitrary locations. On the other hand, modern numerical techniques are available for a more detailed analysis.
The purpose of the thesis is to model and simulate the behavior of inclusions during plastic deformation of steel by means of the finite element method. Such modeling provides detailed information regarding the development of stress and strain fields associated with the inclusions. In this way it becomes possible to analyze the micro-world inside the material.

Fig. 1. A schematic picture showing the Matrix/Inclusion system

Fig. 2. A schematic picture showing the two-level system
2. Behavior of inclusions in plastic deformation of steels

A number of excellent papers [1-9] exists on the subject of non-metallic inclusions. A literature review focusing on the behavior of inclusions in plastic deformation of steels has recently been presented by the author [10].

Inclusions may be categorized from their deformation and fracture characteristics [11]:

a) Inherently plastic inclusions such as MnS, which show a gradual change in plasticity over a wide range of temperatures.

b) Non-crystalline glassy inclusions, which behave rigidly at low temperature and become plastic at some critical temperature. Typical inclusions of this type are glassy silicates, which become plastic at a critical viscosity at the non-plastic/plastic transition temperature.

c) Crystalline ionic solids typified by crystalline silicates, spinels, sesquioxides and certain calcium aluminates. These show no plasticity and often behave in a brittle manner until reaching their solidus temperature when they assume fluid behavior. The non-plastic/plastic transition thus approximates to the solidus temperature.

Simply, non-metallic inclusions in steels can be classified into two basic types, namely into those which deform during hot working (i.e. sulfides, silicates), and those which are largely undeformable (i.e. alumina, spinels).

The morphology of inclusions in wrought products is largely controlled by their mechanical behavior during steel processing, i.e., whether they are ‘hard’ or ‘soft’ relative to the steel matrix. The typical behaviors of different types of inclusions during deformation are schematically illustrated in Fig. 3 [12].

2.1 Deformation of inclusions

The deformation behavior of inclusions during forming processes is of fundamental importance regarding their properties. In fact, inclusion morphology, size and distribution, even composition, can be markedly altered during the deformation. Kiessling and Lange [3] pointed out that the most important physical property of the different inclusion phases is their plasticity as compared with the plasticity of steel at different temperatures. If this property was known for all the different inclusion phases, the steels could be much better ‘tailored’ for different working conditions.
operations such as rolling, forging, deep-drawing and turning. Consequently, if it is required to ‘tailored’ the inclusions in order to minimize their detrimental effects and utilize their beneficial effects, detailed consideration must be given to the plasticity of the inclusions and the way in which they fracture and are disseminated throughout the steel during the forming process.

2.1.1 Relative plasticity

The behavior of an inclusion during hot or cold working depends on the plasticity of the inclusion itself. It is impossible to determine the absolute plasticity of inclusions ‘in situ’ in the steel, and so it has been customary to assess the inclusion deformation by comparison with that undergone by the steel matrix itself.

To measure the relative plasticity of the inclusion to the steel matrix, Malkiewicz and Rudnik [13] defined a deformation index \( \nu \) as

\[
\nu = \frac{\varepsilon_i}{\varepsilon_m}
\]  

(1)

where \( \varepsilon_i \) is the true strain of the inclusion and \( \varepsilon_m \) is the true strain of the steel matrix.

Fig. 3. Schematic presentation of inclusion morphologies before and after deformation
According to this definition, several expressions have been established by Malkiewicz and Rudnik [13], Brunet and Bellot [14], Vodopivec and Gabrovsek [15], Baker and Charles [16].

In Paper B, the relative plasticity index of the inclusion is evaluated directly by using the average equivalent strains both of the inclusion and of the local matrix based on the results from FE-calculation.

In Paper E, the measured dimensions for both inclusions and plate specimens are utilized. For the case of plane strain rolling of a steel plate with cylindrical inclusions, the following expression is used

\[
v = \frac{\varepsilon_i}{\varepsilon_m} = \frac{(\ln \lambda - \ln \lambda_0)/2}{\ln \frac{h_0}{h}}
\]  

(2)

where \(\lambda_0\) and \(\lambda\) are the aspect ratios of an elliptic inclusion before and after rolling.

During the plastic deformation, stresses are exerted on the inclusions by the steel matrix which tend to make them to deform in a manner similar to that of the surrounding material. However, there exist many factors, which may affect the inclusion deformation [17-19]:

- Strength of inclusion and matrix
- Composition
- Inclusion-matrix interface
- Temperature
- Strain and strain rate
- Particle size
- Stress state
- Second-phase particles

2.1.2 Mechanisms of inclusion deformation

The mechanisms of inclusion deformation in steel during hot rolling have been discussed by many researchers [17, 20, 21]. Rudnik [20] thought that deformation occurs because of friction between the inclusions and the flowing matrix. The frictional forces act in the direction of metal flow. They are responsible for the lengthening. Baker and Charles [17] proposed that the steel matrix, in trying to flow over the inclusions, becomes increasingly constrained with increased inclusion deformation because of the friction at the interface. This impedes deformation and
flow of the steel around the inclusion, which in turn produces a corresponding reduction in inclusion deformation. Also Belchenko and Gubenko [21] concluded that plastic inclusions are deformed by frictional forces at the interface. The increase in frictional force also promotes the change in shape of the inclusion from spherical to ellipsoidal, meaning an increased area of the interface. According to Paper B it is believed that the deformation of the inclusions during hot rolling is probably due to the forces operating at the inclusion-matrix interface. Such forces will be influenced by changing the process parameters. A soft inclusion will yield before the matrix at high temperatures. For the same deformation period, it is true that the inclusion will be deformed much more resulting in a high relative plasticity index.

In Paper B, the influences of process parameters, such as rolling temperature, rolling reduction and friction at the roll-workpiece interface, are investigated. The relative plasticity index of a silicate inclusion is found to be heavily dependent on the process parameters. The index gets high values for high temperatures, low rolling speeds and rolling schedules built on small reductions/pass. Some results are consistent with experimental observations. Also the influence of friction, at the roll-workpiece interface, on the profile of the inclusion has been analyzed.

In Paper E, the deformation of MnS inclusions during flat hot rolling is studied experimentally. Particular attention is paid to the effects of rolling temperature and rolling reduction. Also the influence of inclusion orientations is analyzed.

2.1.3 Modeling the deformation of inclusions

A matrix that contains inclusions of different mechanical properties features a heterogeneous strain distribution during plastic deformation. It has been the subject of many modeling efforts.

The conventional mechanical analysis could not be extended to irregular geometries of particles, nor to nonlinear behavior of the matrix. However numerical techniques have improved the development of micromechanics. A big advantage of numerical simulation is that it becomes possible to examine the effects of modifying the geometry, distribution and properties of particles in a metal.

The finite element method has been widely used. Thomson and Hancock [22] carried out an axisymmetric analysis of a rigid or elastic spherical inclusion in an elastic-plastic matrix of power law hardening. Gilormini
and Germain [23] studied both a plane and an axisymmetric case dealing with deformable inclusions in an elastic-plastic matrix. The inclusions were of elliptic, cylindrical or spheroidal shape. Nagayama et al. [24] analyzed the deformation of inhomogeneous materials with inclusions using a rigid-plastic finite element method. In this case the inclusions and the matrix were supposed to be rigid-plastic with different yield stresses satisfying the von Mises yield criterion. The problem of modeling the inclusion-matrix system for large plastic deformations has been treated by Pietzyk et al. [25] and by Milenin [26]. Here the influence of the inclusion shape was examined. All authors mentioned under this paragraph have been treating the problems for the microscopic level, i.e. cell models were utilized in order to analyze stresses and strains in and around the inclusions. Im and Dharan [27] analyzed the micromechanics of unidirectional fibre-reinforced composites using an elastic-plastic finite element approach. They applied the slab method directly to the forming of metal matrix composites to calculate the macroscopic stresses in the workpiece. The overall metal matrix composite is assumed to be loaded by average stresses in horizontal and vertical directions.

*In Paper B*, a mesomechanical approach is applied to the deformation analyses of inclusions. This method connects the micromechanical behavior of the heterogeneous material with its in-service macroscopic behavior. The macro-model evaluates the deformation history throughout each sub-volume of the steel without taking the influence of inclusions into account. The micro-model that includes matrix and inclusion makes use of the deformation history from the macro-model as boundary values. Thus a micro-model cell element is constructed to analyze the behavior of the inclusion. A rigid-plastic finite element code was developed for realizing this goal.

*In Paper C*, a two-level model is proposed, in which uncoupled macro- and micro-models are used. The objective of the analysis is to simulate the local behavior of the material close to non-metallic inclusions during hot rolling. The stress history of sub-volume in the macro-model including workpiece and rolls is utilized as boundary loading conditions for the micro-model comprising both inclusion and steel matrix. The simulations are performed with the commercial finite element package ABAQUS/Explicit.

*In Paper E*, a micro-model is used to analyze the deformation of inclusions in the workpiece during hot rolling. Also here the commercial finite element package ABAQUS/Explicit is used.
In Paper F, a forward and backward tracing scheme is used to analyze the behavior of inclusions during closed-die forging. The simulations are performed by using the commercial finite element code Forge3.

2.2 Void formation at the inclusion-matrix interface

2.2.1 Mechanisms of void formation

It is known that ductile fracture in metal forming is associated with weak interfaces in the material and is prompted by tensile stresses generated by the process. Ductile fracture proceeds in three steps: void initiation, growth and coalescence. This voiding process is generally initiated around the inclusions or second-phase particles. If the inclusions are harder than the steel matrix, voids can form at the inclusion/matrix interface during for example the rolling process. These voids have sharp edges and will have the same effect on the material as a crack. Since numerous inclusions exhibit this type of voids, fracture can occur without further nucleation.

Voids of conical shape are frequently nucleated at the ends of inclusions. It is particularly true if the inclusion is behaving non-plastically [16, 18-21, 28-30]. The initiation and development of voids are mainly dependent upon the following factors:

- Interface strength
- Relative strength of inclusion to steel matrix
- Stress state
- Strain

Baker and Charles [16] thought that the formation of voids appears due to the inability of the steel to flow around the non-deforming inclusion whilst simultaneously maintaining contact with it. The strength of the inclusion/matrix interface is insufficient to withstand the longitudinal tensile stresses caused by the deformation of the surrounding steel. The interface therefore separates, creating an embryonic void. In rolling the voids expand in the rolling direction. The vertical compressive stresses are no longer in balance and the resultant of the vertical and longitudinal stresses causes the steel to move partly into the void, thus producing its characteristic conical shape. In most cases the conical voids are observed to extend into the matrix a distance equal to about half of the inclusion height. Waudby [19] explained that the crack is initiated by the frictional forces acting tangentially to the surface of the inclusion. Both the
frictional force and the force imposed by the flow of metal tend to widen the crack at its base nearest the inclusion so that the surface of the crack is normal to the resultant force, creating the conical void. Belchenko and Gubenko [21] noticed that the matrix flows above and below the undeformable inclusion along the direction of rolling. This can lead to formation of conical cavities, which can be filled by flowing metal under the conditions of high pressure and temperature.

*In Paper A*, the aim is to simulate void formation close an inclusion. Debonding at the interface between the inclusion and the matrix is assumed to occur if the tensile normal stress reaches a critical value. Void propagation is driven by the tendency of separating the matrix from the inclusion. The difference in yield stress between the matrix and the inclusion is one common reason for void initiation and propagation.

*In Paper D*, void formation and evolution around an inclusion in an elastic-viscoplastic matrix under condition of compressive deformation have been simulated. Two kinds of loading conditions, i.e. displacement-controlled and stress-controlled loadings, are applied to the outer boundary of the cell model. The size of voids is strongly affected by temperature as the strain increases.

2.2.2 Modeling the void formation

Theoretical descriptions of void initiation from second phase particles have been developed from both continuum plasticity and dislocation models, Argon et al. [31], Goods and Brown [32], Fisher and Gurland [33], and Thomson and Hancock [34]. The growth of voids under plastic deformation has been analyzed by McClintock [35], Rice and Tracey [36], Glennie [37], Budiansky et al. [38], Taya and Patterson [39], Needleman [40], and Lay et al. [41], all investigations focusing on void nucleation and growth in case of tensile loading. Dunne and Katramados [42] investigated the nucleation and growth of voids in a titanium alloy undergoing high temperature deformations under generally compressive stress states. They developed a micro-mechanical model for void nucleation based on a debonding process between primary alpha particles and the beta matrix. The role of stress state in the void nucleation process has been examined and quantified. Harik and Cairncross [43] presented finite element modeling of time-dependent evolution of interfacial voids at a cylindrical inclusion in plane strain compression. It was found that the profile of interfacial voids changes from convex to convex-concave as the applied external pressure and strain increase.
In Paper A, a cell model is proposed to model the behavior of a matrix containing an inclusion under plane strain condition. A rigid-plastic finite element code that has been developed is utilized.

In paper D, a cell model and a two-level model are applied for two kinds of loading cases, i.e. displacement-controlled and stress-controlled loadings. The commercial finite element package ABAQUS/Explicit is used.

2.3 Fracture of inclusions

Inclusion fractures during hot working of steels can be of four types:

- Brittle fracture of undeformed inclusions;
- Tough fracture of low plasticity inclusions;
- Brittle fracture of inclusions which initially were plastically elongated but which later, at the end of rolling as a result of temperature drop, lost their plasticity;
- Fracture along the phase-separation boundary in multi-phase inclusions.

The investigations regarding fracture of inclusions during plastic deformation are limited to description of the phenomena [11, 44-46].
3. Summary of the papers

3.1 Numerical method

In the present work, the modeling of the inclusion behavior in steel is performed by means of the Finite Element Method. Both rigid-plastic FEM and elastic-plastic FEM are applied.

Rigid-Plastic FEM (RPFEM)

In Papers A and B, the analysis is based on the rigid-viscoplastic formulation. From the variational principle, the functional for the material can be written [see Papers A and B]:

\[
\Phi = \int_{V} \left( \int_{0}^{t} \bar{\sigma} d\bar{\varepsilon} \right) dV + \frac{1}{2} \beta \int_{V} \bar{\varepsilon} : \bar{\varepsilon} dV - \int_{S_t} T_i v_i dS
\]

where \( \bar{\sigma} \) is the effective stress, \( \bar{\varepsilon} \) the effective strain rate, \( V \) the control volume, \( \dot{\varepsilon} \) the volumetric strain rate, \( \beta \) a penalty constant with a large positive value, \( T_i \) the external force acting on a surface \( S_t \), and \( v_i \) the velocity. In the micro-modeling, \( \sigma \) takes the values \( \sigma_M \) in the steel matrix and \( \sigma_I \) in the inclusion.

The current velocity field is evaluated by minimizing the functional \( \Phi \). The solution is obtained in an iterative manner by using the Newton-Raphson method starting from the initial velocity fields derived from the direct iteration. Thus, the minimization of the functional can be replaced by solving the linearized equations:

\[
K \Delta V = F
\]

where \( K \) is the stiffness matrix, \( \Delta V \) the perturbed velocity vector and \( F \) the unbalanced force vector.

Then, an object-oriented code based on RPFEM has been developed, which is applied in Papers A and B.

In the code Forge3 used in Paper F, a similar principle is applied. In the part \( \Omega \), for any virtual velocity field \( \mathbf{v^*} \) and the associated virtual strain rate tensor \( \mathbf{\varepsilon^*} \), the rate form of the virtual work principle is stated in the rate form, with a mixed velocity-pressure formulation [47]:
\[
\int_{\Omega} \sigma' : \dot{\varepsilon} \, dv - \int_{\Omega} \tau \cdot \dot{\varepsilon} \, dv - \int_{\Omega} p \text{div}(\dot{\varepsilon}) \, dV = 0 \quad (5)
\]

\[
- \int_{\Omega} p \text{div}(\varepsilon) \, dV = 0 \quad (6)
\]

where \( \sigma' \) is the deviatoric stress tensor, \( \tau \) the shear stress, \( p \) the pressure field.

Forge3 is a real 3D code that can deal with complex geometries of dies and workpieces. Unfortunately, it cannot model multi-component behavior in the workpiece.

**Elastic-Plastic FEM (EPFEM)**

In Papers C, D and E, the numerical simulations are performed by using the elastic-plastic analysis code, ABAQUS/Explicit. This code constitutes a general-purpose finite element package which is not developed for forming processes only. It has the advantage of enabling multi-level models such as for local stress and strain analyses.

A central difference rule is applied to integrate the equations of motion explicitly through time, using the kinematic condition at one increment to calculate the kinematic conditions at the next increment. At the beginning of the increment the program solves for dynamic equilibrium, which states that the nodal mass matrix, \( M \), times the nodal accelerations, \( \ddot{u} \), equals the total nodal forces (the difference between the externally applied forces, \( P \), and the internal element forces, \( I \))

\[
M \ddot{u} = P - I \quad (7)
\]

The following equations are used for calculating accelerations, velocities and displacements:

\[
\ddot{u}_{(t)} = M^{-1} (P_{(t)} - I_{(t)}) \quad (8)
\]

\[
\dot{u}_{(t + \Delta t/2)} = \dot{u}_{(t - \Delta t/2)} + \frac{(\Delta t_{(t) + \Delta}) + \Delta t_{(t)}}{2} \ddot{u}_{(t)} \quad (9)
\]

\[
u_{(t + \Delta t)} = u_{(t)} + \Delta t_{(t + \Delta)} \left. \dot{u} \right|_{(t + \Delta t/2)} \quad (10)
\]

Eq. (7) is solved incrementally to determine the change in position of every node.
A comparison of the features for all the FEM codes used in the thesis is shown in Table 1.

Table 1. Features of the FEM codes used in the present thesis

<table>
<thead>
<tr>
<th>Features</th>
<th>RPFEM</th>
<th>EPFEM</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Own code</td>
<td>Forge3</td>
</tr>
<tr>
<td>Speed</td>
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<td>separated</td>
</tr>
<tr>
<td>Applications</td>
<td>Papers A, B</td>
<td>Paper F</td>
</tr>
</tbody>
</table>

**Paper A**

3.2 “FEM simulation of void formation close to an inclusion in a uniform matrix during plastic deformation”

This study focuses on void formation during plane strain compression of a matrix containing a hard inclusion. A numerical model is proposed and a rigid-plastic FEM code is developed.

![Fig.4. An inclusion/matrix deformation model](image-url)
The deformation model of the matrix containing an inclusion is presented in Fig. 4. The finite element mesh system is shown in Fig. 5.

Debonding at the interface between the inclusion and the matrix is assumed to occur if the tensile normal stress $\sigma_n$ reaches a critical value $\sigma_c$:

$$\sigma_n > \sigma_c$$  \hspace{1cm} (11)

If this debonding condition is satisfied, the corresponding interfacial elements will be eliminated in order to take away the connectivity between the inclusion and the matrix. Then new inner surfaces of the matrix and the inclusion are formed.

The normal radial stresses acting on the interfacial elements are considered as the interfacial stresses between the inclusion and the matrix. The distributions of the normal radial stresses along the interface for different nominal yield stress ratios $C_i/C_m$ of the inclusion to the matrix at the first iteration step are illustrated in Fig. 6. Fig. 7 shows the propagation of a void close to the inclusion for a nominal yield stress ratio $C_i/C_m$ of 3.0. It is concluded that the difference in yield stress between the inclusion and the matrix leads to the development of tensile stresses at the interface close to the horizontal axis.

This paper also treats the variations of void width along the inclusion-matrix interface with different ratios of $C_i/C_m$ and $C_b/C_m$. $C_i/C_m$ and $C_b/C_m$ represent the relative strength of the inclusion and the interface to the matrix.
Finally, the velocity fields for the inclusion and the surrounding matrix were exhibited and found to agree with the existing experimental results.

![Fig.6. Distribution of normal radial stresses along the interface at the first iteration step](image1)

![Fig.7. Propagation of void close to the inclusion](image2)

**Paper B**

3.3 “Deformation of inclusions during hot rolling of steels”

In this work the inclusion behavior in flat hot rolling has been studied by using a developed rigid-viscoplastic finite element code. The mesomechanical approach is utilized. The method connects the micromechanical behavior of the heterogeneous material with its macroscopic properties.
macroscopic behavior during the plastic deformation process. The macro-model evaluates the deformation history for each macro-element of the slab cross section neglecting the existence of inclusions. The deformation history gives boundary values for analyzing a micro-model cell element including an inclusion.

Fig. 8 shows the finite element mesh in the macro-model. Six representative elements are chosen for the present analysis. The selected elements are traced throughout the whole rolling process, when they move from the entrance to the exit. The locations, velocities and strain histories for the specified elements are stored for each iteration step.

A micro-element extracted from the macro-model is treated as a unit cell containing an inclusion that is placed in the center of the cell element on micro-level, Fig. 9. It is assumed that there is a perfect bonding between the inclusion and the matrix.

Transfer of nodal and elementary information from the macro-model to the micro-model is the key to connect the two-level models. This is done by interpolation, Fig. 10. This figure demonstrates two phases during data transfer: interpolation and embedding.

In order to verify the validation of transferring the data from the macro-model to the micro-model, the results obtained from the macro-model and the micro-model were compared. The method is proved to be correct.
Rolling temperature is the most active process parameter that affects the deformation of silicate inclusions during hot rolling of low carbon steel. Fig. 11 reveals the relation of relative plasticity indices of inclusions as a function of rolling temperature. The relative plasticity index increases with rolling temperature. There exists a narrow transition temperature region, below which the inclusion behaves as rigid and above which it becomes plastic and easily deformed. This trend agrees with experimental results.

Variations of strain for the inclusion and the surrounding matrix from the entrance to the exit of the roll gap are investigated. Influences of other process parameters, such as rolling speed, external friction and rolling schedule, are also examined.
Finally, the mechanism of the inclusion deformation during hot rolling is discussed. Effects of rolling temperature, strain and strain rate are explained.

**Paper C**

3.4 “A mesomechanical approach for studying the material behavior close to non-metallic inclusions in steel hot-rolling”

A two-level model is proposed, in which uncoupled macro- and micro-models are used. It is applied for simulating the local behavior of the material close to non-metallic inclusions during hot rolling of steels. The stress history of the sub-volume in the macro-model, including workpiece and rolls, is utilized as boundary loading conditions for the micro-model comprising both inclusion and steel matrix. This strategy differs from that used in *Paper B* where outer velocities of the cell from the macro-modeling are employed as boundary conditions in the micro-modeling.

As illustrated in Fig. 12, the local behavior of the material around an inclusion can be investigated by means of uncoupled two-level models under plane strain condition: a macro-model and a micro-model. To ensure the validity of transferring stress data from a macro-model to a micro-model, a verification procedure is performed, where the property of the matrix material is adopted for both the inclusion and the matrix.

Fig. 12. Schematic diagram of two-level models
Simulations have been carried out at two rolling temperatures (1200 and 800 °C) when the silicate inclusions behave as ductile and undeformable, respectively. The commercial code ABAQUS/Explicit is employed. As expected, the inclusion exhibits more plasticity than the steel matrix at higher temperature while it is nearly undeformable at lower temperature.

Histories of the average stresses $\sigma_x$ and $\sigma_y$ for the macro-element are plotted in Fig. 13. As expected, the normal stress in the vertical direction is compressive-dominated. It is also found that the normal stress in the horizontal direction becomes tensile near the entrance of the deformation zone. The deformation of the inclusion in the case of high rolling temperature (1200 °C) is presented in Fig. 14. The inclusion is heavily elongated during rolling due to its smaller yield stress compared to the steel matrix.

In the case of low temperature (800 °C), the inclusion has higher yield stress compared to the steel matrix. The deformation of the inclusion will be quite small. If an imperfect interface exists between the inclusion and the matrix, a void will be initiated and propagate. Fig. 15 shows the evolution of voids close to the inclusion at the central line of the workpiece. The void propagates gradually with respect to time elapsed.

If the macro-element is located near the surface of the workpiece, the shear strain and stress of the macro-element might be large. Fig. 16 gives the variation of the normal stresses $\sigma_x$ and $\sigma_y$. It is found that the normal stress $\sigma_y$ has a profile of saddle. It is interesting to note that the stress $\sigma_x$ is in strongly tensile state close to the entrance and the exit of the

---

![Figure 13](image1.png) **Fig. 13.** $\sigma_x$ and $\sigma_y$ histories of the macro-element at the central line of the workpiece (1200 °C)

![Figure 14](image2.png) **Fig. 14.** Changes in profile of an inclusion at the central line of the workpiece (1200 °C)
deformation zone. The result is that the voids open easily when the macro-element passes through these two areas. Three profiles of the voids after 0.0053, 0.016 and 0.028 seconds are shown in Fig.17. It is easy to find out the correspondence between the stress $\sigma_x$ and the opening of voids.

![Fig. 15. Evolution of voids close to the inclusion at the central line of the workpiece (800 °C)](image1)

![Fig. 16. $\sigma_x$ and $\sigma_y$ histories of the macro-element at the surface of the workpiece (800 °C)](image2)

![Fig. 17. Void profiles at three time points close to an inclusion at the surface of the workpiece (800 °C)](image3)

$t_1 = 0.0053$ s  
$t_2 = 0.016$ s  
$t_3 = 0.028$ s

**Paper D**

**3.5 “Evolution of voids close to an inclusion in hot deformation of metals”**

In practical metal forming, such as rolling and forging of steels, non-metallic inclusions and their surrounding metal matrix are often subjected to compressive loading. In this paper, two compressive loading modes are
considered: displacement-controlled loading and stress-controlled loading. The loading modes for the computational domains are shown schematically in Fig. 18.

![Fig. 18. Boundary conditions regarding two loading modes](image)

Attention is directed towards the inclusion-matrix interface. Debonding and friction at the interface are taken into account. In the case of displacement-controlled loading, it is assumed that the interfacial boundary is bonded initially. Interfacial failure in the case may occur either by tangential shear stresses or normal stresses. In the case of stress-controlled loading, it is assumed that an imperfect interface exists between the inclusion and the matrix, which is the situation in Paper C.

Therefore, simulations were carried out for the two cases of loading, where ABAQUS/Explicit code is employed.

The case of displacement-controlled loading is intended for plane strain upsetting. A sequence of convex voids with two cusps are formed around the hard inclusion after interfacial debonding, meanwhile the horizontal width of voids increases with increasing reduction of the matrix. Self-welding of the matrix at a new cusp of the void takes place with the emergence of metals from above and below the inclusion after a certain critical strain. The volume of the void shrinks somewhat with further deformation of the matrix. Afterwards the voids keep its shape almost unchanged. However, the length of the self-welding lines increases (Fig. 19). Evolution of voids with deformation of the matrix regarding self-welding of matrix can be also considered as two major phases: opening of void and self-welding (Fig. 20). From the relative motion at the inclusion-matrix interface, three zones are proposed to describe the deformation
features, which are separating zone, sliding zone and sticking zone. A shearing band and occurrence of virgin surfaces around the inclusion are believed to be significant features under compressive loading.

The case of stressed-controlled loading is intended to analyze the behavior of inclusions during plate rolling. By using a two-level model (refer to Paper C), evolution of voids is also analyzed. Under the condition of hot deformation with viscous inclusions, rolling temperature

Fig. 19. Schematic of void and self-welding line

Fig. 20. Variation in void width with respect to reduction in height

The case of stressed-controlled loading is intended to analyze the behavior of inclusions during plate rolling. By using a two-level model (refer to Paper C), evolution of voids is also analyzed. Under the condition of hot deformation with viscous inclusions, rolling temperature
is one of the most important parameters. The void width varies with temperature, as shown in Fig. 21. Fig. 22 illustrates the propagation of a void at 950 °C. It is seen that temperature has a decisive effect on the formation of voids and their shapes and sizes. In two-pass rolling, self-welding is found to occur during the second pass at low temperature. Finally, the paper treats the formation mechanism of void during rolling.

![Graph showing void width as a function of temperature](image)

**Fig. 21. Void width as a function of temperature**

![Images of voids at different times](image)

**Fig. 22. Evolution of voids at 950 °C**

**Paper E**

### 3.6 “An alternative way for evaluating the deformation of MnS inclusions during hot rolling of steel”

In this paper, automatic image processing technique has been used for analyzing the MnS size, number and morphology in steel during hot rolling of plate. The workpiece was up to a nominal reduction in height of 85% in four passes, at rolling temperatures of 700-1200 °C with interpass reheating. Particular attention was paid to the effect of rolling temperature and rolling reduction (Fig. 23). Histograms showing the orientations of
the inclusions before and after deformation are presented in Fig. 24. Consequently, the relative plasticity and orientation of inclusions are quantitatively assessed with the help of the image-processing tool.

Finite element analyses (ABAQUS/Explicit) are performed in order to scrutinize the conception of “relative plasticity”, which is based on dimensional change of the inclusion. It is clear that aspect ratio calculations, regarding inclusions that are inclined to the major axis of rolling, will underestimate the strain. Furthermore, inclusion reorientation is investigated. A profile evolution for the case of ellipse 45° inclusion is illustrated in Fig. 25. Both elongation and rotation of the inclusion are clear from the figure. Considering reductions less than approximately 40%, the inclusion ‘rotates’ towards the horizontal axis up to 30° and only small elongation occurs. However for heavier reductions inclusion elongation prevails.

Fig. 23. Experimentally obtained results: influence of rolling temperature and reduction on the mean relative plasticity index

Fig. 24. Histogram showing reorientation of inclusions during rolling at 900 °C
Fig. 24. Continued

(b) reduction 30%

(c) reduction 58%

Fig. 25 Orientation and aspect ratio as a function of reduction for ellipse 45° inclusion
3.7 “A study of behavior of inclusions in hot forging of steel by means of three-dimensional FE-analyses”

The principal objective of the study is to develop a FEM-based analytical method that would be capable of exploring the behavior of inclusions in the billet during forging. The main focus is on the movement and deformation of inclusions inside the billet.

The Forge3 code has been employed to perform 3D simulations of the closed-die forging of an intermediate shaft. After completing the simulations, it is possible to trace the deformation of a shape represented by a surface mesh, i.e. the marking grid. A spherical particle is chosen to model the behavior of inclusions or segregation, which are assumed to have the same flow stress as the steel matrix. This tracing can be done in two ways: forward marking and backward marking processes.

The entire forging process consists of two stages: preforming and finish forging. Four positions, represented by A, B, C and D along the x-axis (as shown in Fig. 26), are considered.

Fig. 26. Locations of the points to be analyzed at the end of finish forging

Fig. 27. Deformation of the inclusions at different locations in the x, y, and z directions (the inclusions are located at the center of the cross-section circle at the beginning)
Fig. 27 illustrates the deformation of inclusions along the three co-ordinate directions. The ‘deformation’ is defined as the natural logarithm of the dimension ratios, i.e. $dx/d0$, $dy/d0$ and $dz/d0$, where $dx$, $dy$ and $dz$ represent the projected length of the deformed inclusions on the $x$, $y$ and $z$ axes, respectively, and $d0$ is the initial diameter of the inclusion. The inclusions at positions A and D are up to tensile deformation in the $x$ direction and compressive deformation in the $y$ and $z$ directions. On the other hand, the inclusions at positions B and C are compressed in the $x$ direction and enlarged in the $y$ and $z$ directions. In other words, the inclusions at positions B and C may be deformed, as in axial upsetting of a cylinder. Fig. 28 shows the appearance of inclusions at the different locations after finish forging, as viewed from the negative $y$ direction.

![Fig. 28. Appearance of inclusions at the central line after finish forging](image)

Furthermore, the behaviour of inclusions around the central line, within cross-sections with the same $x$ co-ordinate as positions A or C, is explored. The movements of the three inclusions with orientation angles $0^\circ$, $45^\circ$ or $90^\circ$ within cross-section C are shown in Fig. 29.

Finally, the effect of stress state on the void formation near hard inclusion is examined. Tensile stresses in the $y$ direction are found near to both edges, which may result in possible void formation.
4. Concluding remarks

The finite element method is utilized to model the behavior of inclusions and their surrounding matrix in plastic deformation of steels. Both an own developed code and commercial codes are used. The following concluding remarks can be drawn from the thesis:

1) The numerical simulation (FEM) is an effective tool for analyzing the deformation of inclusions and void formation in a steel matrix during plastic working of materials. If the interfacial strength and flow stresses of inclusion and matrix are known, the behavior of inclusions and the surrounding matrix during can be predicted and monitored.

2) Two-level model can deal with the micro-inclusions and the surrounding matrix where they are experiencing a dynamic deformation process. Influence of process parameters can be analyzed.

3) Automatic image processing technique, used for analyzing the inclusion size, number, and morphology in steel during plastic deformation, is a helpful way to examine inclusions.
4) By using forward and backward tracing techniques, the deformation and position of inclusions can be explored during 3D simulation of forging of steel.

5. Future work

1) The proposed two-level model may be applied to 3D modeling of inclusions and their surrounding matrix. It is also a potential tool for modeling any inclusion-matrix composites.

2) Modeling of multiple inclusions and matrix system should be the subject in the future work. Number, arrangement and orientation of inclusions will be considered.

3) More experimental verifications of the results of the modeling should be carried out. Both plasticine and real materials will be used.

4) Fracture of inclusions is also an interesting and challenging work in the future.

6. References


ABSTRACT: A numerical model is presented, which aims to simulate void formation close to the inclusion in the matrix during plastic deformation. Debonding at the interface between the inclusion and the matrix is assumed to occur if the tensile normal stress reaches a critical value. Void propagation is driven by the tendency of separating the matrix from the inclusion. The difference in yield stress between the inclusion and the matrix is one common reason for void initiation and propagation. A rigid-plastic finite element code has been developed for analyzing behavior of a matrix containing an inclusion under plane strain condition. The Finite element simulations regarding void formation show good agreement with existing experimental results.

1. INTRODUCTION

Most metal materials are microscopically inhomogeneous. Steel with inclusions is a typical example and can be theoretically treated as a composite. In the hot forming of steels containing non-metallic inclusions, it is well known that voids of conical shape are frequently nucleated at the ends of inclusions as for example during rolling. It is particularly true if the inclusion is behaving non-plastically (Rudnik 1966, Charles & Uchiyama 1969, Baker & Charles 1972, Waudy 1972, Klevebring & Mahrs 1973).

For a general growth of voids due to plastic deformation of the matrix, some works have already been done on cylindrical voids (McClintock 1968, Tracey 1971) and spherical voids (Rice & Tracey 1969, Glennie 1972) in plastic materials. The mechanism of void formation during ductile fracture has been the topics of many researchers (Argon et al. 1975).

Physical modeling of ductile fracture during metalforming has been performed by Ståhlberg (1979), Kao & Kuhn (1990).

Numerical simulations regarding deformation of an inclusion in a matrix have recently been conducted. The finite element method (Gilormini & Monttheillet 1987, Nagayama et al. 1989, Pietrzky et al. 1991, Dharan & Kobayashi 1992, Milenin 1995) was used to analyze the strain distributions around an inclusion.

This study focuses on void formation and the mechanisms during plane strain compression of a matrix with a hard inclusion.

2. THEORETICAL MODEL

2.1 Finite element method

The rigid-plastic finite element method, which was proposed by Lee & Kobayashi (1973), is adopted. The correct velocity fields are given by minimizing the functional $\Phi$:

$$\Phi = \int \sigma \varepsilon dV + \frac{1}{2} \beta \dot{\varepsilon}^2 dV - \int T u dS$$

where $\sigma$ is the effective stress, $\varepsilon$ the effective strain rate, $V$ the volume, $\dot{\varepsilon}$ the volumetric strain rate, $\beta$ a penalty constant, $T$ the external force acting on a surface $S$, and $u$ the velocity.

2.2 Analytical model

The deformation model of the matrix containing an inclusion is presented in figure 1. Because of the geometry and loading symmetry, only one quarter of the mesh is considered. The symmetry boundary conditions are enforced by coupling the nodal velocity $V_x$ or $V_y$ along the outer boundary. This modeling technique is commonly defined as the “unit cell” approach.
The finite element mesh system is shown in figure 2. The left lower part (OAE) of the picture is a cylindrical inclusion and the right upper part (ABCDE) is a matrix. They are separated by a thin layer of interfacial elements (curve AE). Here it may not be visible because of its very thin thickness.

In the mesh model (figure 2), DC is the contact surface between the matrix and the tool. In the rigid-plastic finite element analysis, the velocity of DC is prescribed as a known loading condition. CB is free surface. DO and OB are vertical and horizontal symmetry lines.

2.3 Academic problems

At the interface between the inclusion and the matrix, the normal tensile stress is identified as a primary condition for void formation. Debonding at the interface between the inclusion and the matrix is assumed to occur if the tensile normal stress $\sigma_n$ reaches a critical value $\sigma_c$:

$$\sigma_n > \sigma_c$$  \hspace{1cm} (2)

If the debonding condition above is satisfied, the corresponding interfacial elements will be eliminated in order to take away the connectivity between the inclusion and the matrix. Then new inner surfaces of the matrix and the inclusion are formed.

During deformation process, such large geometrical distortions of remaining interfacial elements are found locally that remeshing is necessary.

Correction of nodal points on the inner surface of the matrix is performed to escape to penetration of the matrix to the inclusion.

In order to decrease the influence of the contact friction between the matrix and the tool upon the deformation, a very small friction factor (0.0001) is applied.

3. COMPUTER PROGRAM

The FEM simulation system has been developed to simulate the plastic deformation process of the steel, i.e. composite including matrix and inclusion. The flow stress equation for viscous plastic materials is selected to model hot deformation:

$$\sigma = C \dot{\varepsilon}^m$$ \hspace{1cm} (3)

For different system components (i.e. the matrix, the inclusion and the interface) in figure 2, the constants $C$ and $m$ have different values. From the viewpoint of numerical calculations, the only difference between the matrix and the inclusion is the values of constants $C$ and $m$.

The flow chart of the computer program is showed in figure 3.

The work was done on a PC (Pentium Pro 200 MHz) and the code was implemented using Fortran language.

4. NUMERICAL RESULTS

Numerical simulations were carried out by using following input data. Here, absolute values of the data are not important:

Cell size: 10 × 10 mm
Inclusion radius: 2 mm
Constants: $C_m = 10$ MPa;
$C_i = 12-30$ MPa;
$C_b = 8-15$ MPa;
4.1 Interfacial stress between the inclusion and the matrix

The normal radial stresses acting on the interfacial elements are considered as the interfacial stresses between the inclusion and the matrix. The distributions of the normal radial stresses along the interface for different nominal yield stress ratios $C_i/C_m$ of the inclusion to the matrix at the first iteration step are illustrated in figure 4.

When the ratio $C_i/C_m$ equals to 1, the normal radial stresses are always negative, i.e. compressive. This compressive stress state is gradually increased for increasing values of the angle $\theta$. This means that there is no tendency or driving force for separating the inclusion from the matrix. However, tensile stresses can occur when increasing the nominal yield stress ratio. The maximum tensile stresses are found for a position defined by an angle of approximately 25°.

The schematic picture, figure 5 shows the formation of void. If there exist normal tensile stresses at the interface between the inclusion and the matrix, it will contribute to debonding the interface. When the inclusion is harder than the matrix material, this fact generally means that the matrix/inclusion boundary surface is separated from the inclusion resulting in the creation of a void close to the horizontal axis. Therefore, the stresses at the interface are of importance since they can be used to determine the conditions for interfacial failure during plastic deformation.
4.2 Propagation of void close to the inclusion

Figure 6 shows the propagation of a void close to the inclusion for a nominal yield stress ratio $C_i/C_m$ of 3.0. It is obvious that the surface of the matrix moves away from that of the inclusion to form the void. The void propagates as the reduction of the material proceeds. In fact, there is a strong tendency for the inner surface of the matrix to flow towards positive direction of $x$-axis as long as the void is formed. It is noted that the void ranges from $0^\circ$ to $30^\circ$, which is consistent with the distribution of normal tensile stresses in figure 4.

4.3 Width of void

The width of void is defined as the horizontal distance between two points of same y-coordinate on the inner surfaces of the matrix and the inclusion. It reflects current void sizes. Figures 7-9 show the changes of the width of void along the interface with different ratios of $C_i/C_m$ and $C_b/C_m$. $C_i/C_m$ and $C_b/C_m$ represent the relative strength of the inclusion and the interface to the matrix.

When $C_b/C_m$ is 0.8 and 1.0, voids occur for all cases of $C_i/C_m = 1.2$, 1.5 and 3.0 (figures 7 & 8). When $C_b/C_m$ is 1.5, voids are formed only for two cases of $C_i/C_m = 1.5$ and 3.0 (figure 9). It is found from the figures that the formation of void is more possible for the cases of the hard inclusion and the soft interface.

Figure 10 shows the effect of friction at the interface between the matrix and the tool on the width of void. If the unit cell is located on the contact surface of the matrix with the tool, then the friction will affect the deformation process. The figure indicates that friction will increase the width of void.

4.4 Velocity field

The velocity fields are displayed in figures 11 and 12. For the soft inclusion ($C_i/C_m=1.2$), plastic flow occurs inside the inclusions (figure 11). However, plastic flow is almost absent within the hard inclusion (figure 12). There is a good agreement with an experimental diagram (Ståhlberg 1979).
5. CONCLUSIONS

1) The mechanism of void formation close to the inclusion in the uniform matrix during plane strain compression is analyzed by rigid-plastic FEM.

2) The tensile normal stress at the interface between the inclusion and the matrix can be considered to be responsible for debonding and void formation.

3) The difference in yield stress between the inclusion and the matrix leads to the development of tensile stresses at interface close to the horizontal axis.

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REFERENCES


Paper B
A mesomechanical approach for studying the material behavior close to non-metallic inclusions in steel hot-rolling

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Summary

A two-level model, in which uncoupled macro- and micro- models were used, was proposed to simulate local behavior of material close to non-metallic inclusions during hot rolling of steels. The stress history of sub-volume in the macro-model including workpiece and rolls is utilized as boundary loading conditions for the micro-model comprising both inclusion and steel matrix. Simulations have been done at two rolling temperatures (1200 and 800 °C) when the silicate inclusions behave as ductile and undeformable, respectively. As expected, the inclusion exhibits more plasticity than the steel matrix at higher temperature while it is nearly undeformable at lower temperature. Moreover, the possibility of void formation was found to be high for inclusions close to the surface due to strong tensile stresses acting in the horizontal directions.

1. Introduction

Non-metallic inclusions in steels, depending on their composition and structure, will exhibit different behaviors during hot rolling. It is well known from experimental works [1-12] that ductile non-metallic inclusions are heavily elongated along the rolling direction in a similar way as the steel matrix, and voids may occur close to the undeformable inclusions during hot rolling of steels. A number of studies reported in the literature [13-18] were specifically aimed at investigating plastic deformation of inclusions and related fracture from micromechanical viewpoint where simple loading conditions were applied. There are few works [19-20] done recently regarding behavior of inclusions during rolling process. Im and Dharan [19] analyzed the micromechanics of unidirectional fibre-reinforced composites using elastic-plastic finite element method in investigation of the mechanical behavior of composite materials. They applied the slab method used in classical metal forming processes directly to the forming of metal matrix composites to calculate the macroscopic stresses in the workpiece. The overall metal matrix composite is assumed to be loaded by average stresses in horizontal and vertical directions. The ratio of stresses in these two directions was proposed as a main parameter that affects void formation and fiber-breakage. More recently, Luo and Ståhlberg [20] studied deformation of inclusions during hot rolling of steels by means of rigid-viscoplastic finite element method. The analysis was based on a mesomechanical approach. This method connects the micromechanical behavior of the heterogeneous material with its in-service macroscopic behavior. The macro-model evaluates deformation history throughout each sub-volume of the steel without taking the influence of inclusions into account. The micro-model
that includes both inclusion and steel matrix makes use of the strain history of the macro-element in the macro-model as boundary values.

The influence of inclusions on plastic deformation of metals can be studied theoretically in the same principle way as that used for composite materials. The size of non-metallic inclusions, generally, is much smaller than that of matrix material, which implies difficulties for computer simulations of large plastic deformation processes such as rolling and forging. FE-simulations need extremely long computation time considering the requirement of a discretization at least as fine as the heterogeneities to enable an adequate analysis of the local phenomenon associated with an inclusion. Strictly speaking, this is impossible due to irregular distributions of inclusions throughout the steel matrix. On the other hand, when a micromechanical model for inclusion/matrix cell is employed to study the local behavior of the material, actual loading conditions are required. The advantage of micromechanical model over a macromechanical model is that the stresses can be associated and related to each constituent (inclusion and matrix). Plastic working of steels with inclusions, however, is a dynamic process, which means that the loading conditions of a cell model in the micromechanical analysis should vary with time. Consequently it is significant that loading data for the cell model are obtained directly from the simulation of full-scale forming process. This is regarded as a tie that links the macro-process analysis with the micromechanical analysis.

In the present paper, a mesomechanical framework, in which uncoupled macro- and micro-models were established, was developed to study local behavior of material close to non-metallic inclusions during hot rolling of steels. By means of a macro-model the stress-strain history throughout each sub-volume of the steel was evaluated, where the stress components with respect to time were recorded as history data. No consideration was taken to the existence of inclusions. The micro-model, that includes both inclusion and steel matrix, utilizes the stress components from the macro-model as boundary conditions. The simulations were performed with the commercial finite element package ABAQUS/Explicit.

2. Plasticity models and material properties

During hot rolling process, the steel matrix and non-metallic inclusion are considered as rate-dependent elastoplastic materials, which means that viscoplastic material models are required. The deformations are assumed to be divided into elastic and plastic parts and expressed in the general form as

\[ \mathbf{F} = \mathbf{F}^e \cdot \mathbf{F}^p \]  \hspace{1cm} (1)

where \( \mathbf{F} \) is the total deformation gradient, \( \mathbf{F}^e \) the elastic deformation and \( \mathbf{F}^p \) the plastic deformation.

For small elastic strains the additive decomposition of the rate of deformation into elastic and viscoplastic parts is assumed and given by

\[ \mathbf{D} = \mathbf{D}^e + \mathbf{D}^p \]  \hspace{1cm} (2)
where $D$ is the rate of deformation tensor, $D^e$ the elastic part, and $D^p$ the plastic part. $D$ is the symmetric part of the velocity gradient with respect to the spatial coordinates $x$.

The constitutive equations for the viscoplastic rate of deformation are given by Perzyna [21]

$$
\begin{align*}
D^p &= \gamma \Phi(\hat{F}) \frac{\partial f}{\partial \sigma} \\
&\quad \text{for } \hat{F} > 0 \\
D^p &= 0 \\
&\quad \text{for } \hat{F} < 0
\end{align*}
$$

where $\sigma$ is the Cauchy stress tensor and $\Phi$ is a material functional of the yield function

$$
\hat{F} = \frac{f}{\kappa} - 1
$$

In the present paper, the steel was treated as a composite consisting of an inclusion embedded randomly in a steel matrix. Under the hot working conditions, both steel matrix and inclusion are strain rate dependent. The equivalent plastic strain is given by

$$
e^p = \int_0^t \sqrt{\frac{2}{3}D^pD^p} dt
$$

The flow stresses of the inclusion and the steel matrix were taken from the experimental work by Bernard et al. [11]. The inclusions system MnO-Al2O3-SiO2 was selected. The equivalent stress $\sigma_i$ of the inclusion can be expressed as a function of temperature ($T$) and strain rate ($\dot{\varepsilon}$)

$$
\sigma_i = \frac{3\dot{\varepsilon}}{10} T \exp\left(\frac{3.99 \times 10^4}{T} - 22.06\right)
$$

For a low alloy, carbon steel matrix the equivalent stress $\sigma_M$ can be written [11]

$$
\sigma_M = 3.37 \times 10^6 \exp\left(\frac{5000}{T}\right) \dot{\varepsilon}^{0.23} (0.276\dot{\varepsilon})^{0.1327 - 273/1000}
$$

The numerical simulation is performed as a non-linear explicit dynamic analysis using the general-purpose finite element package ABAQUS/Explicit. A central difference rule is applied to integrate the equations of motion explicitly through time, using the kinematic condition at one increment to calculate the kinematic conditions at the next increment. At the beginning of the increment the program solves for dynamic equilibrium, which states that the nodal mass matrix, $M$, times the nodal accelerations, $\ddot{u}$, equals the total nodal forces (the difference between the external applied forces, $P$, and internal element forces, $I$)

$$
M\ddot{u} = P - I
$$

The following equations are used for calculating accelerations, velocities and displacements:
\[
\ddot{\mathbf{u}}_{(t)} = \mathbf{M}^{-1}(\mathbf{P}_{(t)} - \mathbf{I}_{(t)}) 
\]

(9)

\[
\dot{\mathbf{u}}_{(r+\Delta t/2)} = \dot{\mathbf{u}}_{(r-\Delta t/2)} + \frac{(\Delta t_{(r+\Delta t)} + \Delta t_{(r)})}{2} \ddot{\mathbf{u}}_{(r)} 
\]

(10)

\[
\mathbf{u}_{(r+\Delta t)} = \mathbf{u}_{(r)} + \Delta t \dot{\mathbf{u}}_{(r+\Delta t/2)} + \frac{\Delta}{2} \ddot{\mathbf{u}}_{(r+\Delta t/2)} 
\]

(11)

Equation (8) is solved incrementally to determine the change in position of every node [22].

3. Two-level models

As illustrated in figure 1, the local behavior of material around an inclusion in a rolling process can be investigated by means of uncoupled two-level models under plane strain condition: a macro-model and a micro-model.

A macro-modeling allows us to analyze the overall mechanical behavior during rolling of steels. Figure 2 displays the finite element mesh of a macro-model. Due to the symmetry, only the upper half part is considered. The model includes 2000 4-node bilinear elements with reduced integration, arranging 100 elements in the length direction and 20 elements in the thickness direction. The simulation starts from the initial bite to almost steady state under plane strain rolling condition. By means of the macro-model the stress-strain history throughout each sub-volume (i.e. macro-element) of the workpiece can be evaluated, where the stress and strain components are recorded with respect to time as history data. The global mechanical response of the steel workpiece during rolling is characterized by the overall stresses of steel matrix, while the contribution of inclusion to matrix strength is ignored. Coulomb friction at the workpiece-roll interface is employed in this work and the rolls are assumed to be rigid.

The micro-model, which is constructed by embedding a circular inclusion (I) in a matrix cell (M) extracted from the macro-model, utilizes the stress history obtained from the macro-
modeling as boundary loading condition, as shown in figure 1. This stress history is applied as a function of time. To facilitate the analysis, only normal stresses $\sigma_x$ and $\sigma_y$ were considered in the present paper. When the macro-element is located close to the central line of workpiece, the shear stresses will become so small that their effects can be neglected. Of course, the importance of the shear stresses can not be neglected to materials far from the central line, particularly near the surface of the workpiece. The micro-model adopts 4-node element with a total of 716 elements for the matrix and 179 elements for the inclusion, as shown in figure 3. Because of the symmetry of the loading and the geometry of the cell when no tangential loading being taken into account, only the first quadrant is to be modeled in this paper, the applied boundary conditions are also shown in figure 3. Two interfacial states between the inclusion and the steel matrix are assumed: perfect bonding and debonding. For the latter, Coulomb friction law between the inclusion and the steel matrix is to be employed to model the interfacial interaction. It is worth noting that a local coordinate system ($x'-y'$), which is independent of whole coordinate system ($x-y$) used in the macro-model, was employed.

![Figure 2. Finite element mesh of the macro-model](image2)

![Figure 3. Finite element mesh and boundary conditions of the micro-model](image3)
Consequently, in the mesomechanical approach, the stress history of sub-volume in the macro-model including workpiece and rolls is utilized as boundary loading conditions for the micro-model comprising both inclusion and steel matrix. This strategy differs from what was used in the recent work [20] where outer velocities of the cell from the macro-modeling were employed as boundary conditions in the micro-modeling. The radius of inclusion embedded in the matrix is supposed to be one tenth of the micro-cell so as to reduce the influence of size factor upon the simulation results. The temperature is assumed to be constant throughout the simulation both in the macro- and micro-models.

To ensure the validity of transferring stress data from a macro-model to a micro-model, a verification procedure was performed, where single material property was adopted. The verification compares the equivalent plastic strains from the macro-element with those from the micro-elements, as shown in figure 4. It was found that, the transfer of stress and strain data between the present two-level models is reasonable.

4. Simulation results

The conditions used for the simulation are as follows:

Roll radius: \( R = 110 \text{ mm} \)
Initial thickness of workpiece: \( H = 20 \text{ mm} \)
Rolling reduction: \( \varepsilon = 20\% \)
Rolling temperatures: \( T = 1200 \text{ and } 800\degree C \)
Rolling velocity: \( V_R = 1000 \text{ mm/s} \)
Friction coefficient: \( \mu_{\text{macro}} = 0.3 \) at the interface between the rolls and the workpiece
Friction coefficient: \( \mu_{\text{micro}} = 0.5 \) at the interface between the inclusion and the matrix
Initial inclusion diameter: \( D = 50 \mu\text{m} \)
Young’s modulus: \( E_{\text{matrix}} = E_{\text{inclusion}} = 200 \text{ GPa} \)
Poisson ratio: \( \nu_{\text{matrix}} = \nu_{\text{inclusion}} = 0.3 \)
Numerical experiments were performed on the two-level models to investigate the material behavior close to non-metallic inclusions in hot rolling of steels. Two rolling temperatures (1200 and 800 °C) were chosen for the simulations when the silicate inclusions behave as ductile and undeformable, respectively. To exclude the influence from size factor during simulations as mentioned before, the dimension for the micro-cell is designed as same as that of the macro-element, i.e. the micro-model becomes a sub-model of the macro-model. The stress history of the macro-element obtained from the macro-modeling was transferred to be available for the micro-modeling.

A variation of the equivalent plastic strain for a macro-element at the central line of the workpiece is shown in figure 5. The representative historical locations (1, 2, 3, 4 and 5) with

Figure 6. Schematic diagram of locations of the macro-element at the central line of the workpiece (1200 °C)

Figure 7. $\sigma_x$ and $\sigma_y$ histories of the macro-element at the central line of the workpiece (1200 °C)

Figure 8. Changes in profile of an inclusion at the central line of the workpiece (1200 °C)

Figure 9. Evolution of voids close to the inclusion at the central line of the workpiece (800 °C)

A variation of the equivalent plastic strain for a macro-element at the central line of the workpiece is shown in figure 5. The representative historical locations (1, 2, 3, 4 and 5) with
time are also depicted. Figure 6 illustrates the corresponding locations of the macro-element with respect to time in the roll gap. It is seen that the deformation of the macro-element has almost ended after 0.02 second. Histories of the average stresses $\sigma_x$ and $\sigma_y$ for the macro-element are plotted in figure 7. It is known from the calculation that the shear stress for the macro-element are quite small or even zero when it is located at the central line of the workpiece. As expected, the normal stress in the vertical direction is compressive-dominated. It is also found that the normal stress in the horizontal direction becomes tensile near the entrance of the deformation zone. The deformation of inclusion in the case of high rolling temperature (1200 °C) is presented in figure 8. The inclusion is heavily elongated during rolling due to its smaller yield stress compared to the steel matrix at high temperature. Discussion can be found in the recent work [20]. Voids close to inclusion will not occur under this condition. Computational practices also testify that even if in the debonded interfacial case the interfacial sliding between the inclusion and the steel matrix is quite small.

In the case of low temperature (800 °C), the inclusion has higher yield stress compared to the steel matrix. The deformation of the inclusion will be quite small. If an imperfect interface exists between the inclusion and the matrix, void will be initiated and propagated. Figure 9 shows the evolution of void close to the inclusion at the central line of the workpiece. The void is propagated gradually with respect to time elapsed. At final stage, the profiles of voids change from convex to convex-concave. Figure 10 shows the corresponding variations of average stresses for the macro-element at the central line of the workpiece, which has similar variations as shown in figure 7 but different in values of stresses due to the difference in rolling temperatures. Variation rate of stresses within the deformation zone affects propagation of voids.

If the macro-element is located near the surface of the workpiece, the shear strain and stress of the macro-element might be large. Nevertheless, as mentioned before, only the normal stresses $\sigma_x$ and $\sigma_y$ are imposed on the micro-cell model. It was notice that the basic feature of deformation is still available even when shear stresses are absent. Figure 11 gives the variation of the normal stresses $\sigma_x$ and $\sigma_y$. It was found that the normal stress $\sigma_x$ has a profile of saddle. It is interesting to note that the stress $\sigma_x$ is in strong tensile state near the entrance.
and the exit of the geometry deformation zone. This will result in opening voids easily when
the macro-element passes through these two areas. Three profiles of the voids at time 0.0053,
0.016 and 0.028 seconds are shown in figure 12(a) and (b), without and with tangential
stresses, respectively. It is easy to find out the correspondence between the stress $\sigma_x$ and the
opening of voids. At time 0.0053 second, the void opens like the case in uniaxial tension
when the stress $\sigma_x$ is strong in tensile near entrance of the deformation zone. Under
compressive dominated loading in the vertical direction, the void is to be closed somewhat
during the middle phase (0.016 second). Then the voids open again when the normal stress $\sigma_x$
becomes strongly tensile near the exit of the deformation zone. The importance of shear
stresses is clear from figure 12(b). It is evident that the void will be opened in the direction of
inclination at an angle from the horizontal axis as tangential loadings are considered. It should
be pointed that void formation in figure 12(b) was predicted by using additional micro-
modeling which is constructed under asymmetrical condition due to existence of tangential
loadings.

Figure 13 shows the equivalent plastic strain contours at two temperatures (1200 and 800 °C)
from the micro-modeling. The overall plastic strain is approximately 0.3 while the cell
element changes its profile from square to rectangular. Severe plastic strain happens to the
‘soft’ inclusion at high temperature (1200 °C). The distribution of the equivalent plastic strain
is found to agree with that in the previous work [20]. At low temperature (800 °C), the ‘hard’
inclusion induces a void formation close to it and two large strain regions appear along the

(a) Without consideration of tangential loading

(b) With consideration of tangential loading

Figure 12. Void profiles at three time points close to
an inclusion at the surface of the workpiece (800 °C)
horizontal and vertical axes of symmetry. Distinguished local deformation occurs in these two cases.

5. Concluding remarks

Numerical experiments conducted on hot rolling of steels simulate the materials behavior close to non-metallic inclusions in the process. A mesomechanical approach proposed, which can connect the two-level models, is capable of predicting the local behavior close to the inclusions in steels. The deformation of the inclusion and the void formation and propagation near the inclusion can be explored in detail when using this approach properly. Systematic investigations with consideration of both normal stresses and shear stresses on the micro-cell boundaries are left for the future work.

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References

Paper D
Paper E
Paper F