Micromechanism of Ductile Crack Initiation in Structural Steels Based on Void Nucleation and Growth

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The effect of the specimen geometry and the inclusion content on the critical condition for ductile crack initiation was determined using notched round bar tensile specimens, and the critical void volume fraction and secondary void nucleation effect were investigated using the Gurson–Tvergaard constitutive model. It is shown that the secondary void nucleation from pearlite nodules plays a dominant role in ductile crack initiation, and void nucleation and void growth behavior are strongly affected by the stress triaxiality and the plastic strain. In the large plastic strain and low stress triaxiality region, a large number of secondary voids were nucleated in the early stage of deformation and void volume fraction grew to a critical value in spite of the relatively low void growth rate at low stress triaxiality. On the other hand, in the low plastic strain and high triaxial stress region, void volume can grow rapidly even though the volume of secondary nucleated void was smaller than that of high plastic strain region. Critical void volume fraction decreases largely with increasing in MnS content in the high triaxial stress region; however, the effect of MnS content is small in the low stress triaxiality and large plastic strain region.

KEY WORDS: structural steel; ductile fracture; void nucleation; void growth; crack initiation; FEM analysis; inclusion.

1. Introduction

Ductility is an important property for structural steels and for steel structures, to prevent serious damage of the steel constructions from large earthquakes. Steel buildings are designed to allow plastic deformation of the steel members to absorb seismic energy. However, following a recent large seismic event, it has been reported that strain concentration in sections having structural discontinuity lead to an occurrence of ductile cracking which terminated with brittle fracture of the steel member after a small distance of ductile crack propagation. It can be stated that clarification of the conditions leading to ductile crack initiation in structural steels is needed in order to assure the integrity of the steel structures.

The process of ductile fracture is explained by the behavior of voids through the process such as void nucleation from inclusions or second phase particles, growth of the voids and coalescence of the voids that leads to an onset of ductile tearing. Void growth is accelerated by a triaxial stress state, and many investigations have been done on ductile crack initiation criterion in relation to the void growth rate. Recently the Gurson–Tvergaard constitutive model for void-containing materials, which was originally proposed by Gurson and later modified by Tvergaard, has been gaining popularity and has been widely used for investigation of ductile fracture. The yield surface in the Gurson–Tvergaard model is affected by hydrostatic stress, while classical plasticity assumes that yielding is independent of hydrostatic stress. The Gurson–Tvergaard model can demonstrate the softening behavior of the material in relation to void growth, and a criterion for void coalescence is determined by the critical void volume fraction. Tvergaard and Needleman suggested a constant critical void volume fraction of 0.15, and this criterion has been used for many applications. However, Shi et al. showed strong dependence of the critical void volume fraction on stress triaxiality by experimental investigations, and Koplik and Needleman also suggested that the critical void volume fraction depends on the initial void volume fraction and the stress triaxiality.

In general, ductility of materials is improved by decreasing the volume fraction of nonmetallic inclusions and second phase. Lautridou and Pineau proved that there is a close relation between the COD at crack initiation and the inclusion distribution, and proposed that the characteristic size for ductile fracture is the average distance of inclusions in a plane perpendicular to the crack front. Gladman et al. and Melander and Steninger observed void nucleation at pearlite nodules as a result of cracking in the pearlite colony. Qiu et al. also observed that pearlite nodules are a major nucleation site for the secondary-nucleated voids, and nucleation of the secondary-nucleated voids depends strongly on applied plastic strain. It is considered that...
not only does the growth of the pre-existing voids at primary inclusion affects the ductile crack initiation behavior, but secondary void nucleation from pearlite nodules also plays an important role, and the critical void volume fraction should be affected by the distribution of the inclusions and the pearlite nodules.

Despite the important implications of this microstructural point of view for ductile crack initiation behavior, there are relatively few experimental investigations on structural steels concerning the effects of microstructure on void nucleation and growth behavior. In this study, the effect of the inclusion content on critical conditions for ductile crack initiation was determined using notched round bar tensile specimens, and the critical void volume fraction and the secondary void nucleation effect were investigated using the Gurson–Tvergaard constitutive model.

2. Experimental Procedure

The chemical compositions and microstructural characteristics of the steels used in this study are shown in Table 1. All steels have the tensile strength level of 490 MPa class, but only sulfur contents are different. MnS volume fraction was measured by an image analyzer in the section parallel to the rolling direction; it varies from 0.02% for steel A to 0.13% for Steel C. All steels have ferrite-pearlite microstructure as shown in Fig. 1, and ferrite grain size is almost the same for all steels.

The distances between adjacent inclusions or between pearlite nodules are considered to be important for crack initiation behavior because the voids usually nucleate at MnS inclusions or pearlite nodules, as mentioned above. The mean spacing of MnS inclusions, $\lambda_{\text{MnS}}$, is determined by the following equation:

$$\lambda_{\text{MnS}} = \frac{1}{2d} \sqrt{\frac{3}{2 \pi} \frac{1}{f_{\text{MnS}}}}$$  \hspace{1cm} (1)

where $d$ and $f_{\text{MnS}}$ are, respectively, the mean diameter and the volume fraction of MnS inclusions. The mean inclusion diameter is defined as

$$d = \sqrt{\frac{1}{N_A} \frac{f_{\text{MnS}}}{\pi}}$$  \hspace{1cm} (2)

where $N_A$ is the number of inclusions per unit area. The number of MnS inclusions were measured by using at least 20 different photographs in the section parallel to the rolling direction. The mean spacings of MnS inclusions for each steels are also listed in Table 1. Pearlite phase shows a band-like structure along the rolling direction, but the distance between adjacent pearlite nodules in directions perpendicular to the rolling direction is important because the ductile crack growth direction is perpendicular to the rolling direction in this test. For these directions, the mean spacing of pearlite nodules was about $\lambda_p = 0.02$ mm for all steels.

Ductile crack initiation behavior was determined by using notched round bar specimens, as shown in Fig. 2. Specimens were extracted from the steel plates in the rolling direction. All specimens have the gauge length of 26 mm and notch depth of 2 mm. Three or four types of the specimens with different root radius were used for the test to investigate the effect of stress state on crack initiation. Tensile tests were conducted under quasi-static loading speed, and displacement was measured by the clip gauge with the aid of an attachment fixed on the specimen.

3. Damage Model and Numerical Procedure

3.1. Gurson–Tvergaard Constitutive Model

The Gurson–Tvergaard model assumes plastic flow of a void-containing material as a continuum, and the effect of the voids is averaged through the material. Yield condition for the void-containing material is written as

$$F = \frac{\sigma_y^2}{\sigma_y^2} + 2f_q \cosh \left( \frac{3\mu_2 \sigma_y}{2\sigma_y} \right) - \left[ 1 + (q_1 f)^2 \right] = 0$$  \hspace{1cm} (3)

where $\sigma_y$ is the flow stress of the fully-dense matrix material at the current level of hardening, $\sigma_y$ is the equivalent stress and $\sigma_y$ is the hydrostatic stress of the void-containing material, respectively, and $f$ is the void volume fraction. The parameters $q_1$ and $q_2$ were introduced by Tvergaard, and were taken as $q_1 = 1.5$ and $q_2 = 1.0$ in this study.

The growth of voids and the nucleation of secondary voids were introduced into the Gurson–Tvergaard model by the following definition of the increment of the void volume fraction:

$$\frac{df}{d\varepsilon} = q_1 f q_2 (\sigma_y - \sigma)$$

where $\sigma$ is the true stress and $f$ is the void volume fraction at the current level of hardening.
where \( f \) is the initial void volume fraction. In this study, \( f_0 \) was considered to be the same as the volume fraction of MnS.\(^{10,25,26} \) The value of \( f_0 \) which is obtained directly from integration of Eq. (6), depends only on \( \dot{\varepsilon}_p \) the equivalent plastic strain. It should be noted that the void volume fraction due to growth, \( f_{\text{growth}} \) consists of the growth of initial voids and the growth of secondary nucleated voids. Parameters for void nucleation were chosen as \( s_N=0.1 \) and \( \dot{\varepsilon}_N=0.36,^20 \) and \( f_0 \) was determined by fitting of numerical solution and experimental nominal stress/nominal strain curves of notched round bar specimens, which will be discussed later.

3.2. Finite Element Analysis

FE analysis was carried out to investigate the stress-strain state and void volume fraction around the notch region. The Gurson–Tvergaard constitutive model was implemented into the FE program ABAQUS ver. 5.8 (Hibbitt, Karlsson and Sorensen, Inc.). Axisymmetric second-order elements were used in this analysis. The Poisson’s ratio was taken as 0.3 and the Young’s modulus as 206 000 MPa. True stress/logarithmic plastic strain relation for each steel obtained by smooth round bar tensile test was used as material data characterizing fully-dense matrix. The stress-strain data were extrapolated by a power law equation to the high strain region after necking of the specimen. All the steels show Lüders elongation with the onset strain of hardening at about 1.3%, and hardening exponents were about 0.22 for all steels.

For determination of the local stress-strain state or the void volume fraction by FE analysis, we should be careful about the element size where ductile cracking occurs because calculated data are dependent on the element size. Batisse et al.\(^{23} \) proposed the characteristic length to be the same as the mean spacing of MnS inclusions, and finite elements having the same size as this characteristic length were used for FE analysis on a cracked specimen. In the case of notched round bar specimens, the center of the specimen has a high triaxial stress state similar to a crack tip region, though the notch tip region has low stress triaxiality and high equivalent plastic strain.\(^{21} \) It is expected that secondary void nucleation by large plastic strain will be much more important in the notch tip region. Therefore characteristic length is related to the mean spacing of pearlite nodules in the notch tip region because pearlite nodules are major nucleation sites for the secondary voids, as stated before. Examples of the mesh divisions for FE analysis are shown in Fig. 3. The element size in the center of the specimen applied here is three times the mean spacing of MnS inclusions indicated in Table 1 because it is considered that a larger area than mean spacing of inclusions is needed to form a macroscopic crack. The element size in the notch tip region was chosen as two times the mean spacing of the pearlite nodules. Elements around critical areas, the specimen center and the notch tip, have almost square shapes, as indicated in Fig. 3.

4. Experimental Results

Nominal stress/nominal strain curves of notched round bar specimens for Steel A with different notch radius are shown in Fig. 4. Maximum nominal stress decreases and elongation to failure increases with increasing root radius. Crack initiation points were determined by microscopic observation of the notch region in the center section parallel to the loading direction. Several specimens with the same root radius were used, and loading tests were interrupted at different displacements before breaking of the specimens. Crack initiation points are indicated in Fig. 4. Ductile cracking was initiated in the center of the specimens with the root radii of 1.0 mm and 2.0 mm. On the other hand, in the specimens with sharper root radii, 0.1 mm and 0.25 mm, ductile crack initiation occurred at the notch root. Sudden load drop by ductile crack initiation was observed in the specimens with larger root radii, while ductile cracking was

\[
f = f_{\text{growth}} + f_{\text{nucleation}} \]

\[
f_{\text{growth}} = (1 - f) \dot{\varepsilon}_p \]

\[
f_{\text{nucleation}} = A \dot{\varepsilon}_p^m \]

\[
A = \frac{f_N}{s_N^2} \exp \left[ \frac{1 \left( \frac{\dot{\varepsilon}_p - \dot{\varepsilon}_N}{s_N} \right)^2}{2} \right] \]

where \( \dot{\varepsilon}_p \) and \( \dot{\varepsilon}_N \) are the volumetric plastic strain increment and the equivalent plastic strain increment, \( s_N \) and \( \dot{\varepsilon}_N \) and \( f_0 \) are the standard deviation of void nucleation strain, the mean void nucleation strain, and the volume fraction of the nucleated void, respectively. Although a number of stress-controlled void nucleation models were proposed,\(^{22,23} \) the strain-controlled void nucleation model was applied in this study because the analysis on carbon steels indicated that void nucleation is mainly controlled by plastic strain.\(^{24} \) Growth of voids causes a nonzero volumetric plastic deformation, and Eq. (5) is given by mass conservation. Void volume fraction is obtained by integrating Eq. (4), and expressing it as

\[
f = f_0 + f_{\text{growth}} + f_{\text{nucleation}} \]

where \( f_0 \) is the initial void volume fraction.
initiated around maximum nominal stress in the specimens with sharper notches. Figure 5 shows the relation between nominal strain to crack initiation and root radius for the three steels of differing sulfur content. Nominal strain to crack initiation increases with increasing root radius for all steels. It is clear that increase of sulfur content makes ductile crack initiation easier.

Figures 6(a) and 6(b) show micrographs of the notch section of Steel A with the root radii of 1.0 mm and 0.25 mm, respectively. In the specimen with $\rho = 1.0$ mm, ductile cracking was initiated in the center of the specimen by the coalescence of voids. The average distance between adjacent voids in the center area of Fig. 6(a), in the direction perpendicular to the loading direction, was about 0.05 mm. This distance is smaller than the spacing of MnS inclusions, but larger than that of pearlite nodules. On the other hand, ductile crack initiation was observed at the notch root in the specimen with $\rho = 0.25$ mm. In Fig. 6(b), the distance between adjacent voids near the notch root in the direction perpendicular to the rolling direction is about 0.02 mm, and this is exactly the same as the mean spacing of pearlite nodules in that direction. It can be stated that voids were nucleated at the pearlite nodules, and the secondary-nucleated voids played a dominant role in ductile crack initiation at the notch root. However, in the center of the specimen, it is considered that not only growth of pre-existing voids from MnS inclusions, but also secondary void nucleation from pearlite nodules, affects ductile crack initiation behavior.

5. Results of FE Analysis

5.1. Void Nucleation Parameter

Void nucleation parameter $f_N$ was determined by fitting of numerical solution and experimental stress/strain curves. Figure 7 shows comparison of nominal stress/nominal strain curves for Steel A with $\rho = 1.0$ mm. Ordinary Mises plasticity can not describe load drop after maximum stress precisely. The Gurson model without considering sec-
ondary void nucleation, $f_N=0$ in Eq. (7), gives almost the same result as the Mises model, which shows that the effect of secondary void nucleation is not negligible in this geometry. Nominal stress after maximum stress decreases strongly with increasing values of the void nucleation parameter $f_N$. The value $f_N=0.012$ gives the best fit to the experimental result.

Using the void nucleation parameter, $f_N=0.012$, obtained for the specimen with $\rho=1.0$ mm, FE analysis was conducted on specimens of different root radius. Figure 8 shows a comparison of the nominal stress/nominal strain curves for Steel A. All calculated results show good agreement with the experimental curves up to the crack initiation point. After ductile crack initiation, calculated nominal stress is higher than experimental data because the finite elements in the critical region were assumed to retain load-carrying capacity even if void volume fraction exceeds the critical value for ductile crack initiation. We focus here on the ductile crack initiation behavior, and the subsequent cracking behavior is not a main interest in this study.

The same void nucleation parameters were applied for FE analysis on Steels B and C of different initial void volume fraction. The pre-existing void volume fraction was again taken as the corresponding volume fraction of MnS inclusion. Calculated and experimental nominal stress/nominal strain curves for Steels B and C are shown in Figs. 9(a) and 9(b), respectively. The Gurson–Tvergaard model can be applied for these similar steels of differing initial void volume fraction by using the same void nucleation parameters. It is reasonable to use the same void nucleation parameters because secondary void nucleation is considered to be dominated by pearlite nodule distribution, and all steels have same ferrite/pearlite microstructure.

5.2. Void Nucleation and Growth Behavior

Close examination of the void volume fraction evolution in the regions where ductile cracking occurs, namely the center of the specimen and the notch tip, was carried out by FE analysis in order to reveal the operative micromechanisms of ductile crack initiation behavior. Figure 10 shows radial distribution of the computed void volume fraction in the specimens of steel A with root radii of 1.0 mm and 0.25 mm at the experimentally-observed points of ductile crack initiation. Calculated data were taken from the centroidal point of the elements. Void volume fraction is highest in the center for the specimens with $\rho=1.0$ mm, and at the notch tip for the specimen with $\rho=0.25$ mm. It is obvious that, in both cases, ductile cracking initiated in the region having highest void volume fraction. Void nucleation and growth behavior is affected by equivalent plastic strain and stress triaxiality. Radial distribution of equivalent plastic strain, $\varepsilon_{eq}$, and stress triaxiality, $\sigma_{tr}/\sigma_{eq}$, are shown in Fig. 11 for these same levels of imposed displacements. It is interesting to note that both specimens have high triaxiality in the center and high equivalent plastic strain in the

Fig. 8. Comparison of experimental nominal stress/nominal strain curves and calculated ones for Steel A.

Fig. 9. Comparison of experimental nominal stress/nominal strain curves and calculated ones for Steel B and Steel C.

Fig. 10. Radial distribution of void volume fraction in the notch section for Steel A, taken from the element centroids (undeformed coordinates).
notch tip, but the resulting radial distribution of the void volume fraction, shown in Fig. 10, is completely different between the two specimens. In the center of the specimen, both specimens have almost same stress triaxiality. However, the specimen with \( r = 1.0 \text{ mm} \) has higher equivalent plastic strain. The voids in the center of the specimen with \( r = 0.25 \text{ mm} \) have not grown because of the limited plastic flow in this region. On the other hand, notch-tip values of both stress triaxiality and equivalent plastic strain are higher for the specimen with \( r = 0.2 \text{ mm} \), and this can accelerate both void nucleation and growth rate, leading to ductile crack initiation of the notch tip.

To investigate void nucleation and growth behavior, the void volume fraction due to nucleation, \( f_{\text{nucleation}} \), and the void volume fraction due to growth, \( f_{\text{growth}} \), were evaluated separately. In practice, total void volume fraction, \( f \), was calculated by integrating Eq. (4), and, with \( f_0 \) and \( f_{\text{nucleation}} \) separately defined, Eq. (8) serves to define \( f_{\text{growth}} \). Figure 12 shows contour plots of \( f_{\text{nucleation}} \) and \( f_{\text{growth}} \) at ductile crack initiation for Steel A with \( r = 1.0 \text{ mm} \). The void volume fraction due to nucleation is higher in the notch tip region, while the center of the specimen shows high void volume fraction due to growth. It can be stated that the growth of currently-existing voids by high triaxial stress plays a major role in the center of the specimen, and the void volume fraction in the notch tip is dominated by the secondary void nucleation associated with large plastic strain. Figure 13 shows the evolution of \( f \) with nominal strain in the critical regions of specimens of steel A having root radii of 0.25 mm and 1.0 mm. The value of \( f_{\text{nucleation}} \) and \( f_{\text{growth}} \) are also displayed separately. Secondary void nucleation occurred in the notch tip of the specimen with \( r = 0.25 \text{ mm} \) at small nominal strain, and the volume fraction of nucleated void quickly increased to a saturation value of \( f_{\text{nucleation}} = 0.012 \) (\( = f_0 \)). The void growth rate in the notch tip region of the specimen with \( r = 0.25 \text{ mm} \) is smaller than that in the center region of the specimen with \( r = 1.0 \text{ mm} \) because the stress triaxiality is smaller in this region. However, the notch-tip void volume fraction increased gradually but continuously during deformation and it reached a critical value, resulting in a ductile crack initiation in the notch tip. On the other hand, in the center of the specimen with \( r = 1.0 \text{ mm} \), secondary void nucleation hardly occurred until nominal strain was increased up to about 3.5%, and then, the volume fraction of secondary nucleated void increased slowly. It is considered that voids can grow rapidly in the center of the specimen with \( r = 1.0 \text{ mm} \), due to high stress triaxiality, even though the secondary voids were nucleated in the later stage of the tensile test and the volume fraction of nucleated void was smaller.

5.3. Effect of Stress Triaxiality and MnS Inclusion on Ductile Crack Initiation

As shown in Fig. 5, there should be a strong effect of MnS content on ductile crack initiation, depending on the root radius of the specimens. To investigate the local criteria for ductile crack initiation, the void volume fraction in the critical region where ductile crack occurs, the critical void volume fraction, was calculated by FE analysis. Figure 14 shows the effect of MnS inclusion on critical
void volume fraction for ductile crack initiation as a function of stress triaxiality. In the case of Steel A, the critical void volume fraction is independent of stress triaxiality, and it has a constant critical void volume fraction of about 0.08. Steel B has almost the same critical void volume fraction as Steel A when ductile crack initiates in the notch tip where stress triaxiality is low, but the critical void volume fraction in the high triaxial stress state, in the center of the large root radius specimens, is lower than that of Steel A. Steel C, which contains a large amount of MnS inclusions, has strong dependence of \( f_c \) on stress triaxiality, and the critical void volume fraction in the high triaxial stress region is quite low compared to the other steels. The deterioration of the critical void volume fraction with increasing inclusion content is smaller in the low stress triaxiality region than in the high triaxiality region.

6. Discussion

6.1. Effect of Void Nucleation Site on Void Growth Behavior

It is shown that secondary void nucleation plays an important role in ductile crack initiation both in the notch tip and in the center of the specimen. However, the effect of the void nucleation sites, namely MnS inclusions and pearlite nodules, on void volume fraction is not as clear because the calculated value of the void volume fraction due to growth, \( f_{\text{growth}} \), consists of growth of the initial voids from MnS inclusions and growth of the secondary nucleated voids from pearlite nodules. Since the void growth rate, \( f_{\text{growth}} \), is affected by total void volume fraction, as expressed in Eq. (5), it is difficult to make a precise evaluation of the effects of initial and secondary-nucleated voids separately. But, simple assumptions on the void nucleation and growth model can illustrate the separate effects of MnS inclusions and pearlite nodules on void growth behavior. Figure 15 shows the relation between void volume fraction in the center of the specimen with \( \rho = 1.0 \text{ mm} \) for Steel A and nominal strain with different parameters in the void nucleation and growth model. The initial void volume fraction, \( f_0 \), and the void nucleation parameter, \( f_N \), are considered to represent the effects of MnS inclusions and pearlite nodules, respectively. Only secondary void nucleation is taken into account in the case of the parameter set of \( f_0 = 0 \) and \( f_N = 0.012 \), and the parameter set of \( f_0 = 0.0002 \) and \( f_N = 0 \) gives the void volume fraction without secondary void nucleation. The void volume fraction calculated with the parameter set of \( f_0 = 0.0002 \) and \( f_N = 0 \) is quite small compared to that of the parameter set of \( f_0 = 0 \) and \( f_N = 0.012 \). These results show that the void volume fraction can not be increased enough only by the initial voids from MnS inclusions in this relatively clean steel, and the secondary nucleated voids have a significant effect on the void volume fraction, even in the center of the specimen.

6.2. Secondary Void Nucleation Mechanism and Void Nucleation Parameter

Gladmen et al.\(^{18} \) and Melander and Streninger\(^{19} \) showed, based on evidence of void nucleation from pearlite nodules, that significant plastic strain is needed for cracking in the pearlite nodule, which leads to initiation of the secondary void. It is considered that when the crack propagates across the entire pearlite nodule in association with matrix plastic deformation, the crack behaves as a void, as shown in Figure 16. Subsequently the nucleated void grows in accordance with the void growth theory given by Eq. (5). If all of the pearlite nodules in the critical region crack and act as secondary nucleated voids, the volume fraction of the nucleated voids, \( f_N \), is given by

\[
    f_N = \frac{V_{\text{void}}}{V_{\text{pearlite}}} f_{\text{pearlite}} \quad \text{-------------------(9)}
\]

where \( V_{\text{void}}, V_{\text{pearlite}} \) and \( f_{\text{pearlite}} \) are the volume of the nucleat-
ed void caused by cracking of a pearlite nodule, the volume of the pearlite nodule, and the pearlite volume fraction of the steel, respectively. The void nucleation parameter, \( f_{\text{void}} \), was estimated as 0.012 by fitting of numerical solution and experimental nominal stress/nominal strain curves, and \( f_{\text{pearlite}} \) is about 0.19 for all steels used in this study. Therefore, the void volume nucleated per pearlite nodule, \( V_{\text{void}}/V_{\text{pearlite}} \), becomes 0.063 (6.3%). This number is considered to be reasonable compared to Gladman’s observations.18)

The strain-controlled void nucleation model was used in this study as described in Eqs. (6) and (7). Secondary void nucleation takes place over a certain range of strain in this model, and this deviation is characterized by the parameter \( s_{\text{N}} \). This parameter is mainly based on inhomogeneity of shape or distribution of void nucleation sites, and a narrow range of nucleation strain is expected for material containing homogeneously distributed uniform nucleation sites.28)

Figure 17 shows the effect of the standard deviation, \( s_{\text{N}} \), on the evolution of void volume fraction in the center of the specimen with \( \rho = 1.0 \text{ mm} \) for Steel A. The void volume fraction at crack initiation increases with increasing \( s_{\text{N}} \) because secondary void nucleation starts at smaller nominal strain with larger \( s_{\text{N}} \). Actual void volume fraction at crack initiation in the center of the specimen was evaluated from Fig. 6(a). The averaged value of the void volume fraction in the same area as the center element for FE analysis was about 0.082. The value of the standard deviation \( s_{\text{N}} = 0.1 \) which resulted in a calculated void volume fraction of \( f = 0.076 \), is considered to be fairly reasonable for the steels used in this study.

Qiu et al.29) did a detailed observation for secondary void nucleation, and the void nucleation strain was suggested as \( \varepsilon_{\text{N}} = 0.36 \) for a steel with same mechanical and microstructural properties as the steel used here. The void nucleation parameters used in this study are thought to be accurate, and this is the reason for good agreement between the experimental results and numerical estimations for nominal stress/nominal strain curves of notched round bar. Void nucleation parameters should be carefully chosen in consideration of the micromechanical behavior of the void nucleation.

6.3. Effect of MnS Inclusion on Ductile Crack Initiation

It is obvious from the experimental results that increase of sulfur content causes a deterioration of ductility of the steels. But the effect of MnS depends on the triaxial stress state. As shown in Fig. 14, MnS content shows a significant effect on critical void volume fraction under high triaxial stress state, while the effect of the MnS inclusion content is smaller in regions of low stress triaxiality. Okamoto et al.29) investigated the ductile fracture process by using the V-notch Charpy specimen and found that the crack initiation energy is not affected by MnS content. It is considered that the stress triaxiality in the notch tip of the Charpy specimen is also low, and large plastic strain is needed for ductile crack initiation. It is reasonable that the effect of MnS inclusion on ductile crack initiation is small if other microstructural features are the same because ductile crack initiation in the low triaxial stress and large plastic strain region is dominated by secondary void nucleation from pearlite nodules.

On the other hand, under high stress triaxiality a ductile crack occurs with much smaller void volume fraction for the steel with higher sulfur content. There should be a minimum size of the inclusion in order that it be able to become a void nucleation site. Kobayashi et al.30) reported that the threshold inclusion size for void nucleation is about 0.3 \( \mu \text{m} \) for pure iron, while a large number of non-nucleating inclusions smaller than the critical size were observed in the steel. Okamoto et al.29) suggested that small inclusions under 0.2 \( \mu \text{m} \) in size can not act as a nucleation site for primary void but it can contribute to the inter-void linking. Many small inclusions were also observed in Steel C. Although detailed investigation is necessary to clarify the criterion for inter-void linkage in relation to the spacing of small MnS inclusions and effect of other inclusions such as oxides and carbides, it is expected that small inclusions in the inter-void matrix do affect the linkage of voids by forming a micro void in a localized shear band.

In this numerical calculation, inhomogeneity of shape and distribution of pearlite nodules are introduced into the model as a standard deviation parameter \( s_{\text{N}} \). But, MnS inclusions are considered to have uniform shape and homogeneous distribution, while real microstructures have inhomogeneity in size, shape, and spacing of MnS inclusions. Tensile properties are different in different direction such as rolling, short transverse and long transverse directions. All of these factors may affect void nucleation, growth and coalescence behaviors, and detailed investigation is expected for solving the void coalescence problems.

7. Conclusion

The effects of the specimen geometry and inclusion content on ductile crack initiation in structural steels were determined by using notched round bar specimens, and the micromechanism of ductile crack initiation was investigated based on the Gurson–Tvergaard constitutive model. Results are summarized as follows;

(1) Ductile cracking initiated in the center of the specimens with the root radii of 1.0 mm and 2.0 mm, while in the specimen with sharper root radii, 0.1 mm and 0.25 mm,
ductile crack initiation occurred in the notch tip. Nominal strain to ductile crack initiation increases with increasing root radius and decreasing MnS inclusion content.

2) FE analysis was carried out by using same void nucleation parameters for all steels and different initial void volume fractions corresponding to MnS inclusion content, and calculated nominal stress/nominal strain curves showed good agreement with experimental ones.

3) In the notch tip region of the specimen with sharper notch, which shows large plastic strain and low stress triaxiality, a large number of secondary voids were nucleated in the early stage of deformation, and void volume fraction was increased to a critical value in spite of the relatively low void growth rate. On the other hand, in the low plastic strain and high triaxial stress region, the centers of the specimens with the root radii of 1.0 and 2.0 mm, voids can grow rapidly even though the volume of secondary nucleated void was smaller than in the high plastic strain region.

4) Void volume fraction can not be increased enough only by the initial voids from MnS inclusions, and the secondary nucleated voids from pearlite nodules have a significant effect on the void volume fraction both in the center of the specimen and in the notch tip.

5) Critical void volume fraction decreases largely with increasing MnS content in the high triaxial stress region; however, the effect of MnS content is small in the low stress triaxiality and large plastic strain region.

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