1. Introduction

In tension tests of ductile steels it has been found that in smooth round bar or in notched specimens with obtuse circumferential notches ductile fractures firstly initiate at central areas after large plastic deformations and then grow up to final ruptures, while in notched specimens with acute circumferential notches they initiate at the regions near notch roots and then grow up to final ruptures.\(^1,2\) These ductile fractures have been reported to occur as the effective plastic strain, which depends on the stress tri-axiality (a ratio of mean stress to von Mises effective stress), increases to a limit.\(^3\)\(^-\)\(^5\) Most researches upon the ductile fracture properties have been carried out on smooth or circumferentially notched round specimens. However, few studies have been done on the notched thin plates of ductile steels. Furthermore, it has also been reported that the ductile fractures stated above do not initiate exactly at regions where effective plastic strain is the maximum.\(^1,6\) The effects of the multi-axial stresses on the plastic deformation and the fracture behaviors have not been made clear.

In this study, tension tests were performed on smooth and double-notched specimens of SPCC steel plates with various ligaments and notch root radii. By observing the tensile fracture processes, initial cracks are found to occur at the notch roots, the center and the 2 axi-symmetrical inner areas of ligaments for specimens with acute, obtuse and intermediate notches, respectively. In order to clarify the effect of multi-axial stresses on the ductile fracture mechanisms, distributions of multi-axial stress components in the notched specimens are calculated by finite element method. In a specimen undergoing the maximum load, the mean stress shows the largest value at the region where initial cracks just occur. This behavior is discussed with reference to the effects of multi-axial stress components on the initiation and growth of micro-cavities in specimens. The result suggests that the mean stress component should be a dominant factor influencing the fracture behaviors of the ductile steel plates.

KEY WORDS: tension test; ductile fracture; crack; notch; steel plate; mean stress; finite element method.

2. Material and Experimental Procedure

The test materials were commercial SPCC cold-rolled structural steel plates with a thickness of 2 mm. The chemical composition and the mechanical properties measured in the present tension test are listed in Tables 1 and 2, respectively.

In this work, doubly U-notched plate specimens as well as a JIS5 standard smooth specimen with a gauge length of 50 mm and a width of 25 mm were used. The notched specimens, as shown in Fig. 1, were machined to have 4 kinds of ligament \(L\) of 25 mm, 30 mm, 35 mm and 40 mm with different notch root radius \(R\) of 2 mm, 6 mm and 15 mm. Using these specimens, tension tests were carried out on an Instron type testing machine under a cross head speed of 1 mm/min at room temperature. The tensile properties of the smooth specimen and the double-notched specimens were examined. For each notched specimen, the deformation and fracture process during testing were observed in detail; photographs were taken simultaneously. Furthermore, to investigate the fracture behaviors at internal sections, a small...
part of tension tests were interrupted and the longitudinal
sections of the plastically deformed specimens were ob-
served in detail with a scanning electron microscope
(SEM).

To clarify the tensile fracture behaviors at various stress
states, distributions of multi-axial stress components in the
notched specimens were calculated by nonlinear large dis-
placement analyses with finite element method (FEM),
using MSC/Nastran for windows. The mechanical proper-
ties of the SPCC steel plate obtained by tensile testing on
the smooth specimen were used in the FEM analyses.

Figure 2 shows the model of double-notched plate speci-
mens. Supposed that no stresses exist in thickness direction,
flat plate stress analyses were treated. Due to symmetry, a
quarter of each specimen was modeled with flat plate ele-
ments.

3. Results and Discussion

3.1. Tensile Properties

Figure 3 shows a load–elongation curve with a clear
yield point and a high ductility of the smooth specimen.
Figures 4(a)–4(d) show the load–elongation curves of the
double-notched specimens. From these results, the ultimate
strengths of the smooth and notched specimens were calcu-
lated. They were found to have almost the same values re-
gardless of the specimen shape. However, in the notched
specimens with a same ligament, the plastic strain to rup-
ture exhibits a decreasing tendency with decreasing notch
root radius. The reason for the decrease in rupture strain
with the decrease in notch root radius should be due to the

Fig. 1. Geometries of double-notched plate specimens.

Fig. 2. FEM model of double-notched plate specimens.

Fig. 3. Load–elongation curve of a smooth plate specimen.

Fig. 4. Load–elongation curves of double-notched specimens.
increase of stress tri-axiality caused by the decrease of notch root radius, agreeing with the experimental results on circumferentially notched round specimens.\cite{1,2}

3.2. Deformation and Fracture Processes of Notched Specimens

In this work, for the specimens with acute, obtuse and intermediate notches, incipient ductile fractures were found to occur initially at the notch roots, the center and the 2 axi-symmetrical areas of ligaments, respectively. The tensile fracture processes of the notched specimens having a ligament of 40 mm with various notch root radii are shown as examples in Fig. 5. For each specimen, 3 photographs are pasted in this figure. These photographs were taken from the moment when the specimen was loaded just beyond the maximum load to the one when it was just before rupture. In the specimen with double acute notches ($R/H=2$ mm), the notches were firstly blunted and the regions near notches contracted in thickness direction. When the maximum load was overstepped, cracks firstly initiated at the notch roots and then grew up to the final rupture. Contrastively, in the specimen with obtuse notches ($R/H=15$ mm), as the plastic deformation occurred the central area of ligament contracted in thickness. And, as the maximum load was overstepped, cracks firstly initiated at the central area and then grew up to the final rupture. On the other hand, in the specimen with a notch root radius of 6 mm, as the maximum load was overstepped the 2 axi-symmetrical areas away from notches contracted in thickness, then initial cracks occurred at there and grew up to the final rupture. The relation between $R/L$ and the initial fracture regions is plotted in Fig. 6, in which $R/L$ is a ratio of the notch root radius $R$ to the ligament $L$ of a specimen. It is found that the initial ductile fracture occurs at the ligament center area as $R/L$ is above 0.2, while it occurs near a notch root as $R/L$ is less than 0.13. Furthermore, as $R/L$ is in a range of 0.14–0.18 the initial ductile fracture is found to occur at 2 axi-symmetrical inner areas. From these results, it is considered that the region where initial ductile fracture occurs could be expected by $R/L$, which influences the distributions of multiaxial stresses in a specimen under a tensile load.

To examine the fractures in internal sections of the notched plate specimens, some tension tests were interrupted when the contractions occurred. Figure 7, as an example, shows the SEM micrographs taken on a longitudinal

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Fig. 5. Tensile fracture processes of notched specimens having a ligament of 40 mm with notch root radii of 2 mm, 6 mm and 15 mm, respectively.

Fig. 6. Relation between $R/L$ and the region where initial ductile fracture occurred.
section where the contractions firstly occurred in thickness direction. It can be observed that many micro-cavities initiated in the plastically deformed specimen and some of them expanded into macro-cracks. Such cracks can be confirmed to cause the final fracture of the specimen.

3.3. Results of FEM Analyses

Because a notch can cause a multi-axial stress state, it is generally considered that the fracture behavior of a notched specimen is dominated mainly by multi-axial stress components. In this work the distributions of multi-stress components especially the von Mises equivalent stress and the mean stress in the notched specimens in tension testing are analyzed by FEM. The results of specimens having a ligament of 30 mm or 40 mm with different notches for each ligament are stated as follows. For the specimens having a ligament of 30 mm, the FEM analyses are carried out at 3 points, which are in the elastic region (Load: $F=8 \text{kN}$), the initial plastic region ($F=15 \text{kN}$) and just before the maximum load ($F=21 \text{kN}$), respectively. For those having a ligament of 40 mm, they are also carried out at 3 points in the elastic region ($F=10 \text{kN}$), the initial plastic region ($F=21 \text{kN}$) and just before the maximum load ($F=27 \text{kN}$).

The distributions of equivalent stress in these specimens are shown in Figs. 8 and 9. The abscissa of $2x/L$ shows a fractional distance from ligament center ($2x/L=0$) to notch root ($2x/L=1$). It can be seen that in all notched specimens loaded in the elastic region, the initial plastic region and just before the maximum load, the equivalent stress always shows the largest values at the areas near notch root. The distributions of mean stress in these specimens are shown in Figs. 10 and 11. In all notched specimens loaded in the elastic region, the mean stress shows the largest values at the areas near notch root. However, as the loads increase, a tendency that the peaks of mean stress move from notch roots towards the ligament centers can be found. Especially, for the specimens having obtuse notches ($R=15 \text{mm}$), as the loads increase to the maximums the mean stress shows the largest values at the ligament centers. On the other hand, for specimens having the intermediate notches ($R=6 \text{mm}$), the distributions of mean stress in the specimen with a ligament of 30 mm have the same tendency as in the specimens having obtuse notches ($R=15 \text{mm}$) mentioned above. While in another one with a ligament of 40 mm, as shown in Fig. 11(b), the mean stress presents a clear peak between the notch root and the ligament center when the load reached just before the maximum. As an example, Fig. 12 shows the contour distributions of equivalent stress and mean stress in FEM models of the notched specimens with a ligament of 40 mm loaded just before the maximums.
Fig. 10. Distributions of mean stress in notched specimens having a ligament of 30 mm with a notch root radius of (a) 2 mm, (b) 6 mm and (c) 15 mm.

Fig. 11. Distributions of mean stress in notched specimens having a ligament of 40 mm with a notch root radius of (a) 2 mm, (b) 6 mm and (c) 15 mm.

Fig. 12. Distributions of equivalent stress and mean stress in notched specimens having a ligament of 40 mm under an applied load of 27 kN, which is just before the maximum loads.
The distributions of the stress tri-axiality in these notched specimens are calculated and plotted in Figs. 13 and 14. It can be seen that all of them show increasing tendencies from notch roots towards ligament centers, independent of specimen shape. And, for each specimen no large changes in the stress tri-axiality are shown during testing. Therefore, it is considered that the ductile fracture processes observed on the present notched specimens could not be explained by the stress tri-axiality.

3.4. Discussion

It was observed in the notched specimens that cracks initiated firstly at the regions near notch roots, the central areas and the 2 axi-symmetrical inner areas away from notches, respectively. As stated above, the initiation and growth of these cracks resulting in the final ruptures occurred as the maximum loads were overstepped. Therefore, it is considered that when the load reaches just before the maximum the distributions of multi-axial stress components in a specimen dominate the initiation and growth of the cracks. Furthermore, the initiation and growth of the cracks under multi-axial stress conditions are influenced mainly by equivalent stress and mean stress components. In this study, based on the FEM results of equivalent stress and mean stress in the notched specimens having a ligament of 40 mm, which are given as examples, fracture behaviors in the notched specimens are discussed as follows.

Comparing the FEM results (Fig. 12) with the tensile fracture processes (Fig. 5), it can be found that regardless of notch root radius the regions where cracks initiated correspond well to the points where mean stress shows the largest. From this result, it seems that the initiation of cracks and the mean stress component have a close relationship. On the other hand, in one of the author’s studies a large number of micro-cavities were found to nucleate in a ductile austenitic steel in a torsional creep stress state, in which the mean stress was 0. Thereby the mean stress component was assumed to contribute less to the initiation of cavities. Because the present ductile fracture behavior at room temperature should be substantially identical with such ductile creep fractures, they should be discussed based on that the mean stress component contributes less to the initiation of micro-cavities.

Generally, micro-cavities will nucleate in the interior of a ductile metal when the plastic strain reaches a critical level. It has been known that the plastic deformation in the metal under a multi-axial stress condition is controlled mainly by the equivalent stress component. As shown in the FEM results, large equivalent stress exists in the plastically deformed specimens, even though the largest values exhibit at the notch roots for all specimens. Therefore, it could be supposed that micro-cavities initiate easily in these deformed specimens due to the effect of large equivalent stress. On the other hand, it is necessary to demonstrate further why the initial cracks did not always occur at the notch roots where the equivalent stress exhibited the largest val-
ues in all specimens. It has also been known that the growth of cavities or cracks is promoted strongly by mean stress but not by the equivalent stress.\textsuperscript{12,13} So, in the plastically deformed specimens micro-cavities are easier to grow up at the regions where the mean stresses are larger. When the micro-cavities coalesced, they expanded into cracks and the plastic deformation was promoted further at there. For this reason, it is considered that the initial cracks as well as the visible contractions occurred in these notched specimens due to the larger mean stresses. Eventually, the crack tips propagated further along inclined planes about 45-degree to the load direction, as shown in Fig. 7, the final rupture was then resulted in Knott’s fracture mode.\textsuperscript{14} It is therefore suggested that the mean stress component should be the most dominant factor influencing the ductile fractures of the notched plate specimens.

4. Conclusions

Using a commercial cold-rolled structural steel, SPCC, tension tests were performed on smooth and double-notched specimens. Distributions of multi-axial stress components in the notched specimens were calculated by FEM. The effect of notch shapes on the fracture behaviors of the ductile steel plates was investigated. The results obtained are summarized as follows:

(1) In the specimens with acute, obtuse and intermediate notches, initial cracks were found to occur at the notch roots, the central areas of ligaments and the 2 axi-symmetrical inner areas away from the notches, respectively. The final ruptures occurred due to the growth of these cracks.

(2) Relation between the region, where initial cracks occurred, and $R/L$, a ratio of the notch root radius $R$ to the ligament $L$ of a specimen, was investigated. The initial fracture region could be expected by the value of $R/L$, which influences the distributions of multi-axial stress components in the specimen under a tensile load.

(3) It is found that the micro-cavities initiated due to the plastic deformations are easier to expand into cracks at the regions where mean stresses are larger. It is further suggested that the mean stress component should be a dominant factor influencing the ductile fractures of the present steel plates.

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