Investigation of Ductile Fracture Mechanism in Multipass Drawing of Hollow Specimen\textsuperscript{*1}

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To apply hollow forming technology for car parts, it is necessary to understand the ductile fracture mechanism of hollow forming. In this study, the cold drawing test and the finite element method analysis (FEM) of hollow specimens were carried out. It was clarified that the ductile fracture of hollow specimens in cold drawing was affected by both stress triaxiality and Lode angle parameter. As a result of fracture observation of a hollow specimen, an equiaxed dimple and an elongated dimple were observed. A mixed-mode ductile fracture mechanism (shear deformation of voids and typical void growth and coalescence) for hollow specimens in cold drawing is assumed.

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1. Introduction

Global environmental protection requires us to improve the fuel economy of automobiles and reduce the carbon dioxide emissions of automobiles by reducing the size and weight of automotive parts. For example, shaft parts are hollowed to reduce their weight. Conventionally, the hollowing of parts has been mainly performed by machining with gun drills. From the viewpoints of improving the material yield and reducing the processing cost, techniques with gun drills. From the viewpoints of improving the material yield and reducing the processing cost, techniques have been developed for forming hollow members by plastic working.\textsuperscript{1-5} For example, Hosokawa \textit{et al.}\textsuperscript{1} reported a cold forging technique to produce hollow shafts by extruding punched hollow parts.

To apply hollow forming techniques by plastic working, one issue is to derive hollow forming conditions based on a ductile fracture criterion. For cold forging and drawing, the ductile fracture limit of steel is generally evaluated by upsetting test.\textsuperscript{6} Ductile fracture during forming is predicted by using integral-type ductile fracture criterion equations as represented by Oyane’s equation\textsuperscript{7} and Cockcroft and Latham’s equation.\textsuperscript{8} This prediction method is widely used and its effectiveness is reported.\textsuperscript{9} It is reported, however, that when the material is the same but different in the stress state, the critical damage value that should be peculiar to the material changes with the stress state.\textsuperscript{10,11} It is hard to say that this prediction method can be applied to all processing methods. In this study, we focused on the stress triaxiality-type ductile fracture criterion\textsuperscript{12,13} based on the void growth law,\textsuperscript{14} instead of an integral-type ductile fracture criterion equation. As a result, we confirmed that the occurrence of chevron cracks in solid parts can be predicted by using the stress triaxiality-type ductile fracture criterion.\textsuperscript{15}

When drawing a hollow parts, we assume that the stress and strain states on the inner surface of the hollow parts are different from those of a solid parts. This is thus considered to lead to the overestimation of the ductile crack initiation strain. In recent years, ductile fracture prediction models have been developed by considering the Lode parameter in addition to the stress triaxiality.\textsuperscript{16-21} And, these models are reported to be able to also evaluate ductile crack initiation during cold upsetting.\textsuperscript{22,23}

Consideration of the Lode parameter is expected to improve the prediction accuracy of the stress triaxiality-type ductile fracture criterion. To that end, it is important to understand the mechanism of ductile fracture. For example, \textit{Li et al.}\textsuperscript{24} reported a study on the Lode parameter and the ductile fracture surface morphology. However, there are no reports on the evaluation of ductile fracture and on the changes in the Lode parameter during the drawing of hollow specimens.

This study was designed to understand the ductile fracture mechanism when hollow specimens are drawn. First, we investigated the crack initiation position and the applicability or not of the stress triaxiality-type ductile fracture criterion when hollow specimens are drawn. Then, we scrutinized the relationship between the ductile fracture surface and the Lode parameter during the drawing of hollow specimens and studied the ductile fracture mechanism of hollow specimens in drawing.

2. Experiment

2.1 Materials

Samples of JIS-S55C of medium carbon steel typically used for cold forging were used as the specimens. Table 1 shows its chemical composition. The materials were melted in a furnace and cast into billets. The billets were hot rolled

| Table 1 Chemical composition of test pieces (mass%). |
|-----------------|--------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Steel** | **C** | **Si** | **Mn** | **P** | **S** | **Cr** |
| S55C | 0.55 | 0.31 | 0.76 | 0.014 | 0.005 | 0.17 |

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Table 2 Mechanical properties of test pieces.

<table>
<thead>
<tr>
<th>TS /MPa</th>
<th>YS /MPa</th>
<th>El %</th>
<th>RA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>594</td>
<td>355</td>
<td>30.6</td>
<td>53.9</td>
</tr>
</tbody>
</table>

(a) 22.5 mm from surface of test pieces
(b) D/4 position

Fig. 1 Vickers hardness and SEM image of test pieces after heat treatment.

![Image](image)

Fig. 2 Geometry of cold drawing test specimens.

into 55 mm diameter bars. The bars were spheroidization heat treated by soaking at 1,013 K for 36.0 ks and slow cooling.

The heat treated steel was measured for the Vickers hardness, microstructurally observed, and tensile tested. The Vickers hardness and microstructural observation specimens were each taken at a position corresponding to the inner surface of hollow specimens (at the 22.5 mm position in the radial direction from the surface layer of the spheroidized annealed steel) and at the D/4 position of bar specimens. Tensile test specimens with a parallel portion diameter of 6 mm were taken from the D/4 position of the bar specimens. For the Vickers hardness measurement, the cross section of the heat treated steel specimens was embedded in resin. The specimens were mechanically polished and buffed. The Vickers hardness was measured at nine points under a load of 4.9 N. The nine measurements were averaged to determine the Vickers hardness of the specimens. The Vickers hardness specimens were also used for microstructural observation. The specimens were polished to remove the Vickers hardness measurement marks, etched in nital (3% nitric acid and 97% ethanol), and observed with a scanning electron microscope (SEM). Table 2 shows the mechanical properties of the steel. Figure 1 shows the Vickers hardness and microstructures of the specimens. The microstructures are each mixtures of ferrite, pearlite, and spheroidal cementite. The Vickers hardness measurement results showed no differences.

2.2 Experimental conditions

The heat treated bars were machined into hollow shapes with an inner diameter of φ5, 10, or 15 mm as shown in Fig. 2. The hollow specimens were pickled and bonderized. The drawing test specimens in the present study were preformed 250 mm long and polished on the inner surface. We confirmed that the inner surface roughness was Ra75 = 0.31 against Ra75 = 0.32 for the outer surface roughness. The same FUJIOKA-SEISAKUSHO draw bench as described in our previous report was used for drawing the hollow specimens. A wire drawing die shaped as shown in Fig. 3 was used for drawing. The die angle was set to 2θ = 14° as is generally employed in wire drawing. The drawing test was conducted with the initial diameter φ30 and with the diameter reduced by 1 mm per pass.

2.3 FEM analysis conditions

To calculate the strain and stress during drawing, we carried out elasto-plastic analysis by using the finite element method analysis (FEM analysis) code Marc Version 2014. The FEM analysis of drawing used a two-dimensional half model in consideration of symmetry. After several trials, the mesh size was eventually defined at less than 0.5 mm so that the analysis results would become stable. The mesh size at the evaluation points was set to 0.5 mm by considering the analysis time and convergence. Because the effect of both ends can be ignored by making the specimen length more than three times larger than the specimen diameter, the specimen length during the analysis was set to more than three times larger than the specimen diameter. The friction coefficient was set so that the drawing load and the analysis load would agree with each other. The friction coefficient in this analysis was μ = 0.08. As material properties, the Young’s modulus was set to 206 GPa and the Poisson’s ratio was set to 0.3. The true stress-true strain relationship was extrapolated by extracting the actual data per 0.01 of the true strain until uniform deformation and by using a function approximated by a linear function after uniform deformation. The true stress-true strain curve used for the FEM analysis is shown in Fig. 4. Figure 5 shows the FEM analysis model of drawing. The evaluation points of the equivalent plastic strain and stress during drawing were set as the ductile crack initiation sites.

2.4 Definition of ductile fracture initiation site and arrangement of ductile fracture limit

The ductile crack initiation behavior of the drawn specimens was investigated as described in our previous reports. Tensile test specimens with a parallel portion diameter of φ12 or φ18 as shown in Fig. 6 were taken so that their axial direction matched that of the drawn specimens. The parallel portion length is 40 mm and long enough to measure the crack length. The tensile test specimens were sufficiently cooled in liquid nitrogen and tensile loaded to

Fig. 3 Drawing die geometry.
fracture. The maximum ductile crack length was measured on SEM fractographs. This method can easily distinguish between brittle and ductile fracture surfaces by fracturing the specimens under liquid nitrogen. As a result, the ductile crack length can be accurately measured.

The criterion under which the ductile crack length became 200 µm as described in our previous reports,13,15) was defined as the ductile fracture criterion. The equivalent plastic strain and stress triaxiality at the ductile crack initiation site were calculated by the FEM analysis.

3. Ductile Fracture Criterion in Multipass Drawing

3.1 Stress-strain hysteresis during multipass drawing

Figure 7 shows the relationship between the stress triaxiality and the equivalent plastic strain at the crack initiation site (at the evaluation point in Fig. 5) during drawing. As the inner diameter of the hollow specimens decreases, the average stress increases and the stress triaxiality also increases. No significant difference is observed in the strain per pass. The ductile fracture criterion for the bar specimens is as given by eq. (1). As the stress triaxiality increases, the critical strain at which a 200 µm long ductile crack occurs becomes small.

\[
\varepsilon_{eq} = 3.3 \times \exp\left(\frac{\sigma_m}{\sigma_{eq}}\right) \tag{1}
\]

where \(\varepsilon_{eq}\) is the critical strain and \(\sigma_m/\sigma_{eq}\) is the stress triaxiality.

If the ductile fracture criterion of the bar specimens can be also applied to the hollow specimens, it is evident from Fig. 7 that the stress triaxiality increases as the inner diameter of the hollow specimens decreases. The ductile fracture is thus likely to occur with a small number of passes.

3.2 Crack occurrence during multipass drawing

Figure 8 shows the cracks initiated in a φ10 hollow specimen in the pass 7 (the penultimate pass before fracture initiation). As shown in Fig. 8(a), three cracks were observed on the inner surface of the hollow specimen. The cross-sectional SEM micrograph of one of the cracks is shown Fig. 8(b). As the hollow specimen was drawn, the crack

![Fig. 4 True stress - true strain curve.](image)

![Fig. 5 Finite element model of specimens.](image)

![Fig. 6 Geometry of tensile test specimens.](image)

![Fig. 7 Relationship between equivalent plastic strain and stress triaxiality.](image)

(a) φ5 hollow specimen. (b) φ10 hollow specimen. (c) φ15 hollow specimen.
initiated on the inner surface and propagated in the outer diameter direction (thickness direction).

### 3.3 Ductile fracture limit

Figure 9 shows SEM fractographs. The cracks initiated on the inner surface were ductile fracture facets. The maximum ductile crack length was measured from the SEM fractographs. Figure 10 shows the relationship between the maximum ductile crack length and the equivalent plastic strain calculated from the FEM analysis. As the strain increases, ductile cracks initiate and propagate. The critical equivalent plastic strain at which the ductile crack length reaches 200 µm was determined from the relationship between the equivalent plastic strain and the ductile crack length.

Figure 11 shows the relationship between the stress triaxiality and the critical equivalent plastic strain when the 200 µm long ductile crack initiated. The ductile fracture criterion in the multipass cold-drawing test of the bar specimens and the tensile test of the notched bar specimens is also shown in Fig. 11. The ductile fracture criterion of the multipass cold-drawn bar specimens can be arranged by the ductile fracture criterion acquired in the notched round bar tensile test by considering the cumulative strain. This convinced us that the multipass cold-drawing test results of the hollow test specimens obtained in this study can be compared with the multipass cold-drawing test results of the rod-shaped test specimens.

![Fig. 8 Observation of crack of φ10 hollow specimen. (a) Overview of cross section. (b) SEM observation of crack at cross section.](image)

![Fig. 9 Observation of ductile crack.](image)

![Fig. 10 Relationship between equivalent plastic strain and ductile fracture length.](image)
4. Discussion

4.1 Evaluation of fracture morphology by Lode parameter

The changes in the Lode parameter were investigated when the bar and hollow specimens were drawn. The Lode parameter is a function of the second and third invariants and given by

\[ \xi = \frac{27}{2} \frac{J_3}{\sigma_{eq}^3} \]  \hspace{1cm} (2)

where \( \sigma_{eq} \) is the equivalent stress and \( J_3 \) is the third invariant of the deviatoric stress. The Lode parameter indicates a uniaxial stress state (tension) when \( \xi = 1 \), a plane strain state (shear) when \( \xi = 0 \), and a biaxial tensile state (compression) when \( \xi = -1 \).

Figure 12 shows the relationship between the Lode parameter and the equivalent plastic strain at the ductile crack initiation site during drawing. In the case of the bar specimens, \( \xi \) is always 1 (uniaxial stress state) at the ductile crack initiation site, regardless of the number of drawing passes. In the case of the hollow specimens, \( \xi = 0 \) in the initial stage of drawing, rapidly increases to 1 with the progress of drawing, decreases to 0.4, and again increases to 1. This process is repeated. The ductile crack initiation and propagation in the bar specimens is void growth and coalescence due to tensile deformation. The ductile crack initiation and propagation in the hollow specimens is presumed to occur when the Lode parameters \( \xi \) is 0.4 to 1.0, or, namely, is assumed to be a mixed mode of tensile deformation and shear deformation. As explained in Section 4.2, the relationship between the Lode parameter and the fracture surface morphology were investigated in detail.

4.2 Relationship between Lode parameter and fracture surface morphology

The fracture surface morphology was observed at an arbitrary position from the point of ductile fracture and the relationship with the Lode parameter was investigated. Figure 13 shows the fracture surfaces at the ductile fracture origin, the ductile crack end point, and the intermediate position. Cross-sectional SEM fractographs through the ductile fracture origins are also shown. Only equiaxed dimples were observed in the fractograph (a) of the bar specimen where \( \xi \) was always 1. The cross section through the ductile crack origin was perpendicular to the drawing direction. The fractograph (a) of the hollow specimen at the fracture origin mainly consisted of elongated dimples caused by shear deformation. The cross section lay in the shear direction at an angle of about 45° to the drawing direction. In the fields of view (b) and (c) in the crack propagation process, equiaxed dimples were observed but were coarser than observed in the bar specimen and were torn.

The above study results made clear that the difference in the ductile fracture morphology was a main factor for the inability to arrange the ductile fracture of the hollow specimens during drawing by the ductile fracture criterion of the bar specimens. If a stress triaxiality-type ductile fracture criterion corresponding to the change in load parameter (change in fracture morphology) can be obtained during the drawing of the hollow specimens, the brittle fracture criterion can be accurately predicted. The ductile fracture mechanism of the hollow specimens during drawing is represented by the model shown in Fig. 14. Where the Lode parameter \( \xi \) is near 0 in the ductile crack initiation process, a crack initiates in the shear direction at an angle of 45° to the drawing direction. Where the Lode parameter \( \xi \) is 0.4 to 1.0 in the ductile crack propagation process, voids grow and coalesce by repeating their deformation and typical growth in the shear direction.

Where the Lode parameter \( \xi \) is 0.4 to 1.0, voids in microregions are considered to mainly deform in the shear direction. As seen in Fig. 13, the fracture surface showed no void growth in the equiaxed direction and revealed a dimple...
morphology where the dimples were deformed and torn in the shear direction. Where the Lode parameter $\xi$ is high at 1.0 high, on the other hand, voids are considered to mainly grow and coalesce in an equiaxed manner. It is also considered that the voids deformed in the shear direction grew in an equiaxed manner and were observed as coarse dimples.

The ductile fracture of the hollow specimens during drawing in this study presented a fracture surface morphology not observed in the drawing of the bar specimens as the deformation was repeated in the Lode parameter region of $0.4 < \xi < 1.0$. This study failed to investigate the ductile fracture surface morphology in the region of $0 < \xi < 0.4$. Li et al.\textsuperscript{24} reported that the fracture surface morphology of plate specimens with $\xi < 0.4$ was the shear deformation and growth of voids. This suggests that the fracture surface morphology in the region of $0 < \xi < 1.0$ is a mixed mode of void shear deformation and typical void growth and coalescence. Up to now, many studies have been reported that evaluated the relationship between the fracture surface morphology and the Lode parameter under the conditions where the stress triaxiality changes variously. In order to clarify the ductile fracture mechanism by performing various evaluations with the stress triaxiality kept constant and the Lode parameter changed variously.

5. Conclusions

In this study, in order to understand the ductile fracture mechanism of hollow members during drawing, the ductile fracture criterion in the drawing of the hollow specimens from the changes in the Lode parameter and the ductile fracture surfaces.

(1) We confirmed that ductile cracks initiate on the inner surface of the hollow specimens and found that the critical strain is overestimated in the ductile fracture criterion of the bar specimens.

(2) The ductile crack surface morphology of the hollow specimens were examined, and elongated dimples and equiaxed dimples were observed at the ductile crack initiation site and in the crack propagation region.

(3) The ductile fracture mechanism of the hollow specimens during drawing was inferred to be a ductile crack propagation process consisting of the shear deformation of voids and the typical growth and coalescence of voids in the Load parameter region of $0.4 < \xi < 1.0$.

(4) If a stress triaxiality-type ductile fracture criterion corresponding to the change in in the Lode parameter during drawing can be acquired, the ductile fracture of hollow members during cold-drawing can be evaluated and predicted with high accuracy.

REFERENCES

Investigation of Ductile Fracture Mechanism in Multipass Drawing of Hollow Specimen