Investigation of Crack Prediction Method Using Limiting Surface Strain in High-Strength Steel Sheets

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Abstract. To study cracks, which are affected by bending forming, a hat-shape forming experiment was conducted. Then, a prediction method using limiting surface strain for bending crack was investigated. In the case of high bendability steel, breakage occurred after necking, which grew from the front and rear surface with obvious thickness reduction. In this type of breakage, it was found that the forming limit could be predicted by using a conventional forming limit diagram (FLD), which means that there is a limiting strain at the middle of the thickness direction. On the other hand, in the case of low bendability steel, cracks outside the bending surface occurred and grew, followed by breaking without the necking with obvious thickness reduction. In this case, the forming limit could not be predicted by using FLD, and it was found that the forming limit could be predicted by using limiting surface strain for bending crack, which could be obtained by finite element analysis (FEA) and an experiment by a V-shape bending test.

1. Introduction

In recent automobile development, weight reduction of the auto body, with the objective of preserving the global environment by reducing CO₂ emissions, is an important issue. At the same time, it is also important to improve collision safety performance to meet more stringent collision safety standards. It is necessary to satisfy both of these requirements simultaneously. As one means of achieving this, thinner gauge, higher strength steel sheets are now applied to skeleton parts. It is possible to reduce auto weight by using thinner steel sheets, while also improving absorbed energy in collisions by using higher strength steels. In particular, ultra-high strength steel sheets of over 980N/mm² grade and hot stamping of skeleton parts are increasingly applied to parts around the cabin, such as the center pillar and side sill, in order to protect the occupants in case of a collision.

Many automobile parts are produced by press forming because of its high productivity. Press forming processes are generally classified basic modes such as draw forming, stretch forming, stretch-flange forming and bending forming. Since it is well known that the mechanical properties of steel sheets have a large effect on forming modes, much research has been done to examine this relationship. In experimental and theoretical research, Fukuda clarified the fact that r-value affects the limited drawing ratio in a cylindrical deep drawing experiment[1]. Nakajima et al. showed that steel sheets with high elongation and a high n-value have high stretch formability[2]. Nakagawa et al. reported that stretch-
flange formability exhibited a strong correlation with ultimate deformability in steel sheets\cite{3}. Generally, as the strength of steel increases, elongation and the r-value decrease, and as a result, stretch formability and draw formability tend to deteriorate. On the other hand, as Masuda et al. reported, bending forming has a high forming limit because of the high strain gradient in the thickness direction\cite{4}. Therefore, steel sheets of over 1180 N/mm\(^2\) grade are frequently used in applications which mainly involve stretch-bending forming.

It is known that bending formability is affected by the mechanical properties and microstructure of the convex surface (outside bending surface). Yamazaki et al. showed that ultimate deformability and the homogeneity of the microstructure affect bending formability\cite{5}. Hayashi et al. investigated the deformation behavior of dual phase steel sheets during bend forming microscopically by using a nanoindentation technique and clarified the fact that localized plastic deformation in the soft phase by shear bands causes low bendability\cite{6}. In general, crack by pure bending, which observes on the outer surface of bending, does not occur in 590 MPa steel sheets or less. On the other hand, in over 780 MPa steel sheets, the crack occurs in some materials. Therefore, limit bending radius without surface crack is usually evaluated as a kind of material property by such as V-shape bending test. In the case of crack on the outer surface of bending in pure bending, plastic instability occurs only on the outer surface of bending, and then crack occurs. Therefore, forming limit of bending should be judged by the occurrence of the plastic instability. However it is difficult to judge the plastic instability industrially, and then forming limit in pure bending was judged by an occurrence of the surface crack.

As a prediction method for failure modes such as cracks and wrinkles during press forming, the major and minor strains obtained from a press forming analysis calculated by the Finite Element Method (FEM) are generally compared with the Forming Limit Diagram (FLD). A FLD which was use industrially shows the forming limit strain at the center of thickness for an occurrence of necking. Much theoretical research has been done on this subject. For example, based on a theoretical assumption of the initial inhomogeneity of the sheet metal, Marciniak et al. showed that localized necking occurred in a biaxial tension region\cite{7}, and Stören et al. suggested a theory of localized necking occurrence based on bifurcation theory\cite{8}. Keeler presented a FLD measured by a stretch forming experiment\cite{9}, and Nakajima et al. and Marciniak et al. then suggested experimental measurement methods for the FLD\cite{7}\cite{10}. Forming limit in pure bending cannot be predicted by using the FLD for necking, because the criterion of forming limit of pure bending is the occurrence of cracks on outer surface of bending, and steep strain gradient in thickness reduction affected the crack occurrence.

Typical risky position for breakage in general press forming is stretch-bending position such as the punch shoulder. In this position, breakage sometimes occurs in ultra-high strength steel sheets, although the judgment by using the FLD for necking is no problem. The cause of this breakage is the bending crack on the outer surface, and it is difficult to predict cracks by the conventional method using the FLD.

Recently, some studies have investigated the forming limit and crack prediction methods for stretch-bending of ultra-high strength steel sheets. Tharrett et al. showed that necking formed when the strain on the concave side reached a critical strain\cite{11}. Wu et al. proposed a new failure criterion called BFLC (bending-modified forming limit curve), which was an extension of the traditional FLD\cite{12}. Yonebayashi et al. suggested a crack prediction method using a ductile fracture model\cite{13}\cite{14}. Shirakami et al. showed that a crack or break based on a ductile fracture model occurred under the conditions of a smaller bending radius and higher strength steel\cite{15}. Yonebayashi et al. suggested crack prediction equations which considered ultimate deformability, the n-value and the stress gradient\cite{16}. As mentioned above, as anisotropy can be seen in bending formability, even in the same steel sheet, it is thought that the phase composition and homogeneity of the microstructure of the near surface region affect bendability. However, there are few reports on prediction methods focusing on the crack limit strain at the convex surface in stretch-bending.

In this paper, a hat-shape forming experiment was carried out using 980 N/mm\(^2\) and 1180 N/mm\(^2\) grade steel sheets with different bendability, and the crack occurrence behavior in stretch-bending was investigated. Based on the results, a crack prediction method using the surface strain on the outer side of bending as a threshold was suggested.
2. Crack initiation behavior in stretch bending forming

2.1 Experimental materials

980 N/mm² and 1180 N/mm² cold-rolled steel sheets with different bendability were used as the experimental materials. The thickness of both steel sheets was 1.4mm. The mechanical properties are shown in Table 1, and the r-value and n-value in three directions are shown in Table 2. The mechanical properties, r-value and n-value were measured using Japanese Industrial Standards (JIS) No. 5 tensile test specimens taken in the direction perpendicular to the rolling direction. The r-value was measured after nominal strain of 6% was applied, and the n-value was measured between nominal strain of 2% and 5%. As shown in Table 2, the anisotropy of the r-value and n-value was small.

2.2 Experimental procedure of hat shape forming

Rectangular specimens with dimensions of 50 mm in width and 300 mm in length were used. In order to take specimens in the lowest bendability direction, the longitudinal direction of the specimen was parallel to the direction perpendicular to the rolling direction. The end faces were ground to prevent cracking from the end faces. For strain measurement, small circles 0.5 mm in diameter were transferred to the specimen surface at 1 mm intervals by electrolytic etching. Figure 1 shows a schematic of the tools for the hat-shape forming experiment. The shoulder radius of the punch was 4.0 mm, and that of the die was 5.0 mm. Semicircular beads were made on the die surface. The radius of the beads was 7.0 mm, and the bead height was 3.5 mm. Anti-rust oil was applied to the specimen surfaces as a lubricant. The blank holding force (BHF) was varied up to 441 kN to change the tensile force applied to the specimen.

After hat-shape forming, the convex surface and cross section at the bending position were observed. Surface observation was conducted using a digital microscope, and the occurrence of micro-cracks was investigated. Cross-sectional observation was performed with an optical microscope using the forming specimen immediately before the forming limit, and necking occurrence was investigated. In this paper, the occurrence of micro-cracks and necking was defined as the forming limit.

2.3 Crack occurrence behavior at punch shoulder

Table 3 shows the results of the judgment of crack, i.e., the forming limit at the punch shoulder after hat-shape forming. In material A, crack and necking did not occur up to BHF 343 kN, and wall break occurred over 392 kN. In material B, no crack was observed at the punch shoulder up to 392 kN, and necking occurred between the punch shoulder and wall at 441 kN. In material C, micro-cracks, as shown in Figure 2, occurred on the convex surface at the punch shoulder position from 196 kN, and a break

| Material | Thickness t / mm | Yield point / N/mm² | Tensile strength / N/mm² | Elongation / % |
|----------|------------------|---------------------|--------------------------|---------------|
| A        | 1.4              | 802                 | 1044                     | 15.8          |
| B        | 1.4              | 847                 | 1243                     | 12.8          |
| C        | 1.4              | 743                 | 1194                     | 14.7          |

| Material | r-value 0 deg. | r-value 45 deg. | r-value 90 deg. | n-value 0 deg. | n-value 45 deg. | n-value 90 deg. |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|
| A        | 0.95           | 0.95           | 1.07           | 0.124          | 0.123          | 0.122          |
| B        | 0.90           | 1.01           | 1.03           | 0.093          | 0.092          | 0.090          |
| C        | 0.93           | 0.91           | 1.05           | 0.158          | 0.154          | 0.154          |

Figure 1. Schematic of hat forming tools.
occurred at the punch shoulder at 441 kN. The BHF at the forming limit was 392 kN for material B and 147 kN for material C.

Figure 2 shows the results of observation of the convex surface at the punch shoulder position, and Figure 3 shows the cross-sectional observation results at the punch shoulder for material B at the BHF of 441 kN and material C at 392 kN, that is, immediately before breaking occurred at the punch shoulder. As mentioned above, necking with obvious thickness reduction was observed clearly in material B, but in material C, micro-cracks in the outer surface of bending were observed. Although the thickness reduction was about 10 %, necking with obvious thickness reduction was not observed.

| Material | Elongation / % | Blank holding force / kN |
|----------|----------------|-------------------------|
|          | 49 98 147 196 245 294 343 392 441 |
| A        | 15.8 | No crack | Wall break |
| B        | 12.8 | No crack | Necking |
| C        | 14.7 | No crack | Surface crack | Break |

Table 3. Forming limit judgment after hat forming.

3. Proposal of crack prediction method by using 'limiting surface strain'

3.1 Derivation of limiting surface strain for bending cracking

As mentioned in the preceding section, two kinds of failure were observed in hat-shape forming, one in which necking caused the break and the other in which the growth of surface cracks caused the break. Surface cracks, as will be discussed below, were also observed on the convex surface in the basic V-shape bending test. It is thought that these surface cracks occurred when the surface strain reached the limiting strain. Here, the limiting surface strain was defined forming limit for surface crack in pure bending, and then limiting surface strain was derived from an experiment and a FEM analysis of 90° V-shape bending. Specifically, the relationship between the bending radius and the maximum principal strain of the convex surface was obtained from the FEM analysis, and the maximum principal strain at the limit bending radius of each material obtained from the experiment was then defined as the limiting surface strain.

The FEM analysis was performed by the static implicit method, and ABAQUS was used as the solver. Figure 4 shows the FEM analysis model for V-shape bending. The mesh type was a two-dimensional solid mesh, and an isotropic hardening model was used. The mesh size was 0.14 mm, and the friction coefficient was 0.15. Stress-strain curve applied the FEM analysis was defined from tensile
experiment data mentioned in section 2.1. Experimental true stress-true strain data was used until uniform elongation, and after uniform elongation, true stress-true strain relation approximated by Swift's hardening low was used. Mises locus was used as yield locus. The calculations were performed with the ratio R/t of the punch radius R and specimen thickness t varied in the range from 1 to 3.

The 90° V-shape bending experiment was conducted according to JIS Z 2248:2006. The specimen dimensions were 35 mm in width and 100 mm in length, and the longitudinal direction of the specimen was perpendicular to the rolling direction. The limit bending radius, which means the punch radius without surface cracks, was obtained by changing the punch radius. The limit bending radius and R/t ratio of each material are shown in Table 4.

3.2 Experimental procedure of Forming Limit Diagram (FLD)
In the case of a break caused by necking in the thickness direction due to plastic instability, it is thought that the maximum principal strain at the center of thickness reaches the limiting strain. In this case, industrially, the forming limit is judged when the necking with local thickness reduction occurs. The forming limit prediction method using the conventional FLD for the necking is considered appropriate. Therefore, the FLD of each material was measured by the Nakajima method. Figure 5 shows an example of a specimen for the FLD measurement. In order to change the strain ratio, the width W was varied from 16 mm to 100 mm. Small circles 1 mm in diameter were transferred to the specimen surface at 2 mm intervals by electrolytic etching in order to calculate the strain from the change of the interval. The stretch-forming test was performed using a hemispherical head punch with a 50 mm radius. Vaseline and polyethylene sheets were used as a lubricant between the punch and the specimen. The principal strains were calculated from the distance between the circles at necking occurrence, and the maximum principal strain was defined as the limiting strain for necking.

3.3 Limiting strain of each material
Figure 6 shows the relationship between the R/t ratio and the surface strain at the outside bending surface obtained from the FEM analysis of 90° V-shape bending. As shown in Table 3, the limit R/t ratios of

| Material | Thickness t / mm | Limit bending radius R / mm | R/t |
|----------|------------------|----------------------------|-----|
| A        | 1.4              | 1.5                        | 1.1 |
| B        | 1.4              | 2.0                        | 1.4 |
| C        | 1.4              | 3.0                        | 2.1 |

Table 4. Results of V-shape bending test.
materials A, B and C obtained from the experiment were 1.1, 1.4 and 2.1, respectively. From these results, the limiting surface strains of each material were approximately 0.35, 0.30 and 0.21.

Figure 7 shows the FLD for the necking limit of each material. Because the elongation of materials A and C was higher than that of material B, materials A and C displayed higher limiting strain for necking than material B. The strain region at the punch shoulder in the hat-shape forming experiment was the plane strain region; therefore, from Figure 7, the limiting strain for necking in the center of thickness of each material was approximately 0.19, 0.14 and 0.18, respectively.

In this paper, the limiting strain for a necking on the outside bending surface was defined as the sum of the limit strain for necking obtained from the FLD and the bending strain. Preconditioned on pure bending theory, the bending strain can be calculated by using the bending radius (punch shoulder radius) and the thickness of the material. In this hat-shape forming experiment, bending strain was calculated at approximately 0.14. From these results, the limit strain for necking at the outside surface in stretch bending of materials A, B and C was approximately 0.33, 0.28 and 0.32, respectively.

Comparing the limiting surface strain and the limiting strain for necking, the limiting strain for necking was lower than the limiting surface strain in materials A and B, which have high bendability. In contrast, in material C, which has low bendability, the limiting surface strain was much lower than the limiting strain for necking.

From these results, it is thought that the prediction accuracy for cracking and necking was improved by using the limiting surface strain as a threshold in addition to the conventional limiting strain for necking obtained from the FLD. In order to verify this improvement of prediction accuracy, the prediction method using the limiting surface strain was applied to the hat-shape forming mentioned in Chapter 2 and press forming of an actual part shape.

![Figure 6. Relationship between R/t and surface major strain on convex surface.](image)

![Figure 7. Forming limit diagrams of each steel.](image)

4. Verification of proposed crack prediction method in hat-shape forming

The validity of each limiting strain was verified by a comparison between the forming limit judgment, strain measurement results at the punch shoulder, limiting surface strain and limiting strain for necking obtained in Chapter 3. Figures 8, 9 and 10 show the relationship between BHF and major strain at the punch shoulder in each material. In Figure 9, “Necking” indicates necking occurrence, and in Figure 10, the X marks show micro-crack occurrence on the convex surface. The solid lines and broken lines mean the limiting strain for necking and the limiting surface strain, respectively.

The major strain increased as BHF increased in all materials. At the same BHF, the major strain in material A was higher than those in materials B and C, and the major strain in material B was the same as that in material C. It is thought that the deformation resistance during forming of material A (980
N/mm² steel) is lower than that of materials B and C (1180 N/mm² steels), and as a result, the major strain is higher in material A.

Because wall break occurred in material A, the major strain at the punch shoulder did not reach either limiting strain (limiting surface strain for surface crack, limiting strain for necking). However, since the limiting strain for necking is lower than the surface limit strain, it is estimated that the failure in this case was caused by necking.

In material B, the major strain at the BHF of 441 kN, at which necking was observed, was near the limiting strain for necking. As in material A, it is considered that failure was caused by necking, and it is possible to predict the necking by using the conventional FLD.

On the other hand, in material C, the major strain reached the limiting surface strain at the BHF of 245 kN, and micro-cracks were observed on the surface at the punch shoulder position in the hat-shape forming experiment. When the limiting surface strain is lower than the limiting strain for necking, as in material C, it is considered that micro-cracks occur on the convex surface without necking, the micro-cracks grow and combine under increasing BHF, and this finally results in break. For this reason, it is difficult to predict cracks from the conventional FLD, and it is thought that prediction using the limiting surface strain is effective.

From these results, it was suggested that cracks affected by bending deformation could be accurately predicted by using the limiting surface strain as a threshold.

![Figure 8](image8.png) **Figure 8.** Relationship between BHF and major strain in punch shoulder in material A.

![Figure 9](image9.png) **Figure 9.** Relationship between BHF and major strain in punch shoulder in material B.

![Figure 10](image10.png) **Figure 10.** Relationship between BHF and major strain in punch shoulder in material C.
5. Summary

- In materials with low bendability, micro-cracks occur on the outer surface of stretch-bending without necking, and then a fracture occurs. On the other hand, in materials with high bendability, necking grows and leads to a fracture.
- Cracks of outer surface of bending in stretch-bending deformation area can be judged by using limiting surface strain obtained from pure bending test such as V-shape bending.
- The results of crack prediction in hat forming experiments demonstrated that the judgement by the limiting surface strain obtained from V-shape bending test in addition to the conventional judgement by using FLD for necking is necessary in order to predict the forming limit in stretch-bending deformation area accurately.

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