Effect of strain gradient on stretch flange deformation limit of steel sheets

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Abstract. The effect of strain gradient on the stretch flange deformation limit of steel sheets was investigated by hole expansion test under some forming conditions and by FEM. Hole expansion ratio was changed by changing initial hole diameter and punch shapes. It was clarified that a limit stretch flange deformation strain basically depends on not the initial hole diameter and the punch shape by themselves but the strain gradient in the radial direction. The strain gradient along the direction toward the maximum principal strain did not affect limit deformation strain. The limit deformation thickness strain of the stretch flange portion could be changed by changing strain gradient. These results suggest that the formability of stretch flange deformation area should be determined from not only the maximum principle strain but also the strain gradient and blanking clearance.

1. Introduction

The demand for high strength steel sheets has been increasing to enhance vehicle weight reduction, as well as crash performance. One of the biggest problems in press forming of high strength steel sheets is fracture which often occurs in stretch flanging areas, such as in frame and underbody parts. Therefore, there has been a strong demand for the improvement of the predictive accuracy of the stretch flange formability of high strength steels using finite element method (FEM) forming simulations [1].

To improve the predictive accuracy of the stretch flange formability by the FEM analysis, the estimation of deformation limit is generally important as well as the estimation of deformation behavior of the material. Regarding the stretch flange deformation behavior, Kuwabara et al. [2] investigated the influence of the anisotropy yield function. Regarding the stretch flange deformation limit, many studies have shown that the influence of the shearing edge conditions [3] or the pre-deformation conditions [4].

Regarding the influence of strain gradient on the stretch flange deformation limit, Masuda et al. [5,6] investigated the hole expansion ratio by the conical punch increases with increase of the strain gradient. In most of the studies, the stretch flange deformation limit were basically evaluated by the results at shearing edge conditions. There are no studies which were estimated quantitatively about the influence of the strain gradient on the stretch flange deformation limit at the shearing edge. Later, there will be also no studies which verified the stretch flange formability considered influence of the strain gradient of the stretch flange deformation portion in the FEM forming simulations.

In this study, the effect of strain gradient on the limit stretch flange deformation strain of steel sheets was investigated by hole expansion test under some forming conditions and by the FEM
forming simulations. Hole expansion ratio was changed by changing initial hole diameter and punch shapes. As a result, it was clarified that the limit stretch flange deformation strain basically depends on not the initial hole diameter and the punch shape by themselves but the strain gradient in the radial direction. Therefore, the formability of stretch flange deformation area should be determined from not only the maximum principle strain but also the strain gradient and blanking clearance.

2. Experimental procedure

2.1. Material
In order to clarify the effects of strain gradients on limit stretch flange deformation strains, 5 kinds of steels which are frequently used for automotive parts, were used in experiments. The thicknesses of the test material are 1.2mm and those mechanical properties are shown in Table 1. Yield strength YS, tensile strength TS, elongation El were obtained by uniaxial tensile tests in the rolling direction (R.D.).

| Material | YS/MPa | TS/MPa | El/% |
|----------|--------|--------|------|
| A        | 168    | 309    | 49   |
| B        | 330    | 459    | 35   |
| C        | 419    | 643    | 28   |
| D        | 603    | 823    | 20   |
| E        | 787    | 1005   | 18   |

2.2. Hole expansion test
The initial hole diameter and punch shapes were changed in order to investigate the effects of strain gradients on stretch flange deformation limits. Table 2 shows the experimental conditions for the hole expansion tests by conical punches and table 3 shows the experimental conditions for the hole expansion tests by flat-bottomed punches in this study. To make fracture occur from a hole edge intentionally by a flat-bottom hole expansion test, the punch diameter was changed suitably according to the material.

The hole expansion ratio is defined as follows:

\[ \lambda = \frac{d - d_0}{d_0} \]  

Where \( d_0 \) is an initial hole diameter and \( d \) is the hole diameter after a hole expansion test.

Table 2. Experimental conditions for hole expansion tests by conical punches.

| Diameter/mm | Shoulder radius/mm | Material |
|-------------|--------------------|----------|
| Piercing punch | Punch | Die | Die |
| 10          | 50     | 59.6 | 5   | All |
| 25          | 98     | 150  | 5   | All |
| 50          | 140    | 160  | 5   | All |
Table 3. Experimental conditions for hole expansion tests by flat-bottomed punches.

| Material  | 10 | 25 | 50 |
|-----------|----|----|----|
| Punch     | 50 | 80 | 150|
| Die       | 59.6| 160| 160|
| Punch     | 8  | 5  | 10 |
| Die       | 5  | 5  | 5  |

Table 4 shows the experimental conditions for ellipse expansion tests by flat-bottomed cylindrical punches in order to clarify the effects of strain gradients along major strain direction on limit stretch flange deformation strain.

All initial holes were punched out with a clearance between punch and die taken to be 12.5%. All hole expansion tests applied anti-rust oil to the lubrication condition, and made the burr the die side.

Table 4. Experimental conditions for ellipse expansion tests by flat-bottomed cylindrical punch.

| Material  | 25 | 25 |
|-----------|----|----|
| Punch     | 80 | 80 |
| Die       | 160| 160|
| Punch     | 5  | 5  |
| Die       | 5  | 5  |

2.3. Oblong tensile test

Figure 1 shows the specimen and figure 2 shows an example of crack after oblong tensile test in order to clarify the limit stretch flange deformation strain when the strain gradient is small enough.

Figure 1. Specimen for oblong tensile test.

Figure 2. Example of crack after oblong tensile test.

3. Results

3.1. Results of hole expansion tests

Figure 3 shows the effect of initial hole diameter on hole expansion ratio of conical punches and figure 4 shows the effect of initial hole diameter on hole expansion ratio of flat-bottomed punches.
Figure 3. Effect of initial hole diameter on hole expansion ratio of conical punches.

Figure 4. Effect of initial hole diameter on hole expansion ratio of flat-bottomed punches.

The initiation portion of crack is the hole edge by all cases. All materials indicated the tendency which depends on the punch shape for the hole expansion ratio and decreases with increase in the initial hole diameter.

3.2. Effect of strain gradient on limit deformation strain

Figure 5 shows the effect of strain gradient on limit deformation strain. The limit deformation strain was calculated by $\lambda$ value as the average deformation strain of the hole edge. The strain gradient was defined as the average gradient of the maximum major strain between the 5mm at the radius direction (the way which crosses at right angles with the maximum major strain direction) from the hole edge, and was analyzed by the FEM forming simulation.

Figure 5. Effect of strain gradient on limit deformation strain.

The strain gradient in the forming limit decreased with increase of the punch diameter in spite of the punch shape. The limit deformation strain was increased linearly mostly with increase of the strain gradient, and not to depend on the punch shape and the initial hole diameter.

4. Discussion

4.1. Effect of initial hole diameter on thickness strain distribution along hole edge

In order to clarify the limit deformation strain increases with increase of the strain gradient, thickness strain distributions along hole edge were measured. Figure 6 shows the results of measurements. The thickness were measured by pint micro meter.
Figure 6. Thickness strain distributions along hole edge of conical punch forming.

In the case of an initial hole diameter of 10mm with the largest strain gradient, thickness strains in the hole edge of all the materials are less than those of larger initial hole diameter cases in all the directions. These results suggest that the limit deformation strain increases with increases the strain gradient by the delay of strain localization. When judging the stretch flange formability by the thickness strain, it can be said that the strain gradient should be considered.

4.2. Effect of strain gradient along major strain direction on limit deformation strain

Ellipse expansion tests were carried out in order to clarify the effects of strain gradients along major strain direction on limit stretch flange deformation strain. Figure 7 shows the effect of strain gradient along major strain direction on limit deformation strain of material C. It was found that the influence of the strain gradient of the maximum major strain direction on limit deformation strain is small. When estimating stretch flange formability by the FEM forming simulation, this result suggests that the necessity which considers the strain gradient of the maximum major strain direction is small.

4.3. Proposal of evaluation method of stretch flange formability by FEM forming simulation

The limit stretch flange deformation strain strongly depends on the strain gradient as well as the blanking clearance. Then, effects of strain gradients and blanking clearances on limit stretch flange deformation strain were investigated by hole expansion tests. Regarding the effect of blanking clearance, limit deformation strain were investigated by the clearance conditions about 15% as the best cases, and about 30% as the worst cases [3]. Figure 8 shows the limit deformation strain lines of material B for judgment of stretch flange formability that considers strain gradients and blanking clearances. The zone A was defined the area where the maximum major strain of stretch flange portion is smaller than limit deformation strain line of worst clearance case. The zone C was defined the area where the maximum major strain of stretch flange portion is larger than limit deformation strain line of best clearance case. The zone B was
defined the area where the maximum major strain of stretch flange portion is between the line of worst clearance case and the line of best clearance case.

**Figure 7.** Effect of strain gradient along major strain direction on limit deformation strain of material C.

**Figure 8.** Limit deformation strain lines of material B for judgment of stretch flange formability that considers strain gradients and blanking clearances.

The standard when judging formation in the formability of the stretch flange deformation portion by the maximum major strain and the strain gradient of FEM analysis, is indicated as follows. When the result of the FEM maximum major strain and strain gradient analysis is located in zone A, it'll be the judgment it's possible to form in spite of the clearance. When the result of the FEM maximum major strain and strain gradient analysis is located in zone C, it'll be the judgment it's impossible to form in spite of the clearance. When the result of the FEM maximum major strain and strain gradient analysis is located in zone B, it'll be the judgment which depends on a clearance whether it's possible to form.

5. Conclusion

The effect of strain gradient on the stretch flange deformation limit of steel sheets was investigated by hole expansion test under some forming conditions and by FEM. As a results, following conclusions were obtained.

(1) Limit stretch flange deformation strains of all materials are increased linearly with increases of the strain gradients.
(2) Limit deformation strain increases with increases the strain gradient by the delay of strain localization.
(3) Influence of strain gradient of the maximum major strain direction on limit deformation strain is small.
(4) Formability of stretch flange deformation area should be determined from not only the maximum principle strain but also the strain gradient and blanking clearance.

**References**

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