Effect of pre-strain on stretch flange deformation limit of steel sheets

E Iizuka¹, K Higai², Y Yamasaki³

¹ Steel Research Laboratory, JFE Steel Corporation, 3-28-12, Meieki, Nakamura-ku, Nagoya, Aichi Pref., 450-6427 JAPAN
² Steel Research Laboratory, JFE Steel Corporation, 1, Kawasaki-cho, Chuo-ku, Chiba, Chiba Pref., 260-0835 JAPAN
³ Steel Research Laboratory, JFE Steel Corporation, 1 Kokan-cho, Fukuyama, Hiroshima Pref., 721-8510, JAPAN

E-mail: e-iizuka@jfe-steel.co.jp

Abstract. The effect of pre-strain on the stretch flange deformation limit of steel sheets was investigated by hole expansion tests under various pre-strain conditions. Pre-strain was given by stretch forming with a cylindrical punch. The strain ratio and amount of pre-strain were controlled by changing the blank shape and forming height. The hole expansion tests were carried out with a conical punch and cylindrical punch in order to clarify the effect of the strain gradient. The effect of the strain ratio of pre-strain on the stretch flange deformation limit can be expressed by equivalent strain. In the case of higher strain gradients, the stretch flange deformation limit increased with increasing pre-strain. However, at lower strain gradients, the stretch flange deformation limit was almost constant. These results suggest that the formability of the stretch flange deformation area given by pre-strain should be determined from not only the total equivalent strain but also the strain gradient and the amount of pre-strain expressed by equivalent strain.

1. Introduction

Demand for high strength steel sheets is increasing with the aims of realizing larger vehicle weight reductions and enhanced crash performance. One of the largest problems in press forming of high strength steel sheets is fracture, which often occurs in stretch flanging areas, not only in inner panel parts but also in frame and underbody parts. Therefore, there has been strong demand for improvement of the predictive accuracy of the stretch flange formability of high strength steels by finite element method (FEM) forming simulations [1].

To improve the predictive accuracy of stretch flange formability by FEM analysis, estimation of the deformation limit as well as estimation of the deformation behavior of the material is generally important. Regarding stretch flange deformation behavior, Kuwabara et al. [2,3] investigated the influence of the anisotropy yield function. Regarding the stretch flange deformation limit, many studies have shown the influence of the shearing edge condition [4] and material properties [5].

In most studies of the influence of the strain gradient on the stretch flange deformation limit, the stretch flange deformation limit was basically evaluated by the results under shaving edge conditions. However, no studies have reported quantitative estimations of the influence of the strain gradient on the stretch flange deformation limit at the shearing edge. Thus, there will also be no subsequent studies which verify stretch flange formability considering the influence of the strain gradient of the stretch flange deformation portion in FEM forming simulations.

In this situation, Iizuka et al. [5,6] investigated the effect of the strain gradient on the limit stretch flange deformation strain of steel sheets. The results clarified the fact that the limit stretch flange deformation strain basically depends on the strain gradient in the radial direction. As conclusions, it was suggested that the formability of the stretch flange deformation area should be determined from not only the maximum principle strain or the thickness reduction, but also the strain gradient and blanking...
clearance. However, since those studies did not consider the effect of pre-strain, it is unclear whether pre-strain has an influence on the stretch flange deformation limit. Hence, the conclusions could not be applied to the evaluation of formability of the stretch flange deformation area given by pre-strain.

In this study, the effect of pre-strain on the limit stretch flange deformation strain of steel sheets was investigated by hole expansion tests under various pre-strain conditions. Pre-strain was given by stretch forming with a cylindrical punch. As a result, it was suggested that the formability of the stretch flange deformation area given by pre-strain should be determined from not only the total equivalent strain but also the strain gradient and amount of pre-strain expressed by equivalent strain. As a result, a new method for evaluation of the formability of the stretch flange deformation area given by pre-strain was proposed.

2. Experimental procedure
The experimental procedure of this study is shown in Figure 1. Pre-strain was given by stretch forming with a cylindrical punch. The stretch flange deformation limit was evaluated by the hole expansion limit.

2.1. Material
In order to clarify the effects of pre-strain on the limit stretch flange deformation strain, three kinds of steels which are frequently used for automotive parts were used in experiments. Their material properties are shown in Table 1. Yield strength YS, tensile strength TS and elongation El were obtained by uniaxial tensile tests.

| Material | Steel Grade (JIS) | Thickness / mm | YS / MPa | TS / MPa | El / % |
|----------|------------------|----------------|-----------|-----------|--------|
| A        | JAC270D          | 0.7            | 166       | 293       | 49     |
| B        | JSH590R          | 2.6            | 502       | 618       | 29     |
| C        | JSH590B          | 2.6            | 448       | 603       | 32     |

2.2. Pre-strain procedure
First, the stretch forming test with the cylindrical punch was carried out in order to give a certain pre-strain. The strain ratio and amount of pre-strain were controlled by adjusting the blank shape and forming height.
2.3. Hole expansion test procedure
The hole expansion tests were carried out in order to evaluate the stretch flange deformation limit given by pre-strain. Two punch shapes (conical, cylindrical) were selected to investigate the effects of the strain gradient on the stretch flange deformation limit. All initial holes of the test materials which were given pre-strain were punched out with a clearance between the punch and die of approximately 15%. In all hole expansion tests, anti-rust oil was used as the lubrication condition, and burr was formed on the die side.

3. Results

3.1. Results of hole expansion tests by conical punch
Figures 2, 4 and 6 show the effects of the pre-strain ratio and pre-deformation equivalent strain on the subsequent deformation limit strains of materials A, B and C. Figures 3, 5 and 7 show the effects of the pre-strain ratio and pre-deformation equivalent strain on the total deformation limit equivalent strains of materials A, B and C.

**Figure 2.** Effects of pre-strain ratio and pre-deformation equivalent strain on subsequent deformation strain of material A.

**Figure 3.** Effects of pre-strain ratio and pre-deformation equivalent strain on total deformation limit equivalent strain of material A.

**Figure 4.** Effects of pre-strain ratio and pre-deformation equivalent strain on subsequent deformation strain of material B.

**Figure 5.** Effects of pre-strain ratio and pre-deformation equivalent strain on total deformation limit equivalent strain of material B.
In the hole expansion test with the conical punch, the effect of the pre-deformation strain ratio on the subsequent stretch flange deformation limit can be expressed by the pre-deformation equivalent strain. The total deformation limit equivalent strain increases as the amount of pre-deformation equivalent strain increases. However, in this case, the increasing ratio of the total deformation limit equivalent strain depends on the kind of material.

### 3.2. Results of hole expansion tests with cylindrical punch

Figures 8 and 10 show the effects of the pre-strain ratio and pre-deformation equivalent strain on the subsequent deformation strain limit of materials A and B. Figures 9 and 11 show the effects of the pre-strain ratio and pre-deformation equivalent strain on the total deformation limit equivalent strain of materials A and B. A sample was eliminated from the results if an inside crack of the hole edge occurred. Therefore, the crack initiation area is the hole edge in all cases. Figure 12 shows typical examples of an edge crack and inside crack in the hole expansion test with the cylindrical punch.
Figure 10. Effects of pre-strain ratio and pre-deformation equivalent strain on subsequent deformation strain of material B.

Figure 11. Effects of pre-strain ratio and pre-deformation equivalent strain on total deformation limit equivalent strain of material B.

Figure 12. Typical examples of edge crack and inside crack in hole expansion test with cylindrical punch.

In the hole expansion test with the cylindrical punch, the effect of the pre-deformation strain ratio on the subsequent stretch flange deformation limit can also be expressed by the pre-deformation equivalent strain. However, the total deformation limit equivalent strain shows an almost constant value independent of the amount of pre-deformation equivalent strain in this case. Therefore, to select the equivalent strain as the index of the stretch flange deformation limit, the maximum major strain of the stretch flange deformation limit in the case of no pre-strain can essentially be replaced by the total deformation limit equivalent strain as the stretch flange deformation limit given by pre-strain.

4. Discussion
In a hole expansion test with the conical punch, the total deformation limit equivalent strain increases as the amount of pre-deformation equivalent strain increases. On the other hand, in the hole expansion test with the cylindrical punch, the total deformation limit equivalent strain shows an almost constant value independent of the amount of pre-deformation equivalent strain. These results suggest that the effect of pre-strain on the stretch flange deformation limit depends on the strain gradient. In general, the strain gradient of the hole expansion test with a conical punch is larger than the strain gradient of the hole expansion test with a cylindrical punch [5,6]. Due to this large strain gradient, the results with the conical punch were relatively more affected by the local deformation ability rather than by the wide area deformation ability. Hence, the results with the cylindrical punch were relatively more affected by the deformation of pre-strain in comparison with the results with the conical punch.
5. Proposal of new evaluation method for formability of stretch flange deformation area given by pre-strain by FEM forming simulation

Figure 13 shows a new evaluation method for the formability of the stretch flange deformation area given by pre-strain by a FEM forming simulation. The stretch flange deformation limit line with pre-strain can be obtained by connecting the results by the hole expansion tests with pre-strain. In the hole expansion test with the cylindrical punch with pre-strain, the value of the vertical axis does not change, but the horizontal axis can shift slightly due to the difference between the strain gradients without pre-strain [6] and that with pre-strain. In the hole expansion test with the conical punch with pre-strain, the value of the vertical axis increases to the stretch flange deformation limit line without pre-strain [6] as the amount pre-strain increases, and the amount of increase of vertical axis can be determined by the amount of the pre-strain and the kind of material. As in the test with the cylindrical punch, the horizontal axis can also shift slightly due to the difference between the strain gradients without and with pre-strain. By using the stretch flange deformation limit line obtained by this evaluation method, the formability of the stretch flange deformation area given by pre-strain can be judged by a FEM forming simulation.

![Figure 13. Proposed method for evaluation of formability of stretch flange deformation area given by pre-strain.](image)

6. Conclusion

The effect of pre-strain on the stretch flange deformation limit of steel sheets was investigated by hole expansion tests under various pre-strain conditions. As the results, the following conclusions were obtained.

1. The effect of the strain ratio of pre-strain on the stretch flange deformation limit can be expressed by equivalent strain.
2. In the case of higher strain gradients, the stretch flange deformation limit increased with increasing pre-strain.
3. In the case of lower strain gradients, the stretch flange deformation limit showed an almost constant value independent of the amount of pre-strain.
4. The formability of the stretch flange deformation area given by pre-strain should be determined from not only the total equivalent strain but also the strain gradient and amount of pre-strain expressed by equivalent strain.

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