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1 Introduction

In recent years, trials have been made to quantitatively determine the loads of automobiles on the global environment from the standpoint of LCA (life cycle assessment), which includes everything from the mining of material metals to the scrapping of products. Because driving energy accounts for approximately 80% of total energy consumption[1], the weight reduction of vehicles, along with the improvement of power trains, is recognized to be very important. The ULSAB project[2] which steelmakers from all over the world are involved in, is designed to reduce the weight of automotive bodies, expand the application of high-strength steel sheets, and adopt new manufacturing processes, etc. On the other hand, for collision safety or crashworthiness, the body structure is being improved on a company-by-company basis. To improve crashworthiness, it is effective to strengthen automotive bodies by using reinforcements, thicker materials etc., but this usually causes, the weight of automotive bodies to increase. In order to avoid this tendency as much as possible, much effort is being made to high-strength steel sheets, and optimize the body structure[3]. When high-strength steel sheets are used, a deterioration in shape fixability and formability are inevitable. However, the application of high-strength steel sheets to automotive bodies has been recognized as one of the most effective means to reduce the body weight in spite of these problems and the application of high-strength steel sheets has increased gradually. In the mid 1990s, vehicles consisting high-strength steel sheet by an amount of more than 45% began to be manufactured[4]. If a deterioration in the formability of high-strength steel sheets can be predicted beforehand, it can be prevented by improving forming dies and in some cases, changing to a simpler design.

In the application of high-strength steel sheets to automotive bodies, the prediction of formability, evaluation of collision energy as the body function, etc., are indispensable techniques. The finite element method (FEM) has come into wide use as an effective prediction technique. Although structural analyses by FEM have been conducted for a long time, it is relatively recent that this method has come into use to analyze the form-

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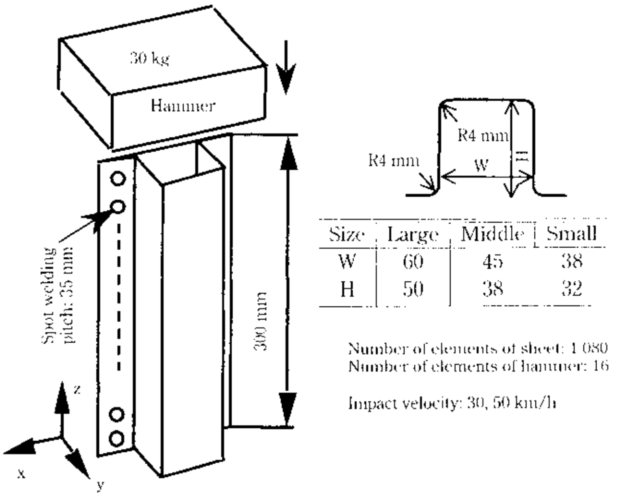
ing of automotive steel sheets and the functions of automotive bodies. This may be because progress has been made with solvers, which play a principal role in analyses by the finite element method, preprocessors, post-processors for input and output, and computers which actuate them.

In this paper, an FEM analysis is used to evaluate formability of high-strength steel sheet and its crashworthiness, which is one of the main objection in a case of applying it to automotive body. Results of FEM analysis and their comparison with experiments are discribed.

2 Analysis of Collision and Deformation of Structural Members

In general, the higher the member strength, the larger the energy absorption during a collision; therefore, high-strength steel sheets are suited to structural members such as front side members[5-11]. Materials that generate a high stress at a high strain rate and have large energy, which is expressed by area in a stress-strain diagram, are suitable as collision-resistant members. To quantitatively and systematically solve collision problems, analyses by the finite element method are considered to be effective because of difficulties in performing experiments and data sampling. This analysis clarifies the effects of the strain distribution, strain rate, etc., of materials on the collapse behavior during a collision. For this purpose, the axial-direction, high-rate compression deformation of structural members was analyzed by the finite element method of dynamic explicit algorythm "LS-DYNA." The dynamic explicit method provides for high consistency in the calculations.

As an example of analysis, a hat-shape section model in which a front side member is simulated was used as shown in **Fig. 1**. The model has three size levels, i.e., large, medium and small, and the sheet thickness is 1.6 mm in all three levels. In this analysis, a 30 kg weight was caused to collide with a sample in the axial (z) direction of the sample and the deformation behavior during a collision was analyzed. In the FEM analysis, the number of elements of a material is set to be 1 080 and that of a weight is set to be 16. In consideration of the symmetry of the model, half of these numbers was used in the analysis for both the material and the weight. As boundary conditions, all displacements and rotations were kept constrained for the nodes on the bottom surface. Also x-direction displacements and rotations with respect to y- and z-direction, for nodes located on a symmetric plane were kept under constraint. The Belytschko-Tsay shell element (4 nodes) was adopted, and isotropic elasto-plastic elements were obtained by an approximation of a stress-strain diagram by polygonal line. The element of the weight was an 8-node solid element, and the weight was assumed to be a rigid body. The model materials consisted of steel sheets of 4 levels, (A) to (D), with a tensile strength of 300 to 590 MPa as shown in **Fig. 2**. Characteristics at a high strain rate were measured using an impact tensile testing machine by the Hopkinson 2 bar method[11].



Size	Large	Middle	Small
W	60	45	38
H	50	38	32

Fig. 1 Collision analysis model of hat shape section

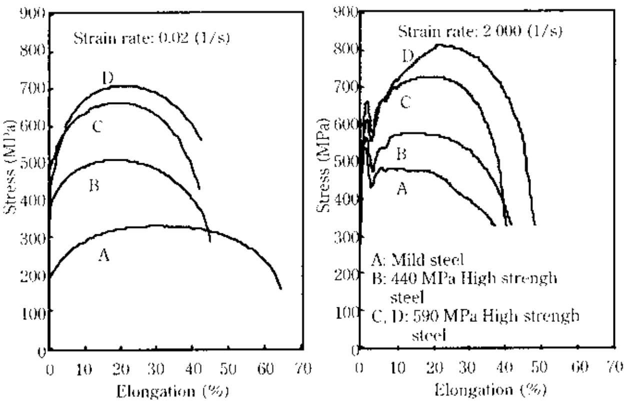


Fig. 2 Stress-strain relation of materials used in collision analysis

A comparison of collapse length between experimental results and calculated values is shown in **Fig. 3**. As the collision speed increases or the material strength decreases, the collapse length increases. It is apparent that the calculated results are in good agreement with the experimental ones. The collapse shape also showed the same configuration as in the experiment. When the same energy is given, the higher the strength of a steel sheet, the smaller the collapse length. In other words, when the collapse length is equal, the higher the material strength is, the larger the absorbed energy (energy required by deformation) becomes.

Next, strain rates and strain behavior in buckling deformation at such high speeds were investigated. **Figure 4** shows changes with time in strain rate in 16 elements from the top end of the material to a point, 80 mm apart from the top end (almost equivalent to the collapse length) during a collision at 50 km/h. Strain rate peaks

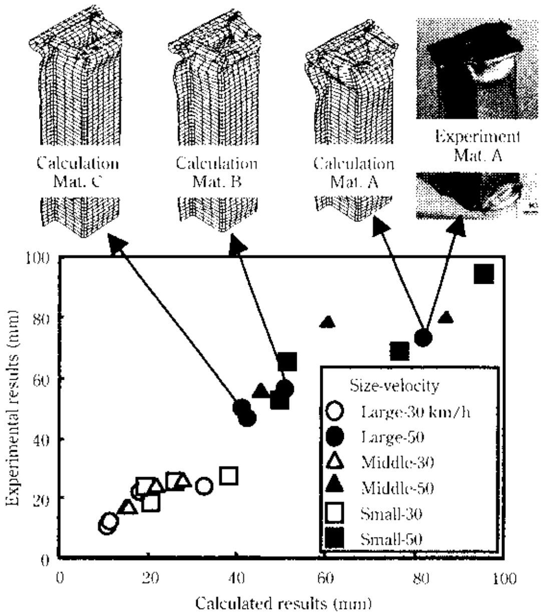


Fig. 3 Comparison of collapse length of model between experimental and calculated results

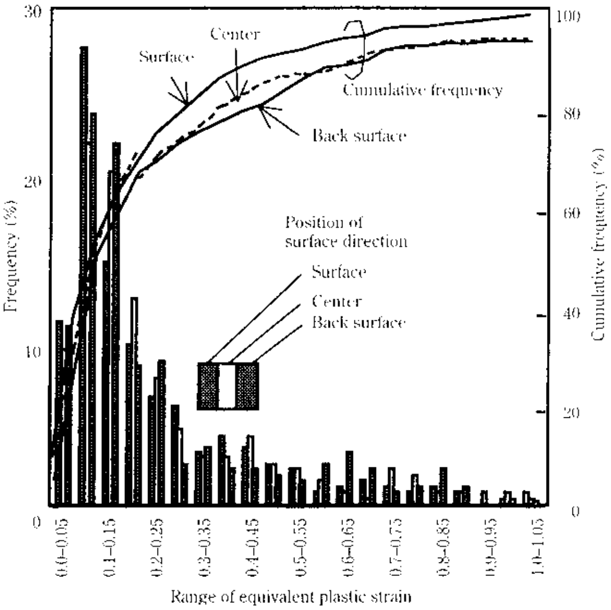


Fig. 5 Frequency of strain at collapse zone of model

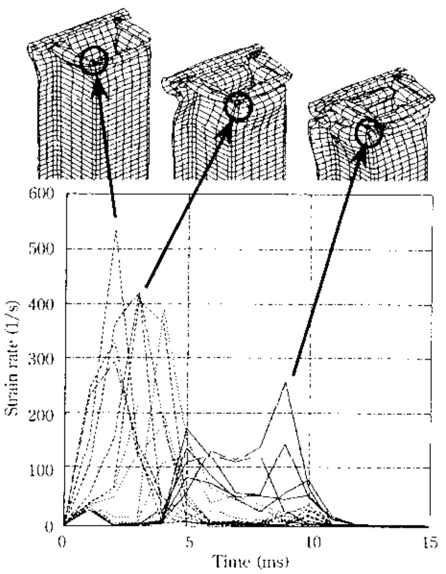


Fig. 4 Change of strain rate at corner collapse portion during collision

are observed at three points; they are the points indicated by the arrows in the figure where buckling occurred. The highest strain rate was observed in the buckled part near the top surface where the speed of the weight is the highest and this strain rate is approximately $550\ \mathrm{s}^{-1}$.

Figure 5 shows a histogram of strains of all the elements (surface, center and back surface of sheet) corresponding to the collapse zone (80 mm apart from the top end). As shown in the figure, the high frequencies can be seen over a range of relatively low strains of 0.05 to 0.1. The cumulative frequency shows the frequencies in a strain range of less than 0.3 accounts for more than 80%.

The results of the high-speed collapse behavior in the axial direction are summarized as follows:

(1) The high-speed collapse behavior could be simulated by an FEM analysis and calculated values were in good agreement with experimental values.

(2) The higher the strength of a steel sheet, the smaller the collapse length. Conversely, when the collapse length was equal, the absorbed energy was large.

(3) In the case of a collision at a speed of 50 km/h, the maximum value of strain rate of materials was approximately $550\ \mathrm{s}^{-1}$.

(4) Even when a member underwent buckling deformation in the form of bellows, strains of less than 30% were generated in portions of more than 80%.

3 Analysis of Forming of Tailor-Welded Blanks

Techniques of joining and press forming different kinds of steel sheets have been put into practical use12-14) because of many expected benefits such as increase in rigidity, reduction of automotive body weight, improvement in the material yield and reduction of die cost. Blanks joined and integrated by lasers, mash seam welding, etc. are called tailor-welded blanks and have recently been applied to collision-resistant members such as front side members to ensure efficient energy absorption during a collision. This section describes the results of experiments of plane-strain forming and deep-drawing forming, and those of a forming simulation results by use of FEM (LS-DYNA). In the experiments and analyses, three types of steel sheets were used: mild steel, 370 and 440 MPa steel sheets with a thickness of 0.7 mm were formed after being joined by a CO_2 laser welding.

3.1 Deformation by Plane-Strain Stretching

Fracture during press forming is apt to occur in plane-strain portions. To simulate this, a welded blank of 100 × 190 mm was stretch-formed using a round bottomed punch of 100 mm in diameter. A very small friction (frictional coefficient $\mu < 0.05$) was given by laying several layers of lubricated vinyl sheets between the test specimen and the punch. When the area near the weld portion undergoes plane-strain deformation during forming and the forming height increases, necking occurs in a soft material portion adjacent to the weld portion, resulting in fracturing as shown in **Photo 1**. FEM analysis was performed for the same conditions as the experimental ones. A blank is assumed to be jointed with mild steel and 440 MPa steel. The number of elements was 3 402.

Figure 6 shows the results of a main strain distribution measurement along the broken line shown in Photo 1, together with the results of the FEM analysis. The portion on the right-hand side of the weld portion corresponds to a mild steel portion. The area near the weld portion has the largest strain and the strain decreases as distance from the weld portion increases. The main strain distribution obtained by means of the FEM analysis shows the same tendency.

3.2 Deformation by Deep Drawing

To investigate the deep-drawing deformation behavior of tailor-welded blanks, welded blanks each composed of a mild steel and a 440 MPa steel were formed by deep drawing. The blank size was 93 mm in diameter and three different types of welded blanks were prepared as shown in **Fig. 7**. They are a blank (A) in which 3/4 of the diameter was made of the 440 MPa steel and the remainder was mild steel, a blank (B) in which the two

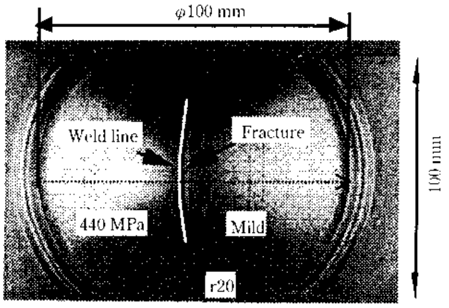


Photo 1 Weld line and fracture portion of test piece after plane strain stretch forming

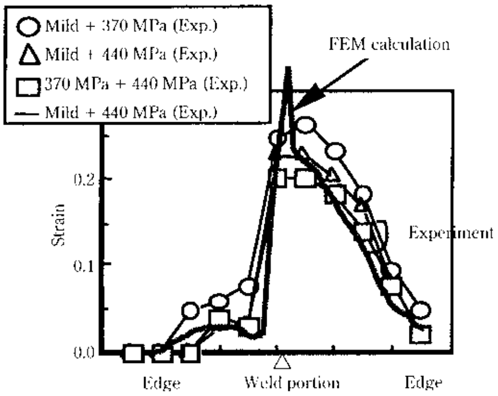


Fig. 6 Principal strain distribution after plane strain forming (right-hand side: lower tensile materials)

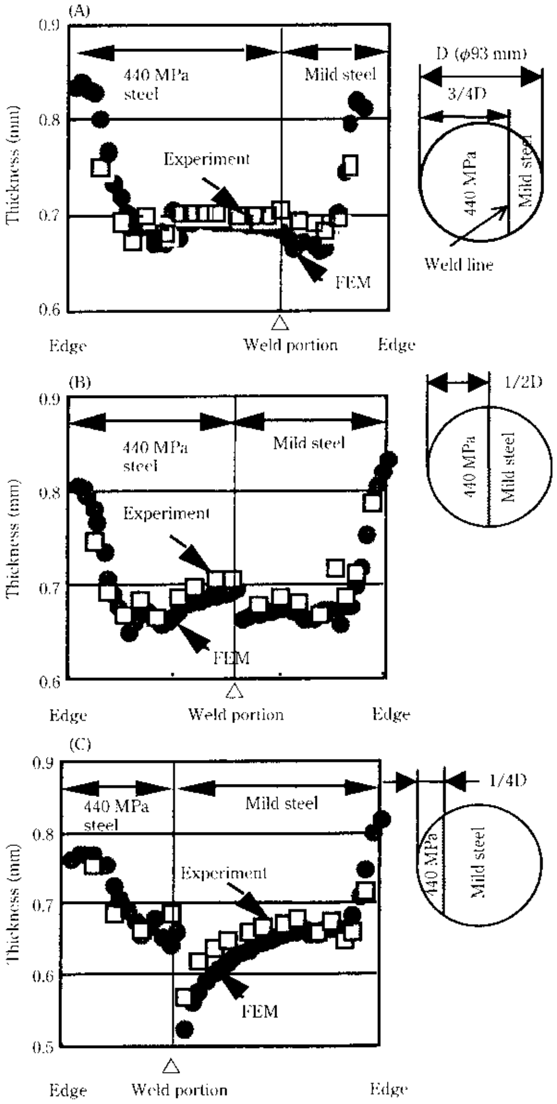


Fig. 7 Comparison in thickness distribution of cups between experimental and calculated results after deep drawing

steels were welded together at the center, and a blank (C) in which the configration of materials was the opposite of blank (A). The blanks were each formed to a prescribed height and the sheet thickness distribution, etc., were investigated. On the other hand, a simulation by FEM was conducted under the same conditions. The number of elements ranged from 1 792 to 2 145.

A comparison between experimental and calculated values is shown in Fig. 7. For all blanks including (A) to (C), the experimental values are in good agreement with the calculated ones. In blank (A), the two materials have an almost similar sheet thickness distribution. In blank (B) in which the soft material and the hard material consisted of two semicircles, there was a steeper decrease in sheet thickness on the soft material side across the weld portion. In blank (C), the further steeper decrease in sheet thickness near the weld portion was observed in blank (B) and this might indicate a danger of fracturing. In the case of deep drawing, a portion vulnerable to fracture depends on the location of weld line. Therefore, it is necessary to carry out design, in which materials of different properties are combined, by considering fracture during forming in addition to the functions of parts.

The following became apparent from the above-described results:

(1) In both plane-strain deformation and deep-drawing deformation, the FEM calculations were in good agreement with the experimental results.

(2) In forming tailor-welded blanks, it is necessary to optimize a combination of material strength levels and the position of weld portion, which can be successfully predicted beforehand by the FEM simulation.

4 Analysis of Shape Fixability of High-Strength Steel Sheets

It is no exaggeration to state that the greatest problem in the application of high-strength steel sheets to automotive bodies is shape fixability, i.e., springback and curling, in addition to the occurrence of fractures and wrinkles. At Kawasaki Steel, the relationship between materials and shape fixability is quantitatively determined by two techniques. Firstly when the amount of bending deformation is known, an analysis based on the elasto-plastic strain increment theory[15,16] is applied. Second, when the amount of bending deformation is unknown, an FEM analysis is applied. This section describes examples of analysis based on these techniques.

4.1 Analysis Based on Elasto-Plastic Strain Increment Theory

In this technique, elements are finely divided in the sheet thickness direction and stresses are calculated by giving a bending strain increment to each element. The main assumptions in the calculations are as follows:

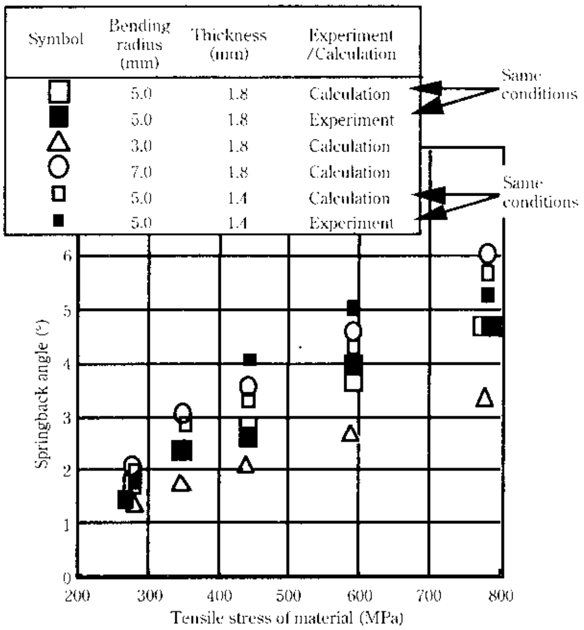


Fig. 8 Effect of tensile stress, thickness and bending radius on springback, and its comparison between experimental and calculated results

(1) Plane stress in the sheet thickness direction is assumed to be zero.

(2) Plastic anisotropy only in the sheet thickness direction is taken into considaration.

(3) Shearing stresses are ignored.

As for the work hardening characteristics of materials, stress increments, and a relational expression of strain increment, refer to the literature[15].

Shape fixability was examined for a case where materials were subjected to relatively simple hat-shape bending as with front side members. In general, the shape fixability after hat-shape bending is evaluated in terms of springback at a punch shoulder radius and a curl at a wall portion. In order to examine the validity of the above analysis, an experiment, in which attention is given to the springback angle at a punch shoulder and the curvature of a curl at a wall portion, were conducted and the results of the experiment were compared with those of the analysis results.

To clarify the effect of material characteristics on the springback behavior at a punch shoulder, a bending experiment on various steel sheets of 270 to 780 MPa class was conducted and the springback angle after forming was measured. It is apparent from the results of the bending experiment shown in **Fig. 8**. The amount of springback becomes large with increases in strength of steel sheet and the punch shoulder radius and with decrease in sheet thickness. Furthermore, there is good agreement between the experimental and calculated values.

Next, to clarify the effect of material characteristics on the behavior of a curl at a wall portion in hat-shape

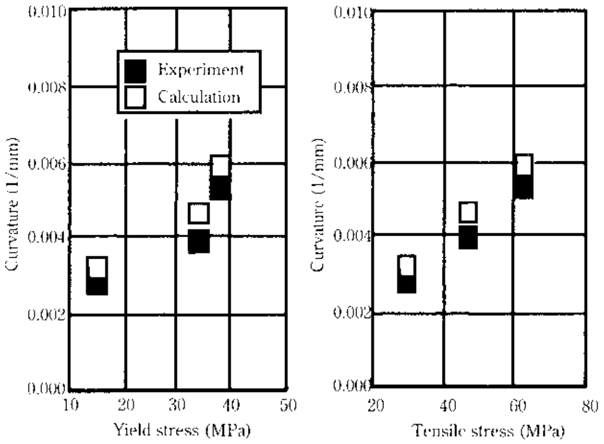


Fig. 9 Effect of yield stress and tensile stress on wall curvature of specimen after bending-reverse bending, and its comparison between experimental and calculated results

bending, equivalent bending and unbending were given to a wall portion by hat-shape bending, and the curvature of the curl after unloading was investigated. The results of this experiment are shown in **Fig. 9**. It is apparent that when the strength of a sheet is high the curvature of a curl is large and the shape fixability is low and that the curvature had a stronger correlation to tensile stress than to yield stress. Although the calculated values showed the similar tendency as the experimental values, in the case of high-strength steels, the calculated values were higher than the experimental ones. This might have been because the analysis was based on the assumption that the material was wound completely on the die shoulder, whereas in actual forming, the material is not completely wound on the die shoulder under some conditions.

When the bending radius is known beforehand, shape fixability can be predicted with relatively high accuracy by adopting the above technique. However, as with the results of the analysis of the curl of the high-strength steel sheet, there are cases where calculated values are slightly different from experimental values. This occurs, as described above, when the material is not bent to a predicted bending radius. In such cases, an analysis by FEM as will be described later is effective.

4.2 Analysis of Springback by FEM

When the amount of bending is unknown and bending is accompanied by three-dimensional deformation such as torsion, an FEM analysis is effective. An example of analysis in which JSTAMP-WORKS is used as an FEM program is described below. In this program, calculations are made by using the above LS-DYNA based on a dynamic explicit method for the step of forming and by using NIKE3D based on a static implicit method during springback.

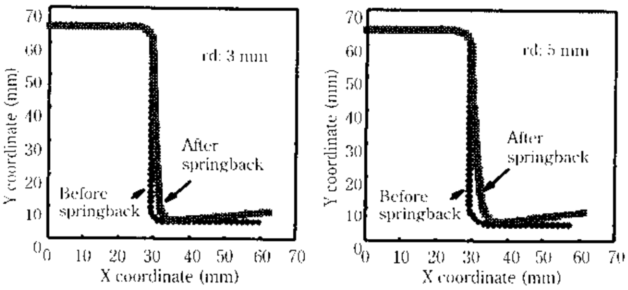


Fig. 10 Comparison of die shoulder radius (rd) on sectional shape of specimen after forming by FEM analysis

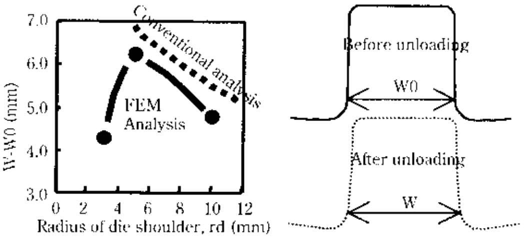


Fig. 11 Effect of die shoulder radius (rd) on springback by FEM analysis

Figures 10 and **11** show examples of analysis of shape fixation behavior when 590 MPa class high-strength steel sheets were subjected to hat-shape bending by changing the die shoulder radius. Shape fixability was evaluated by the degree of aperture shown in Fig. 11. In the analysis not based on FEM, the bending strain increased with decreasing bending radius at the die shoulder. In this case, therefore, the bending moment increased and, as schematically shown by the broken line in Fig. 11, the aperture increased with decreasing die shoulder radius. On the other hand, in the FEM analysis, the degree of aparture was small when the die radius was small. And this is in a good agreement with the shape fixation behavior actually experienced. It is difficult to determine this phenomenon by techniques other than FEM. FEM analysis is an effective technique for analyzing the shape fixation behavior when the amount of bending is unknown.

4.3 Measures to Improve Shape Fixability

Methods for improving shape fixability were examined on the basis of the above elasto-plastic strain increment theory. The results of the examination are described below. The following principles may be useful for improving shape fixability:

(1) To reduce the bending moment generated by the stress distribution in the sheet thickness. This could involve giving tension in the last period of forming, minimizing bending deformation at the die shoulder, etc.

(2) To apply the moment in opposit direction. For example, at a wall portion, a curl in a direction

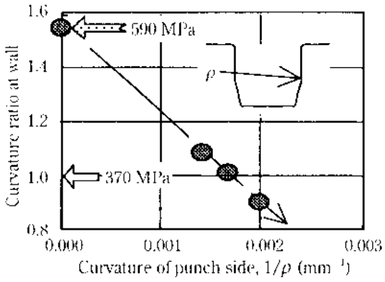


Fig. 12 Example of improvement of wall curl by reverse moment at punch side

reverse to a curl predicted after unloading is given by the punch side surface. Furthermore, to prevent springback by the punch shoulder, a tool with a punch shoulder radius smaller than in the first step of forming should be used in the second step of forming.

Figure 12 shows an analysis of an improvement in shape fixability for a case where a 1.8 mm thick 590 MPa steel sheet was subjected to hat-shape bending using a tool with a die shoulder radius of 10 mm. The ordinate represents the ratio of the curl of the 590 MPa steel to the curl of vertical wall portion of 370 MPa steel and the abscissa represents the curvature of the punch side surface (corresponding to the wall portion of the material). Curvature in a opposite direction to an predicted curl was given to the punch side surface, thereby correcting the curl. When a conventional tool with a flat punch side surface ($1/\rho = 0$) was used, the curl of the 590 MPa steel was approximately 1.6 times that of the 370 MPa steel. However, the curl approached the curvature of the 370 MPa steel formed by a conventional tool when forming was conducted by giving the 590 MPa steel curvature in the opposit direction to the punch side surface as shown in the figure, and the curl could be reduced to the level of the 370 MPa steel by giving a curvature of 0.001 7 (radius: 600 mm).

In summary,

(1) An analysis based on the elasto-plastic strain incremental theory in which plastic anisotropy is considered can be applied to a case where the amount of bending deformation is known beforehand, and it is possible to predict springback and curl.

(2) When the amount of bending deformation is unknown, FEM analysis is effectively applied.

(3) Technique for correcting a curl occurring on a vertical wall during hat-shape forming was shown.

5 Conclusion

The crashworthiness and formability of high-strength steel sheets when they are used in automotive bodies were evaluated mainly by FEM analyses and the following findings were obtained:

(1) A collision analysis of structural members clarified the effects of the strength of materials, collision speed, strains, strain rate, etc., on the collapse deformation during collisions.

(2) Analyses and experiments on tailor-welded blanks in basic plane-strain deep-drawing forming were conducted and the validity of the evaluation by FEM analyses was confirmed.

(3) The shape fixability of high-strength steel sheets was analyzed and the effects of material strength, sheet thickness, bending radius on shape fixability, etc. were made clear.

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