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Shape Control Techniques for High Strength Steel in Sheet Metal Forming

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Abstract

Springback is one of the most difficult problems in applying high strength steel (HSS) to automotive body parts. In this paper, the mechanism of springback behavior is studied and shape control techniques for HSS are examined. Effects of applying reverse bending in die gap, increasing wall tension at lower dead point, applying compression in thickness direction, forming in warm working condition and decreasing bending strain at die shoulder without blank holding force are investigated. Springback at punch shoulder and side wall warp were improved by these shape control techniques. And FEM analysis of springback processes are also performed and predicted results of springback shapes correspond with the experimental ones. In the near future, shape-fixability of HSS in the mass production processes are highly improved by applying shape control techniques and FEM simulations, and expanded application of HSS to automotive parts is expected.

1. Introduction

Since the international conference on the issues of the global environment in 1997, it has become a necessity more urgent than before to reduce the weight of automobiles along with an inevitable increase in the use of high strength steel or aluminum alloy sheets. In addition to the conventional solid-solution-hardened or precipitation-hardened steel, high strength steel for application to auto bodies under development has extended to easily formable ones, including DP (Dual Phase) steel, TRIP (Transformation Induced Plasticity) steel, and high burring steel[1-4]. However, the defect of shape fixability is posing an increasingly serious problem in line with the improvement of strength to a higher degree, one of the most important tasks to be overcome in the application of high strength steel for weight reduction.

However, shape fixability owes a great deal to the Young's modulus, a physical property value peculiar to material, making it difficult to deal with from a material side. Various control techniques have therefore been devised so that shape fixability can be improved[5, 6]. The techniques generally employed include a method of compression at the end of forming, a method of bending called Crash forming, and a method of modification die shape taken into account the amount of springback. Since the prediction of springback shapes is considered difficult even for well-experienced die designers, it is highly desired to establish a technique to solve the problem. In this report will be summarized the shape fixability, a great obstacle in the application of high strength steel to auto parts, about the mechanism of its occurrence, its countermeasures, and examples of the FEM analysis of springback.

2. Mechanism of Springback Behavior (the basic theory)

The factors of the occurrence of the defect of shape fixability as a result of bending can be broadly divided into 1) springback at a punch shoulder, 2) a side wall warp, and 3) the defect of three di-

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mensional shape fixability (twisting and cambering). As **Fig. 1** shows, 1) and 2) are caused even by simple hat-shaped bending, occurring by the bending moment due to an uneven stress in thickness direction. 3) occurs in parts complicated in shape, and is induced by the uneven stress within the panel surface. The mechanism of the occurrence of the defect of shape fixability as given in 1) and 2) is described simply here. When pure bending is done under the assumption that stress-strain curve of the material is fitted by n-power work hardening law as **Fig. 2** shows, springback $\Delta\theta/\theta$ in simple bending can be given by the following formula in which M_p is a moment required for plastic bending to the radius of curvature, R (= $1/\rho_1$), and M_E, a moment required for elastic bending to radius of curvature R:

$$\frac{\Delta\theta}{\theta} = \rho_1\left(\frac{M_P}{EI}\right) = \frac{M_P}{M_E} \qquad (1)$$

Here, E: Young's modulus in bending direction
I : Geometrical moment of inertia

It therefore follows that the amount of springback becomes larger in high strength steel sheets, with plastic bending growing large, than in mild steel specimens.

On the other hand, as **Fig. 3** shows, a side wall warp assumes a shape with elasticity recovered after unloading at point d through a, a point before bending starts, b, a point after bending, and c, a point after unbending. †The amount of a side wall warp after unbending, S_b, can be given by the following formula in which M_p is a moment required for plastic bending to radius of curvature R, and M_E, a moment required for elastic bending to radius of curvature R:

$$S_{b'} = \frac{\Delta\varepsilon'_s}{\varepsilon'_s} = \frac{-M_P}{-M_E} \qquad (2)$$

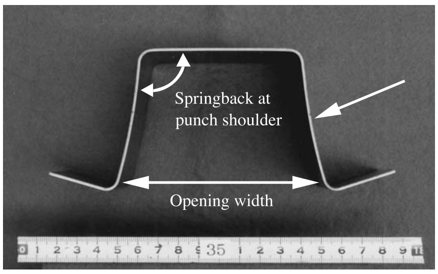


Fig. 1 Springback in hat-shaped bending

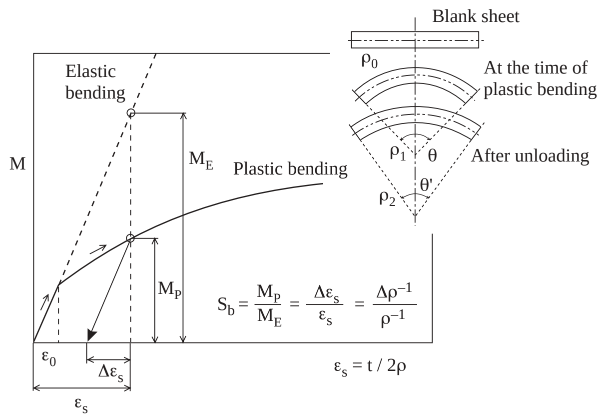


Fig. 2 Springback in pure bending

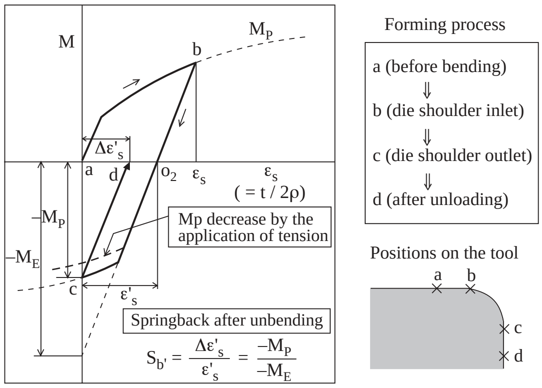


Fig. 3 Mechanism of the occurrence of side wall warp

Accordingly, it is possible to hold down to a low degree the amount of a side wall warp for decreasing bending moment M_p at point c when a processing method to lower M_p is employed, for example, when tension is applied.

3. Techniques for Improvement of Shape Fixability

3.1 Application of reverse bending in a die gap

As a measure of preventing a side wall warp, a technique is proposed by which a reverse bending phenomenon taking place in a die gap is utilized as **Fig. 4** shows[7]. **Fig. 5** gives one example showing the changes in side wall warp when die shoulder R is changed. As a test sample was used a 590MPa material (precipitation-hardened), 1.4 mm in sheet thickness. Under respective tool conditions, wall

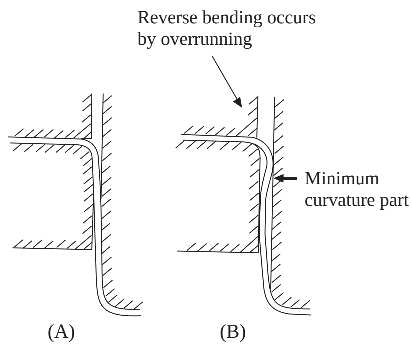


Fig. 4 Reverse bending phenomenon within die gap

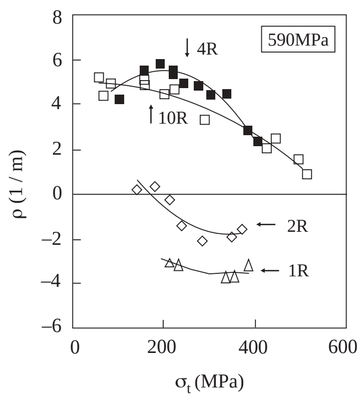


Fig. 5 Influence of die shoulder R on side wall warp

tension σ_t of the x-axis was varied by changing blank holder forces (BHF). σ_t was calculated by the following formula:

$$\sigma_t = P/2wt \qquad (3)$$

P: Maximum bending load
w: Blank width
t: Blank thickness

As Fig. 5 shows, the conditions in which no side wall warp occurs when die shoulder R is 2 mm were found. Furthermore, the result leading to the inverse warp, spring-go, was also found. This accounts for the fact that when die shoulder R lessens against sheet thickness, a state near the die shoulder separates from tools resulting in the occurrence of reverse bending within the clearance. Although it is possible to eliminate side wall warping by setting up proper die shoulder R or a clearance according to material strength or sheet thickness, there are the problems of the difference in conditions under which reverse bending occurs when a stretch and shrink flange exists as in actual parts and a risk of rupture increased by lessening die shoulder R.

3.2 Control of wall tension

It is reported that as a method of changing wall tension in the process of bending, a bad shape can be improved by variable blank holder force (BHF)[8]. This method consists in reforming a shape by controlling BHF at a higher level in the final stage of forming with a comparatively low BHF given in the initial stage of forming. This method drastically improves both springback and side wall warp in comparison with another case in which a constant force was applied. It is necessary for this method of variable blank holder force (BHF) to have a peculiar function within a press forming machine which a blank holder force can be varied on the way of forming. It is difficult for most of the conventional press forming machines to apply this method at the present.

The authors tried to apply a technique in which an effect can be given similar to controlling a blank holder force by increasing a wall tension with a bead, attached to the die, pushed out in the later stage of forming by utilizing a cam. **Fig. 6** shows an effect of reducing side wall warp (a change in curvature) by the variable uplifted bead method. The figure is a schematic view. The bead height can be changed, and so set that it is pushed out before the lower dead point. With the variable uplifted bead employed, it is possible to enable even a high strength material at a level of 690 MPa to obtain the shape fixability superior to that of a 390-MPa material by giving in the final stage of forming such a high bead tension as will rupture (a material) when the tension was given constantly.

3.3 Application of compression in sheet thickness direction

As is known generally, springback or side wall warping is caused by a bending moment due to an uneven stress in the thickness direction of a material bent or unbent. A technique of compression at the end of forming is therefore employed to apply a compressive stress in sheet thickness direction at the lower dead point so that a bending moment in sheet thickness direction can be reduced. **Fig. 7** gives springback at a punch shoulder that changes with a bottom compression load (a compression load at the end of forming), plotted on the x-axis, when BHF is changed from 0 to 20 kN in hat-shaped bending. It was clarified that a springback angle is lowered to 90° or less when a compression load at the end of forming is applied higher.

The occurrence of spring-go that will lead to the angle lower than 90° as described above can be described by the fact that as **Fig. 8** shows, a looseness of material at the punch bottom in the initial stage of forming is crushed by compression at the end of forming to enlarge a bending area near punch shoulder resulting in lessening an springback angle after unloading. When BHF is large as Fig. 7 shows, the amount of spring-go becomes smaller due to a decrease in the looseness at the punch bottom in the initial stage of forming. Compression at the end of forming is effective in controlling the changes in angle, but not so for side wall warping. Other measures are therefore necessary to reduce side wall warp. Similar forming methods are reported, including the making of a protrusion or a groove at the punch shoulder area[9, 10], convexing the punch bottom or utilizing a cusp when making a tool as coining.

3.4 Warm forming techniques

The techniques for improving formability have so far been studied by the application of the dependence on temperature of the mechanical characteristic values of material. The warm forming method focused only on the improvement of formability in the past, but was

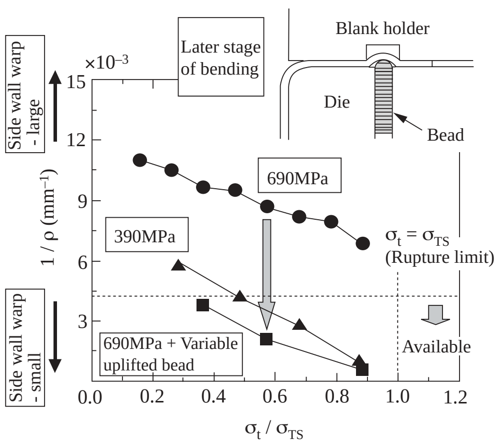


Fig. 6 Effect of reducing the extent of side wall warp in variable uplifted bead forming

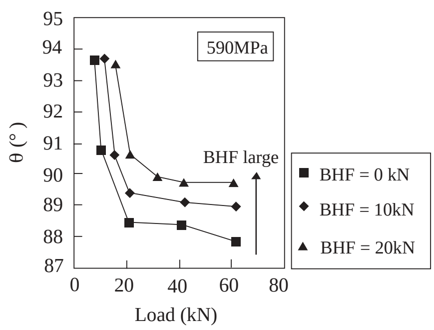


Fig. 7 Influence of compression load at the end of forming on springback at punch shoulder

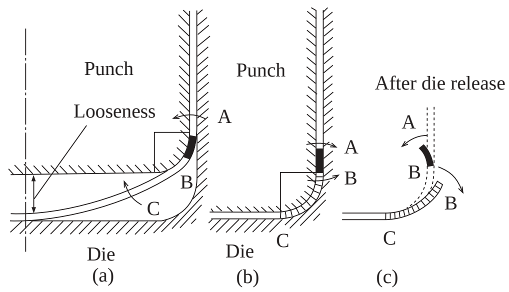


Fig. 8 Mechanism of the occurrence of spring-go in simple U-bending[6)]

proven also effective for improving shape fixability. A hat-shaped bending test was carried out at high temperature using a 590MPa material which decreases its tensile strength at high temperature (400°C) as **Fig. 9** shows for the measurement of a side wall warp. **Fig. 10** shows an effect of decreasing the amount of a wall warp in warm forming in comparison with that in room-temperature forming. Forming at 400°C improves the shape fixability of a 590MPa material to a level equivalent to that of a 440MPa material. Furthermore, the experiment by the authors. has clarified that the shape fixability equivalent to that of mild steel can be obtained even with a 590MPa material by warm forming and high BHF if high BHF can be given by the application of a lubricant with a high lubricity.

3.5 Improvement of forming methods (crash forming and form drawing)[11]

An example is increasing in number, in which crash forming (bending) is used at a working site as a measure to prevent springback problems of high strength steel sheets. Crash forming is to form without applying a blank holding force, enabling to reduce side wall warp because it renders the amount of bending strain at a die shoulder smaller than draw bending. On the other hand, its demerit is increasing wrinkle risk because BHF is not applied. It is therefore used for parts with basically only a few changes in sectional shape. Crash forming can be considered one of the suitable forming method for high strength steel sheets. However, basic data are not sufficient reported in the past. Here, the result of the study of comparison between crash forming and draw bending about springback using a bumper model tool are introduced. Furthermore, by form drawing, which is crash forming applying tension on side wall at the final stage of forming, it is possible to produce parts excellent in shape fixability even with high strength steel sheets. The effect of this forming method will be reported using same tools.

Fig. 11 shows a process of the crash forming (counter load: 20 kN) of a sample, 1.4 mm × 300 mm × 300 mm, using a bumper-shaped die with a step at punch bottom (Curvature in longitudinal direction of the die: 4000R, punch shoulder R: 5 mm; die shoulder R: 5 mm; forming height: 70 mm). As forming process 2 in Fig. 11 shows, crash forming is characterized by the loose twining of material round the die shoulder R part with the flange springing up in the middle of forming. As forming process 3 shows, almost the same shape returns at the lower dead point as in normal draw bending.

Fig. 12 shows the comparison between measurements of the shapes of springback in cases of crash forming and draw bending under the conditions with a counter load applied to the punch bottom and without a counter load. This figure clearly shows that crash forming (with a counter load applied) renders the amount of springback width smaller than draw bending due to a decrease in side wall warp. In addition, the amount of the material flowing out from the punch bottom near the lower dead point increases by removing the counter load of the punch bottom. This enables the holding down of the springback at the punch shoulder to a small degree which results in reducing springback width even further. However, it was made clear that a side wall warp still remains in 590-MPa and 780-MPa materials and that the shapes of the corners of the punch and die shoulders are also rendered loose in crash forming without a counter load.

For further improvement of the shape fixability of a high strength material, form drawing (crash forming + tension) was tried, in which BHF is applied to the flange part, before proceeding to the final process of crash forming (compression at the end of forming). **Fig. 13** shows the results. It is evident that form drawing enables to reduce the amount of springback width further after unloading. Furthermore, it can be considered that both crash forming and crash forming + tension are one of the suitable forming for high strength steel sheets because of a tendency shown that the amount of reducing springback width becomes greater in proportion to an increase in material strength.

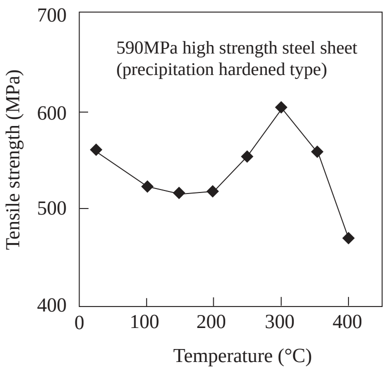


Fig. 9 Influence of temperature on tensile strength of 590MPa high strength steel sheet

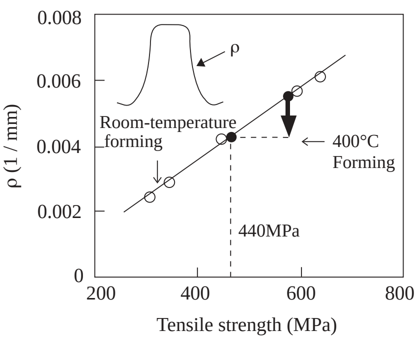


Fig. 10 Effect of decreasing side wall warp by warm forming at 400°C

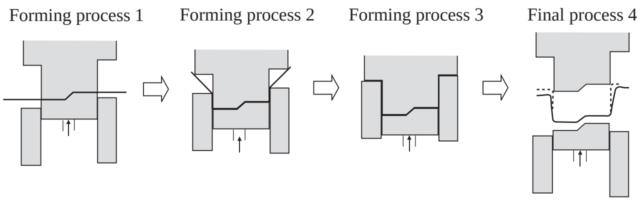


Fig. 11 Process of crash forming (bending) of bumper model

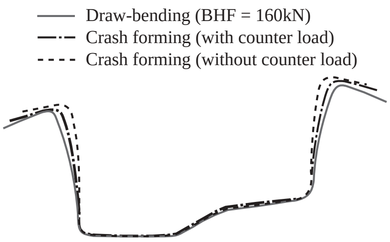


Fig. 12 Springback shapes after crash forming

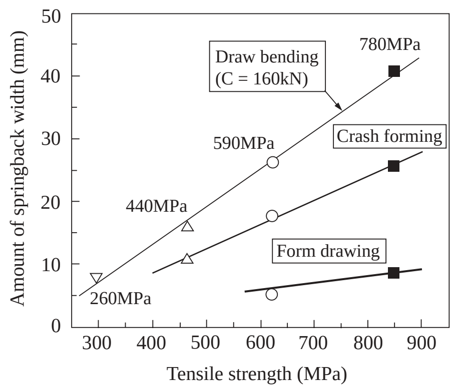


Fig. 13 **Influence of bending method on the amount of springback width**

4. Springback Simulation

A method of modification die shape taken into account the amount of springback is used for a measure generally to prevent springback problems. It is difficult even for an experienced die designer to decide how much the die shape should be changed. A prediction of springback by FEM should therefore be established. As a technique of predicting springback behavior theoretically, a proposal is made of a prediction technique to use elementary analysis or an empirical formula about hat-shaped bending etc.. However, because of its problems that reverse bending is impracticable and that it is unfit for general use, FEM analysis is much expected. Stamping simulation has made steady progress in its application to designing and to the production site with the advance in the application of the dynamic explicit method in the 1990's and the improvement of user interface. However, its application is used for the prediction of rupture and wrinkle mainly in the process of forming, and only a few examples are reported in which it was used for deformation analysis after unloading, that is, the prediction of springback behavior.

The main reason of above may be expressed shortly that simulation in the present state is wholly unable to satisfy the production site in the accuracy of springback, and many factors can be considered for the failure in achieving the accuracy. The dynamic explicit method mainly used for the analysis of actual parts is not required to solve the stiffness matrix, because it solves directly the equation of motion for every node. It is suitable for the simulation of forming complicated shapes, but not so for the analysis of springback, because the equilibrium of force is not calculated. Still further, it is pointed out that simulation results of springback is also greatly influenced by the type of finite element or the constitutive law of material[12, 13]. Here, with the intention of investigating the quantitative prediction accuracy of springback behavior on the basis of the present FEM analysis, a comparison was made with experimental results after a basic analysis with the solid element of the static implicit method employed about the bumper model forming test described in the previous section[14].

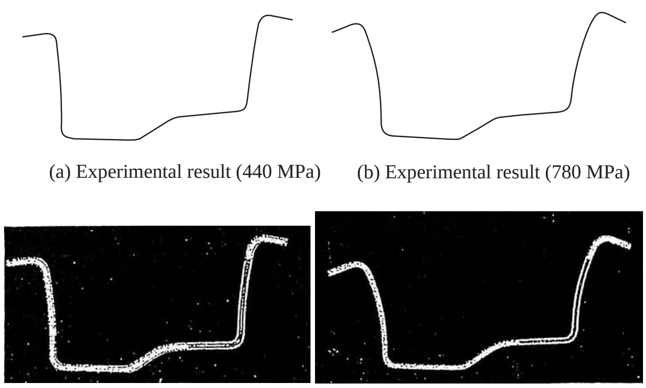
With the commercially available program of the static implicit method employed as a solver, an elastic plastic analysis was carried out using the 4-nodes plane strain element. A die was made rigid, and a blank was divided into five sections (0.28 mm) in the thickness direction, and into 500 (0.6 mm) in the width direction. The material hardening law, based on isotropic hardening, was inputted by approximating with the Swift-type hardening law. A coefficient of friction between the tool and the material was set at 0, because a blank holder was not used for forming, and frictional force was considered small. A calculation of the processes of unloading was made in the order of counter load unloading, punch unloading, and die unloading after punch forming with a counter load applied.

Fig. 14 shows results of the analysis of springback about the 440MPa and 780MPa materials. Springback width and side wall warp increase for the kinds of steel higher in tensile strength. They were confirmed to agree with a trend of the experimental data. **Fig. 15** shows a comparison between FEM and experiment about the radii of curvature of left and right side wall warp, ρ_1 and ρ_2. Both agree for the most part quantitatively, suggesting a possibility that the processes of bending and unbending deformations can be satisfactorily analyzed with FEM. The reason for a slight decrease in the calculated value in the radius of curvature of side wall warp of the 440MPa material is that r-value is not considered in the analysis of this solid element.

The reason for the satisfactory results of the curvatures of side wall warp by this analysis can be attributed to the following:

1) Modeling was available for making two-dimensional shape because only a few changes were observed in sectional shape in longitudinal direction in this bending; and
2) Crash forming minimized the influence of friction force in the process of bending.

It is necessary to study by three-dimensional analysis to apply to real parts including the change of sectional shapes, stretch flange and a shrink flange in the future. However, as described earlier, a



(a) Experimental result (440 MPa) (b) Experimental result (780 MPa)

(c) Analytical result (440 MPa) (d) Analytical result (780 MPa)

Fig. 14 Springback shapes after crash forming

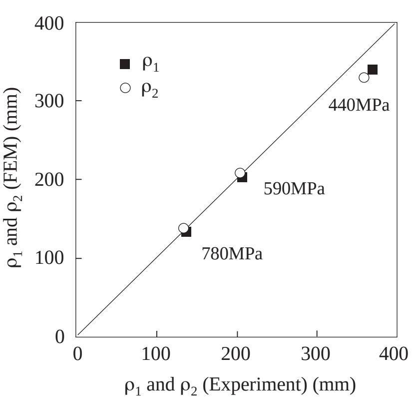


Fig. 15 Comparison of the curvature radii of side wall warp

technique of calculation is not established because of the differences in the results of analysis according to the conditions of calculation in the analysis using the shell element.

Fig. 16 shows the result of the influences of the time integration methods (S-I: Static implicit method; D-E: Dynamic explicit method) and the number of integration points (IP) in thickness direction with the shell element. Analytical results of the process of forming by the dynamic explicit method show unexceptionally a decrease in springback width and side wall warp, clearly underestimating springback in comparison with the static implicit method or the experimental data. Additionally, the influence of the number of integration points shows the same tendency as in both of the dynamic explicit and static implicit methods. Springback is small when the number of integration points is 3, with almost no difference between 5 and 7 points.

As described above, the influence of the conditions of springback analysis using the shell element is so great that it becomes necessary to establish conditions under which accurate analysis can be made. Furthermore, material models used for commercially available software can be used only for isotropic hardening in many cases, posing a problem of not being able to consider the Bauschinger effect that takes place when bending and unbending material. For the solution of this problem a trial of introducing into FEM the constitutive law capable of representing accurately the stress-strain relationship when unloading has been proposed[15-17], those are future tasks including also the expansion of material database.

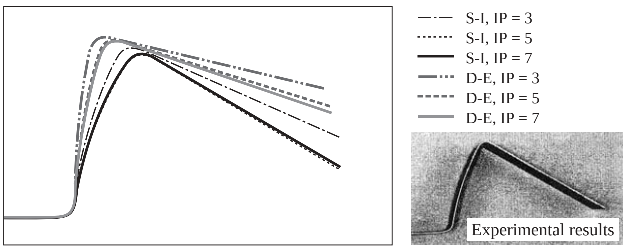


Fig. 16 Influence of analytical conditions on the results of springback simulation about hat-shaped bending

5. Conclusion

A study was made of springback, a great obstacle in the application of high strength steel sheets to automobile parts, about the mechanism of its occurrence and the techniques to counter it. Experiments were carried out on how to utilize reverse bending that takes place in the process of forming, how to reduce side wall warp by increasing wall tension in the middle of the forming process, how to improve uneven stress by applying a stress in sheet thickness direction, how to improve bendability by warm forming, and how to reduce the plastic strain of a die shoulder without applying blank holder force thus to study the influences of those methods on springback. It was made clear that springback at a punch shoulder or side wall warp can be reduced sufficiently by those methods. With the introduction of the examples of analyzing springback using FEM, it was indicated that the analysis enables to predict the influence of material strength. It is considered possible to decrease springback problems in actual parts in the future by the application of those techniques of improving shape fixability and FEM analysis.

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