

Forming Technology to Reduce Dimensional Variation of Automotive Parts by Using Bauschinger Effect

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Abstract:

Dimensional variation is a severe problem in press forming of ultrahigh-strength steels (UHSS), because of material strength variation in mass production. In this study, camber back, which occurs in longitudinally curved parts, was examined, and a new forming method whereby dimensional variation of camber back can be suppressed by the Bauschinger effect was developed. The new method consists of two processes. In the 1st process, a blank is formed with a large curvature compared with that in the 2nd-process. In the 2nd process, that part is formed to a smaller curvature than in the 1st process. The new method was applied to hat-shaped models of 590, 980, and 1 180 MPa-grade steels in which the radius of curvature in the longitudinal direction was 1 600 mm. The experimental results showed that the difference in the amount of camber back between the 590 MPa and 1 180 MPa steels formed by the developed method decreased by 95% compared with parts formed by the conventional method.

1. Introduction

In recent years, application of ultrahigh-strength steels (UHSS) to automobile frame parts has advanced with the aims of lightweighting of the automobile body and improvement of collision safety¹⁾. Almost all automobile frame parts are manufactured by the high-productivity process of press forming, but poor dimensional accuracy due to springback is one challenge for press forming of UHSS^{2,3)}. This is a problem because springback increases due to the large stress at the bottom dead center of press forming as material strength increases, resulting in deviation from the required accuracy.

In addition to this issue of dimensional accuracy, since the variations in the material strength of UHSS

during mass production of the material are large, if large stress is generated at the bottom dead center of press forming, the stress variations at the bottom dead center during mass production of automobile parts will also be large, giving rise to the problem of large variations in dimensional accuracy (dimensional variation). In other words, if the material lot changes, deviation from the required accuracy of the parts is a possibility, even if material strength is within the standard.

In the past, a large number of countermeasure technologies for poor dimensional accuracy have been proposed, but few countermeasure technologies focused on dimensional variation relative to the dimensional tolerances, particularly in curved parts. Thus, countermeasure technologies for dimensional variation are necessary and indispensable for wider application of UHSS.

Therefore, to overcome this problem, JFE Steel developed a method called the Stress Reverse™ forming technology utilizing the Bauschinger effect⁴⁾ that occurs during stress reversal of UHSS^{5,6)}. The developed technology simultaneously reduces the absolute value of stress at the bottom dead center in the final process of press forming, and the difference in stress caused by variations in material strength.

This paper describes the mechanism of the occurrence of dimensional variation, the concept of the developed technology, and the results of verification of the developed technology using simple models. In addition, examples of adoption in mass production are also introduced.

2. Issues of Dimensional Variation in Mass Production of Automotive Pressed Parts

Springback can be classified as wall opening due to vertical wall warp and punch shoulder angle change,

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and longitudinal springback of pressed parts that occurs in curved parts, such as plan-view curved parts, side-view curved parts, etc. First, the issues related to wall opening springback will be explained. **Photo 1** shows hat model pressed parts using 590 MPa and 980 MPa materials. Wall opening caused by springback becomes large as material strength increases. This occurs because the stress at the bottom dead center becomes larger as material strength increases, and if the springback becomes excessive like this during mass production of automobile parts, deviation from the required accuracy is a concern.

On the other hand, the standard width of the material strength of steel sheets used in press forming is set wider for high-strength materials than for low-strength materials, as shown in **Fig. 1**. If such materials are applied in mass production of automotive press-formed parts, the above-mentioned dimensional variation will occur, making it difficult to satisfy the target accuracy.

Dimensional variation will be explained in more detail by using the hat model parts shown in **Photo 1** as examples. **Figure 2** shows the relationship between the tensile strength of the materials used in the hat model parts and the amount of wall opening. As mentioned above, wall opening displays an approximately linear relationship with material strength, becoming larger as strength increases. Here, assuming cases where material strength variation occurs, the material strength variation of ② the 980 MPa material is relatively large compared to that of ① the 590 MPa material. Since variation in dimensional accuracy is proportional to the magnitude of strength variation, as shown in **Fig. 2**, the dimensional variation of the 980 MPa material is larger than that of the 590 MPa material. Countermea-

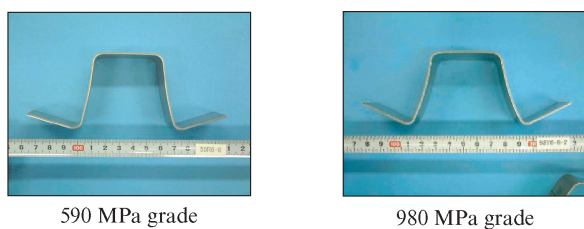


Photo 1 Hat model pressed part⁷⁾

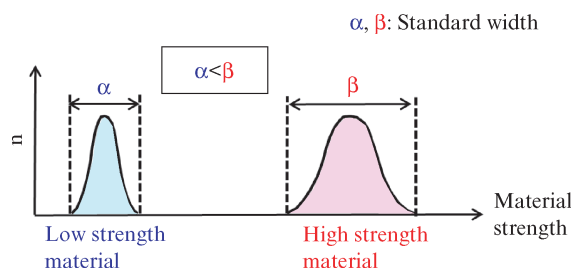


Fig. 1 Image of material strength standard width⁷⁾

asures for this kind of wall opening which occurs in the hat cross section and its dimensional variations are possible by applying a press forming technology that cancels out springback deformation. For example, measures such as ridge shift bending³⁾ were proposed from an early date.

However, there are few countermeasure technologies for dimensional variation for camber back, which occurs in side-view curved parts, as shown for example in **Fig. 3**. The stress distribution at the bottom dead center when a steel sheet (blank) is pressed by draw forming is shown in **Fig. 4**. Camber back occurs due to the bending moment caused by the stress difference between the tensile stress of the punch top and compressive stress of the flange at the bottom dead center. **Figure 5** shows a schematic diagram of the stress-strain relationship at the punch top when forming mass-production materials in the one-step press forming with materials of the highest and lowest strength in the same steel grade. If the material strength changes, the stress distribution at the bottom dead center will also change, resulting in dimensional variation.

For poor dimensional accuracy caused by camber

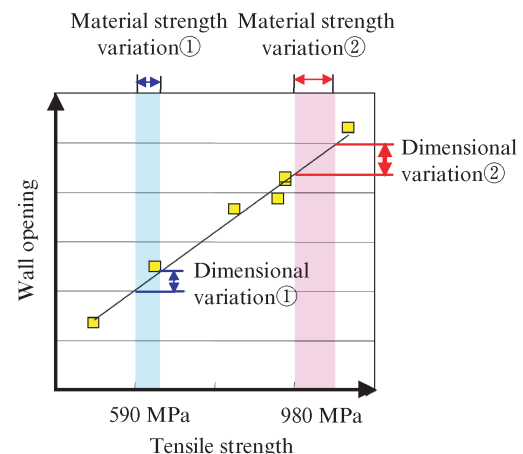


Fig. 2 Relationship between tensile strength and wall opening⁷⁾

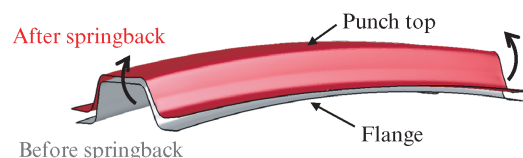


Fig. 3 Camber back of curved part⁷⁾

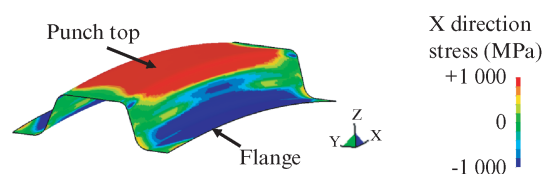


Fig. 4 Stress distribution at bottom dead point⁵⁾

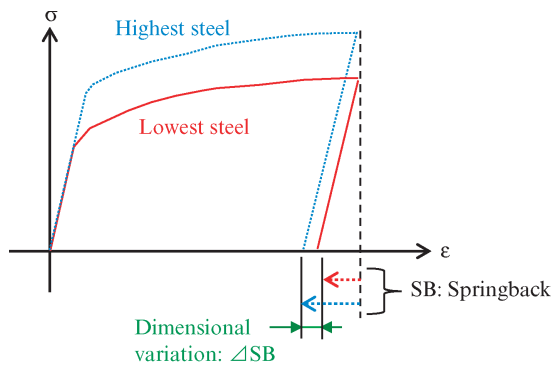


Fig. 5 Schematic diagram of stress-strain relationship at punch top with 1st process forming⁷⁾

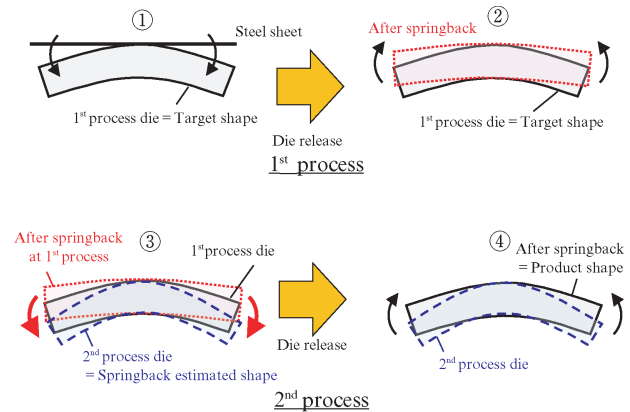
back, the conventional approach was to form the material to a shape close to the product shape in the initial process, and then satisfy dimensional accuracy by forming with a shape that includes an allowance for springback (springback compensation) in the final process^{8,9)}. **Figure 6** shows a schematic diagram of the process in the case of two-step forming with springback compensation and the springback behavior and stress-strain relationship at the punch top with the conventional countermeasures. The target product shape is achieved after springback (④) in the 2nd process with the material with the highest strength. However, if the material strength changes, the stress at the bottom dead center will also change, resulting in dimensional variation, as in one-step press forming.

From the viewpoint of achieving carbon neutrality of recent years, further lightweighting of the automobile body to improve fuel efficiency has been studied, and as one solution, application of UHSS such as 1 470 MPa grade, etc. is expanding. However, since material strength variation has become even larger in these UHSS steels, the issue of dimensional variation has become even more remarkable.

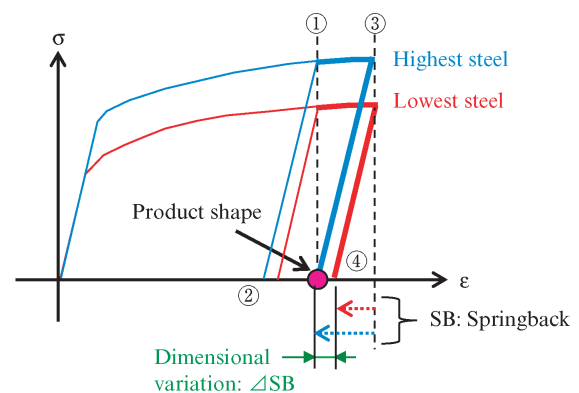
3. Concept of Developed Dimensional Variation Countermeasure Technology

To address the issue of dimensional variation described in Chapter 2, JFE Steel developed the Stress ReverseTM forming technology, which is a method utilizing the Bauschinger effect that occurs during stress reversal of high-strength steels^{5,6)}. This chapter introduces the concept of the developed technology.

There are two key points in the developed technology. This first is “Utilizing the Bauschinger effect that occurs during stress reversal of high-strength steels.” The Bauschinger effect is a phenomenon in which yield strength decreases upon stress reversal⁴⁾. The stress reversal behavior of 1 180 MPa material is shown in **Fig. 7 (a)**. In comparison with ① stress of 1 283 MPa



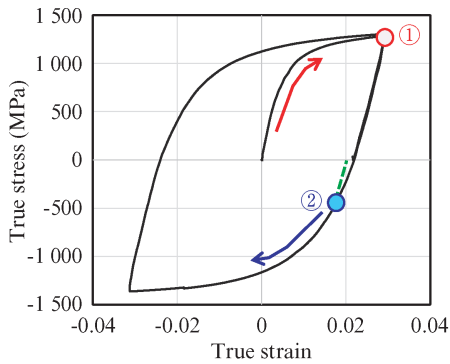
(a) Forming process and springback behavior in conventional countermeasures



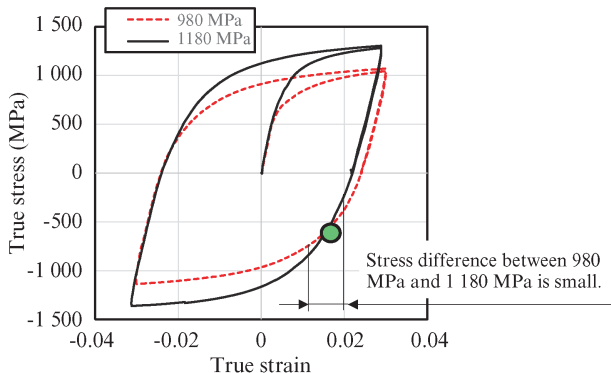
(b) Schematic stress-strain curve of lowest and highest strength steel sheets of one grade

Fig. 6 Schematic diagram of stress-strain relationship at punch top and springback behavior in conventional countermeasures⁷⁾

under tension, ② yield strength decreases greatly after stress reversal, becoming 388 MPa. In conventional FEM analysis of sheet press forming when applying high-strength steels, it is known that the accuracy of the analysis of the amount of springback is improved by applying the Yoshida-Uemori model (Y-U model), which can reproduce the Bauschinger effect¹⁰⁾, and it is common knowledge that the Bauschinger effect influences the amount of springback. However, no forming technology utilizing the Bauschinger effect had been proposed until now, as it was thought that use of the Bauschinger effect reduces the stress at the bottom dead center. Assuming the occurrence of material strength variation, the stress reversal loading behaviors of 980 MPa material and 1 180 MPa material are shown in **Fig. 7 (b)**. When stress is reversed from tensile stress to compressive stress, a point where the curves of the 980 MPa material and 1 180 MPa material intersect appears. Based on this fact, it was thought that the springback of the 980 MPa material and 1 180 MPa



(a) Bauschinger effect in 1180 MPa steel



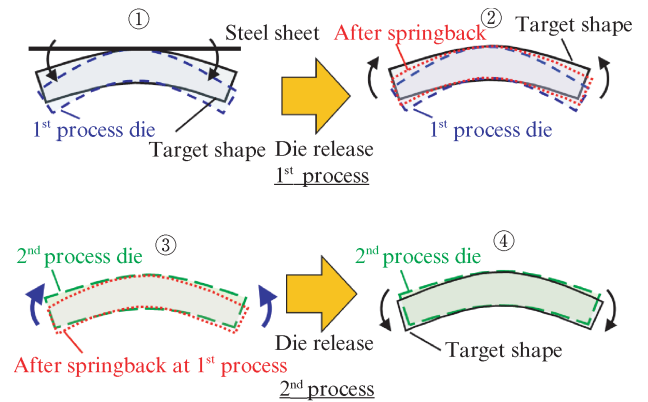
(b) Bauschinger effect in 980 MPa and 1180 MPa steel

 Fig. 7 Stress-strain curve in tension and compression test⁷⁾

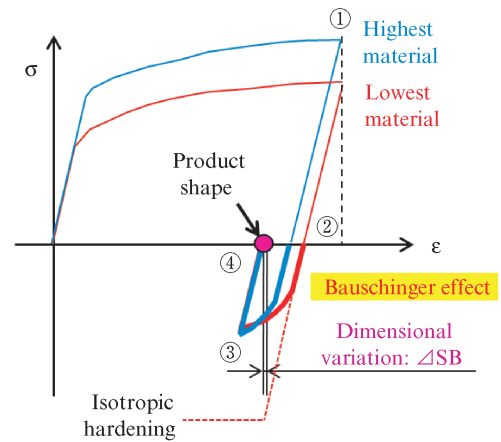
material will become approximately the same, resulting in reduced dimensional variation, by designing the die so that the bottom dead center is near this point. Although this intersection point also appears in isotropic hardening models, it is thought that the Bauschinger effect expands the strain region where there is little difference in stress.

In designing a production process that utilizes the Bauschinger effect to reduce the stress at the press bottom dead center, the second key point is “Order of springback compensation.” As described in Chapter 2, in the mass-production press forming process, which is a multi-step process, springback countermeasures had been applied in the final process. However, with that conventional order of springback compensation, large stress occurs in UHSS parts at the bottom dead center in the final process, and dimensional accuracy variations become excessive.

Based on the two points described above, JFE Steel developed a process in which compensation is applied in the preceding process, so that the Bauschinger effect appears in the subsequent process. Considering the part shape in Chapter 2, in the 1st process, the longitudinal curvature radius is formed with a curvature radius smaller than that in the 2nd process, and a curvature radius larger than that in the 1st process is then formed in the 2nd process. Since the structure is bent back in



(a) Forming process and springback behavior in development technology



(b) Schematic stress-strain curve of lowest and highest strength steel sheets of one grade

 Fig. 8 Schematic diagram of stress-strain relationship at punch top and springback behavior in development technology⁷⁾

the 2nd process, this results in an appropriate stress reversal at the punch top (panel web) and flange at the bottom dead center in the 2nd process. **Figure 8** shows a schematic diagram of the forming process and springback behavior in the developed process, and the stress-strain relationship when the materials with the highest and lowest material strength in the same grade are applied. If stress is reversed in the 2nd process and the geometry of the 1st process is designed so that the stresses generated in the respective materials are the same, dimensional variation will decrease. Moreover, since the Bauschinger effect appears in the 2nd process, the absolute value of the stresses generated in the punch top and flange decreases in comparison with one-step press forming, and as a result, the amount of springback also decreases. Based on the above, it is considered possible to simultaneously reduce both the amount of springback and the dimensional variation associated with springback by applying the developed technology.

4. Verification of Effects of the Developed Technology Using Simple Models

4.1 Verification of the Developed Technology by FEM Analysis

4.1.1 Conditions of FEM Analysis

A press forming analysis was carried out to verify the effects of the developed technology. The FEM analysis was performed using the finite element method software LS-DYNA ver.971. As the material model, the study was conducted with shell element using the YU model, which is capable of expressing the Bauschinger effect. The longitudinal curved model with a hat-shaped cross section shown in **Fig. 9** was used. The longitudinal length of the model was 400 mm, and the standard curvature radius was set to a constant curvature of R 1 600 for the punch top and R 1 560 for the flange. To evaluate dimensional variation, 590 MPa to 1 180 MPa grade cold-rolled steel sheets with the mechanical properties (JIS No. 5, C direction) shown in **Table 1** were used. The forming process comprised two processes, drawing in the 1st process and bending with a pad in the 2nd process, as shown in **Fig. 10**. The BHF (Blank Holder Force) in the 1st process was 490 kN, and pad load in the 2nd process was 98 kN. In

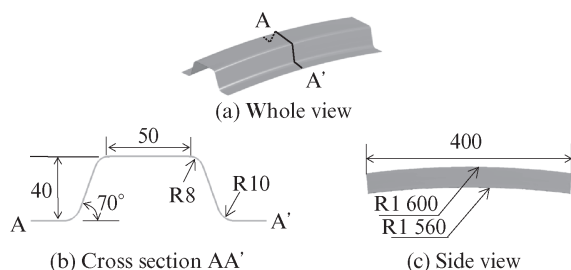


Fig. 9 Model shape⁵⁾

Table 1 Mechanical properties of each steel used in CAE

Steel	t (mm)	YS (MPa)	TS (MPa)	EL (%)
JSC590Y	1.4	426	621	28
JSC980Y	1.4	685	1 037	17
JSC1 180Y	1.4	856	1 242	13

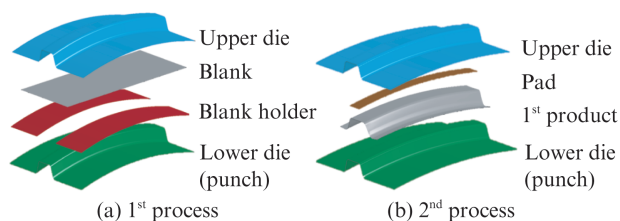


Fig. 10 Press forming process⁵⁾

this study, forming was performed with the punch top curvature radius of the die in the 1st process varied in the range of R 1 000 to R 1 600 and a constant vertical wall height, and with R 1 600 in the 2nd process. The amount of camber back was evaluated based on the curvature radius of the punch top (web of panel). Since wall opening occurs in conjunction with camber back, C-chamfering¹¹⁾ was applied to the bending ridge line as a countermeasure against wall opening in order to study the effect of camber back in isolation.

4.1.2 Results of FEM Analysis

Figure 11 shows the relationship of the respective punch top curvature radius of the die in the 1st process and curvature radius of web of panel after springback formed in the 1st process for various materials strengths. Under the condition that the die curvature radius in the 1st process was R 1 200 or less, the curvature radius after springback decreased to R 1 600, which is die curvature of the 2nd process, or less with all materials.

Next, **Fig. 12** shows the relationship between tensile strength and the curvature radius of web of panel after springback formed in 2nd process, arranged by the cur-

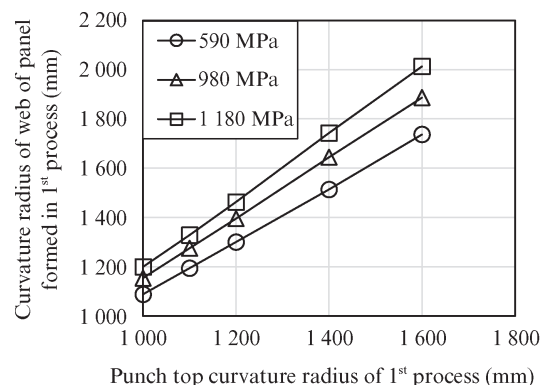


Fig. 11 Relationship of punch top curvature radius of 1st process on curvature radius of web of panel formed in 1st process¹²⁾

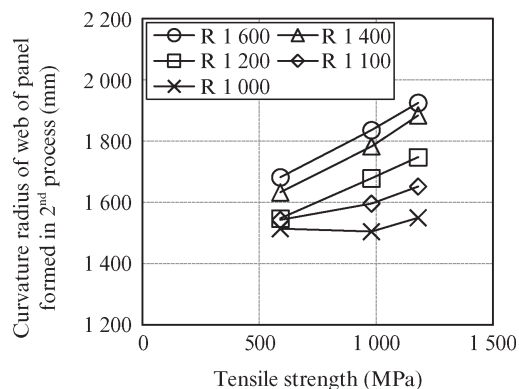
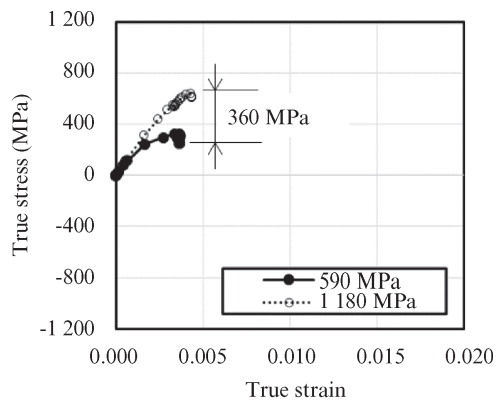


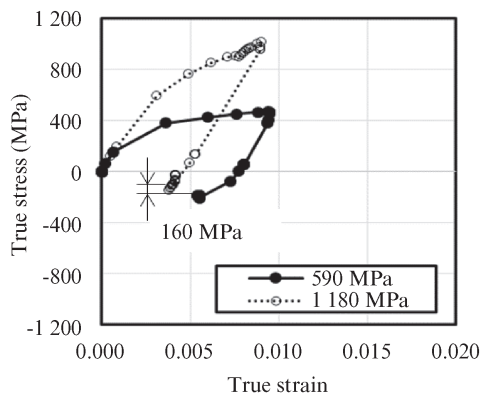
Fig. 12 Relationship of tensile strength of steel sheet on curvature radius of web of panel formed in 2nd process¹²⁾

vature radius of the die in the 1st process. Dimensional variation, which is shown by the slope of the graph, was suppressed most effectively under the condition that the die curvature radius in the 1st process was R 1 000. The difference in the curvature radii with the material strengths from 590 MPa to 1 180 MPa was 243 mm with R 1 600 in the 1st process, but decreased to 36 mm with R 1 000 in the 1st process, showing a reduction of approximately 85%.

Figure 13 (a) and (b) show the transition of the average stress and average strain of the punch top in forming in the one-step press forming with the R 1 600 die geometry (i.e., no countermeasures), and with R 1 000 in the 1st process and R 1 600 in the 2nd process (developed technology). In the one-step press forming, tensile stress was generated during forming, and the stress difference at the bottom dead center between the 590 MPa material and the 1 180 MPa material was 360 MPa. However, with the developed technology, stress was reversed in the 2nd process and transitioned to the compressive side, and the stress difference between the 590 MPa material and the 1 180 MPa material was reduced to approximately 160 MPa. It is considered that dimensional variation decreased as a result of these decreases in the stress difference and the absolute value of stress.



(a) 1st process forming



(b) Development technology

Fig. 13 Stress and strain transitions at punch top¹²⁾

4.2 Verification of Effects of the Developed Technology by Press Experiments

4.2.1 Experimental Method and Conditions

A press experiment was carried out to verify the effects of the developed technology presented in Section 4.1. An example of a press trial panel is shown in **Photo 2**. As in Section 4.1, C-chamfering was applied to eliminate the effect of wall opening. Three steel grades, 590 MPa, 980 MPa and 1 180 MPa (t 1.4 mm) with the mechanical properties shown in **Table 2** were used. In the experiment, forming was performed with two processes, with forming under the two conditions of R 1 000 (developed technology) and R 1 600 (no countermeasures) in the 1st process, and R 1 600 under both conditions in the 2nd process.

4.2.2 Experimental Results

Figure 14 shows the relationship between the material tensile strength and curvature radius of web of panel after springback in the 2nd process under each forming condition. In both the FEM analysis and the

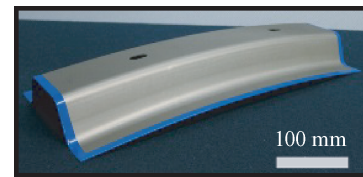


Photo 2 Curved panel formed in press trial¹²⁾

Table 2 Mechanical properties of each steel used in experiment

Steel	t (mm)	YS (MPa)	TS (MPa)	EL (%)
JSC590Y	1.4	454	650	33
JSC980Y	1.4	676	1 046	16
JSC1180Y	1.4	856	1 242	13

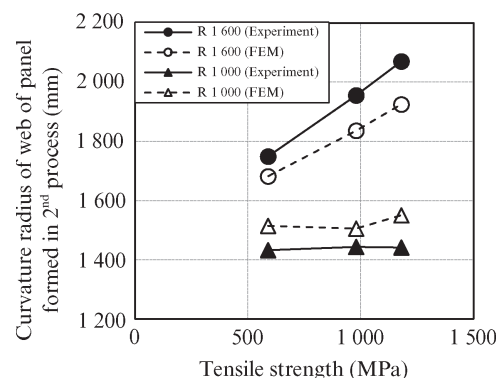
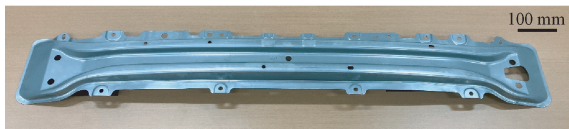


Fig. 14 Relationship of tensile strength of steel sheet on curvature radius of web of panel formed in 2nd process in experiment and FEM¹²⁾



(a) Roof center R/F



(b) Member front bumper

Photo 3 Mass production parts using the developed technology⁷⁾

experimental results, dimensional variation was reduced by using the R 1 000 die curvature radius in the 1st process, and the curvature radius difference between the 590 MPa and 1 180 MPa materials in the experiment was reduced from 320 mm to 10 mm, for a decrease of approximately 95%. These results confirmed the dimensional variation reduction effect of the developed technology.

5. Adoption of the Developed Technology in Mass Production

The developed technology has been adopted as a mass-production press forming technology for the roof center R/F applying 1 470 MPa cold-rolled steel sheets¹³⁾ (Photo 3 (a)) as the first example, as well as member front bumpers of 980 MPa to 1 180 MPa cold-rolled steel sheets (Photo 3 (b)) and other parts. Since UHSS is applied in these parts, poor dimensional accuracy and dimensional variation had been major challenges. These problems have been improved by applying the developed technology, contributing to expanded application of UHSS and stable production of automobile parts.

6. Conclusion

With the conventional press forming process, dimensional variation of press formed automobile parts without countermeasure technologies had been a

challenge. To overcome this problem, JFE Steel developed a new press forming technology utilizing the Bauschinger effect, which is a tensile-compressive property of the steel sheet, and this process was adopted as a mass-production technology. It is also considered possible to apply the mechanism of the developed technology to springback that occurs with other curved shapes. In the future, we aim to achieve further expansion of ultrahigh-strength steels and the developed technology.

References

- 1) Seto. K. High Strength Sheet Steels and their Application Technologies for Automotive Weight Reduction. *Trans. Soc. Automot. Eng.*, 2010, vol. 64, no. 11, p. 29–34.
- 2) Hayashi. H. Trend of forming of high strength steel sheets. *J. Jpn. Soc. Technol. Plast.*, 2011, vol. 52, no. 606, p. 756–760.
- 3) Iwaya. J. Countermeasures of defects in dimensional precision in press forming technique of high strength steel sheets. *J. Jpn. Soc. Technol. Plast.*, 2011, vol. 52, no. 606, p. 772–776.
- 4) Uemori. T. Influence of Bauschinger Effect on Forming Simulation Result and Its Solution. *J. Jpn. Soc. Technol. Plast.*, 2016, vol. 57, no. 662, p. 194–198.
- 5) Tobita. S.; Shinmiya. T.; Yamasaki. Y.; Hiramoto. J. Development of Forming Technology to Reduce Dimensional Scattering of Automotive Parts with Cambers by Using Bauschinger Effect. *J. Jpn. Soc. Technol. Plast.*, 2019, vol. 60, no. 701, p. 155–160.
- 6) Tobita. S.; Shinmiya. T.; Yamasaki. Y.; Iizuka. E.; Tamai. Y. Development of Forming Technology to Reduce Dimensional Scattering of Automotive Parts with Cambers by Using Bauschinger Effect. *Proc. 71st Jpn. Jt. Conf. Technol. Plast.*, 2020, p. 191–192.
- 7) Tobita. S. Forming Technology to Reduce Dimensional Scattering of Automotive Parts with Cambers Using Bauschinger Effect. *Bull. Jpn. Soc. Technol. Plast.*, 2025, vol. 8, no. 87, p. 116–120.
- 8) Sasahara. T. Optimization of Springback Compensation in Stamping Die Surface Geometry. *J. Jpn. Soc. Technol. Plast.*, 2005, vol. 46, no. 534, p. 607–611.
- 9) Maeda. S.; Eguchi. H. Simulation Yosoku Gizyutsu wo Katsuyoushita Kanagata Zukuri [Die Manufacturing Using Prediction Technology by Simulation]. *Press Working*, 2009, vol. 47, no. 7, p. 34–39.
- 10) Yoshida. F.; Uemori. T. A Model of Large-strain Cyclic Plasticity and Its Application to Springback Simulation. *International Journal of Mechanical Sciences*, 2003, vol. 45, no. 10, p. 1687–1702.
- 11) Urabe. M.; Saito. T.; Kano. H.. JP. 4992048.
- 12) Tobita. S.; Shinmiya. T.; Yamasaki. Y.; Hiramoto. J. Forming Technology to Reduce Dimensional Scattering of Automotive Parts by Using Bauschinger Effect. *Bull. Jpn. Soc. Technol. Plast.*, 2023, vol. 6, no. 72, p. 740–744.
- 13) NIKKEI BP. The Nikkei Automotive. 2022, no. 132, p. 54–59.