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Research Report

Hot Stamping Process Design for Improvement of Formability

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Report received on Apr. 11, 2018

■ABSTRACT■ Although steel sheets have excellent elongation at high temperatures, deep drawability is extremely low in the hot stamping process. This stems from the temperature distribution generated by contact with the die during forming. This paper proposes two main approaches of temperature control to improve hot deep drawability. In one approach, the area in which deformation was to be promoted, i.e., the flange area, was softened at a higher temperature by reducing the contact duration and the die contact area. In the other approach, the area in which local deformation was to be prevented, i.e., the wall area, was partially cooled by air blowing to increase the deformation resistance before forming. Furthermore, to be able to apply these techniques to various automobile body parts, a procedure involving a thermo-mechanical simulation was developed to determine a suitable initial temperature distribution for hot deep drawing. Finally, formability improvement techniques were applied to a deep drawing test. Experimental results showed that the integrated formability improvement technique achieved a three times larger forming limit depth compared to the standard hot stamping process. This suggests that a greater variety of shapes can be fabricated by hot stamping through controlling the temperature distribution.

■KEYWORDS■ Hot Stamping, Deep Drawing, Formability, Process Design, Temperature Control, Partial Cooling, Forming Simulation, Boron Steel

1. Introduction

In the automotive industry, the use of ultrahigh-strength parts manufactured by the hot stamping process has been increasing rapidly to reduce automobile body weight without compromising crash safety performance. The process known as hot stamping (also press hardening or hot forming die quenching) is used with boron steel sheets to perform press forming and quench hardening simultaneously, and thus ultrahigh-strength parts having a tensile strength of 1500 MPa can be obtained.⁽¹⁾ For further weight reduction, excellent formability is required to increase the diversity of shapes. However, in the standard hot stamping process, deformable parts are limited to simple bent shapes, such as pillars and reinforcements.⁽²⁾ This is because hot stamping is characterized by extremely low deep drawability in contrast to excellent bend-formability.⁽³⁾

This low deep drawability is related to the temperature distribution generated by contact with the

forming die during the forming step. In the standard hot stamping process, a blank sheet is heated above the austenitization temperature (Ac3, approximately 850°C), transferred to the press and subsequently formed and quenched in the die. Boron steels show excellent ductility at uniform elevated temperatures.⁽⁴⁾ However, the actual hot stamping process is a non-isothermal forming process for sheet metals.⁽⁵⁾ Even when a steel sheet is heated uniformly, a temperature distribution is generated, owing to contact with the cold die. The deformation resistance of steel sheets depends on temperature;⁽⁶⁾ therefore, temperature gradients strongly influence the deformation behavior. Focusing on the temperature distribution generated during forming, the deep drawing process is illustrated in **Fig. 1**. A deep-drawn part has three sections: the flange, wall, and head areas. The flange is normally compressed between the upper die and the blank holder to suppress the formation of wrinkles. At this time, the temperature of the flange decreases dramatically. Consequently, the flange

hardens, and thus no material inflow can be expected from the flange. In contrast, the wall does not contact the die until the press reaches the bottom dead center. Therefore, the wall is still at a higher temperature, and it is softer. As a result, local deformation tends to occur in the wall, leading to cracks with low forming depth.

However, in order to increase the diversity of formable shapes, excellent deep drawability is required for hot stamping. Deep drawing involves all of the major deformation modes of sheet metal forming. Deep-drawn parts undergo not only bending deformation but also compressive deformation of the flange, and tensile deformation of the wall and head areas. Improvement of hot deep drawability enables the fabrication of deep-drawn parts such as floor panels and inner panels by hot stamping. Furthermore, the requirement of excellent hot deep drawability has been accelerated by a trend to integrate parts with tailored properties.⁽⁷⁾

In this paper, two approaches to controlling the temperature distribution are proposed in order to improve hot deep drawability. Furthermore, to apply these techniques to a variety of automobile body parts, a procedure is developed to determine the appropriate initial temperature distribution for hot deep drawing by using a thermo-mechanical simulation. Finally, formability improvement techniques are applied to a deep drawing test. In this experiment, all of the proposed forming techniques are integrated into one process with the expectation that they will lead to a synergistic formability improvement effect.

2. Formability Improvement Techniques in Hot Stamping

A number of research studies have been conducted to improve formability in the hot stamping process. Process variants for improving hot deep drawability are illustrated in Fig. 2. First, the hot stamping process is divided into two main methods: a direct and an indirect method. The direct method is the typical hot stamping process: the steel sheet is heated and then formed and quenched simultaneously in the die. In the indirect method, the steel sheet is pre-formed at room temperature and then heated to the austenitic phase, and subsequently quenched in the die. The pre-forming step is applied to avoid low deep drawability due to the temperature distribution. However, this method requires one more forming step

than the direct hot stamping method. For the direct method, two main strategies have been proposed: (i) reducing the frictional resistance to induce deformation,⁽⁸⁾ and (ii) controlling the deformation behavior by generating a temperature distribution.⁽⁹⁻¹²⁾ Furthermore, temperature control has been achieved by one of two approaches: (i) suppressing the temperature drop, and (ii) partial cooling.

In this section, the mechanisms of three representative formability improvement techniques are described for the two temperature control approaches. In Sec. 2. 1, two main techniques for suppressing the temperature drop in the flange are described; the high-speed forming method⁽⁹⁾ and the flange gap forming method.⁽¹⁰⁾ Sec. 2. 2 describes the partial cooling method^(11,12) used to suppress the local deformation of the wall area.

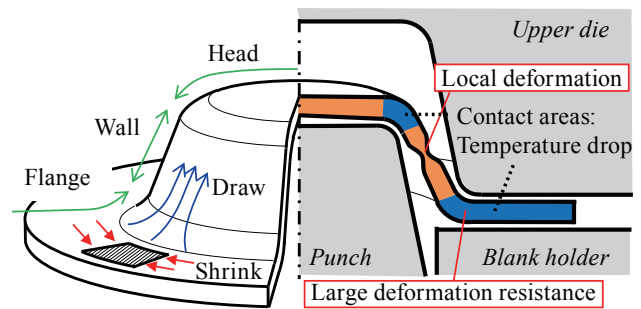


Fig. 1 Schematic of deformation mechanism during deep drawing process in hot stamping.

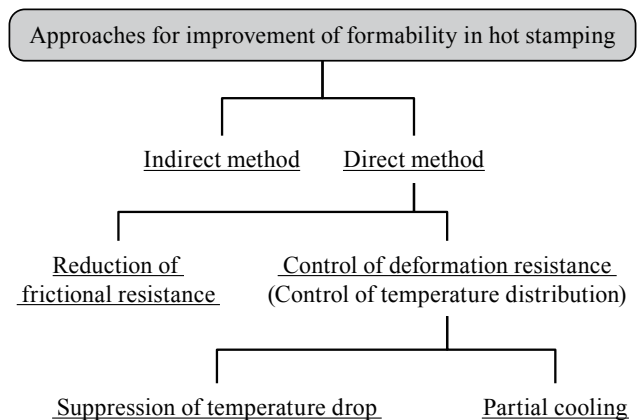


Fig. 2 Process variants for improvement of formability in hot stamping.

2.1 Suppression of Temperature Drop in the Flange Area

2.1.1 High-speed Forming

The duration of contact between a steel sheet and the die during forming is shortened by the high-speed forming process. Shortening of the contact duration can suppress the temperature drop. Therefore, the flange area and the punch shoulder can be formed in a softer state at a higher temperature.

2.1.2 Flange Gap Forming

Figure 3 illustrates the process of flange gap forming. By leaving a clearance between the blank sheet and the die, wrinkles are generated in the shrink flange area. These wrinkles reduce the number of contact points between the die and the blank sheet. Thus, the temperature drop can be suppressed. Also, frictional resistance can be reduced. However, this technique has a drawback. The remaining wrinkles must be sufficiently flattened if wrinkles cannot be allowed in the hot-stamped parts. Furthermore, if tension is required to stretch surface deflection of the blank sheet, the clearance becomes smaller. Therefore, the clearance needs to be adjusted to suppress the temperature drop in the flange area and to increase tension in the wall area.

2.2 Partial Cooling of Potential Cracking Area

Figure 4 illustrates the partial cooling technique. In this technique, the potential cracking area is cooled to harden it before forming by air blowing. The cooled

wall area becomes harder, and thus, local deformation can be suppressed. At the same time, deformation is induced in the surrounding area: Stretching of the head area and drawing of the flange area are expected. Also, full hardened properties can be obtained by controlling the blank temperature to maintain the supercooled austenitic state while the partial cooling technique is applied.

3. Calculation of Suitable Initial Temperature Distribution

In the approach involving temperature drop suppression, a higher deep drawability is expected by providing both a larger clearance and faster press motion. In the partial cooling approach, the suitable temperature distribution depends on the product shape. When the extent of cooling exceeds the suitable condition, a local deformation occurs near the partially cooled area. In this section, a procedure is proposed for determining the suitable initial temperature distribution for hot deep drawing.

3.1 Calculation Procedure

Figure 5(a) shows the proposed procedure for calculating a suitable initial temperature distribution that involves iterating a forming simulation. In this procedure, the forming limit strain ϵ_{limit} and potential cracking strain $\epsilon_{caution}$ were defined as calculation parameters. ϵ_{limit} corresponds to the critical strain at which necking or crack occurs. It can be measured from material tests such as the Nakajima test⁽¹³⁾ or Marciniark test.⁽¹⁴⁾ $\epsilon_{caution}$ must be adjusted to narrow down the target elements for the cooling calculation.

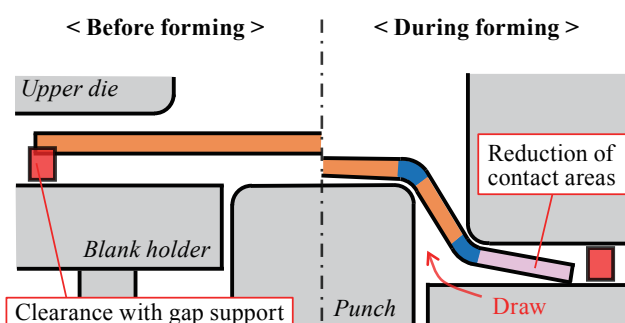


Fig. 3 Schematic of forming process with flange gap.

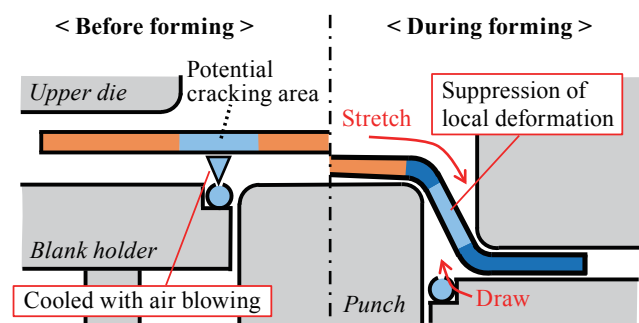


Fig. 4 Schematic of partial cooling technique.

The procedure consists of the following six steps:

- (1) Run a forming calculation with a blank sheet that has a uniform temperature.
- (2) Stop the calculation when an element exceeds ϵ_{limit} .
- (3) Select the elements that exceed $\epsilon_{caution}$.
- (4) Calculate a new initial temperature distribution with cooling nodes around the elements selected in step (3). The cooling conditions used in the present study are shown in Fig. 5(b).
- (5) Re-run the forming calculation with a blank sheet having the new initial temperature distribution calculated in step (4).
- (6) Iterate steps (2) to (5) until the forming limit depth is maximized. The temperature distribution at the maximum forming depth represents a suitable initial temperature distribution.

3.2 Calculation Conditions

According to the procedure described in the previous section, a suitable initial temperature distribution was calculated for the oval-shaped model shown in Fig. 6. As a blank sheet, a 1.4-mm-thick GA-coated boron steel was assumed, and a temperature-dependent flow stress was used in the super-cooled austenitic state

of the boron steel.⁽⁶⁾ First, a standard hot stamping calculation was carried out at a uniform temperature of 873 K (600°C). The forming limit depth was investigated at 1 mm intervals. In this calculation, the parameters shown in Fig. 5(b) were used. The forming limit strain ϵ_{limit} was set to 0.45, and the potential cracking strain $\epsilon_{caution}$ was set to 0.35. The value of 0.45 for ϵ_{limit} is in good agreement with the value reported by Li et al.⁽¹⁵⁾ To calculate the extent of cooling, the nodes of the selected element were cooled by 5 K, and the nodes next to the selected element were cooled by 2 K. This procedure was iterated until the forming depth was maximized. This simulation was conducted using a LS-DYNA solver. As the material model, an elastic-viscoplastic model including temperature calculations was used. Axial symmetry boundary conditions were defined to reduce the calculation time. The element size was set to 2 mm. The friction coefficient was assigned a measurement value of 0.2 for GA-coated boron steel at elevated temperature. The blank holder pressure was set to 7.4 MPa, and the forming speed was set to 60 mm/s.

3.3 Calculation Results

Figure 7(a) shows the calculated initial temperature

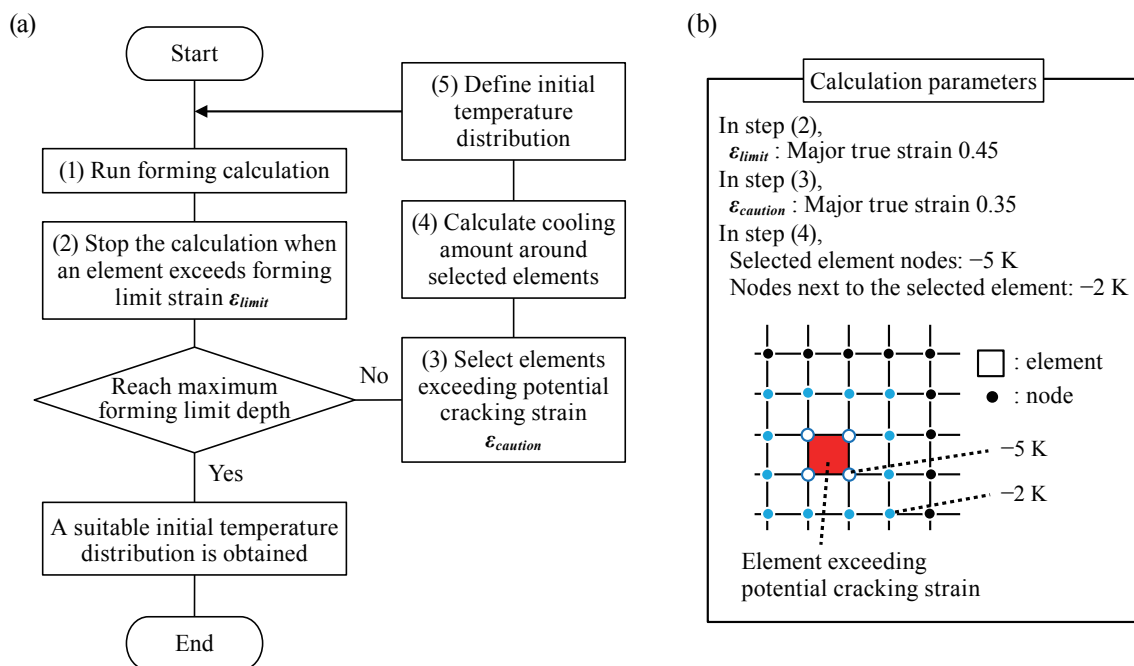


Fig. 5 Calculation procedure to determine a suitable initial temperature distribution for deep drawing: (a) flow chart, (b) calculation parameters used in this paper.

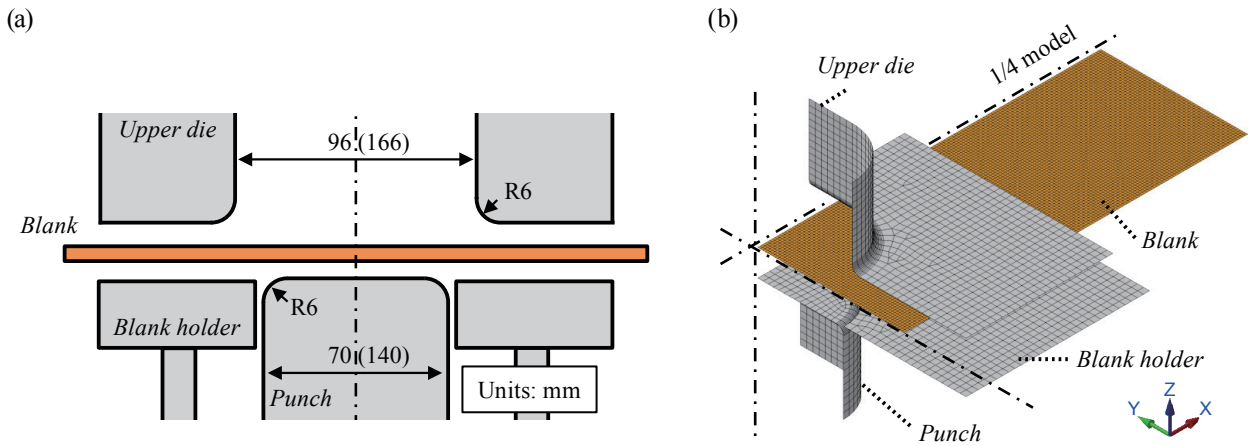


Fig. 6 Oval forming die: (a) dimensions of the die from the short axis side (long axis side values are given in brackets), (b) overview of the simulation model.

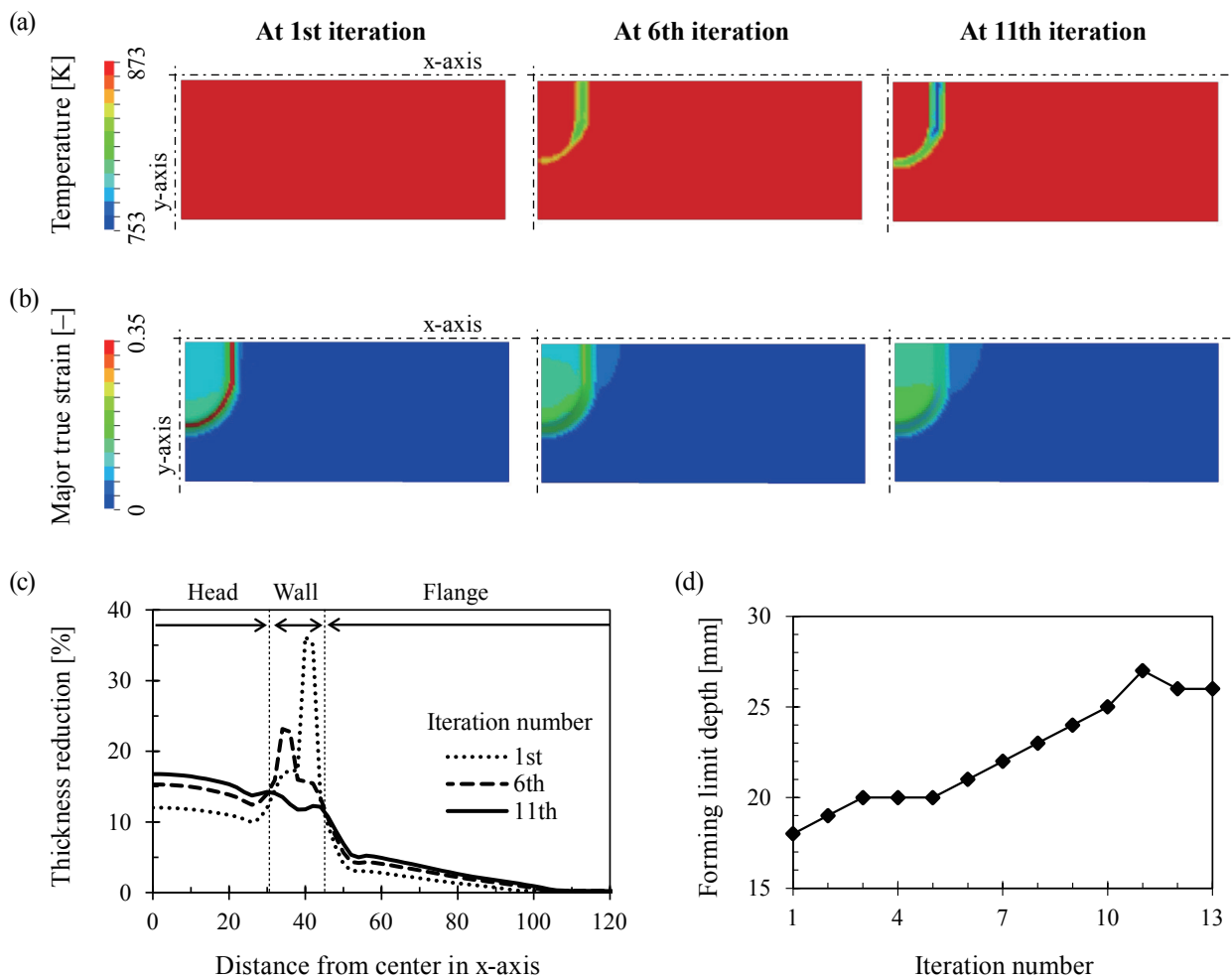


Fig. 7 Forming states in the iterative calculations: (a) initial temperature distribution at 1st, 6th, and 11th iteration, (b) strain distribution at a depth of 18 mm at 1st, 6th, and 11th iteration, (c) thickness reduction along x-axis at a depth of 18 mm at 1st, 6th, and 11th iteration, (d) forming limit depth of iterative calculations.

distribution at the 1st, 6th, and 11th iteration. At the 11th iteration, the wall area of the blank sheet was cooled by about 120 K before forming. Figures 7(b) and 7(c) show the major strain distribution and thickness reduction along the x-axis at a depth of 18 mm at the 1st, 6th, and 11th iteration. The concentrated deformation on the wall area diminished, and deformation of the head and flange areas was induced with increasing number of iterations. Figure 7(d) shows the dependence of the forming limit depth on the number of calculation iterations. With a partially cooled blank sheet, the forming limit depth increased with the number of iterations until reaching a maximum at the 11th iteration. Thus, this 11th initial temperature distribution was taken to be a suitable condition. At the 11th iteration, deformation concentration was observed on the head area instead of the wall area.

4. Experimental Comparison and Integration of Formability Improvement Techniques

The formability improvement techniques introduced in Sec. 2 were applied to the deep drawing test. Furthermore, the proposed forming techniques were integrated into one process, with the expectation of a synergistic effect.

4.1 Experimental Conditions

The experimental conditions are summarized in Table 1. The forming test was conducted by using an oval-shaped die having the same dimensions as that in Fig. 6(a). This die can help to determine deep drawability up to an arbitrary depth of 45 mm. The

forming limit depth was investigated at 2.5-mm intervals and compared with that of each basic condition. As a blank sheet, a 1.42-mm GA-coated boron steel was used. In test No. 1, the standard hot stamping process was assumed. The forming test was performed at 973 K (700°C), and the forming speed was set to 60 mm/s. The blank holder pressure was set to 2.2 MPa. In tests No. 2-4, each of the basic conditions was applied. In test No. 2, the forming speed was faster at 300 mm/s. Assuming a depth of 30 mm, the forming duration was shortened from 0.5 to 0.1 s because of the five-fold increase in forming speed. In test No. 3, there was a clearance equal to the sheet thickness + 0.2 mm between the upper die and the blank holder. In test No. 4, the wall area was partially cooled using the air blowing tool, as shown in Fig. 8(a). The cooling tool was located in the blank holder. The temperature in the partially cooled area was 150 K lower than that in the surrounding area, as shown in Fig. 8(b). In test No. 5, the techniques of tests No. 2-4 were integrated into a single process, as shown in Fig. 9. In this paper, a step for flattening the wrinkles that appeared in the flange area was added. In order to apply a higher load to the wrinkles, the blank holder was adjusted to contact the base plate at the bottom dead center. For reference, the boron steel and a mild steel sheet for deep drawing in a cold state were also examined in tests No. 6 and 7. Test No. 6 was carried out as the indirect hot stamping method. No lubricant was used in any of these tests.

4.2 Experimental Results

The forming limit depth results are summarized in Fig. 10. In the standard hot stamping process, test No. 1, the forming limit depth was only 15 mm. At

Table 1 Experimental conditions for the deep drawing test.

	STD HS	High speed	Flange gap	Partial cooling	Integration	Indirect HS	Mild steel
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Forming speed	60 mm/s	300 mm/s	60 mm/s	60 mm/s	300 mm/s	60 mm/s	60 mm/s
Flange gap	-	-	0.2 mm	-	0.2 mm	-	-
Partial cooling	-	-	-	Applied	Applied	-	-
Forming temperature	973 K	973K	973 K	973 K	973 K	RT	RT
Material	Boron steel	Boron steel	Boron steel	Boron steel	Boron steel	Boron steel	Mild steel sheet

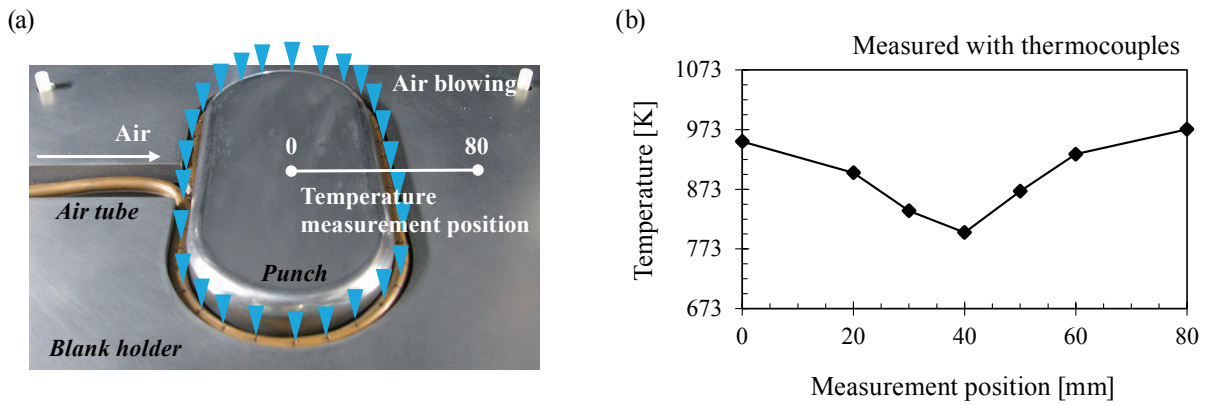


Fig. 8 Experimental apparatus for partial cooling process and its performance: (a) air blowing tool, and (b) temperature distribution with partial cooling along the line indicated in (a).

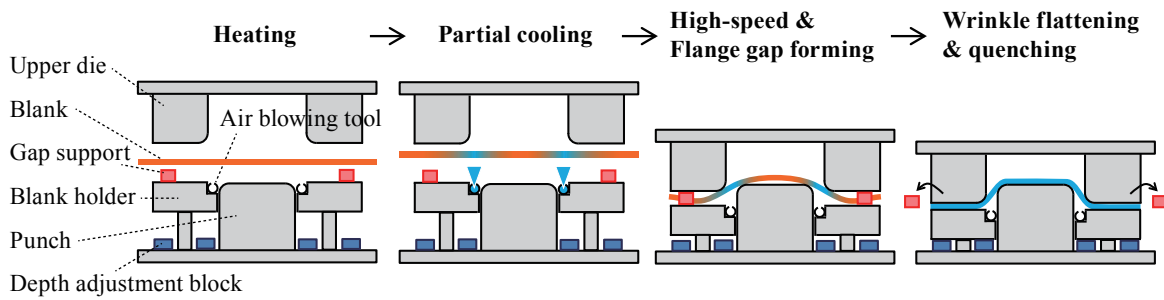


Fig. 9 Process integrating the partial cooling technique and the technique for suppressing temperature drop.

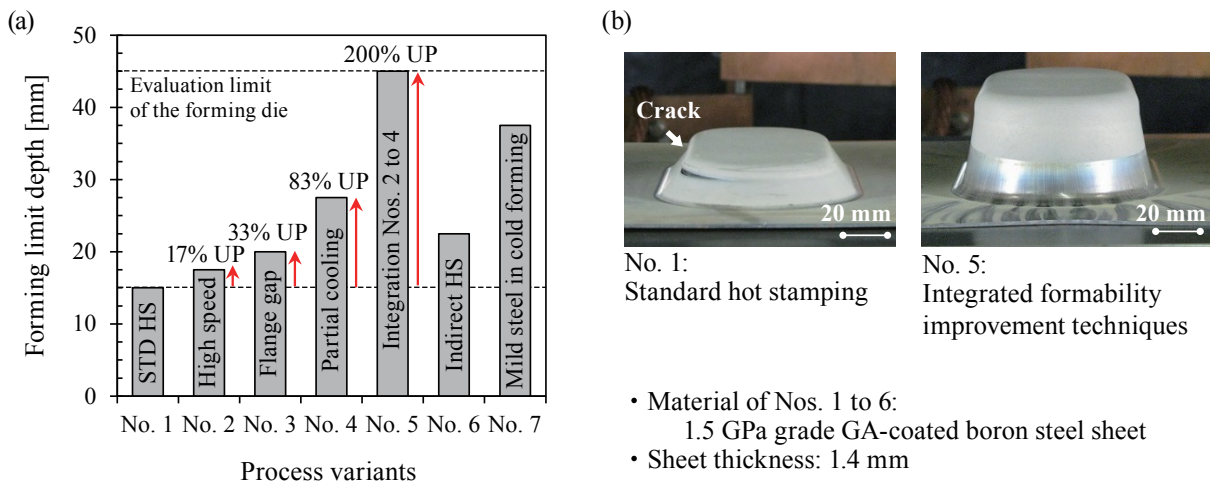


Fig. 10 Experimental results of the deep drawing test: (a) forming limit depth, (b) tested specimens.

this depth, the sheet thickness at the center of the head area was reduced by 10% from its initial thickness. Compared to the result of test No. 1, the techniques of the temperature drop suppression increased the forming limit depth up to 17% in test No. 2, and 33% in test No. 3. The partial cooling technique, test No. 4, increased the forming limit to an 83% larger depth than test No. 1. Under the test No. 4 condition, the thickness at the center of the head area decreased by 39%. The deformation of the head area was significantly increased by the partial cooling technique. Also, this result showed superior formability in the result of test No. 6 (indirect hot stamping). The integration of these techniques, test No. 5, showed the largest depth: the forming depth reached 45 mm, which is the measurement limit of the die. In this condition, the thickness at the center of the head area decreased by 30%. This deep-drawn specimen is shown in Fig. 10(b). The proposed process realized a three times deeper cup as compared to the standard hot stamping process and a cup twice as deep as that achievable by the indirect hot stamping process. This 30-mm depth increase was larger than the sum of the increases observed for technique Nos. 2-4, which means there was a synergistic effect. The cause of this synergistic effect is considered in the next section. Furthermore, the present depth of 45 mm was also larger than that obtained with a mild steel sheet at room temperature.

4.3 Discussion

The cause of the remarkable improvement in hot deep drawability with the integrated technique is thought to be the following. The amount of material inflow from the flange area is determined by the balance between the deformation resistance and the drawing force of the flange area. This drawing force increases as the elongation in the wall area decreases. Thus, the drawing force of the flange area is increased by hardening the wall area using the partial cooling technique. When the thickness reductions of tests No. 4 and 5 at the center of the head area are compared, the deformation of No. 5 is found to be smaller than that of No. 4. Thus, the synergistic effect is mainly due to the increase in the deformation of the flange area. According to the calculation results in Sec. 3, the partial cooling technique induces deformation of the flange area. In other words, the partial cooling technique presumably enhances the formability improvement effect of the

techniques used for suppressing the temperature drop.

5. Conclusion

In this paper, to further improve the formability during hot stamping, several formability improvement techniques were integrated. By using a technique for suppressing the temperature drop, the flange area was maintained at a high temperature, and thus in a softer state, for ease of drawing. Potential cracking areas, such as the wall, were hardened by partial cooling to prevent local deformation prior to forming. Furthermore, a procedure was developed to calculate a suitable initial temperature distribution for hot deep drawing. The proposed process enabled a three-fold increase in cup depth as compared with the standard hot stamping process. This suggests that a greater variety of shapes can be fabricated by hot stamping if the temperature distribution is controlled.

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Figs. 1, 3-4, 8-10 and Table 1

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Figs. 5 and 7

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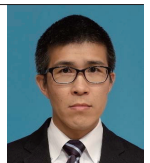
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