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Improvement of formability for hot stamping of aluminum alloy sheets by press motion control

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Abstract. In this work, the formability of Al-Mg-Si aluminum alloy sheets during hot stamping has been improved by controlling the press motion. In the hot stamping, a heated blank sheet is cooled partially by contacting with the dies; therefore, its deformation proceeds non-isothermally. The resulting temperature distribution leads to cracking at low forming depths during deep drawing despite the excellent tensile properties of the alloy at high temperatures. Local deformation, i.e. necking, tends to occur in a high-temperature area that is not in contact with the dies until the press reaches the bottom dead center. To suppress this deformation, the potential cracking area near the walls was cooled and hardened by holding the heated blank sheet between the blank holder and the upper die before the forming step. The proposed technique was applied to the square cup forming of a 1.0 mm thick 6000 series aluminum alloy sheet. As a result, the forming limit depth was increased to twice depth with 1.0-s die-holding duration before the forming step as compared to that obtained for the standard hot stamping procedure without the press motion control.

1. Introduction

The weight of automobile bodies can be reduced by using high-strength aluminum alloy sheets for manufacturing body panel parts. However, many high-strength aluminum alloys such as those of 6000 (Al-Mg-Si) and 7000 (Al-Zn-Mg) series have low elongations at room temperature and, therefore, are mainly used to the fabrication of simple shapes. Recently, the hot stamping of aluminum alloy sheets has attracted much attention as a forming method capable of achieving both excellent formability and high strengths [1]. In this process, a blank sheet is heated to a solution heat treatment temperature and then is formed and quenched simultaneously in dies [2]. In this method, the blank sheet can be formed at a high temperature condition with excellent elongation.

However, the formable shapes obtained through the standard hot stamping process are mostly limited to the bended ones because of the generated temperature distribution. To fabricate the deep drawn parts, indirect hot stamping method has been proposed [3]. In this method, pre-forming at room temperature is performed before heating and quenching step. By studying the deep drawability of boron steel, it was found that its forming limit depth under the hot stamping conditions was lower than that at room temperature [4]. The deformation resistance of a material depends on temperature [5]; therefore, its deformation behavior is affected by the temperature distribution generated during the forming step. In other words, the deformation is greater in softer areas and leads to the formation of cracks with low depths despite the high elongation of the blank at high temperatures.

Two approaches have been suggested for the improvement of steel formability by controlling the temperature distribution during forming: (i) promoting the deformation process by suppressing the temperature decrease during the forming step and (ii) partial cooling of the potential cracking area to suppress the local deformation [4]. In reference [6], a partial cooling technique involving the air blowing to the potential cracking area before the forming step was proposed as a method for suppressing the deformation during the hot stamping of boron steel. However, aluminum alloy sheets exhibit higher thermal conductivity as compared to that of steels; therefore, it is difficult to obtain a sharp temperature distribution in these sheets by partial air blowing.

In this study, a press motion control technique is proposed to suppress the local deformation during the hot stamping of aluminum alloy sheets. The potential cracking area was cooled and hardened by holding the heated blank sheet between the blank holder and the upper die before the forming step. First, suitable press motion conditions for improved formability were determined via forming simulations. After that, the formability improvement effect was experimentally confirmed by subjecting a 1.0 mm thick 6000 series aluminum alloy sheet to a square cup forming test.

2. A new formability improvement technique: Press motion control

In this section, a formability improvement technique is proposed for the hot deep drawing/stretch-forming process with press motion control. This technique is aimed at increasing the forming limit depth by decreasing the strain concentration generated during hot stamping.

The two types of deformation observed during cold and hot deep drawing are illustrated in Figure 1. In the cold deep drawing process, a deep shape is formed by drawing the material from the flange area to the wall area. In contrast, during hot deep drawing, the blank sheet is cooled partially by contacting with the dies, making the deformation a non-isothermal process. The flange area is cooled and hardened during the blank-holding step; thus, no material inflow from this region is expected. Whereas, the wall area is softer because it does not contact with the dies until the press reaches the bottom dead center. As a result, local deformation, i.e. necking, tends to occur in the wall area and produce cracks with low forming depths despite the high elongation of the blank sheet.

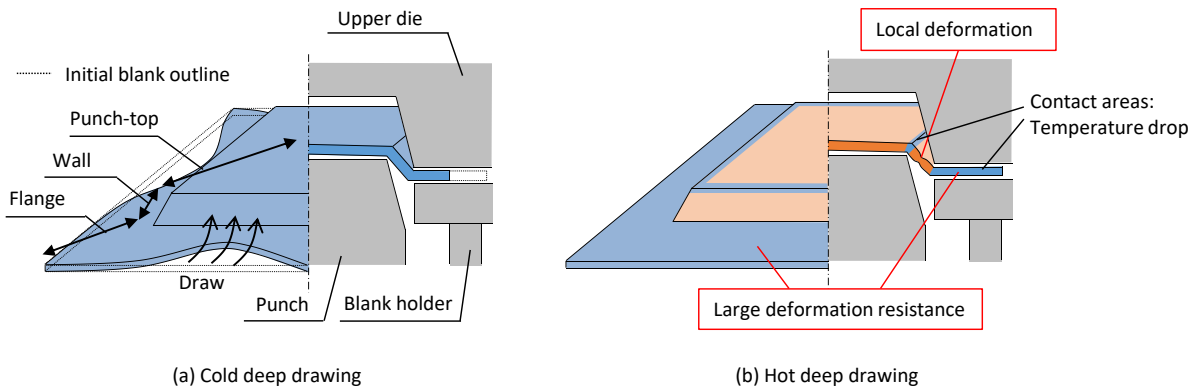


Figure 1. Schematic illustrations of the deformation processes observed during (a) cold deep drawing and (b) hot deep drawing.

The schematic diagram describing the press motion control technique is shown in Figure 2. Here, a unique die-holding step is added between the blank-holding and forming steps. In this step, the heated blank sheet is clamped between the blank holder and the upper die for a few seconds following the blank-holding step. Hence, heat is transferred from the flange area to the forming dies, and the wall area is cooled and hardened by thermal conduction. In addition, a recess area is designed on the punch-top to avoid contact between the punch and the blank sheet. Consequently, the strain concentration in the wall area is decreased, while the stretch deformation in the punch-top area can be promoted. As a result, the forming limit depth is increased by using the proposed method.

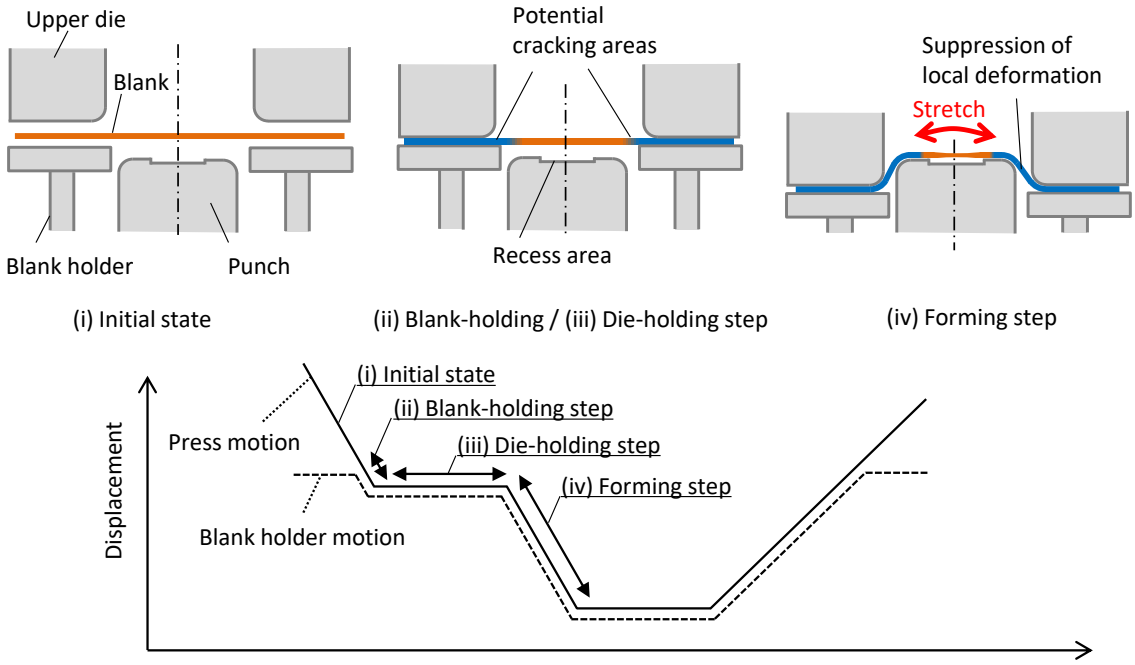


Figure 2. Schematic diagram describing the press motion control technique with die-holding.

3. Forming simulation

In this section, suitable press motion conditions for improving the formability were determined via forming simulations, in which the influences of the die-holding duration and forming velocity on the forming limit depth were investigated.

3.1. Simulation conditions

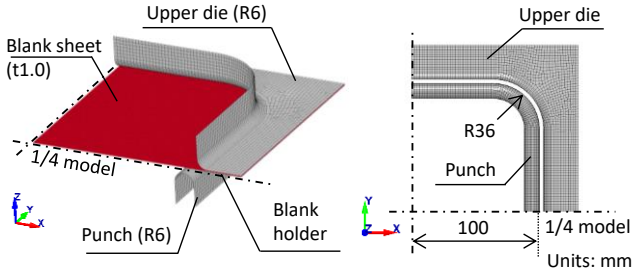
Two process parameters strongly affect the deformation behavior of a material: (i) the die-holding duration that influences temperature distribution before the forming step and (ii) the forming velocity that affects the temperature change during the forming step. In this work, forming simulations were conducted using LS-DYNA software under the following process conditions, and their influences on the forming limit depth were investigated.

(i) Die-holding duration: 0, 0.5, 1.0, 1.5, and 2.0 s
(ii) Forming velocity: 60, 120, and 300 mm/s

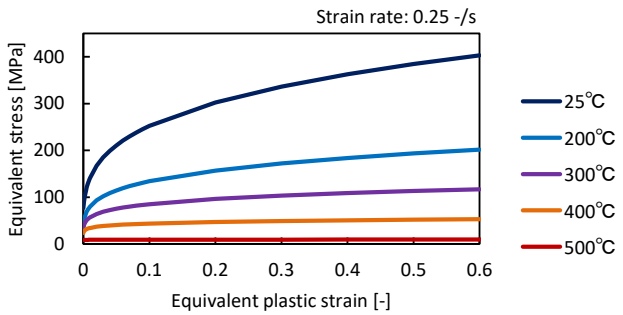
The forming limit depth was calculated at each process condition and 1.0 mm intervals for the 200 mm square cup model depicted in Figure 3a. Here, in order to simplify the evaluation of the formability, the forming limit depth was defined as a depth at which the maximum major strain exceeded 0.5. This value was decided from a forming limit strain in plane strain state at 350 °C in consideration of the temperature decrease during the blank-holding step to forming step. A 1.0 mm thick A6016-T4 aluminum alloy sheet was used as the blank sheet. The utilized temperature-dependent flow stress is shown in Figure 3b. The initial temperature was set to 420 °C in all calculations. According to reference [7], the strain rate dependence of the yield stress corresponded to the Cowper-Symonds model described by the formula $1 + (\dot{\varepsilon}_p/C)^{(1/p)}$. Here, $\dot{\varepsilon}_p$ is strain rate of effective plastic strain, and C and p are the model parameters. The blank holder pressure was adjusted to 9.2 MPa in order to investigate the influence of the die-holding duration on the stretch formability. The other calculation parameters are summarized in Figure 3c. The following parameters were not considered in the simulation model to achieve reasonable accuracy and decrease the computation time:

· Temperature-dependent forming limit criteria,

- Pressure-, drawing velocity- and temperature-dependent coefficient of friction,
- Temperature dependence of the strain rate sensitivity on the flow stress,
- Contact pressure / Gap dependence of the heat transfer coefficient.



(a) Simulation model



(b) Flow stress

Simulation software:	LS-DYNA ver. 971
Blank sheet	
Material:	A6016-T4
Material model:	Mat106: Elastic viscoplastic shell element with temeprature effects
Mesh size:	1 mm
Young's modulus:	70 GPa
Poisson's ratio:	0.33
Flow stress:	Fig. 3b
Cowper-Symonds parameters:	C = 6500, p = 4
Thermal conductivity:	229.1 W/m/K at 400 °C
Heat capacity:	1070 J/kg/K at 400 °C
Tool	
Material:	SKD61
Material model:	Rigid shell element
Thermal conductivity:	22.5 W/m/K
Heat capacity:	443 J/kg/K
Contact type:	Surface to surface
Friction coefficient:	0.2
Heat transfer coefficient	
Blank sheet - Tool:	1,000 W/m2/K
Blank sheet - Air:	20 W/m2/K
Blank holder pressure:	9.2 MPa
Room temperature:	27 °C

(c) Forming simulation conditions

Figure 3. (a) Forming simulation model, (b) flow stress dependences on the plastic strain and strain rate, and (c) forming simulation parameters.

3.2. Simulation results and discussion

First, the temperature distribution generated during the die-holding step was calculated. The temperature distributions obtained at various die-holding durations before the forming step are shown in Figure 4a. Here, the temperature of the flange area contacting with the dies drastically decreased from 420 °C to 300 °C in 0.5 s. In contrast, the temperature of the punch-top (non-contact) area remained high. It was also found that the cooling area could be adjusted by varying the die-holding duration and that its magnitude should be 1.0 s or greater to decrease the temperature of the wall area.

Next, the deformation behavior was calculated. In the condition of a forming velocity of 60 mm/s, major strain distribution obtained when its maximum strain exceeds 0.5 are depicted in Figure 4b. It shows that the strain is concentrated in the wall area at die-holding durations of 0 and 0.5 s. In contrast, when the die-holding duration exceeded 1.0 s, the whole punch-top area was deformed, and the maximum strain area was moved from the wall area to around the punch corner. The observed deformation behavior was in good agreement with the mechanism described in section 2.

Finally, the forming limit depths calculated under all conditions are summarized in Figure 5. The maximum strain position was moved from the wall area to the punch-top area by extending the die-holding duration at all forming velocities. Furthermore, this transition timing tended to be shorter with decreasing the forming velocity, and the maximum forming limit depth was between 26 and 27 mm regardless of the forming velocity.

The reason why the forming limit depth decreases when exceeding a certain die-holding duration is discussed below.

The temperature of the wall area is decreased with extending the die-holding duration; therefore, the longer the die-holding duration, the higher the deformation resistance of the wall. Consequently, the deformation areas transition in the order of (i) to (iii): (i) mainly the wall deformation, (ii) both deformation of the wall and the punch-top, and (iii) mainly the punch-top deformation. In the forming velocity of 60 mm/s, it is considered that the both areas, the wall and the punch-top, are stretched with a good balance in the die-holding duration of 1.0 s.

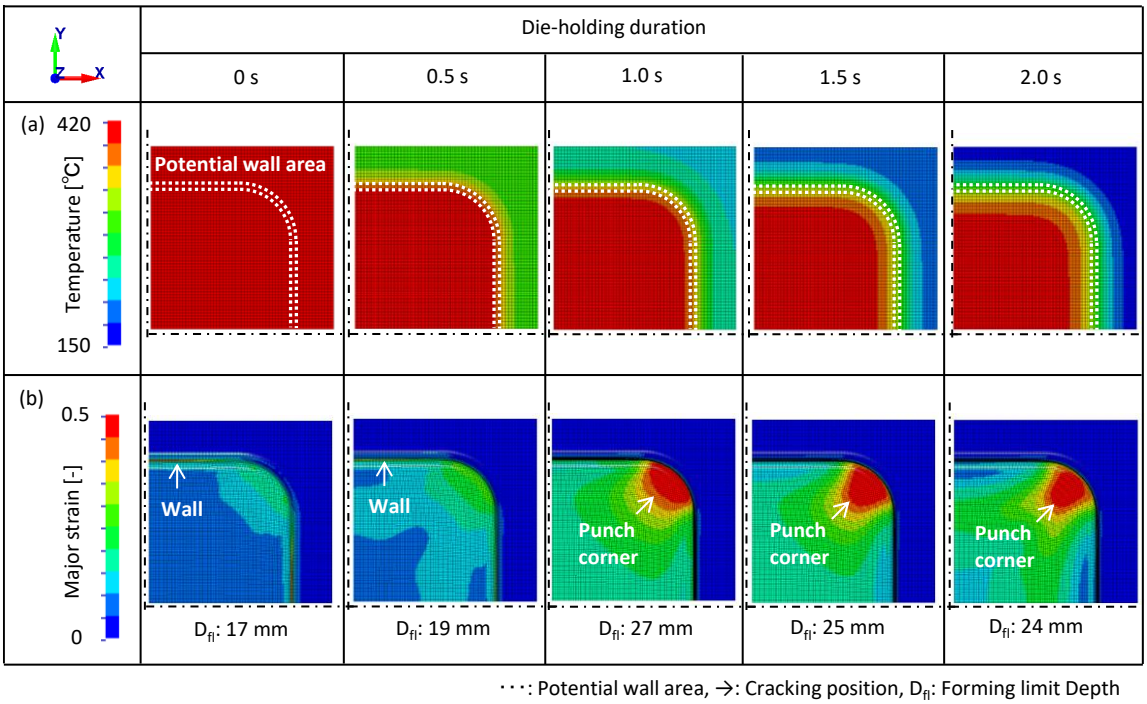


Figure 4. (a) Calculated temperature distributions after the die-holding step and (b) major strain distributions determined at the forming limit depth and forming velocity of 60 mm/s.

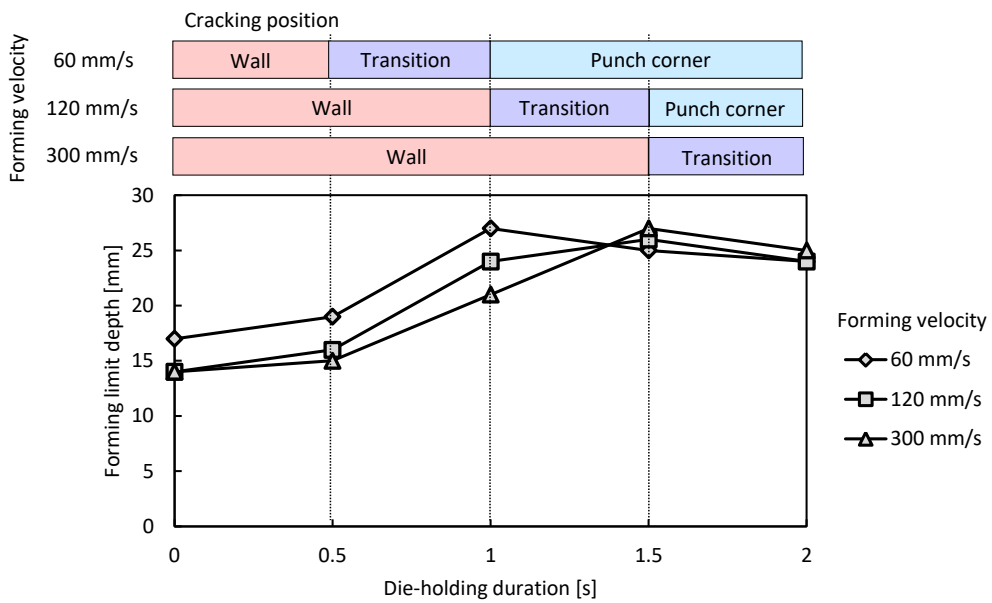


Figure 5. Calculated values of the forming limit depth.

4. Experimental demonstration

In this section, the formability improvement effect was experimentally verified by using a 1.0 mm thick aluminum alloy sheet (equivalent to A6016-T4) to form the square-shaped closure panel model depicted in Figure 6a. As a reference, Figure 6b shows the panels deep drawn at room temperature from mild steel (SPC270D) and aluminum alloy (equivalent to A6016-T4) sheets with thicknesses of 1.0 mm using the same die set. This model was successfully deep drawn from the mild steel sheet without cracks; however, in the case of the aluminum alloy sheet, cracks were formed in the wall area.

4.1. Experimental conditions

This experiment contained the following steps:

(i) Heating / transport of the blank sheet: After heating the blank sheet in a furnace at 560 °C for 360 s, it was transported to the die-set in 12 s.

(ii) Temperature distribution produced by die-holding: The blank temperature at the start of the die-holding step was set to 420 °C. The heated blank sheet was sandwiched between the blank holder and the upper die to obtain a temperature distribution. The die-holding duration was varied between 0, 1.0, and 2.0 s. Die-holding for 0 s corresponded to the standard hot stamping procedure.

(iii) Forming / evaluation: The forming depth was set to 28 mm, and the formability of the alloy sheet was evaluated by verifying the existence of cracks after forming and measuring the sheet thickness. The blank holder pressure was set to 9.2 MPa, and the forming velocity was 300 mm/s. The punch was coated with DLC and no lubricant was used. A 3000-kN servo press (SDE - 3030SF, AMADA) was used for this experiments.

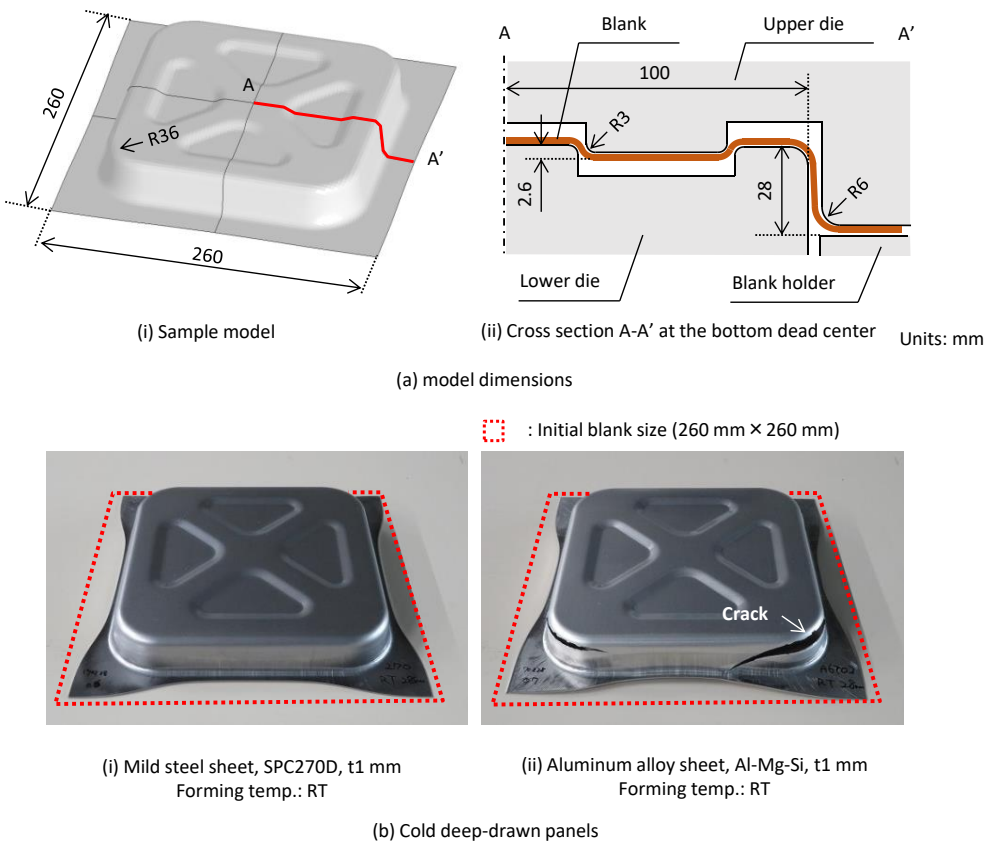


Figure 6. Sample closure panel model: (a) dimensions and (b) cold deep-drawn panels.

4.2. Experimental results and discussion

The result obtained under the standard hot stamping condition (without die-holding duration) is displayed in Figure 7a. It shows that the formation of cracks occurred in the wall area and that the forming limit depth is 14 mm, which is two times smaller than the maximum depth of 28 mm.

The experimental results obtained after applying the die-holding step are shown in Figures 7b and c. No cracks were formed in the wall area under both conditions. However, at a die-holding duration of 2.0 s, cracks were observed around the corner of the punch-top area. In this experiment, two hypotheses were verified: (i) strain concentration in the wall area can be avoided by longer die-holding duration, and (ii) the forming limit depth decreases with excessive die-holding duration.

Finally, the increased deformation of the punch-top area due to die-holding step was confirmed. The thickness distribution obtained after the forming test is shown in Figure 8. At the standard hot stamping condition, the sheet thickness of the punch-top area remained thicker than 0.85 mm. However, after die-holding for 1.0 s, the sheet thickness around the punch corner was reduced to 0.4 mm.

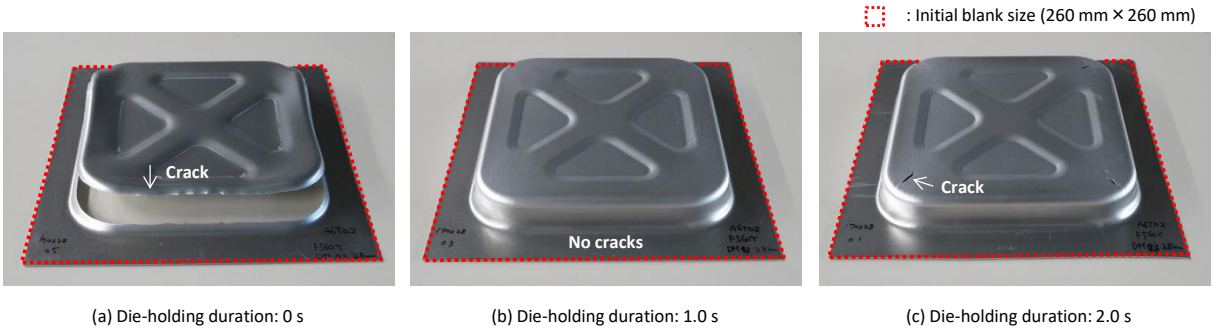


Figure 7. Hot-stamped panels at the depth of 28 mm: (a) without die-holding duration, (b) with die-holding for 1.0 s, and (c) with die-holding for 2.0 s.

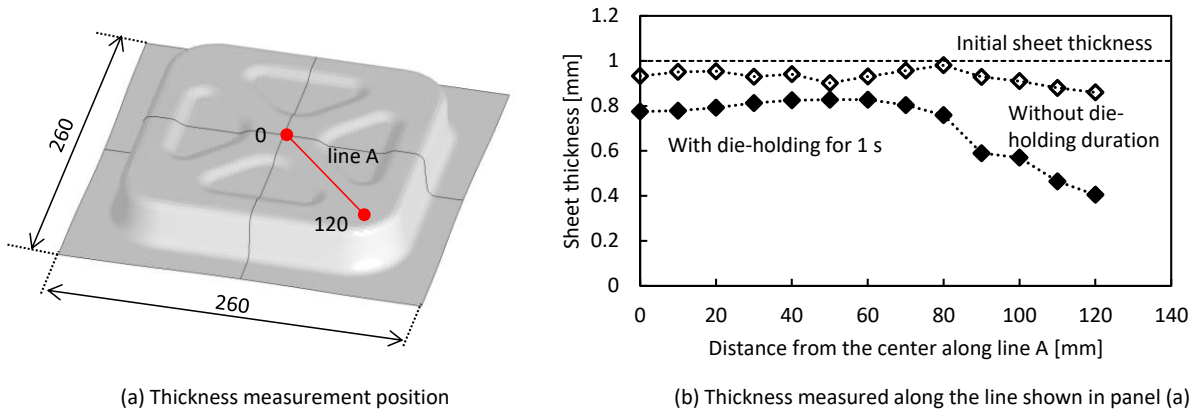


Figure 8. Sheet thickness after the forming step: (a) thickness measurement position and (b) thickness measured along the line shown in panel (a).

In addition, at a die-holding duration of 1.0 s, the model shape can be completely stretch-formed without cracking; therefore, the blank sheet size could be minimized in the flange area. For example, in the deep-drawing forming process depicted in Figure 6b, the square with a size of 260 mm is required to form a deep shape by drawing the material from the flange area. In contrast, using the proposed press motion control technique, the amount of material in the flange area can be reduced; therefore, if the flange size is set to 10 mm, the required size of the square blank sheet would be 240 mm. As a result, the material size is reduced by 15%.

The process conditions for maximizing the forming limit depth are discussed below. During the square cup forming test conducted in this study, the resulting temperature distribution can apparently

deform both the wall and punch-top areas with a good balance. In other words, if the cooling of the wall area is insufficient, the strain concentrates in the wall area; however, if cooling is excessive, the strain concentrates in the punch-top area. The reason for the shorter optimal die-holding duration at the lower forming velocity is the temperature decrease observed during the forming step. It means that die-holding duration should be determined with consideration of temperature decrease both for the die-holding step and the forming step. Although the stretch formability was evaluated in this paper, higher forming limit depth can be expected by a stretch-drawing forming process with adjusting the blank holder pressure. In addition, since the friction behavior is one of the most important factors that influences the formability, higher formability can be expected by using a lubricant.

Although the tendency of the formability improvement effect by the press motion control technique was able to be expressed under the forming simulation conditions of this paper, further discussion on material properties to be considered for simulation is required to more accurately reproduce the experimental deformation behavior.

5. Conclusions

In this study, a press motion control technique was proposed to suppress the local deformation during the hot stamping of aluminum alloy sheets. The potential cracking area near the walls was cooled and hardened by holding the heated blank sheet between the blank holder and the upper die before the forming step. The proposed technique was applied to the square cup forming of a 1.0 mm thick 6000-series aluminum alloy sheet. As a result, the forming limit depth was increased to twice deeper depth through 1.0 s die-holding duration before the forming step as compared to that obtained via the standard hot stamping procedure without press motion control. This result suggests that the proposed process can minimize the blank size since the square cup shaped panel was formed without drawing the material from the flange area.

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