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Warm Forming of Aluminum Alloys

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Abstract

This study examines the application of warm forming of aluminum alloys for automotive panels. Warm forming improved not only the deep-drawing formability of aluminum alloys but also their shape fixability in hat-shaped bending. With increasing BHF, the shape fixability improved further and was comparable to that of steel. Although Molybdenum disulfide have been used in warm forming so far, oil for the exclusive use of this forming is developed. The amount of dynamic recovery reduces with increasing forming rate. A coupled thermo–mechanical finite-element analysis is an efficient method that can be used for forming simulation.

1 Introduction

In recent years, automotive panels have been fabricated from aluminum alloys in place of steel. In response to the ever-growing need to reduce the weight of car bodies, the use of aluminum alloys has been increasing. The main properties required of materials for automotive panels are strength and formability. Regarding formability, it is known that the ductility of aluminum alloys is inferior to that of conventional mild steels. For example, the annealed A5052 alloy—a standard of the 5000-series aluminum alloys, which are already in use for automotive panels—has a total elongation (measured in a tensile test) of 25%,[1] far smaller than the 40% - 49% for mild steels (JAC270D). Because of such poor formability, when an aluminum alloy is to be used as a material for automotive panels, it is necessary to set a certain limit to the shape of the panel to which the aluminum alloy is applied. Thus, the scope of application of aluminum alloys in the automotive industry is still limited.

With the aim of improving the formability of aluminum alloys to expand the scope of their application, several new forming methods that may be used in place of the conventional cold forming process have been studied. One of them is hot blow forming, which was developed to achieve higher ductility in aluminum alloys than that attained in conventional cold forming. In hot blow forming, the aluminum alloy is first heated and then subjected to stretch forming using a high-pressure gas. With this method, it is possible to fabricate aluminum alloys into complicated shapes that cannot be obtained by the conventional cold forming process.[2] In addition, hot blow forming offers good stretch formability for aluminum alloys whose Mn and Cr contents are appropriately adjusted. Another forming method that utilizes heat is the warm forming method. Instead of heating the aluminum alloy as in the previous method, this method uses a previously heated tool to deep-draw the material. Unlike hot blow forming, warm forming does not impart high ductility (stretch formability) to the material. However, for a general-purpose aluminum alloy, warm forming offers better deep drawability than cold forming.[3-9]

Warm forming has not yet been applied in automotive parts production. However, since it can be carried out using a standard cold press, the investment required to implement it will not be very large. It is quite possible, therefore, that this forming method will be put into practical use to manufacture automotive parts in the near future.

In this report, the author describes the main characteristics of warm forming technology applicable to aluminum alloy sheets and discusses the major problems involved in putting this technology into practical use. The warm forming process is outlined and the enhancement of shape fixability and deep drawability attainable by warm forming is explained. Regarding the problems associated with the warm forming technology, this report focuses on three issues: a lubricant developed specifically for use in warm forming, clarifying the influence of the forming speed, and developing technology for simulating the warm forming process.

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2. Method of Warm Forming

Warm forming is a deep-drawing method that uses a die and a blank holder, which are heated to a certain temperature by a heater or other means, and a punch, which is kept at room temperature by water cooling or other means, as shown in **Fig. 1**.[3-9] The blank, which is not heated beforehand, is clamped by the die and blank holder and subjected to deep drawing. In a deep-drawing test of A5182 alloy using a cylindrical die, the limiting drawing ratio (LDR) at room temperature was about 2.1. With a rise in the temperature of the die and blank holder, LDR increased continuously, reaching about 2.8 at 250°C.[7] In the case of A5083 alloy, the LDR at room temperature was also about 2.1, but it exceeded 2.8 at 200°C.[9] Thus, the deep drawability of aluminum alloys improves markedly when a heated die is used.

Fig. 2 shows the change in the temperature of the blank relative to that of the die/blank holder when the blank was clamped between the die and the blank holder (the punch was kept in contact with the blank). The punch used had a 75 mm^2 cross section and was kept at 25°C by water cooling. The blank was a 1 mm-thick, 150 mm^2 A5182 alloy sheet. The blank temperature was measured by a thermocouple embedded in the blank. The temperature of the blank at the interface with the punch was measured at the bottom of the punch making contact with the punch corner straight side section, and the temperature of the flange was measured at a point 15 mm from the center of the straight side section of the blank toward the blank center, that is, near the center between the flange end and the die shoulder.

The temperature of the flange was equal to that of the die/blank holder. On the other hand, the temperature of the blank in contact with the punch was not constant: it rose with the increase in die/blank holder temperature as a result of heat transfer from the die and blank holder. Because of the heat removal by the punch, the rise in the blank temperature was not as high as that in the flange temperature. Thus, the difference in temperature inside the blank widened with the rise in die temperature. It appears that the widening of the temperature difference caused the difference in the material properties of the blank to increase, which in turn helped enhance the deep drawability of the blank.

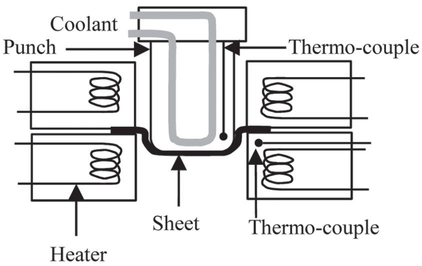


Fig. 1 Schematic illustration of warm forming

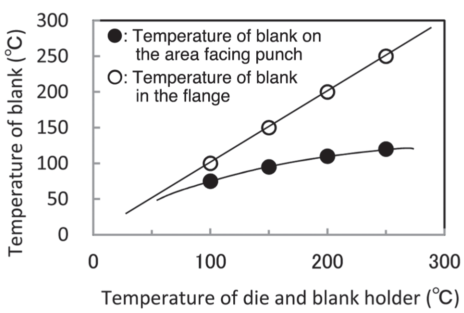


Fig. 2 Temperature dependence of blank

In warm forming, the material strength of the flange of the blank decreases as it is heated to a high temperature. As a result, the inflow resistance during deep drawing decreases. Ohwue et al. report that the enhancement of the deep drawability of the blank in warm forming is attributable entirely to the decline in deformation resistance and the increase in ductility of the flange.[7] On the other hand, Naka et al., who made a simple approximation of the deep drawability relative to the temperature of the vertical wall between the die end and punch shoulder, present a more detailed interpretation of the enhancement of the deep drawability based on the results of an elementary analysis.[9] In either interpretation, the enhancement of deep drawability is attributed to the decline in the deformation resistance of the flange and to the difference in stress in the punch shoulder or vertical wall.

3. Improvement of Shape Fixability

Improving the springback (shape fixability) of the blank is an important challenge in the forming of parts. Recently, inadequate shape fixability has become a problem with high-strength steel sheets that are being increasingly used in car bodies. Under that condition, various techniques to improve the shape fixability of the blanks have been studied. For example, by adopting a variable uplifted bead whereby the vertical wall tension is varied in the forming process, it is possible even for a high-strength steel of 690 MPa class to secure better shape fixability than that of a high-strength steel of 390 MPa class.[10] The shape fixability of the blank in warm forming has also been studied. For a 590 MPa high-tensile steel sheet, the tensile strength decreased at a temperature of 400°C, whereas the shape fixability measured in a hat-shaped bending test at the same temperature improved to the level of a 440 MPa steel sheet.[10] In its warm forming temperature region (100°C and above), the tensile strength of the aluminum alloy also decreased markedly compared with its tensile strength at room temperature.[7-9, 11] Therefore, it is expected that in warm forming of aluminum alloys, a similar improvement in shape fixability will be achieved. Hence, we carried out a warm hat-shaped bending test to study the improvement in shape fixability and the influence of the vertical wall tension due to the blank holding force (BHF).

The punch used was a square punch with a shoulder radius of 8 mm. The punch temperature was maintained at 25°C by water cooling. The temperature of the die and blank holder was varied between room temperature and 250°C so as to measure the shape fixability of the blank at different temperatures. The specimens used were a 5000-series aluminum alloy sheet containing 5.5wt% Mg and a mild steel sheet, both 1 mm in thickness. The width of the opening, the angle of the opening, and the radius of curvature of the vertical section of the hat-shaped part shown in **Fig. 3** were measured.

Figs. 4, 5, and **6** show the temperature dependence of the opening width, opening angle, and radius of curvature of the vertical section, respectively. In the figures, symbols ● and ■ indicate the values obtained with the hat-shaped part of the aluminum alloy under a BHF of 10 kN. With an increase in the die temperature, the opening width decreased and the shape fixability improved. The change in the two opening angles accompanying the temperature rise was smaller than that in the radius of curvature, suggesting that the improvement in shape fixability is mainly due to the increase in the ra-

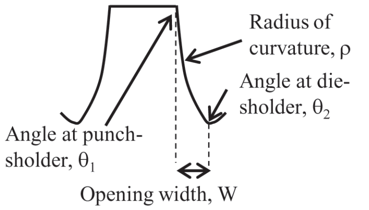


Fig. 3 Spring-back in hat-shaped bending

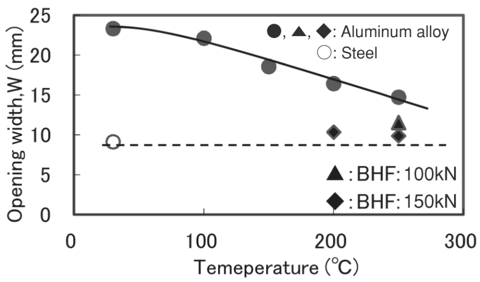


Fig. 4 Temperature dependence of opening width

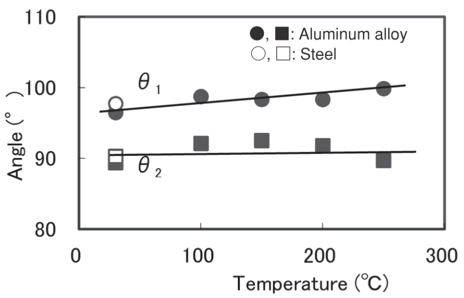


Fig. 5 Temperature dependence of angle

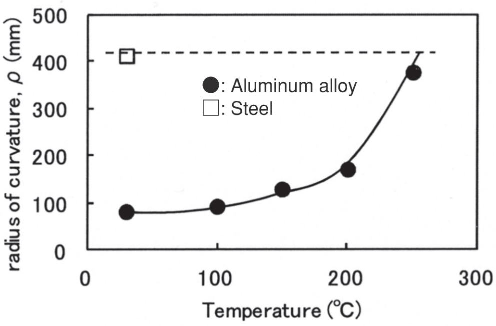


Fig. 6 Temperature dependence of radius of curvature

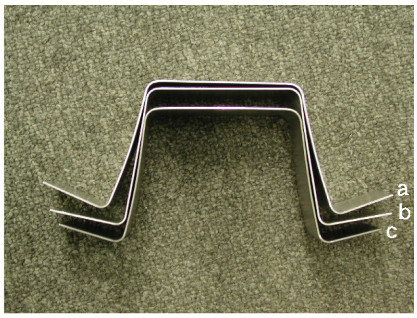
dius of curvature of the vertical section. During the hat-shaped bending, the vertical section undergoes a bending–unbending deformation at the die shoulder. After the deformation, a difference in stress occurs between the two sides of the vertical section. In the above warm hat-shaped bending, the difference in stress between the two sides of the vertical section after the bending–unbending deformation at the die shoulder was smaller than that measured in the cold hat-shaped bending. This could account for the improvement in shape fixability in warm hat-shaped bending.

In the above figures, symbols ○ and □ indicate the values obtained with the cold hat-shaped part of the mild steel sheet under a BHF of 10 kN. In cold hat-shaped bending, the shape fixability of the aluminum alloy sheet is inferior to that of the mild steel sheet. In warm hat-shaped bending, however, the difference in the opening width between them decreases. From Figs. 5 and 6, it can be seen that the difference in shape fixability between the aluminum alloy sheet and the mild steel sheet in the cold hat-shaped bending is mainly due to the difference in the radius of curvature of the vertical section. **Photo 1** shows the cold and warm hat-shaped parts of the aluminum alloy and the cold hat-shaped part of the mild steel, all obtained under a BHF of 10 kN. The radius of curvature in the warm forming is larger than that in the cold forming and is close to the radius of curvature of the cold hat-shaped part of the mild steel sheet. However, even in warm forming with a die temperature of 250°C, the shape fixability of the aluminum alloy sheet is inferior to that of the mild steel sheet in cold forming.

In Fig. 4, symbols ▲ and ◆ indicate the opening widths of the hat-shaped parts of the aluminum alloy sheet under BHFs of 100 kN and a BHF of 150kN, respectively. It can be seen that the shape fixability of the aluminum alloy sheet can be made comparable to that of the mild steel sheet by applying warm hat-shaped bending and by increasing BHF, thereby giving additional tension to the vertical section. **Photo 2** shows the warm hat-shaped parts of the aluminum alloy obtained under BHFs of 10 kN and 150 kN, respectively, and the cold hat-shaped part of the mild steel sheet obtained under a BHF 10 kN. It can be seen that increasing BHF increases the radius of curvature of the warm hat-shaped part of the aluminum alloy

a: Aluminum alloy in cold forming
b: Aluminum alloy in warm forming at 250°C
c: Steel in cold forming

Photo 1 Hat-shaped bending samples



a: Aluminum alloy in warm forming at 10kN in BHF
b: Aluminum alloy in warm forming at 150kN in BHF
c: Steel in cold forming at 10kN in BHF

Photo 2 Hat-shaped bending samples

sheet.

From the above facts, it was found that in warm hat-shaped bending, the shape fixability of the aluminum alloy improved markedly. We believe that the major reason for this is that the difference in stress between the inside and outside of the vertical section after the bending–unbending deformation decreases, which in turn causes the radius of curvature of the vertical section to increase. It was also found that by increasing BHF to give additional tension to the vertical section, the shape fixability of the aluminum alloy could be made comparable to that of mild steel sheet. It should be noted, however, that increasing BHF increases the inflow resistance and thereby causes the deep drawability of the blank to decline. In practice, it is considered effective to either provide beads or set the variable bead that was proposed in the discussion on the use of high-tensile steel sheets, although the latter involves a considerable amount of investment.[10)]

4. Applying Warm Forming: Problems and their Solutions

4.1 Lubricants

There are several problems that must be solved before warm forming technology can be put into practical use. One of them is the absence of a lubricant developed specifically for use in warm forming. Formerly, an aqueous solution of industrial soap in which molybdenum disulfide or its powder is dispersed was used as a substitute for a lubricant.[6-9)] If a purpose-made lubricant becomes available, the existing cleaning and degreasing processes could be utilized, and hence, the investment needed to implement warm forming in the manufacturing sector could be reduced significantly. In addition, a purpose-made lubricant could be applied and removed more easily than the conventional molybdenum-disulfide-based lubricants.

The major properties required of a lubricant for specific use in warm forming are heat resistance and formability. If the existing cleaning and degreasing processes are to be utilized, degreasing ability is also required. Nippon Steel Corporation, Nippon Quaker Chemical, and Furukawa-Sky Aluminum have co-developed a lubricant for exclusive use in warm forming, which meets the above three requirements.

In order to secure better formability in warm forming than in cold forming, it is necessary to use a temperature of 150°C or higher. Therefore, the developed lubricant should display good heat resistance, formability, and degreasing ability at 150°C and higher temperatures.

The abovementioned newly developed lubricant contains fatty acid ester, synthetic hydrocarbon, antioxidant, phosphate ester, and emulsifier. It has a flashpoint of 262°C and a dynamic viscosity of 35 mm^2/s (at 40°C).

Using the new lubricant, we carried out a warm forming test of an A5182 alloy square shell. The punch had a 78 mm^2 cross section and was kept at a constant 25°C by means of water cooling. The die and blank holder temperature was maintained at room temperature in cold forming and at 200°C in warm forming. In the test, the maximum blank size that could be deep-drawn without any fracture of the blank and without any wrinkling of the flanges was determined. The maximum blank size was 120 mm square at the die temperature of 25°C and 160 mm square at the die temperature of 200°C (**Fig. 7**). Thus, it was confirmed that warm forming enhanced the formability of the blanks.

The degreasing ability of the lubricant was evaluated as follows. First, using a brush, the new lubricant designed for warm forming use

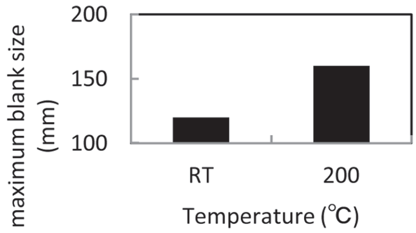


Fig. 7 Deep-drawing formability using lubricant oil

was applied to both surfaces of an A5182 alloy sheet at a coating weight of 0.5 - 1.0 g/m^2. Next, the alloy sheet was kept at 200°C for 4 min with the surfaces covered with a sheet of aluminum foil to prevent the lubricant from dispersing during the heating process. The alloy sheet was then cooled down to room temperature and immersed in a 40°C degreasing solution for 2 min. Finally, the alloy sheet was washed in a water spray for 30 s. Immediately after that, it was set upright and kept in that position for 30 s. The wetted area on each of the sheet surfaces was visually checked. The pH value of the alkaline degreasing solution (FC-E2082 of Nihon Parkerizing) was adjusted to pH 11.0 by blowing carbon dioxide into the solution. In a visual check, the wetted area was found to cover more than 90% of the surface area. Therefore, the new lubricant was judged to have good degreasing ability under the above test conditions.

As described above, it was demonstrated that warm forming using the new lubricant was practical. It should be noted, however, that since the degreasing conditions differ according to the automotive production line, putting warm forming into practical use requires adjusting the properties of the lubricant or developing a new lubricant suitable for the production line.

4.2 Influence of the forming speed

In order to secure high productivity in warm forming, it is necessary to understand the relationship between forming speed and formability.

It has been reported that in a warm deep-drawing test of A5083 alloy, LDR increased with temperature rising to 150°C or higher, but the rate of LDR increase decreased as the forming speed was increased.[9)] A similar tendency was observed with A5182 alloy.[8)] **Fig. 8** shows the temperature dependence of the tensile strength of A5182 alloy for different strain rates. At all strain rates, the tensile strength decreased sharply with rising temperatures above 100°C, whereas it increased with the rise in strain rate regardless of the temperature. In warm forming, the reduced high-temperature strength caused the inflow resistance at the flange to decrease, which in turn enhanced deep drawability. This indicates that the decline in deep drawability with the increased forming speed is due to the in-

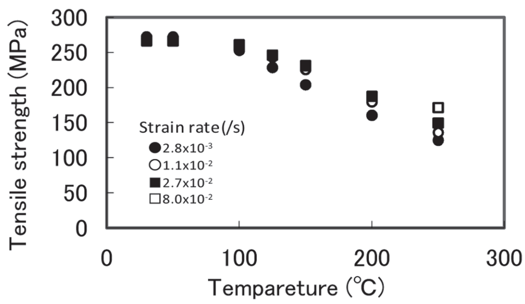


Fig. 8 Temperature dependence of tensile strength

crease in tensile strength caused by the rise in strain rate.

Ayres studied the temperature and strain rate dependence of the tensile properties of Al-Mg-based alloys containing different amounts of Mg and reported that the dependence of high-temperature tensile strength on strain rate is because of dynamic recovery.[11] Thus, it is considered difficult to inhibit the decline in LDR due to higher forming speeds by means of material control. In order to secure high productivity in actual warm forming, the author considers it necessary to determine the highest forming speed that permits forming a blank of specific shape without causing it to fracture.

4.3 Simulation technology for warm forming

When designing parts and setting their manufacturing conditions it is important to determine the formability of those parts and to be able to predict the condition of the formed parts by computer-aided simulations. In order to put warm forming into practical use, it is necessary to establish the technology for simulative calculations for warm forming.

One thing to consider in warm forming is how to handle the conduction of heat within the blank. During warm forming, the temperature of the blank interior is not uniform. Moreover, as the forming progresses, the temperature distribution inside the blank changes since the flange flows to the vertical section that is not heated. Thermal–mechanical coupling analysis is a technique that calculates the temperature of each element in each of the forming processes and uses the material characteristic values associated with the individual temperatures to produce the simulations; hence, it is considered suitable for simulations of warm forming. Therefore, we discuss the applicability of a thermal–mechanical coupling analysis in simulative calculations for warm forming.

The punch used was a square punch having a 78 mm^2 cross section. The die/blank holder temperature was set at 200°C. The forming speed was 5 mm/s and BHF was 10 kN. For lubrication, the newly developed lubricant for warm forming described in section 4.1 was used. The blank was a 1-mm-thick 140 mm^2 A5182 alloy sheet. With a shell formed to a height of 25 mm, its wall thickness was compared with the thickness obtained by simulative calculations. Note that under the above forming conditions, the blank cannot be formed to a height of 25 mm by cold forming without causing the blank to fracture.

For the above simulative calculations, the thermal–mechanical coupling analysis subroutine[12] of LS-DYNA (product of Livermore Software Technology Corporation) was used. With a blank mesh size of 1 mm, the sheet thickness within the blank was evaluated by using a 1/4-scale model. The tensile characteristic (stress-strain curve) that was used in the calculations was the stress-strain diagram between room temperature and 200°C, obtained with the same blank at a tension speed equal to the forming speed. **Fig. 9** shows the contour map of wall thicknesses of a shell obtained by simulative calculations. In the calculations, the parts that were very likely

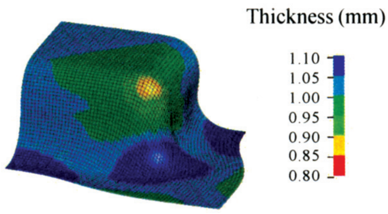


Fig. 9 Contour map of thickness in square shell calculated by forming simulation

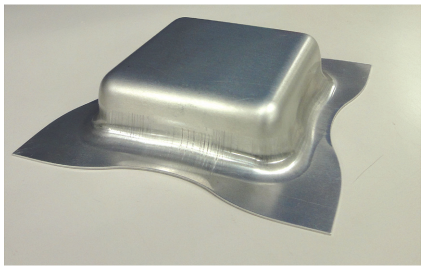


Photo 3 Square shell in warm forming

to fracture were right under the punch corners, where the wall thickness was about 0.8 mm. **Photo 3** shows the actual shell formed. The shell parts having the smallest wall thickness were right under the punch corners, as indicated by the calculation results, and the smallest wall thickness was also about 0.8 mm.

Thus, in a test of simple square shell deep drawing, the fracture-sensitive parts of the warm-formed shell were in good agreement with those obtained by the thermal–mechanical coupling analysis. Although this analysis is considered as one of the simulative calculation methods applicable in warm forming, putting it into practical use will require setting criteria for assessing fractures and improving the accuracy of the calculation of the distribution of thickness and the amount of inflow, etc., to the level that has been attained for cold forming.

5. Conclusion

In this report, we discussed warm forming as a technology for improving the formability of aluminum alloys and presented our studies on the enhancement of shape fixability by warm forming and the major problems involved in putting warm forming into practical use. The results of our study showed that warm forming improves not only the deep drawability of the blank but also the shape fixability of the blank in hat-shaped bending. With an increase in the forming temperature, the opening width in the hat-shaped bending decreased. The decrease in the opening width was mainly due to the increase in the radius of curvature of the vertical section caused by the temperature rise. It was also found that in cold hat-shaped bending, the shape fixability of the aluminum alloy sheet is inferior to that of mild steel sheet, but that the shape fixability of the aluminum alloy in hat-shaped bending can be made almost comparable to that of mild steel by adopting warm forming and by increasing BHF to give additional tension to the vertical section of the blank. With respect to the lubrication of the blank—another problem in practical application of warm forming—a new lubricant for use specifically in warm forming has been developed. On the other hand, in warm forming, the deep drawability of the blank declines as the forming speed is increased. This is due to a decrease in the amount of dynamic recovery of the blank. Therefore, it is considered difficult to control the decline in LDR attributed to the increase in forming speed by improving the properties of the material. The results of a simple warm forming test of square shells confirmed that thermal-mechanical coupling analysis was a suitable method for simulative calculations in warm forming. We expect that the newly developed lubricant and simulative calculations for warm forming will help promote the practical application of warm forming technology.

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