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Effects of Temperature and Blank Holding Force on Biaxial Forming Behavior of Aluminum Sheet Alloys

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Biaxial forming behavior is investigated for three aluminum sheet alloys (Al 5182 containing 1% Mn (5182 + Mn), Al 5754, and 6111-T4) using a heated die and punch in the warm forming temperature range of 200-350 °C. It is found that, while all three alloys exhibit significant improvement in their formability compared with that at room temperature, the non-heat-treatable alloys 5182 + Mn and 5754 give higher part depths than that of heat-treatable 6111-T4. The formability generally increases with decreasing BHP (BHP), but increasing the forming temperature and/or BHP minimizes the wrinkling tendency and improves the forming performance. The stretchability of the sheet alloys increase with increasing temperature and increasing BHP. For the alloys and forming conditions involved in the current study, the formability, measured in terms of part depth, comes mainly from the drawing of metal into the die cavity, although stretching effects do influence the overall forming behavior. The optimum formability is achieved by setting the die temperature 50 °C higher than the punch temperature to enhance the drawing component. Setting the die temperature higher than the punch temperature also improves the strain distribution in a part in such a manner that postpones necking and fracture by altering the location of greatest thinning.

Keywords aluminum alloys, blank holding pressure, isothermal/gradient heating, strain distribution, warm biaxial forming

1. Introduction

Despite the high strength/weight ratio offered by aluminum (Al) alloys, their poor formability at room temperature compared with steel has created a major barrier to their use in large industries like the automotive industry.[1] One way of overcoming the poor formability of Al is to use a higher forming temperature in the warm forming temperature range (i.e., about 200-350 °C). Warm-forming studies date back to 1946 when Finch et al.[2,3] investigated the deep-drawing behavior of various Al alloys in the both annealed and hardened tempers, and their results showed that significant improvement in the drawability could be achieved even at a relatively moderate temperature of 150 °C. The oil crisis in 1973 called for an improvement in the fuel economy of passenger automobiles, providing an impetus for further research on the formability of lightweight Al alloys. Subsequently, warm-forming techniques were used at General Motors[4,5] and Chrysler[6] to improve the formability of Al sheet alloys, and it was demonstrated that deep-drawn automotive components (e.g., inner door panels and V-6 oil pans) could be produced at commercial press rates. However, there were no follow-up studies on the warm stretch forming of Al alloys in the years that followed. In recent years, the interest in the use of Al alloys in the automotive industry has greatly increased as efforts have been made to improve fuel economy, safety, resource conservation, and environmental friendliness. Thus, more attention from the automotive industry has been paid to the use of Al alloys.[7] Systematic investigations on the warm forming of Al alloys are needed to clarify and quantify the various complicated issues of formability, and the effects of various material parameters and extrinsic forming factors.

Formability depends on both the intrinsic or constitutive properties of the sheet metal and the extrinsic factors involved in a forming operation. Regarding the properties of the material, experimental[8-11] and analytical[12-16] investigations on forming behavior confirm that strain hardening and, especially, strain rate hardening, have strong influences on thinning and forming limits. Since these properties depend on the microstructural characteristics of the material, formability is found to be influenced by alloying,[17] grain size,[18] precipitation treatment,[19] and texture.[20] Extrinsic factors (e.g., mechanical and environmental factors) also have significant, sometimes even more dominant, effects on the formability. Typical extrinsic variables include temperature gradient,[2,3,21] forming rate/strain rate,[8,9,11,17,22] blank holding force,[23] tooling geometry,[2,24] lubrication,[2-6,25] and deformation history.[11,26]

In the present investigation, the warm biaxial forming behavior is studied for two strain-hardenable Al alloys (Al 5754 and Al 5182 + 1% Mn) and a precipitation-hardenable Al alloy (Al 6111-T4). The selection of these materials was guided by their existing usage in the automotive industry. The first two alloys were given a thermomechanical treatment to develop a fine grain size. The formability study focused on the effects of extrinsic conditions, namely, temperature gradient and blank holding pressure (BHP), on the forming performance of the sheet alloys.

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2. Experimental

The sheet materials used for the biaxial forming study were the strain-hardenable Al alloys Al 5754 and Al 5182 + Mn (modified by adding 1% Mn to Al 5182), and the precipitation hardenable alloy Al 6111 in the naturally aged (T4) condition. The modification of commercial alloy 5182 with an addition of about 1% Mn as a dispersoid former was expected to enhance the strain rate sensitivity of the flow stress and to refine the grain structure. The chemical compositions of the three alloys are listed in Table 1. The as-received 5xxx alloys were cold-rolled from an initial thickness of 5.3 mm for Al 5754 and 7.5 mm for Al 5182 + Mn to a final thickness of 0.9 mm. This resulted in reduction ratios of 83% for Al 5754 and 88% for Al 5182 + Mn. Alloys 5754 and 5182 + Mn were formed in the as-cold-rolled condition in which some initial recovery occurred during heating to the forming temperature. Alloy 6111 was given a cold-rolling reduction of 74%, followed by a solution heat-treatment at 532 °C for 30 min, water quenching, and natural aging for more than 5 days (i.e., formed under the condition of T4). The starting sheets were cut to a rectangular blank sample size of L = 200 mm and W = 140 mm, with L oriented in the rolling direction. Prior to forming, the surface of these blanks were marked with a square grid pattern by means of an electrochemical method with a cell size of 1.27 × 1.27 mm. For lubrication at elevated temperatures, the blanks were sprayed with a thin layer of boron nitride and baked. This lubricant could be easily removed by washing in water after the forming operation.

To simulate commonly observed biaxial parts and die edge radii, forming tests were performed on a heated rectangular die-punch device that was designed at the University of Michigan. The rectangular punch geometry offered edge and corner radii similar to those found in actual stamping operations. The cross-sectional area was 110 × 50 mm for the die cavity, and 100 × 40 mm for the punch. Both the die edge and the punch had a radius of about 5 mm. Upper and lower blank holding plates and the punch are schematically shown in Fig. 1. The die and the punch were heated with embedded heating elements. Thermocouples were inserted into different heating areas of the die and the punch, and temperature was controlled within ±4 °C by using proportional integral derivative (PID) controllers. The punch-die assembly was mounted on an Instron-1116 (Canton, MA) testing machine with 250 kilo Newton (kN) capacity. The punch was moved by displacing the crosshead. The upper die plate was maintained in a fixed position in the die apparatus, while the lower die plate was moved upward by using the pistons of three ENERPAC (Milwaukee, WI) hydraulic cylinders to clamp the sheet between them. The die and the punch were preheated to the desired temperature(s), and then the sheet sample was put onto an aligned, centrally located position marked on the lower die. A specified BHP was then applied rapidly to the sheet resting between the upper and the lower die plates to tightly clamp it. The forming test temperature was selected to lie between 200 and 350 °C, with room temperature tests used as the baseline reference. Thermal calibration was performed by attaching thermocouples to test specimens and closing the dies on them. It was found that thermal equilibrium could be reached in just a few seconds. The punch advance speed was fixed at 10 mm/s, the maximum speed attainable in this machine. This provided local strain rates in the small test sample close to the commercial stamping strain rate. The fast heat transfer and punch movement prevented significant microstructural change in the sheet metal during forming, and this was confirmed by metallurgraphy and mechanical testing after sheet forming. Load-versus-punch displacement curves were recorded using an X-Y data recorder, and the data were used to obtain the depth of a formed part at peak load (where necking occurred on the sheet). This part depth was used as a measure of formability.

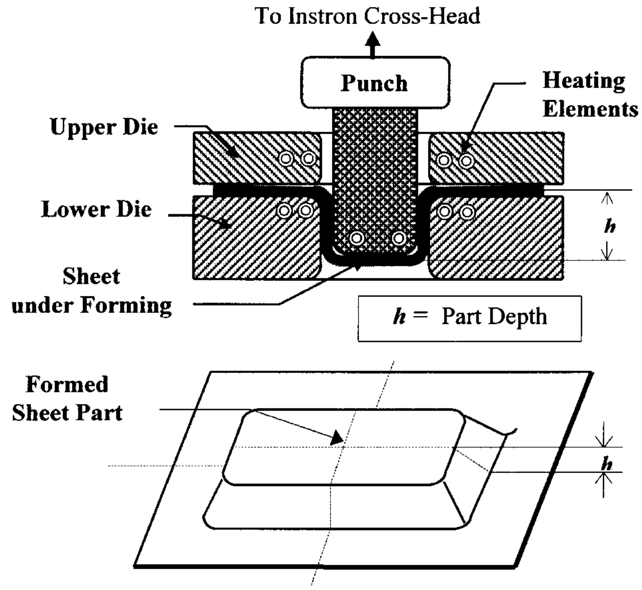

Fig. 1 Schematic diagram of the punch-die configuration, with a definition of part depth

Table 1 Chemical Compositions of Sheet Alloys Used

Alloy	Si	Mg	Cu	Mn	Fe	Al
5754	0.2	3.1	0.04	0.25	…	Balance
5182 + Mn	0.07	4.05	0.03	1.26	0.22	Balance
6111	0.5–0.9	0.6	…	…	…	Balance

To evaluate the magnitude and distribution of the forming strain, the grid size (before and after forming) in areas of interest was measured by a video camera and digitally processed by a computer program (Scion Image, Frederick, MD) for the formed rectangular parts. Engineering principal strains (e_1, e_2) were calculated for both major (longitudinal) and minor (transverse) dimensions.

3. Results and Discussion

3.1 Temperature Dependence of Formability

The value of punch displacement at peak load on the load-versus-punch displacement curve was determined to represent the maximum part depth before crack initiation (hereafter referred to as part depth). In Fig. 2, part depth is plotted against

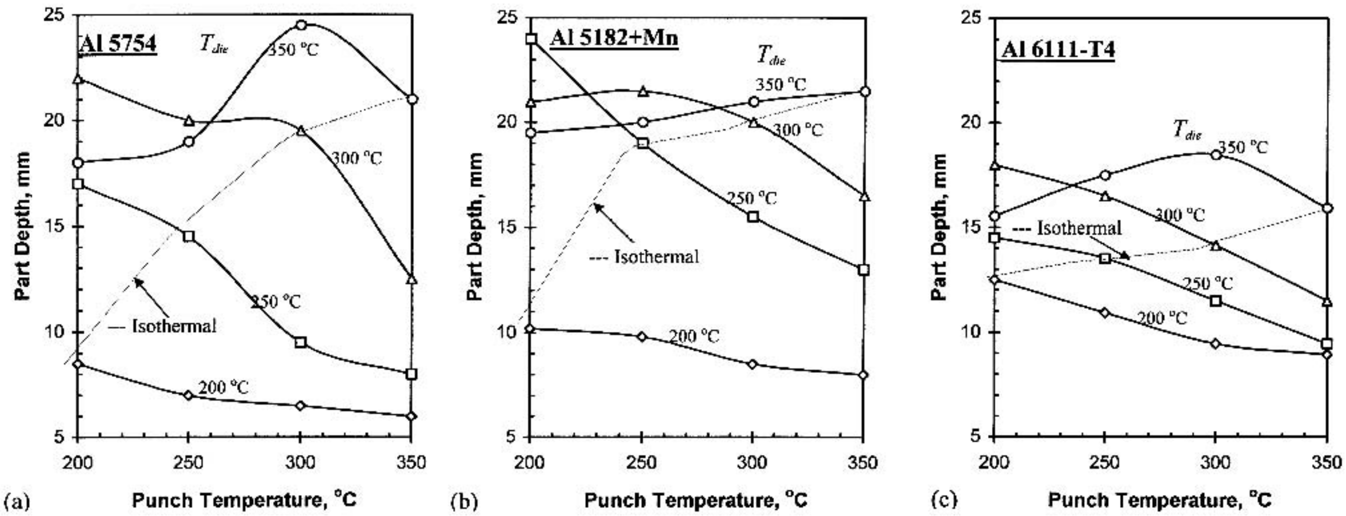

Fig. 2 Variation of part depth with die and punch temperatures for Al sheet alloys of **(a)** 5754, **(b)** 5182 + Mn, and **(c)** 6111-T4. BHP is fixed at 1.1 MPa.

punch temperature at different die temperatures for the three sheet alloys, with alloys 5754 and 5182 + Mn in the cold-rolled conditions, and alloy 6111 in the T4 condition prior to warm-forming tests. The results are compared for a fixed BHP of 1.1 MPa. The data contain results for both isothermal conditions (dashed lines) and non-isothermal conditions (solid lines). Both punch temperature and die temperature are seen to influence part depth appreciably, and their effects do not follow a monotonic relation but depend on die-punch temperature combinations. By comparing these results with those of part depths at room temperature for the three alloys (2.5, 5.5, and 6 mm, respectively, for alloys 5182 + Mn, 5754, and 6111-T4), it is clear that warm forming significantly improves the part depths of these sheet alloys. Under isothermal conditions (i.e., die and punch at the same temperature), the increase in formability is essentially monotonic with increasing forming temperature. However, under non-isothermal conditions, several interesting and complicated effects are seen. At low die temperatures (i.e., below ~300 °C for alloys 5754 and 6111-T4, and below ~250 °C for alloy 5182 + Mn), part depth generally decreases with increasing punch temperature. For a given punch temperature, part depth still increases with increasing die temperature. Increasing punch temperature relative to die temperature causes an increase in the ratio of the material being stretched over the punch relative to the material being drawn into the die. Due to low stretchability at low temperatures, which has been attributed to lower strain rate sensitivity, the greater the extent of stretching, the sooner fracture initiates. In other words, the decrease in part depth with increasing punch temperature means that drawability of the metal cannot be effectively used, and its contribution to formability is reduced with increasing punch temperature. For higher die temperatures, part depth first increases with punch temperature, saturates at a maximum value, and then decreases. At these die temperatures (especially at 350 °C), if the punch temperature is maintained at a low level, it is also possible to have a part depth lower than that formed by using a lower die temperature. In the high die temperature range, the stretchability of the sheet metal near the die entry radius begins to play a more significant role than at lower die temperatures. The excessive thinning in this region can then cause fracture before more material can be drawn into the die. The temperature difference between die and punch (or the thermal gradient) can, thus, be an important factor for controlling the ratio of drawing relative to stretching.

To understand this effect more completely, the data from Fig. 2 are re-plotted against the parameter $\Delta T = T_d - T_p$ (Fig. 3), where T_d and T_p are the temperatures of the die and the punch, respectively. Given the fast heat transfer between die-sheet and punch-sheet contacts, ΔT reflects the corresponding temperature gradient between the circumferential (flange) and the central (cup) areas of the sheet being formed. When ΔT is below a somewhat critical value (dashed vertical line), a systematic single trend is found (i.e., for a definite die temperature, part depth increases with increasing ΔT). This critical ΔT is about 50 °C for alloys 5754 and 6111-T4, and 30 °C for alloy 5182 + Mn. This trend suggests a dominant role of drawing in this range of die-punch temperature combinations, where increasing the die temperature relative to the punch temperature increases the drawing contribution. As ΔT exceeds this critical value, the trend becomes almost opposite, revealing the importance of the stretchability of the sheet metal. This critical ΔT parameter may be used to control deformation during part fabrication to obtain the best warm-forming window. In Fig. 3, in the drawability-controlling range (left of the dashed line), increasing the die temperature relative to the punch temperature may be used to control a forming process since it promotes improved formability. It is important to note, however, that both punch and die need to be at the prescribed temperatures, and a fast heat transfer needs to be achieved between die-sheet and punch-sheet contacts to take advantage of this parameter. As far as the sheet alloys investigated in the present investigation, and within the present warm-forming temperature range, the optimum forming performance in terms of part depth is found to be achieved under a thermal gradient condition by setting ΔT at around 50 °C. This value may be affected by part geometry to some extent.

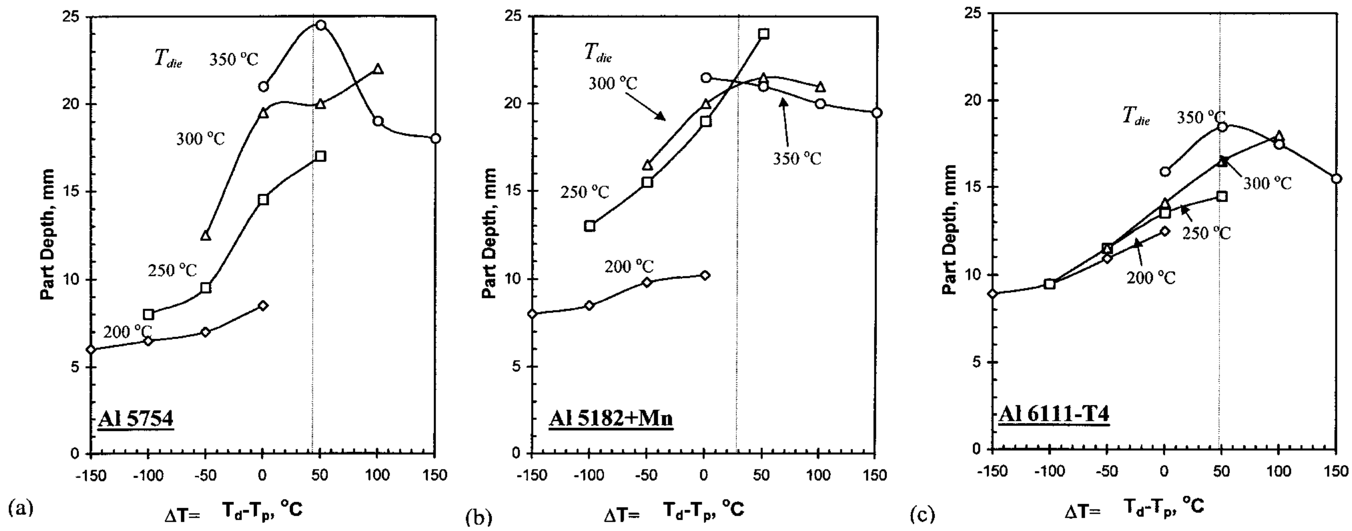

Fig. 3 Dependence of part depth on the die-punch temperature difference parameter, $\Delta T = T_d - T_p$, where T_d and T_p are die and punch temperatures, respectively, for Al sheet alloys **(a)** 5754, **(b)** 5182 + Mn, and **(c)** 6111-T4. BHP is fixed at 1.1 MPa.

Since microstructural change during forming can evidently influence the formability of sheet metal,[18-20] the possibility for change was minimized in the present investigation by using a thin sheet and a high punch speed. This eliminated the need for post-forming processing to recover required mechanical properties. However, the formability is strongly affected by alloy strain hardening, especially strain rate hardening,[8-16] which is a function of temperature. Consequently, the aforementioned dependence of formability on ΔT actually reveals the dependence of these deformation properties of the material on temperature in the respective areas of drawing and stretching.

As is summarized by the results in Fig. 2 and 3, for the two strain-hardening alloys 5754 and 5182 + Mn the formability of the former seems to be more sensitive to forming temperature than the latter. At die temperatures ≥300 °C, the part depth of alloy 5182 + Mn becomes quite insensitive to variations in punch and die temperature. While a high sensitivity of formability to forming temperature can provide some flexibility in tailoring the performance of the sheet metal, a low sensitivity means more ease in handling during processing. The selection of process conditions should be based on part complexity and/or the robustness of the manufacturing process used. For the three alloys studied, the formability of the heat-treatable alloy 6111-T4 is certainly inferior to the two strain-hardenable alloys (5754 and 5182 + Mn).

To understand the relative contributions of drawing and stretching during warm forming, detailed measurements have been made along the minor axis of the formed rectangular parts to determine how deep the sheet metal has been drawn into the die (i.e., the slip-in depth) and stretched (i.e., the stretch depth), respectively. The region of material drawn into the die is identified by the sliding (or rubbing) marks against the lubricant (BN) layer on the die radius. A slip-in depth, L_s, is defined on the schematic illustration of the part (Fig. 4) as the distance from the point where the sheet starts contacting the die entry radius to the point where it reaches the end point of contact on this radius. This part of the material also undergoes stretching as it is drawn into the die cavity. The stretch depth is defined as the elongation of the rectangular cup bottom and is obtained by measuring the distance from the part center point to the point of initial contact with the die entry radius (L_d in Fig. 4), less the original distance of this material (i.e., the number of etched grids within this distance times the original grid size).

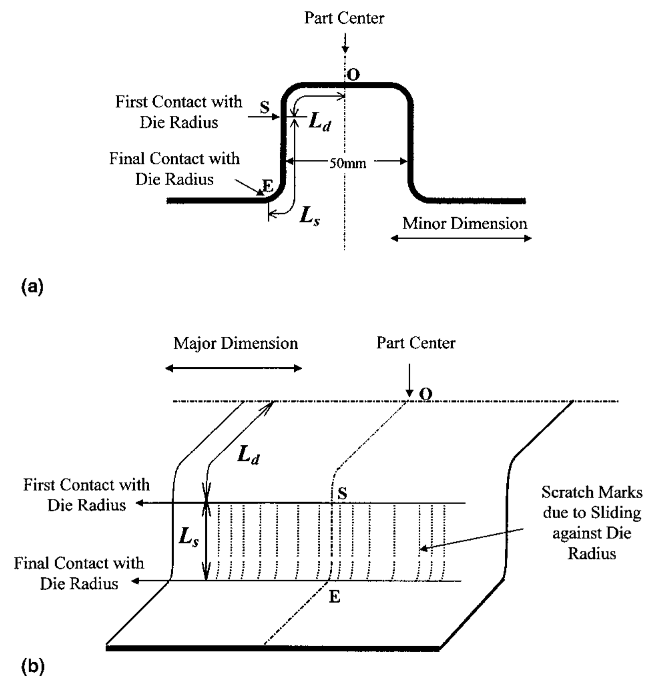

Fig. 4 Schematic diagrams showing the measurements of slip-in (draw-in) depth (L_s) and stretch depth ($L_d - N$a, where N is the number of grids between O and S, and a is the original grid size): **(a)** side view; **(b)** top view

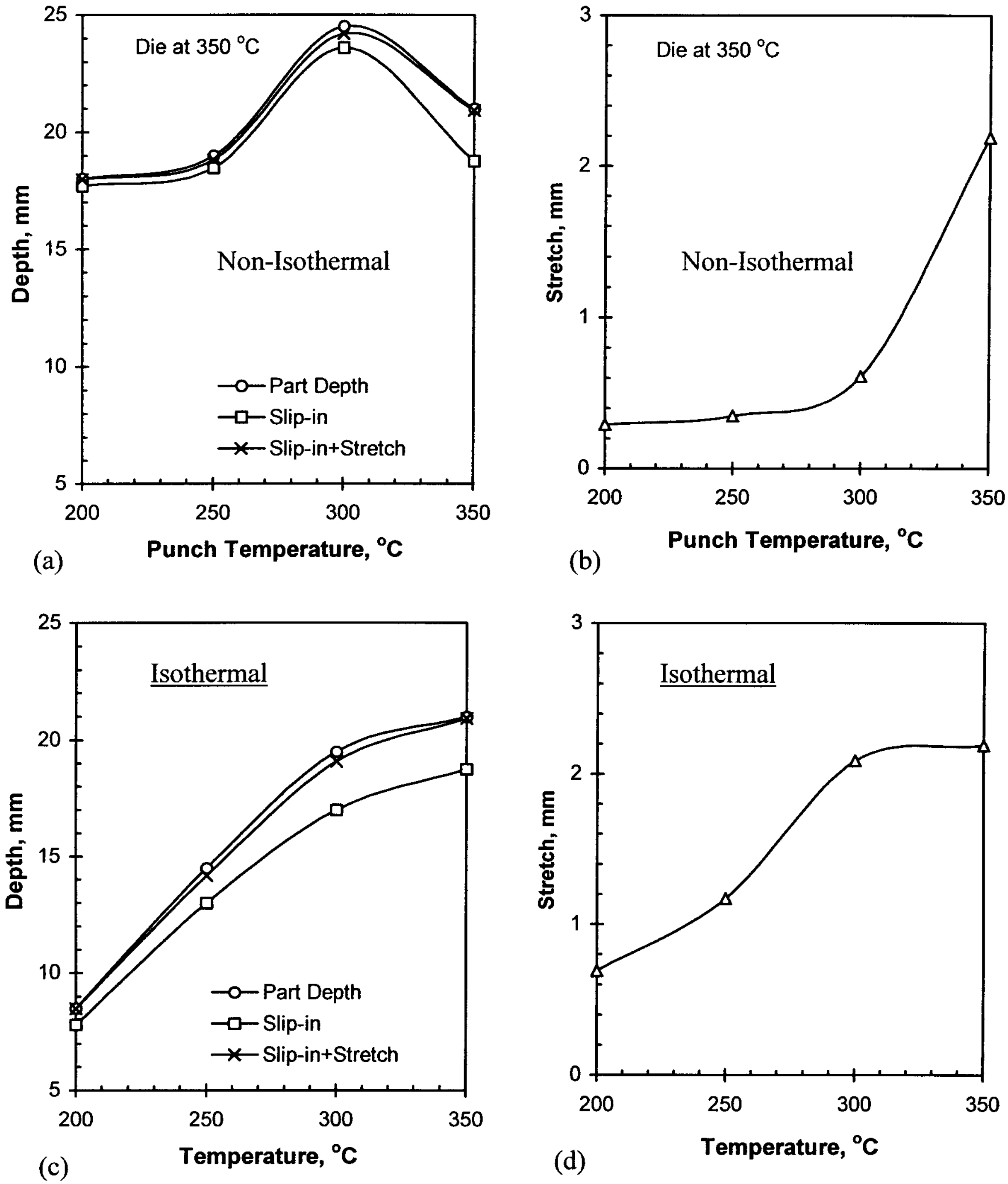

Fig. 5 Contributions of slip-in (draw-in) depth (**a**, **c**) and stretch depth (**b**, **d**) to part depth under conditions of thermal gradient (a, b) and isothermal heating (c, d) for alloy 5754 (BHP = 1.1 MPa; die width = 50 mm)

This depth is very close to the stretch depth, but it is not exactly the same value due to the contribution of the punch nose radius. With these measurements, slip-in depth and stretch depth are plotted with part depth (Fig. 5 and 6) to show how they contribute to part depth under different forming temperature conditions. Figure 5 shows the data for alloy 5754 under conditions of thermal gradient (Fig. 5a and b) and isothermal heating (Fig. 5c and d). While slip-in depth follows the same trend as that of part depth, stretch depth monotonically increases with increasing die and/or punch temperatures. It is found in Fig. 5 that under both heating conditions, slip-in depth contributes the most to part depth, especially when the forming temperature is low. For instance, at 350 °C, stretch depth attains its maximum value but still contributes only ~10% to part depth. This result would be expected to change with part geometry and part depth, but nevertheless drawing can be substantial. The sum of

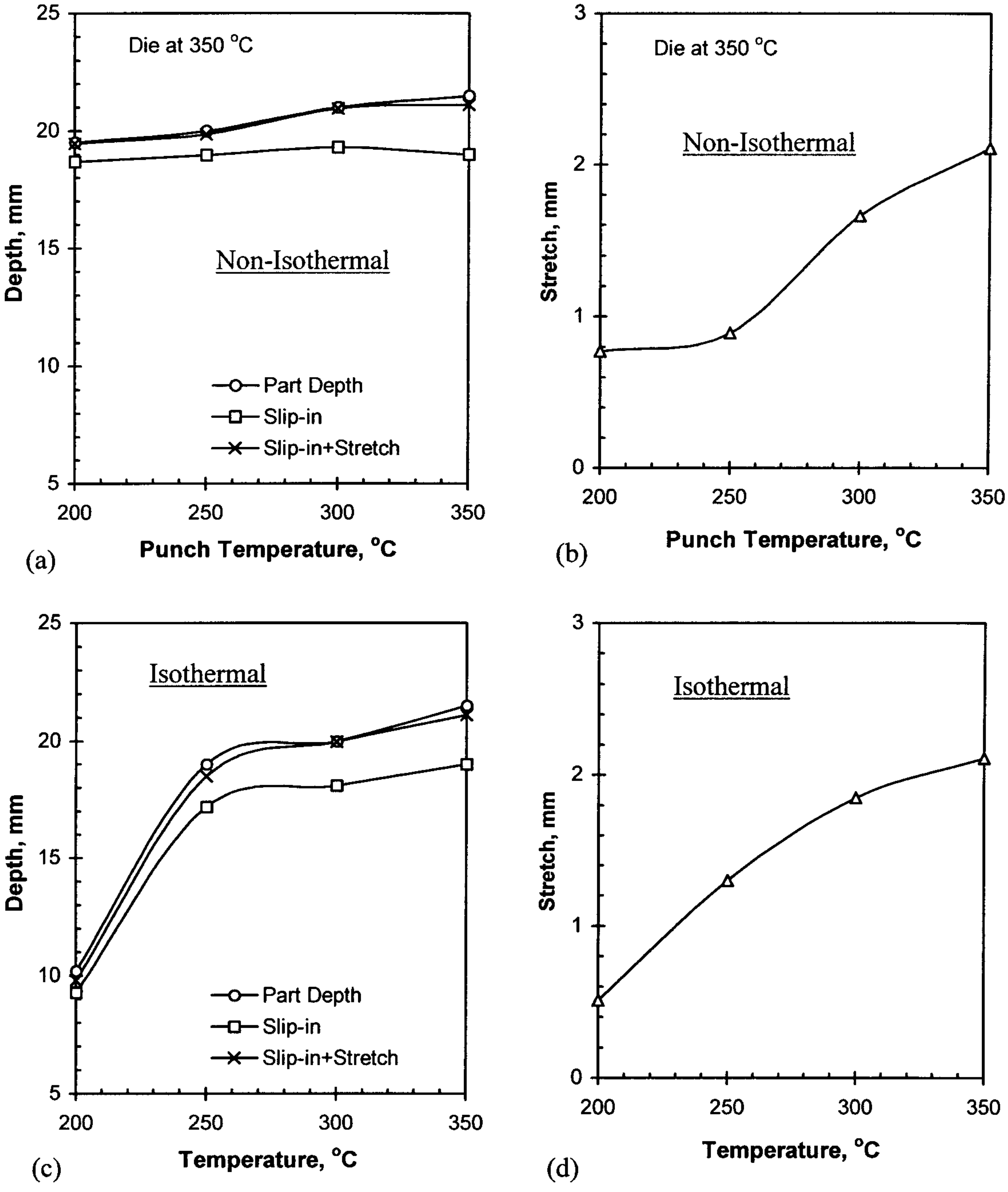

Fig. 6 Contributions of slip-in (draw-in) depth **(a, c)** and stretch depth **(b, d)** to part depth under conditions of thermal gradient (a, b) and isothermal heating (c, d) for alloy 5182 + Mn (BHP = 1.1 MPa; die width = 50 mm)

slip-in depth and stretch depth (the "slip-in+stretch" in Fig. 5) is very close to the value of part depth, verifying the correctness of the above analysis. Alloy 5182 + Mn shows similar behavior (Fig. 6). The stretchability, in terms of stretch depth, of alloy 5182 + Mn is greater than that of alloy 5754 under thermal gradient heating conditions (Fig. 5b and 6b), but the two alloys show similar stretchability under isothermal heating conditions (Fig. 5d and 6d).

3.2 Dependence of Formability on Combined Effects of BHP and Temperature

The blank holding force controls sheet metal drawing. The effects of blank holder force on the formability of sheet metal parts have been recently reviewed by Obermeyer and Majlessi.[23] However, the warm-forming process brings new characteristics to the blank holder force effects when compared

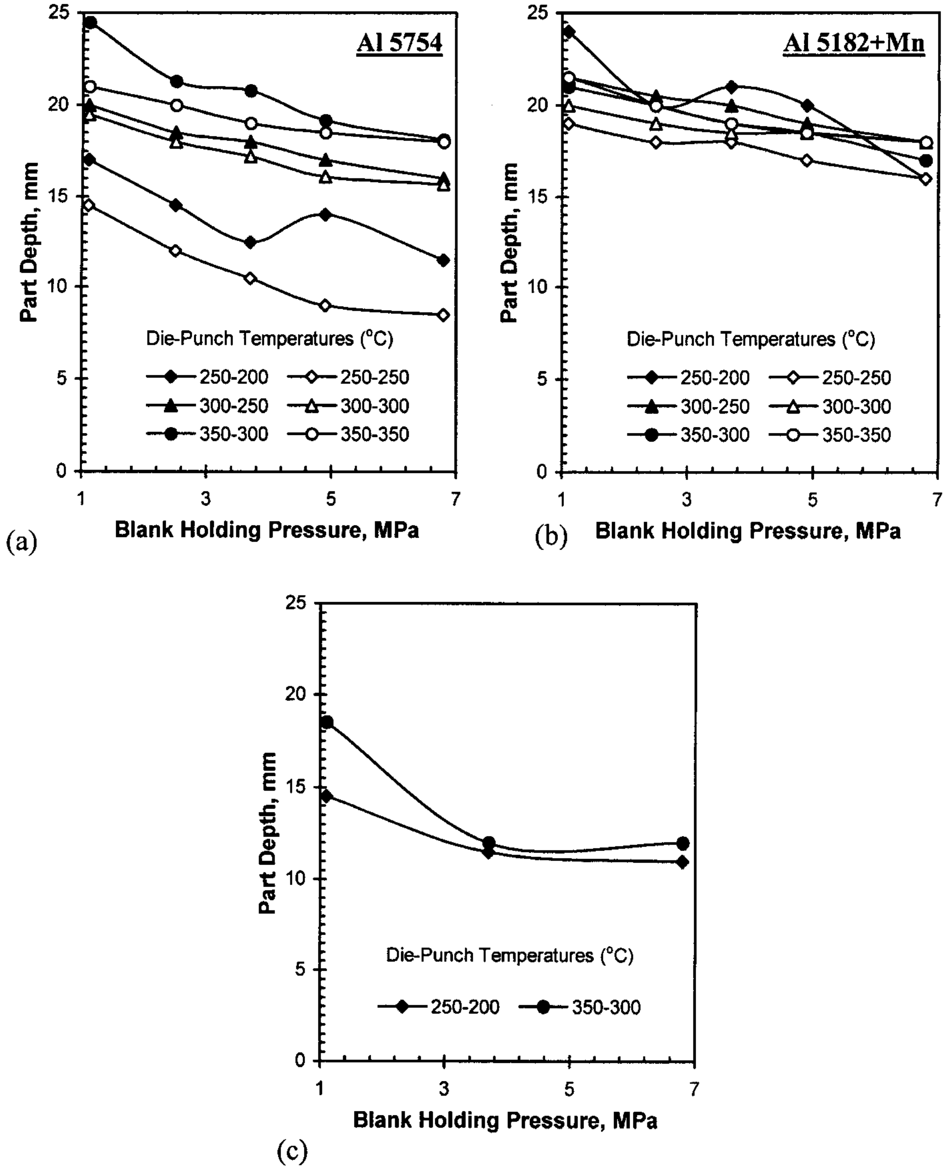

Fig. 7 Effect of BHP on part depth tested at different die-punch temperatures for sheet alloys **(a)** 5754, **(b)** 5182 + Mn, and **(c)** 6111-T4

with ambient temperature forming. The main results with varying BHP are shown in Fig. 7 for alloys 5754, 5182 + Mn, and 6111-T4. The overall trend of BHP is that the formability, in terms of part depth, generally decreases with increasing BHP. This is due to the increased difficulty of drawing sheet metal into a die cavity as the BHP increases. The dependence of part depth on BHP is similar for all three alloys, although 6111-T4 has inherently lower part depth. The temperature dependence of these data is least in the case of alloy 5182 + Mn but is highest in the case of alloy 5754. The higher sensitivity of formability to forming temperature for alloy 5754 may pose a problem for manufacturing reproducibility, but it also shows the highest part depth, which may be used to make more complex parts. In Fig. 7, for 5xxx alloys at low forming temperatures, it is seen that there is a trough and a peak associated with some intermediate BHP values under thermal gradient conditions. This effect may be related to the variation in drawability, stretchability, and wrinkling as the BHP varies.

The contributions of slip-in depth and stretch depth (as defined in Fig. 4) to the overall part depth have also been investigated in terms of BHP effects (Fig. 8 and 9). In Fig. 8, the BHP effects are shown for the case in which the thermal gradient is set at +50 °C ($T_d = T_p + 50$ °C). At a relatively low die-punch temperature, $T_d = 250$ °C and $T_p = 200$ °C (Fig. 8a and b), wrinkling in the flange region occurs more easily (Fig. 8a, the left side of the dashed line). The occurrence of wrinkling obstructs the flow of the material into the die and minimizes the drawing contribution. As BHP reaches a value between 1.1 and 2.5 MPa for alloy 5182 + Mn, and between 2.5 and 3.7 MPa for alloy 5754, wrinkling disappears. Thus, slip-in depth initially decreases with increasing BHP, but as wrinkling begins to disappear slip-in depth does not decrease. The crush-

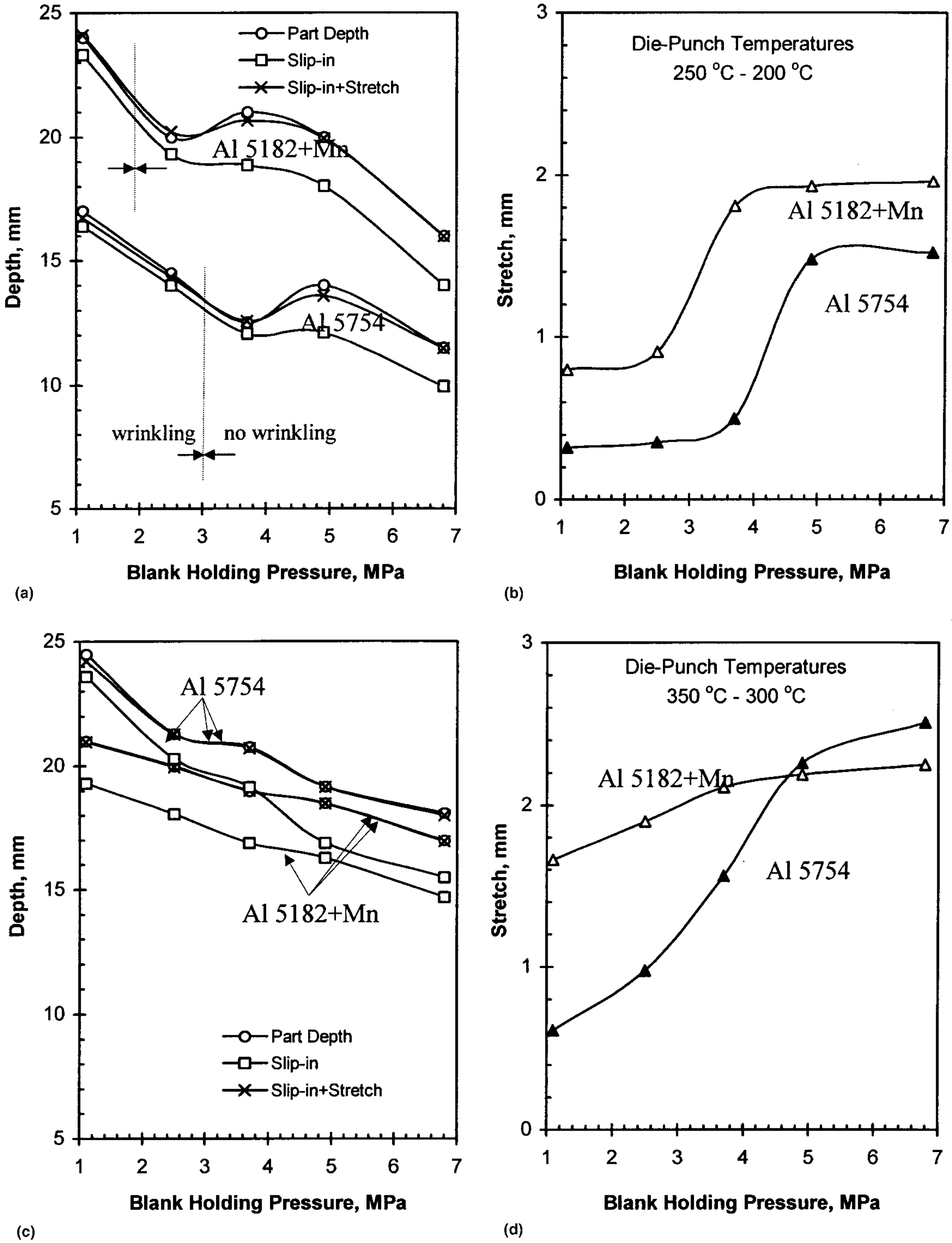

Fig. 8 Effects of BHP on part depth, slip-in depth, and stretch depth under thermal gradient conditions, with die-punch temperatures set at **(a, b)** 250-200 °C and **(c, d)** 350-300 °C (die width = 50 mm)

ing of the wrinkles by the higher BHP helps to minimize the build-up of slip-in resistance from the wrinkles. Eventually, with a further rise in BHP, the slip-in component can be reduced again. The stretch depth contribution, however, increases with increasing BHP at this stage. At a higher die-punch temperature, T_d = 350 °C and T_p = 300 °C (Fig. 8a and

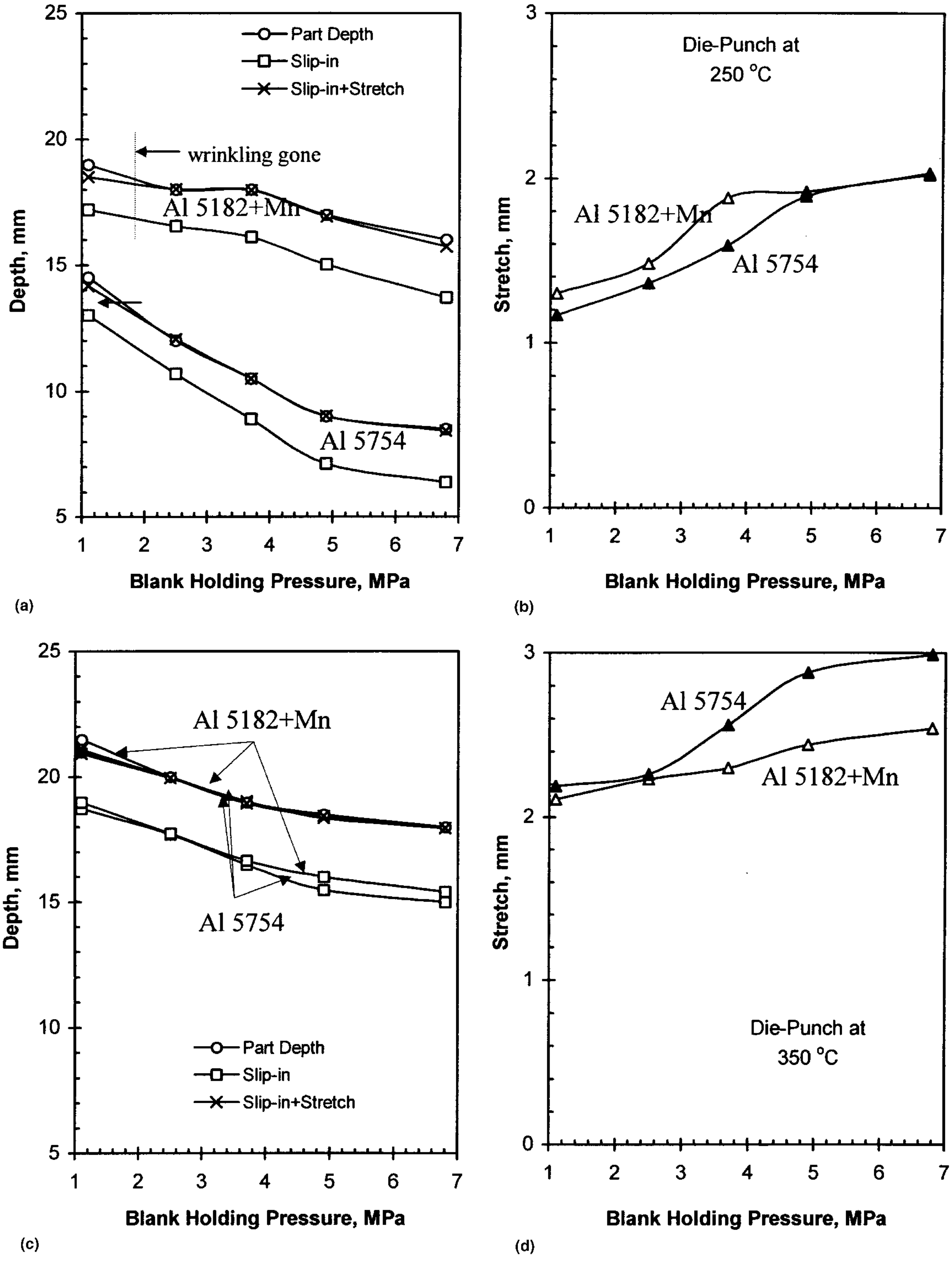

Fig. 9 Effects of BHP on part depth, slip-in depth, and stretch depth under isothermal conditions, with die and punch set at **(a, b)** 250 °C and **(c, d)** 350 °C (die width = 50 mm)

b), wrinkling is no longer a concern since it disappears when the temperature is high enough. This is in accordance with the findings that increasing temperature can result in a decrease in the occurrence of wrinkling.[27] At high forming temperatures, stretch depth increases with increasing BHP, while slip-in depth decreases with increasing BHP (Fig. 8c and d). Under

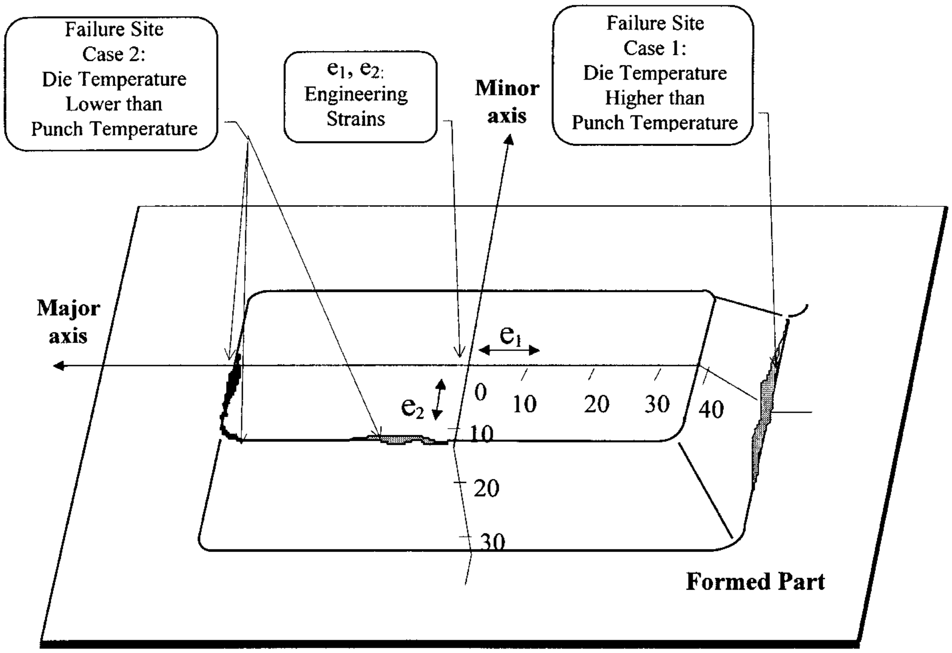

Fig. 10 Schematic diagram showing regions of strain distribution measurement and failure sites for different die-punch temperature assignments: case 1, die temperature > punch temperature; case 2, die temperature < punch temperature

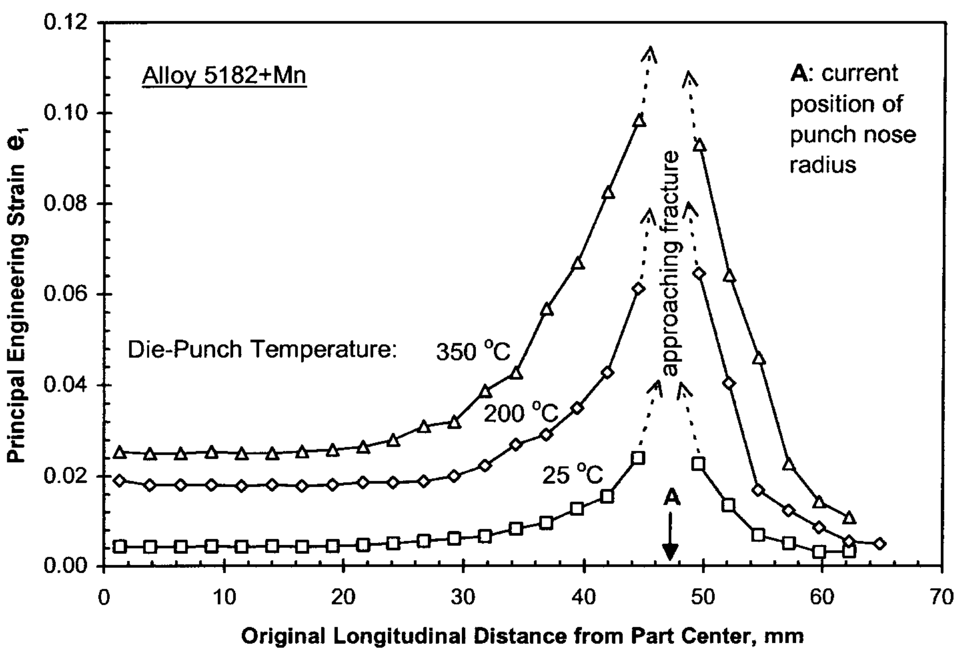

Fig. 11 Effect of forming temperature on the distribution of principal engineering strain e_1 along major axis in biaxially formed parts of sheet alloy 5182 + Mn (BHP set at 1.1 MPa)

conditions of isothermal heating ($\Delta T = 0$), the occurrence of wrinkling is less likely than for $\Delta T > 0$ (Fig. 9). With little or no occurrence of wrinkling, a single trend of variation of forming performance with BHP is expected. As evidenced in Fig. 9, slip-in depth decreases, while stretch depth increases monotonically with increasing BHP. Regarding stretchability, it is observed from Fig. 8 and 9 that the stretch depth for high BHP and high forming temperature is greater for alloy 5754 (as high as ~3 mm) than that for alloy 5182 + Mn, although the stretch depth of alloy 5182 + Mn is greater than that of alloy 5754 under most BHP and die-punch temperature conditions. In summarizing the results on BHP effects under both thermal gradient (Fig. 8) and isothermal (Fig. 9) conditions, it is seen that slip-in depth contributes more to the overall part depth,

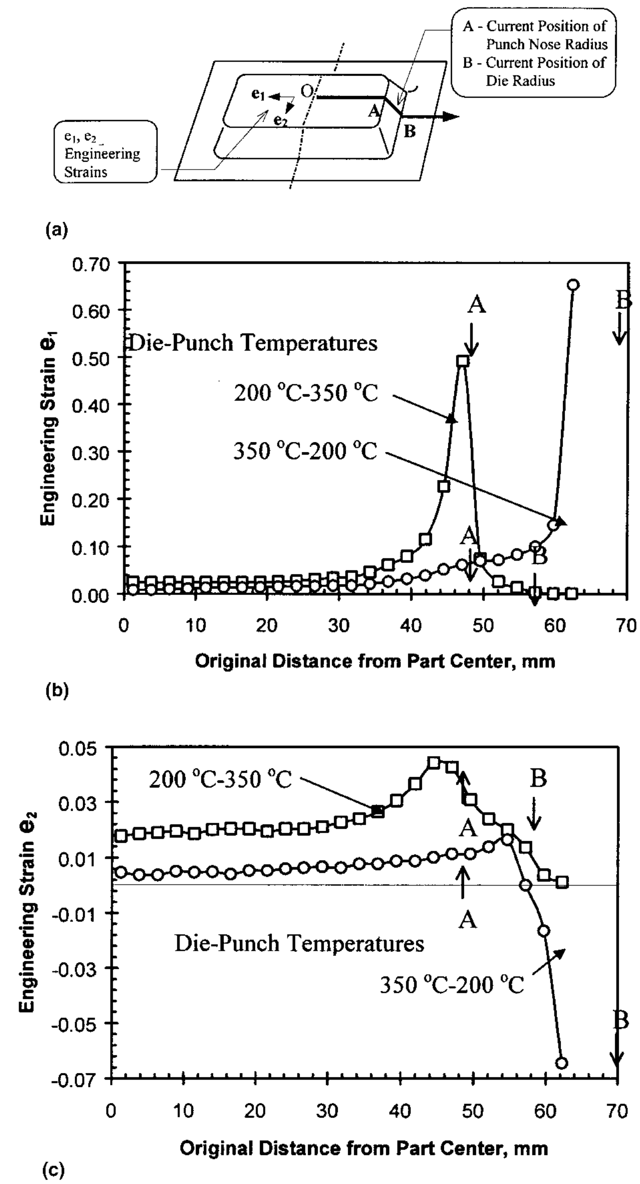

Fig. 12 Forming strain distribution of principal engineering strains e_1 (**b**) and e_2 (**c**) along the major axis (highlighted arrow in panel **a**) in biaxially formed parts of sheet alloy 5182 + Mn, giving a comparison for two die-punch temperature settings: 350-200 °C and 200-350 °C

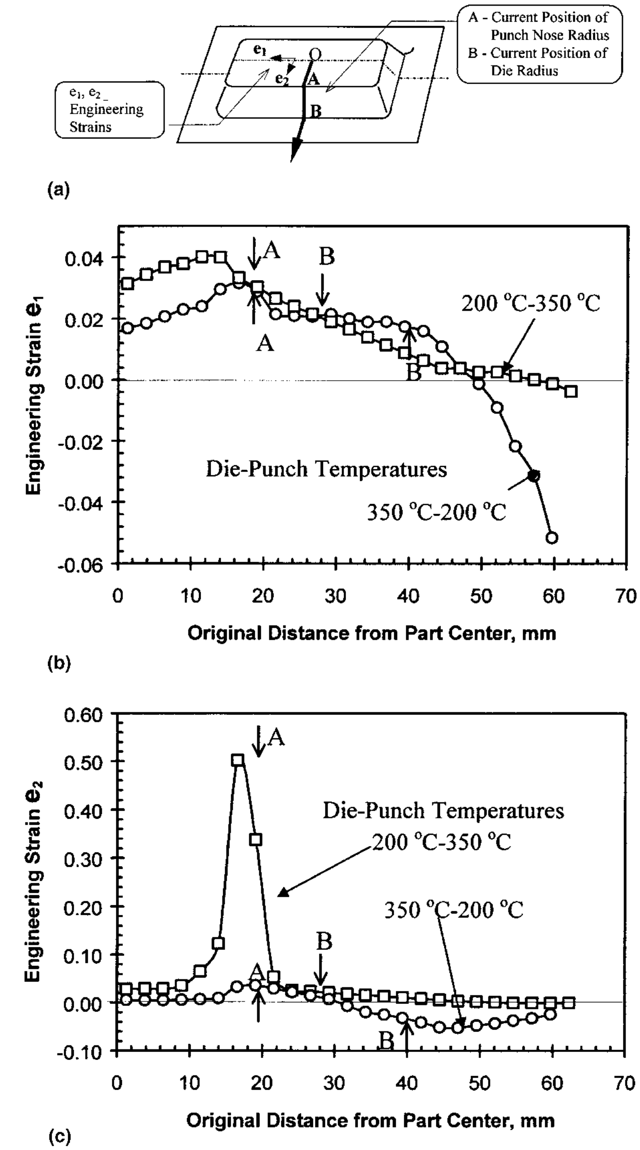

Fig. 13 Forming strain distribution of principal engineering strains e_1 (**b**) and e_2 (**c**) along the minor axis (highlighted arrow in panel **a**) in biaxially formed parts of sheet alloy 5182 + Mn, giving a comparison for two die-punch temperature settings: 350-200 °C and 200 -350 °C

as was observed in the case of temperature effects. Among other important outcomes is that both elevated temperature and increased BHP can effectively prevent the occurrence of blank wrinkling so that the formability of the sheet metal improves.

3.3 Strain Distribution Versus Forming Behavior

The preceding discussion on part depth is directly associated with the uniformity of strain distribution in a part. This distribution provides information on the tendency for strain localization. Among other variables, temperature has been regarded as an important parameter to control the distribution of strain in a formed part.[11,21] From the pre-etched grids on the formed rectangular parts, strain distribution was determined along both the major and minor axes of the rectangular part, which is schematically shown in Fig. 10. The principal engineering strains, e_1 (longitudinal strain) and e_2 (transverse strain), are calculated along each axis and are plotted against the original distance with typical results shown in Fig. 11-13. Measurements were not taken for the grid element containing the failed site. Different patterns of strain distribution reflect different failure modes, as characterized by the specific crack initiation sites. As shown in Fig. 10, two possible failure sites have been identified in the present investigation, resulting from the different die-punch temperature conditions. When die temperature is higher than punch temperature (case 1 in Fig. 10), the cooler punch promotes easier drawing in of material along the minor axis than along the major axis, and, hence, failure occurs in the hotter section of the die entry radius on the more restrained direction (major axis). On the contrary, when die temperature is lower than punch temperature (case 2 in Fig. 10), the hotter punch allows for more stretching on the central section of the part than in case 1, and, hence, strain concentration and failure generally occur near the punch nose radius, along an edge, or at the corner. Under isothermal heating conditions (i.e., the die and punch at the same temperature), failure has been seen at both sites (case 1 and case 2), but with more likelihood of a case 2 failure. These failure locations were also found to be independent of BHP (i.e., for BHP up to 7 MPa in this work).

Figure 11 shows the distribution of the principal engineering strain (e_1) along the longitudinal dimension of the part formed under isothermal heating conditions. It is clear from Fig. 11 that as the forming temperature is increased, the strain level over the flat central section of the part increases and the breadth of the strain peak also increases. This is a direct result of increased strain rate sensitivity with increasing temperature. The improved formability at elevated temperatures is attributed to the higher capability of distributing strains over the flatter regions of the part, which generally do not stretch much.

Figures 12 and 13 show the strain distribution along the major and minor axes of the rectangular part, respectively, for two different ΔT conditions. An important trend to notice in Fig. 12 is that a negative ΔT (the punch being hotter) tends to increase the strain in the flat central section of the part (square symbols), which promotes failure on the nose radius of the punch. A positive ΔT (circular symbols), on the other hand, shifts the region of strain concentration toward the other edge (i.e., flange region). Failure occurs on the die entry radius with associated negative minor strain indicative of drawing effects.

The negative ΔT, which promotes greater straining over the punch face, also increases the minor strain in that region (see Fig. 13b), leading to a strain peak at the punch nose radius (square symbols). The e_1 distributions in Fig. 13 are rather benign and do not lead to a peak of major significance. Toward the edges, both distributions show negative values that are indicative of the drawing effect. The larger negative strains are seen for the positive ΔT case. These strain distribution plots strengthen the findings discussed earlier in the article and provide actual magnitudes of strains achievable in the various regions of the part.

4. Concluding Remarks

The current study demonstrates the potential of using Al sheet alloys to form parts for automotive applications. Of the three alloys tested, 5754 and 5182 + Mn exhibit better formability than 6111-T4. The formability of 5754 is more sensitive to forming temperature and BHP than is 5182 + Mn.

The biaxial formability of parts in the present investigation comes from two basic sources: drawability and stretchability. The stretchability generally increases with increasing forming temperature (i.e., die and punch temperatures) and with increasing BHP. The drawability increases dramatically with decreasing BHP but is degraded by wrinkling, which diminishes as temperature and/or BHP increase. Under isothermal heating conditions, drawability also increases with increasing forming temperature. In the present warm-forming temperature range, the drawability contributes the most to the formability, as expressed by part depth.

As far as the present testing conditions are concerned, the difference of punch temperature and die temperature (i.e., $T_d - T_p$) acts as a useful parameter that divides the forming temperature (drawability-controlled) from other factors, including stretchability, which may also be important to the formability. In the drawability-controlled range, the formability in terms of part depth increases with increasing forming temperature. For the three sheet alloys studied, an optimum part depth is achieved by setting ($T_d - T_p$) at 50 °C. Al alloy sheet forming at a positive ($T_d - T_p$) value tends to distribute strain in such a way that the strain concentration and, hence, crack initiation shifts toward the position of die radius. On the contrary, for Al alloy sheet forming at a negative ($T_d - T_p$) value, strain tends to concentrate at the punch nose radius, and cracking occurs, leading to total failure.

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