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Cylindrical cup deep drawing of ZEK100 sheet at elevated temperatures

S Kurukuri[1], M Boba[1], C Butcher[1], M J Worswick[1], R Mishra[2]

[1]University of Waterloo, 200 University Avenue West, Waterloo, ON, Canada
[2]General Motors Research and Development Center, Warren, MI, USA

srihari.kurukuri@uwaterloo.ca

Abstract. Cylindrical cup deep drawing experiments are performed on as-received magnesium rare-earth alloyed ZEK100 rolled sheet between room temperature and 250 °C. All tests are performed using warm tooling comprising a 101.6 mm (4") diameter cylindrical punch and smooth die and blank holder. Both isothermal and non-isothermal experiments are performed with a draw ratio of 2.25. Warm temperature formability of ZEK100 is investigated through determination of draw depths of cylindrical cups under isothermal and non-isothermal conditions. The effect of sheet anisotropy during deep drawing operation is investigated by measuring the earring profiles by means of digital imaging as well as sheet thickness from the center to the outer diameter in the rolling direction. It is found that ZEK100 sheets exhibit significantly better warm temperature drawing performance over commercial wrought magnesium alloy sheet – e.g. a full draw of 203.2 mm (8") blanks of ZEK100-O was achieved with tool temperature of 150 ºC compared to a full draw for AZ31B-O with a tool temperature of 225 ºC. Temperature process windows are used to present a direct comparison of forming behavior between ZEK100 and AZ31B. The increased forming performance of ZEK100 at elevated temperatures is attributed to the weakened texture resulting from alloying with Zr and Nd, respectively, allowing for elevated slip activity at lower temperatures.

1. Introduction

The ongoing demand for increased fuel economy in vehicles continues to drive the development of lightweight alloys and automotive components. Recent advances in magnesium alloys, with a density of 1.74 g/cm^3 and high strength-to-weight ratio, suggest that it is a potential candidate to replace many automotive components made from conventional steel (7.8 g/cm^3); however there remains a need for further research on magnesium alloys to address manufacturing issues, such as formability during stamping, and in-service performance issues such as corrosion and fracture under high strain rate crash conditions. Magnesium sheet alloys at the forefront of sheet forming research include ZEK100 and AZ31B with the latter being the most commonly used commercial magnesium alloy sheet. Lately ZEK100 has drawn the attention of researchers since it has demonstrated enhanced formability compared to AZ31B [1]. Kurukuri *et al.* [2-4] conducted constitutive characterization of both ZEK100 and AZ31B, showing that ZEK100 exhibits considerable weakening of crystallographic texture with lower anisotropy and superior elongation compared to AZ31B. Such formability gains have been reported by Boba *et al.* [1] who demonstrated that ZEK100 can be formed at much lower temperatures than AZ31B. The enhanced performance of ZEK100 has led to successful warm forming of prototype full-scale automotive panels [5].

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In this study, the deep drawing performance of ZEK100, in particular the effect of elevated tooling temperature on drawability is investigated. Recent work by Ghaffari Tari *et al.* [6] has shown that AZ31B can be drawn at elevated temperatures. They report a non-isothermal deep drawing process window in which a punch temperature that is lower than the die/blank holder temperature leads to enhanced cup depths. In the current work, similar experiments are performed for ZEK100 to ascertain if the more desirable texture and grain size allows the use of lower forming temperatures for deep drawing of ZEK100 magnesium alloy sheet. 100 mm diameter cup draw experiments are performed on ZEK100 sheet under both isothermal and non-isothermal conditions in the temperature range of 25-250ºC. The effect of temperature and temperature gradient on anisotropy is examined by measuring punch force, earring profiles and thickness profiles. Finally, a temperature process window for ZEK100 is developed to summarize and compare the formability of ZEK100 to that of AZ31B-O sheet.

2. Material

The current work considers a 1.6 mm thick ZEK100 sheet in the as-received condition, with a nominal composition of 1.3 %wt. Zn, 0.2 %wt. Nd, 0.25 %wt. Zr and 0.01 %wt. Mn. Compared with the current industry-utilized magnesium alloy, AZ31B, ZEK100 has shown marked improvements in warm temperature formability between room temperature and 150 °C [1,7]. ZEK100 sheet has a more random and weakened crystallographic texture distribution, as seen in Figure 1. Detailed constitutive characterization of ZEK100 has been published by Kurukuri *et al.* [7].

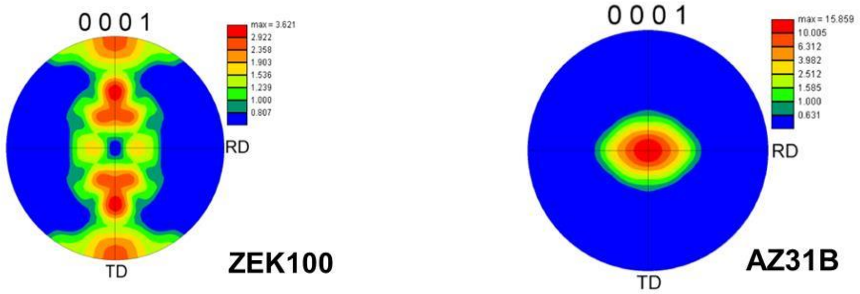

Figure 1. Initial texture: (a) ZEK100; (b) AZ31B.

3. Experimental procedure

All deep drawing experiments were conducted with a double-action, closed-loop servo-hydraulic press, with a 60 ton blank holder capacity and a 75 ton punch capacity. The tooling was heated via embedded cartridge heaters. The cylindrical punch was optionally heated with embedded cartridge heaters or cooled with water channels within the punch. The punch speed was set to 4 mm/s for all cylindrical deep draw experiments. The binder force was set to 60 kN for the majority of the experiments which corresponds to the force level required to suppress wrinkling for room temperature forming of a blank with DR equal to 2.25. All testing was conducted with 0.07 mm Polytetrafluoroethylene (PTFE) film, commonly known as Teflon, as a lubricant between all blank-tooling interfaces. Prior to each test using different temperatures, the heating time and temperature were verified to ensure consistent conditions with Type K thermocouple probe. It was repeatedly found in each test that within 90 seconds the recorded temperature of the blank would begin stabilizing and achieve quasi-equilibrium after 120 seconds of heating time for temperatures between 50°C and 200°C. To attain desired blank temperatures of 250°C a longer heat time of 6 minutes was adopted.

Cross-sectional thickness measurements from as-formed cups were taken along the rolling direction using a digital Vernier calliper. The cups were cut into quarter sections along each axis and edges were deburred. Measurements were taken at 10 mm intervals measured along the surface of the deformed cups, starting at the centre of the cup with the interval decreasing to 5 mm near and on the punch nose and die entry radii. Earring profiles were also obtained for both isothermal and non-isothermal deep drawn cups. Measurements were divided into two cases: the first corresponding to conditions that resulted in a successful complete draw and the second for which cups fractured prior to reaching a fully-drawn condition. For cases in which the cup was able to be drawn fully, earring measurements were taken from subsequent tests interrupted at a punch depth that was 20 mm prior to the full draw depth in order to leave sufficient flange area for earring profile measurements. For cases in which the cup fractured, earring measurements were taken from the flange region of specimens interrupted at a punch depth that was 3 mm less that the fracture depth.

Measurements of earring profiles were obtained by creating a high-contrast photographic image of the formed blank colored in white against a black background, as shown in figure 2(a). This high-contrast image was then processed through image processing software which binarized the image, creating an image file containing only white or black pixels (figure 2(b)). The edge between the black background and white specimen was then extracted (figure 2(c)). The radius of the edge of the blank relative to the blank center was then determined as a function of angular position around the blank periphery, with 0° adopted as the blank rolling direction.

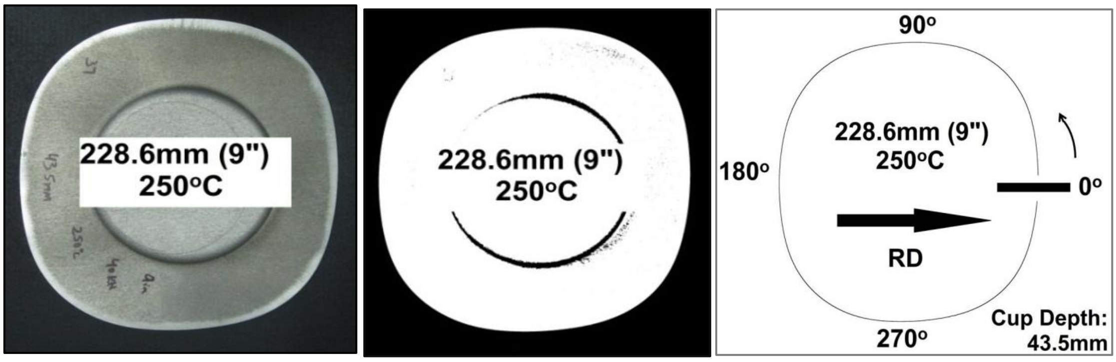

Figure 2. (a) top view image of specimen, (b) binary image, (c) processed image of edge of specimen.

4. Results

4.1. Punch force-displacement response during deep drawing

Blanks were drawn under isothermal conditions in which the die, blank holder and punch were heated to uniform temperatures of 100, 150, 200, and 250 °C. The load-displacement response for drawing blanks with a draw ratio (DR) equal to 2.00 and 2.25 are shown in figure 3. Note that scatter bands are not shown, however, the estimated scatter in the load and displacement measurements are ±2 kN and ±2 mm, respectively. The smaller draw ratio (2.00) exhibited better drawability than the larger draw ratio (2.25). With DR = 2.00, cups were drawn to a full depth of 80 mm for all tested temperatures except for 100 °C (figure 3(a)). The blanks with DR = 2.25 (figure 3(b)), however, resulted in fractures for all temperature conditions, with cup depths of 24.8, 45, 57 and 45.5 mm at temperatures of 100, 150, 200, and 250 °C, respectively. All DR = 2.25 cups fractured at the punch tip as seen in figure 4. Increasing the temperature beyond 200 °C resulted in a lower cup depth. This is thought to be due to excessive softening of the material at the punch tip, coupled with a constant binder load adopted for all temperature conditions. In general, it is possible to increase draw depth by reducing binder force which in turn will reduce frictional resistance to draw-in, the lower limit of binder force being the onset of wrinkling. To simplify the test matrix, however, the binder force was held constant for the results presented in Sections 5.1-5.4. Binder force reductions were considered in the process window development presented in Section 5.5.

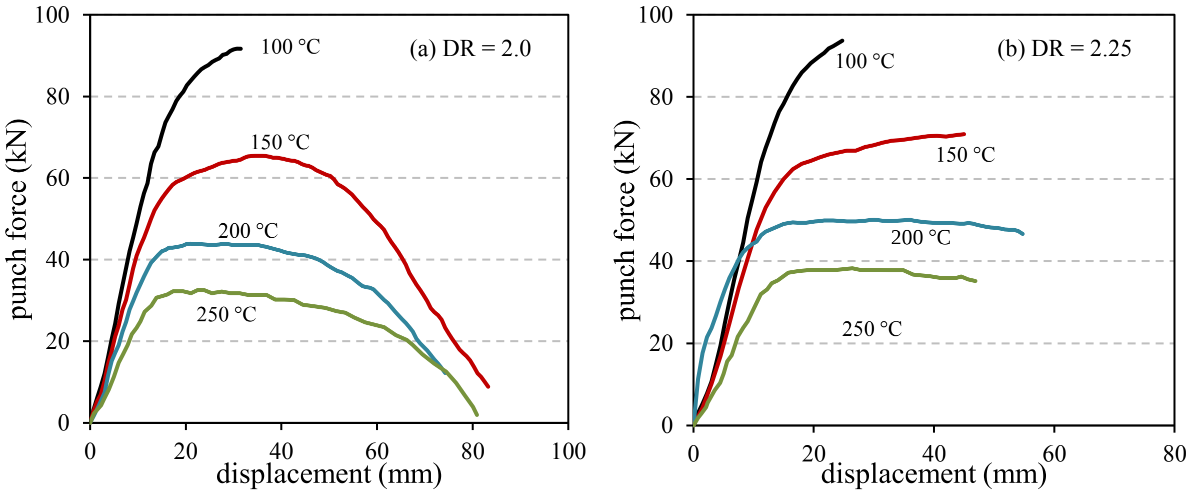

Figure 3. Load-displacement response for an isothermal draw (a) DR = 2.00, (b) DR = 2.25.

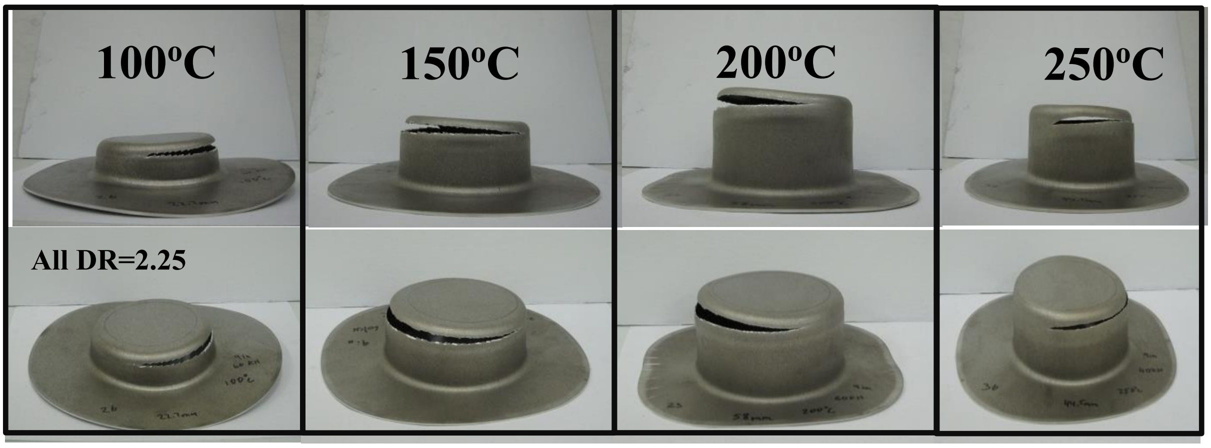

Figure 4. Deep drawn ZEK100 cups formed under isothermal conditions.

Cups were deep drawn with an imposed temperature difference between the punch and the die/blank holder. Figure 5(a) shows the measured punch force versus displacement response for blanks with a DR of 2.25, flange temperature of 150 °C, and punch temperature ranging from 150 °C (isothermal case) down to 25 °C. The isothermal case draws until fracture at the punch radius at a depth of 45 mm. Reducing the temperature to 100 °C in the punch region increases the strength of the blank in the punch area such that the load in the sidewall of the cup can be supported, thus increasing the draw depth. Reducing the punch temperature further to 50 °C and 25 °C also resulted in fully drawn cups. The effect of varying the temperature in the flange region can be seen in figure 5(b). Plotted are the measured punch load versus displacement response for die and blank holder temperatures in the range 150°C to 250 °C, a punch temperature of 25 °C, and a DR of 2.25. It can be seen from the figure that all of the blanks achieved a full draw. As the die and blank holder temperature is increased from 150 °C to 250 °C, the maximum punch load for each drawn cup decreases from 78 to 44 kN, respectively.

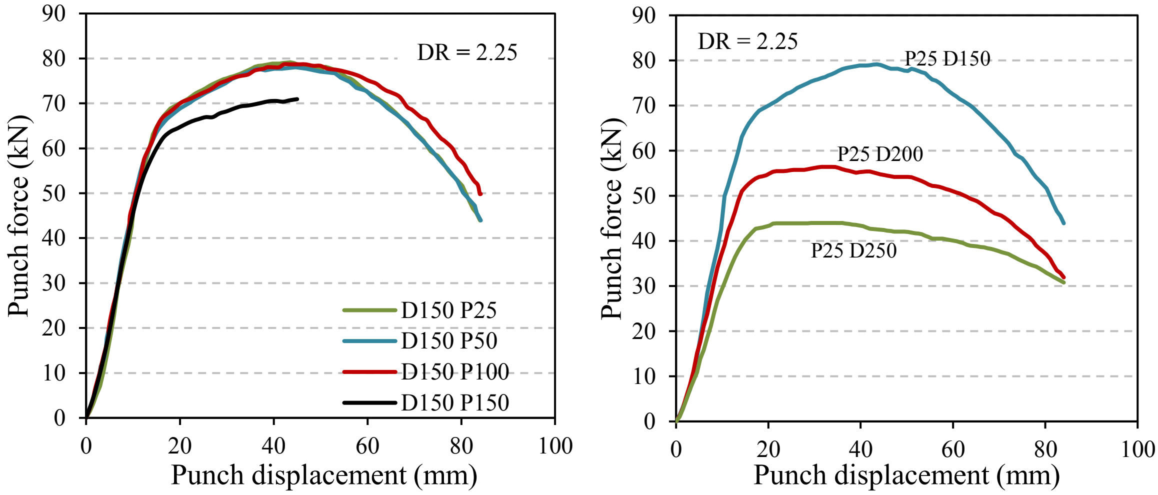

Figure 5. (a) Effect of punch temperature during non-isothermal forming with a die temperature of 150 °C, and punch temperature in the range 25-150 °C (b) Effect of die and blank holder temperature for a punch temperature of 25 °C and die/blank holder temperatures in the range 150-250 °C.

4.2. Earing behaviour of ZEK100deep drawn cups

The deep drawing of ZEK100 resulted in an uneven cup rim. This behavior is due to the material anisotropy and is often quantified by means of earring profiles in which the number of ears, their location in relation to the sheet rolling direction and their amplitude are characterized. The earring profiles obtained from the ZEK100 experiments interrupted at intermediate punch depths appear to fall in between the shapes of an ideal square and an ideal circle, as seen in figure 6(a) which shows a cup drawn to a punch depth of 43.5 mm at 250 °C and DR = 2.25. More severe earring is evident for higher punch depths, as shown in figure 6(b) which illustrates the dramatic earring tendencies of this sheet material for a non-isothermal case (punch temperature of 150 °C and die temperature of 25 °C, DR=2.25). Note that mild asymmetry is present in the cup draw-in, the cause of which is uncertain, but may be due to imperfect centering of the blank relative to the die prior to forming or variation in binder pressure during forming.

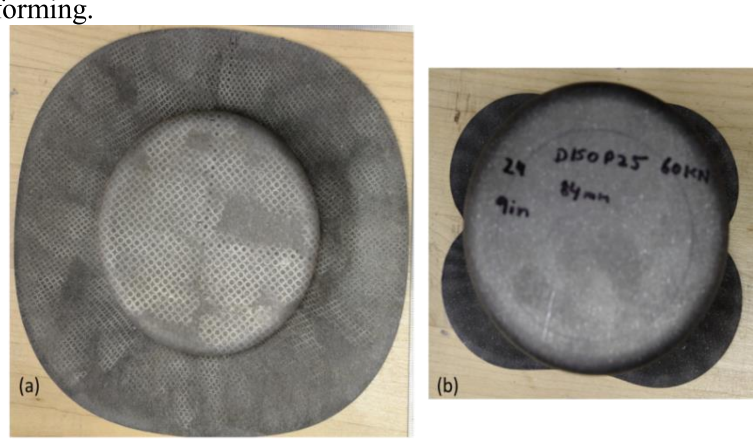

Figure 6. Top view of as-drawn cups for earring profile analysis, DR = 2.25: (a) isothermal draw at 250 °C interrupted at 43.5 mm punch depth - rolling direction is aligned with bottom of photo; (b) non-isothermal draw with die temperature of 150 °C and punch temperature of 25 °C tested to 84 mm punch depth - note that blank edge has entered the die cavity on the RD side, but not on the TD side.

Blanks with DR = 2.25 were formed in interrupted tests to 3 mm prior to fracture for isothermal tests from 100°C to 250 °C. The draw depths for the blanks were 21.8, 42, 54, and 42.5 mm at temperatures of 100, 150, 200, and 250 °C, respectively. Figure 7 shows the resulting earring profiles (note that a negative "excursion from a perfect circle" implies more draw-in relative to positive values). The nominal flange diameters for the corresponding deep drawn cups were 205, 186, 157, 187 mm at test temperatures of 100, 150, 200, 250 °C, respectively.

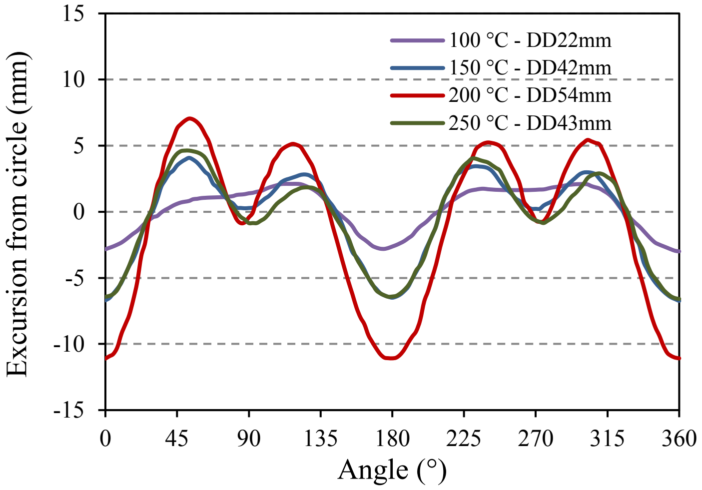

Figure 7. Isothermal earring profile, DR = 2.25. Forming temperatures and draw depths (DD) are indicated in the legend.

The effect of temperature gradient on the ZEK100 earring profile was investigated by forming with varying temperatures for the die/blank holder and punch. In the first case, as seen in figure 8(a), the die and blank holder temperature were held constant at 150 °C while the punch temperature was increased from 25 °C to 100 °C. All formed cups achieved a full draw depth of 84 mm, so the earring profile tests were interrupted at 64 mm punch depth (20 mm prior to full draw) to leave a flange area sufficient for earring measurements. Varying the punch temperature and keeping the flange temperature constant had very little effect on the resulting earring profile. This is expected since most of the deformation occurs near the flange region. In contrast, if the punch temperature was held constant, there was a mild reduction in the extent of earring when the die and blank holder temperature were increased from 150 °C to 250 °C, as shown in figure 8(b), where cups were drawn to the same draw depth of 64 mm. This behavior suggests that the degree of anisotropy decreases as temperature increases. The overall trends in measured earring were similar for the isothermal and non-isothermal deep draw cases.

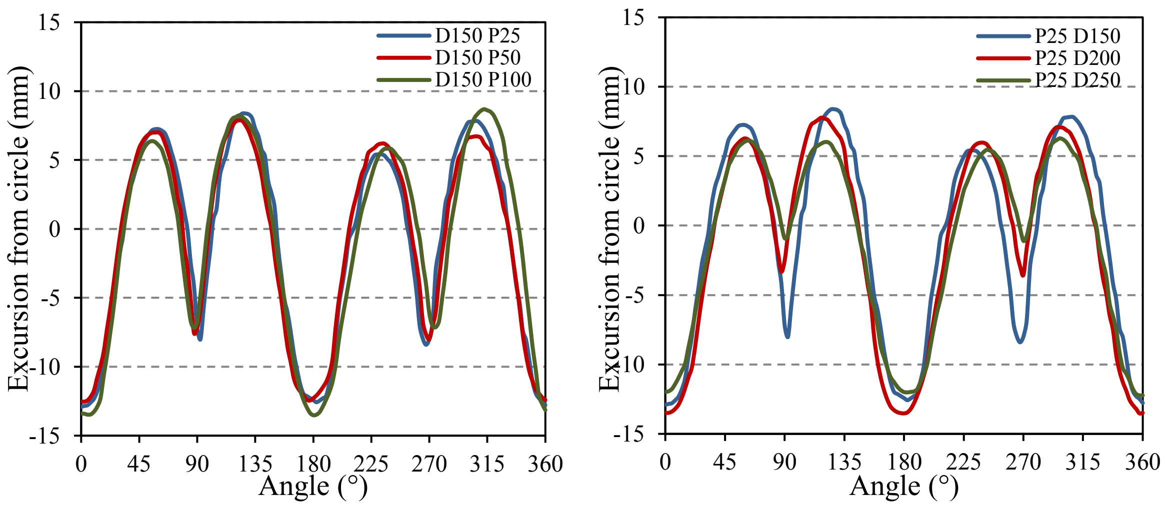

Figure 8. Non-isothermal earring profile: (a) die temperature held constant at 150 °C and punch temperature in the range 25-150 °C, (b) punch temperature held constant at 25 °C and die/blank holder temperatures in the range 150-250 °C.

4.3. Thickness distributions within ZEK100deep drawn cups

ZEK100 blanks of DR = 2.25 were drawn at temperatures of 100, 150, 200, 250 °C during which the tests were interrupted at 3 mm prior to fracture, resulting in varying cup heights due to the forming limits at different temperatures leaving more or less material in the flange area as shown in figure 9(a). All specimens experienced significant thickening in the flange section and thinning in the punch nose region, with the sharpest thickness reduction at the punch nose radius, as shown in figure 9(a). The difference in thickness between the punch nose and flange increased with increasing temperature (and draw depth); as the temperature is increased, the punch face experiences greater amounts of thinning.

The most favourable forming conditions were achieved by prescribing a lower punch temperature in relation to the die and blank holder temperature. The effects of varying the temperature between the punch and die on the thickness and strain distributions were investigated by using the punch temperature was held constant at 25°C while the die and blank holder temperature was varied from 150, 200, 250 °C. For these non-isothermal cases, the measured thickness distributions are all very similar with mild increase in thinning of the material at the punch profile radius as punch temperature is increased.

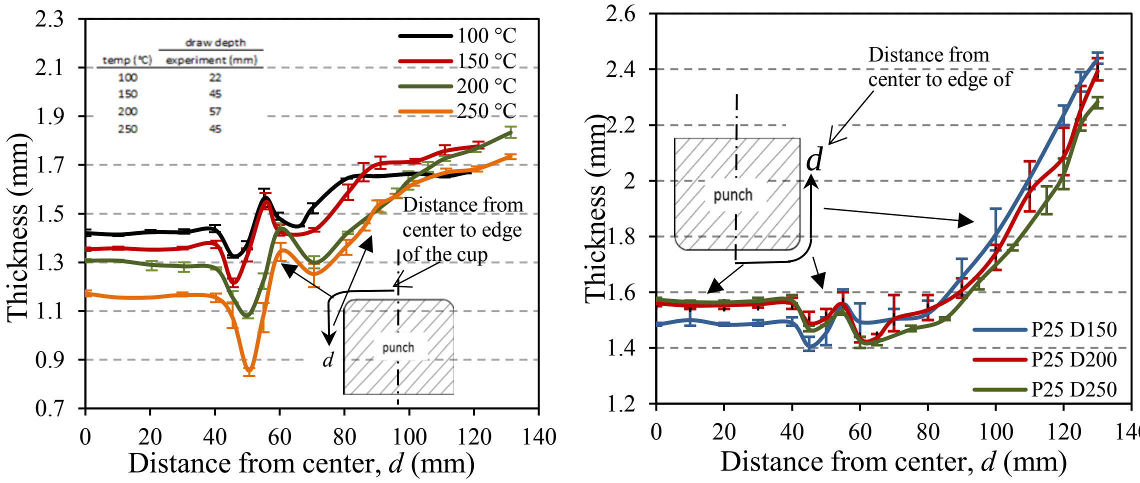

Figure 9. Thickness Profile for DR = 2.25 in the rolling direction at various temperatures. Initial thickness was 1.6 mm. (a) isothermal: draw depths corresponding to the measured thickness profiles are given in the inset table. (b) non-isothermal: punch at 25 °C, dies at 150, 200, and 250 °C in the RD. The inset figures shows the punch profile and the manner in which *d*, the "Distance from centre" of the punch, was measured along the cup surface. The arrows indicate the regions of the cup corresponding to the thickness measurements.

4.4. Thermal process window

The drawability of ZEK100 was experimentally characterized *via* measuring the punch load *vs.* punch displacement for each circular blank under various isothermal and non-isothermal temperature conditions. Table 1 show the tooling temperature conditions, between 25 and 250 °C, under which blanks were formed into deep drawn cups and figure 10 plots the corresonding process window shows the tooling temperature conditions, between 25 and 250 °C, under which blanks were formed into deep drawn cups. In the table the green cells indicate conditions resulting in a successful full draw and red cells indicate conditions resulting in fracture during the draw. The value within each cell indicates the binder force which was varied in some cases, primarily at the lower temperature conditions, to attempt to improve draw depth. Experiments to determine the thermal process window began at the top right temperature combination in the corresponding table and progressed down towards the temperature combinations on the left. Once fracture was observed, the binder force was reduced to allow for easier drawing until wrinkling was observed. Ghaffari Tari *et al.* [6] developed a similar thermal process window for AZ31B-O blanks with DR = 2.25 that were drawn under various non-isothermal conditions. A direct comparison to the current ZEK100 experiments is presented in figure 10. An additional temperature of 270 °C for the die was tested to allow direct comparison to work performed on AZ31B by Ghaffari Tari *et al.* [6]. It is evident that the thermal process window for ZEK100 is substantially larger than that of AZ31B-O and that ZEK100 can be drawn at much lower temperatures. This lower temperature process window translates into shorter heating times, lower heating costs and lower tooling and lubricant requirements for production of components using ZEK100 *versus* AZ31B.

Table 1. Deep draw process window experiments: 228.6 mm blank, DR = 2.25. Shaded cells indicate conditions tested to determine process window. Values in first column indicate the die temperature, while values in bottom row correspond to the punch temperature.

Full Draw Fractured

Die Temperature (°C)						
270						80kN
250	60kN					60kN
200	60kN	60kN			60kN	
150	60kN	80kN / 40-60	60kN	60kN		
100			60kN			
50						
0	25	50	100	150	200	250

Punch Temperature (°C)

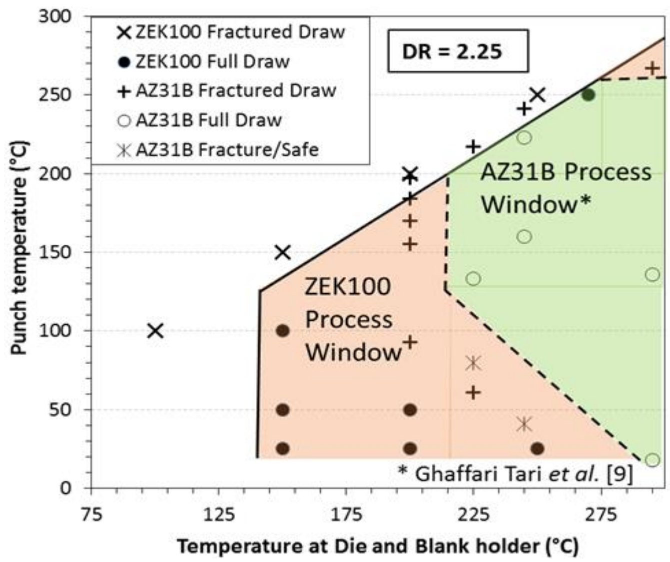

Figure 10. Thermal process window for DR = 2.25: ZEK100 versus AZ31B. Data for AZ31B from Ghaffari Tari *et al.* [13] replotted here in terms of die-punch temperatures.

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