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Title: A numerical study on warm deep drawing of polypropylene

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Abstract

Warm deep drawing of polypropylene, a semi-crystalline thermoplastic polymer, is studied using finite element analysis. In this process, a circular polypropylene blank is preheated to a temperature much below its melting temperature and deep drawn into the shape of a flat-bottom cylindrical cup using a punch-die combination, both initially at 25°C. The material model used for the analysis considers the effects of varying temperature and strain rate during the deep drawing process on the depth of draw. The effects of blank holder force, initial blank temperature, blank diameter, and die and punch corner radii on the depth of draw are determined. Thickness, temperature and strain variations in the drawn cups, punch forces, and failure modes are also determined.

Keywords: polypropylene, deep drawing, modelling, thickness distribution, failure modes

1. Introduction

Deep drawing is a well-established metal forming process [1] and is widely used with steels, aluminum alloys and other metals in the automotive as well as non-automotive industries. Even though several articles have been published on deep drawing of polymers [2-7], it has not found widespread application in the plastics industry. One of the common manufacturing processes in the plastics industry is called thermoforming in which a preheated thin plastic sheet is placed on a mold and vacuum formed into the shape of the mold [8]. The preheating temperature is much above the glass transition temperature for amorphous polymers and close to or slightly above the melting point for semi-crystalline polymers. There are several variations of the thermoforming process, one of which is called plug-assist vacuum forming. In all these variations, the major deformation mode of the preheated sheet is biaxial stretching. In deep drawing operation, on the other hand, the deformation of the sheet takes place by a combination of drawing and stretching.

During the past several years, polypropylene (PP) has found an increasing number of applications in automotive components such as instrument panels and housings, and in household products, such as containers. The reasons for selecting PP in many such applications can be attributed to its low density of 0.9 g/cm^3, relatively low cost, and a balance of mechanical properties. In addition to weight and cost savings, other qualities offered by PP are very low water absorption, good chemical resistance, high food safety and low electrical conductivity.

Manufacturing polypropylene products using a deep drawing process has not been explored much in the past. Research on deep drawing of polymers has dealt mostly with amorphous polymers, such as acrylonitrile-butadiene-styrene (ABS) and polycarbonate [2-7]. In these studies, the emphasis was more on the relationship of deep drawability with material parameters and not with process parameters. In addition to several amorphous polymers, Evans [3] performed cup drawing tests on polypropylene at 23°C and observed failure by necking in the cup wall. Machida and Lee [7] reported experimental results on the cup drawing of propylene-ethylene copolymer under isothermal and differential heating conditions at temperatures up to 130°C. Although cups could be formed under both heating conditions, differential heating in which the flange area of the blank was at a higher temperature than the punch area produced a higher draw depth than isothermal heating in which the flange and punch areas of the blank were at the same temperature.

In the current work, deep drawing of a polypropylene homopolymer was numerically studied using LS-DYNA, a commercially available and widely used finite element software for non-linear analysis of structures and processes. PP has a glass transition temperature of -20°C and a melting point of 170°C [9]. It exhibits brittle behavior at temperatures at or below -10°C, and above the melting point, it transforms into a liquid state. In general, PP is difficult to thermoform because of its narrow melting range, low melt strength and low sag resistance during heating [8]. A manufacturing process called solid phase stretch forming is used with polypropylene to produce cylindrical and rectangular containers. The recommended initial sheet temperature to successfully form these containers is 150-160°C, which is in the thermoforming temperature range of 145-166°C of polypropylene.

In this study, the processing window for deep drawing of PP was selected to be between 25°C and 125°C, much below its thermoforming temperature range [9]. The die and punch temperatures were both at 25°C prior to the start of punching of the PP. The forming speed was set at 100 mm/s. The effects of temperature and strain rate variations in the PP blank during deep drawing were accounted for in the numerical study using the material constitutive model described below. Because of the relatively low forming temperature and high forming speed, sagging of the blank during deep drawing was not considered. The deep drawability of PP was determined by the depth of draw and drawing limit for successful forming of circular blanks to round cup shapes. The effects of blank holder force, initial blank temperature and blank diameter were also studied.

2. Tensile characteristics of polypropylene

The following three-parameter nonlinear constitutive model proposed by Zhou and Mallick [10] was used to develop a series of tensile stress-strain curves of PP needed as an input for FE simulations of the deep drawing process.

$$\sigma = \frac{E(\dot{\varepsilon}, T)\,\varepsilon}{1 + E(\dot{\varepsilon}, T)\,\beta(\dot{\varepsilon}, T)\,\varepsilon^{m}} \qquad \text{(Eq. 1)}$$

In Equation 1, the stress σ is expressed as a function of strain ε, modulus E, and compliance factor β and strain exponent m. Both E and β depend on the strain rate $\dot{\varepsilon}$ and temperature T, but m is considered a constant.

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Zhou and Mallick [11] presented the experimental tensile stress-strain curves for an unfilled polypropylene homopolymer at various strain rates and temperatures. The corresponding modulus and yield strength (at 0.2% of strain), compliance factor β and strain exponent m are given in Table 1. It is evident from Table 1 that both modulus and yield strength values are temperature and strain rate dependent. Compliance factor shows an increasing trend with temperature and a decreasing trend with strain rate. Strain exponent m on the other hand does not show any trend with either temperature or strain rate; hence it is considered independent of both temperature and strain rate. The values of m in Table 1 were averaged to obtain the value of the strain exponent m as 1.31.

To account for the effects of varying temperature and strain rate on the modulus, yield strength and compliance factor of the PP during the deep drawing operation, a parametric equation of the general form given by Equation 2 was used. In this equation, the parameters *a, b,* and *c* are different for the modulus, yield strength and compliance factor. T_0 and $\dot{\varepsilon}_0$ in Equation 2 are the reference temperature and strain rate, respectively. The parameters *a, b* and *c* were determined using MATLAB Curve Expert to fit the data given in Table 1. Their values are listed in Table 2. The reference temperature and strain rate were 21.5°C and 0.05 s^{-1}, respectively.

$$E, \sigma_y, \beta = a\left(1 + b \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot exp\left(c \cdot \left(T - T_0\right)\right) \qquad \text{(Eq. 2)}$$

Table 1. Constitutive parameters of PP determined from experimental curves in Fig.1.

Temp (°C)	Strain rate (min^{-1})	Modulus (MPa)	Yield strength (MPa)	m	β (MPa^{-1})
21.5	0.05	1420	15.62	1.2425	0.03813
21.5	0.5	1760	18.18	1.2595	0.03781
21.5	5	1901	18.87	1.2714	0.03729
50	0.05	735	10.46	1.3182	0.05514
50	0.5	866	11.25	1.3281	0.05198
50	5	1040	11.76	1.2969	0.04649
75	0.05	480	6.36	1.3585	0.08082
75	0.5	523	6.83	1.3916	0.07903
75	5	613	7.79	1.35	0.06988
100	0.05	287	4.16	*	*
100	0.5	381	4.49	1.3445	0.12906
100	5	465	4.75	1.2947	0.09757

Using Equations 1 and 2, theoretical stress-strain curves were generated for temperatures varying from 20 to 130°C in intervals of 10°C and at strain rates of 0.1, 10, 100 s^{-1}. The values of the modulus and compliance factor at various temperatures and strain rates were obtained using Equation 2 and were then

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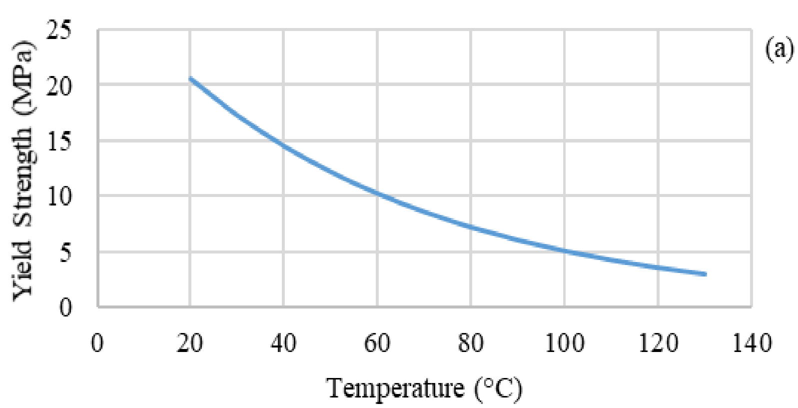
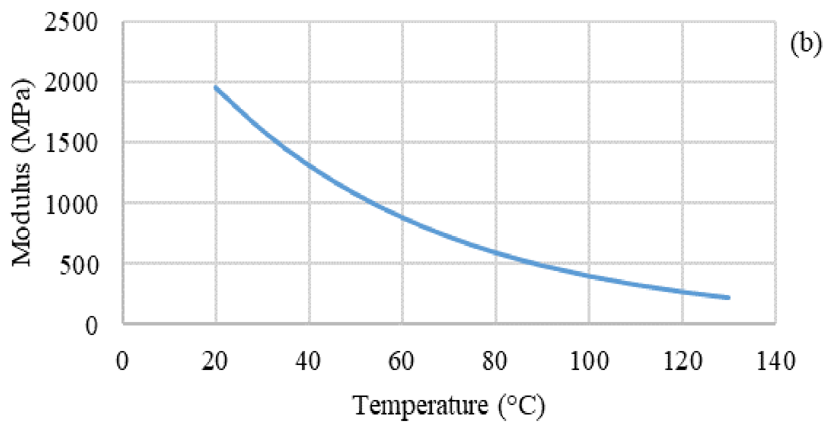
substituted in Equation 1 to obtain the theoretical stress-strain curves for PP as function of incremental strain. Theoretical stress-strain curves were compared with the available experimental curves, and they showed a very small difference. The theoretical stress-strain curves thus generated were given as input for the FE simulations to study the warm deep drawing behavior of PP. The variations of yield strength, modulus and failure plastic strain of PP with increasing temperature at 0.1 s^{-1} strain rate are shown in Figs. 1(a), 1(b) and 1(c) respectively. The variations of yield strength and modulus with temperature were obtained from Equation 2 and were used as input to the FE simulations.

Table 2. Parameters in Eq. (2) to determine the variations in modulus, yield strength and compliance factor β as functions of strain rate and temperature.

	a	*b*	*c*
Modulus (E)	1420	0.07132	-0.01992
Yield strength (σ_y)	15.62	0.0597	-0.0174
β	0.034105	0.005165	0.015245





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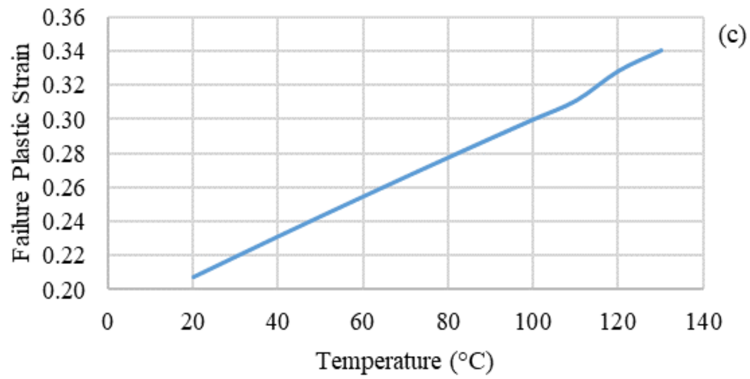

Fig. 1. Variations of (a) yield strength (Eq. 2), (b) modulus (Eq. 2) and (c) failure plastic strain of PP (experimental) as a function of temperature at a strain rate = 0.1 s^{-1} [1].

3. Deep drawing setup

Fig. 2 shows the die-punch setup consisting of an open die, a flat-bottomed punch and an annulus blank holder used in this study. The inside diameter of the die was 52.8 mm, and the punch diameter was 50 mm. For blank holder, the inside and outside diameters were 52.8 mm and 120 mm, respectively. A circular polypropylene blank of 1.2 mm thickness was selected. Since the die opening diameter was 52.8 mm, the die-punch clearance was 1.4 mm. These dimensions were selected based on the guidelines prescribed by Donaldson et al. [12] for sheet metal deep drawing. The die, punch and blank holder material was aluminum.

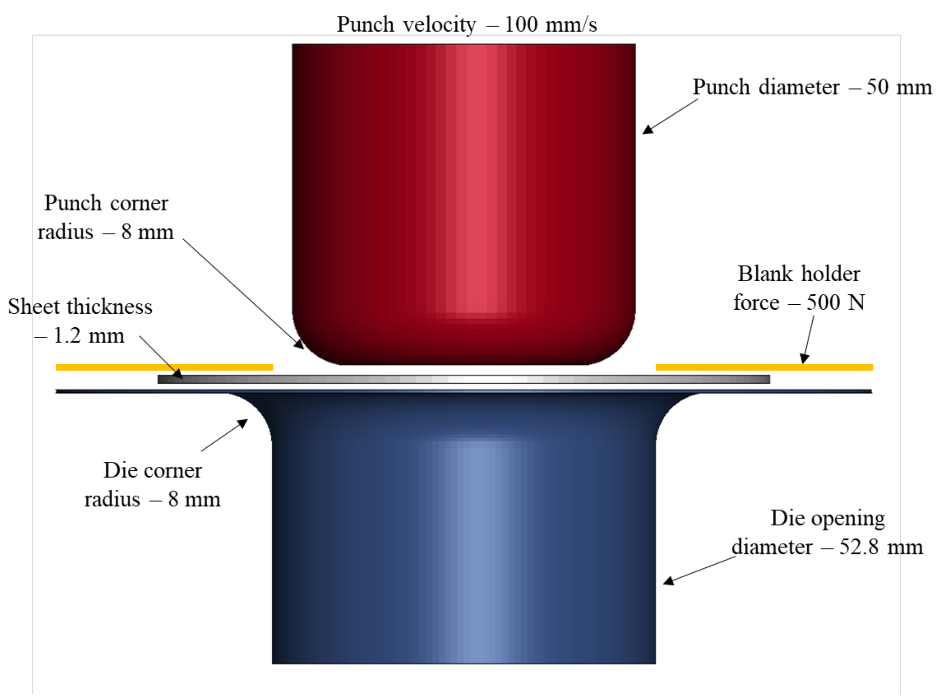

Fig. 2. Deep drawing setup.

Table 3. Deep drawing parameters considered in the study.

Study	Deep drawing parameters
Effect of blank holder force	Blank diameter = 90 mm, Initial blank temperature = 100°C, Punch velocity = 100 mm/s, Die and punch corner radii = 8 mm, **Blank holder force = 200, 500, 1000, 1500 N**.
Effect of initial blank temperature	Blank diameter = 90 mm, **Initial blank temperature = 25, 50, 75, 100 and 125°C**, Punch velocity = 100 mm/s, Die and punch corner radii = 8 mm, Blank holder force = 500 N.
Effect of blank diameter	**Blank diameter = 80, 90 and 100 mm**, Initial blank temperature = 100°C, Punch velocity = 100 mm/s, Die and punch corner radii = 8 mm, Blank holder force = 500 N.
Effect of die corner radius	Blank diameter = 90 mm, Initial blank temperature = 100°C, Punch velocity = 100 mm/s, **Die corner radius = 4, 6, 8, 10 mm**. Blank holder force = 500 N,
Effect of punch corner radius	Blank diameter = 90 mm, Initial blank temperature = 100°C, Punch velocity = 100 mm/s, **Punch corner radius = 4, 6, 8, 10 mm**. Blank holder force = 500 N,

Deep drawing parameters used in the study are listed in Table 3. The first three of these parameters can be considered the process parameters, while the last two are the tool design parameters. For the first three studies, the die and punch corner radii were 8 mm, which was also based on the guidelines given in Ref. [12].

4. Finite element modeling

Deep drawing simulations were conducted using LS-Dyna to study the variations of depth of draw or cup draw depth, punch force, blank temperature distribution, cup thickness and plastic strain with process and tool design parameters listed in Table 3. The mesh size for the die and the punch was selected as 1.5 mm except at the punch and die corners where a higher mesh density was used so that the blank can accommodate the geometrical inconsistencies. For the blank, the mesh size was 1 mm.

The material model used to simulate the behavior of PP during the warm deep drawing operation was MAT_106 (MAT_ELASTIC_VISCOPLASTIC_THERMAL). Since the behavior of PP is both temperature and strain rate dependent; the material model which considers both temperature and strain rate effects was selected. Theoretical stress-strain curves obtained by using Equations 1 and 2 were given as input for the FE simulations. The aluminum die-punch set was modelled using rigid shell elements and material model MAT_20 (MAT_RIGID). Thermal properties of both PP and aluminum, tabulated in Table 4, were incorporated using the material model T_01 (THERMAL_ISOTROPIC).

Blank temperature changes from its initial value as the punch contacts the blank and draws it into the die due to conduction heat transfer between the blank and the punch/die surfaces. Some amount of heat will be generated because of friction at the surfaces of contact, and also due to the plastic deformation of PP. This will also contribute to the changes in the blank temperature with time. Variations of yield strength

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and modulus due to changes in blank temperature were given as inputs for the FE simulations. Examples of such variations are shown in Fig. 1(a) and 1(b). Variation of plastic strain at failure with temperature (Fig. 1(c)) was given as an input to predict failure of the PP blank during the deep drawing operation. Fig. 1(c) was obtained from experimental stress-strain curves of PP which shows that the plastic strain at failure increases with temperature, but the effect of strain rate is relatively small.

Table 4. Thermal properties of aluminum and PP.

Parameter	Aluminum [13]	Polypropylene [14]
Heat Capacity (J/kg. K)	900	1800
Thermal conductivity (W/m. K)	205	0.14

Three regions of contact were considered in the FE simulations: (1) contact between the punch and the blank, (2) contact between the blank holder and the blank, and (3) contact between the die wall and the blank. Friction conditions at these contact areas play an important role in the deformation of PP blanks. Also, the friction conditions will be different at different temperatures and will include sliding friction at lower temperatures and sticking friction at higher temperatures. Friction coefficient variation as a function of temperature shown in Fig. 3 is from the study by Chung et al. [15] and was given as an input for the FE simulations.

Thermal contact conductance value was given as input based on the study conducted by Marotta et al. [16]. The thermal conductance values govern the conduction heat transfer that occurs between the PP and the aluminum surfaces during the deep drawing operation. Thermal contact conductance of PP with aluminum was found to be between 276.7-324 W/m^2. °K [16]. An intermediate value of 300 W/m^2. °K was selected for this study.

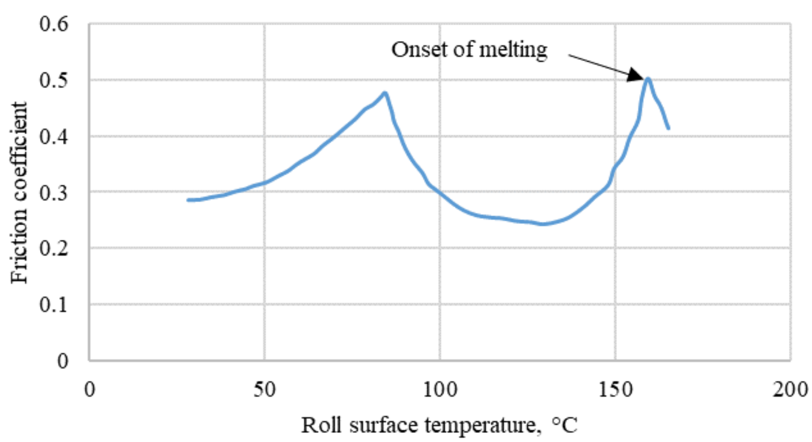

Fig. 3. Friction coefficient between PP and aluminum surfaces as a function of temperature [15].

5. Results

The results of the warm deep drawing simulation studies on PP are reported in this section in terms of the variations of depth of draw or cup draw depth, drawing limit, punch force, blank temperature distribution, cup thickness, and plastic strain. The drawing limit, as defined by Machida and Lee [7], is equal to $\left[1-\left(\frac{d_f}{d_o}\right)\right]$, where d_f is the final flange diameter and d_o is the initial blank diameter. The failure modes and failure locations in deep drawn cups are also identified for each of the five studies conducted.

5.1 Blank holder force

Blank holder force plays a very important role in deep drawing since it affects the flow characteristics of a circular blank. As the blank is drawn into the die, its flange is subjected to tensile stress in the radial direction and compressive stress in the circumferential direction [1]. There is also a compressive stress in the thickness direction of the blank, which is equal to the blank holder force per unit surface area of the blank. Too low a blank holder force does not offer enough resistance for the flow of the blank material against the dies, which in turn leads to lesser stretching of the blank, can cause the edges of the blank to lose contact with the blank holder and result in the formation of wrinkles due to circumferential compressive stress. Too high a force may prevent the flow of the blank material into the space between the die and the punch and can cause failure of the blank due to excessive thinning and tearing at or near the die corner due to high radial tensile stress. In this study, blank holder forces considered were 200 N, 500 N, 1000 N and 1500 N. The cup draw depths attained just before failure at these blank holder forces are given in Table 5 and the locations of failure are shown in Fig. 4.

Table 5. Draw depth just before failure and failure locations at different blank holder forces (at 100°C initial blank temperature)

Blank holder force	200 N	500 N	1000 N	1500 N
Draw depth attained before failure (mm)	12.89	18.87	18.34	17.31
Max. punch force (N)	1371.4	2476.4	2705.5	2843.2
% max. thickness reduction, minimum thickness	5% 1.14 mm	7.5% 1.11 mm	9.17% 1.09 mm	15.84% 1.01 mm
Drawing limit = (1- d_f/d_o)	0.0649	0.1391	0.1160	0.0940
Failure	Wrinkling in the flange area	Plastic strain exceeding failure strain at the top corner radius		Tearing at the bottom corner radius

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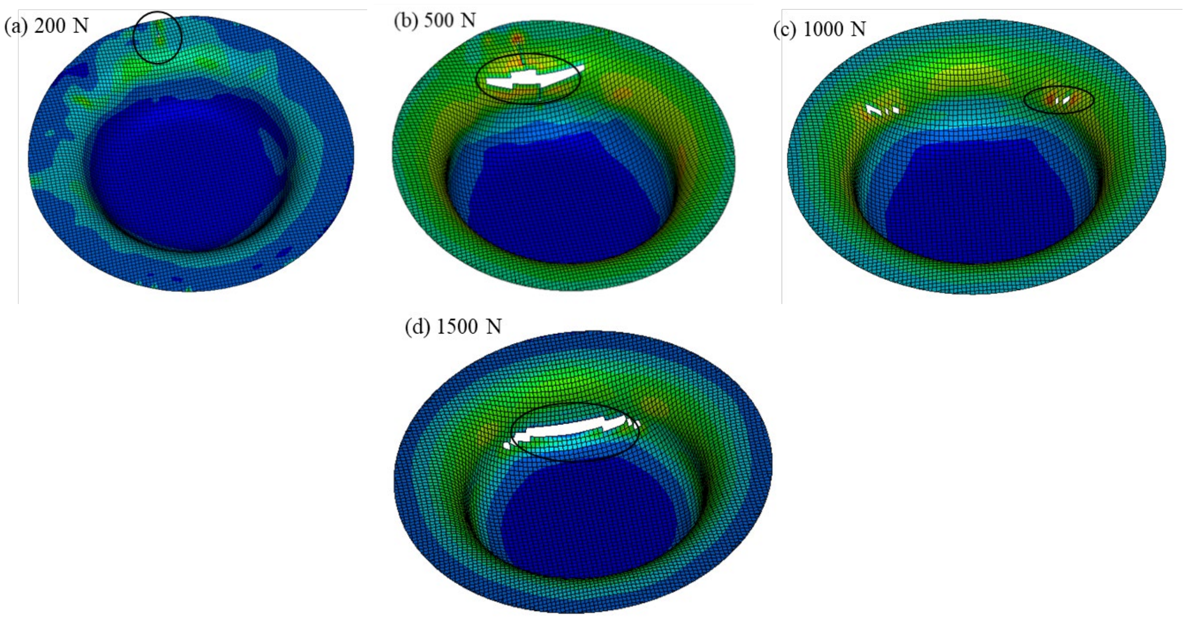

Fig. 4. Failure location at different blank holder forces.

Failure in the blank at 200 N blank holder force can be attributed to the formation of wrinkles in the flange area. Failure at 500 and 1000 N blank holder forces was observed when the plastic strain in the PP cup at the top corner radius exceeds the failure limit. At 1500 N blank holder force, the failure can be attributed to excessive thinning and tearing of the blank along the cup wall near the bottom corner radius due to high resistance to the flow of the blank material. The highest depth of draw just before failure was observed with 500 N blank holder force. Similar observation can be made by considering the variation of drawing limit as a function of blank holder force plotted in Fig. 5. It shows that at a blank temperature of 100°C, the highest drawing limit is obtained at 500 N blank holder force.

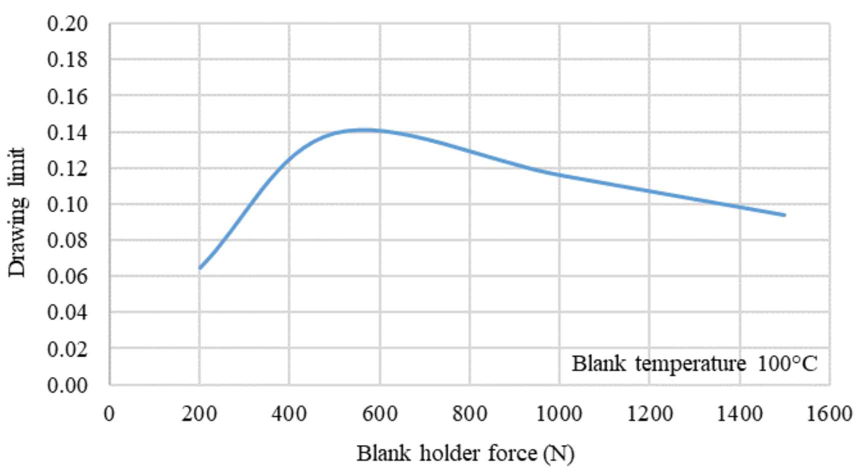

Fig. 5. Drawing limit as a function of blank holder force for a blank diameter of 90 mm and initial blank temperature of 100°C.

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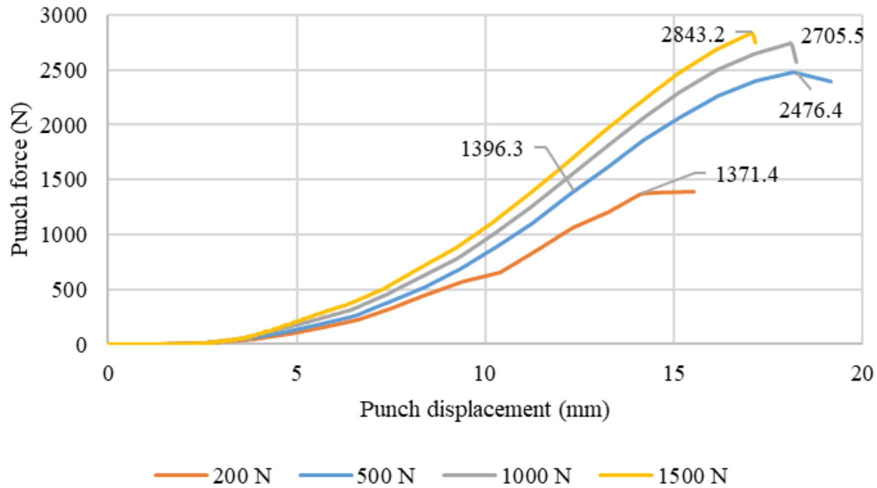
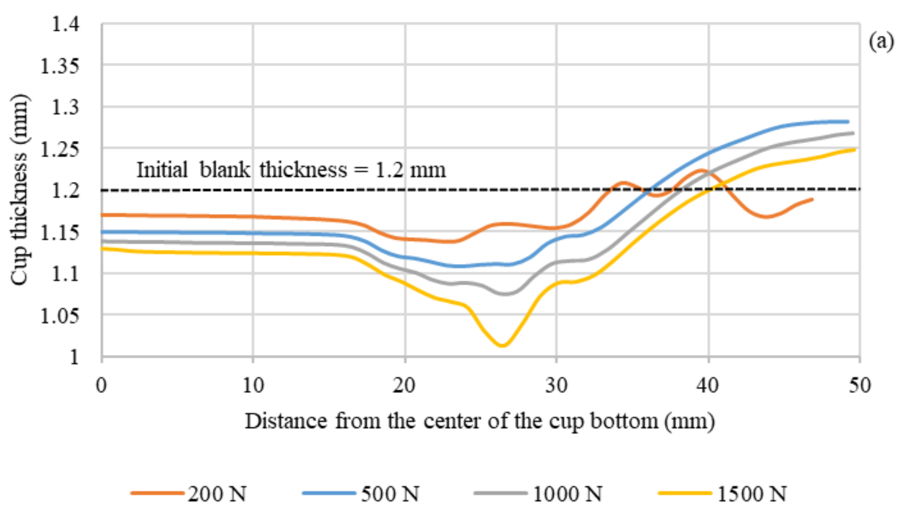


Fig. 6. Effect of blank holder force on punch force vs. punch displacement diagrams.

Fig. 6 shows the effect of blank holder force on punch force vs. punch displacement diagrams. The punch force required to deep draw the blank increases with increase in blank holder force which can be attributed to the higher resistance offered by the material to the drawing of the blank. Sudden drop in load is due to the failure of the blank which is either due to wrinkling, plastic strain exceeding the failure strain or excessive thinning and tearing of the blank.



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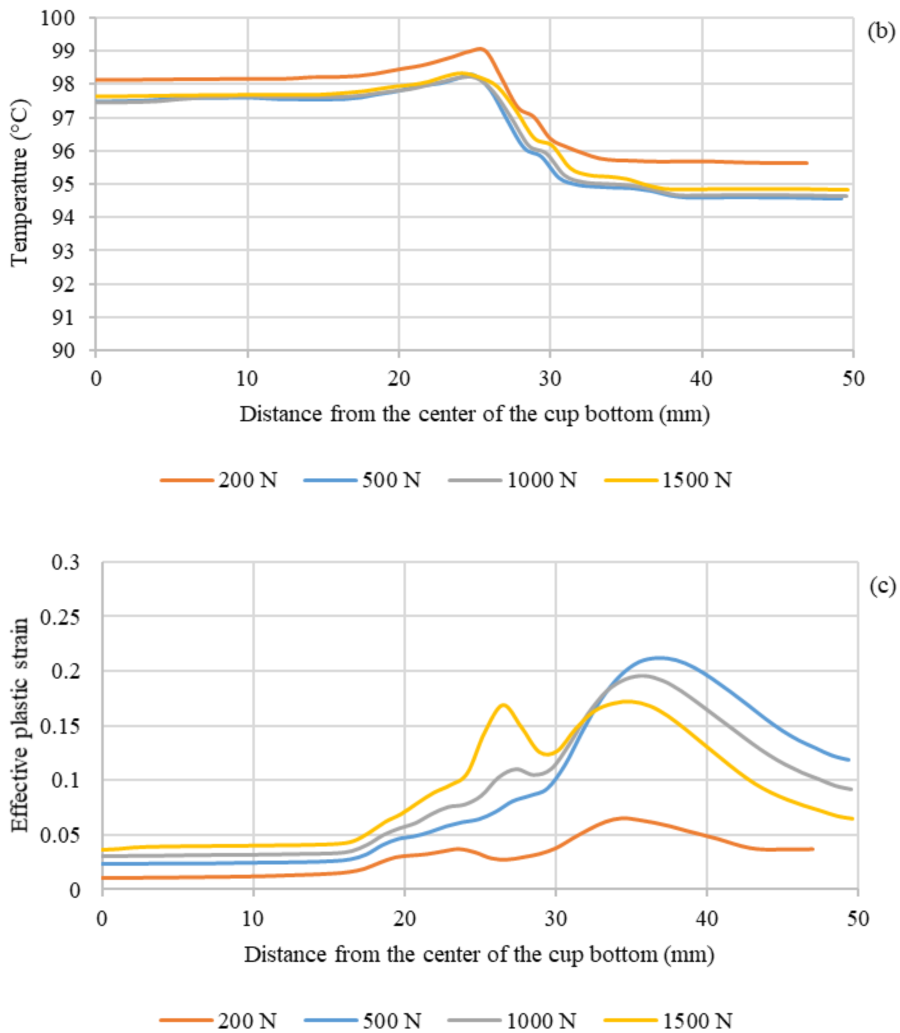

Fig. 7. Variations in (a) cup thickness, (b) temperature distributions and (c) effective plastic strain in deep-drawn cups at different blank holder forces (Blank dia. = 90 mm, initial blank temp. = 100º C, and time=just before failure).

Thickness variations in the deep-drawn cups at the draw depths attained just before failure are plotted in Fig. 7(a) along the distance from the center of the cup bottom to the end of the flange. Thickness in the cup bottom and cup wall decreased with increasing blank holder force. Increase in cup thickness in the flange area was lower at higher blank holder forces (Fig. 7(a)) due to increased resistance to the flow of the blank material and higher compressive stress in the thickness direction. At 200 N blank holder force, cup thickness shows very little variation, since the blank failed at a lower draw depth due to the formation of wrinkles in the flange area. At 1500 N blank holder force, decrease in thickness of the cup wall was higher due to a higher amount of stretching of the blank as it is drawn into the die. The highest thinning occurred at the bottom corner radius of the cup where the wall thickness was 1.013 mm, a 16% decrease from the initial sheet thickness of 1.2 mm. Higher thinning and thickness variations were observed in both thermoforming and plug-assist thermoforming of polypropylene as reported by O'Connor et al. [17]. In experiments and numerical modeling, they observed more than 50% decrease in the wall thickness of tapered cups that were thermoformed using 1.23 mm initial sheet thickness and at 150-160ºC temperature range.

Temperature distribution profiles at the cup bottom and cup wall shown in Fig. 7(b) were found to be similar for deep drawing with 500 N, 1000 N and 1500 N blank holder forces. Deep drawing with 200 N blank holder force shows a lower drop in temperature which can be attributed to the failure of the blank at a lower draw depth and therefore, a shorter time of contact with the punch. Temperature along the flange showed a higher drop compared to the cup bottom since the flange area is in contact with both blank holder and die, while the cup bottom is only in contact with the punch. The highest temperature was found along the bottom corner radius which can be attributed to the heat generation due to thinning and due to lesser contact surface area.

Effective plastic strain variations in deep drawn cups are shown in Fig. 7(c). Plastic strain at the cup bottom was found to increase only slightly with blank holder force, since the cup bottom does not experience much stretching. Plastic strains are much higher in the cup wall due to increased amount of stretching with increasing blank holder force. They reach a peak at the die entry radius where the blank undergoes bending and unbending. For deep drawing at 1500 N blank holder force, the plastic strain at the die entry radius was found to be less compared to those at 500 and 1000 N, but higher in the cup wall near the bottom corner radius which is the failure location in the cup at 1500 N blank holder force. Fig. 7(c) also indicates that stretching and thinning of the blank increase with increase in blank holder force.

5.2 Initial Blank Temperature

Blank temperature plays an important role in deep drawing of PP sheets, since decreasing the blank temperature decreases the failure strain of PP and increasing the blank temperature too high can cause the PP blank to lose its stiffness and cause sagging before the punch comes in contact with the blank. In this section, deep drawability of PP sheet is studied at five different initial blank temperatures, namely 25°C, 50°C, 75°C, 100°C and 125°C. The blank holder force was maintained at 500 N. The draw depths with these five initial blank temperatures are reported in Table 6. It can be observed in this table that the draw depth increased with increasing initial blank temperature, which is due to higher failure plastic strain at higher temperatures.

Failure in the flange area (Fig. 8) with initial blank temperatures at 25°C, 50°C and 75°C can be attributed to the blank exhibiting higher stiffness at these temperatures and therefore, offering higher resistance to flow. Draw depth attained at 25°C is low due to low failure strain of PP at this temperature. Wrinkles were also observed on the flange surface at 50°C and 75°C. For deep drawing at 100°C and 125°C,

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failure occurred at the top corner radius when the strain exceeded the respective failure strain. The draw depth attained before failure increases with increase in initial blank temperature as can be seen in Table 6. Drawing limit as a function of blank temperature is plotted in Fig. 9 for a blank diameter of 90 mm and a blank holder force of 500 N. It shows a slowly increasing trend with blank temperature like that observed by Machida and Lee [7] in their deep drawing experiments with propylene-ethylene copolymer under isothermal heating conditions. The drawing limit values are similar to the experimental values reported in their work [7].

Table 6. Draw depth just before failure and failure location at different initial blank temperatures (with blank holder force at 500 N)

Initial blank temperature	25°C	50°C	75°C	100°C	125°C
Draw depth attained before failure (mm)	10.63	11.33	13.79	18.87	20.64
Max punch force (N)	1674.3	1516.0	1686.1	2476.4	1618.3
% max. thickness reduction, minimum thickness	*	12.5% 1.05 mm	12.5% 1.05 mm	7.5% 1.11 mm	10% 1.08 mm
Drawing limit = (1- d_f/d_o)	0.0433	0.0482	0.0744	0.1391	0.1471
Failure	Strain exceeding failure strain in flange area			Strain exceeding failure strain at top corner radius	

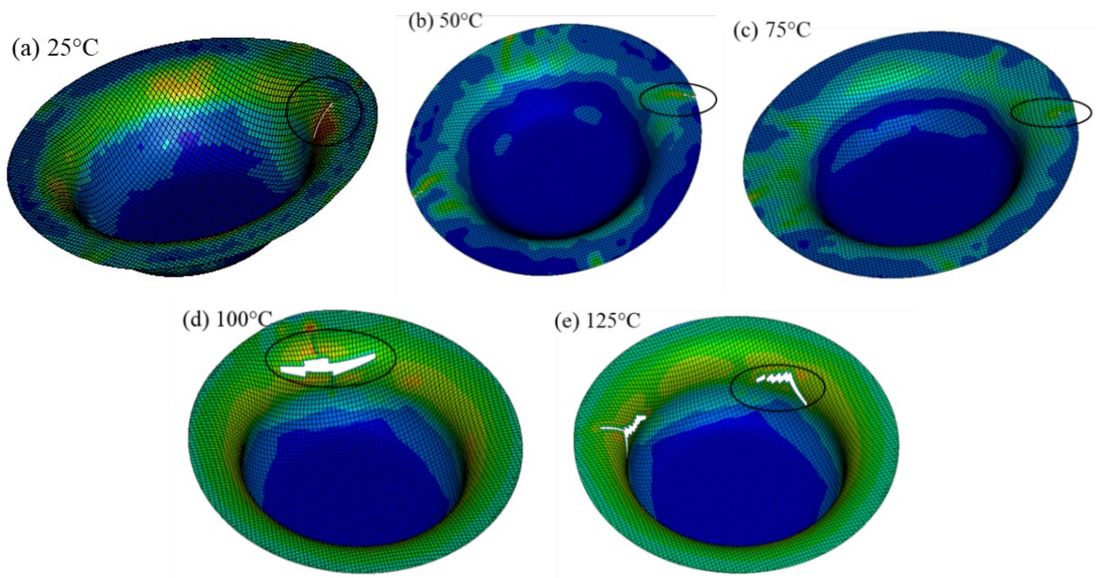

Fig. 8. Failure locations at different initial blank temperatures.

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The punch force required to draw the PP blank decreases with increasing initial blank temperature. Decrease in the slopes of the punch force vs. punch displacement diagram can be attributed to lower stiffness and lower stress-strain behavior of PP at higher temperatures so that the force required to produce the deformation in the blank decreases with increase in initial blank temperature.

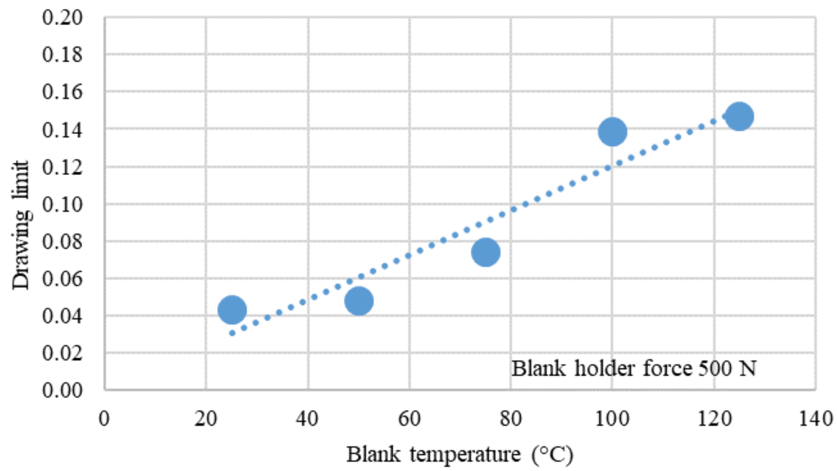
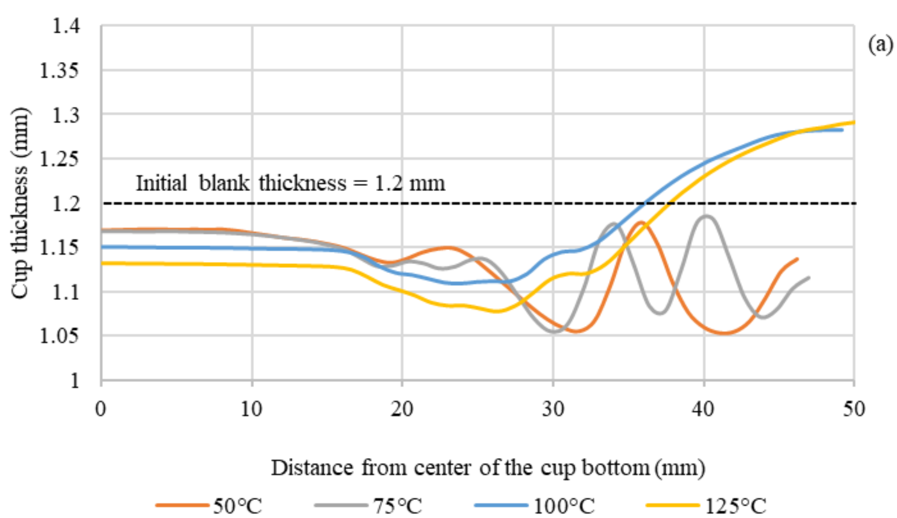


Fig. 9. Drawing limit as a function of blank temperature for a blank diameter of 90 mm and a blank holder force of 500 N.



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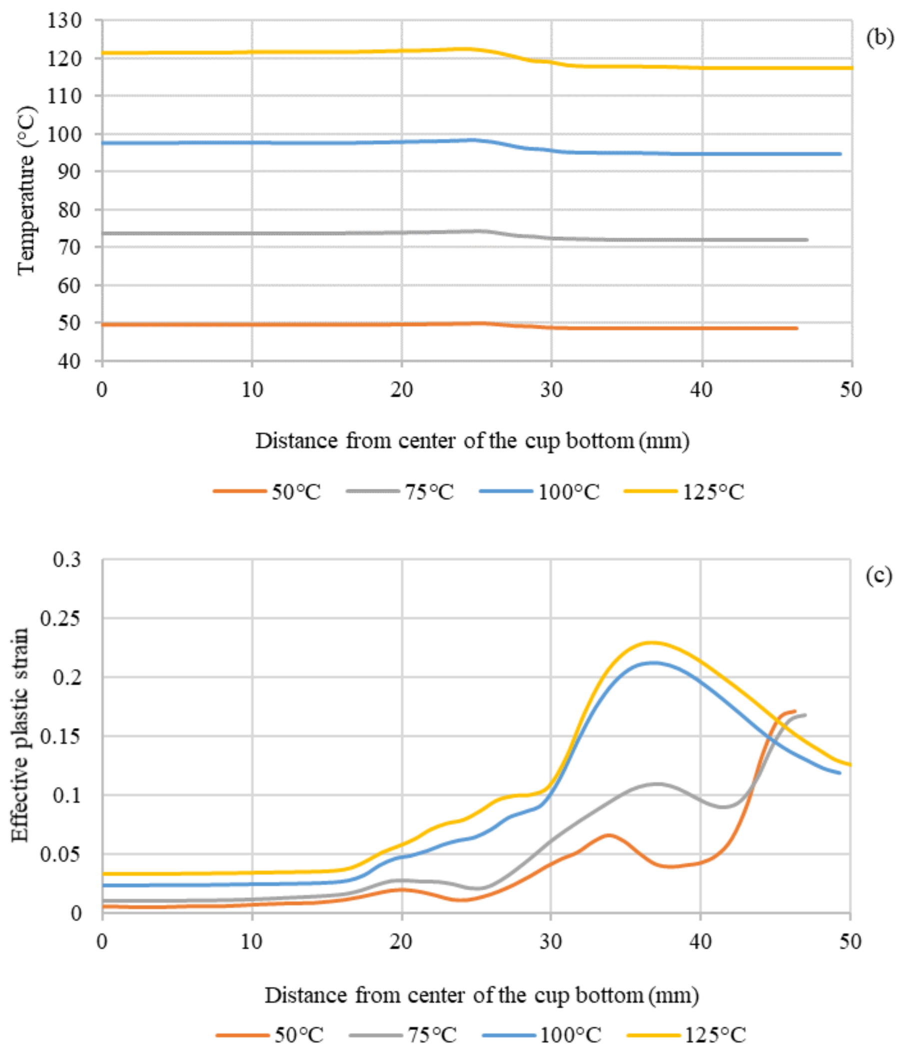

Fig. 10. Variations in (a) cup thickness, (b) temperature distributions and (c) effective plastic strain in the deep drawn cups for deep drawing at different initial blank temperatures (Blank holder force = 500 N, blank dia. = 90 mm and time = just before failure).

Fig. 10 shows the variations in cup thickness, temperature, and effective plastic strain at the draw depth before failure for deep drawing at different initial blank temperatures. Cup thickness variation plots in Fig. 10(a) show that deep drawing at 100°C and 125°C have the lowest thickness along the cup wall near the bottom corner radius indicating stretching and thinning, while deep drawing at 50°C and 75°C produces the lowest cup thickness in the flange area and the top corner radius indicating lower deformation due to higher stiffness of the PP blank material at these temperatures. The up and down thickness variations in the flange area at 50°C and 75°C occur due to periodic fold formation. Cup thickness variation for blanks at 50°C and 75°C showed almost a similar trend. Along the cup bottom, the blank at 125°C showed a greater decrease in blank thickness compared to 100°C.

Heat lost by the blank to the die-punch set up due to conduction heat transfer increases with increase in temperature as can be seen from Fig. 10(b). At higher temperatures, there is a clear distinction between the regions for contact of the blank with die-punch set up, while at lower temperatures, the temperature distribution profile was found to be almost linear with no variation. The little variation in the temperature profiles for 50°C and 75°C blank temperatures can be attributed to the failure of blank at lower draw depths, thus reducing the time of contact for the conduction heat transfer to occur.

Plastic strain variations show that the maximum strain occurred at the top corner radius irrespective of the initial blank temperature as can be seen from Fig. 10(c). At this location, the blank bends first and then unbends as it enters the space between the punch and the die. For deep drawing at 50°C and 75°C, plastic strain in the flange area was found to be almost the same as the strain at the top corner radius which can be attributed to a higher stiffness of the blank at lower temperatures. Along the cup bottom, plastic strain increased with increase in initial blank temperature.

5.3 Blank Diameter

Selection of blank diameter depends on the draw depth required and on the die design. Higher draw depth can be attained with higher blank diameter, but care must be taken to ensure that the die-punch setup is able to accommodate the increase in flange thickness which will occur with increase in blank diameter. Process variables suitable for a particular blank diameter may not be suitable for another blank diameter. Also, a higher blank diameter increases the frictional resistance against radial flow of the blank because of the increased surface area of contact between the blank and the die, while press forming with lower blank diameter causes the blank to lose contact with the blank holder at lower draw depths which leads to the formation of wrinkles at the flange surface or on the top rim of the cup and subsequent failure of the blank. Hence, determination of the correct blank diameter suitable for deep drawing under given process conditions is very important. Note that the punch and die inner diameters were held constant for these experiments at 50 and 52.8 mm, respectively. The blank holder force was maintained at 500 N. However, as the blank diameter was increased, the blank holder force per unit contact area of the blank was decreased.

To determine the effect of blank diameter on draw depth, three different blank diameters, namely 80 mm, 90 mm, and 100 mm, were considered with the initial blank temperature at 100°C and the blank holder force at 500 N. Table 7 lists the draw depths attained just before failure and the failure locations for deep drawing with different blank diameters. Failure locations are shown in Fig. 11.

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Table 7. Draw depth just before failure and failure location for different blank diameters
(at 100°C initial blank temperature and 500 N blank holder force)

Blank diameter	80 mm	90 mm	100 mm
Draw depth attained before failure (mm)	16.49	18.87	13.38
Max. punch force (N)	1650.4	2476.4	1656.0
% max. thickness reduction, minimum thickness	5% 1.14 mm	7.5% 1.11 mm	6.67% 1.12 mm
Failure	Plastic strain exceeding failure strain at the top corner radius		Wrinkling in the flange area

Failure of the 80 mm diameter blank occurs when the flange area of the blank loses contact with the blank holder. For the 90 mm blank diameter, failure was observed at the top corner radius where the blank entered the space between the punch and die. For the 100 mm blank diameter, failure occurred at a lower draw depth compared to 90 mm which is due to the initiation of flange wrinkling attributed to a combination of lower blank holder force per unit contact area with the blank holder and lower modulus of the material at 100°C.

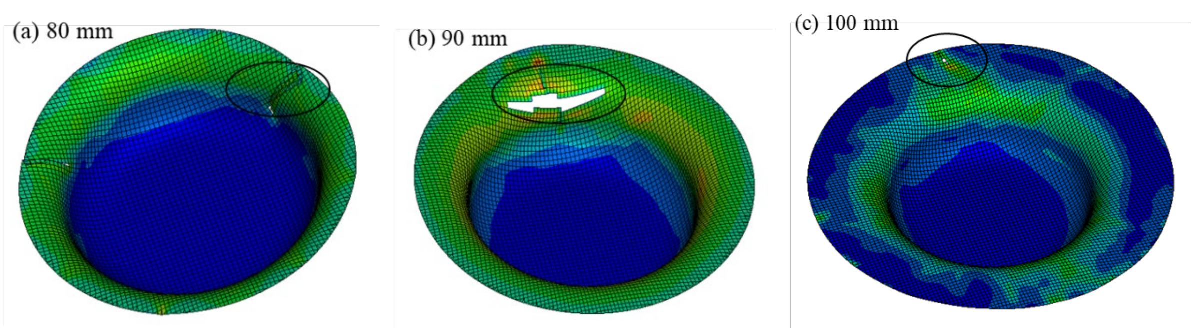

Fig. 11. Failure location for different blank diameter.

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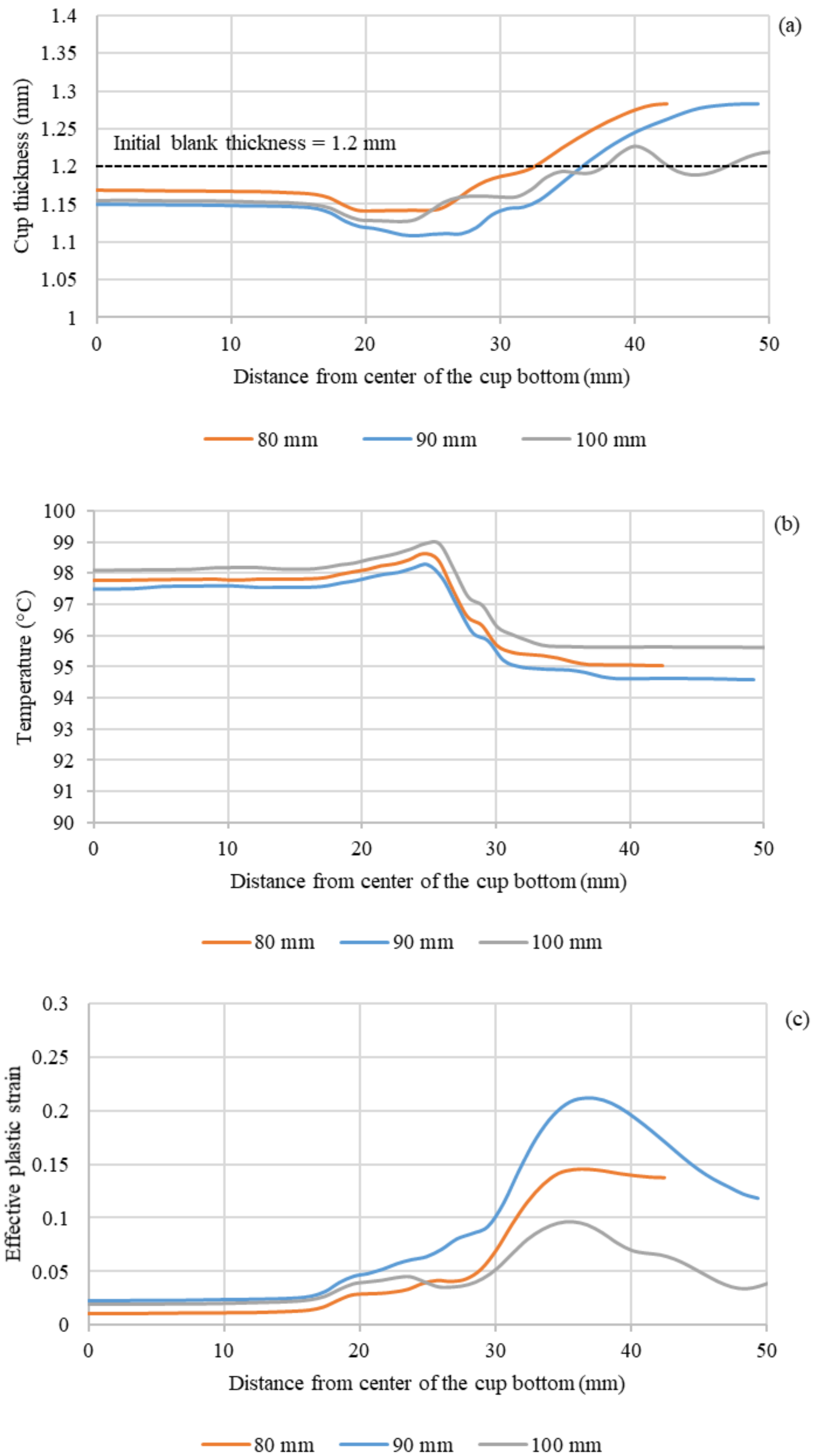

Fig. 12. Variations in (a) cup thickness, (b) temperature distribution and (c) effective plastic strain variations for different blank diameters (Blank holder force = 500 N, initial blank temp. = 100ºC, and time = just before failure).

Fig. 12(a) shows the variation of the cup thickness just before failure along the distance from center of the cup bottom to the flange region. Cup thickness variation was found to be lower for 80 mm and 100 mm diameter blanks when compared to 90 mm diameter blank (Fig. 12a). For the 80 mm blank, the lower variation in thickness can be attributed to the less surface area of the blank in contact with the lower die and blank holder, which did not cause enough stretching of the blank material and for the 100 mm blank, the lower variation in blank thickness can be attributed to failure at a lower draw depth.

Temperature distribution was found to be similar irrespective of blank diameter as can be seen from Fig. 12(b). Small variations in the temperature distribution can be attributed to the failure of the blanks at different draw depths and therefore, different times of contact between dies and the blank. For all the blanks, the lowest temperature was recorded in the flange area and the highest at the cup wall near the bottom corner radius. Plastic strain variation plots until failure for different blank diameters show that irrespective of the blank diameter, the maximum strain occurs at the top corner radius which can be observed in Fig. 12(c).

The effects of the tool design parameters, die corner radius and punch corner radius, are discussed below. For brevity, the results are presented in table form.

5.4 Die corner radius

In deep drawing, the die corner radius should be as large as possible to permit smooth flow of PP into the space between the die and the punch as it passes over the die corner radius. However, if it is too large, the blank will lose contact with the blank holder too soon and wrinkling will result in the deep drawn cups. Too sharp a radius will hinder the normal flow of the material, increase the stresses at the cup corner, and cause uneven thinning and tearing of the cup wall.

In this section, deep drawability of PP sheet is studied for four different die corner radii of 4, 6, 8 and 10 mm with a blank holder force of 500 N, initial blank temperature of 100°C and punch corner radius of 8 mm. Table 8 lists the draw depth just before failure, % of max thickness reduction and locations of failure for four different die corner radii.

The draw depth increased with increasing die corner radius and achieved the highest value at 10 mm die corner radius. Failure in the blank for deep drawing with 4 mm die corner radius occurred due to circumferential buckling along the flange area as the sharp die corner radius restricts the flow of the blank material into the space between the die and the punch. Failure for die corner radius of 6 and 8 mm was observed along the die entry radius. Deep drawing with 10 mm die corner radius showed progressive failure, with failure originating along the top corner radius and progressing over the flange area.

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Table 8. Draw depth just before failure and failure location at different die corner radii (at 500 N blank holder force).

Die corner radius	4 mm	6 mm	8 mm	10 mm
Draw depth attained just before failure (mm)	13.09	17.07	18.87	20.67
Max. punch force (N)	1704.7	2463.7	2476.6	2394.3
% max. thickness reduction, minimum thickness	17.5% 0.99 mm	9.17% 1.09 mm	7.5% 1.11 mm	9.17% 1.09 mm
Failure	Wrinkling in the flange area	Strain exceeding failure strain at the top corner radius		

5.5 Punch corner radius

The convexity of the punch corner radius affects the final shape of the bottom of the drawn cup. A sharper radius will require a higher punch force when the blank is folded around the punch corner and result in excessive thinning or tearing at the bottom corner of the cup. A larger radius may distort the shape and produce close to an oval-shaped cup bottom instead of a flat cup bottom. In this section, deep drawability of PP sheet is studied at four different punch corner radii of 4, 6, 8 and 10 mm with the applied blank holder force at 500 N, the initial blank temperature of 100°C and a die corner radius of 8 mm.

Table 9. Draw depth just before failure and failure region at different punch corner radii (at 500 N blank holder force).

Punch corner radius	4 mm	6 mm	8 mm	10 mm
Draw depth attained just before failure (mm)	17.83	18.20	18.87	19.24
Max. punch force (N)	2557.2	2535.0	2476.4	2355.1
% max. thickness reduction, minimum thickness	19.42% 0.96 mm	10.66% 1.08 mm	9.99% 1.08 mm	9.20% 1.09 mm
Failure	Strain exceeding failure strain at the die entry radius			

The cup draw depths attained just before failure, % of max thickness reduction and the locations of failure at different punch corner radius are given in Table 9. Failure in the deep drawn cup with different punch corner radius was observed to occur at the top corner radius of the cup due to the plastic strain exceeding the failure strain. Changes in draw depth with increasing punch corner radius were relatively small compared to the changes observed with increasing die corner radius.

6. Summary and conclusions

A numerical study of warm deep drawing characteristics of a polypropylene homopolymer was conducted using a circular blank to form a cylindrical cup with flat round bottom. The forming temperatures and forming speed were selected such that the cups can be formed in a short processing cycle time. Effects of the three most important process parameters, namely blank holder force, initial blank temperature, and blank diameter, on drawing depths, failure modes and final thickness distribution were determined. Depending on the parameters, the failure modes observed in the deep drawn cups were flange wrinkling, tearing at the top corner radius and tearing at the end of the vertical wall. In most cases, the cup wall thickness was the lowest at the top of the bottom corner radius and highest in the flange area. Wall thinning and thickness variation were observed to be lower than those observed in thermoforming of polypropylene.

With increasing blank holder force, the punch force required to deep draw polypropylene increases. At low blank holder forces, failure occurs due to wrinkling, while at higher blank holder forces, excessive thinning along the cup wall results in failure by tearing. There is an optimum blank holder force at which the maximum draw depth is obtained.

The higher the initial blank temperature, the higher is the draw depth which can be attributed to increased plastic deformation, reduction in stiffness of the blank, and increase in failure strain with increase in blank temperature. Hence the optimal values of the blank temperature must be considered such that the behavior exhibited by polypropylene is not too stiff, yet the maximum blank temperature is below its melting point.

Changing the blank diameter requires selection of the parameters such as blank holder force and die-punch setup (die corner radius and punch corner radius) that would yield the largest draw depth just before failure. For low blank diameter, the blank holder force may not be sufficient to cause enough stretching in the blank and an early release of the blank from the blank holder will lead to failure by wrinkling. For deep drawing of blanks with large diameter, resistance offered to the flow of the material increases which is due to an increase in surface area and care must be taken to ensure that the die-punch set up is able to accommodate the increase in flange thickness.

Out of the two tool design parameters considered in the study, the die corner radius has much larger effect on draw depth compared to the punch corner radius. It was observed that the increasing the die corner radius increases the draw depth; however, if the die corner radius is too large, the cup will have a tendency to slip off without forming a smooth flange.

Other parameters that may increase the draw depth of polypropylene are its material parameters, such as higher failure strain at forming temperatures, and process parameters, such as differential heating in which the flange and the punch area of the blank are initially at different temperatures. In general, polypropylene copolymers have higher failure strains and it is expected that their draw depth will be higher

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than that of polypropylene homopolymer. The experimental work by Machida and Lee [7] has shown the benefit of differential heating; however, more research needs to be done to fully understand the deep drawing characteristics of polypropylene and other polymers under differential heating conditions.

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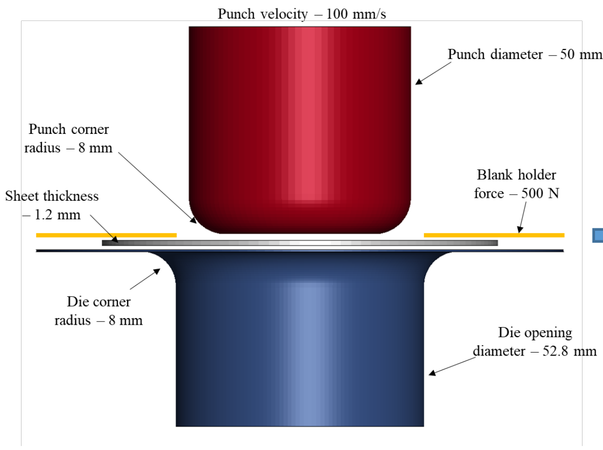
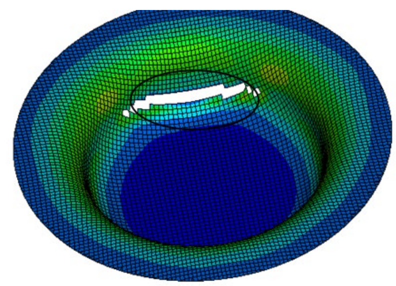
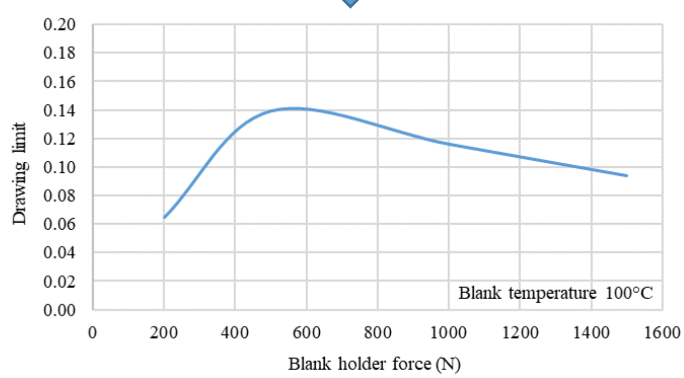
Graphical Abstract



Deep drawing setup



Failure location



Drawing limit showing optimum blank holder force

Warm deep drawing of polypropylene, a semi-crystalline thermoplastic polymer, is studied using finite element analysis. In this process, a circular polypropylene blank is preheated to a temperature much below its melting temperature and deep drawn into the shape of a flat-bottom cylindrical cup using a punch-die combination, both initially at 25°C. The material model used for the analysis considers the effects of varying temperature and strain rate during the deep drawing process on the depth of draw. The effects of blank holder force, initial blank temperature, blank diameter, and die and punch corner radii on the depth of draw are determined. Thickness, temperature and strain variations in the drawn cups, punch forces, and failure modes are also determined.