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ORIGINAL ARTICLE

Improving deep drawability of HC300LA sheet metal by warm forming

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Abstract The formability of high-strength sheet materials is limited at room temperatures. In this study, the first of its kind to be conducted, experimental research was performed on the formability of HC300LA-grade sheet material using the warm deep drawing (WDD) method. Temperature control is among the most important parameters in the WDD method. To increase the limiting drawing ratio (LDR) of HC300LA-grade sheet material, a new warm deep drawing method featuring sensitive temperature control was designed and manufactured. With this new method, the formability of HC300L-grade sheet material was considerably increased by heating the flange zone of the blanks under blank-holder force (BHF). Before the experimental study, unidirectional tensile tests were applied at room temperature (RT), 150 °C, and 300 °C. At the completion of the test conducted at 300 °C, dynamic strain aging (DSA) was seen in the test specimen. As a result of DSA, the HC300LA-grade sheet material became brittle and its formability decreased. Experimental studies were therefore conducted in the temperature range of 170 and 295 °C. LDR for a 1.2-mm sheet thickness of HC300LA-grade sheet material, which is 2.14 at RT, increased to 2.61 after applying this method. In experimental studies on LDR involving 1.5-mm sheet thickness, which is 2.15 at RT, the ratio increased to 2.59. The drawing ratio (DR) increased by 21.96 and 20.45 % for 1.2 mm sheet thickness and 1.5 mm sheet thickness, respectively. Moreover, the microstructures of the warm cup's punch corner region, and wall and bottom regions were investigated under an optical microscope. The results showed whether any changes occurred in the microstructures.

Keywords Warm deep drawing · Microstructure · LDR · HC300LA

1 Introduction

Sheet metal forming is defined as either the ability of material to deform plastically or the conversion of the sheet metal into a required shape without necking or cracking. The material properties, such as yield strength, elastic modulus, anisotropy and strain hardening coefficient, and the process parameters, as punch and die geometry, lubrication, punch speed, and blank-holder force (BHF) serve a vital role in all of the sheet metal forming operations, as they ultimately determine the forming quality. Therefore, to ensure that the sheet metal forming process is successful, suitable material must be selected and the optimum forming parameters determined. The common sheet metal forming processes that can be used to achieve the simple and complex procedures are blanking and piercing, bending, stretch forming, extrusion, stamping, deep drawing, tube forming, fluid forming, coining, and ironing. Sheet metal parts (automotive and aerospace applications) that are produced by stretch forming tend to be stiff and have a good strength to weight ratio. However, for any given process and deformation geometry, the forming limits vary from material to material. The basic concern is whether the desired deformation can be accomplished without causing functional failure of the work piece. Research and development studies, therefore, continue to be conducted in order to evaluate the forming limits of the sheet metals [1–4].

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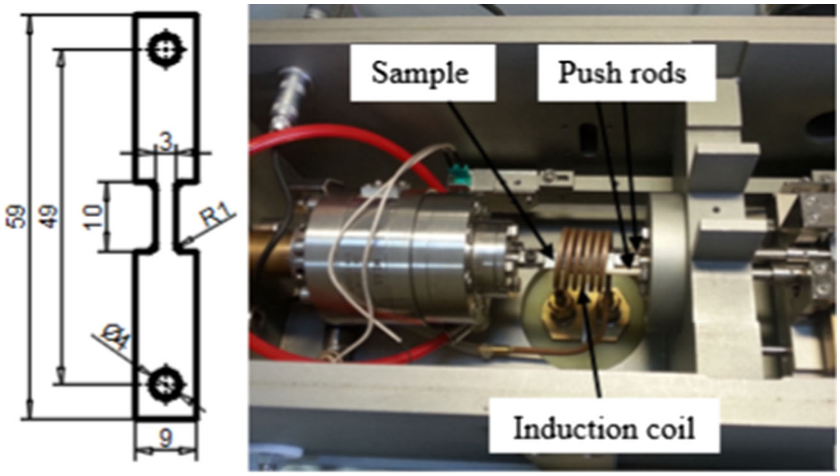


(a) (b)

Fig. 1 **a** The dimensions of the tensile test specimen and **b** top view of dilatometer assembly

Deep drawing is an important and popular process used in the assessment of formability of sheet metal [5]. Serkan T. et al. conducted research on (Al–Mg) alloys and observed that at room temperature (RT), the surface quality of the final products of this alloy material was poor. After tests were conducted in warm conditions, at temperatures ranging from 200 to 300 °C, the formability of these alloys increased, resulting in a better surface quality of the final product [6]. Patrick et al. found that below the recrystallization temperature under warm conditions, complex shapes can be drawn easily and with better quality by using elevated temperatures [7]. Recently, Singh et al. investigated the formability of extra deep drawing (EDD) steel under warm conditions at elevated temperatures and found that there was a rapid increase in the formability of EDD steel as the temperature of the material increased [8]. And lastly, Pellegrini et al. studied the effect of warm-forming conditions to determine the best combination of process parameters within the warm-forming temperature range [9].

The examples presented above demonstrate in part that most of the previous studies on warm forming have focused on the formability of aluminum, magnesium alloys, and stainless steels. The literature on this subject, however, features no studies on the warm formability of HC300LA-grade steel, which is widely used in many industries.

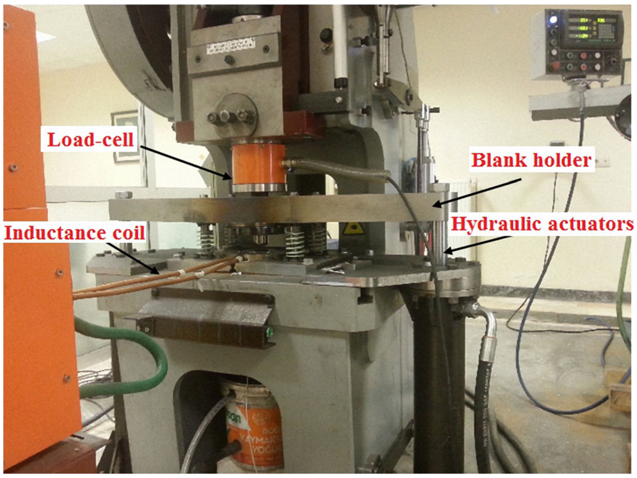


Fig. 2 80T mechanic eccentric press test rig

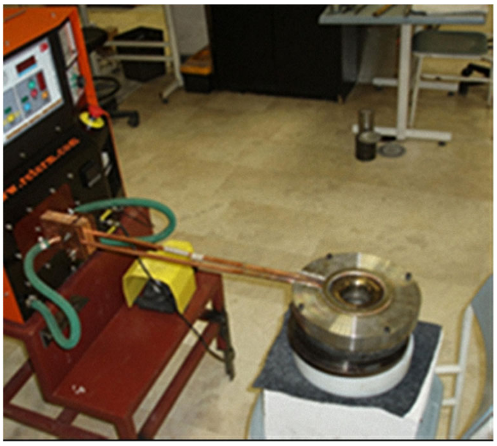


Fig. 3 Induction annealing machine

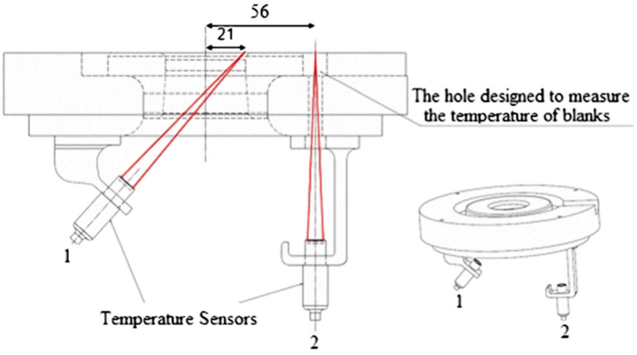


Fig. 4 Die heater configuration

In this study, the deep drawability of HC300LA-grade steel using the warm deep drawing (WDD) method was investigated experimentally. In applying the WDD method, the heating of the flange region of the circular blank specimens and the cooling of the punch contact region are important parameters for increasing deep drawability. A new method, unlike any used in previous studies on warm forming, has been developed in this study for conducting both heating and cooling processes. The heating time of the circular blank specimen and the mold is reduced by using induction heating, which lowers energy consumption and oxidation in the circular blank specimen. In the developed cooling system, the punch contact region of sheet metal is cooled by water droplets fed through an orifice on the top opened in the punch core and through a sprinkler on the bottom side of the test piece.

2 Experimental studies

2.1 Materials

In this study, HC300LA-grade, cold-rolled, and annealed high-strength low-alloy sheet metal of 1.2 and 1.5 mm nominal thickness was selected as the experiment material. The chemical composition of the material was 0.035 % C,

Table 1 The main dimensions of tools for deep drawing tests

Sheet material (HC420LA)	For 1.2 mm thickness	For 1.5 mm thickness
Punch diameter, d_p (mm)	42.12±0.05	40.89±0.05
Punch radius, r_p (mm)	6±0.1	8.125±0.1
Die hole diameter, d_d (mm)	45±0.05	44.63±0.05
Die radius, r_d (mm)	6±0.1	8.125±0.1

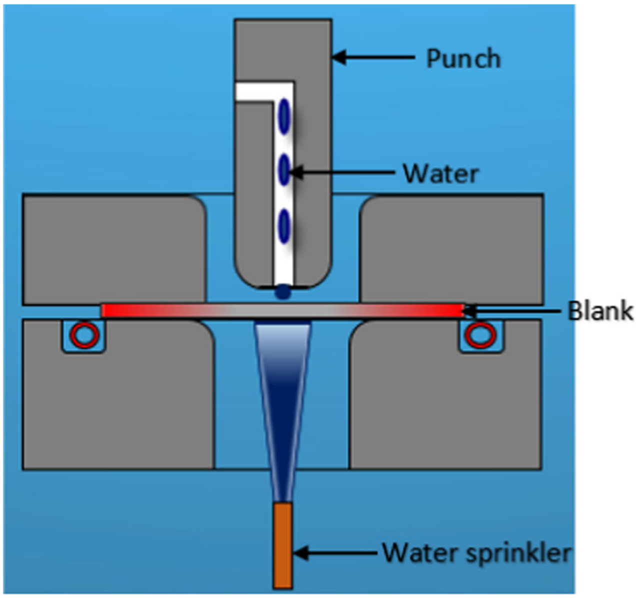


Fig. 5 Schematic representation of the cooling of the circular blank specimen

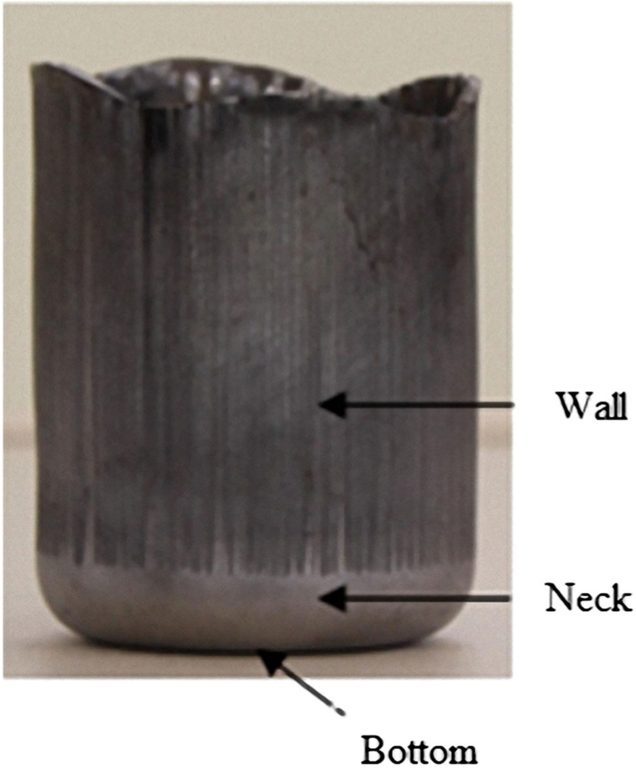


Fig. 6 Schematic illustration of regions examined with optical microscope

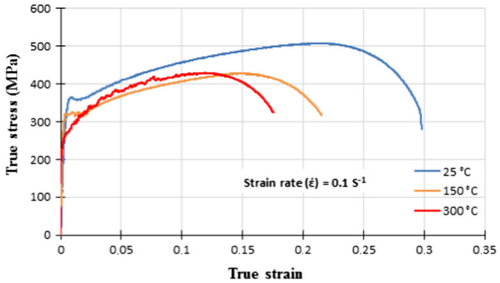


Fig. 7 Tensile test curves of HC300LA at various temperatures for t= 1.2 mm sheet thickness

0.005 % Si, 0.251 % Mn, <0.0005 % P, 0.004 % S, 0.052 % Al, and <0.001 % Ti.

2.2 Tensile tests conducted at various temperatures

Tensile testing specimens to be tested at RT, 150 °C, and 300 °C were prepared using the wire electro discharge machine (EDM). The dimensions of the tensile testing specimen are shown in Fig. 1a.

To determine the mechanical properties of the test specimen and the optimum forming temperature range, tension tests of the sheet material were conducted at the strain rate of 0.1, at RT, 150 °C, and 300 °C, using the Bähr DIL805A/D test equipment shown in Fig. 1b from top view.

2.3 Experimental setup

RT and WDD experiments were conducted using an experiment setup that featured a specifically designed heating and cooling system and an 80-ton capacity mechanical eccentric press, as shown in Fig. 2. In WDD experiments, in order to heat the flash zone of the blank and die system, time and temperature variables were tested and an induction annealing machine (50 kW) controlled by a programmable logic control (PLC) system was used. Moreover, to heat the blanks in the die and under BHF, the heater was embedded into the copper pipe die. The induction heater and the assembly of it on the die are shown in Fig. 3. A data collection system (National Instrument NI USB–6259M Series DAQ Device. BNC Data Logger) acquires input parameters, like punch travel, load applied on the blank, and blank holding pressure by the press from the test rig, and transmits them to a computer, where these data are processed and converted to plots diagramming information such as variation of load with displacement.

Two infrared temperature sensors, shown in Fig. 4, were assembled on the die in the experiment setup to measure the flange zone of the blanks' temperatures. The temperature sensor numbered 1 was focused on the point at the beginning of flange zone, while the temperature sensor numbered 2 was focused on the exterior point of the flange zone via a hole drilled on the die plate. With this setup, a new measurement method was developed for measuring the temperature of the flange zone. The assembly of the sensors on the die and the temperature measurement method are shown in Fig. 4.

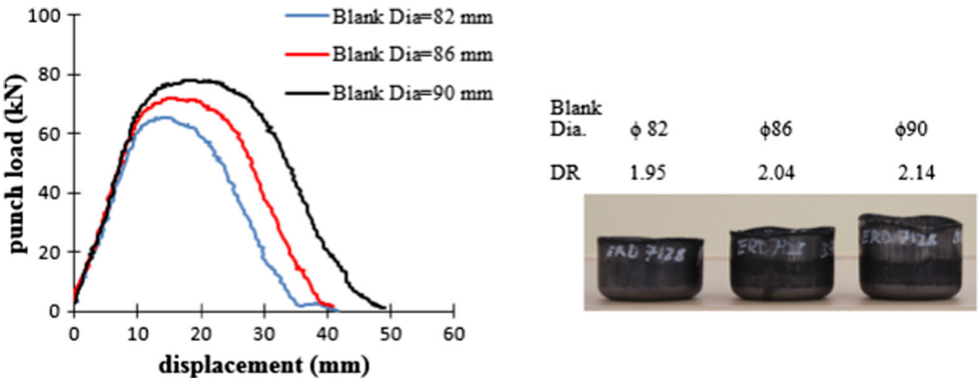
2.4 Warm deep drawing procedure

This experimental setup was specifically designed to perform deep drawing operations at elevated temperatures. The experiment parameters for deep drawing are listed in Table 1. Circular shape blanks were prepared by water jet. Diameters of blanks were chosen in 2-mm increments in order to determine the drawing ratio (DR) exactly. First, limiting drawing ratio (LDR) at room temperature was determined experimentally before conducting the WDD tests.

After performing experiments at RT, the WDD experiments were conducted. The die and blank holder were heated by the induction annealing machine to the required temperature, and the test setup was opened. Next, Graphite 702 (spray lubricant) and sheet

Table 2 The mechanical properties of HC300LA at the strain rate of 0.1 for t=1.2 mm sheet thickness

Temperature (°C)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)	Strain hardening (n)	Strength coefficient (K)
RT	357	507	24.69	0.13	792
150	320	427	40.06	0.12	695
300	265	429	44.94	0.13	728



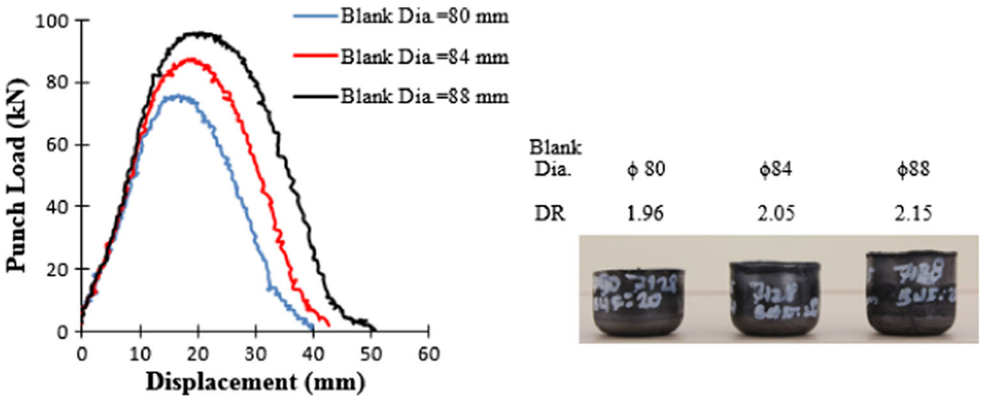
(a) (b)

Fig. 8 **a** Punch displacement vs. load at RT and **b** LDR vs. blank diameter and drawn cups at RT for 1.2 mm thickness

polytetrafluoroethylene (PTFE) were put as lubricant on both surfaces of each blank, except for the area in contact with the punch, to reduce friction at the elevated temperature. The blank was placed at the center of the die and clamped with a blank holder and then heated together. Finally, the forming process was completed by pressing the center of the blank with punch.

In this study, a new cooling system was designed to prevent the midpoint of the blank (punch contact zone) from increasing to higher temperatures during the heating of the test specimen in the WDD process. In WDD experiments, it is important to keep the flange zone of the die warm and the punch contact zone cool. With the system used in this study, water droplets were sent onto the top center of the blank through the hole drilled on a punch and water was sprayed to the bottom center of the blank 2–3 s before the punch moves to facilitate cooling of the sheet material's punch contact zone. The cooling system is shown schematically in Fig. 5.

In the second stage of the study, the changes in the microstructure of test samples that had been warm deep drawn at temperatures between 170 and 295 °C were examined. After the deep drawing process, samples were prepared using standard metallographic techniques. Cups were cut and prepared to observe the microstructure along the section. These samples were mounted in Bakelite and then polished to a 1-μm finish using diamond suspensions. For etching, 2 % nital (2 % NH_3 98 % alcohol) was used. The microstructures of dried samples were observed at various regions, i.e., at the bottom, neck, and on the wall, using a light optical microscope (LOM, Leica DM ILM) (see Fig. 6).



(a) (b)

Fig. 9 **a** Punch displacement vs. load at RT and **b** LDR vs. blank diameter and drawn cups at RT for 1.5 mm thickness

Fig. 10 DR vs. blank diameter and drawn cups at warm deep drawing for 1.2 mm thickness

3 Results

3.1 Flow curves

Curves obtained from tensile tests using dilatometry equipment at the strain rate of 0.1 and at the temperatures of RT, 150 °C, and 300 °C are shown in Fig. 7.

In the tensile test conducted at 150 °C, load fluctuations were not seen, while in the tensile test conducted at 300 °C, load fluctuations were observed due to the effect of dynamic strain aging (DSA), as shown clearly in Fig. 7. The DSA of metallic materials resulting from the solute atom diffusion to mobile dislocations induce deformation instability with load fluctuations and deformation localizations. Moreover, the effects of DSA cause brittleness in the structure of sheet material as well as decrease the material's formability. Some DSA phenomena occur within a certain temperature range. Given that DSA is seen for HC300LA-grade sheet material at temperatures of 300 °C and above, warm deep drawing experiments were performed within a temperature range of 170 to 295 °C. The mechanical properties obtained from the tensile test of HC300L-grade sheet material conducted at the strain rate of 0.1 are shown in Table 2.

3.2 Limiting drawing ratio

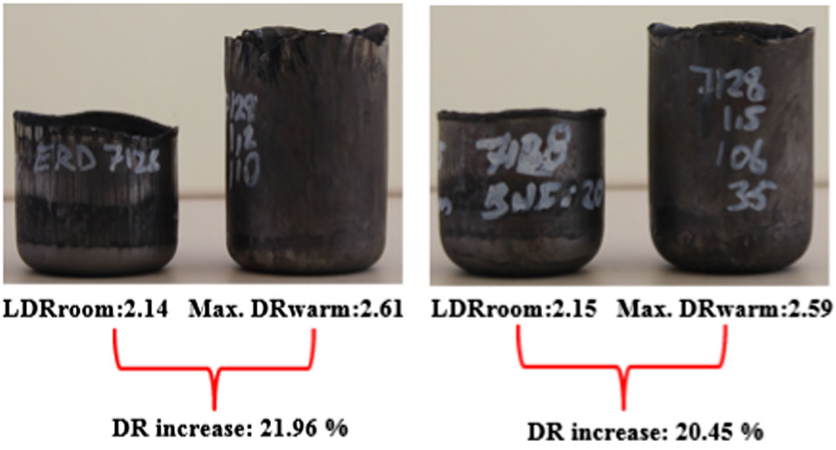
In the cup drawing test, a circular blank with an initial diameter D_0 is drawn by a punch with diameter D_{punch}. The representative formability index in this test is the LDR. The LDR is the maximum DR, defined as D_0/D_{punch}, for which a cup can be manufactured without fracture or wrinkle. During the test, most of the deformation occurs in the flange and in the wall, the latter of which transmits the force between the flange and the bottom of the punch. If the blank-holder force (BHF) is too large, the strength in the wall may exceed a critical value, thereby causing failure. In contrast, if the holding force is too small, wrinkling may occur in the flange. Optimized BHFs were obtained in experimental trial-and-error results. Figs. 8a and 9a show punch load-displacement, and Figs. 8b and 9b show the drawn cup results from the RT deep drawing process.

LDR is an indicator of a material's formability. Results obtained from deep drawing experiments conducted at RT and warm temperatures to evaluate the formability of HC300LA-grade sheet material are given in Figs. 8b and 9b. In experimental studies conducted at RT, a t=1.2 mm, maximum Ø=90 mm blank and a t=1.5 mm, maximum Ø=88 mm blank were successfully formed. However, at RT, a t=1.2 mm, Ø=94 mm blank and a t=1.5 mm, Ø=90 mm blank were not able to be formed. Tearing caused by thrust bearing load or wrinkle in flange zone of blank was observed. At RT, LDR values were determined as β=2.14 and β=2.15 for t=1.2 mm and t=1.5 mm, respectively.

In the warm-forming process, to evaluate the DR increase obtained, DRs obtained in WDD were measured, the results of which are given for t=1.2 mm and t=

Fig. 11 DR vs. blank diameter and drawn cups at warm deep drawing for 1.5 mm thickness

Fig. 12 DR increase: **a** t=1.2 mm and **b** t=1.5 mm



(a) (b)

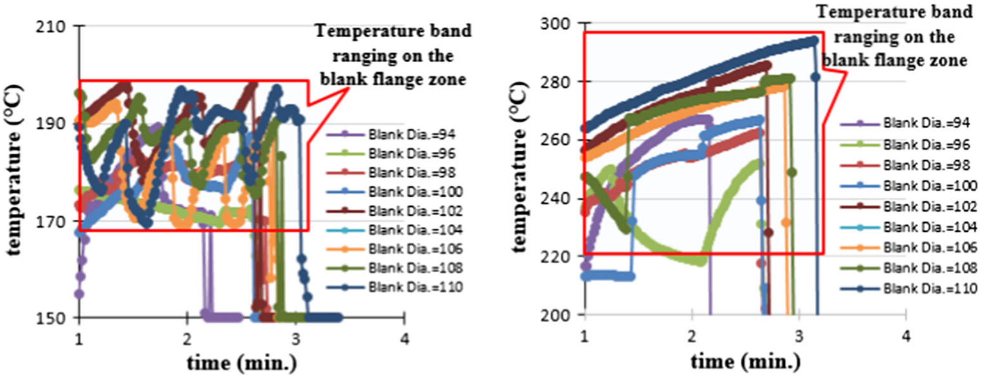
1.5 mm in Figs. 10 and 11, respectively. For t=1.2 mm WDD experiments, starting with a 94-mm diameter blank, a maximum 110-mm diameter blank was formed. For t=1.5 mm forming experiments, starting with a 90-mm diameter blank, a maximum 106-mm diameter blank was able to be formed. As a result of WDD experiments, DR values were determined as β=2.61 and β=2.59 for t=1.2 mm and t=1.5 mm, respectively.

DR increase obtained from the results of experimental studies was 21.96 % for t=1.2 mm and 20.45 % for t=1.5 mm. These results are shown in graph form in Fig. 12. For different material classes, similar investigations were reported by H. Jong Bong et al., S. Gall et al., and S.H. Zhang et al. [10–12]. The results confirm that significant improvement of formability can be achieved by increasing the temperature of the flange region.

3.3 Temperature control in warm-forming process

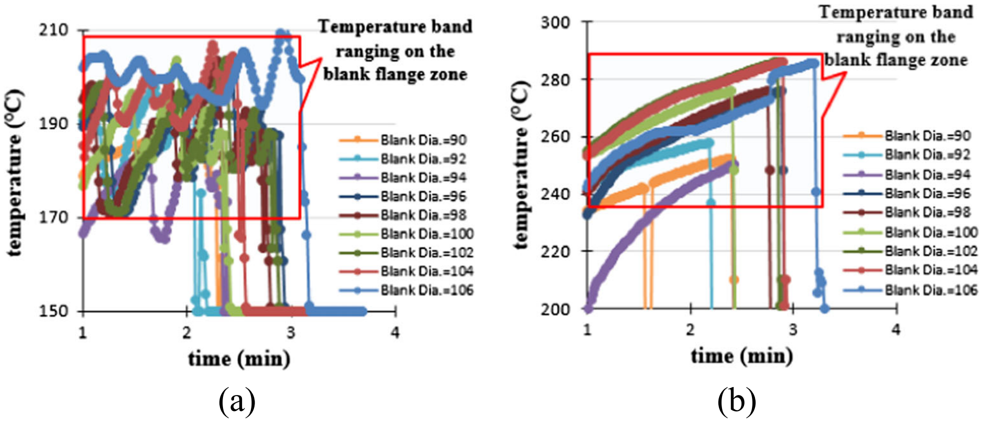
The purpose of temperature control in WDD experimental studies is to keep the middle of the blank cold and the flange zone warm. Using a nozzle cooler from only the bottom for the cooling process increases the time required to decrease the temperature of blanks' midpoint (punch contact zone). This long period of time leads to the cooling of the flange zone, which needs to remain warm. Therefore, the increase of the temperature of the middle section to higher values during heating was prevented by water droplets sent from the punch air

Fig. 13 Time vs. temperature for 1.2 mm thickness: **a** the first sensor data and **b** the second sensor data



(a) (b)

Fig. 14 Time vs. temperature for 1.5 mm thickness: **a** the first sensor data and **b** the second sensor data



hole to the center of test specimen. Before punch move, water was sprayed from the bottom of the blank to the center of the blank for 2–3 s to decrease the temperature to desired temperature range within a short time and bring the deep drawing process to completion.

The temperature of the blanks' flange zone in WDD experiments was measured using contactless infrared temperature sensors embedded in a die. Time-temperature curves obtained from the first sensor and the second sensor are given in Figs. 13a, b and 14a, b, respectively. Temperature decreases seen after the observed temperature increases found in Figs. 13a and 14a were achieved by water droplets sent from punch air hole to the midpoint of blank.

Punch load-displacement graphs obtained from deep drawing experiments conducted at RT (Figs. 8a and 9a) were compared with those obtained from WDD experiments (Fig. 15a, b). An 80-kN load is required to form a 90-mm diameter blank at RT for a 1.2-mm sheet thickness, while in the WDD process, a 75-kN load is enough to form a 110-mm diameter blank for the same sheet thickness. For 1.5 mm sheet thickness, a 95-kN load is required to form an 88-mm diameter blank at RT, while in the WDD process, a 85-kN load is enough to form a 106-mm diameter blank for the same sheet thickness. These results are shown graphically in Fig. 16.

The mean flow stress in any sheet metal material usually decreases with the increasing temperature, which results in a decrease in forming load. This phenomenon is caused by the fact that the increase in the dislocation density does not occur with the temperature increase in sheet materials. Another possible reason for this is that the increase in temperature induces grain boundary sliding, whereby the force necessary to keep grains together decreases. Grains slide over one another as a result of the activation of a diffusion mechanism in the material's microstructure. This situation causes the main flow

Fig. 15 Punch load vs. displacement in WDD: **a** 1.2 mm thickness and **b** 1.5 mm thickness

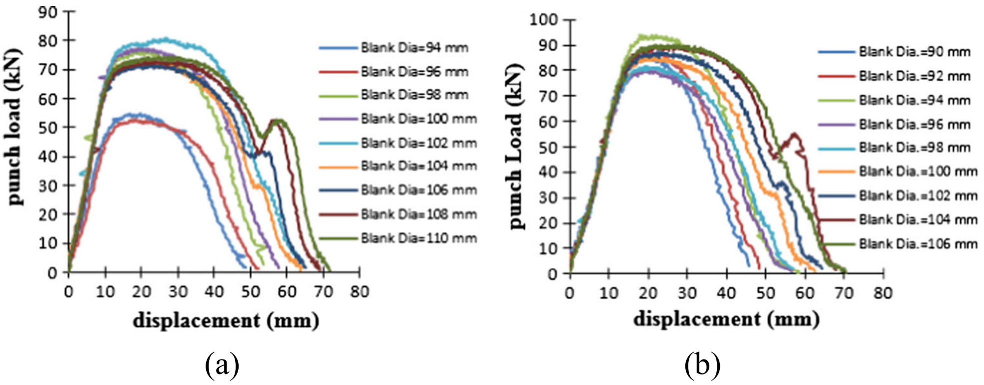
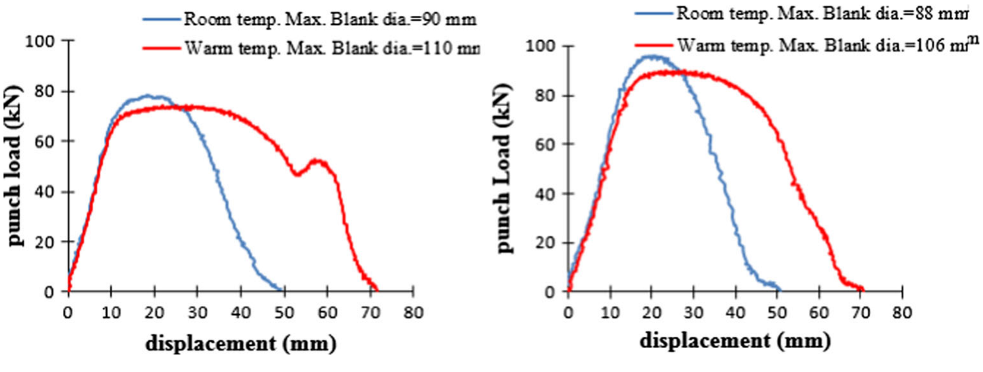


Fig. 16 The comparison of punch load vs. displacement in WDD and RT max. blank diameter: **a** t=1.2 mm thickness and **b** t=1.5 mm thickness



(a) (b)

stress of the material to decrease at higher temperatures. Accordingly, blanks with greater diameters can be formed under lower forces. In the studies conducted by [8, 13] Singh et al. and Jayahari et al., the increase in the temperature of material was shown not only to decrease the flow stress at the point where material at which the material can be deformed but also to increase the ductility of the material. These studies also showed that there was a temperature range in which the material can be drawn safely.

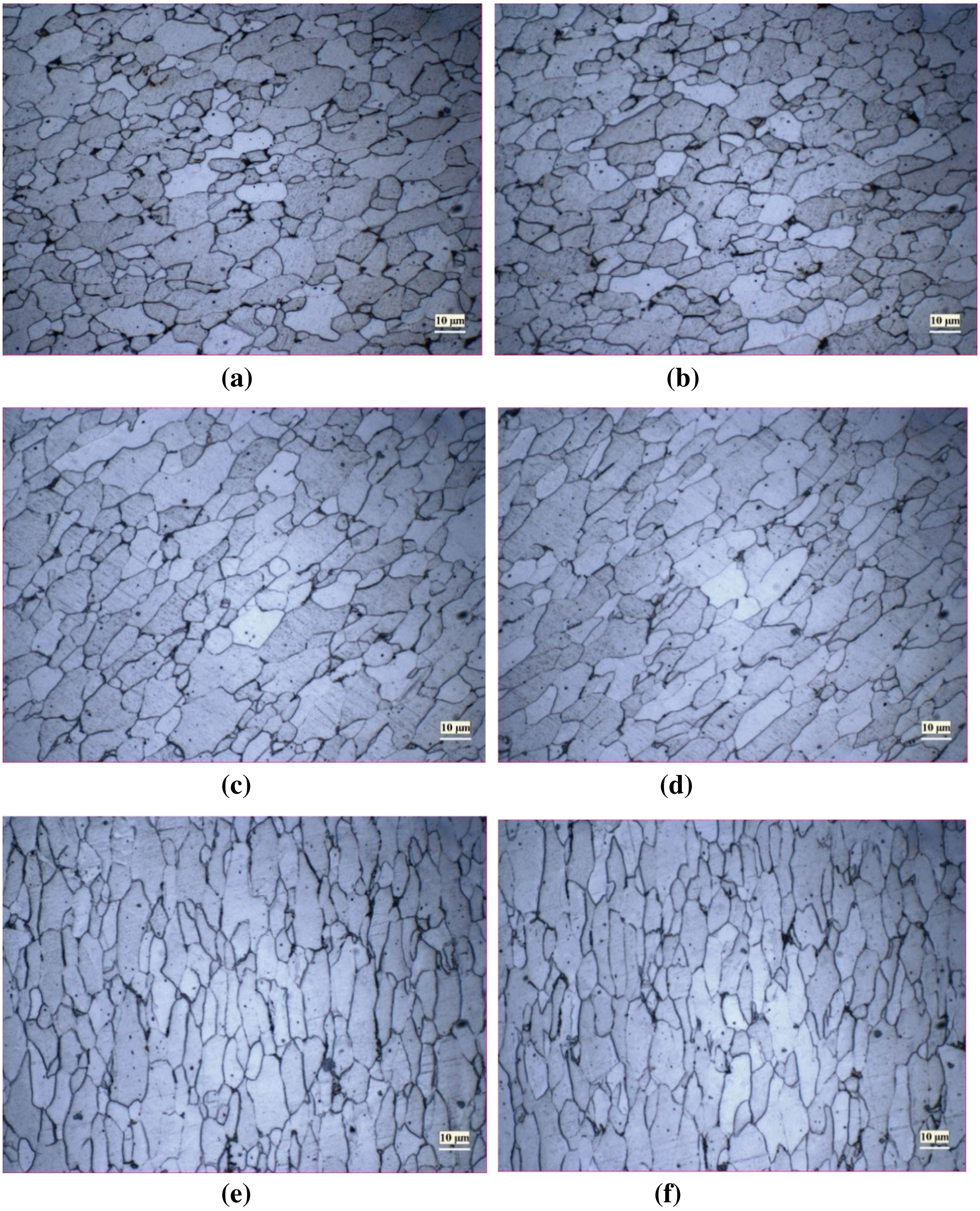
The formability of sheet material during the deep drawing depends on the temper and thermally activated processes. During deep drawing, the stress condition is biaxial, not uniaxial as in tension tests. Dynamic recovery also occurs during deformation at elevated temperature. Generally, it leads to steady-state deformation due to annihilation of dislocations by cross-slip and climb supported by applied stress and increased diffusion. The dynamic recovery effect increases with increasing temperature due to diminishing strain hardening through the annihilation of the accumulating dislocations. The flow curves show that dynamic recovery is present and indicate dissolution of the strengthening precipitates. Both of these processes will be associated with the increase in limited drawing ratio and depth at an elevated temperature. There is a loss in ultimate tensile and yield strengths.

In this study, the grain size for the deep drawn cups at temperatures ranging from RT to 295 °C was investigated. It was observed that significant changes did not occur in the grain size at the bottom, neck, and wall portion of the cup drawn at temperatures ranging from RT to warm (Fig. 17a–f). No changes occurred due to WDD experiments being performed at a temperature far below recrystallization. However, grain elongation did occur in the neck and wall portion of the deep drawn cups as a result of the warm deep drawing process. For different material types, similar studies were reported by Hua Zhang et al. [14].

4 Conclusions

The WDD process is very useful for sheet metal forming. The main advantages of this process include its high drawability (higher limiting drawing ratio) and reduced friction, punch load, and BHF, all of which result in better product quality and higher productivity. This process holds great potential for the automotive and aviation industries, where it can be used in the production of different types of components. The following highlights the results obtained from the experimental study.

- After applying unidirectional tensile tests to HC300LA-grade sheet material at RT, 150 °C, and 300 °C, dynamic strain aging (DSA) was observed in sheet materials at 300 °C.
- A new cooling system was developed, in which water droplets were sent from the top to cool punch contact zone of blanks and sprays were used from the bottom.
- The heating of blanks in the die with the use of induction-type heater prevented possible oxidation in blanks. This study was the first to use this type of heating for the blanks in the die.
- A microstructure investigation was conducted on the cups obtained from WDD experiments. While no change was found in the microstructure, grain elongations were observed only in the neck and wall regions.
- In the WDD process, the time required to heat blanks was minimized with the use of induction heater, which prevented grain growth.



(a) **(b)**

(c) **(d)**

(e) **(f)**

Fig. 17 Optical micrographs (×100) of the bottom region (**a** and **b**), the neck region (**c** and **d**), and the wall region (**e** and **f**) of the warm deep drawn cup

- In the forming of HC300LA-grade sheet material by WDD, there was an increase in DR by 21.96 % for t= 1.2 mm and by 20.45 % for t=1.5 mm compared to the forming at RT.
- Optimum temperature range (for flange zone) of HC300LA-grade sheet material for WDD method was found to be between 170 and 295 °C.
- Yield stress and forming force decreased with the increase in the temperature in the WDD process.

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