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Research Article

Experimental and Numerical Investigation of Warm Deep Drawing Process of AA5052 Aluminum Alloy

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ABSTRACT

Aluminum alloys have a high strength-to-weight ratio and proper anti-corrosion properties that are used in the automotive, shipbuilding and aerospace industries. The major problem with forming aluminum sheets is the low formability of aluminum sheets at room temperature. Therefore, in the present study, warm deep drawing (WDD) of AA5052-O aluminum alloy sheets with a thickness of 1mm was investigated at the different forming temperatures of 25, 80, 160, and 240°C (in the two isothermal and nonisothermal conditions) and punch speeds of 260, 560 and 1950 mm min^{-1} using experimental tests and finite elements simulation. The finite element simulation predictions show a good agreement with the experimental data. The results showed that an increase in forming temperature and a decrease in forming speed led to a decrease in forming force and an increase in cup height. Additionally, a microstructural and experimental investigation showed that the fracture of the cup corner radii occurs in the early stages of drawing at forming temperature of 25°C whereas, by increasing the forming temperature to higher than 160°C, the drawability of aluminum sheets increases due to dynamic recovery that takes place during the WDD process.

1. Introduction

Aluminum alloys are used in various important industrial fields and have a wide range of applications such as in aerospace, automobile, chemical, and electrical industries due to their high strength to weight ratio, good corrosion resistance, and low density. Therefore, aluminum alloy sheets have been used in a variety of automotive applications, while the limited formability of aluminum in comparison to mild steel is a major obstacle in developing aluminum auto body applications [1]. Due to the low formability of aluminum alloys at ambient temperature, the formation of these alloys is performed at elevated temperatures and hence leading to the development of warm forming methods [2]. Consequently, warm forming is used to enhance the formability and surface quality.

Nowadays, the warm deep drawing (WDD) process, as one of the most applicable sheet metal forming processes, has been used because of their application advantages such as producing complicated shapes, controlled plastic flow, improved formability, and decreased manufacturing time. The temperature affects the material behavior during the forming and accuracy of completed parts [1, 2]. The warm press forming of aluminum alloy sheets promoted a great interest with the 5xxx series especially, since the warm forming process has become a widely used alternative to the traditional forming processes shaped at environment temperature [3]. In warm forming, the challenge for process design is

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to study the complicated interaction between thermal and mechanical influences on the formability of metals.

Schmoeckel et al. [2] studied the drawability of ferrous materials at elevated temperatures. Bin Huanga et al. [3] experimentally studied non-isothermal deep drawing of magnesium alloys and validated it by simulation. Kim et al. [4] performed coupled thermo-mechanical finite element analysis for the forming of aluminum rectangular cups at elevated temperatures. The results of their investigation suggested that higher forming temperature results in higher deformation ranges. Also, an increase in the temperature gradient between the punch and die led to increased formability of the material.

In recent years, a few efforts have been made to investigate the warm deep drawing (WDD) processes of aluminum alloy sheets. For instance, Ayres [5] first developed the capability of warm forming by deep drawing a circular cup and observed that the cup height increased with increasing forming temperature for AA5182-O alloy. Li and Gosh [6] showed that warm forming can extremely improve the formability of the aluminum alloy sheet. Bolt et al. [7] illustrated that the formability of AA5754-O can be highly improved by using warm forming methods at temperatures ranging from 100 to 250°C. Abedrabbo et al. [8] studied the warm forming of two AA5182-O and AA5754-O aluminum alloys and developed a temperature-dependent anisotropic material model for finite element analysis and its formability simulation and reported that the warm forming process is particularly suitable for use with aluminum alloy sheets since their ductility and formability are enhanced at elevated temperatures.

More recently, Van den Boogaard et al. [9] and McKinley et al. [10] studied non-isothermal deep drawing of the aluminum cup at different temperature gradients and observed that the formability of Al-Mg aluminum alloy sheet can be improved by increasing the forming temperature in the selected regions of the aluminum sheet.

A new experimental setup was developed by Laurent et al. [11] for warm deep drawing using heating the tools separately from the sheet. The obtained results verify that the formability of AA5754-O aluminum alloy was enhanced when the die and the blank holder were heated to temperatures above 150°C

Takuda et al. [12] presented the simulation results of warm deep drawing of aluminum alloy and observed that the forming limits and necking site were successfully predicted by simulation. The deep drawing on the aluminum sheet at elevated temperatures was also studied by Boogaard and Huetink [13]. Kim et al. [14] analytically developed a non-isothermal model for WDD using various temperatures and punch speeds. The results showed that the temperature and punch speed had a considerable effect on the thickness distribution and LDR given that LDR decreased by increasing the punch speed. Palumbo and Tricaico [15] clearly illustrated that the formability with partial heating in die or blank holder area was much better than those obtained with homogeneously heated tools. Besides, the temperature in the blank center strongly affects the punch force and sheet formability. A local heating and cooling system to improve the formability of magnesium alloy sheets was developed by Yoshiohara et al. [16]. The WDD of magnesium alloy using experimental and finite element (FE) modeling methods was investigated by Chen et al. [17]. Prediction of the forming results such as thickness distribution, thinning, and spring back of the sheet metal with the finite element analysis studied by Zein [18]. Takuda et al. [19] conducted both simulation and experimental studies under WDD of stainless steel 304. The warm deep drawing behavior of Inconel 625 alloy using constitutive modeling was done and validation of Seller's model and determining the effect of process parameters were investigated over thickness distribution and increase in height of the cup and also the experimental results were validated with FEA combined with different yield criteria [20]. Panicker et al. [21] investigated the nonisothermal warm deep drawing and warm redrawing processes to successfully improve the forming depth of AA6082 sheets. The influence of different heat treatment conditions on the cup wall strength was also evaluated, and the corresponding microtexture and microstructure characterizations were carried out by them. The comparative study was carried out on the utilization of different approaches and techniques for deep drawing of various sheet metals by Takalkar and Chinnapandi [22]. The effects of geometrical and process parameters were considered for the elimination of defects like tearing, wrinkling, earing, and spring-back. This research also focused on deep drawing of the sandwich composite materials at elevated temperatures. The different behaviors and formability were reported from the result for different materials at the elevated temperatures. The effect of the heating temperature on the drawability of circular metal cups of aluminum, mild steel and stainless steel that were drawn from the blank was investigated by Basril et al. [23]. Their experiments were conducted at room temperature, 100 °C, 150 °C, and 200 °C. The hot deep drawing of CP titanium was investigated using numerical and experimental studies by Vahidshad and Ayaz [24]. It was observed from the results that in order to prevent wrinkling, the die radius should be increased while the blank diameter should be decreased. The optimal condition of the parameters for conducting the hot deep drawing process without any wrinkling and tearing of the CP titanium blank was obtained at temperature of 400°C.

Ren et al. [25] studied WDD of Mg alloy AZ31 sheets by both the experimental approach and the finite element analysis. This investigation illustrated that the most important factor affecting the deep drawability of the magnesium alloy sheet is temperature.

In the present investigation, AA5052-O aluminum alloy sheets are deep-drawn under warm conditions using 65 tons hydraulic press at various forming speeds of 260, 560, and 1950 mm min^{-1} at test temperatures of 25-240°C under both isothermal (the blank was heated during the tests) and non-isothermal (the blank was heated and the punch was water-cooled during the tests) conditions. Moreover, the WDD process of AA5052-O alloy sheet in a circular die is simulated using the implicit finite element software named ABAQUS/Standard. In order to validate the numerical results, the punch force, cup height, and the limit drawing ratio (LDR) are compared with the experimental results at different punch speeds and forming temperatures.

2. Experimental Procedure

The chemical composition of the AA5052 aluminum alloy sheet employed in this work has been given in Table 1. The mechanical properties of the AA5052 aluminum alloy sheet have been indicated in Table 2. Blanks with 1 mm thickness and 12 mm diameters were machined from the rolled sheets. Annealing heat treatment was employed to achieve proper and similar initial microstructure in aluminum alloy samples which were rolled. To investigate changes of microstructure, the compressed specimens were sectioned parallel to the compression axis. Then, specimens were mechanically polished and etched in Barker's reagent (5 ml of HBF_4 (48%) + 200 ml of H_2O) by applying direct electrical current of 20 V for 90 s. The microstructure of the annealed aluminum alloy (AA5052-O) sheet has been presented in Fig. 1.

Table 1. Chemical composition of the AA5052 aluminum sheet

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn
balance	0.25	0.40	0.10	0.10	2.4	0.28	0.10

Table 2. Mechanical properties of the AA5052 aluminum alloy sheet [26]

Parameters	Value
Yield strength at a temperature (MPa)	89.6
Density (kg/m^3)	2680
Modulus of elasticity (GPa)	70.3
Poisson's ratio	0.33

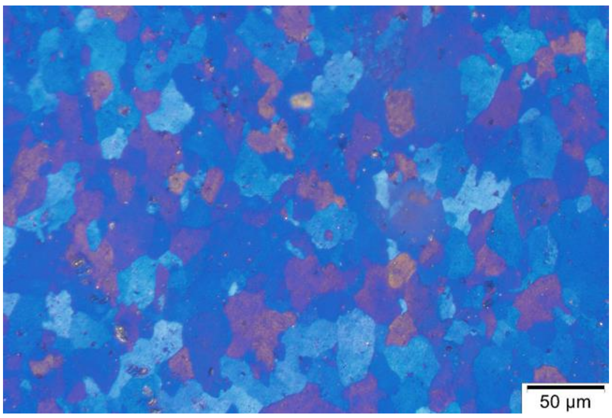

Fig. 1. PLM of the initial microstructure of the annealed AA5052 aluminum alloy.

Moreover, to obtain the mechanical properties of the aluminum sheet, a tensile test specimen is prepared according to the ASTM E08 standard (Fig. 2) and the true stress-strain curve of this sample has been given in Fig. 3.

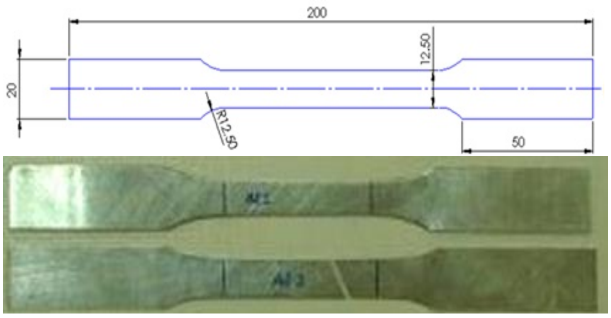

Fig. 2. (a) Specimen dimensions and (b) samples of tensile test of AA5052 aluminum alloy sheet.

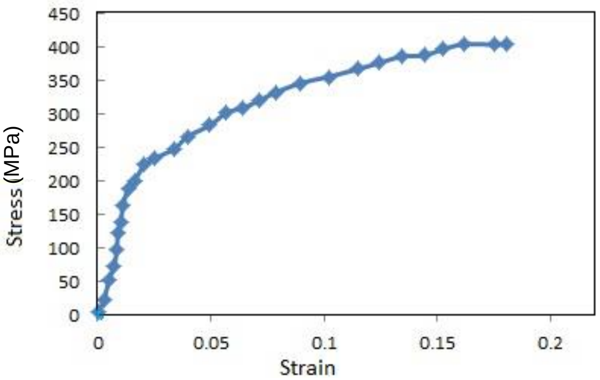

Fig. 3. The true stress-strain curve of the AA5052 aluminum alloy sheet.

The scheme of the experimental equipment used for WDD has been illustrated in Fig. 4. As it is shown in this figure, the WDD test consists of a draw die and punch with a circular shape, a blank holder, springs which provide blank holder force, and heating equipment. Moreover, Dimension values of some equipment of the WDD test have been presented in Table 3. The test equipment has been specially designed so that WDD processes can be performed at different temperatures. Die, punch, and blank holders are composed of a set of forming tools made of AISI H13 tool steel. The metal flow of the blank is controlled by a blank holding force which is supplied with the blank holder on the sheet metal. This restraining effect is mainly applied through friction, as an insufficient flow may lead to wrinkles within the blank, while excessive flow can result in tearing or fracture. The oil with graphite powder is used for lubrication. Two annular electrical heaters with the power of 2.1 kW are employed to elevate the blank temperature. The annular electrical heaters are inserted in between the drawing die and blank holder in a spiral way within the peripheral groove of the die block. The heaters warm up the drawing die and blank holder; as a result, the blank is heated indirectly. Besides, a thermocouple is placed in the die, and a digital thermostat with the precision of 1°C is used which controls the die temperature by sending signals to the controller after the temperature of the die reaches the adjusted level, the power of the heating tool is turned off. Deep drawing of the sheets is carried out using a 65 tons hydraulic press at various forming speeds of 260, 560 and 1950 mm min^{-1} at test temperatures of 25, 80, 160, and 240 °C (the range that the blank is heated whilst the punch is water-cooled during the tests) under both isothermal and non-isothermal conditions. To measure the force of the forming process, a load cell with a capacity of 50 tons is used (Fig. 5). During the heating stage, the punch is kept far from the heaters and the blank is clamped between the die and the blank holder for a short time before drawing. When the temperature of the blank reaches the expected value, heating stops and the testing starts (Fig. 5(b)).

Table 3. Drawing tool geometry and process parameters

Parameters	Dimension (mm)
Punch diameter	63
Punch radius	5
Sheet blank diameter	130
Sheet thickness	1
Die diameter	65
Die radius	5

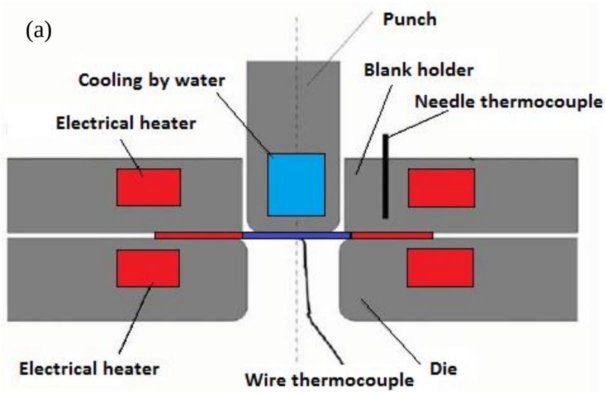

Fig. 4. Schematic view of the (a) WDD testing equipment and (b) exploded view.

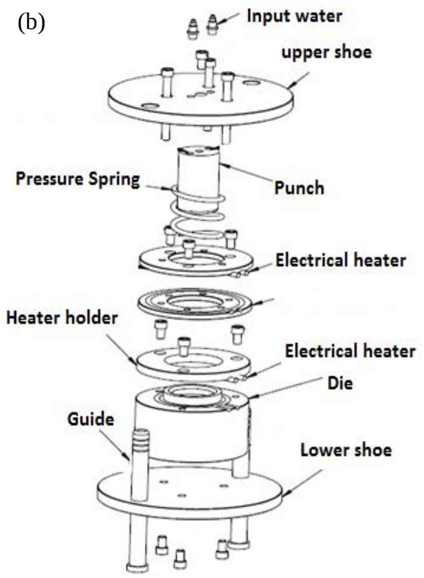

Fig. 4. Continue.

3. Finite Element Simulation

In the last years, the use of numerical methods has been continuously increasing in industries. The numerical simulations have gained great importance in industries in helping reduce conceptions time, costs, and consequently, contributing to an increase in the companies' competitiveness. Among other things, numerical methods are applied to predict the forming behavior of metal sheets. The finite element modeling and analysis of the WDD process was carried out with the ABAQUS software. The finite element models of the tools and sheet were developed, as shown in Fig. 6. Only one-quarter of the geometry was modeled due to the symmetric geometry. The circular sheet blank was modeled with the desired thickness and diameter. The cylindrical upper punch, the cylindrical bottom hollow die was created with proper outer and inner radius and corner radius. Die, punch, and blank holder have been regarded as rigid materials whereas to introduce the characteristics of the sheet, Johnson Cook's model has been used which is almost available in most of the commercial finite element commercial codes. In this model, the three fundamental plastic material responses were considered consisting of strain hardening, strain rate sensitivity, and thermal softening. These three effects are applied in a multiplicative manner as shown in Eq. (1), as the Johnson-Cook constitutive equation [27].

$$\sigma = (A + B\varepsilon^n)\left(1 + C\, ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\left(1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right) \qquad (1)$$

where ε is the effective plastic strain, T, T_r, and T_m are the blank temperature, reference temperature, melting point, or solidus temperature of the material, respectively, also $\dot{\varepsilon}$ and $\dot{\varepsilon_0}$ are the strain rate and the reference strain rate, respectively. A is the yield stress, B is the hardening modulus, C is the strain rate factor and n and m are the strain and temperature exponent, respectively. The required material parameters of AA5052 alloy for the simulations have been presented in Table 4.

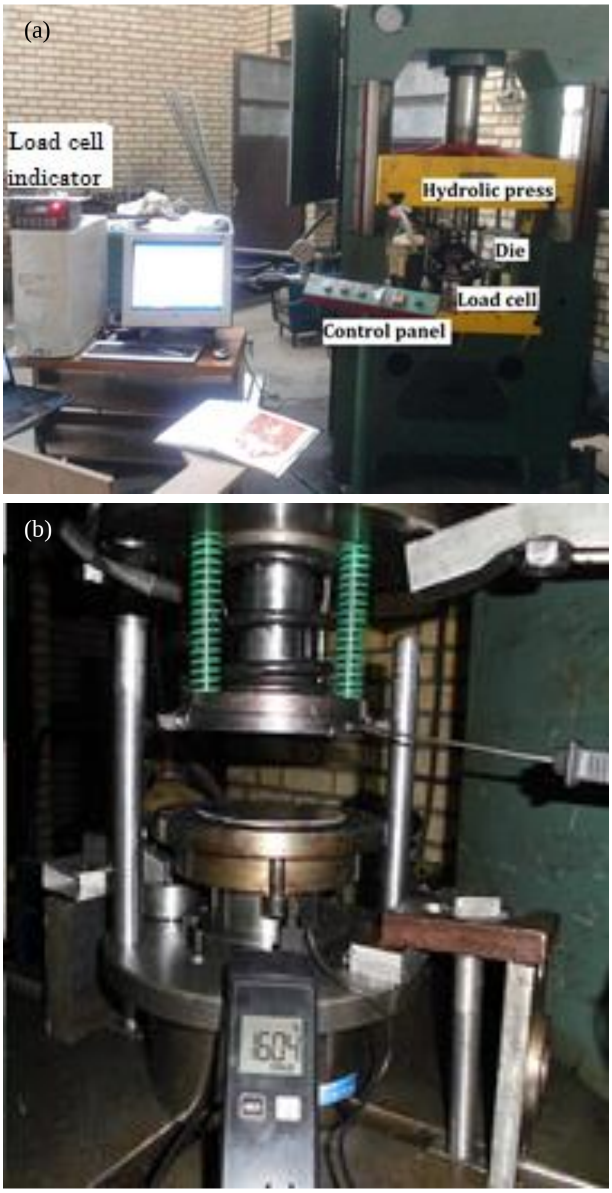

Fig. 5. (a) Experimental equipment and (b) die and punch setup of WDD test.

Table 4. Values of the Johnson-Cook material model parameters of AA5052 [28]

A (MPa)	B (MPa)	n	C	m	T_m(°C)
170	315	0.34	-0.001	2.01	620

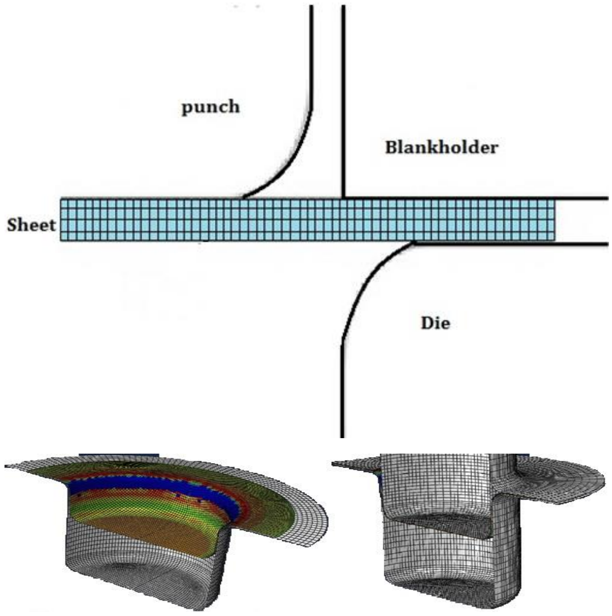

Fig. 6. Finite element model of studied WDD.

In the FE model of WDD, the deep drawability is quantitatively evaluated by the maximum reduction of thickness before the fracture appears. Based on the ABAQUS, an FE model of the warm drawability of the sheet is established with the Johnson-Cook fracture criterion to study on the fracture behaviors. The Johnson-Cook fracture criterion is put forward by Johnson and Cook based on cumulative-damage theory [29]. Johnson-Cook fracture criterion is defined as Eq. (2). As shown in Eq. (2), the Johnson-Cook fracture criterion considers the strain rate and temperature for calculating equivalent plastic fracture strain, and it is widely used in the sheet metal forming process. So, this equation can be conveniently used for the simulation of the AA5052 aluminum alloy sheet during deep drawing processes at elevated temperatures and various punch speeds. To simulate the damage in the sheet, damage parameters are included in the Johnson-Cook material model. Damage in the material tries to take path dependency into account by accruing the incremental effective plastic strain as the forming process proceeds [30]. In this material model, the failure strain is a function of the strain rate, temperature and effective stress. The equation of the equivalent plastic fracture strain is given as [30].

$$\bar{\varepsilon}_f^{pl} = \left[D_1 + D_2 \exp\left(D_3 \frac{\sigma_P}{\bar{\sigma}}\right)\right]\left[1 + D_4 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 + D_5 \frac{T-T_0}{T_m-T_0}\right] \quad (2)$$

where, σ_P is hydrostatic stress, $\bar{\sigma}$ the effective stress, $\dot{\varepsilon}$ is strain rate, and D_1, D_2, D_3, D_4 and D_5 are the fracture model constants. The damage to an element is defined as Eq. 3 [29],

$$D = \sum\left(\frac{\Delta\bar{\varepsilon}}{\bar{\varepsilon}_f}\right) \quad (3)$$

where $\Delta\bar{\varepsilon}$ is the increment of the equivalent plastic strain, which would occur during the integration cycle, and $\bar{\varepsilon}_f$ is the equivalent strain to fracture under the current condition of temperature, equivalent stress, and strain rate. A fracture occurs when the damage parameter D reaches the value of one, and the corresponding failed elements are deleted [31]. Johnson Cook's failure parameters for the AA5052 aluminum have been shown in Table 5.

Table 5. Johnson-Cook damage parameters of AA5052 aluminum alloy [30]

Parameters	D_1	D_2	D_3	D_4	D_5	Amount of displacement in failure
value	0.306	0.0446	-1.72	0.0056	0	0.012

Drawability is a measure of the ability of a material to be drawn in, as in forming a cup from a flat metal blank. During deep drawing, the metal blank undergoes different strains in different directions. The drawability of sheet metal or LDR can be determined from different diameters of blanks with constant thickness. The LDR can be expressed as shown in Eq. (4).

$$LDR = \frac{d_0}{d_1} \quad (4)$$

Where, d_0 is initial blank diameter before drawing process and d_1 is the maximum diameter of the successful formation of the cup.

4. Results and Discussion

In order to confirm the validity of the FEM simulation results, a comparison of the FEM results and experimental data was required.

Comparison of the FEM results and experimental data of the force-displacement curve recorded during these tests at the forming temperature of 240°C have been shown in Fig. 7.

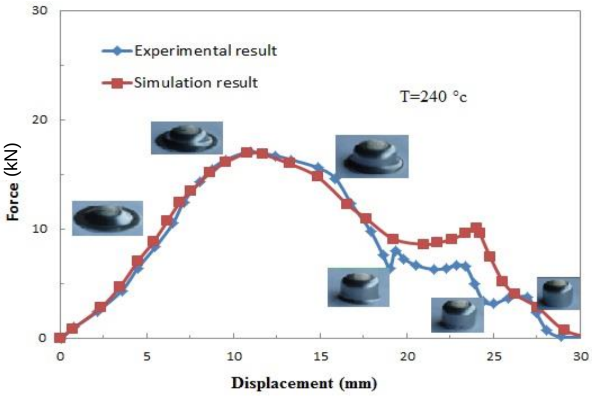

Fig. 7. Comparison of the FEM simulation results and experimental data of punch force vs. displacement curves at the temperature of 240 °C.

As it is clear, the forming force increases at the beginning of deformation stages and after the initial contact of the punch with the aluminum sheet. After forming the radii region of the punch and in the continuance of the process, deformation resistance enhances by increasing the work hardening. The maximum punch force value of 16.5 kN has been obtained at a punch displacement of around 11 mm to 11.5 mm, corresponding to the time when the radii of the tools have been completely formed by the aluminum sheet. The punch force has been subsequently recovered at 20 mm, due to the loss of contact between the die and the blank holder. In the following, the force increase has been recorded at 24 mm corresponding to the ironing step between the punch and the die. This step is due to the increase in the blank thickness which occurred during the first forming step when the material has been strongly compressed circumferentially in the region of the flange. The effect of forming temperature on the force amount and force-displacement curves have been shown in Fig. 8. As it is obvious from the curves of experimental and simulation results, the forming force decreases with increasing forming temperature from 25°C to 160°C. The comparison of the FEM results and experimental data show that the developed FE model is very useful and proper for the study of WDD of AA5052 aluminum alloy.

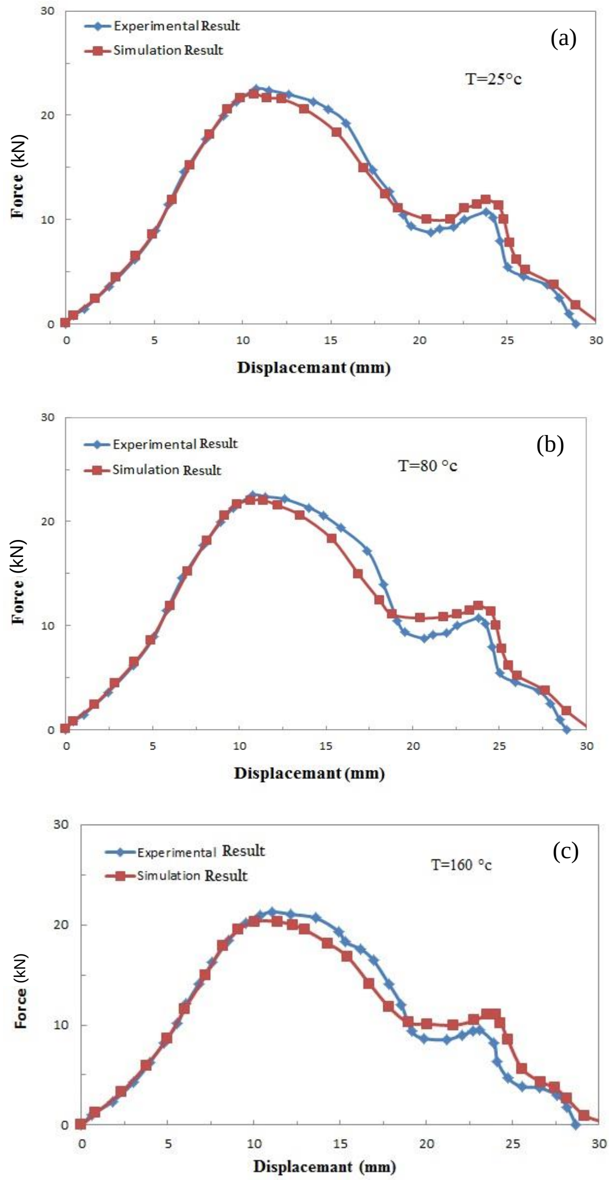

Fig. 8. Experimental and numerical punch force-displacement curves at forming temperature of (a) 25°C, (b) 80°C and (c) 160°C.

Figure 9 shows the maximum drawing depth of cups at different forming temperatures. As it is clear, the depth of cups increases with a rise in forming temperatures from 25°C to 240°C, so the maximum of cup height is obtained at forming temperatures of 240°C.

The effects of forming temperature on the depth of drawn cups have been displayed in Figs. 10 and 11. As it is clear in Fig. 10, the fracture of the cup corner radii occurs in the early stage of the drawing at a forming temperature of 25°C, so the lowest limit of the forming temperature appears to be approximately 25°C. Whereas, the simulation and experimental results of warm deep drawing of the aluminum sheet at a temperature of 240°C (Fig. 11) show that the cup fracture occurs in the final stages of the drawing at the forming temperature of 240°C. The formability of the blank material can be maximized by increasing the forming temperature.

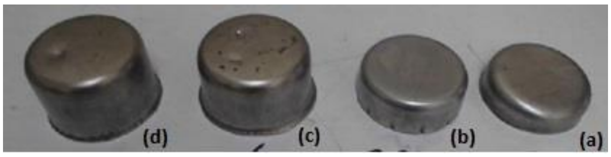

Fig. 9. The warm deep-drawn cups at different forming temperatures of (a) 25°C, (b) 80°C, (c) 160°C, and (d) 240°C.

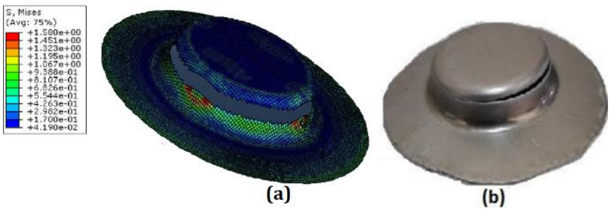

Fig. 10. The fractured cup at the punch corner in the (a) simulation and (b) experimental results of the warm deep drawn sheet at forming temperature of 25°C.

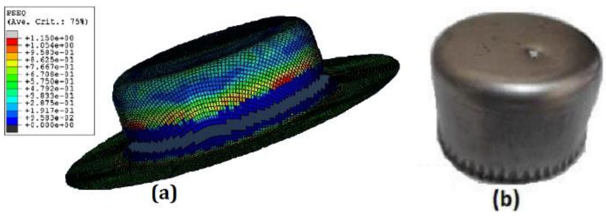

Fig. 11. The (a) finite element simulation and (b) experimental results of the warm deep drawn sheet at forming temperature of 240°C.

As it is shown in Fig. 10 when the punch force reaches the fracture strength of the sheet in the punch corner region sheet fractures during the deep drawing process. Therefore, in order to consider the effects of forming speed and temperature on the forming conditions, the Limit Drawing Ratio (LDR) is used, to know the deformation characteristics of the aluminum alloy under various conditions of temperature and punch speed is essential [32].

The optical micrographs in Figs. 12 and 13 show the grain structures at the different regions of the warm deep-drawn cups which have been deformed at forming temperatures of 25°C and 240°C, respectively. As it is obvious the microstructure of the bottom region of the cup remains almost unchanged and the shape of the grains remains equiaxed whereas the microstructures of the corner radii (B-zone) and wall (C-zone) regions of the cup alter and the grains are elongated along the deep drawing directions resulting in the flow of the aluminum sheet into the die. By comparison, when the deformation is further increased, the grains are severely elongated along the drawing direction and fibrous grains are obtained in the sheet drawn at forming temperatures of 25°C.

Some decreases in formability or drawability may also be obtained by work hardening (hardening of material with deformation). Work hardening results from interaction and multiplication of dislocations during plastic deformation. By increasing dislocation density, the mean free path decreases making it more difficult to continue further deformation of the aluminum sheet. Therefore, as it is shown in Fig. 12, formability or drawability of the aluminum sheet decreases with increase deformation and dislocation density increases at the forming temperature of 25°C resulting in the initiation of tearing in the corner radii of the aluminum cup.

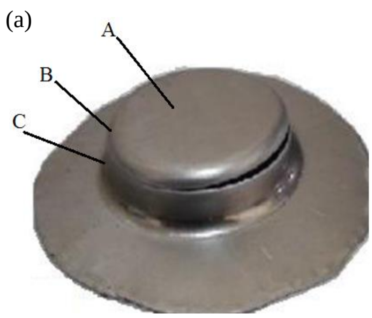

Fig. 12. The warm deep drawing of AA5052-O sheet at a 25°C forming temperature (a) the drawn cup and optical microstructure of the (b) bottom (A-zone), (c) corner radii (B-zone), and (d) wall (B-zone) of the drawn cup.

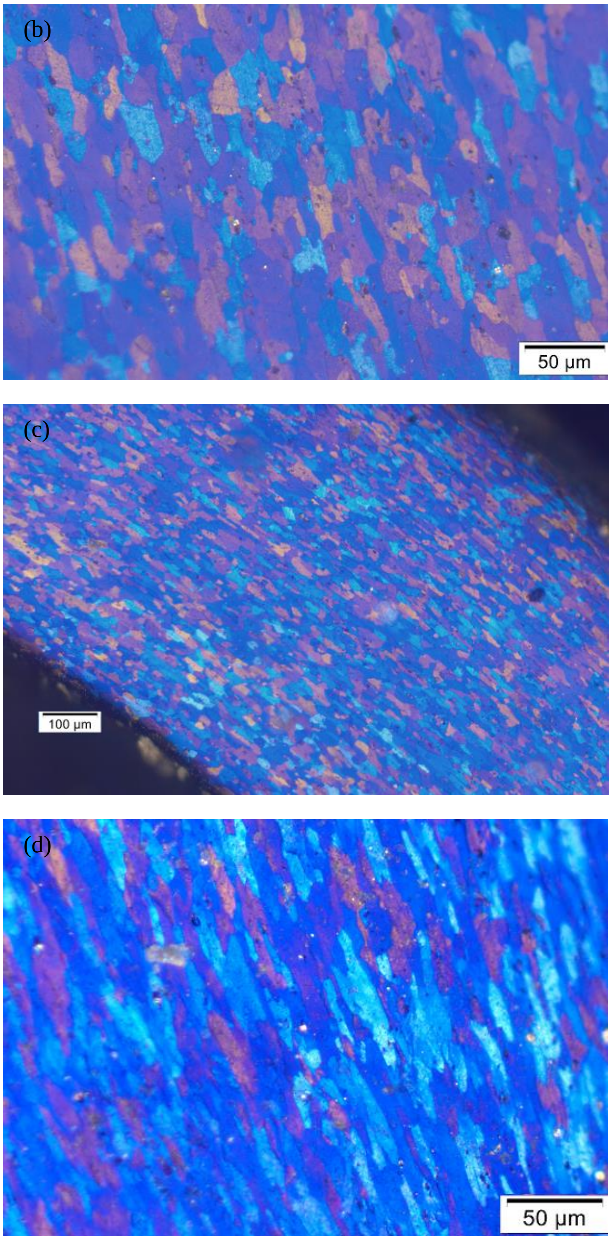

Fig. 12. Continue.

In aluminum alloys, work hardening significantly decreases at elevated temperatures due to dynamic recovery and recrystallization effects, i.e. dislocation multiplication is immediately compensated. The primary disadvantage of a work-hardened material is its inability to be used at higher temperatures, where recovery would soften it, thus, dynamic recovery tends to lower the effective rate of work hardening [33].

Dynamic recovery occurs most strongly in metals and alloys with high stacking fault energies such as aluminum alloys. The investigation shows that the recovery process of the AA5052-O aluminum sheet starts at 90-140 °C, while the temperature around 200 °C is required for stress relief. As the dislocation mobility increases with increasing forming temperature, the dynamic recovery effects become stronger at elevated temperatures. While recovery gradually softens the work-hardened sheets, The movement of dislocations relief partial distortion energy, resulting in the rearrangement and counteraction of dislocation and polygonization on the vertical slip plane, thereby, the initial subgrain boundary appears in the warm deep-drawn sheets reported by other researchers [34-36].

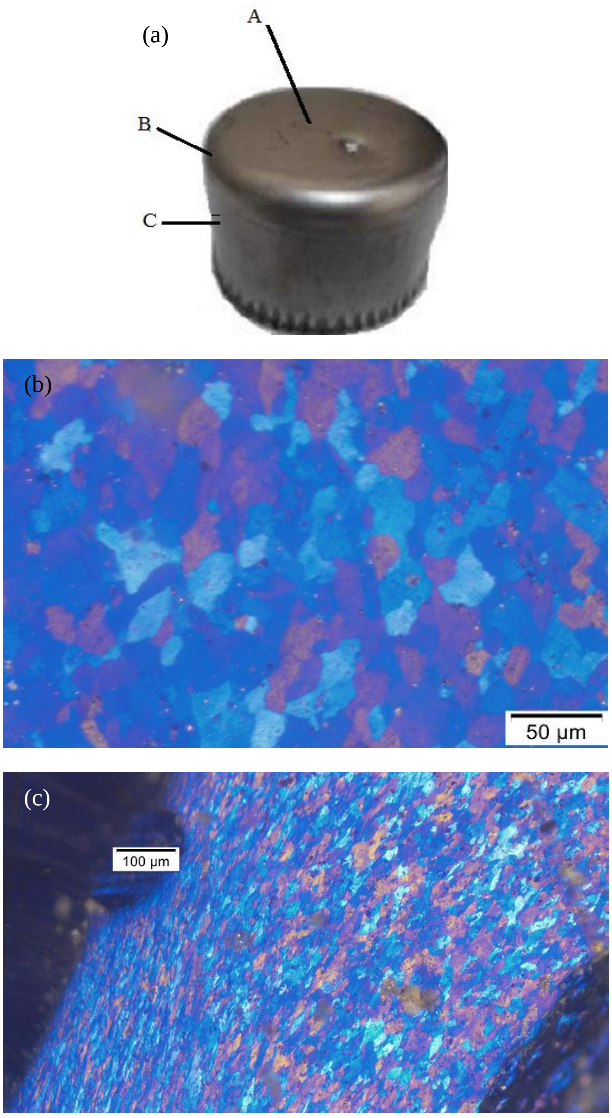

Fig. 13. The warm deep drawing of AA5052-O sheet at forming temperature of 240°C (a)the drawn cup and optical microstructure of the (b) bottom (A-zone), (c) corner radii (B-zone), and (d) wall (B-zone) of the drawn cup.

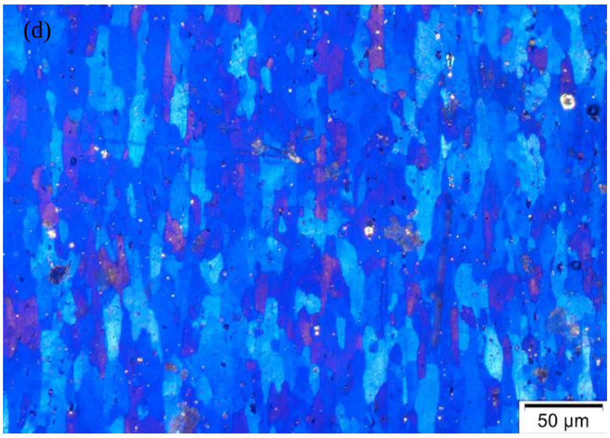

Fig. 13. Continue.

Recovery occurs at relatively low temperatures and exponentially decreases the material strength accumulated during warm deep drawing by reducing the dislocation density with annihilation and/or re-arranging the (accumulated) dislocation density and substructure.

However, under the condition of warm deformation, the dislocation cell structure was formed in the deformed grains, and many dislocations distribute in the cell wall. At the same time when deep drawing is carried out at a higher temperature, the climbing of the edge dislocation and the cross-slip of the screw dislocation will make partial dislocations disappear, and most of the dislocations will be redistributed to make the cell wall clear and flattened as has been investigated before [36, 37]. The results of the microstructural investigations show that dynamic recovery mechanisms are activated by increasing the forming temperature from 150°C. As it is clear from microstructures of different regions of the drawn cup in Fig. 13, dynamic recovery is the main restoration mechanism at a deep drawing temperature of 240°C and the shape of the grain is still elongated as depicted in these microstructures.

Figure 14 shows that Limit Drawing Ratio (LDR) increases by rising the forming temperature and decreasing the punch speed as warm drawing improves the formability of aluminum alloys because the work-hardening of the AA5052 aluminum alloy decreases at elevated temperatures (higher than 80°C).

The effect of forming temperature on the forming force and force-displacement curves in isothermal conditions where the tools and blank were heated up to the same temperature levels has been shown in Fig. 15. The maximum force reached is 22.4 kN at room temperature at a displacement of 11 mm.

Following the conducted experiments, Fig. 16 shows the required punch forces to form aluminum alloy sheets at room temperature as well as isothermal state, and non-isothermal state. It can be seen that the maximum punch force is related to room temperature, followed by isothermal state, and the minimum value belongs to the non-isothermal state. In the isothermal warm state, all areas are warm, but in the nonisothermal state, the flange area and the wall are warm, and the radius of the punch head is at 25°C; therefore, in the nonisothermal state, less force is required for formation.

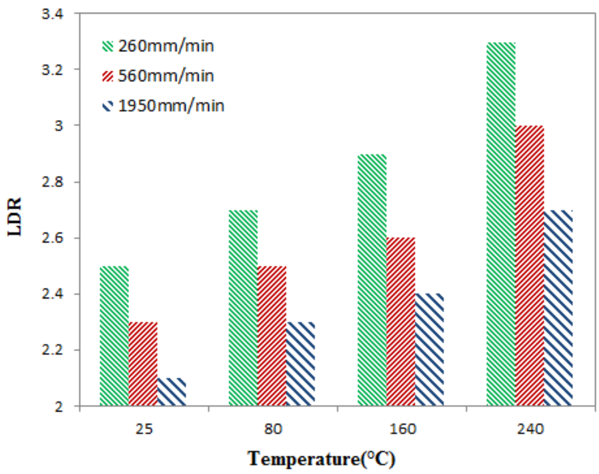

Fig. 14. LDR changes of AA5052-O at different forming temperatures and the punch speeds.

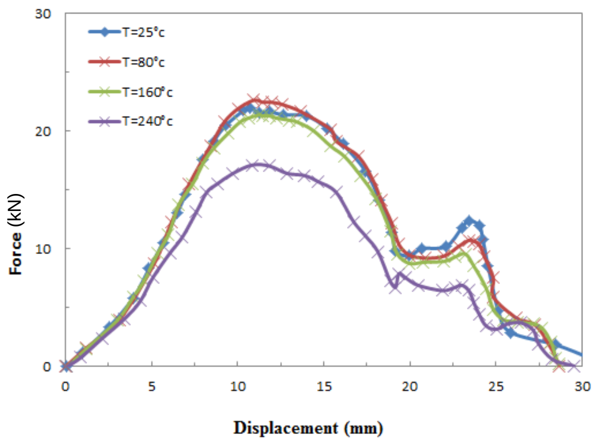

Fig. 15. The experimental force-displacement curves at different forming temperatures in the experimental conditions.

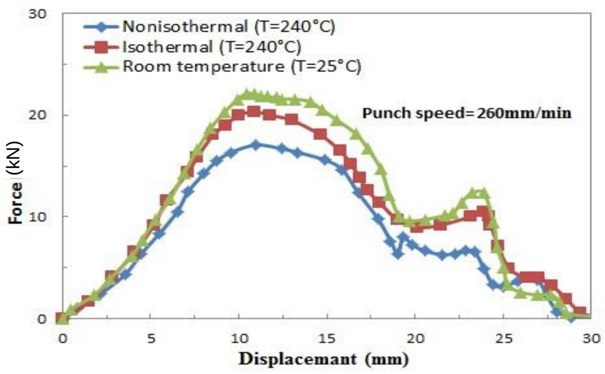

Fig. 16. The experimental force-displacement curves at different thermal conditions consist of room temperature, isothermal and nonisothermal states.

As mentioned earlier, three different speeds (260, 560, and 1950 mm/min) were selected for punch, the results of simulations and experiments are investigated.

As it is clear in Fig. 17, the maximum force required for sheet forming is related to the punch speed of 1950 mm/min, and after that, the punch speed of 560 mm/min and 260 mm/min have the maximum forming force, respectively.

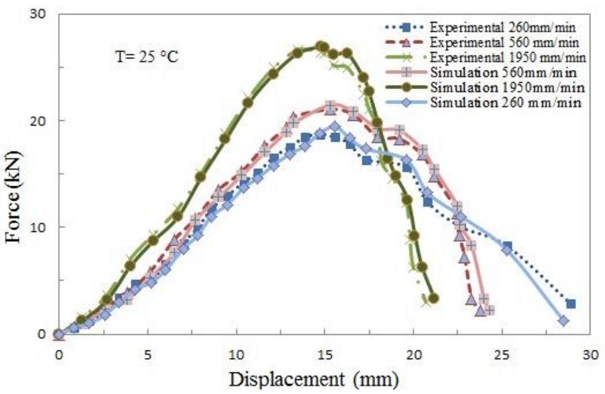

Fig. 17. Comparison of the FEM simulation results and experimental data of the force-displacement diagram for different punch speeds.

Figure 18 shows the forming temperature impacts on the maximum forming force, as it is clear, the forming forces decrease with increasing forming temperature due to dynamic recovery.

The experimental and simulation results show that the cup height increases with increases in the forming temperature at a constant punch speed (Fig. 19) which can be attributed to a decrease in strength or an increase in drawability of the aluminum sheet.

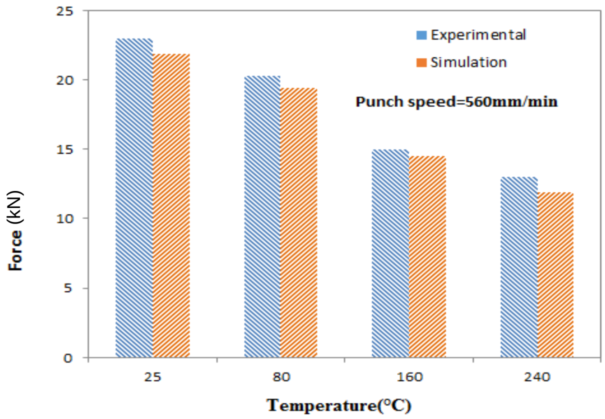

Fig. 18. Comparison of the simulation results and experimental data of the forming force at different forming temperatures at punch speed of 560 mm/min.

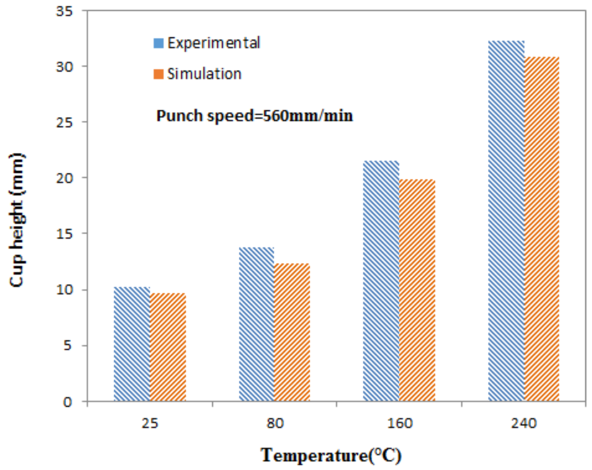

Fig. 19. Comparison of the simulation results and experimental data of the cup height at different forming temperatures at a punch speed of 560 mm/min.

5. Conclusions

The low formability of aluminum sheets is the major industrial problem at room temperature. Therefore, in the present study, warm deep drawing (WDD) of AA5052-O aluminum alloy sheets with a thickness of 1mm was investigated at the temperature range of 25-240°C (in the two isothermal and nonisothermal conditions) and punch speed range of 260- 1950 mm min^{-1} using experimental tests and finite elements simulations with ABAQUS software. The carried out examinations led to the following results:

- The thinning distribution, fracture, LDR, and forming forces observed in the simulation matches the experimental results. A comparison of the FEM results and experimental data showed that the developed FE model was very useful in the study of WDD of AA5052 aluminum alloy.

- The maximum thinning and tearing were observed in the punch corner radius at the forming temperature of 25°C while at the forming temperature higher than 80°C, the thinning and tearing occurs in the cup wall.
- Work hardening takes place at the lowest investigated temperature of 25°C for aluminum sheets. Moreover, by increasing forming temperatures from 160°C, dynamic recovery occurs leading to an increase in drawability, and depth cup and lower dislocation density, flow stress, and fracture of the drawn cup.
- In the isothermal condition of WDD, the drawing depth to failure increased with increasing forming temperature, and drawability was further increased using nonisothermal conditions of WDD so the forming force of the nonisothermal state was lower than that of the isothermal state, and forming force and drawability had the lowest value in deep drawing at the room temperature.
- With an increase in forming temperature, the forming force applied on the punch dropped and the cup height increased as minimum forming force and maximum cup height were presented at forming temperature of 240°C, which can be attributed to a decrease in strength of the sheet and flow tension.

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بررسی عددی و تجربی فرآیند کشش عمیق گرم آلیاژ آلومینیوم ۵۰۵۲

حمیدرضا رضایی آشتیانی و مهرداد گنجی ارجنکی

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چکیـــده

آلیاژهای آلومینیوم دارای نسبت استحکام به وزن بالایی به همراه مقاومت خوردگی به بالایی می باشند که در صنایع اتومبیل سازی، هوا فضا و کشتی سازی مورد استفاده قرار می گیرند. مشکل عمده در شکل گیری ورق های آلومینیوم، شکل پذیری پایین ورق های آلومینیوم در دمای اتاق است. بنابراین در مطالعه حاضر، کشش عمیق گرم (WDD) ورق های آلیاژ آلومینیوم ۵۰۵۲ با ضخامت ۱ میلی متر در دماهای مختلف شکل دهی ۲۵ ، ۸۰ ، ۱۶۰ و ۲۴۰ درجه سانتیگراد (در دو حالت هم دما و غیر هم دما) و سرعت پانچ ۲۶۰ ، ۵۶۰ و ۱۹۵۰ میلی متر در دقیقه با استفاده از آزمایش های تجربی و شبیه سازی المان محدود مورد بررسی قرار گرفت. پیش بینی های شبیه سازی المان محدود، توافق خوبی با داده های تجربی نشان داد. نتایج نشان داد که افزایش دمای شکل دهی و کاهش سرعت تغییر شکل منجر به کاهش نیروی شکل دهی و افزایش ارتفاع فنجان می شود. همچنین بررسی های ریزساختاری و تجربی نشان داد که شکست و پارگی ورق در شعاع گوشه فنجان کشیده شده در مراحل اولیه کشش در دمای شکل دهی ۲۵ درجه سانتیگراد رخ می دهد در حالیکه با افزایش درجه حرارت شکل دهی به بالاتر از ۱۶۰ درجه سانتیگراد، قابلیت کشش ورق های آلومینیوم بدلیل رخ داد بازیابی دینامیکی افزایش می یابد.

واژه‌های کلیدی: کشش عمیق گرم، دمای شکل دهی، ریزساختار، نمودار جابجایی-نیرو، ورق آلیاژ آلومینیوم ۵۰۵۲، بازیابی دینامیکی