A comprehensive study on soundness, microstructure, and uniformity of 2024 aluminum cups hydro-mechanically drawn at elevated temperatures

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Abstract
In the present research work, the hydro-mechanical deep drawing (HMDD) process of 2024 aluminum alloy is performed experimentally and numerically for elevated temperatures. The main variables of the forming process include the fluid pressure, the pre-bulge pressure, and the process temperature. The effects of these parameters on the thickness distribution and uniformity index of the final product have been investigated. Using the hardness test, the preferred crystallographic orientation, the energy-dispersive spectroscopy, and the microstructure images obtained from an optical microscope and a scanning electron microscope, the relationship between the grain size, hardness, and effective plastic strain is studied and discussed. The findings imply that the HMDD process without the pre-bulge pressure reduces the uniformity of the final product and, on the other hand, excessive increase in this parameter causes tearing of the workpiece. The hardness distribution along the cup wall was in agreement with grain refinement and the Hall–Petch relationship, but it was not correspond to the expectations made via the texture analyses. The images gained from the energy-dispersive spectroscopy for different areas of the 2024 Al sample demonstrated that the \( \text{Al}_2\text{Cu} \) precipitations in the product wall were finer than the other areas and mainly dispersed at the grain boundaries. This type of precipitation distribution was the main origin for increasing the hardness of the cup wall in comparison with the cup corner and bottom. In other words, the precipitation hardening overwhelmed the influence of the preferred orientation of the grains in HMDD operation of Al 2024.

Keywords Hydro-mechanical deep drawing · Thickness reduction · Product uniformity · Fluid pressure · Process temperature · Microstructural studies

1 Introduction
Hydroforming is a relatively new forming process which is growingly employed in various industries. The advantages of making a product via hydroforming process include high efficiency, dimensional accuracy, and significant cost savings. The hydroforming of a sheet is very similar to traditional deep drawing process in which the periphery of the blank is kept onto the top face of the matrix and the sheet is drawn into the die by means of a punch [1]. There are different sorts of hydroforming process [2]. Hydro-mechanical deep drawing (HMDD) is a type of hydroforming technique with various components shown in Fig. 1. The radial pressure at the edge of the blank assists the flow of material into the die and, by this means, the required load is decreased and the drawing ratio can be increased [3].

Aluminum alloys have a very good strength/weight ratio and are corrosion resistant. That is why they are suitable replacement for steel in various applications, namely aerospace and automotive industries. Nevertheless, some of these alloys do not possess sufficient formability and toughness at room temperature. For this reason, they should be formed at elevated temperatures [4]. It is obvious that under these conditions, the temperature plays an important role in the forming operation. For instance, conducting a hydroforming process at high temperatures increases the limit drawing ratio (LDR), provides a better thickness distribution, and reduces the required forming load [5].
Although the research regarding the warm hydroforming started in 1997 [6], because of certain difficulties, not many investigations have been performed about this operation. Liu et al. [7] improved the plastic deformation of the sheet using hydroforming with the optimized pre-bulging process. The results of their research indicated that the average strain and other variables are directly affected by the pre-bulge pressure. Wang and Li [8] examined the effects of wrinkling prevention method on the forming accuracy of the 1050 aluminum alloy sheet. In their investigation, a finite-element model was developed to study the influence of paraffin layer thickness, paraffin particle size, and fluid pressure. The results of their study showed that by increasing the fluid pressure and the thickness of the paraffin layer, the uniformity of the final product had been improved. Raja Satish and Ravi Kumar [9] researched the formability of 6061 aluminum alloy sheets in warm forming. The purpose of their study was to investigate the effects of punch speed, process temperature, and sheet thickness on the FLD diagram. Salahshoor et al. [10] investigated the influence of tool (such as die profile radius and clearance between the die and blank holder) and process parameters (such as pressure path and friction coefficient) on the hydrodynamic deep drawing of copper sheets at the room temperature. The main objectives of their research were to reduce the forming force and improve the thickness distribution. Yaghoubi and Fereshteh-Saniee [11] studied the effect of fluid pressure and pre-bulge pressure in the HMDD process to produce aluminum-steel bimetallic specimens. The results of their research showed a remarkable improvement in uniformity of the final product in the presence of appropriate fluid and pre-bulge pressures. Yuan et al. [12] presented a novel process for deep drawing of Al alloy at the cryogenic temperature. In their investigation, the influences of variables such as material flow, drawing ratio, and drawing load for cups drawn under different process temperatures were studied. Wang and Shen [13] investigated hydrodynamic deep drawing process by utilizing a combined floating and static die cavity. The results of their research revealed that the conical cups produced via this method become more robust in comparison with the products obtained from the conventional hydrodynamic deep drawing process.

Aluminum alloys have extensive applications in various industries. Heat-treatable and high-strength properties of aluminum alloys are usually included in 2XXX, 6XXX, and 7XXX series [14]. The present research is concerned with HMDD of 2024 Al blanks. With this regard, many experiments and numerical simulations were conducted and the influences of the pre-bulge pressure, temperature, and fluid pressure were studied. Despite previous researches, in which only the reduction of maximum thinning was considered the main target, the thickness uniformity of the final component is additionally taken into account in this research work to attain the best process conditions. Moreover, for a better observation of the effects of various process parameters, the hardness tests are conducted and the required micrographs are prepared using an optical microscope (OM) and a scanning electron microscope (SEM). Two new investigations in the current research work are studying the preferred grain orientations and the analysis of precipitation hardening and their relations with the changes in the mechanical properties of 2024 Al cups. To the authors’ best knowledge, the crystallographic texture test and the deep study of precipitation hardening have not been employed by the previous researchers to interpret the mechanical properties as well as thickness distribution and uniformity of the HMDD final products.

### 2 Experimental procedure

As mentioned previously, Al 2024-T6 alloy is employed for experimentation in this research. Figure 2 illustrates the true stress–strain curves of this wrought Al sheet for different temperatures, gained from standard tensile tests.

It is clear that the higher the temperature, the lower is the flow curve and the greater is the elongation of the alloy. An 800-kN instrumented hydraulic press was utilized for conduction of the practical HMDD tests at elevated temperatures. The fracture mechanism of 2024 Al alloy at the room temperature is relatively far from the completely ductile fracture mechanism and it tends towards a combined ductile–brittle mechanism. In order to provide a facility for drawing process of this alloy, the die set is equipped with several electrical elements, each with 500-W power, for heating the blank. To apply the pressure underneath the central
region of the blank, a manual Enerpac pump with a capacity of 280 MPa is employed. Figure 3 illustrates the pump and hydraulic circuit together with the assembled die set. A safety valve, a check valve, and a pressure transducer are the main components of the designed hydraulic circuit. The function of this circuit is such that by moving the punch downward, the fluid pressure increases up to a certain value and, then, the excessive pressure is relieved through the safety valve. The geometrical parameters of HMDD die set employed for the current research work (Fig. 3) have
numerically been optimized for 2024 Al alloy in a separate research work by Yaghoubi and Fereshteh-Saniee [15].

3 Finite-element simulations

To numerically simulate the HMDD process at elevated temperatures, the Abaqus software was employed. Since the die, workpiece and generally the process were axisymmetric and in order to reduce the computational time, their 2D profiles were created for the analyses. For the workpiece, which was deformable, 4-node CAX4RT elements were utilized to create the FE model. These elements possess a temperature degree of freedom besides the displacement ones. The punch, blank holder, and matrix were modeled as analytical rigid surfaces. In the die set, the punch was moved only in the vertical direction and the other die components (matrix and blank holder) were considered fixed. The material flow curves were introduced based on Fig. 2. In the “interaction” module, the surface-to-surface contact mode and Coulomb’s friction law were employed. To model the friction, the penalty method is used, which allows movement of the surfaces in contact relative to each other. The amount of slip between the surfaces is limited by the simulator software. The purpose of controlling the amount of slip by this numerical simulator is that the shear stress caused by the slip does not exceed its critical amount. The friction coefficient in the blank-blank holder and blank-matrix interfaces was 0.06 because layers of oil existed in these regions. But, the friction at the contact surface of the punch with the blank was defined to be 0.15 [16]. The FE analysis was performed as a single coupled temperature-displacement step. After application of temperature and displacement boundary conditions, a uniform fluid pressure between 5 and 15 MPa was exerted onto the underneath and side surfaces of the blank. The pressure at the side surface was actually the radial pressure applied to the blank, facilitating the flow of the sheet into the die. Explicit methods have an acceptable ability to solve nonlinear differential equations governing the plastic deformation processes. Due to the high capacity of the explicit methods for solving the metal-forming problems and based on Gedikli’s suggestion [17], a dynamic-explicit solution was selected in the present numerical modeling. The simulation outcomes demonstrated that by increasing the number of elements excess to 45 in the radial direction, the value of the maximum thickness reduction did not remarkably vary. According to these findings, and to reduce the run time, the number of radial elements in the blank was considered 45. The finite-element model created for the HMDD process is presented in Fig. 4.

4 Results and discussions

In order to examine the quality of the hydro-mechanically drawn cups, the maximum percentage reduction in thickness is calculated for each case, based on the following relationship [18]:

\[ R_{th} = \frac{t_0 - t_f}{t_0} \times 100 \]  

(1)

\( t_0 \) is the initial thickness of the blank and \( t_f \) is the minimum thickness of the product at the end of the process. Having a desirable quality is a unanimous objective in various sheet metal-forming processes. Different criteria can be employed in order to inspect the quality of a hydro-mechanically drawn cup. As the previous investigations, the maximum thinning percentage introduced by Eq. (1) is one of the criteria which also utilized in this research work. However, another quality index is additionally proposed and employed in the present study. This index is the uniformity of the final product. In other words, when the difference between the thicknesses of the final drawn cup at its various regions in comparison with the average value is the minimum, one can conclude that the product possesses an almost uniform wall thickness. This difference can mathematically be calculated using the below equation [19]:

\[ V_{th} = \sum_{i=1}^{n} \left| \frac{t_{ave} - t_i}{t_{ave}} \right| \]  

(2)

\( n \) is the number of points selected on the profile of the deformed part for measuring the thickness. \( t_{ave} \) is the average thickness of the whole product, and \( t_i \) is the sheet thickness at each specific point on the profile of the drawn cup. It is worth mentioning that both the variables introduced in Eqs. (1) and (2) are dimensionless and this is a favorable
advantage. In current research work, the maximum reduction in both parameters of $R_{th}$ and $V_{th}$ in the produced products is desirable. A piece of this article is assigned to studying the influences of different process parameters on these variables. These effects are not the same for various regions of the workpiece. For this reason, the product profile is divided into three main areas, namely the bottom or the base of the cup (A), the area which is in contact with the punch corner (B), and the main wall of the cup (C).

4.1 Design of experiments

In this section, in order to evaluate the degree of effect of each process variable on uniformity of the final product and to examine the importance of the interactions between different factors, the design of experiments (DOE) employed in this study is described. The parameters investigated for HMDD of Al 2024 sheets consist of the maximum fluid pressure (in three levels of 5 MPa, 10 MPa, and 15 MPa), process temperature (in two levels of 200 °C and 250 °C), and initial diameter of the workpiece (in two levels of 70 mm and 73 mm). Therefore, altogether 12 practical HMDD experiments based on the full factorial approach were performed. The percentage effects together with the design matrix of the tests are demonstrated in Fig. 5. As shown in Fig. 5, any change in each process variable definitely affects the response obtained from the practical experiments. This figure also implies that the most important factors affecting the quality of the drawn cup are the blank diameter, the process temperature, and the maximum fluid pressure, respectively. On the other hand, the maximum interaction in production of the Al cups has occurred between the temperature and the initial blank diameter. However, the levels of interactions are negligible in comparison with the main effects of the process variables. For this reason, in specifying the optimum conditions for HMDD of 2024 Al sheets, the effect of interactions can reasonably be ignored.

4.2 Validation of FE simulation results

Figure 6 shows two cups drawn under the same test conditions but with different heights. Both the experimental sample (Fig. 6a) and the relevant numerical model (Fig. 6b) are illustrated together for a better comparison between the real and FE components. It should be noted that the samples in Fig. 6 are produced by applying 15 MPa fluid pressure and at 250 °C. In order to validate the findings obtained from the finite-element simulations, the experimental and numerical thickness distributions for these specimens are illustrated in Fig. 6c. The distance from the center of the workpiece is obtained along the diametrical section of the final product. The thickness of the deformed sheet was measured at different regions of the workpiece using a QLR point micrometer. The correlation between the FE model and experimental results is encouragingly very good and the maximum difference between these two sets of findings is about 6%. Moreover, it is obvious from Fig. 6 that, the minimum thickness of the drawn cup is around the punch corner-blank contact area.

4.3 Repeatability of experimental results

In order to verify the repeatability of the practical HMDD experiments, a typical test considered for studying each process variable was carried out twice (Table 1). The process variables in Table 1 include the fluid pressure ($P$), the pre-bulge pressure ($P_b$), and the process temperature ($T$), with the influences comprehensively discussed in the following sections. The results of the repeated experiments together

![Graph](image-url)
with those of the original ones are given in the Table 1. The outcomes presented in this table confirm a good consistency of the experimental findings and, consequently, one can deduce that the HMDD tests are repeatable.

### 4.4 The effect of fluid pressure

The fluid pressure is one of the important operation variables which could affect the uniformity of the product in sheet hydroforming process. The pressure paths employed for practical HMDD tests in this research are shown in Fig. 7. The mechanism of applying the pressure is such that by moving the punch downwards, the oil in the container underneath the blank is compressed up to a specific level. Afterwards, the safety valve is opened and the excess pressure is relieved. For the three pressure paths shown in Fig. 7, the relevant HMDD experiments were conducted and the thickness distributions of the products are plotted in Fig. 8. The corresponding numerical distributions of the thickness are also included in the same figure. The process temperature and the height of the deformed sheet in these experiments were considered to 250 °C and 22.6 mm, respectively. Figure 8 implies that the greatest effect of the fluid pressure can be observed in regions C and, then, B, where the ultimate variations (either thickening or thinning) with respect to the initial thickness of the blank occur. This is due to the presence of fluid pressure on the underneath of

![Image](image_url)

**Fig. 6** The 2024 Al cups drawn with different heights but under the same process conditions. a The picture of the experimental specimens. b The relevant FE models. c A comparison between the FE and experimental thickness distributions

| Specimen no. | P (MPa) | \(P_b\) (MPa) | \(T\) (°C) | \(H\) (mm) | \(R_{th}\) | \(V_{th}\) |
|--------------|--------|------------|----------|---------|--------|--------|
| 1            | 15     | 0          | 250      | 22.6    | 10.7   | 0.842  |
| 2 (R)        | 15     | 0          | 250      | 22.6    | 10.1   | 0.825  |
| 3            | 15     | 0          | 200      | 22.6    | 15.6   | 0.737  |
| 4 (R)        | 15     | 0          | 200      | 22.6    | 15.9   | 0.761  |
| 5            | 15     | 3          | 250      | 22.6    | Torn   | Torn   |
| 6 (R)        | 15     | 3          | 250      | 22.6    | Torn   | Torn   |

Table 1 Results for inspecting the repeatability of HMDD experiments for Al 2024 alloy
the workpiece, which can prevent the cups from sudden rupture. Furthermore, the fluid pressure causes a uniform distribution of the punch force during the forming process. According to Fig. 8, there is the least thickness change at the bottom of the product (region A). The reason for this phenomenon is the reduction of tensile strains in region A due to the frictional force occurred at the punch-workpiece contact surface and the slight slipping of the sheet on the punch face. The largest influence of change in fluid pressure inside the die chamber on the variation of thickness is related to the corner (region B) and wall (region C) of the final drawn cup. In region B, the workpiece is bent and stretched simultaneously, and this can cause relatively large strains at this area. The maximum compressive stress, instead, is created in the flange and wall regions of the product. Drawing the sheet into the die cavity and, consequently, reducing its radius and perimeter can increase the thickness at the flange area. The increase in thickness is due to hoop compressive stresses.

Table 2 summarizes $R_{th}$ and $V_{th}$ of cups with initial blank diameters of 70 mm and 73 mm, drawn with various maximum fluid pressures and at two different process temperatures. By increasing the maximum fluid pressure from 5 to 15 MPa, $R_{th}$ of the final product with the initial blank diameter of 70 mm and process temperature of 200 °C and 250 °C decreased by 17.1% and 28.3%, respectively. The maximum improvements in thickness variation of the product for the same pressure range and at process temperatures of 200 °C and 250 °C were obtained equal to 27.9% and 31.7%, respectively. As the initial diameter of the blank increases, the amount of contact surface and the related friction at the workpiece-matrix interface in the flange area increases and more areas of the sheet are subjected to large bending strains due to the die curvature. Therefore, with the downward movement of the punch, the blank enters the die cavity with more difficulties and the thinning and consequently the thickness variation in the deformed cup with a larger initial diameter increases. The results demonstrated in Table 2 are in accordance with the real conditions of the HMDD process.

The maximum thickness reduction versus changes in the fluid pressure at 200 °C and 250 °C are shown in Fig. 9. The trend of variation in the maximum thickness reduction is similar for both the temperatures. Moreover, it can be seen that with increasing the fluid pressure in the process at 200 °C, the slope of the curve is less than that of 250 °C. This is mainly due to the increased formability of the material at higher temperatures. Again, a good correlation exists between the FE and experimental findings shown in Fig. 9. It is obvious that for pressures greater than 15 MPa, no significant enhancement in the maximum thickness reduction can be achieved. For this reason and since excessive fluid pressure in the container considerably increases the required forming load, a pressure of 15 MPa has been selected for the remaining HMDD tests in the present investigation.

4.5 Influence of the pre-bulge pressure

Pre-bulge pressure ($P_{pb}$) is another process parameter influencing the quality of the HMDD products. This pressure is different from the fluid pressure in the container and is applied underneath the blank just before starting the punch movement. In fact, the pre-bulge pressure causes the upward swelling of the central region of the work sheet before downward displacement of the punch. Figure 10 shows how the amount of pre-bulge pressure affected the soundness of the drawn cup. The percentage maximum reductions ($R_{th}$) together with the values of the uniformity index ($V_{th}$) for these three cases are summarized in this figure. For these experiments, the maximum fluid pressure and process temperature were 15 MPa and 250 °C, respectively. The variations in the product thickness are also plotted in Fig. 10 for a couple of defect-free
parts deformed with various pre-bulge pressures. Applying pre-bulge pressure at the beginning of the HMDD process can reduce the negative effects of the die curvature on both the $R_{th}$ and $V_{th}$. This initial pressure has the role of a holder at the underneath of the sheet and it is expected that this initial pressure prevents application of extra load from the punch to the sheet before movement of punch and the contact with the workpiece. This parameter could also have a positive influence on the uniformity of the final product. On the other hand, with an excessive increase in the pre-bulge pressure, the punch needs greater force at the beginning of the movement, and the interaction between the mechanical load and the fluid pressure on both sides of the worksheet has a negative effect on it. As shown in Fig. 10, the application of pre-bulge pressure had initially positive impacts on the maximum percentage of thinning (about 17%) and the thickness variation of the final product (about 30%). Nevertheless, an excessive level for the pre-bulge pressure has caused tearing of the product. All these figures imply that for 2024 aluminum alloy under consideration, the most uniform and sound cup can be hydro-mechanically drawn with a pre-bulge pressure of 1 MPa.

4.6 Influence of the process temperature

By increasing the drawing temperature, one can improve the ductility of the blank to attain deeper cups. Nevertheless, the energy consumption increases and the strain hardening behavior decreases when the HMDD operation is carried out at elevated temperatures. For this reason, four levels, namely 100 °C, 200 °C, 250 °C, and 300 °C, around the transition temperature of the alloy have been selected for conducting the HMDD experiments. Figure 11 demonstrates the products drawn at different temperatures and a fluid pressure of 15 MPa together with the relevant values of $R_{th}$ and $V_{th}$ for regions A and B of the cups. It should be noted that no pre-bulge pressure has been considered for drawing the specimens shown in Fig. 11. It is clear that there is no significant reduction in thickness in region A of the workpiece. This is mainly due to the increased adhesion between the sheet and the punch face, which consequently decreased the plastic deformation of the sheet. By increasing the temperature, the value of $R_{th}$ at region A is slightly and monotonically decreased. The main effect of operation temperature occurs at region B, where at 100 °C the blank is torn, at 200 °C value of $R_{th}$ is 15.6%, at 250 °C it decreases to 10.7%, and finally at 300 °C thickness reduction is again increased to 17.9%. In the current study, with increasing the process temperature from 200 to 250 °C and from 250 to 300 °C, the thickness variation respectively increased 14.2% and 41.2%. Considering both the quality indices (i.e., $R_{th}$ and $V_{th}$), the appropriate temperature for the HMDD process of Al 2024 alloy is considered to be 250 °C.

4.7 Microstructural studies

One of the important effects of a forming operation is the change in the microstructure of the component which in turn affects the mechanical properties of the product. After grinding and polishing the test samples with different sandpapers having various grades, a Buehler Ltd. micro-hardness tester was employed to evaluate the hardness distributions, shown in Fig. 12. With this regard, a force of 100 grf was applied for 20 s [20]. For each point, the hardness was evaluated three times and their average was considered the final value. The average hardness in regions A, B, and C was calculated to be 142 H_V, 152 H_V, and 175 H_V, respectively. It should be mentioned that the Al cups studied in this section were drawn at a temperature of 250 °C.
A barker’s solution was used to obtain an appropriate microstructural image of 2024 aluminum alloy sheet [21]. The proper time for etching process was considered to be about 60 s. A micrograph of region A (with maximum average grain size) and another for region C (with minimum average grain size) are shown in Fig. 13. Using the linear intercept method, the average grain size for these two areas was calculated to be 15 μm and 12 μm, respectively. In order to establish a relationship between the grain size and the strength of the material in the present research, the Hall–Petch relation can be employed [22]:

\[
\sigma_y = \sigma_0 + kd^{-0.5}
\]  

(3)

\(d\) and \(\sigma_y\) represent the grain diameter and the yield strength, respectively; and \(k\) and \(\sigma_0\) are the constant material parameters. Based on Eq. (3), one can be realized that the grain size has an inverse relation with the strength and, consequently, with the hardness of the material. Comparing the grain sizes obtained from microstructural studies (Fig. 13) with the hardness values (Fig. 12) for different regions of the component, one can confirm the accuracy and validity of the experimental results for the present investigation.

Another important analysis in microstructural studies is related to the texture of the material, which is one of the important factors in changing the mechanical properties of polycrystalline structures. Macrotexture measurements were carried out on the plane of RD-TD surface using X-ray diffraction (XRD). The texture was determined employing a PANalytical X-ray diffractometer with Cr Kα radiation up to a tilt angle of 75°. Two incomplete pole figures (PFs) including those of \{111\} and \{200\} planes were utilized to calculate the inverse pole figures (IPFs) using the TexTools software. Since the maximum and minimum hardness and grain sizes were related to regions A and C, the texture study was carried out for these two areas. In FCC crystal structure, the \{111\} plane is the main slip plane and \(<110>\) is the main slip direction. The best condition for plastic deformation is when the \{111\} planes of majority of grains are oriented parallel to the sheet surface. The IPFs of rolling direction (RD), transverse direction (TD), and normal direction (ND) for regions A and C are shown in Fig. 14. The IPF of RD for region A demonstrates contour lines with the maximum intensity of 1.2 MRD which is concentrated in \{111\} direction, implying that this direction of many grains is parallel to the RD. The IPF of TD shows that the main texture is \{203\}║TD with the maximum intensity of 1.4 MRD. Finally, the IPF of ND expresses that there is a very strong \{001\}║ND texture in region A with a maximum intensity of 1.9 MRD. On the other hand, for region C, the IPF of RD does not show any significant change in maximum texture intensity. However, the main texture direction was changed from \{111\} to \{110\}. The maximum texture intensities of TD and ND IPFs for the cup wall region are decreased to 1.1 MRD and 1.7 MRD, respectively. The main texture direction of ND for this region was changed into [3 2 3] plane.

![Fig. 10](image1.png)

**Fig. 10** The final Al specimens hydro-mechanically drawn under the same process conditions but with different pre-bulge pressures

![Fig. 11](image2.png)

**Fig. 11** The final Al specimens hydro-mechanically drawn under the same process conditions but with different process temperatures

| Temperature (°C) | Maximum thickness reduction (%) | Thickness variation |
|------------------|---------------------------------|--------------------|
|                  | region A                        | region B           |
| 100              | 2.7                             | torn               |
| 200              | 1.3                             | 15.6               |
| 250              | 1.0                             | 10.7               |
| 300              | 0.9                             | 17.9               |
|                  |                                 | 1.189              |
The preferred crystallographic orientation is one of the most important and influential factors on the microhardness of the specimens. For aluminum alloy with FCC structure, [1 1 1] direction is introduced as the high-density crystallography direction, because of the closed-pack atomic arrangement in this direction. It can be claimed that when the texture is such that the [1 1 1] direction is aligned to the axis of the indenter in a hardness test, a higher $H_V$ should be perceived in the experiment. The texture intensities of [1 1 1] $\parallel$ RD for regions A and C were calculated to be 1.15 MRD and 0.83 MRD, respectively. Based on this observation, region A should possess a higher hardness in comparison with region C. This outcome is in contrasting with the experimental results of the hardness test and Hall–Petch estimation for these two areas, i.e., the finer the grains (region C), the harder the material. After facing the difference between evaluations of the Hall–Petch equation and the crystallographic texture in interpreting the hardness test results, it was decided to examine the precipitation hardening which is another factor influencing the hardness of the material. Indeed, the precipitation hardening is one of the main mechanisms for strengthening 2024 Al alloy. For this reason, the study of development and morphology of precipitations, secondary phases, and intermetallic compounds in this Al alloy could be helpful to investigate the factors changing its mechanical properties such as hardness. Therefore, the distribution of precipitations in different regions of a typical 2024 Al alloy drawn cup has been examined. The weight percentages of the elements constituting 2024 Al alloy are given in Table 3. Considering that after aluminum, the copper element has the maximum weight percentage in the chemical composition of 2024 Al alloy, the presence of copper precipitations in the material is likely. In order to investigate the precipitations produced in the workpiece during the forming process, the energy-dispersive

**Fig. 12** The hardness distribution in terms of distance from the center of the workpiece

![Graph showing hardness distribution](image)

**Fig. 13** Microstructural pictures of different areas of the finally drawn cup. a OM image for region A. b OM image for region C. c SEM image for region A. d SEM image for region C

![Microstructural images](image)
spectroscopy (EDS) test was carried out. Figure 15 illustrates the results of EDS tests for different regions, namely A and C, of the final product. As can be seen in this figure, Al₂Cu precipitations could be considered the main intermetallic compounds distributed discontinuously at the grain boundaries in region A. However, in region C, Al₂Cu precipitations are observed more continuously at the grain boundaries, compared with the dispersion in region A. The presence of continuous precipitations at the grain peripheries is a sign of increase in the hardness of the alloy. The grain boundaries are usually considered one of the most sensitive areas for the formation of defects in a material. Thus, the presence of precipitations at the grain boundaries prevents creation of defects at these areas and, consequently, increases the hardness of the alloy. On the other hand, accumulative or colonial precipitations are observed in both the regions. The image obtained from the EDS test demonstrates that the colony precipitations formed in region C are smaller than those of region A. Moreover, they are scattered inside the grains with comparatively smaller dimensions. This type of precipitation distribution is another source of hardness enhancement in region C. Therefore, it is reasonable that an intensified increase in the hardness of region C, in comparison with region A, should be detected. Now it can be claimed that the presence and sort of distribution of Al₂Cu particles as high-hard intermetallic compounds has a more significant and meaningful influence on the micro-hardness of 2024 Al cups than the preferred grain orientation.

Table 3  The weight percentages of the elements making up 2024 Al alloy under consideration

| Element | Weight percentage |
|---------|-------------------|
| Al      | 93.50             |
| Cu      | 4.40              |
| Mg      | 1.50              |
| Mn      | 0.60              |
Conclusions

More uniform thickness of the product and reducing the probability of the sheet tearing are two main advantages of hydro-mechanical deep drawing (HMDD), in comparison with the traditional process. The present article is concerned with experimental and numerical studies on HMDD of 2024 Al sheets. With this regard, the influences of the fluid pressure, the pre-bulge pressure, and the process temperature on the maximum percentage thinning and uniformity index of the drawn cup are investigated. Moreover, the hardness measurements for different regions of the product are correlated to the relevant microstructure, the preferred crystallographic orientation, and the distribution of the effective strain obtained from the numerical simulations. Based on the interpretations made in the present research work, the conclusions can be summarized as below:

- The most effect of the fluid pressure corresponds to the area of the sheet which is in contact with the punch corner (i.e., where the maximum reduction in thickness occurs). By increasing this pressure, one can decrease the maximum thinning in this critical region, although after reaching a specific value, it remains nearly constant. Thus, excessive increase in the fluid pressure is not rec-
ommended because it just intensifies the forming load and the energy requirement.

- The pre-bulge pressure represents a positive influence on the uniformity of the product. Nevertheless, the extra pre-bulge pressure would increase the drawing force, which is not desirable. For the 2024 Al cup drawn in the present investigation, a pre-bulge pressure of 1 MPa was found to be suitable.

- A temperature of 250 °C is appropriate for warm HMDD of 2024 Al sheets. A higher temperature could intensify the maximum thickness reduction and result in unevenly distribution of deformation. A lower temperature, on the other hand, could increase the risk of tearing in the product because of extreme brittleness of the material.

- The hardness distribution was in agreement with the grain refinement of different regions of the cup wall. However, the results obtained from the texture analysis of 2024 Al drawn cup did not confirm the hardness spread. This was mainly due to the presence of high-hard Al2Cu particles as intermetallic compounds at the grain boundaries. In other words, the precipitation hardening of 2024 Al2Cu alloy had a greater effect on the micro-hardness of the drawn component, in comparison with the preferred orientation of the grains.

The authors declare that this manuscript is not submitted to more than one journal for simultaneous consideration. The submitted work is also original and has not been published elsewhere in any form or language.

Availability of data and material The datasets during the current study are available from the corresponding author on reasonable request.

Declarations

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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