Numerical and Experimental Study of Elastic Recovery in Deep Drawing of Low Carbon and Galvanized Steel Sheet Conical Products

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Abstract. Deep Drawing is an important sheet metal forming process. It has numerous applications in different industrial fields. Due to improvements in technological techniques, modern industries focused on products dimensional accuracy especially for the products that have inclined walls since it may suffer from the effect of elastic recovery or what is known as springback. Springback is considered a major defect besides thinning, earing, and other deep drawing defects. It may cause serious deviation from demand dimensions particularly for the products inclined by certain angle such as conical shells or products. This study investigates the effect of wall inclination angle, punch velocity, type and thickness of the sheet material on elastic recovery behaviour. Two types of sheet metal, low carbon (AISI 1008) and galvanized steel sheets, of 110 mm diameters circular blanks at 0.9 and 1.2 mm thickness are formed by tooling set (punch, die, and blank holder). Conical dies were used to execute the experimental work and numerical having inclination angles at 70°, 72°, and 74° where, the punch velocity was 100, 150, and 200 mm/min. Numerical simulation was conducted using ABAQUS 6.14 where dynamic explicit solver was used to perform formation of conical products and static or standard solver to predict the behaviour of springback effect. A comparison between the experimental and numerical simulation was conducted. The results show that elastic recovery decreased with increasing of die wall angle, punch velocity, and sheet or blank thickness while increased with increasing of metal yielding stress. The springback factor rose by 0.003 to 0.007 with die angle increasing by 0.002 to 0.006 with punch velocity and thickness increasing, while it decreased by 0.001 to 0.003 with increasing of yielding point. The numerical simulation results show same tendency and high agreement with experimental results with a maximum discrepancy of 4%.

Keywords. Elastic, Deep drawing, Steel sheet, Numerical.

1. Introduction
Sheet metal forming includes mixture of elastic plastic, stretch, and bending deformity of formed part [1]. In the course of forming operation like stamping and deep drawing where bending-unbending is prevail, the zone about the neutral axis or plane in the material suffers from elastic and plastic deformation. As the punch reaches final drawing depth and then removed, material elastic strain recovered leading to springback in the formed part because of uneven distribution of the stresses in sheet [2]. Spring back is the quantity of elastic deformation in the material that has to undergo prior to
permanently form. Elastic recovery is the quantity of elastic tolerance, which exists in every material according to the nature of this material, whether it is ductile, annealed metal or hardened steel [3]. Elastic recovery in simple words represents deviation in formed part dimension that appears because of elastic recovery after the punch force is removed [4]. The prediction of springback is very important due to economical aspect [5]. Springback represents a stand problem in automotive manufacturing field, taking into account the use of ultra-high-strength steel, high strength steel, complex phase type steel etc. [6]. Useful tables and graphics [7-9] were used in some cases as conventional methods to predict elastic recovery. The value of springback of ductile material is lower than that of hard material due to its dependence on material of yield strength of elasticity. Also, it was noted that springback increases with increasing material yielding strength or strain hardening ratio. Both cold forming and heat processing cause an increasing in the value of springback [10].

Three forms of springback can be noticed [11]

- **Angular change.** In some cases, called springback, is when bended edge of the part generates angle distortion from tool (punch) edge (figure 1). The deviation angle is measured from punch radius. In case there is no curling in the side wall, then, the angle stays constant along the wall.

- **Side-wall curling.** It is known as the curvature generated in the wall of the formed product (figure 1). This phenomenon can be seen when the sheet metal is drawn over die or punch radius or by draw bead. The main reason for side wall curling is non-uniform stress distribution or stress components cross sheet thickness.

- **Twist.** Twist happens when two cross sections are rotated in different manner through their own axis. Twist occurs due to torsion moments in part thickness direction. Twist displacement generated from uneven springback and residual stresses which generate force couple causes the rotation of one end of the fabricated part to another commonly seen in bending processes.

![Angular Change and Curl](image)

**Figure 1.** Schematic diagram the angular and sidewall curling springback.

Springback is considered a challenge for industrialists who want to achieve certain dimensions. This problem is considered important in cases where high accuracy is demanded in assembly of parts in automotive or airplane industries when the part is required to achieve particular tolerance. So, minimizing and restriction of springback allow the designers to attain high process management and in the same time decrease the number of failed parts [12]. These days, finite element simulation becomes a popular tool to compensate elastic recovery for different metal forming processes. For instance, an accurate simulation of the springback in bending operation is considered very important in order to obtain the over bend angle needed to compensate the effect of springback. A suitable model is prepared to reveal the springback effect in the process. It is very vital to diagnose springback in his initial stage to minimize trial-and-error, scrap, and rework [13]. Ayres [14] proposed a multi-step operation in order to reduce the effect of springback in stamping processes. Liu [15] suggested changing the binder force through forming operation which provides tensile before-loading to minimize the springback. Many methods proposed to decrease springback effect involve stretch forming, pinch die, and arc bottoming.
Yet, these methods pass large amount of tensile stresses to deformed part wall leading to maximizing the possibilities of part failure due to tearing, especially for parts that have complex shapes.

2. Experimental work

2.1. Materials and mechanical properties

Two types of sheet metal were used in this study; low carbon and galvanized steel sheets of thickness 0.9 and 1.2 mm. Circular blank rod 110 mm were machined from the steel sheets as work specimens in the forming operation along with a set of tensile specimens by water jet machine in order to characterizes the mechanical properties of the materials used and archive high accurate finite element simulation. The tensile test specimens were fabricated according to ASTM standard E8M specification, with respect to rolling direction: 0° to rolling direction, 45° diagonal to rolling direction, and transvers to rolling direction (90°) as can be seen in figure 2 and figure 3.

![Figure 2. Tensile test specimens according to rolling direction.](image)

![Figure 3. Tensile test specimen dimensions according to ASTM standard E8M specification.](image)

Figure 4 illustrates the relation between true stress-true strain for the two materials after the tensile test was conducted and table 1 represents the mechanical properties of the materials used in this study.
Figure 4. The relationship between true stress-true strain curves along different angles to rolling direction for A) low carbon steel and B) galvanized steel.

Table 1. Mechanical properties of low carbon steel and galvanized steel at different angles with respect to rolling direction.

| Material              | Rolling Direction | Yield Strength (MPa) | Tensile Strength (MPa) |
|-----------------------|-------------------|----------------------|------------------------|
| Low carbon steel      | 0°                | 205                  | 376                    |
|                       | 45°               | 211                  | 385                    |
|                       | 90°               | 218                  | 411                    |
| Galvanized steel      | 0°                | 243                  | 407                    |
|                       | 45°               | 253                  | 444                    |
|                       | 90°               | 263                  | 431                    |

2.2. Tooling and equipment

Three conical punches and dies of inclination angles 70°, 72°, and 74°, were used to draw circular blanks of 110 mm at thickness of 0.9 and 1.2 mm. Punches and dies were designed to handle more than one thickness which means that one punch and die can be used to draw blanks of 0.9 and 1.2 mm thickness. Punches and dies were made of St.37 tool steel using CNC turning machine and punch and die profile radius kept constant, the value of punch profile radius and die profile radius are 9 and 11 mm respectively, for all punches and dies (70°, 72°, and 74°). Figure 5 demonstrates the drawing set arrangement while figure 6 shows punches and dies used in this study.
2.3. Deep drawing operation
The drawing experiments were conducted using WDW200E testing machine, 200 KN maximum loading capacity, associated with computerized control unit which plot the material behavior during deformation process as load displacement curve. The drawing operation was conducted at three punch velocities 100, 150, and 200 mm/min. In order to study the effect of punch velocity on the behavior of springback the experiments were designed using Minitab 18 software package using full factorial method. Figure 7 shows fully drawn conical products of various die wall angles, materials types, punch velocities, and sheet thickness. The first set formed from Galvanized Steel and the second set of Low Carbon Steel.
Figure 7. Photographs shows the cups produced from different die wall angles, punch velocities, materials types, and sheet thicknesses where the set 1 made from Galvanized Steel and set 2 from Low Carbon Steel.

3. Numerical simulation
ABAQUS 6.14 was used to analyze and simulates the deep drawing process and prediction of springback behavior in conical products. Table 2 demonstrates the mechanical properties of both materials used in finite element simulation. The values of stresses and strains used in simulation are from true stress-true strain curve that were obtained experimentally.

| Material          | Property       | Value      |
|-------------------|----------------|------------|
| Low Carbon Steel  | Young’s modulus| 200 GPa    |
|                   | Density        | 7.8 g/cm³  |
|                   | Poisson ratio  | 0.3        |
|                   | Yield stress   | 205 MPa    |
| Galvanized Steel  | Young’s modulus| 210 GPa    |
|                   | Density        | 7.85 g/cm³ |
|                   | Poisson ratio  | 0.29       |
|                   | Yield stress   | 243 MPa    |

The model in this study has four components: punch, die, blank, and blank holder where the punch, die, and blank holder are defined as rigid bodies and the blank is defined as deformable body. Figure 8 demonstrates the model generated using ABAQUS 6.14 pre-processor. Rigid bodies (punch, die, and blank holder) meshing use R3D4 and R3D3 elements. These elements are specified for rigid bodies and the global size value is 3. In the case of deformable body (blank), it was meshed using C3D8R and C3D6 elements. These types of elements are known as 8-node and 6-node 3D reduced integration elements where sweep technique was utilized in meshing as shown in figure 8 for shell and solid model.
3.1. Formatting the title Contact and loading

In order to achieve effective contact modeling for the interaction of rigid and deformable parts, a surface-to-surface dynamic explicit contact with finite “sliding penalty” based contact algorithm was used, associated with three contact pairs: punch-top blank, holder-top blank and die-bottom blank. The coefficient of friction between the interacted surfaces is assumed to be 0.1 for holder-top blank and die-bottom blank contact pairs and 0.15 for punch-top blank contact pair. The loading consists of three steps; the first step is called initial step where the boundary condition is implemented, the second step represents the applied holding force while the third step represents the actual drawing process. The resulting products show a good agreement with the experimental work. Figure 9 illustrates the final products from the experimental and simulation processes.

3.2. Spring back modeling

The springback analysis can be performed using ABAQUS/Explicit but it was found that solving springback analysis with ABAQUS/Standard is more efficient because springback analysis is
considered as a static simulation without exterior load or contact. ABAQUS 6.14 provides the ability to import results back and forth between Explicit and Standard solver which allows preforming of forming analysis in ABAQUS/Explicit and springback simulation in ABAQUS/Standard. The process of modeling springback depends on considering the final state of ABAQUS/Explicit (forming result) as the initial state in ABAQUS/Standard. The modeling of springback in ABAQUS starts by copying the forming process model or Explicit model and creates a new model and since only the blank needed in springback analysis, the simulation begins by deleting some features from the copied model:

1. All rigid instances: Punch, Die, and Blank Holder.
2. All rigid bodies' references: RefDie, RefPunch, and RefHolder.
3. All surfaces.
4. All contacts, interactions, and boundary conditions.
5. All analysis steps.

The general static step is created in the copied model including the geometric nonlinearity and automatic stabilization because springback analysis may suffer from instabilities. The next step is creating the predefined field in order to define the explicit process as the initial step and redefined the necessary boundary conditions intended by symmetry along z-axis and x-axis. It is important to define a fix signal point at the center of the blank in order to exclude rigid body motion. The springback is measured by defining new coordinate system with its origin at the center of the blank, then creating a path containing two nodes and extracting their coordinate from the new system, and finally calculating the springback angle from equation slope. Figure 10. Demonstrates the results obtained from springback modeling from ABAQUS / Standard.

4. Spring back measurements

The measurement of the value of produced conical cup wall springback is achieved by defining the desired angle at transverse direction, and the punch wall angle (punch angle) as a reference value. To identify the difference between the punch and cup side wall angle after unloading a straight path of points set up along transverse direction. Figure 11 illustrates an example of measurement technique used. Their coordinate was measured by the inner surface of the cup using C-Tek KM-80D coordinate.
system 3-Axis milling machine as shown in figure 12, by setting the original point (0, 0, 0) of the machine at the cup inner center and the third axis parallel to transverse direction. In this case, the y-axis is set parallel to the transverse direction. The same technique is used with simulated model to measure wall angle by identifying new coordinate system with its original point at the center of the cup and determining the coordination of two nodes in the inner cup surface along transverse direction. In order to calculate the value of springback angle, line slope equation is used as follows,

\[ M = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1} = \tan \theta \]  

(1)

\[ \theta = \tan^{-1} M \]  

(2)

Where: \( M \) = slope of the line, \( \theta \) = cup side wall angle, and \((x_1,y_1),(x_2,y_2)\) are any two points on the straight line path.

Figure 11. A) The path of straight points set up along transverse direction and B) Redefined original point at the inner cup center.

Figure 12. C-Tek KM-80D 3-axis milling machine used in this study in Training and Workshop Center/ University of Technology.

5. Results and discussion

Conical products are characterized by their wall inclination angle so that springback has a clearer effect on them than that of straight walled products. In this work, the springback and the angular change type are due to the changes at punch radius zone of the cup affected by different forming conditions causing a wall inclination. Springback factor will be used to demonstrate the behavior of springback and this factor can be obtained from the following equation, [16-17]

\[ K_s = \frac{A_{final}}{A_{initial}} \]  

(3)

Where: 
\( K_s \) = springback factor, \( A_{final} \) = angle after unloading and \( A_{initial} \) = angle under loading
The value of springback factor is between (0) and (1). When it is (0) this means there is no deformation and when its (1) this means there is no springback. Figures 13 and 14 show that the factors increase with increasing die wall angle. The main reason is that, at small wall angle, the material thickness direction undergoes elastic deformation along with certain amount of plastic deformation at punch nose zone of the cup which leads to an increase of springback phenomenon. As the wall angle increases, the expansion of the plastic deformation zone in thickness direction increases on the account of elastically deformed region. The material strength increases as a result of strain hardening and this will increase the material resistance to deformation, minimizing the effect of springback, but this does not mean its absence.

Tables 3 and 4 demonstrate the relation between punch velocity and springback factor for both materials as shown in the above tables and the springback factor tends to increase with increasing of punch velocity. This can be related to strain hardening of the materials as the velocity increases rapidly in strain hardening of the materials which causes an increase in drawing force and drawing stress leading to magnifying the effect of plastic deformation in thickness section of the cup at punch nose zone causing restriction of springback effect. From these results, shape accuracy can be enhanced by increasing punch velocity within acceptable range.

The relation between sheet thickness and material type with springback factor are demonstrated in Tables 3 and 4 EXP and FES respectively, where the springback factor increases with increasing of sheet thickness, which is considered an important parameter affecting springback. At small sheet thickness, lower plastic zone generated result in higher springback with increasing sheet thickness. This zone becomes larger leading to reduce springback behavior [18-20]. On the other hand, the springback factor for galvanized steel is less than of low carbon steel; this is due to the direct relation between the springback effects with material yield strength. The value of yield strength for galvanized steel along transverse direction is 263 MPa and for low carbon steel is 218 MPa which means that the value of springback factor decreases with higher yield strength due to increasing the point where plastic stage begins. When the yield strength has a high value, this means that the point where plastic flow started is also high.
Figure 13. The effect of Die wall inclination on the behavior of Springback for L.C.Steel products along transverse direction with different values of Punch Velocity and sheet thickness.

Figure 14. The effect of Die wall inclination on the behavior of Springback for G.Steel products along transverse direction with different values of Punch Velocity and sheet thickness.
### Table 3. Springback factor values obtained experimentally.

| Material Type          | Sheet Thickness (mm) | Die wall angle (°) | Punch Velocity (mm/min) | Springback Factor (Kₛ – EXP) |
|------------------------|----------------------|-------------------|-------------------------|------------------------------|
|                        |                      |                   | 100                     | 150                          | 200                          |
| Low Carbon Steel       | 0.9                  | 70°               | 0.973571                | 0.977143                     | 0.98                          |
|                        | 72°                  |                   | 0.979861                | 0.982639                     | 0.985417                     |
|                        | 74°                  |                   | 0.987838                | 0.990541                     | 0.992568                     |
|                        | 0.9                  | 70°               | 0.978571                | 0.982143                     | 0.985                          |
|                        | 72°                  |                   | 0.984722                | 0.986806                     | 0.990278                     |
|                        | 74°                  |                   | 0.990541                | 0.993243                     | 0.995541                     |
| Galvanized Steel       | 0.9                  | 70°               | 0.971429                | 0.973571                     | 0.976429                     |
|                        | 72°                  |                   | 0.977778                | 0.980556                     | 0.983333                     |
|                        | 74°                  |                   | 0.985135                | 0.987838                     | 0.989865                     |
|                        | 70°                  |                   | 0.987514                | 0.990278                     | 0.993243                     |
|                        | 72°                  |                   | 0.982639                | 0.985417                     | 0.988194                     |
|                        | 74°                  |                   | 0.989054                | 0.991892                     | 0.993919                     |

### Table 4. Springback factor values obtained from simulation.

| Material Type          | Sheet Thickness (mm) | Die wall angle (°) | Punch Velocity (mm/min) | Springback Factor (Kₛ – FES) |
|------------------------|----------------------|-------------------|-------------------------|------------------------------|
|                        |                      |                   | 100                     | 150                          | 200                          |
| Low Carbon Steel       | 0.9                  | 70°               | 0.974429                | 0.978143                     | 0.981429                     |
|                        | 72°                  |                   | 0.981944                | 0.985417                     | 0.988056                     |
|                        | 74°                  |                   | 0.989595                | 0.992703                     | 0.994595                     |
|                        | 0.9                  | 70°               | 0.980857                | 0.984                          | 0.987143                     |
|                        | 72°                  |                   | 0.9875                  | 0.989306                     | 0.993056                     |
|                        | 74°                  |                   | 0.992568                | 0.995405                     | 0.997568                     |
| Galvanized Steel       | 0.9                  | 70°               | 0.973429                | 0.975571                     | 0.978571                     |
|                        | 72°                  |                   | 0.980278                | 0.983056                     | 0.985556                     |
|                        | 74°                  |                   | 0.987297                | 0.99                          | 0.992973                     |
|                        | 1.2                  | 70°               | 0.978                      | 0.981714                     | 0.985                      |
|                        | 72°                  |                   | 0.985                    | 0.987778                     | 0.990556                     |
|                        | 74°                  |                   | 0.991081                | 0.993649                     | 0.995676                     |

### 6. Conclusions

1. The results show high agreement between the experimental work and numerical work with a maximum discrepancy of 4%.
2. Increasing die wall angle leads to an increase in springback factor by about 0.003 to 0.007 experimentally and 0.005 to 0.0075 numerically due to expansion of plastic deformation zone through thickness direction.
3. Increasing punch velocity causes an increase in the springback factor by about 0.002 to 0.003 and by 0.002 to 0.004 experimentally and numerically respectively because high velocity increases the strain hardening of the material which leads to an increase in the forming load and magnifying the plastic zone volume.
4. Thickness increasing minimizes the effect of springback and raises the springback factor by 0.003 to 0.005 due to the increasing of permanently deformed region.
5. The value of springback factor decreases with a difference of about 0.001 to 0.003, with the increasing of yielding point of the formed material. The reason for that is when yielding strength increases, the force required to deform material plastically also increases which means springback factor decreases with high yielding point.
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