Research Journal of Applied Sciences 4 (5): 192-201, 2009
ISSN: 1815-932X

Springback and Side Wall Curl of Metal Sheet in Plain Strain Deep Drawing

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Abstract: In the industrial forming of metal sheet or plate component by means of bending operation, a constant problem is the change of shape, or Springback of the formed part under the stress that are released elastically when the forming load is removed, for the close tolerance forming of such component, an accurate means of calculating the Springback is of great value, as this enables a corrective allowance to be made when designing and performing the forming operation itself. In this research, the effect of material type, sheet thickness, blankholder force, punch speed rate, rolling direction and friction conditions on springback values were studied analytically under the plane strain conditions, Springback device has been designed and manufactured experimentally with a specimen. These devices can carry out all the tests of the Springback. The results showed the effect of the parameters on the die angle, punch angle and the sidewall curvature. by using MATLAB program, a polynomial function could be estimate the relationship between all the parameters to find the value of slops and curvature with fixed dimensions: die Angle = $1.8519x^3 - 2.9630x^2 - 1.0926x + 13.3222$, punch Angle = $-2.7778x^3 + 8.6111x^2 - 10.4444x + 21.7667$, radius of Curvature = $1.1111x^3 - 1.7778x^2 + 1.3444x + 5.0933$, where x is the holdown force value between (200-1100 N).

Key words: Springback, side wall curl, deep drawing, sheet metal forming, U bending, plain strain

INTRODUCTION

Sheet metal forming is one of the most widely used manufacturing processes for the fabrication of a wide range of products in many industries. The reason behind sheet metal forming gaining a lot of attention in modern technology is due to the ease with which metal may be formed into useful shapes by plastic deformation processes, in which the volume and mass of the metal are conserved and metal is displaced from one location to another (Kishor and Kumar, 2002). Deep drawing is one of the extensively used sheet metal forming processes in the industries to have mass production of cup shaped components in a very short time. In deep drawing, a flat blank of sheet metal is shaped by the action of a punch forcing the metal into a die cavity. Sheet metal can be formed using simple procedures, such as bending, or they can be very complex, such as deep drawing of non-axisymmetrical shapes. Sheet metal or sheet metal products can also be divided into two or more parts using blanking and piercing. Sheet metal is usually cold-formed, but in certain cases, such as bending or deep drawing, material can also be heated, usually only locally, in order to increase its formability. Since, sheet metal is formed using tensile or tensile-pressure forming, tools used are less loaded than during bulk forming. Product accuracy, especially for thick sheet metal, is not great, since surfaces are partially free and material is formed along the easiest natural path.

Springback and side wall curl: In sheet metal forming processes, at the end of the operation the blank being formed conforms closely to the shape of tools. After the load is released and the tools are removed u-shaped undergoes significant changes of its geometrical and shape parameters (Bogdan, 2003). This phenomenon is called a springback. Springback parameters are mainly influenced by the following factors:

- Material type
- Punch and die radii
- Initial clearance
- Friction conditions
- Blankholder force
- Sheet thickness
- Punch speed rate
- Constitutive behavior in plastic zone

During the forming process of the u-shaped part, the sidewall suffers complicated bending and stretching phenomena, the stress distribution on the side near the die is subjected to tensile stress and the side near the

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punch is subjected to compressing stress, which would promote a residual bending moment a result in sidewall curl. Introducing a considerable blankholder force into the forming process is useful in removing sidewall curl. When the holdown force is increased, namely increasing the flow resistance of the material, the stress distribution through the thickness of the sidewall may be turned to tensile stress over the whole section. Accordingly, springback directions of both sides become consistent, which is conducive to decreasing shape distortion (Samuel, 2000).

MATERIALS AND METHODS

Theoretical modeleling: Springback in the stretch bending of elastic nonlinear research hardening material is consider an initially straight beam of a rectangular cross section of width b and depth h, which is loaded by pure bending moment M and a tensile axial force N as shown in Fig. 1.

The material of the beams is considered to be elastic exponential research hardening, i.e. obeying the stress-strain relationship and is represented mathematically by:

$$\sigma = \begin{cases} Ee & \text{for } e \le e_y \\ \sigma_y + E_p\left(e - e_y\right)^n & \text{for } e_y \le e \le e_{ult} \end{cases} \quad (1)$$

where, σ, σ_y are the stress and yield stress, respectively, e and e_y are the engineering strain and engineering yield strain, respectively, e_{ult} is the ultimate tensile engineering strain, n is the research hardening index. E and E_p are the elastic and plastic modulii, respectively. Assuming that the plane sections of the beam remain plane during the elasto-plastic stretch bending i.e., the strain at a point in the beam is proportional to its distance from the neutral axis and the total deflection is small compared to the length of the beam, so that the additional bending moment caused by N can be neglected. For a different combination of M and N, the stress distribution across the section of a rectangular beam is derived for the following cases.

- Totally elastic case, for which no in the beam is strained beyond the yield point (Fig. 2a)
- Primary plastic case, for which layer on one side of the neutral axis are beyond the yield condition (Fig. 2b)
- Secondary plastic case, for which layer on both sides of neutral axis are strained beyond yielding (Fig. 2c)

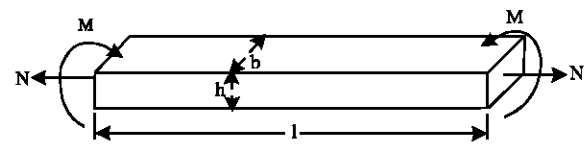


Fig. 1: An initially straight beam of rectangular cross section, loaded by pure bending moment and an axial force

These three cases are illustrated schematically in Fig. 2. It is convenient to define the following initial yield quantities, bending moment Me, axial force Ne and curvature κe of the section as:

$$\left.\begin{aligned} M_e &= \sigma_y bh^2/6 \\ N_e &= \sigma_y bh \\ \kappa_e &= 2\sigma_y/hE \end{aligned}\right\} \quad (1a)$$

Evaluation of N and M in plain strain deep drawing;
Hold-down force N_h
Friction force $F_h = \mu N_h$
$N = F_h$

$$1/R = \frac{M}{EI}$$

For the deep drawing with zero radius of die; it will be assumed that the radius of bend is equal to half thickness plus the clearance of die.
R = h/2+clearance
E = is the Young modulus of sheet metal

$$I = bh3/12$$

then,
M = (Ebh3/12)/ (h/2+clearance)

The dimensionless moment m, stretching force nr and curvature ϕ are defined as:

$$\left.\begin{aligned} m &= |M|/M_e \\ n_r &= |N|/N_e \\ \phi &= |\kappa|/\kappa_e \end{aligned}\right\} \quad (1b)$$

The non-dimensional quantities for stress geometry are $\gamma = c/(h/2)$, $\delta = d/(h/2)$ and $f = (1-\delta+\gamma)$ where, c is the distance between the neutral axis (N.A) and the yielding layer and d is the distance between N.A and centeroidal axis C.A, which are shown in Fig. 2.

This is the case, when the strain at the outer layer is greater than e_y and the strain at the inner layer is smaller or equals to e_y. Referring to Fig. 2b and Eq. 2.

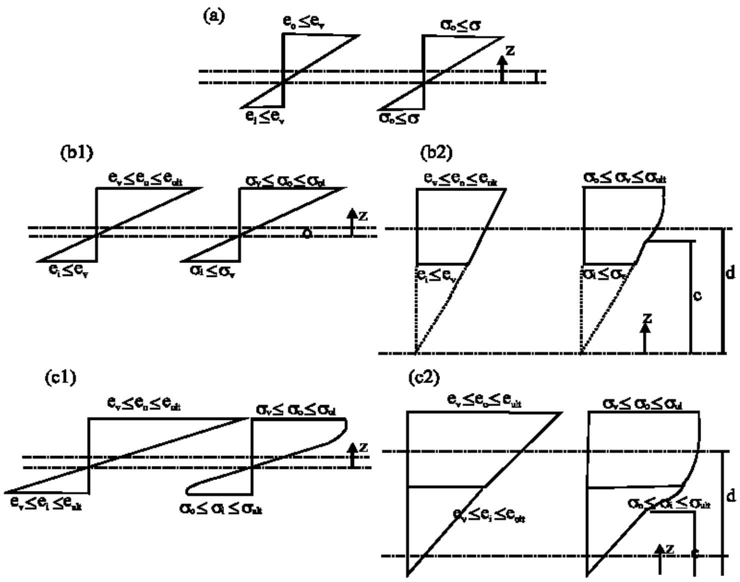


Fig. 2: The stress and strain distribution across a section of beam of elastic exponential research hardening material. a): Wholly elastic regime (E); b): Primary plastic regime (P_I) and c): Secondary plastic regimes (P_{II} and $P`_{II}$)

$$\sigma = \begin{cases} Ee & \text{for } e \le e_y \\ \sigma_y + E_p\left(e - e_y\right)^n & \text{for } e_y \le e \le e_{ult} \end{cases} \quad (2)$$

we get,

$$\sigma = \begin{cases} Ee & \text{for } -h/2 \le z \le h/2 + d \\ \sigma_y + \mu E\left(e - e_y\right)^n & \text{for } c \le z \le h/2 + d \end{cases}$$

where, μ is the ratio of the plastic modulus Ep to the elastic modulus. The strain is linearly proportional to the distance from N.A. and the stress at the outer layer (σ_o) when, z = h/2, Fig. 2b, is therefore,

$$\sigma_o = \sigma_y + \mu E\left(e_o - e_y\right)^n = \sigma_y + \mu E\left(\frac{\sigma_y}{E\gamma}\right)^n (1 + \delta - \gamma)^n \quad (3)$$

The stress distribution for the thickness is shown in Fig. 2b.

When, δ = 0 which is the special case where pure bending is applied, Eq. 3 is reduced to

$$\sigma_o = \sigma_y + \mu E\left(\frac{\sigma_y}{E\gamma}\right)^n (1 - \gamma)^n \quad (4)$$

Which is the same expression obtained by Johnson and Yu (1981) for pure bending only of elastic exponential work hardening material. In the secondary plastic regimes, PII and P`II, this is the case where the strain in the inner and outer layers is greater than ey as well as the strain in the outer layer. Referring to Fig. 2c and the strain at z = c, ey = c/R = σy/E, i.e. 1/R = σy/ (E×c). At z = h/2 + d:

$$e_o = \frac{\sigma_y}{E}\left(\frac{1+\delta}{\gamma}\right)$$

and

$$\sigma_o = \sigma_y + \mu E\left(\frac{e_y}{\gamma}\right)^n (2 - f)^n \quad (5)$$

at z = -h/2 +d, the stress σi and strain ei at thinner layer can be written as:

$$e_i = c/R = (-h/2+d)/E = \sigma y\,(-1+\delta)/\gamma$$

$$\sigma_i = \sigma_y + \mu E\left(\frac{e_y}{\gamma}\right)^n (f - 2\gamma)^n \quad (6)$$

For the case, when the N.A inside the cross section (Fig. 2c). The moment equilibrium equation through the section of beam is:

$$M = \int_c^{h/2+d} b\left\{\sigma_y + \mu E\left(\frac{e_y}{c}\right)^n (z-c)^n\right\}(z-d)\,dz + \int_{-c}^{c} \frac{zb\sigma_y}{c}(z-d)\,dz + \int_c^{h/2-d} b\left\{\sigma_y + \mu E\left(\frac{e_y}{c}\right)^n (z-c)^n\right\}(z-d)\,dz \quad (7)$$

and the axial load equilibrium equation for a section of the beam is:

$$N = \int_{-c}^{c} b\sigma_Y \frac{z}{c} dz + \int_{c}^{b/2+d} b\left\{\sigma_Y + \mu E\left(\frac{\sigma_Y}{Ec}\right)(z-c)^n\right\} dz$$
$$- \int_{c}^{b/2-d} b\left\{\sigma_Y + \mu E\left(\frac{\sigma_Y}{Ec}\right)(z-c)^n\right\} dz$$

Then, after integrating and arrangement that found:

$$m = \frac{(3-\gamma^2)}{2} + \frac{3\mu}{2}\frac{e_Y^{n-1}(1-\gamma)^{n+1}}{\gamma^n}\frac{(n+1+\gamma)}{(n+1)(n+2)}$$

$$n_1 = 1 + \frac{\mu e_Y^{n-1}}{2\gamma^n (n+1)}\left\{(2-f)^{n+1} - (-f)^{n+2}\right\}$$

The dimensionless curvature ϕ of this regime is simplified to

$$\phi = 1/\gamma = m/\mu \qquad (8)$$
$$\phi^F = \phi - \phi^E$$

where, $\phi^F = \kappa^F/\kappa_e$ is the non-dimensional final curvature of the beam, ϕ is the elasoplastic curvature determined by Eq. 8, ϕ^E is the elastic curvature.
Since,

$$Arc = \frac{\pi}{2}R \qquad (9)$$

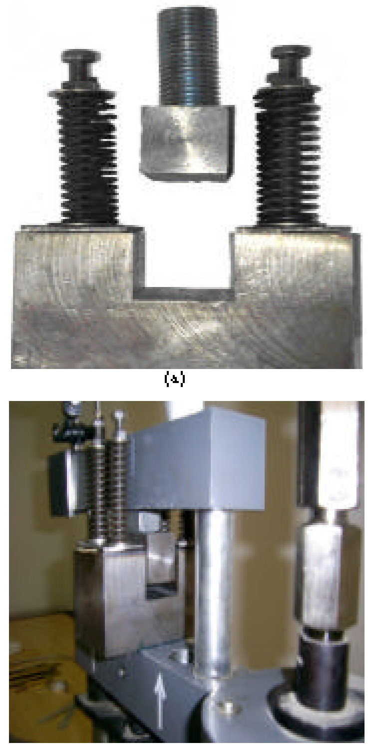
after found the value of the non-dimensional final curvature of the beam ϕ^F we can find the value of κ_F from Eq. 2 and the value of arc from Eq. 9. Since,

$$R_F = \frac{1}{\kappa_F} \qquad (10)$$

then calculate the angle value θ by substitute in Eq. 11:

$$\theta = \frac{Arc}{R_F} \qquad (11)$$

Experimental research: The major objective of the experimental research is to design a die and a punch to obtain the u-shaped specimen then determine the springback ratio and side wall curl of sheet metal specimens. Then selection of the materials to be used for create the specimens of the metal sheet is an important initial step in the design process. Have been chosen for create of the sheet of galvanized steel, brass and aluminum. The specimens must be fit the die and punch with a suitable clearance. It should be a rectangular sheet of 20 mm of width and 150 mm of length with 0.5-1 mm thickness.



(a)

(b)

Fig. 3: Springback device with details, a): Springback instrument, b): Device components

Springback device design: Springback testing device shown in Fig. 3a was fully designed and manufactured locally. The main parameters were design with new ideas to overcome the difficulties of Springback testing and these main parameters as listed:

Die and punch design: The die and the punch are made of steel to be rigged enough in order to have a negligible deflection, the dimension selected to be fit into the hydraulic compression device, which already exists. The Punch and die clearance was adjusted for sheets of different thickness to maintain a clearance to thickness ratio of (1-2) (Jang and Thomson, 1989). This value was chosen as a standard condition because, it provided a gap large enough not to cause reverse bending of punch and die clearance on springback and side-wall curl.

Hold down force technique: The compression forces were applied by means of the hydraulic compression apparatus, which acts on the punch, the screw works as a converter, it converts the torque into force with some loses because of the friction between the contacts areas, to overcome this problem, Eq. 12 was used.

$$F = K.x \qquad (12)$$

where, F is the half of the hold down force, K is the spring constant and x is the displacement of the screw.

Device components: The device as shown in Fig. 3b is consisted of the following components.

Compression device: A compression device type PHYWE, model D-3300 where, used to compress the punch into the die with axial force with selecting the speed rate.

Die: The frame made from steel (405) channel 100×60×60 mm, which is very rigid.

Screw: Four screws (M6) are used to control hold down force on the specimen.

Covers: Two clamps made of steel to transfer the hold down force from the springs to the specimen with a specific coefficient of friction.

Punch: The punch also made from steel (405) with dimension 26×60×30 mm.

Spring: four springs to convert the nut displacement to a force with an easy way of calculations.

Stead: the steed used is (M 20), which is used to fixed the punch with the hydraulic press.

Pressure gauge: A pressure gauge that read the applied axial force on the punch.

Dial gauge: the dial gauge, which is used to read the axial deflection of the punch by the mean of the compressed fluid in the compression device.

Digital camera: A PC digital camera was used to record the readings of the load gauges and the dial gauge by creating a movie for them throughout the test, by pausing this movie; it is possible to draw the force-deflection curve.

Effective parameters

Punch position: The punch position is an important parameter in this study, which is effect directly on the shape of the specimen, so, in this study a central position was selected to make a symmetrical shape.

Punch speed rate: The hydraulic press the punch with different speed of punching (0.34 and 0.48 mm sec^{-1}).

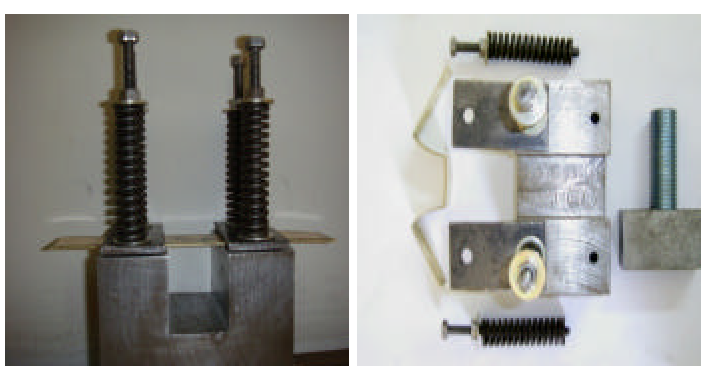
Rolling direction: Sheet metals that exhibit different flow strengths in different directions in the plain of the sheet are defined as having planar anisotropy. Parallel, perpendicular and 45° to the rolling direction represent the three vectors of the planar anisotropy. Anisotropy has a great effect on the bending limit with the relative differences in yield strength.

Friction conditions: This prevents the tension across the face of the punch from increasing sufficiently to stretch the material over the face of the punch. The effect of friction is to reduce the tension at the nose and spread the strain.

Testing method and procedure:

Applying load: After the specimen fixed on the instrument where, hold-down force is acting on the sheet by fixed the screw into the spring and then acting it on the covers with the requirement displacement, Hence, the peripheral parts of the specimen are kept in place as shown in Fig. 4a.

- Fixed the die and punch in the compression device. The punch is moved downwards the specimen till it reaches the sheet



(a) (b)

Fig. 4: Applying and releasing load, a): Loading specimen, b): Releasing hold down force

- The punch is now in contact with the sheet and the sheet is drawn through the opening in the die. It slides over the die edge. As the punch proceeds downwards the outer radius of the research piece is reduced. In this process, the specimen is formed through stretching in the drawing
- At the end of processes the blank being formed conforms closely to the shape of die

Releasing the load: After the load is released and the tools are removed, the u-shaped part undergoes significant changes of its geometrical and shape parameters.

To unfasten the u-shaped specimen out of the device the following procedures are followed:

- Returning the compression device to its initial position after the final end of the punch stroke by open the screw of reset tool
- Freeing the specimen from the hold down force by removing one screw from each side of the die perpendicular to the site of view of the specimen
- Rotating the two covers with 180° away of the punch as shown in (Fig. 4b)
- Finally, the formed component (u-shape specimen) will be released directly from the die

RESULTS AND DISCUSSION

The theoretical and experimental tests, which were described earlier are listed and discussed in details now. The validity of the theoretical modeling results has been checked by comparing it with the experimental test results.

Experimental modeling results: The results of a Springback tests are presented here. The data was obtained by hand plotting technique, using the milimetric pad after the specimen shape was plotted on the study and then the data was measured by using protractor and vernier.

Radius of curvature estimation: The interpolating polynomial was used to find the equation of side wall curl curve that show in Fig. 4 that choosing m point out of given (n+1) point we could pass a^n (m-1) degree polynomial through these m point. It follows that a^n (m-1) degree interpolation gives us a^n (m-1) degree interpolation polynomial (Louis, 2006).

$$p_{m-1}(x) = \sum_{i=0}^{m-1} a_i x^i = a_0 + a_1 x + a_2 x^2 + \dots + a_{m-1} x^{m-1} \quad (13)$$

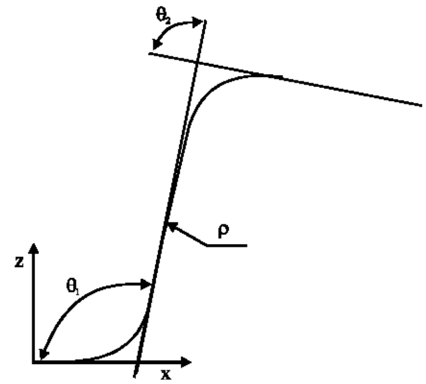


Fig. 5: Parameters to quantify Springback, a): With rolling direction, b): Normal rolling direction

Then, for sidewall curve substitute (m = 6) in Eq. 13:

$$y = f(x) = a_0 + a_1 x - a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \quad (14)$$

MATLAB program interpolating polynomial was written to find the coefficients of the polynomial by substituting the coordinate of different six points that are taken from the side wall curl arc. Differentiated Eq. 14 and substitute in Eq. 15 (Meriam and Kriage, 2007) to obtain an approximate value to the side wall radius of curvature.

$$\rho_{xy} = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}} \quad (15)$$

where, ρ_{xy} is the radius of curvature at any point.

Die and punch angels estimation: The die angle and punch angle were measured from the u-shaped of specimen as shown in Fig. 5, by draw the tangential line of sidewall arc and crossed it with the tangential line of the part of a specimen formed from the holdown force. These springback parameters whose variation was observed during experimental research are as:

θ_1- the die angle between the bottom of die and the sidewall. θ_2- the punch angle between the effect of holdown force and the sidewall.
The effective factors are:

- Holdown force values (200, 600, 800 and 1100) (N)
- Thickness 0.5 and 1.0 mm of brass, aluminum and galvanized steel specimens
- Speed rate of punch force 0.34 and 0.48 mm sec^{-1}
- With and normal rolling direction
- Lubricant with oil SAE 50

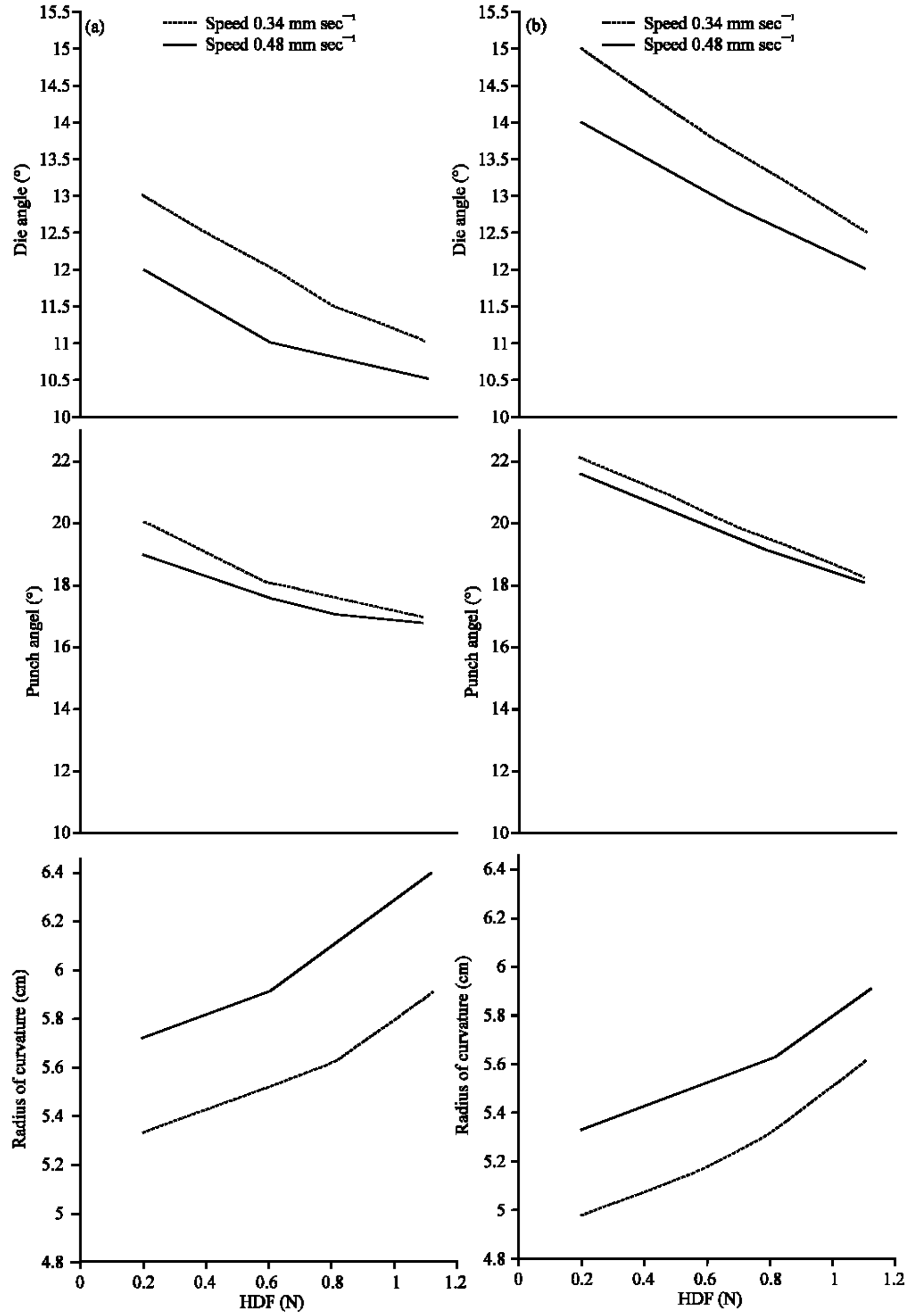


Fig. 6: Brass (0.5 mm) without lubricant, a): With rolling direction, b): Normal rolling direction

And a complete set of the test results for all types of specimens under these effective factors are tabulated in Table 1, the graphical relationships were shown in Fig. 6 and 7 and the comparing results as shown in Fig. 8 and 9, which show good correlations in relationship between the experimental and theoretical results.

The neutral axis moves towards the external side of the specimen, which is towards the die. This is due to the higher forces required to bend the thicker specimens. The increase is due to the increasing friction that is developed between the specimen and the die and the punch. Due to the increased friction forces the amount

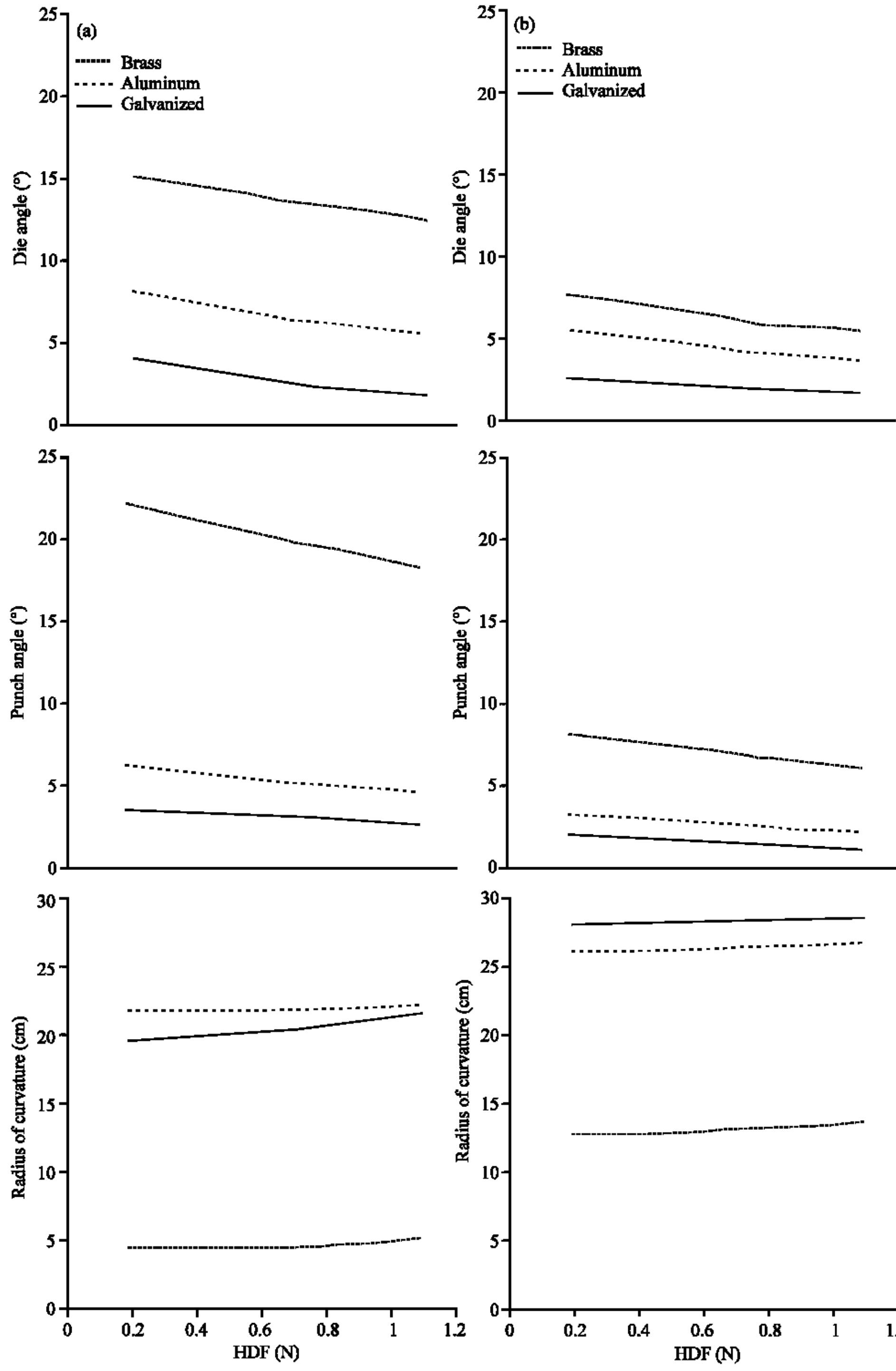


Fig. 7: Normal direction of rolling in speed (0.34 mm sec^{-1}) without lubricant a): Thickness 0.5 mm, b): Thickness 1.0 mm

of sliding between the specimen and the die is reduced and higher deformations occur for the thicker specimens. This increases the flat length required.

The variation of springback results is as follows:

- The die angle θ_1
  - Has decreased by 20% with the increase of the holdown force
  - Has increased by 26.66% with the increase lubricant oil

Table 1: Springback results of 0.5 mm Brass without lubricant

Hold down force (N)	Rate of speed (mm sec^{-1})	Rolling direction	Die angle (θ_1°)	Punch angle (θ_2°)	Sidewall curvature (cm)
200	0.34	90	105	68	4.95
		0	103	70	5.3
	0.48	90	104	68.5	5.5
		0	102	71	5.7
600	0.34	90	103.8	69.83	5.15
		0	102	72	5.5
	0.48	90	103	70.2	5.65
		0	101	72.4	5.9
800	0.34	90	103.3	70.62	5.3
		0	101.5	72.5	5.6
	0.48	90	102.6	71	5.75
		0	100.8	72.9	6.1
1100	0.34	90	102.5	71.83	5.6
		0	101	73	5.9
	0.48	90	102	72	6
		0	100.5	73.2	6.4

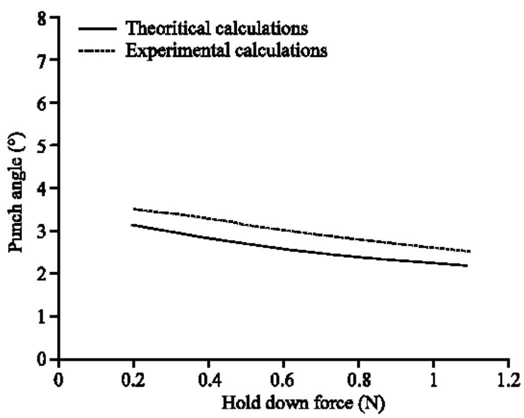


Fig. 8: Comparing the results of 0.5 mm galvanized under effect of HDF

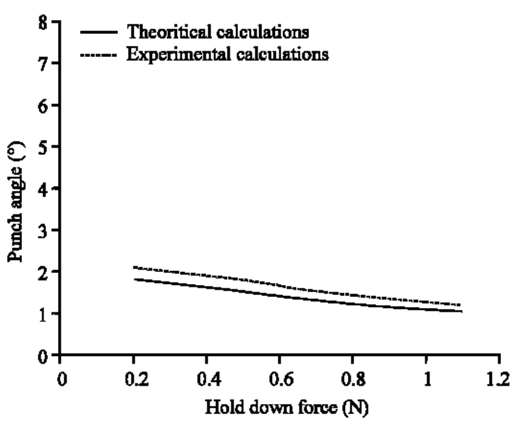


Fig. 9: Comparing the results of 1.0 mm galvanized under effect of HDF

- Has decreased by 15.38% with the change in rolling direction from with to normal
- Has decreased by 7.14% with the increase punch speed rate
- The punch angle θ_2
  - Has decreased by 21.07% with the increase of the holdown force
  - Has increased by 22.72% with the increase lubricant oil
  - Has decreased by 10% with the change in rolling direction from with to normal
  - Has decreased by 2.3% with the increase punch speed rate
- The sidewall curvature ρ
  - Has decreased by 11% with the increase of the holdown force
  - Has increased by 81.8% with the increase lubricant oil
  - Has decreased by 7% with the change in rolling direction from with to normal
  - Has decreased by 10% with the increase punch speed rate

By using MATLAB program, a polynomial function could be estimate the relationship between all the parameters to find the value of slops and curvature with fixed dimensions:

$$\text{Die angle} = 1.8519\,x3 - 2.9630\,x2 - 1.0926\,x + 13.3222$$

$$\text{Punch angle} = -2.7778\,x3 + 8.6111\,x2 - 10.4444\,x + 21.7667$$

$$\text{Radius of curvature} = 1.1111\,x3 - 1.7778\,x2 + 1.3444\,x + 5.0933$$

where, x is the holdown force value in (N), to obtain the accurate results that substituted any values of holdown force between the ranges (200-1100 N) with multiply the equations by the percentage values of any effects parameters on the results.

CONCLUSION

The following conclusions were drawn from the study of all factors that govern the evolution of the stress state in sheet material have a direct influence on the amount of Springback. The remaining conclusions are derived from overall shape change:

- Due to the extent of the affected area the shape change associated with simple bending, springback is much smaller than that related to sidewall curl

- Applying tension drastically reduces springback, although, a drop region of smaller dependence appears for back forces, i.e., the die angle and punch angle has decrease with the increase of speed rate of punch force
- Lubricant has increase Springback and side wall curl in sheet metal forming
- A rolling direction has a little effect on the springback values that decrease when change rolling direction from 0-90°
- Die angle and punch angle has decrease with increase of holdown force
- The percentage of comparing results between theoretical and experimental is (10-15%)
- When, thickness increases the die and punch angle decrease but radius of curvature increase

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