Springback Behavior of DP600 Steel: An Implicit Finite Element Simulation

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ABSTRACT

The paper deals with simulating the springback behavior of DP 600 sheet metal, widely used in automotive industry, after the bending process. ANSYSY commercial software was used to analyze the forming operation. Tensile tests had been conducted to obtain stress-strain curve, strain hardening exponent and anisotropy coefficients. The experimental data were used as input for the modeling. The finite element analysis is carried out to determine the degree of springback of four different bending angles, five different punch radiuses and six different sheet metal thickness. Springback is found to be dependent on the punch radius to sheet metal thickness ratio. An equation is proposed to calculate the degree of springback for DP600 dual phase steel sheet, taking into account die angle, punch radius and sheet metal thickness. To investigate the springback elimination, bottoming was simulated after bending for different forming angles. The stroke of the punch was increased by 3%, 6% and 9% of sheet metal thickness for bottoming analysis after bending. The analysis showed that the springback has been reduced by bottoming.

Keywords: Springback; Implicit Analysis; Dual Phase Steel; Bottoming, Bending.

Nomenclature			
Symbol	**Notation**	**Symbol**	**Notation**
n	Strain hardening exponent	R_m	Normal anisotropy
R_0	Rolling direction	Δr	Planar anisotropy
R_{45}	Transverse to rolling direction	R_p	Punch radius
R_{90}	Normal to rolling direction	R_D	Die radius
σ	Yield stress	a	Die allowance
K	Strength coefficient	R_{DE}	Radius of die allowance
ε	Strain	t	Sheet metal thickness
w_f	Final width of sheet	μ	Friction coefficient
w_0	Initial width of sheet	S	Springback
t_f	Final thickness of sheet	DA	Die angle
t_0	Initial thickness of sheet		

INTRODUCTION

Bending operations are a basic type of forming application. The bending of sheet metals is very common in industrial mass production. The operation is typically used in automotive, aircraft, and defense industries as well as domestic appliances and kitchen tools. The main parameters of bending operations are shape, thickness, and mechanical properties of sheet metals. One major drawback of the operation is springback, which causes elastical distortion in demanded geometry after unloading in the forming operation (Carden et al. 2002). Springback phenomena depend on different parameters and result in complex manufacturing problems. It relies upon geometrical and mechanical properties of bended material and forming operation variables. Preventing springback problems is not 100% possible, but elimination of springback failures could be attainable during the forming processes. Adjustments with regard to springback are crucial in die design to obtain demanded final geometry of the part. Numerous experimental studies have been conducted to determine springback characteristics of sheet metals (Boger et al. 2005; Erdin and Atmaca 2016; Levy 1984; Tekiner 2004; Xue et al. 2017). Anisotropy is a main parameter affecting springback behavior. The elastical distortion after forming of isotropic sheet metal parts is less than that of those that have higher anisotropy (Verma and Haldar 2007). Springback is almost proportional to the normal anisotropic value and strain hardening coefficient of the material (Leu 1997). Fouda clarified the springback behavior of different sheet metals by considering different tool geometries with the help of numerical analyses in which MARC computer code had been used to simulate the U-bending process (Fouda and Samuel 2015). Gan and Wagoner declared a new method for the design of dies by calculating springback by an finite element method and displacement vectors at each node to alter die design (Gan and Wagoner 2004). Chatti et al. claim a new approach to compensate for springback in air bending by an incremental superposition of stress through the bending region (Chatti et al. 2009). In addition, the effect of blankholder force on the springback phenomenon was investigated by researchers using finite element methods (Mrad, Bouazara, and Aryanpour 2013; Pourboghrat and Chu 1995; Wang, Neng-Ming; Tang 1988). Moreover, various studies have been conducted on the effects of deformation induced ferrite transformation, grain refinement and strain hardening properties in dual-phase steels (Caballero et al. 2009; Mukherjee, Hazra, and Militzer 2009; Shan et al. 2008).

In this paper, the springback behavior of dual phase (DP) sheet steel, specifically DP600, was studied within different bending conditions by using finite elements analysis. The analysis considered the main parameters of bending operations: bending angle, sheet metal thickness and punch radius. Finite element simulations were conducted for four different bending angles (U-shaped, 60^o, 90^o, 120^o), six different sheet metal thickness (0.5, 1, 1.5, 2, 3, 4 mm) and five different punch radius (2, 4, 6, 8, 10 mm). Elimination of springback was also discussed in this work.

Bottoming analysis after bending was carried out to reduce the degree of springback. To investigate this issue, the stroke of the punch was increased by 3%, 6% and 9% of the sheet metal thickness.

METHODOLOGY

Deformation behavior of dp600 sheet metal used in the analysis

Commercial grade DP600 steel sheets were used to determine deformation behavior. Mechanical properties of DP600 steel were determined via "ASTM E8/E8M: Standard Test Methods for Tension Testing of Metallic Materials." "ASTM E646-16: Standard Test Method for Tensile Strain-Hardening Exponents (n Values) of Metallic Sheet Materials" was employed to obtain the strain hardening exponent of sheet metal. In addition, plastic strain ratios and degrees of planar anisotropy coefficients were calculated with respect to "ASTM E517-00: Determination of Plastic Strain Ratio." Four individual tensile test specimens for 0^o – 45^o – 90^o rolling directions were prepared to examine true stress and strain curve; thus, in all, 12 specimens were used. As Figure 1 shows, true stress-strain curves of DP600 steel at different rolling configurations present similar results for both in elastic and plastic deformation regions. The average behavior for tensile specimen stands for all stress-strain curves is also displayed in Figure 1a and the log-log scale of plastic regions are displayed in Figure 1b.

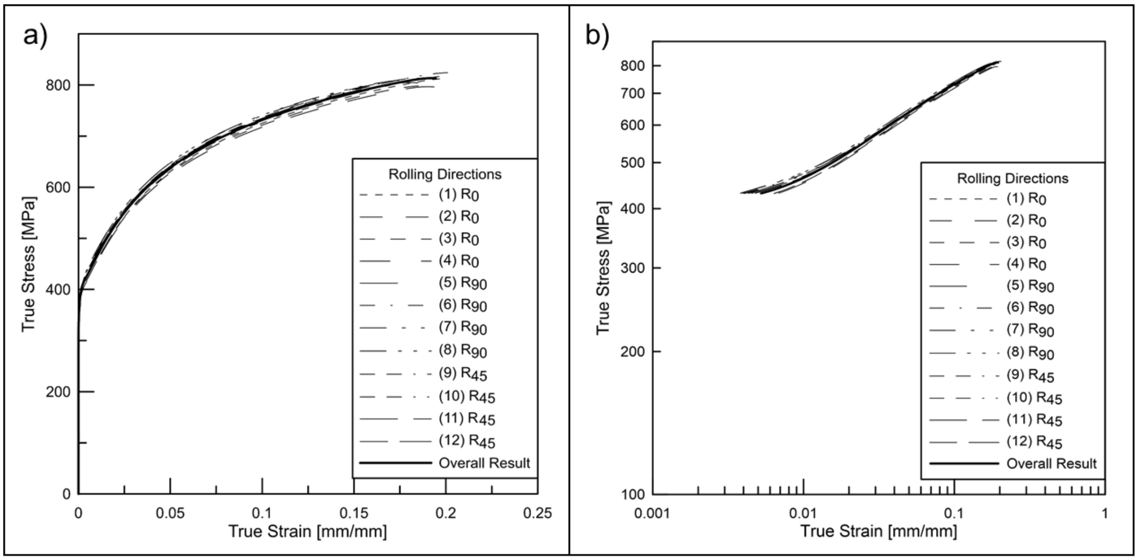

Figure 1. True stress-strain curve of DP600 for different rolling directions **a)** Linear scale **b)** Log-log scale.

According to Figure 1b, the material true stress-strain curve could be expressed in the form of Holloman law where K is the strength coefficient and n is the strain-hardening exponent of the material.

$$\sigma = K\varepsilon^n \quad \text{(Equation 1)}$$

Experimental results of tensile testing of 12 speciemens used to plot an average stress-strain curve. Calculated average values for yield strength, tensile strength and strain hardening exponents of investigated materials are identified as 401.5 MPa, 674.8 MPa and 0.182, respectively.

Moreover, the plastic anisotropy ratio of the sheet was calculated using Equation 2.

$$r = \frac{Strain\ in\ width\ (\varepsilon_w)}{Strain\ in\ thickness\ (\varepsilon_t)} = \frac{\ln({}^{w_f}/_{w_0})}{\ln({}^{t_f}/_{t_0})} \quad \text{(Equation 2)}$$

These ‘r’ values were further used to obtain the normal anisotropy of the sheet metal as expressed in Equation 3 and planar anisotropy as in Equation 4.

$$R_m = \frac{R_0 + 2 \times R_{45} + R_{90}}{4} \quad \text{(Equation 3)}$$

$$\Delta r = \frac{R_0 + R_{90} - 2 \times R_{45}}{2} \quad \text{(Equation 4)}$$

Table 1 shows anisotropy coefficients considering separate directions (R_0, R_{45}, R_{90}), normal anisotropy (R_m) and degree of planar anisotropy (ΔR). Overall tensile specimen’s test results deviate from the other specimens mainly in the ultimate tensile strength in a range of ±5%.

Table 1. Plastic strain ratios and degree of planar anisotropy due to rolling directions.

Specimen Number	Rolling Direction	Plastic Strain Ratio (R)	Average R		
1	0°	0.7695	R_0 = 0.78	**R_m= 0.85**	**ΔR= 0.0125**
2	0°	0.7579			
3	0°	0.8015			
4	0°	0.7799			
5	90°	0.9609	R_{90} =0.95		
6	90°	0.9647			
7	90°	0.9391			
8	90°	0.9381			
9	45°	0.8406	R_{45} = 0.84		
10	45°	0.8007			
11	45°	0.8677			
12	45°	0.8712			

By virtue of experimental results shown in Table 1, R_m value of sheet metal is close to 1, and ΔR value is adjacent to 0. Therefore, the anisotropic behavior obtained for DP600 sheet steel is not pronounced. The results illustrated in Figure 1a and the anisotropy data exhibited in Table 1 indicate that deformation behavior of DP600 steel sheet could be considered isotropic behavior. It should be noted that the two dimensional finite element model of bending process does not consider planar anisotropy. As a result of isotropic plasticity, von Mises yield criterion and isotropic hardening rules can be applied to the model in finite element analysis.

Finite elements modelling

Different types of finite elements model (FEM) algorithms allow analysis of forming operations within a wide range of commercial software. The nonlinear equations of forming issues are translated into linear equations using an iterative approach. There are two main approaches behind the iterative formulations: explicit and implicit methods. The explicit method iterates the solutions while ignoring the reached step condition. Convergence is not an issue in the explicit method, so the results are less stable. On the other hand, the implicit method iterates the solutions while considering the reached step conditions, so the previous iteration results are used as trial result parameters for each new step. Moreover, the assumptions made at the beginning of an iteration should be valid at the end of the iteration for the success of convergence. While the convergence is reached, new assumptions are constructed for the next iteration of the solution. The implicit method allows to get correct results in which convergence is a challenging issue to analyze problems such as plastic deformation processes that have complex boundary conditions: large deformations, nonlinear material behavior, very high deformation speeds and unstable geometry of system. Hence, an implicit method was applied to simulate bending operations and springback characteristics of DP600 steel metal.

Average true stress-strain curve and isotropic hardening behavior received from executed tests were used as inputs for finite element analysis. The commercial software package of ANSYSY Workbench was used in the analysis. The structure of the finite element model and geometry affect the accuracy of the results (Papeleux and Ponthot 2002; Sen 2015). Assigned meshes along with the thickness, contact surfaces, calculation time, number, distribution and size of elements on the model are the main parameters of FEM analysis that affect the validity of the simulation results (Lee and Yang 1998). In the present work, finite element solid models generated in ANSYSY Workbench for U-Bending and V-Bending models are depicted in Figure 2.

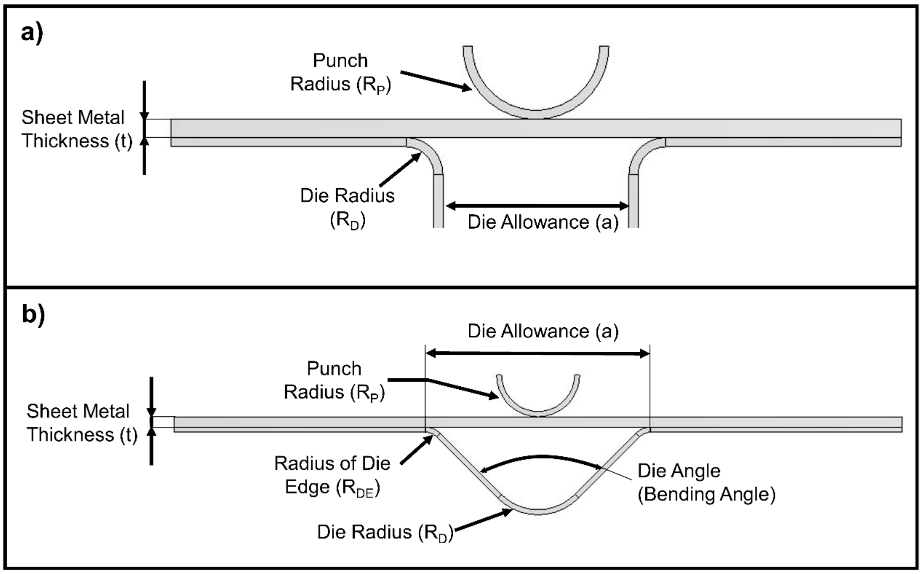

Figure 2. Solid model for **a** U-bending **b** V-bending analysis.

Models with different element sizes (meshes of different finesses) were considered to optimize the calculation time and the accuracy of results. It is well-known that mesh density affects the accuracy of results. The increment in the mesh density yields to high accuracy. On the other hand, higher mesh density requires larger amount of process time and memory. For the constant 1 mm of sheet metal thickness, 4, 6, 8, 10,12 and 14 elements through the thickness were tested to achieve optimum mesh size represented in Figure 3. The degree of springback and equivalent plastic strain results of the FEM, produce trivial alteration in the results after 10 elements through the thickness of sheet. It was determined that 10 elements through the thickness of the layer were the optimum analysis parameters.

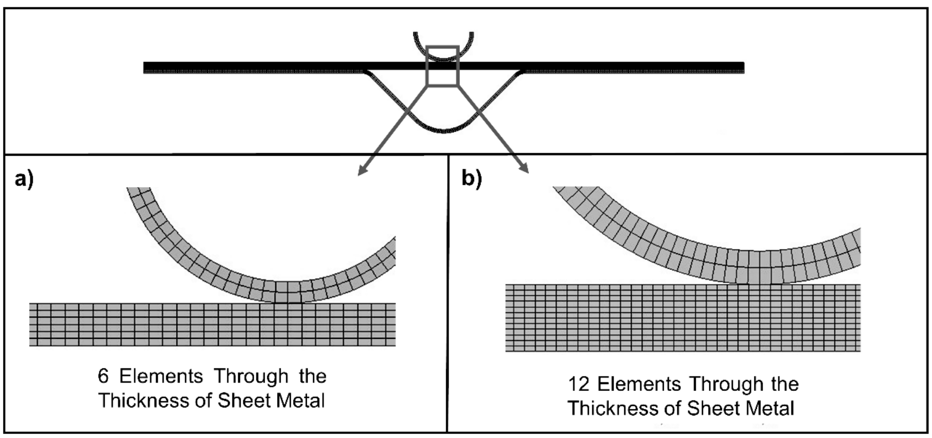

Figure 3. a 6 **b** 12 elements through the thickness of sheet metal.

Different finite element analyses have been conducted concerning the effect of friction coefficient, but no serious effect was observed. Therefore, the friction coefficient μ is selected as 0.1.

After bending process, the punch removes away from the workpiece and thus unloading takes place. For all bending angles (0^0, 60^0, 90^0, 120^0) the springback is measured after unloading the sheet in the FEM. The bend angle shows difference with the geometry of the sheet being closed in the die.

In addition, the effect of die allowance has been investigated (a) and die allowance to punch radius ratio (a/R_P). Three individual punch radii, 4 mm, 10 mm and 20 mm, are selected to investigate the effect of die allowance. Appropriate die allowances (a) are calculated for all bending angles (0^0, 60^0, 90^0, 120^0). Accordingly, the effect of die allowance itself has not been identified as crucial, and the die allowance was selected as "$a=2(R_P+t)$" in the simulations (Yurci 1992).

Verification of the Finite Element Model

To verify the simulation of bending and springback, the implicit finite element analysis results executed in this work were compared with the experimental and numerical results given in work by Kılıç. In the comparisons, the die angle was selected as 60^o and bend radius as 20 mm for experiments. Table 2 shows that the nonlinear implicit model results of this study are correspond more with the experimental results given by Kılıç (Kılıç 2009).

Table 2. Experimental-explicit-implicit springback results (Kılıç 2009).

	Material Model	Sheet Metal Thickness [mm]	Springback [Degree]	Deviation Compared to Experimental Results %
Kılıç (2009) Experimental Results	-	0.9	27.06	-
		1.3	13.89	
		1.6	11.46	
		1.8	10.76	
Kılıç (2009) DynaForm Explicit FEA	Power Law Plasticity	0.9	11.04	59
		1.3	7.22	48
		1.6	6.30	45
		1.8	6.03	44
	Piecewise Linear Plasticity	0.9	17.29	36
		1.3	9.31	33
		1.6	6.88	40
		1.8	6.06	44
	Barlat-Lian	0.9	16.58	39
		1.3	9.1	34
		1.6	6.8	41
		1.8	5.38	50
	Anisotropic Elastic Plastic	0.9	17.58	35
		1.3	9.52	31
		1.6	7.04	39
		1.8	6.13	43
Current Study Implicit FEA	Multi-linear Isotropic Hardening	0.9	22.98	**15**
		1.3	15.7	**8**
		1.6	12.39	**7**
		1.8	11.73	**8**

By use of a data set provided in Table 2, the degree of the springback with regard to sheet metal thickness was plotted in Figure 4. The finite element analysis was executed using the multi-linear isotropic hardening model and implicit finite element solver. Figure 4 depicts that the implicit analysis results of existing work reveals better convergence to the experimental curve compared to the other numerical results given in the literature.

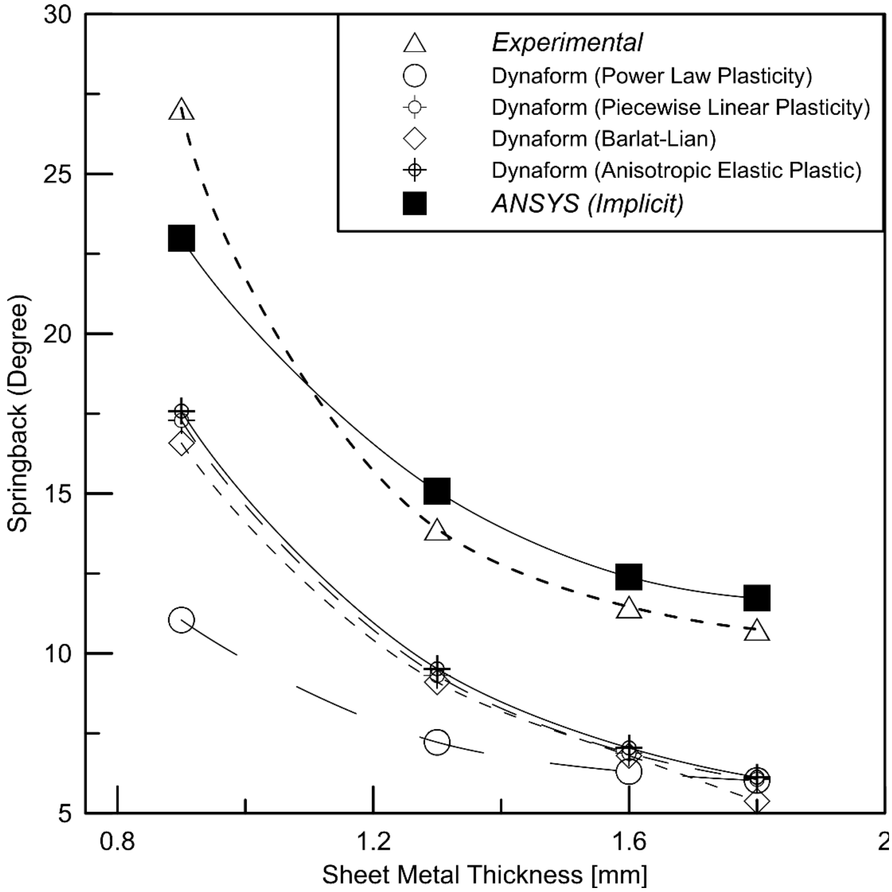

Figure 4. Degree of springback results regarding different FEA solvers.

RESULT AND DISCUSSION

The springback behavior of DP600 sheet steel was investigated within various bending conditions. Five different punch radii, including 2, 4, 6, 8 and 10 mm, were used to investigate the effect of punch radius to sheet metal thickness (R_p/t) ratio for 0.5. 1.0. 1.5. 2.0. 3.0 and 4.0 mm of sheet metal thicknesses. These geometrical parameters were conducted in finite element analysis through four different bending angles: U, 60^0, 90^0, and 120^0. These input parameters for the analysis are listed in Table 3.

Table 3. Analysis parameters and variables.

Punch Radius [mm]	2	2	2	2	4	4	4	4	6	8	10
Sheet Metal Thickness [mm]	0.5	1	1.5	2	1	2	3	4	1	1	1
R_p/t Ratio	4	2	1.33	1	4	2	1.33	1	6	8	10

Results of Finite Element Analysis for Springback Behavior

Representative analysis of U-shaped and V-60^0 shaped bendings are shown in Figure 5 to give an idea about the FEA system. There is a symmetrically distributed compression state at the inner bending area and tension state at the outer bending area of the deformed model, as expected.

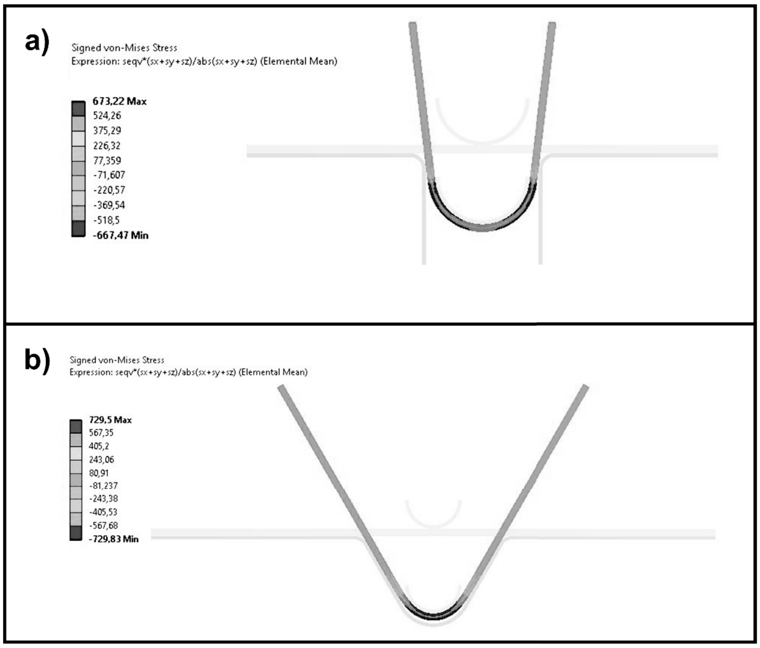

Figure 5. Representative scheme of **a** U **b** V bending simulation.

Springback behavior is investigated with respect to die angle, and the results are depicted in Figure 6 with respect to different R_P/t ratios. The numerical results are displayed in Figure 6 for U, 60^0, 90^0 and 120^0 bending angles. FEM results show that the degree of springback increases with increasing R_P/t ratio. The degree of springback is dependent on the punch radius to sheet metal thickness (R_p/t) ratio.

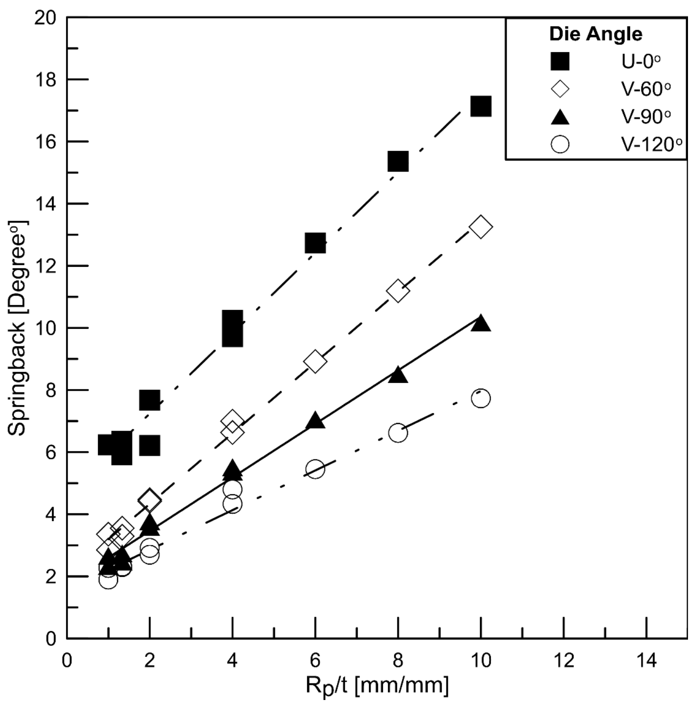

Figure 6. Degree of springback for different die angles.

Appropriate curves were fitted considering the individual punch radius to sheet metal thickness ratio. Figure 7 exhibits the simplified linear polynomials where “y=kx+c” suited properly to mathematical modeling of the results. The constants of polynomials in consideration of fitted curves are presented in Table 4. Regression analyses were also conducted for gathered “k” and “c” values given in Table 4.

Table 4. Curve fitting values for Figure 8.

Die Angle	*Fitted Polynomials*	*Regression (R-square)*
U	y=1.294x + 4.654	0.9861
60	y=1.138x + 2.061	0.9964
90	y=0.86x + 1.745	0.9923
120	y=0.639x + 1.578	0.9821

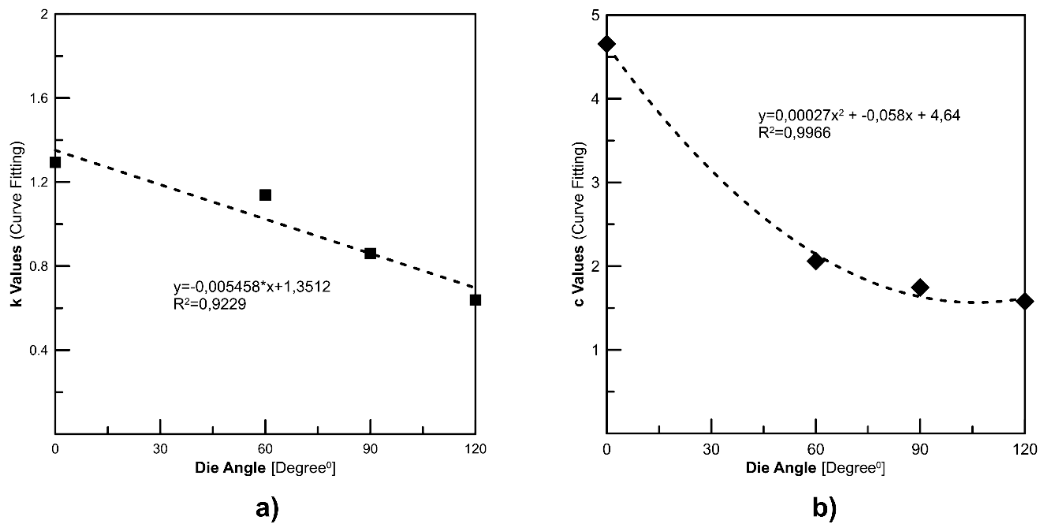

Figure 7. The curve fitting values of **a** “k” and **b** “c” with respct to die angle.

By considering the equations given in Figure 7, Equation 5 is proposed to calculate the degree of springback for DP600 dual phase steel sheet. The proposed equation depends on the bending die angle and punch radius/sheet metal thickness ratio.

In Equation 5:

S: Springback [Degree°]

DA: Die angle [Degree°]

R_p: Punch radius [mm]

t: Sheet metal thickness [mm]

Eq 5:

$$\mathbf{S} = \left(\frac{R_p}{t}\right) \times [1.3512 - 0.005458 \times (DA)] + [(DA)^2 \times 0.00027 - (DA) \times 0.058 + 4.64] \quad \text{(Equation 5)}$$

The success of the springback prediction (Eq. 1) produced is evaluated in Table 5 by comparing with the results of FEA. The governing equation results provides error percentages of no more than 10% compared with the FEM simulations.

Table 5. Comparison of FEM results and Eq. 1 for 0^0, 60^0, 90^0 and 120^0.

Rp/t	**1**		**1.33**		**2**		**4**		**6**	**8**	**10**
a/2	**3**	**6**	**2.75**	**5.5**	**2.5**	**5**	**2.25**	**4.5**	**6.5**	**8.5**	**10.5**
U-0^o	6.24	6.06	5.91	6.35	6.72	7.67	10.24	9.72	12.75	15.36	17.13
Eq.1	5.99	5.99	6.44	6.44	7.34	7.34	10.04	10.04	12.75	15.45	18.15
Error (%)	-3.99	-1.14	8.99	1.44	9.26	-4.27	-1.91	3.34	-0.02	0.58	5.97

Rp/t	**1**		**1.33**		**2**		**4**		**6**	**8**	**10**
a/2	**3**	**6**	**2.75**	**5.5**	**2.5**	**5**	**2.25**	**4.5**	**6.5**	**8.5**	**10.5**
V-60^o	2.95	3.36	3.29	3.55	4.42	4.47	6.63	6.85	8.92	11.19	13.25
Eq.1	3.16	3.16	3.50	3.50	4.18	4.18	6.23	6.23	8.27	10.32	12.37
Error (%)	6.97	-6.08	6.29	-1.49	-5.44	-6.50	-6.08	-9.10	-7.24	-7.76	-6.65

Rp/t	**1**		**1.33**		**2**		**4**		**6**	**8**	**10**
a/2	**3**	**6**	**2.75**	**5.5**	**2.5**	**5**	**2.25**	**4.5**	**6.5**	**8.5**	**10.5**
V-90^o	2.44	2.66	2.71	2.74	3.59	3.68	5.37	5.51	7.05	8.51	10.18
Eq.1	2.47	2.47	2.75	2.75	3.33	3.33	5.05	5.05	6.77	8.49	10.21
Error (%)	1.11	-7.26	1.61	0.50	-7.33	-9.59	-6.02	-8.40	-4.02	-0.27	0.26

Rp/t	**1**		**1.33**		**2**		**4**		**6**	**8**	**10**
a/2	**3**	**6**	**2.75**	**5.5**	**2.5**	**5**	**2.25**	**4.5**	**6.5**	**8.5**	**10.5**
V-120^o	2.08	2.27	2.32	2.30	2.92	2.70	4.33	4.51	5.45	6.62	7.93
Eq.1	2.26	2.26	2.50	2.50	2.96	2.96	4.35	4.35	5.75	7.14	8.53
Error (%)	8.86	-0.25	7.60	8.54	1.39	9.65	0.53	-3.48	5.42	7.82	7.57

Table 5 indicates that the equation obtained from finite element simulation's springback results could be used to predict springback (Eq. 1) for the U, 60^0, 90^0 and 120^0 bending conditions.

Result of finite element analysis for bottoming effects on springback

The elimination of springback is not 100% possible and also is an important issue because it affects obtaining parts' final geometry. One approach to decrease the degree of springback is bottoming the punch as offered by Chou and Hung (Chou and Hung 1999). To clarify the effect of bottoming level on the springback, the stroke of the punch is increased by 3%, 6% and 9% of workpiece thickness in the simulations. The bottoming analysis was carried out for the sheet metal thickness of 1 mm. An example of a bottoming analysis scheme is shown in Figure 8, in which the punch radius (R_p) is 4 mm, sheet metal thickness is 1 mm and die allowance (a/2) is 10.1 mm. Equivalent plastic strain before and after 9% bottoming is shown in Figure 8. After the bending operation (Figure 8a), the plastic deformations in the bended cross section spread through the elastic region, which is in the neutral axis of bending. On the other hand, after bottoming (Figure 8b), the symmetrical distribution of plastic deformation broke down.

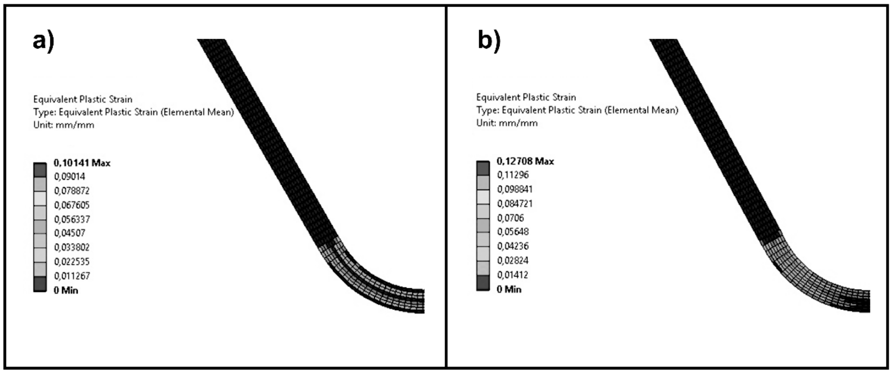

Figure 8. Distribution of equivalent plastic strain of the **a** bended **b** 9% bottomed after bending.

In Figure 9, hydrostatic stress distribution of the simulated part can be seen. As expected, the part has a compression state in the inner side and a tension state at the outer side. The distribution of stress is symmetrical. The symmetrical distribution of the hydrostatic stress causes the bending moment (high compressive stresses at the inside and high tension stresses at the outside of the bent sheet) and thus springback. After bottoming, average hydrostatic stress has increased nearly 100 MPa, and compressive hydrostatic stress became dominant at the cross section of the part. As a result, the bending moment, which is the driving force of springback, is reduced.

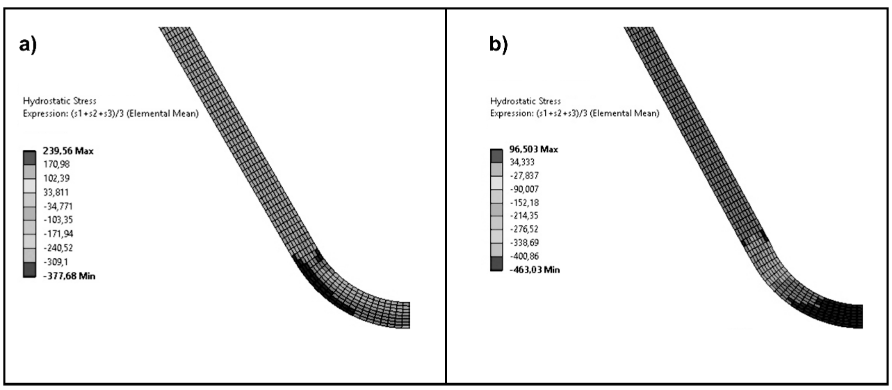

Figure 9. Distribution of hydrostatic stress **a** bended **b** 9% bottomed after bending.

Figure 9 shows that symmetrical distribution of compression elastic energy stored and tensile elastic energy stored with respect to neutral axis of bending is modified. Figure 9 shows that the symmetrically distributed stress area disappeared: springback has been reduced by bottoming.

The degree of springback alteration with respect to bottoming rate is shown in Figure 10. It should be noted that when the workpiece bottoming rate was increased, the plastic deformation through the cross section of sheet metal increased as expected. Obtained results of the analysis indicate that the degree of springback shows a significant decrease below 1^o for all bending angles analyzed after bottoming 9% of the sheet metal thickness.

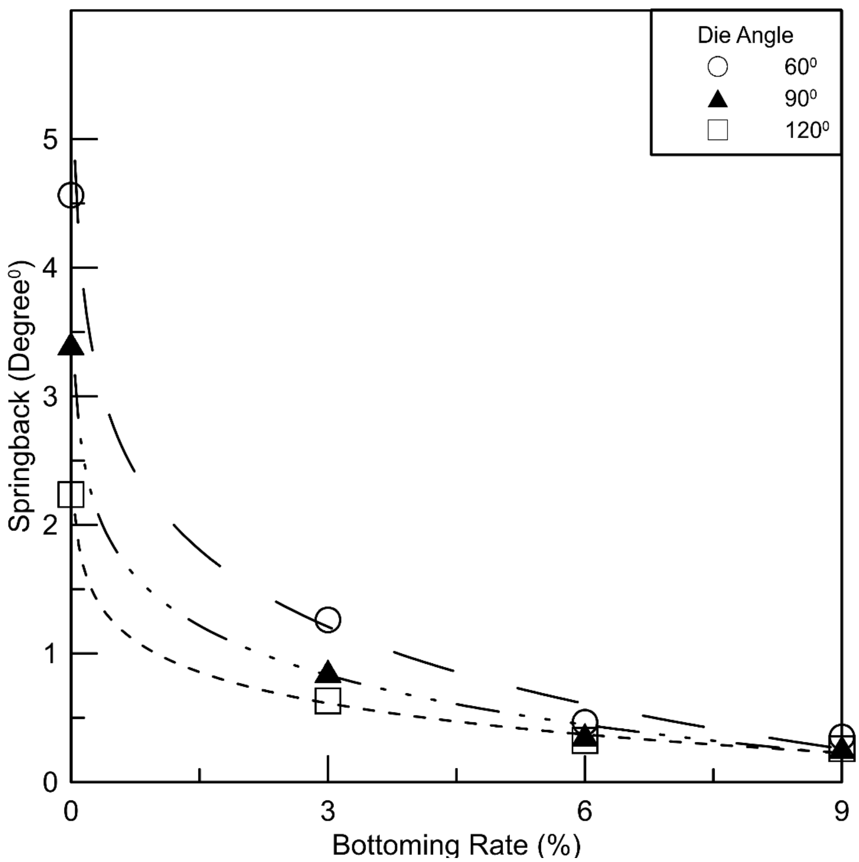

Figure 10. Springback results for different bottoming rates.

CONCLUSION

In this study, springback behavior of DP 600 sheet metal after bending operation was simulated using commercial software ANSYSY. The analyses were conducted for different bending angles (U, 60^0, 90^0 and 120^0), for different punch radii and for different sheet metal thicknesses. An implicit method, which requires a lot of memory and long computation times, was used to obtain accurate and stable results. Simulations exhibit better convergence to experimental values compared to other approaches. The following conclusions were drawn from the simulations.

1) The degree of springback increases with the increasing R_P/t ratio.
2) An equation that provides an error percentage less than 10% is proposed to determine the degree of springback for DP600 sheet metal in U-bending and V-bending.
3) Springback has been reduced by bottoming, and a 9% bottoming rate is sufficient to take precautions concerning the degree of springback when springback is less than 1^o for all die angles.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that they have no conflict of interest