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A Numerical Investigation on the Springback in Air V-Bending of Aluminum 1050 A

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Abstract

Bending is a sheet forming operation in excess of the elasticity limit of the material. Currently, in the industry, bending operation is carried out by a successive test method in order to have the geometry of the part, which generates the operation quite long and too expensive. In fact, springback brings about geometric changes in the folded parts. This phenomenon affects the angle and radius of curvature and can be primarily influenced by multiple factors. In this work, we predict the springback during the air v-bending procedure with the finite element calculation software ABAQUS to pass the test on the first try. The simulation parameters followed the real setting taking into account the characteristics of the punch and the die of the hydraulic press. The simulation was then checked using experimental tests and analytical models, we study this particular springback in 1050 A aluminum specimens through the analytical models of Gardiner and Queener. As a final result, the springback comparison effect between simulation and experiment is presented, and the evaluation of the experimental results with those of the simulation and theoretical models is conclusive. The simulated data show good agreement with the experimental and the analytical models the Finite Element Method (FEM) is a reliable tool for the analysis and simulation of the air v-bending process of Aluminum 1050 A sheet.

Keywords: Aluminum 1050 A, Air v-bending, Springback, Gardiner, Queener.

1 | Introduction

To begin with, bending is extensively used in modern automobiles, aircraft, and mechanical engineering industries as an eminent manufacturing method for producing parts such as frames, consoles, and other structural parts. Indeed, during the bending of the metal sheets and after the return of the punch and removal of the loads, the phenomenon of springback occurs which methodically causes geometric changes in the parts to be bent. Therefore, simulating and developing the bending mechanics allows us to understand well springback and to predict it, in order to take it into consideration in the design phase and thus the compensation of the shapes of the dies which obtain high dimensional precision of the parts to bend.

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In general, existing studies aimed at predicting springback have attempted to gain a basic understanding of this phenomenon by developing analytical, numerical and experimental models in the process of bending sheets. Indeed, these studies tried to take into account the influence of a number of factors on springback such as the type of material, the thickness of the sheet, the geometry of the punch and the die etc.

Nevertheless, many studies have been carried out for the prediction of springback during the process of bending sheets by experimental [1], analytical [2] and numerical methods [3] and [4] for a plurality of different materials and shapes of the parts to be bent. Additionally, different types of geometries have been produced to provide for springback, in particular during air v-bending [1]-[5], v-bending [6]-[8], Z-bending [9] or u-bending [10] and [11] and L-bending [6].

A number of analytical models for springback prediction are namely defined by analytical solution approaches that predict springback primarily based essentially on geometric data and material properties. Initially, a first formulation which exhibits only the yield strength and Young's modulus as material parameters is that of Gardiner [1]-[12]. Further, it is the most used in the calculation of springback in the manufacturing field. However, the formula proposed by Queener [1] took into account the plastic behavior which integrates the law of hardening of the material. In contrast, Hasford and Cadell [19] have developed a model which takes into account the plastic behavior of the material.

In addition, the Finite Element Method (FEM) is a reliable tool for the analysis and simulation of the sheet folding process under different materials and test conditions [13]. Whereas, the FEM is a method which takes a lot of time and which is also very sensitive to the numerical parameters such as the type and the size of the elements, the algorithms, the definition of the contacts and the convergence criteria of the solution, etc. [14].

Recently, there has been a sharp increase in the application of the experimental method based mainly on the practical trials [15]. Moreover, several experimental modelling techniques with varying degrees of complexity have been widely applied, such as experimental methodology design [1]-[16], artificial neural network [3]-[17] and data-driven prediction [18].

The main topic presented in the following article deals mainly with the ability to springback in order to shape parts with precision and at a desired angle when air v-bending sheets. Significantly, a numerical simulation obtained by the FEM is developed and the results thus obtained will be compared with those determined experimentally during the bending tests of aluminum sheets 1050A of thickness t = 1.5mm and t = 2mm on a press bending machine. In addition to this, the springback values predicted by the analytical models of Gardiner [1]-[12] and Queener [1] are compared to the FEM simulation results are also introduced in this article.

Nomenclature.

FEM: finite element method.

r: springback.

α_i : angle before the withdrawal of the punch.

α_f : angle after the release of the sheet and after unloading.

R_i: initial radius (during loading).

R_f: radius after unloading.

E: Young's modulus.

ν: poisson's ratio.

t: thickness of the sheet.

K: work hardening coefficient.

n: work hardening exponent.

σ_e: the elastic limit.

w: the opening of the half-matrix.

P: the depth of movement of the punch.

R_m: the tensile strength.

ε_0 : plastic deformation.

f : the coefficient of friction.

n_r: punch nose radius.

α_p: punch angle.

α_d: die angle.

2 | Methods for Estimating the Springback of Aluminum 1050 A

2.1 | Theoretical Modelling of Springback

Once the punch has successfully removed and the stresses have been released, a springback occurs, permanent deformation persists and, ultimately, the dimensions are out of tolerance.

It should be noted, the springback (*r*) comes in several forms such as the difference between the angle before the withdrawal of the punch (a_i) and the angle after the release of the sheet (α_f) in *Fig. 1*.

$$r = \alpha_f - \alpha_i. \tag{1}$$

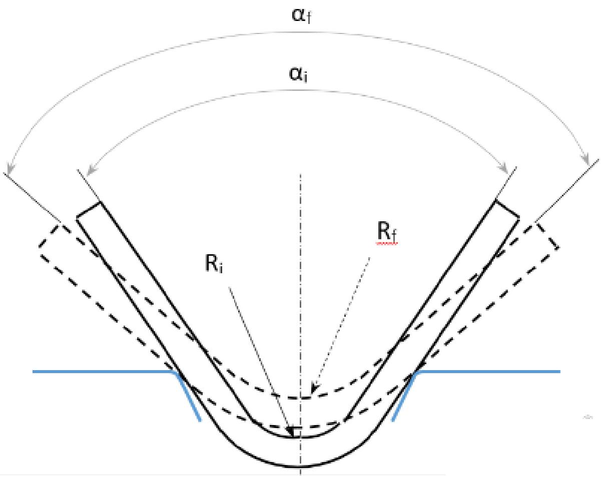


Fig. 1. Angles before and after punching off.

While theoretically several formulations have been proposed for scrutiny, such as a first modeling, which shows the springback by a ratio of the radii of curvature before the withdrawal of the punch (R_i) and the angle after the release of the sheet (R_f) expressed by the model of Hasford and Cadell [19]:

$$r = \frac{1}{R_i} - \frac{1}{R_f} = \frac{6\,K'\left(1-\nu^2\right)}{(n+2)\,t \times E}\left(\frac{t}{2\,R_i}\right)^n, \tag{2}$$

with

$$K' = K\left(\frac{4}{3}\right)^{\frac{n+1}{2}}. \tag{3}$$

Or by the model of Queener [1] which is defined evidently by the ratio of the radii of curvature and it takes into account the parameters (K, n) of the plastic behavior of the material.

$$r = \frac{R_i}{R_f} = 1 - \frac{3\,K\left(1-\nu^2\right)}{(2+n)E\left(\frac{3}{4}\right)^{\frac{1+n}{2}}}\left(\frac{2R_i}{t}\right)^{1-n}. \tag{4}$$

Or by Gardiner's model [1]-[12], it is expressed as a function of the Young's module (E) of the material and the elastic limit (σ_e).

$$r = \frac{R_i}{R_f} = 4\left(\frac{R_i\,\sigma_e}{E\,t}\right)^3 - 3\left(\frac{R_i\,\sigma_e}{E\,t}\right) + 1. \tag{5}$$

Altogether, the quality of the final part obtained by air bending is highly dependent on the penetration of the punch, with small variations in the stroke can greatly modify the final angle. Proof this, the work of Wang et al. [5], were able to show the effect of the penetration of the punch on the angle at the end of the air bending operation.

Since, the initial (loaded) radius of curvature R_i can be approximated from the geometry of the tooling, the thickness of the sheet, the angle of curvature α_i and the depth of displacement of the punch.

$$R_i = \frac{w\tan\alpha_i + \frac{t}{2} - P}{\sec\alpha_i - 1}. \tag{6}$$

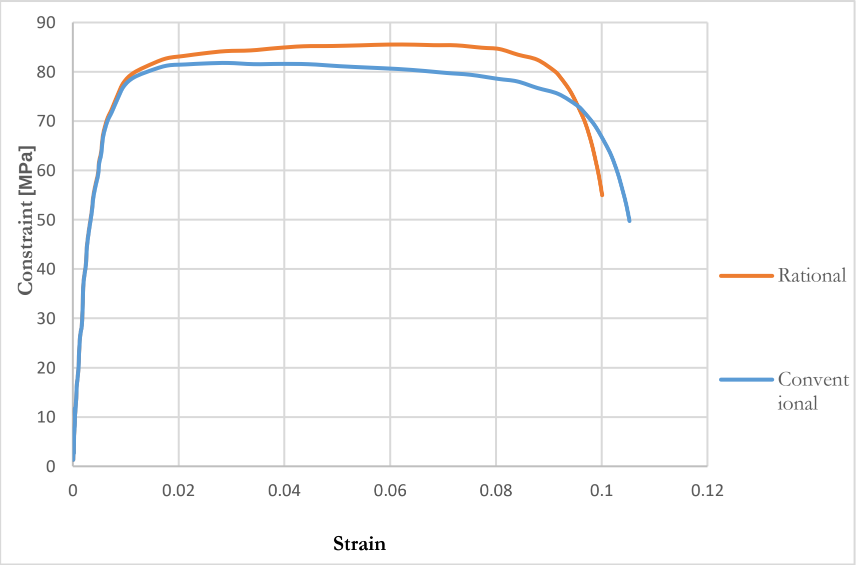
2.2 | Numerical Simulation Modeling

Since sheet metal is defined as a ductile frame, the introduction of the characteristics of the material into the simulation will therefore be essential. What is more, to identify these parameters related to the nature of the material, it is worthy to go through the tensile test on standard test specimens at first, in order to determine the main mechanical properties such as the modulus of elasticity, and the elastic limit and mechanical strength as well (see *Table 1*). Insofar as the tests are carried out on aluminium specimens (1050 A H12), laser cut in accordance with EN 10002/1 in the direction of rolling.

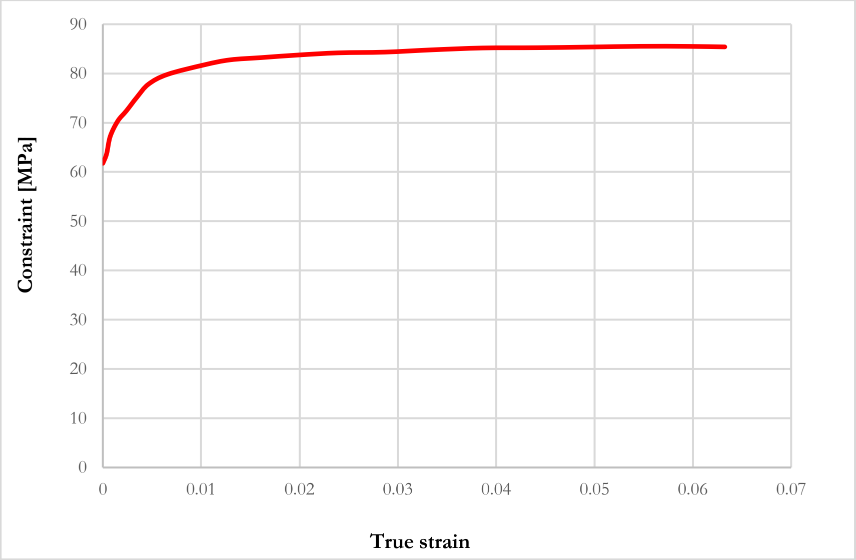
Table 1. Mechanical properties of 1050 A aluminium.

Characteristics (MPa)	σe	Rm	E
Aluminum 1050 A	67.5	84	69105

In order to obtain an intrinsic behavior of the material, not dependent on the geometry, we obviously introduced the stress and strain quantities which represent the conventional curve, and we have passed to the rational curve indeed, which represents the accurate stress as a function of the verifiable strain (see *Fig. 2.a*).



a.



b.

Fig. 2. Characterization of 1050 A aluminum; a. conventional and rational curve, b. flow curve.

From the rational curve (see *Fig. 2.a*) of the sheet metal cut in the rolling direction we characterized the plastic behavior of the material (See *Fig. 2.b*) according to Swift's law in *Table 2*.

Table 2. Anisotropy coefficients as per Swift law.

Coefficients	K	ε0	n
Aluminum 1050 A	102 MPa	0.000155	0.045

Moreover, we will numerically design the air v-bending process by simulation with the ABAQUS finite element calculation software. Following the use of the Abaqus CAD interface, we modeled the tool in 2D (see *Fig. 3*) while respecting carefully the shape and dimensions of the die and the punch, the specimen to be bent is rectangular in shape, we therefore selected the BIAS mesh represented by 100 elements distributed over all the length of the beam.

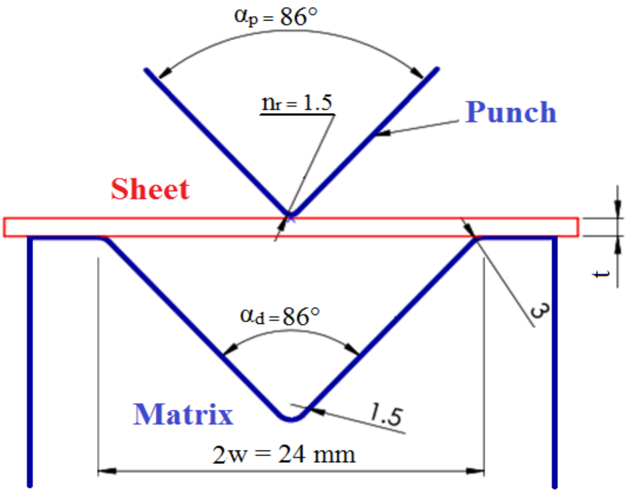
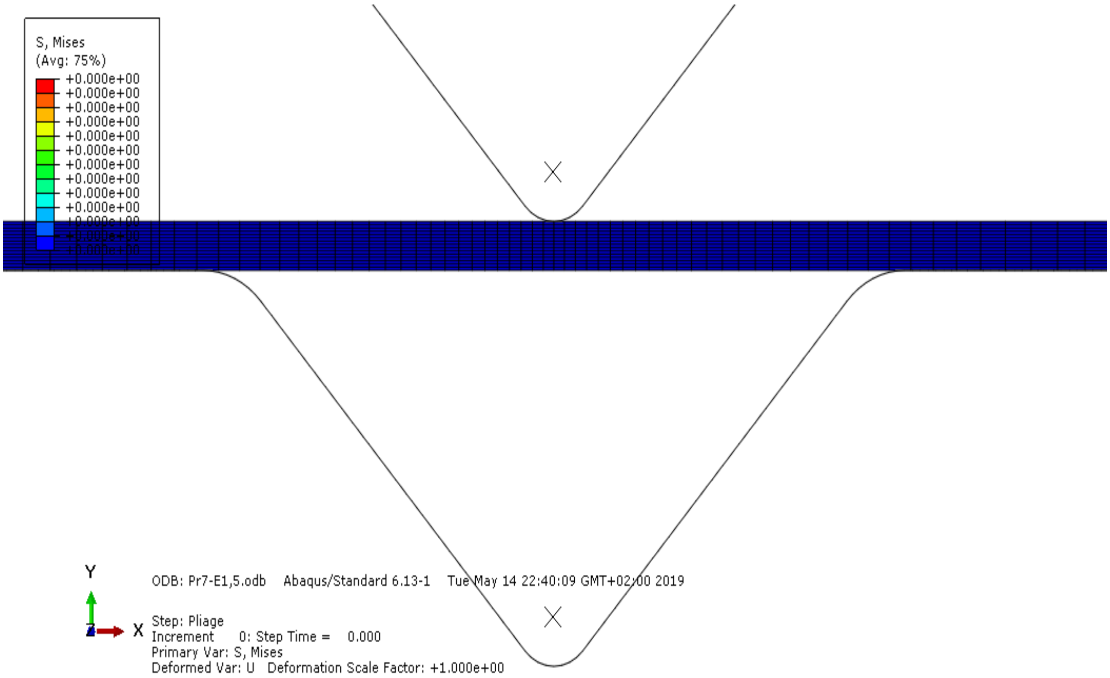


Fig. 3. Model representation.

As, the coefficient of friction has an important impact on the performance of the simulation process. By contrast, the value used in our simulation is that of Steel/Aluminum with the value f = 0.15.

In our simulation, we consider the punch and die as rigid bodies that suffer no deformation during bending. Then, the stress study specifies a concentration at the middle of the sheet which definitively justifies the choice of the BIAS mesh. The approximate simulation output is presented in *Fig. 4*.



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ODB: Pr7-E1,5.odb    Abaqus/Standard 6.13-1    Tue May 14 22:40:09 GMT+02:00 2019

Step: Pliage
Increment    0: Step Time =    0.000
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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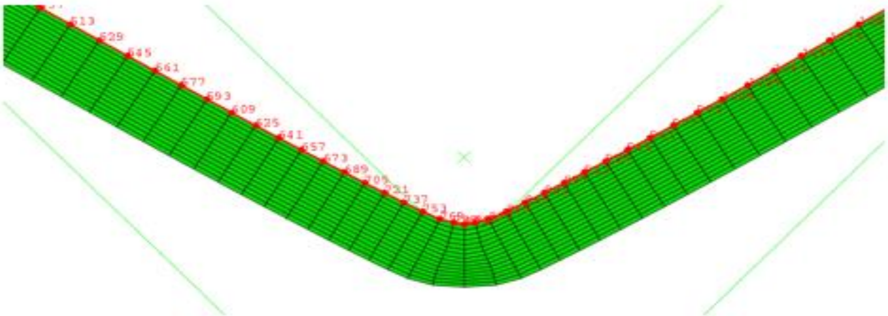
a.



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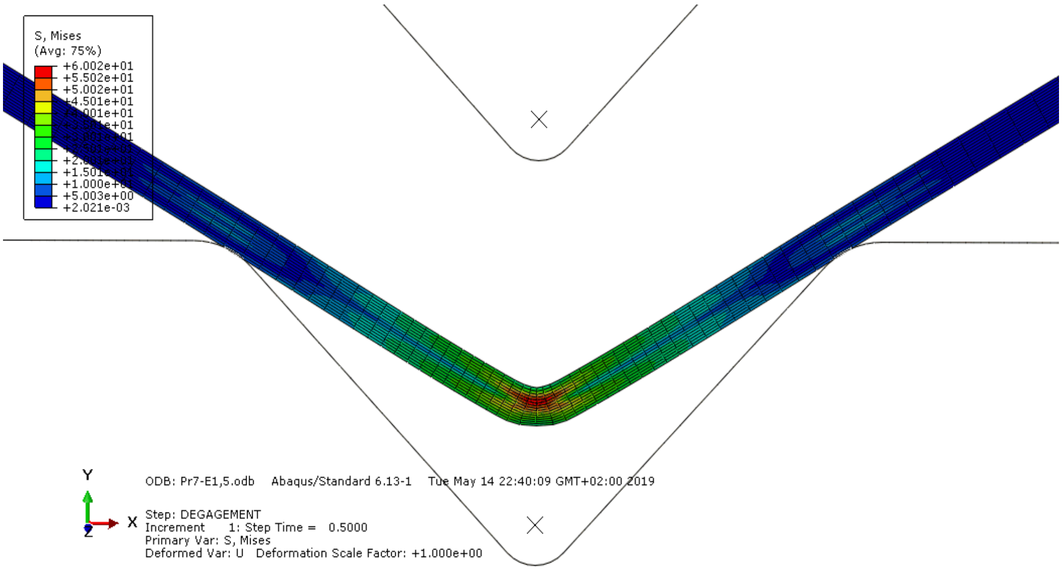

c.

Fig. 4. Simulation results; a. the initial state before deformation, b. simulation of bending during the descent of the punch, c. simulation of springback after retraction of the punch.

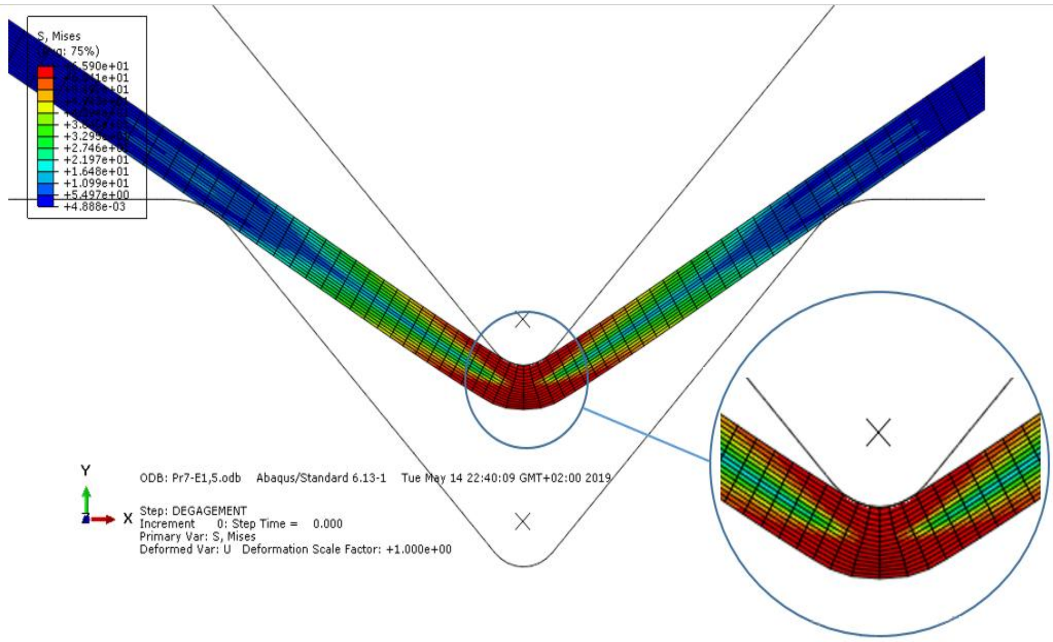

Fig. 5. The nodes of the upper line.

We have cautiously chosen to determine the displacements of all the nodes located at the top line through the coordinates of the points before the withdrawal of the punch and after the springback in *Fig. 5*.

Running the simulation allows us to have the (x0 y0) coordinates of each node during loading and the (x y) coordinates after unloading from the ABACUS software. These displacements are collected to create a database that will be processed to determine the bend angles, bend radii and springback for piling 1050 A sheets. *Table 3* shows the final result of the simulation after processing the data for a sheet thickness of 2 mm.

Table 3. Springback of a 2 mm sheet.

	Parameters				Springback		
P	**R_i (mm)**	**R_f (mm)**	α_i (°)	α_f(°)	α_f - α_i (°)	**R_i/R_f**	**$1/R_i$-$1/R_f$**
1	15.85	16.293	170.111	171.191	1.079	0.9728	0.00171
2	4.426	4.460	161.063	162.124	1.060	0.9924	0.00172
3	2.592	2.602	152.415	153.433	1.018	0.9958	0.00158
4	1.900	1.904	144.274	145.227	0.952	0.9974	0.00136
5	1.535	1.538	136.886	137.769	0.882	0.9980	0.00129
6	1.355	1.357	130.286	131.105	0.819	0.9986	0.00098
7	1.237	1.239	124.571	125.323	0.752	0.9988	0.00093

2.3 | Experimental Tests

The tests are carried out on aluminum 1050 A specimens, as a clear instance and cut in rectangular form of length L = 100 mm and width l = 20 mm at thicknesses of 1.5 mm and 2 mm by laser.

The specimens are bent on the HACO PPM 2060 60 Ton programmable hydraulic press brake. The shape of the punch and die is a V-shape, the punch used is characterized by a punch angle $\alpha p=86°$ and a nose radius of nr=1.5 mm, the die used is characterized by a die angle $\alpha d = 86°$ and an opening 2 w = 24 mm as shown in *Fig. 6*.

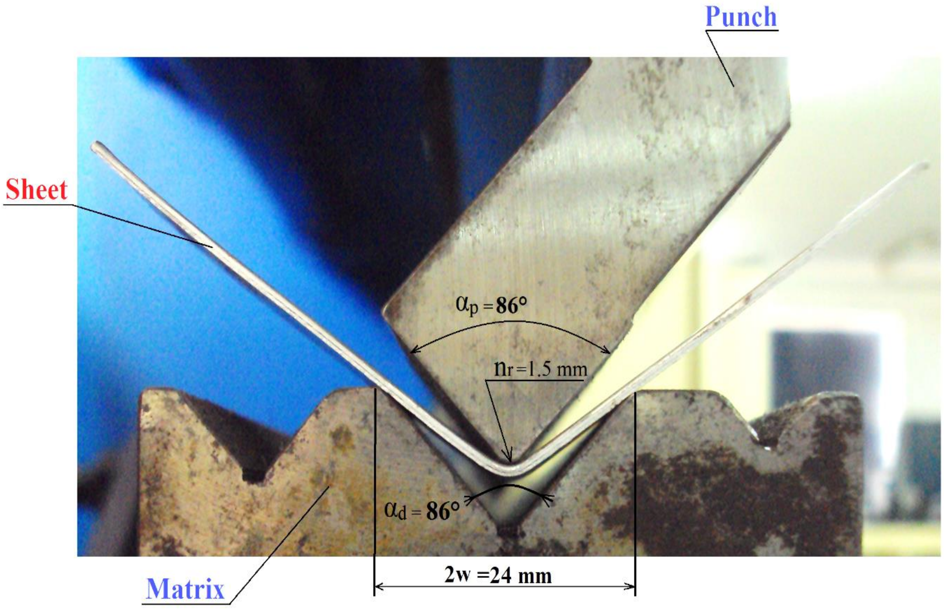

Fig. 6. Experimental matrix and punch.

So that, the angle under load was measured using a simple arrangement with two gauge blocks of the same size [1] as shown in *Fig. 7*.

$$\alpha i = 180° - 2\beta i. \tag{7}$$

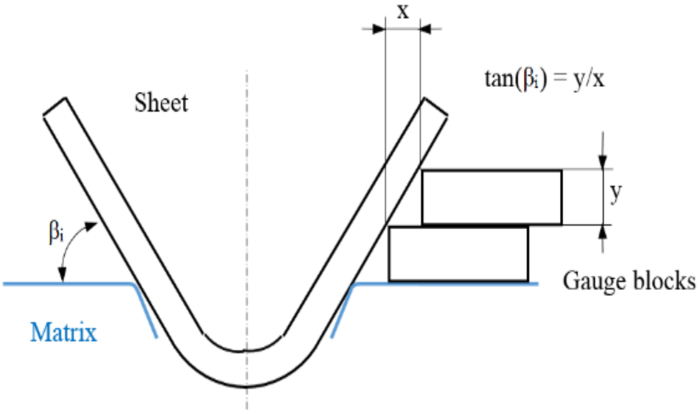

Fig. 7. The initial angle α_i during loading.

At the end of each bending test, the angle formed by the test piece after springback (α_f) is notably measured by a profile projector PJ-A3000 with an accuracy of ± 0.01 degrees.

3 | Result and Discussion

3.1 | Numerical Simulation Result

Fig. 8 shows the evolution of the springback (r) as a function of the depth of penetration of the punch for the different thicknesses (t) from 1 to 3 mm was predicted from the numerical simulation.

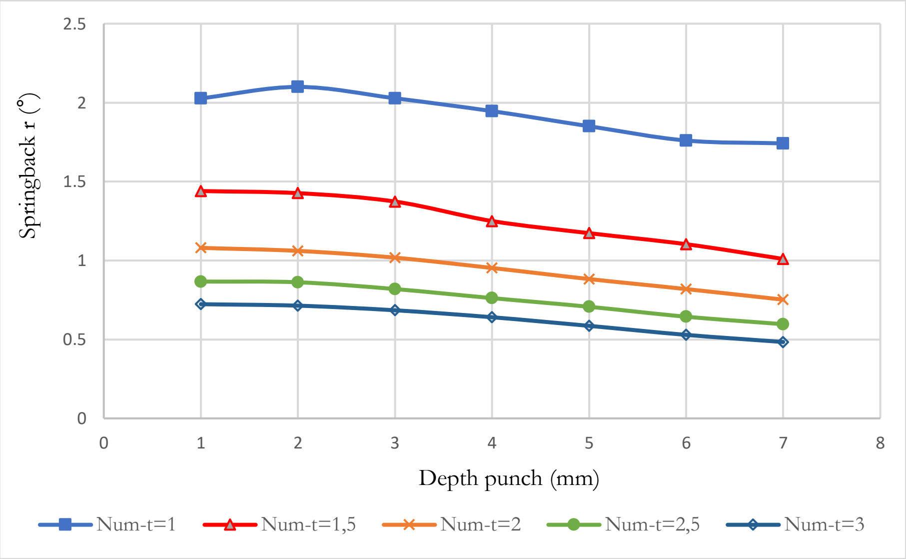

Fig. 8. The evolution of springback (Num.) as a function of depth punch.

Fig. 9 shows the evolution of springback (r) as a function of thickness for different values of punch depth (P) which varies between 1 and 7 mm.

The value of the springback decreases with the increase of the thickness and that can wait for a minimum value of 0.33° for the thickness 4 mm and maximum of 2.15° for the thickness 1 mm. The springback of Aluminum 1050 A is strongly dependent on the thickness of the sheet, while the influence of depth on springback is negligible.

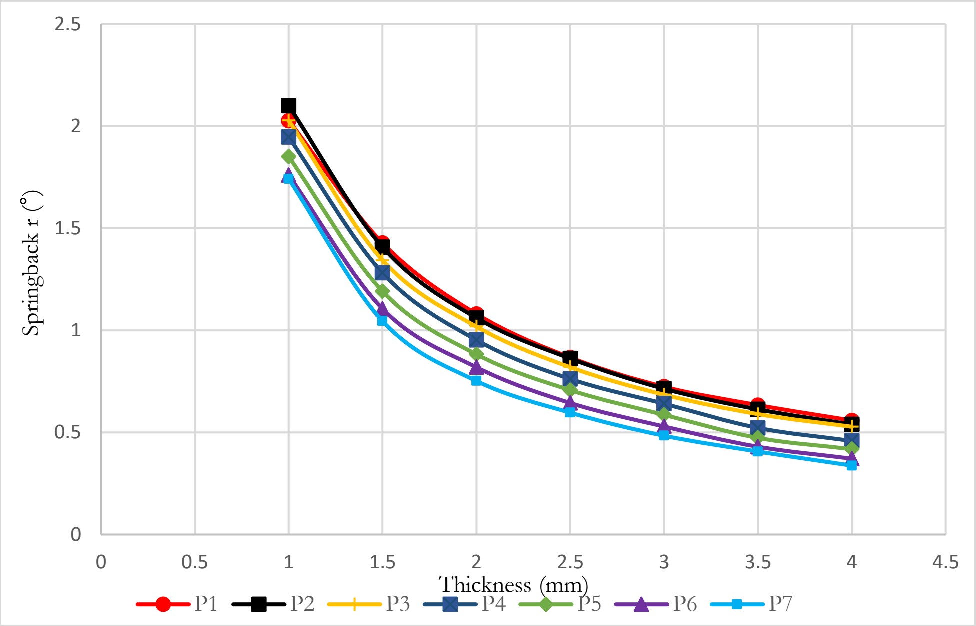

Fig. 9. The evolution of springback (Num.) as a function of thicknesses.

3.2 | Experimental Result

The experimental tests are carried out on specimens of 1.5 and 2 mm thickness and for punch depths that vary between 1 mm and 7 mm (see *Table 4*) with three repetitions, i.e., a total of 66 tests to ensure the reproducibility of the results.

Table 4. Springback of thicknesses 1.5-2 mm.

	Springback (°)						
Depths (mm)	1	2	3	4	5	6	7
Thickness 1.5 (mm)	1.44	1.43	1.37	1.25	1.17	1.10	1.01
Thickness 2 (mm)	1.05	1.01	0.97	0.91	0.85	0.78	0.72

Fig. 10 shows the evolution of experimental springback as a function of depth for the thickness of 1.5 mm and 2 mm.

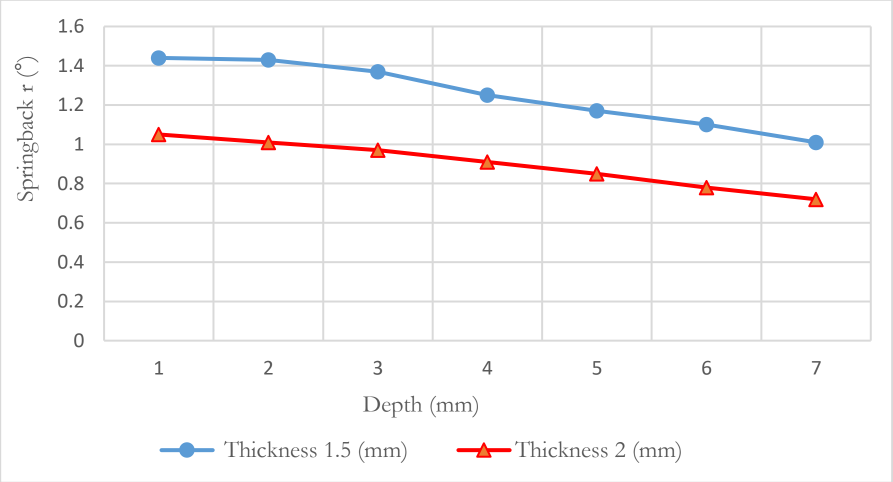

Fig. 10. The evolution of the experimental springback as a function of the depth punch.

Experimental measurements of springback were carried out with several parameters that intervene in the process and have a considered impact on springback. Among these parameters, the sheet thickness, the bending depth and the tool dimensions are particularly noteworthy. Therefore, these experimental tests constitute a data bank that serves as a reference to validate the numerical simulation of the considered process.

4 | Validation of Results

4.1 | Comparison of Experimental Results with Numerical Model

Eventually, the numerically simulated results with ABAQUS were compared to the experimental results for the thicknesses of 1.5 and 2 mm as shown in *Figs. 11* and *12*.

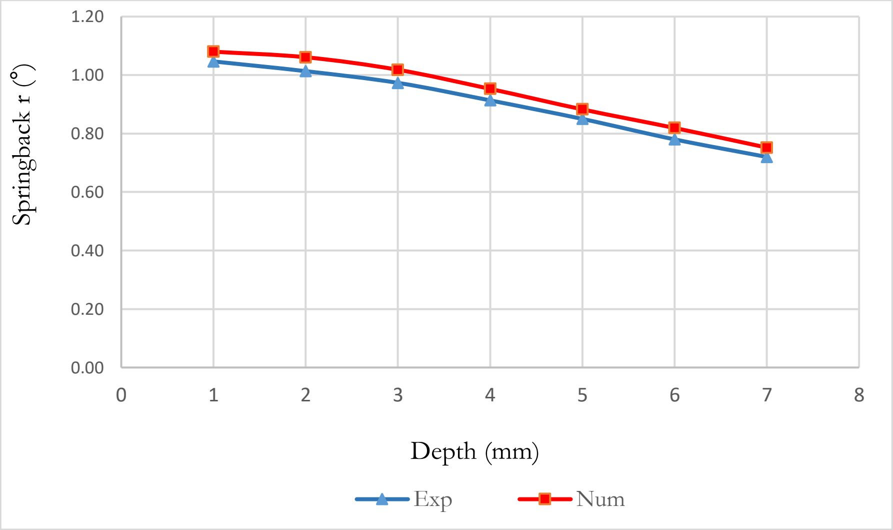

Fig. 11. Comparison of the results for the thickness of 1.5 mm.

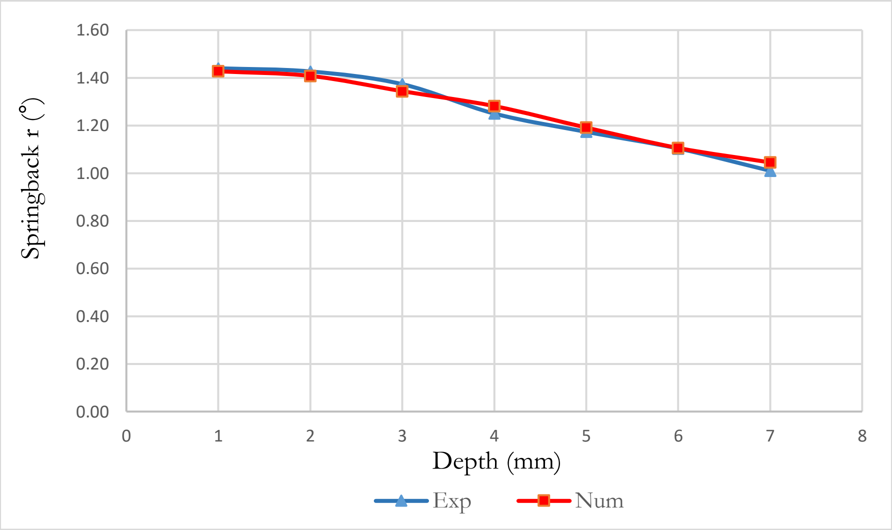

Fig. 12. Comparison of the results for the thickness of 2 mm.

Thereupon, springback simulations have shown that they have better agreement with the experimental results. Whenever the predicted results for the thicknesses 1.5 and 2 mm, are compared to the experimental results they have revealed that they are of slight mistakes compared to the experimental ones (see *Tables 5* and *6*).

Table 5. Error for thickness 1.5 mm.

	Springback α_f-α_i		Error
P	**Experimental (°)**	**Numerical (°)**	**%**
1	1.44	1.427	1%
2	1.43	1.408	1%
3	1.37	1.343	2%
4	1.25	1.281	3%
5	1.17	1.191	2%
6	1.10	1.105	0%
7	1.01	1.045	3%

Table 6. Error for thickness 2 mm.

	Springback α_f-α_i		Error
P	**Experimental (°)**	**Numerical (°)**	**%**
1	1.05	1.079	3%
2	1.01	1.061	5%
3	0.97	1.018	5%
4	0.91	0.952	4%
5	0.85	0.882	4%
6	0.78	0.819	5%
7	0.72	0.752	4%

4.2 | Confrontation of Gardiner's Model with Numerical Model

To better validate the representativeness of Gardiner's theoretical *Eq. (5)*, the simulated springback responses are compared to those calculated theoretically. Gardiner springback is expressed solely by the ratio R_i/R_f.

Fig. 13 shows the evolution of springback as a function of depth for thickness (t) from 1 to 2.5 mm.

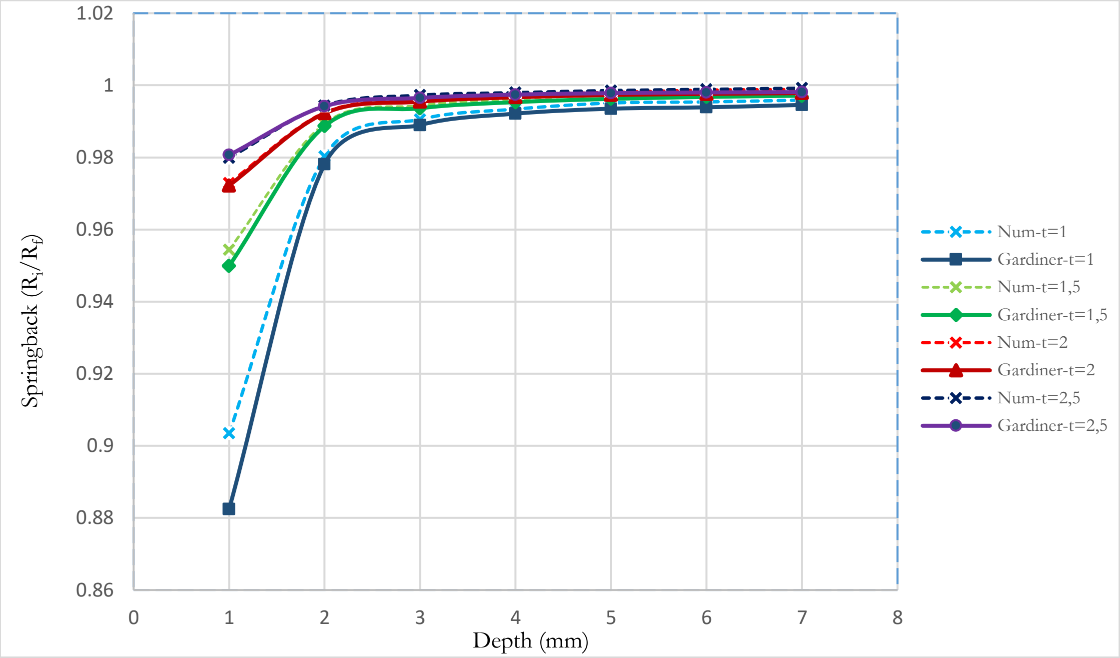

Fig. 13. Comparison of the numerical results with the results of the Gardiner model.

Not only, the confrontation of the theoretical Gardiner curves and the numerical one represented in *Fig. 13* all have the same appearance for the different thicknesses, but also we found that any increase in the depth (P) causes an increase in springback (R_i/R_f).

Table 7 presents the comparison of the springback developed numerically and according to the Gardiner model for each depth of the punch and in terms of relative error, for the thickness 1.5 mm. Overall, we can observe that the relative error is much less than 5% and the extreme error values equal to 0.47%.

Table 7. Gardiner model error versus numerical simulation for 1.5 mm thickness.

	Springback R_i/R_f		Error
P	Numerical	Gardiner	%
1	0.95439128	0.94990259	0.47 %
2	0.98937226	0.98868021	0.07 %
3	0.99440359	0.99363385	0.077%
4	0.99625244	0.99533015	0.093%
5	0.99723331	0.99622645	0.101%
6	0.9976449	0.99678529	0.086%
7	0.99834108	0.99710915	0.123%

4.3 | Comparison of Queener Model with Numerical Model

Last but not least, the results of predicting the springback of metal sheets by the *Queener Model (4)* were also compared with the FEM simulation results. A well-detailed comparison of the springback is presented in *Fig. 14*, which corresponds to the variation of the springback as a function of the depth for four the thickness. *Fig. 14* shows the evolution of the springback as a function of the depth of the descent of the punch for metal sheets of thickness varying from t = 1 mm to t = 2.5 mm.

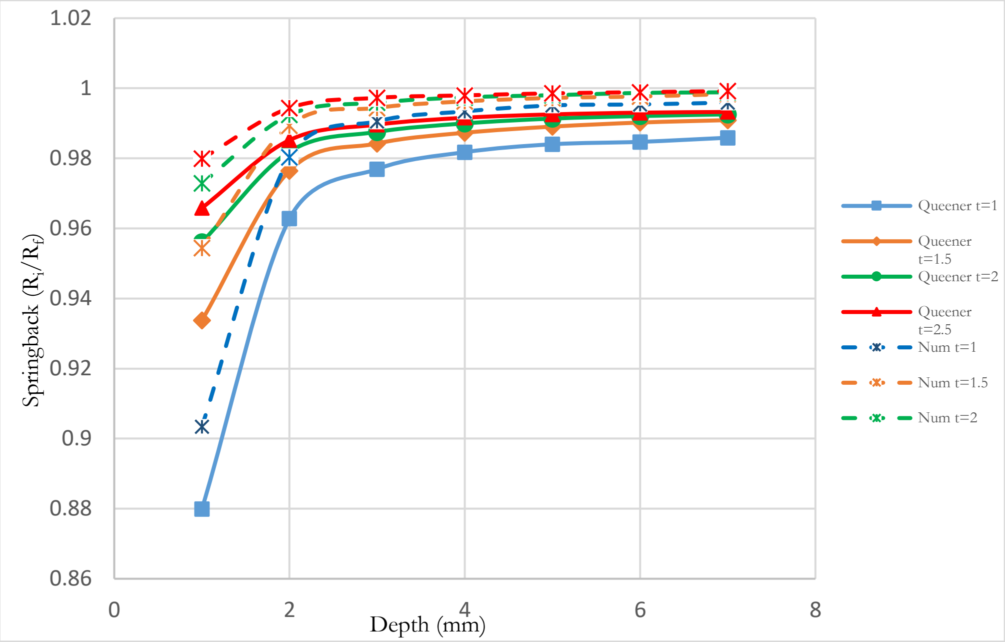

Fig. 14. The evolution of analytical and numerical springback as a function of depth.

Table 8 shows the error between the springback results determined by the Queener analytics model and the FEM numerical simulation, for the 2mm thickness.

Fig. 14 shows that the springback results predicted by Queener's analytical model are in agreement with the FEM simulation data, the relative error is less, than 5% and the extreme error values equal to 1.68% as shown in *Table 8*, we can typically assume that the result is quite satisfactory.

Table 8. The error in the Queener and FEM results for t = 2 mm.

	Springback R_i/R_f		Error
P	Numerical	Queener	%
1	0.97286481	0.95605817	1.68%
2	0.99240463	0.98191644	1.05%
3	0.99589027	0.98753924	0.84%
4	0.9974072	0.98996187	0.74%
5	0.99801634	0.99134426	0.67%
6	0.99866407	0.99206477	0.66%
7	0.99884207	0.99255076	0.63%

5 | Conclusion

A springback prediction model based on a numerical simulation with the finite element calculation software ABAQUS in the case of the air v-bending of sheets is presented in this study.

The obtained results of this numerical simulation are compared with those determined experimentally by air v-bending tests of 1050 A Aluminum sheet with thickness 1.5 mm and 2 mm on a press brake.

It should be noted that there is a good agreement between the experimental results and the numerical results of this simulation and that the maximum error is about 5%, also stress that the measurements made on the springback are perfectly accurate.

Additionally, these FEM numerical simulation results are also compared to those predicted by Gardiner and Queener theoretical models. These comparisons demonstrate that the numerical model has not only a better ability to predict springback, but also a very high predictive accuracy.

The springback of Aluminium 1050 A is highly dependent on the thickness of the sheet, while the influence of the depth on the springback is negligible.

- *Taking into account the variation in penetration depth for small thicknesses, we obtain a better correlation between the numerical analysis of the springback simulation and the experimental results.*
- *The simulation results show that the analytical model of Gardiner is the best adapted to evaluate the springback with an error of 0.47%, while the analytical model of Queener has an error of 1.68% more superior in the process of air v-bending.*

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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