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ANALYSIS OF DEFORMATION AND SPRINGBACK BEHAVIOR OF A FREEFORM SURFACE IN THE AUTOMOTIVE FIELD

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Abstract: *The paper presents a methodology for parametric modeling and numerical simulation of a freeform surface using Autodesk Inventor and Altair Form software. The surface geometry was generated based on the Witch of Agnesi curve defined on an upper plane and two parallel lines defined on a lower plane, with the two planes positioned parallel to each other. To evaluate the influence of geometric parameters on the final shape and deformation behavior, four design configurations were developed, corresponding to distances between the planes of 20 mm, 30 mm, 40 mm, and 50 mm. The models created in Autodesk Inventor were exported and utilized in Altair Form to design the tooling assembly (die and punch) required for the sheet metal forming simulation. Crash-form simulations were conducted to analyze the actual bending process and the strain distribution within the blank. Subsequently, springback simulations were performed to determine the elastic recovery of the sheet metal after unloading and to evaluate the final geometric accuracy. The results highlight the direct influence of the distance between the generating profiles on surface curvature, stress distribution, and springback behavior. This study demonstrates the importance of geometric parameterization and numerical simulation in optimizing sheet metal forming processes for complex surfaces.*

Key words: *Freeforms, Springback, Witch of Agnesi, Plastic Deformation, Aluminium.*

1. INTRODUCTION [1]

In modern industry, freeform surfaces are widely used in fields such as the automotive, aerospace, and industrial product design industries, due to their geometric flexibility and the ability to create complex shapes with superior functional and aesthetic properties. Particularly in the automotive sector, the development of components with complex geometries contributes to both improving aerodynamic performance and optimizing the aesthetic appearance and structural characteristics of vehicles. The advancement of CAD/CAE systems enables both the parametric modeling of these surfaces and the analysis of their behavior during technological sheet metal forming processes [1, 2].

Sheet metal forming processes involve complex phenomena of elastic and plastic deformation, which are directly influenced by the geometry of the tools used and the configuration of the active surfaces. In the case of freeform surfaces, the non-uniform distribution of stresses and strains can lead to significant geometric deviations, among which the springback phenomenon represents one of the main challenges in achieving the final dimensional accuracy [3–5].

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In this context, numerical simulations carried out using CAE applications offer the possibility to analyze material behavior before the actual manufacturing process, thereby reducing the costs associated with prototyping and tooling optimization. The use of crash-form and springback simulations allows for the evaluation of stress distribution, the degree of deformation, and the elastic recovery of the blank after unloading [6].

The paper proposes a methodology for modeling and analyzing a freeform surface generated from the Witch of Agnesi curve and two parallel linear profiles, utilizing Autodesk Inventor for geometric modeling and Altair Form for sheet metal forming simulation. The study aims to develop a geometry with potential applicability in the automotive industry and analyzes the influence of the distance between the generating planes on the surface geometry, as well as on the deformation and springback behavior, for four design configurations corresponding to distances of 20 mm, 30 mm, 40 mm, and 50 mm.

2. MODELING IN AUTODESK INVENTOR

To create the sheet metal shape that will serve as a reference model for modeling the die and punch, the Freeform function in Autodesk Inventor was utilized. The modeling process began by creating a base plane on which two parallel lines were drawn, each having a length of 200 mm and spaced 200 mm apart from each other.

Subsequently, a parallel plane to the base plane was created, positioned at heights of 20 mm, 30 mm, 40 mm, and 50 mm. On this plane, the Witch of Agnesi curve was drawn, centrally located between the two parallel lines; the initial configuration of this profile assembly is illustrated in Fig. 1. The curve represented the main profile used to generate the freeform surface.

To define the extremities of the shape, two planes perpendicular to the base plane were created. On each of these planes, two connecting lines were drawn between the ends of the parallel lines and the extremities of the Witch of Agnesi curve.

After defining all the curves and guide lines, the surface generation command was used to create a new surface bounded by the four contour lines. The process was repeated for both areas of the model, ultimately resulting in two freeform surfaces (Fig. 2).

These surfaces were created in such a way as to ensure a continuous and uniform transition between the defined profiles, representing the final shape of the sheet metal part (Fig. 3).

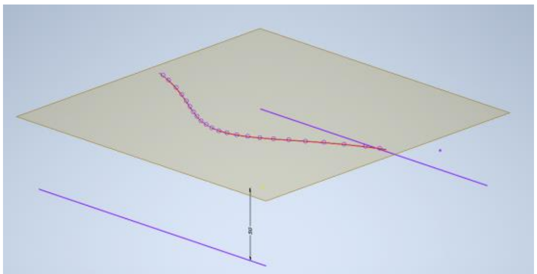

Fig. 1. Initial construction.

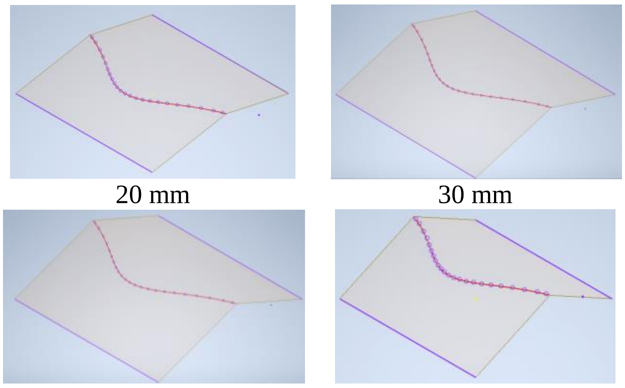

Fig. 2. Freeform model for different heights.

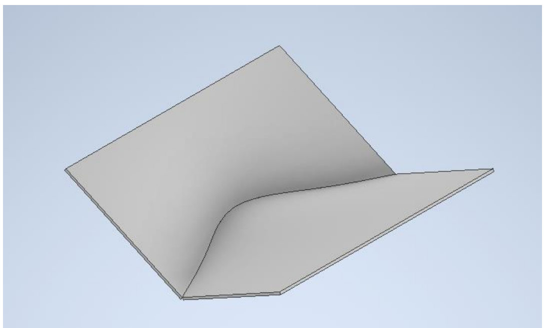

Fig. 3. 3D model of the sheet metal part.

3. SIMULATION OF THE COLD PLASTIC DEFORMATION PROCESS

For the analysis of the sheet metal bending process, Altair Form software was used, which allows for the numerical simulation of plastic deformation processes in the sheet metal forming industry, as well as the analysis of the springback process after the force application ceases.

In the initial stage, the geometries of the active tool components, namely the die and the punch, previously created in Autodesk Inventor, were imported. Additionally, the blank sheet was defined with dimensions of 200 mm × 200 mm × 0.8 mm, positioned between the die and the punch to replicate the actual configuration of the bending process. The choice of a 0.8 mm thickness was made considering that, in the automotive industry, the sheet metal used for body components typically ranges in thickness between 0.6 mm and 0.9 mm [7]. For the blank, the 5182 aluminum alloy [8] was selected, a material widely used in the automotive sector due to its mechanical properties, low weight, and favorable behavior during plastic deformation processes (Fig. 4).

To reduce computation time and correctly define the interactions between components, the contact surfaces of the die and punch were extracted. For the sheet metal, the mid-surface was extracted – a method frequently used in sheet metal forming simulations because it allows the mechanical behavior to be represented with a reduced number of finite elements while maintaining high accuracy of the results (Fig. 5).

Fig. 4. The 3D model of the die, punch, and sheet metal blank.

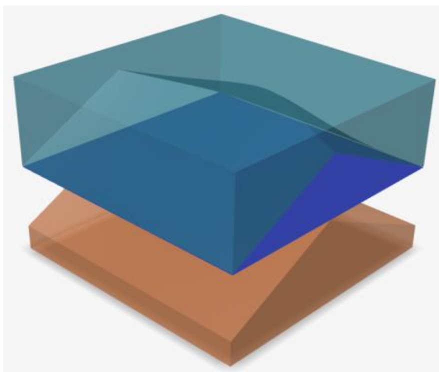

Fig. 5. Representation of the model.

After preparing the geometry, the roles of each component within the simulation were assigned: the punch was defined as the active element responsible for applying the displacement and achieving the deformation through the application of pressure, the die was defined as the supporting element, and the sheet metal was defined as the deformable blank. Subsequently, the material properties for each component were introduced, depending on their mechanical characteristics. For the die and punch, ABS material was chosen due to the possibility of manufacturing the components using FDM 3D printing technology a method frequently used for rapid prototyping and experimental validation of design solutions.

For the analysis of the process, the Crash Form simulation type was selected, a method based on the explicit resolution of contacts and large deformations. This approach is appropriate for sheet metal forming processes because it allows for faithful modeling of the contact between the tools and the blank, as well as the evaluation of stress distribution, strains, and potential defects occurring during the bending process.

Through the simulation, the main characteristics of the process were monitored, such as the distribution of plastic strains, the variation in material thickness, and the final shape obtained after bending. The results allow for the evaluation of the blank's behavior and the validation of the designed tool's configuration.

Table 1

Proprieties for materials

Material name	Elasticity modulus [MPa]	Poisson`s ratio	Density [g/cm^3]	Tensile Strength Ultimate	Tensile Strength Yield
Generic Abs	2400	0.35	1.07	50	45
Aluminium 5182	70000	0.33	2.66	275	125

Tabel 2

Results of crash form simulation

Result type	**Height –**							
	20 mm		**30 mm**		**40 mm**		**50 mm**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Thinning	–0.19	3.39	–1.07	3.95	–0.72	1.73	–2.83	4.57
Thickness	0.773	0.802	0.768	0.809	0.786	0.806	0.763	0.823
Formability	Safe		Safe		Loose Metal		Safe	
Failure	0	$1.012e^{-1}$	0	$1.448e^{-1}$	0	$4.324e^{-2}$	0	$1.382e^{-1}$
Plastic Strain	0	4.663e-2	0	$8.316e^{-2}$	0	$2.437e^{-2}$	0	$7.630e^{-2}$
Major Strain	$-4.428e^{-4}$	$3.975e^{-2}$	$-3.426e^{-4}$	$5.648e^{-2}$	$-4.843e^{-4}$	$1.714e^{-2}$	$-1.955e^{-3}$	$5.775e^{-2}$
Minor Strain	$-5.150e^{-3}$	$6.649e^{-3}$	$-2.654e^{-2}$	$1.103e^{-2}$	$-1.517e^{-2}$	$9.324e^{-3}$	$-5.170e^{-2}$	$2.411e^{-2}$
Strain Tensor	$-2.759e^{-3}$	$7.713e^{-3}$	$-1.913e^{-2}$	$1.224e^{-2}$	$-1.127e^{-2}$	$9.877e^{-3}$	$-2.471e^{-2}$	$2.483e^{-2}$
Stress Tensor	$-1.223e^{+2}$	$9.714e^{+1}$	$-1.017e^{+2}$	$1.203e^{+2}$	$-1.084e^{+2}$	$1.011e^{+2}$	$-1,403e^{+2}$	$1.591e^{+2}$
Edge Strain	$-3.987e^{-3}$	$2.670e^{-2}$	$-1.845e^{-2}$	$3.802e^{-2}$	-1.482^{e-2}	$1.537e^{-2}$	$-4.592e^{-2}$	$4.979e^{-2}$
Curvature	$-2.030e^{-2}$	$4.216e^{-2}$	$-2.398e^{-2}$	$1.458e^{-1}$	$-1.154e^{-2}$	$1.452e^{-1}$	$-1.615e^{-1}$	$1.599e^{-2}$
Dominant Deformation	0	0.977	0	0.991	0	0.976	0	0.991
Equivalent Stress	0	$2.480e^{+2}$	0	$2.965e^{+2}$	0	$1.839e^{+2}$	0	$3.047e^{+2}$
Displacement	0	$2.083e^{+1}$	0	$3.022e^{+1}$	0	$3.762e^{+1}$	0	$4.989e^{+1}$
Edge Displacement	0	$2.083e^{+1}$	0	$3.022e^{+1}$	0	$3.762e^{+1}$	0	$4.784e^{+1}$
Contact Force	0	$9.644e^{+2}$	0	$1.389e^{+4}$	0	$1.154e^{+3}$	0	$8.132e^{+3}$

In the following, representative screenshots for each type of result obtained from the simulation will be presented, in order to highlight the areas characterized by maximum and minimum values of stresses, strains, and thickness variations occurring during the bending process. The results are shown in Figs. 6–11 for the 20 mm thickness, Figs. 12–17 for 30 mm, Figs. 18–23 for 40 mm, and Figs. 24–29 for 50 mm.

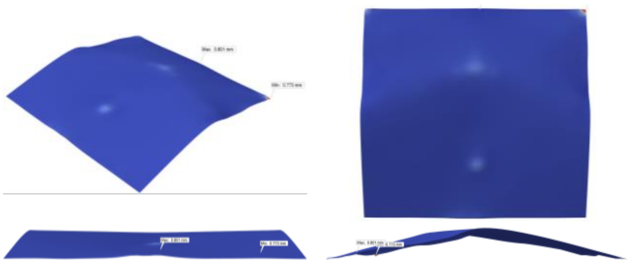

Fig. 7. Thickness for 20 mm.

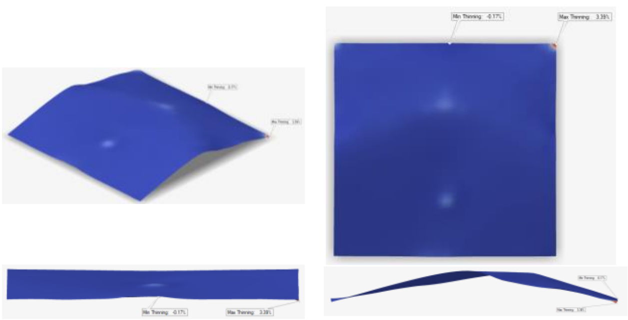

Fig. 6. Thinning for 20 mm.

Fig. 8. Formability for 20 mm.

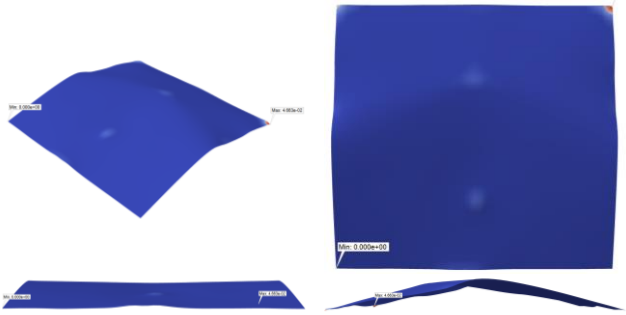

Fig. 9. Plastic Strain for 20 mm.

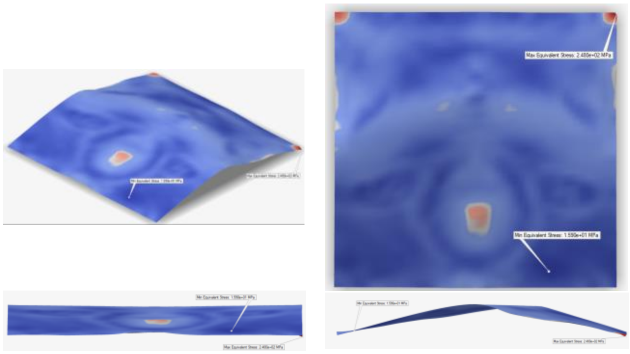

Fig. 10. Equivalent Stress for 20 mm.

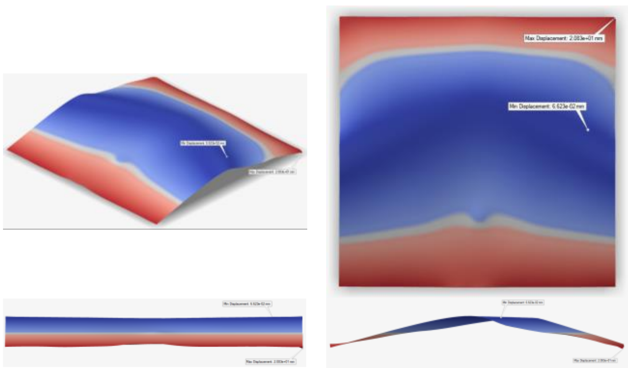

Fig. 11. Displacement for 20 mm.

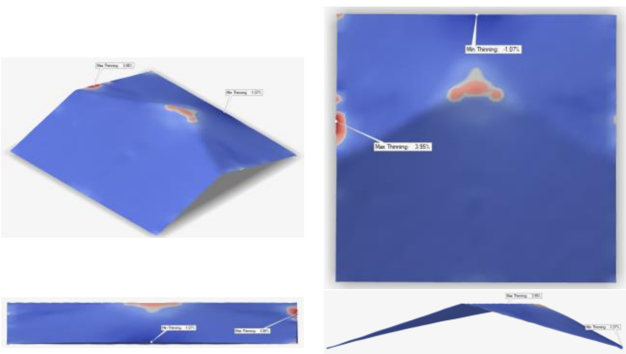

Fig. 12. Thinning for 30 mm.

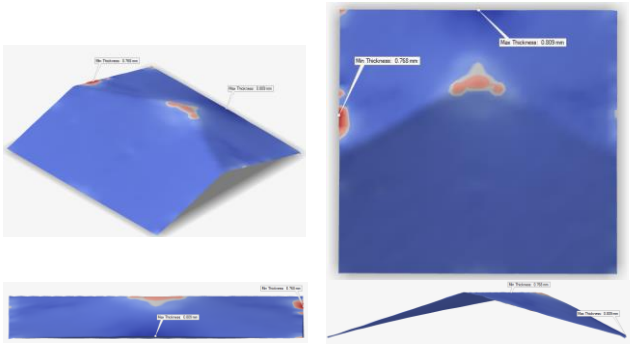

Fig. 13. Thickness for 30 mm.

Fig. 14. Formability for 30 mm.

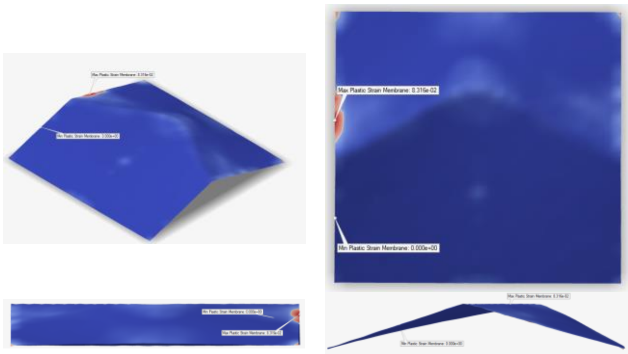

Fig. 15. Plastic Strain for 30 mm.

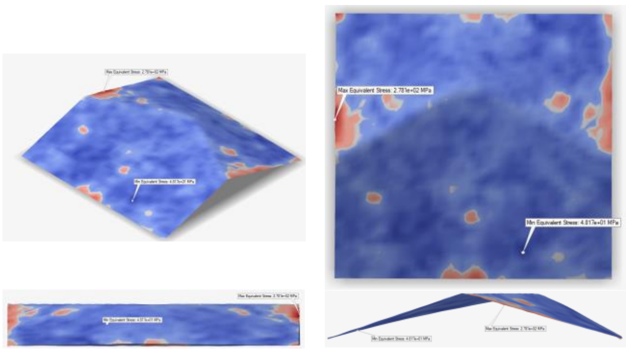

Fig. 16. Equivalent Stress for 30 mm.

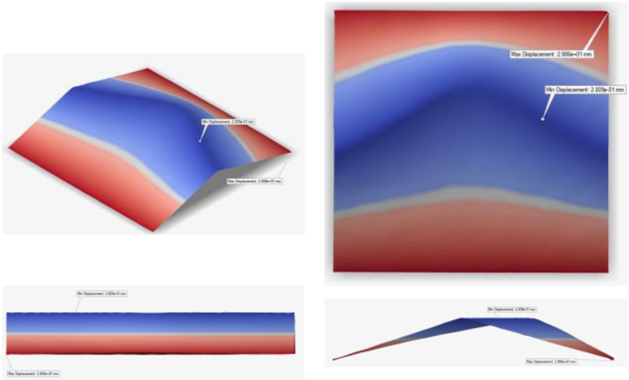

Fig. 17. Displacement for 30 mm.

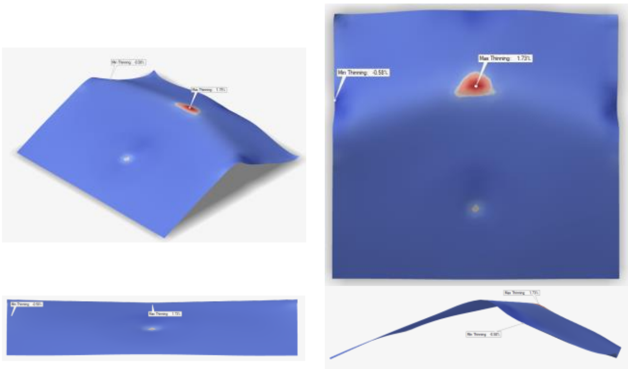

Fig. 18. Thinning for 40 mm.

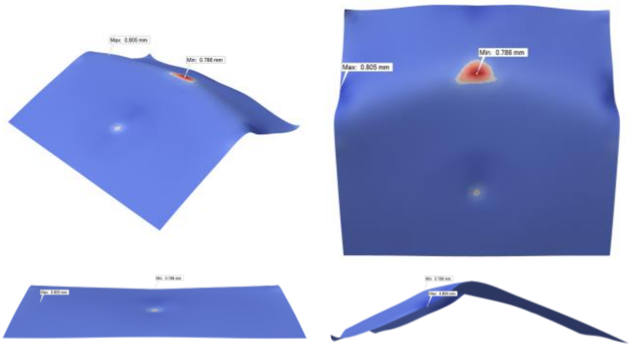

Fig. 19. Thickness for 40 mm.

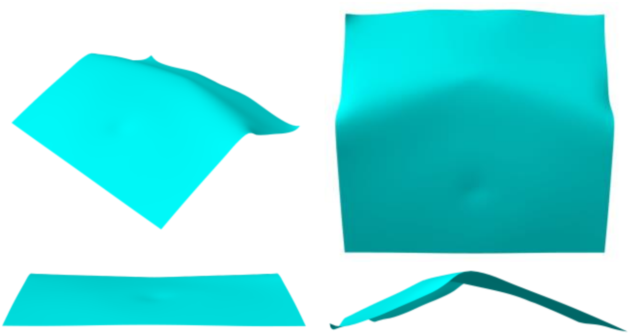

Fig. 20. Formability for 40 mm.

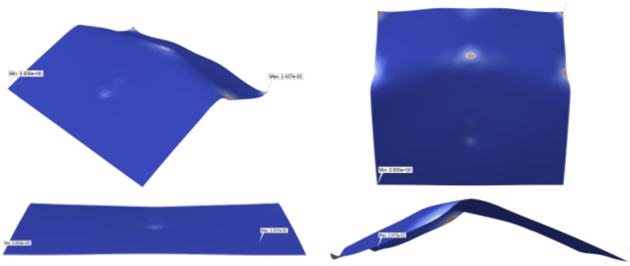

Fig. 21. Plastic Strain for 40 mm.

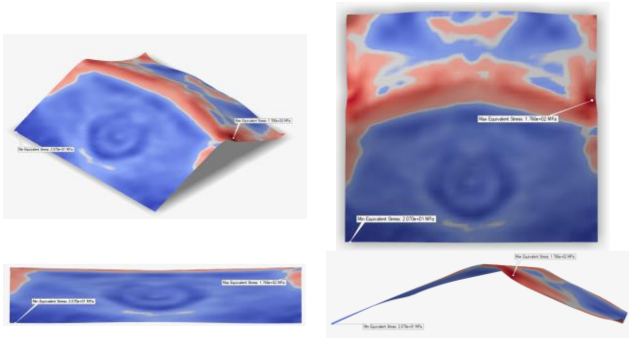

Fig. 22. Equivalent Stress for 40 mm.

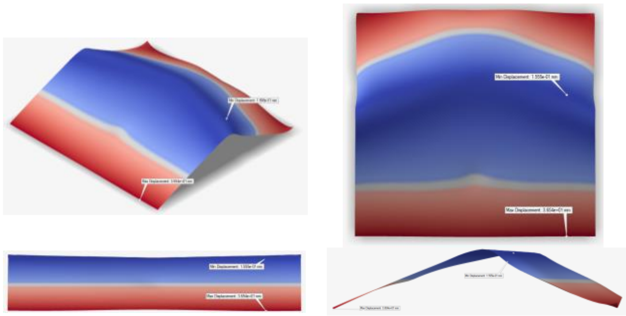

Fig. 23. Displacement for 40 mm.

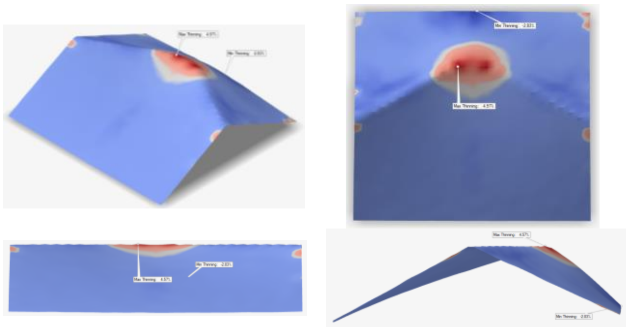

Fig. 24. Thinning for 50 mm.

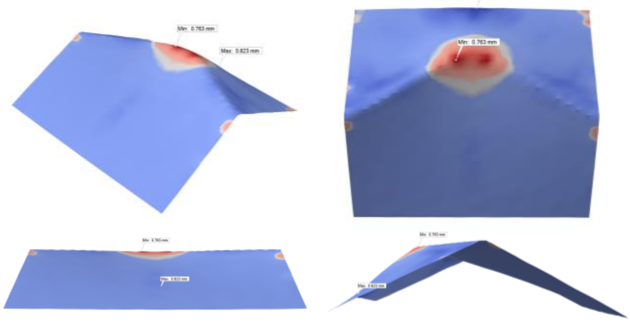

Fig. 25. Thickness for 50 mm.

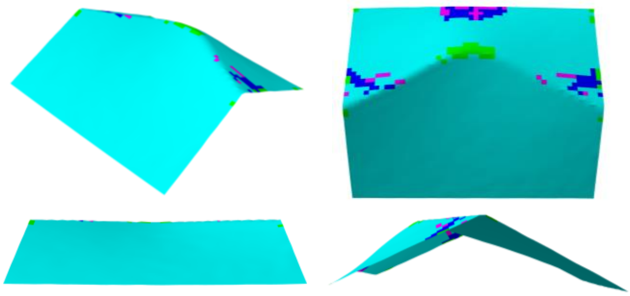

Fig. 26. Formability for 50 mm.

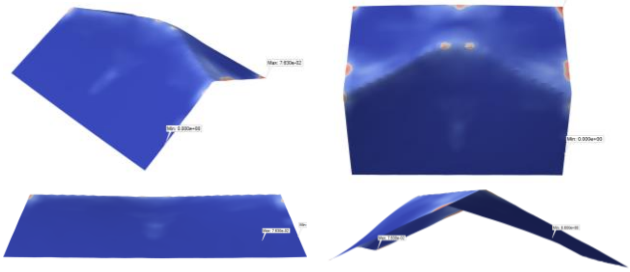

Fig. 27. Plastic Strain for 50 mm.

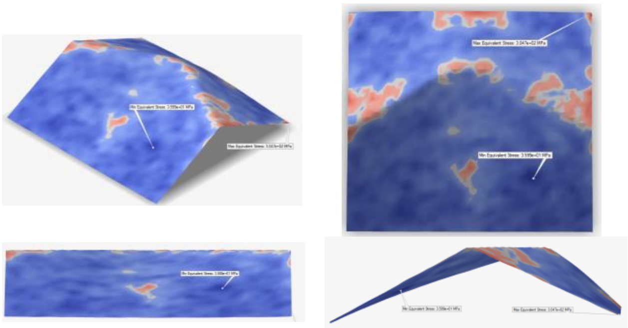

Fig. 28. Equivalent Stress for 50 mm.

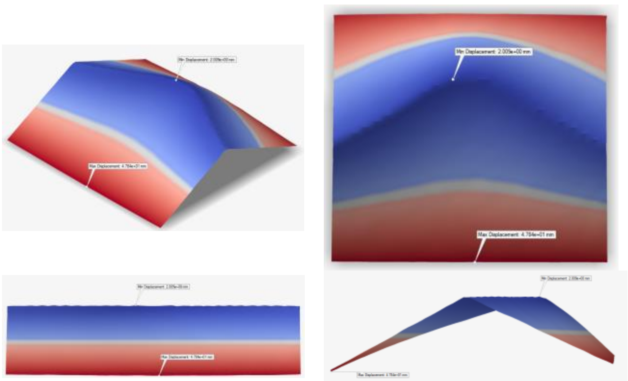

Fig. 29. Displacement.

4. SIMULATION OF THE SPRINGBACK PROCESS

Following the completion of the Crash Form plastic deformation simulation, the analysis of the springback phenomenon was performed. The purpose of the springback simulation is to evaluate the elastic behavior of the blank after the removal of the forming forces and the retraction of the punch a phenomenon that leads to a modification of the final part shape compared to the geometry imposed during the bending process.

The elastic recovery phenomenon represents one of the main challenges encountered in sheet metal forming processes, as it directly influences the dimensional and geometric accuracy of the resulting parts. In the case of components with complex surfaces, specific to the automotive industry, the effects of springback can lead to significant dimensional deviations, which necessitates the use of numerical simulations to estimate material behavior right from the design stage.

In the following, representative screenshots of the results obtained from the springback simulation will be presented, with the main analyzed parameters being the displacement of the blank and the equivalent stress (Figs. 30–37), in order to highlight the areas characterized by maximum and minimum values of the elastic recovery after the bending process.

5. CONCLUSION

The present paper proposed and validated an integrated methodology for parametric modeling and numerical simulation of a freeform surface with applicability in the automotive industry, utilizing the Autodesk Inventor and Altair Form software chain.

The freeform surface generated based on the Witch of Agnesi curve demonstrated potential for use in the design of body components, offering a continuous and controllable transition between the generating profiles. The four analyzed design configurations (20 mm, 30 mm, 40 mm, and 50 mm) highlighted the direct influence of the distance between the generating planes on the surface geometry and the deformation behavior.

From the analysis of the Crash Form simulations, it is found that as the distance between the planes increases, both the maximum sheet thinning increases (from 3.39% for 20 mm to 4.57% for 50 mm) and the maximum equivalent stress increases (from 248 MPa to 304.7 MPa).

Table 3

Results for springback

Result type	**Height**							
	20 mm		**30 mm**		**40 mm**		**50 mm**	
	Min	Max	Min	Max	Min	Max	Min	Max
Thinning [%]	–0.17	3.39	–1.07	4.01	–0.62	1.73	–2.83	4.57
Thinning Delta [%]	–0.07	0.05	–0.08	0.06	–0.08	0.04	–0.11	0.07
Thickness [mm]	0.773	0.802	0.768	0.809	0.786	0.805	0.763	0.823
Formability	Safe		Safe		Loose Metal		Safe	
Failure	0	1.012e^{-1}	0	1.463e^{-1}	0	3.520e^{-2}	0	1.382e^{-1}
Plastic Strain	0	4.663e^{-2}	0	8.316e^{-2}	0	2.437e^{-2}	0	7.630e^{-2}
Major Strain	–4.428e^{-4}	3.975e^{-2}	–3.426e^{-4}	5.697e^{-2}	–2.523e^{-4}	1.393e^{-2}	–7.467e^{-4}	5.775e^{-2}
Minor Strain	–5.150e^{-3}	6.649e^{-3}	–2.653e^{-2}	1.103e^{-2}	–1.279e^{-2}	8.939e^{-3}	–5.170e^{-2}	2.411e^{-2}
Strain Tensor	–3.017e^{-3}	7.937e^{-3}	–1.913e^{-2}	1.224e^{-2}	–9.464e^{-3}	9.715e^{-3}	–2.471e^{-2}	2.483e^{-2}
Stress Tensor	–5.381e^{+1}	9.713e^{+1}	–9.493e^{+1}	1.040e^{+2}	–7.192e^{+1}	1.011e^{+2}	–6.787e^{+1}	1.124e^{+2}
Edge Strain	–2.884e^{-3}	2.670e^{-2}	–1.845e^{-2}	3.773e^{-2}	–1.188e^{-2}	1.347e^{-2}	–4.592e^{-2}	4.979e^{-2}
Curvature	–2.030e^{-5}	4.216e^{-5}	–1.224e^{-5}	5.292e^{-5}	–1.110e^{-5}	1.452e^{-4}	–1.615e^{-4}	3.920e^{-6}
Dominant Deformation	0	0.980	0	0.987	0	0.976	0	0.992
Equivalent Stress [MPa]	1.515	2.480e^{+2}	1.355e^{+1}	2.781e^{+2}	8.111e^{+1}	1.766e^{+2}	1.401e^{+1}	3.047e^{+2}
Displacement [mm]	0	1.299e^{+1}	0	1.536	0	1.071e^{+1}	0	1.077
Edge Displacement [mm]	0	1.299e^{+1}	0	1.536	0	1.071e^{+1}	0	1.077
Contact force [N]	0	0	0	0	0	0	0	0

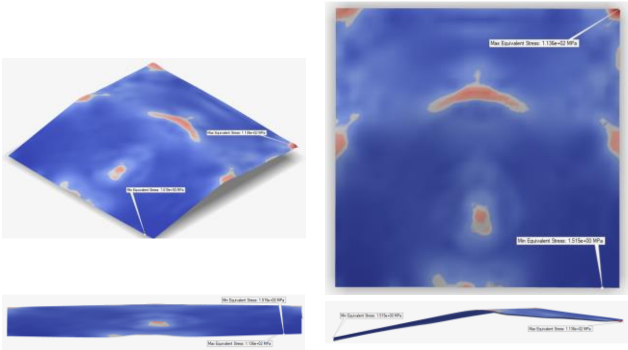

Fig. 30. Equivalence Stress for 20 mm.

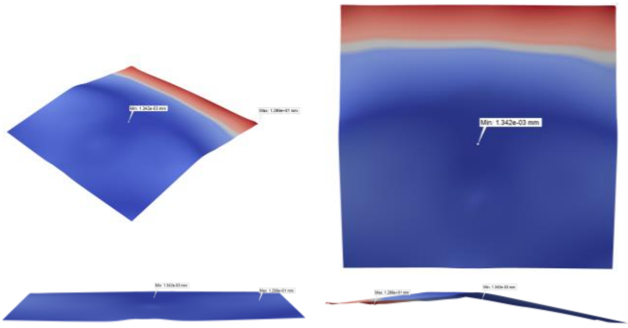

Fig. 31. Displacement for 20 mm

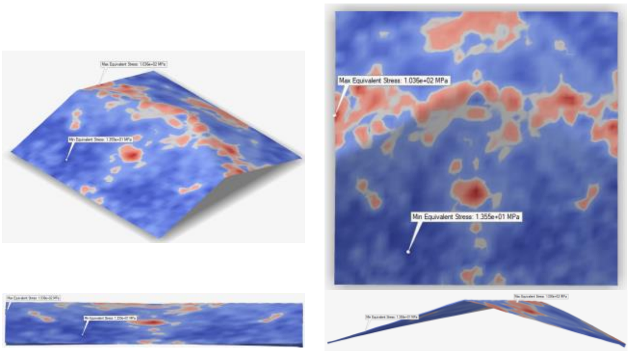

Fig. 32. Equivalence Stress for 30 mm.

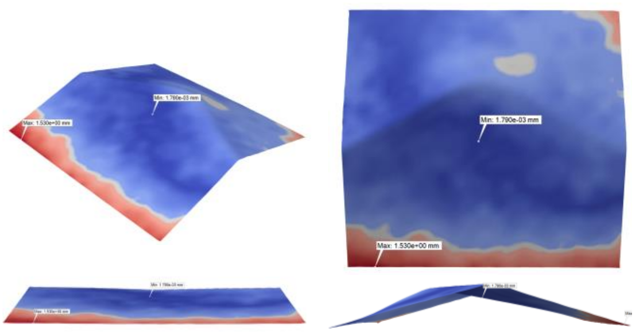

Fig. 33. Displacement for 30 mm.

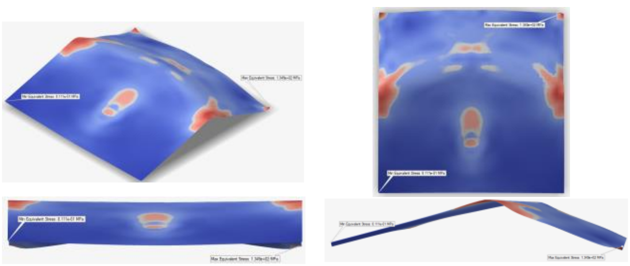

Fig. 34. Equivalence Stress for 40 mm.

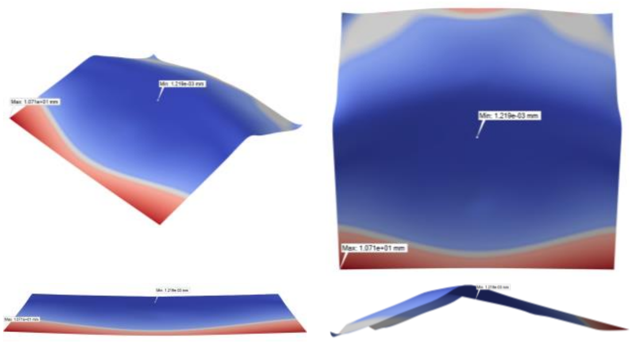

Fig. 35. Displacement for 40 mm.

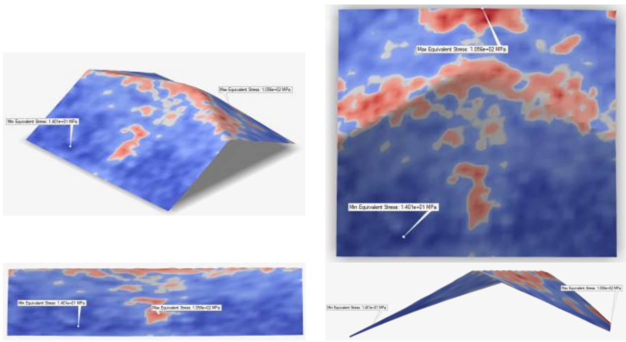

Fig. 36. Equivalence Stress for 50 mm.

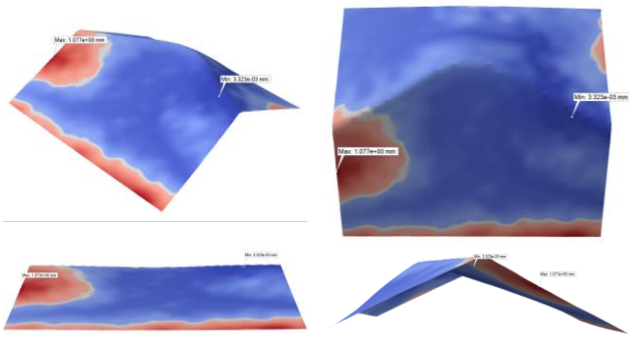

Fig. 37. Displacement for 50 mm.

The 30 mm variant exhibited a "Loose Metal"issue in the formability evaluation, indicating a non-uniform stress distribution in the central area of the surface and the need to adjust the design or technological parameters for this specific configuration.

The springback simulation resulted in significant differences in elastic recovery depending on the height of the analyzed variant. The maximum post-springback displacements were 12.99 mm (for 20 mm), 1.536 mm(for 30 mm), 10.71 mm (for 40 mm), and 1.077 mm (for 50 mm), highlighting a non-linear behavior of the springback in relation to the distance between the planes. The reduced springback values for the 30 mm and 50 mm variants (1.536 mm and 1.077 mm, respectively) compared to the 20 mm and 40 mm variants (12.99 mm and 10.71 mm) suggest that they may be more advantageous from the standpoint of final dimensional accuracy. The non-linear behavior of the springback in relation to the distance between the planes is consistent with trends reported in the literature. Direct numerical comparisons remain difficult, as studies in the literature express springback as angular deviation (degrees),

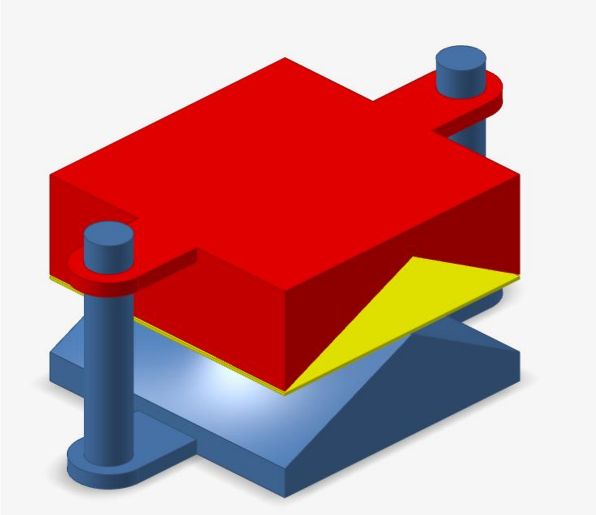

Fig. 38. Punch and dies for conducting physical experiments.

whereas the present paper reports absolute post-deformation displacements (mm), which is specific to Crash Form and springback simulations on freeform surfaces.

The obtained results confirm that numerical simulation represents an essential tool in optimizing sheet metal forming processes on complex surfaces, allowing for the identification of potential defects and the estimation of elastic recovery before the physical manufacturing of the tools, thereby significantly reducing prototyping costs.

As future research directions, it is proposed to experimentally validate the results through the actual forming of the 5182 aluminum alloy blanks, analyze the influence of other parameters (sheet thickness, punch speed, blank holder force), and extend the study to other freeform geometries with applicability in the automotive industry. In Fig. 38, the complete assembly for manufacturing a punch and die for conducting physical experiments can be observed.

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