



Finite Element Investigation and Parametric Optimization of Sheet Metal Bending Using Explicit Dynamics and Response Surface Methodology

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ABSTRACT

This study presents a numerical investigation of sheet metal bending behaviour with emphasis on stress development and internal energy evolution during deformation. Three materials—copper, Al 1100 and Al 5083—were analysed using an explicit dynamic finite element framework in ANSYS Workbench. A parametric punch–die–sheet configuration was subjected to velocity-driven loading with frictional contact interaction. Transient responses including total deformation, equivalent stress, shear stress and accumulated internal energy were evaluated for material comparison.

Simulation results indicated that Al 5083 experienced the largest deformation (40.241 mm), while copper exhibited the highest equivalent stress (539.94 MPa) and internal energy storage (305070 mJ). Differences in response were attributed to variations in material stiffness and plastic behaviour under identical geometric and loading conditions.

To examine geometric influence, die angle and die length were optimized using Taguchi-based experimental design coupled with response surface modelling. Statistical analysis identified die angle as the dominant factor influencing stress variation within the investigated range. The proposed numerical–statistical approach provides an efficient framework for evaluating bending response and identifying geometry-sensitive stress regions without extensive experimental trials.

Keywords:- Sheet forming simulation; Explicit dynamic analysis; Finite element modelling; Springback behaviour; Statistical optimization; Response surface modelling; Internal energy evolution; Die geometry sensitivity

1. INTRODUCTION

Sheet metal bending is a fundamental deformation process employed in manufacturing industries for producing structural and functional components. In applications where dimensional precision is critical, control of elastic recovery after unloading becomes essential. The phenomenon of springback, which occurs due to partial release of elastic strain energy stored during deformation, often leads to deviation from the intended geometry and increases tool compensation requirements.

Accurate prediction of bending response requires detailed evaluation of stress development, deformation progression and energy distribution during loading. Numerical simulation techniques, particularly three-dimensional finite element modelling, enable systematic examination of contact interaction between punch, die and sheet under transient loading conditions. Compared to purely experimental approaches, computational modelling provides greater flexibility in evaluating material behaviour and geometric sensitivity without repeated physical trials.

While stress and strain distributions are commonly reported in bending investigations, comparatively less emphasis is placed on analysing internal energy evolution during deformation. Since elastic recovery is directly related to stored strain energy, understanding its accumulation pattern can provide additional insight into springback tendency.

In the present work, explicit dynamic finite element analysis is employed to investigate the bending behaviour of copper, Al 1100 and Al 5083 sheets under identical loading conditions. In addition to material comparison, geometric parameters of the die are optimized using a Taguchi-based design of experiments coupled with response surface modelling to identify stress-sensitive regions. The combined numerical–statistical framework enables both mechanical interpretation and parameter optimization within a unified study.



2. BACKGROUND AND RESEARCH GAP

Numerical simulation of sheet metal bending has been extensively explored using commercial finite element platforms. Previous investigations have primarily focused on predicting springback magnitude, stress distribution across the thickness and formability limits under varying process parameters such as punch radius, die radius, blank holder force and friction conditions. These studies established the capability of finite element modelling to capture elastic–plastic behaviour during bending and unloading stages.

Several researchers have incorporated statistical optimization techniques, including response surface methodology and Taguchi design frameworks, to reduce forming defects and improve dimensional accuracy. Such approaches are commonly applied in deep drawing and hydroforming processes where multiple geometric and material parameters interact simultaneously. However, most optimization studies concentrate predominantly on minimizing stress concentration or thickness variation without detailed consideration of energy evolution during deformation.

From a mechanical perspective, springback is directly associated with the elastic strain energy stored within the material during bending. Despite this physical relationship, comparatively limited investigations explicitly evaluate internal energy accumulation alongside stress response in bending simulations. Furthermore, many reported works examine a single material system or focus exclusively on process parameter variation without integrating multi-material comparison and geometric optimization within a unified modelling framework.

Therefore, a need exists for a systematic investigation that simultaneously:

- compares deformation and stress response of multiple sheet materials under identical loading conditions,
- evaluates internal energy progression during explicit dynamic bending,
- and quantifies the sensitivity of die geometry parameters using statistical response modelling.

The present study addresses these aspects through combined explicit dynamic finite element simulation and parametric optimization of die angle and die length.

3. OBJECTIVES

The primary objective of this investigation is to establish a computational framework for analysing and optimizing sheet metal bending behaviour using explicit dynamic simulation. The study is structured to achieve the following specific goals:

1. To develop a three-dimensional punch–die–sheet assembly using ANSYS DesignModeler and implement explicit dynamic analysis for transient bending conditions.
2. To evaluate deformation characteristics, equivalent stress distribution, shear stress evolution and internal energy accumulation for copper, Al 1100 and Al 5083 sheets under identical process parameters.
3. To generate a structured experimental design using the Taguchi method for systematic variation of die angle and die length.
4. To construct response surface models for predicting stress and deformation behaviour based on geometric parameters.
5. To identify dominant die parameters influencing stress response and determine conditions that minimize equivalent stress during bending.

4. METHODOLOGY

4.1 Geometric Modelling

A three-dimensional representation of the bending setup was created in ANSYS DesignModeler consisting of a punch, die and deformable sheet positioned within a V-die configuration. The geometry was constructed using parametric sketching and extrusion operations to allow controlled modification of die angle and die length during optimization. All components were aligned concentrically to ensure symmetric contact interaction during loading.

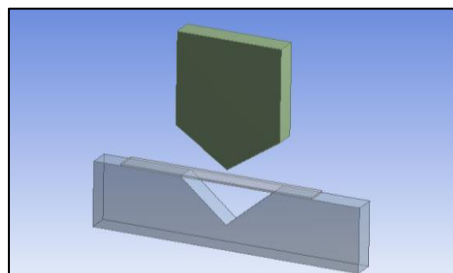


Fig -1

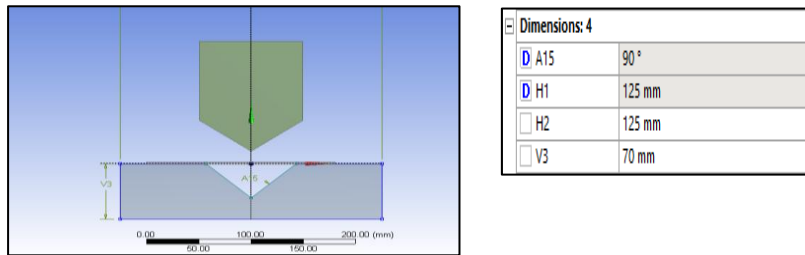


Fig -2

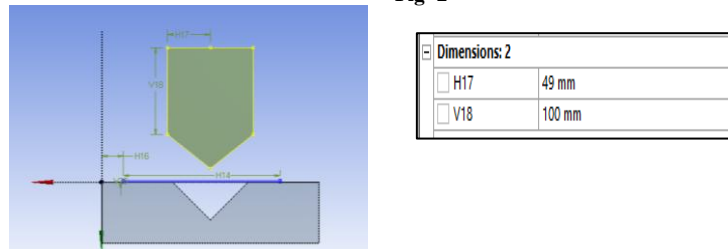


Fig -3

Figures 1–3 illustrate the complete assembly and geometric parameters selected as design variables.

4.2 Mesh Generation

The assembled model was discretized using finite elements suitable for large deformation analysis. A refined mesh was applied in the bending zone to accurately capture curvature development and stress concentration near the contact interface. The complete model contained 3259 nodes and 2147 elements. Mesh density was selected to balance computational efficiency with solution accuracy.

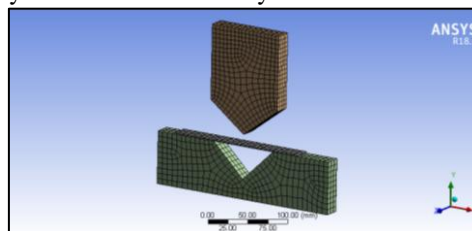


Fig -4: Finite element mesh of punch–die–sheet assembly

4.3 Boundary Conditions and Loading

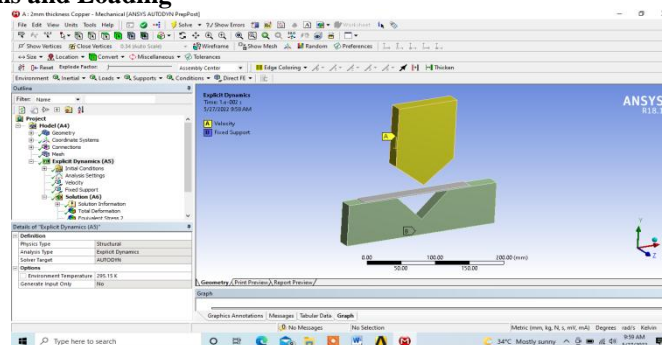


Fig -5: Boundary conditions showing fixed die support and velocity-controlled punch

The die component was constrained to prevent rigid body motion. Bending action was initiated by assigning a downward velocity of 5 m/s to the punch, producing transient friction contact with the sheet. Frictional interaction between contacting surfaces was defined using a Coulomb friction model with a coefficient of 0.1. Contact formulation was configured to allow separation after unloading.



4.4 Material Properties

Material data for copper, Al 1100 and Al 5083 were defined in ANSYS engineering database.

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	8300	kg m ⁻³		
4	Isotropic Elasticity				
5	Derive from	Young's...			
6	Young's Modulus	1.1E+11	Pa		
7	Poisson's Ratio	0.34			
8	Bulk Modulus	1.1458E+11	Pa		
9	Shear Modulus	4.1045E+10	Pa		
10	Specific Heat	385	J kg ⁻¹ ...		

Fig -6: Mechanical properties of copper sheet used in simulation

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2707	kg m ⁻³		
4	Specific Heat	884	J kg ⁻¹ C ⁻¹		
5	Sterberg Gurnan Strength				
14	Shear Modulus	2.71E+10	Pa		
15	Shock EOS Linear				
16	Grunesen Coefficient	1.97			
17	Parameter C1	5386	m s ⁻¹		
18	Parameter S1	1.339			
19	Parameter Quadratic S2	0	s m ⁻¹		

Fig -7: Mechanical properties of Al 1100 sheet

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2700	kg m ⁻³		
4	Specific Heat	910	J kg ⁻¹ C ⁻¹		
5	Johnson Cook Strength				
14	Bulk Modulus	5.833E+10	Pa		
15	Shear Modulus	2.692E+10	Pa		

Fig -8: Mechanical properties of Al 5083 sheet

4.5 Simulation Type

An explicit dynamic solver was employed to capture transient contact behaviour and nonlinear large deformation effects. Time-dependent outputs including total deformation, equivalent (von Mises) stress, shear stress and internal energy were recorded throughout the simulation duration. The explicit formulation ensured numerical stability during rapid contact and nonlinear material response.

5. RESULTS AND DISCUSSION

5.1 Deformation Behaviour

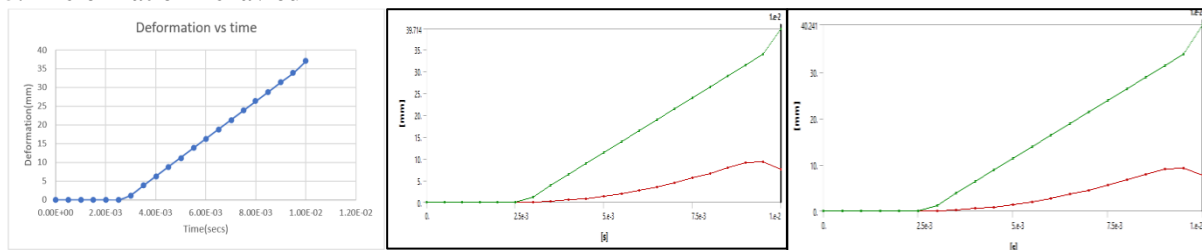


Fig -9: Comparative deformation–time response of copper, Al 1100 and Al 5083 sheets

The deformation–time response obtained from explicit dynamic analysis reveals distinct material-dependent bending characteristics. Among the three materials, Al 5083 exhibited the highest final deformation (40.241 mm), followed by Al 1100 (39.714 mm), whereas copper showed comparatively lower deformation (37.052 mm).

The variation in deformation magnitude can be associated with differences in elastic modulus and yield strength. Materials with relatively lower resistance to plastic flow undergo greater curvature under identical punch velocity conditions. Since all geometric and contact parameters were maintained constant, the observed deformation differences are attributed primarily to intrinsic mechanical properties of the sheet materials.

5.2 Equivalent Stress Analysis

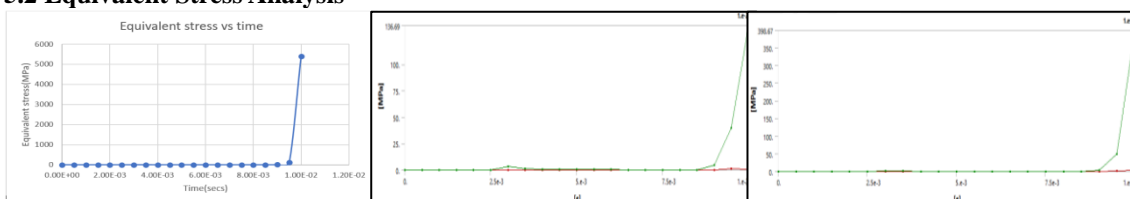


Fig -10: Comparative equivalent stress–time response for three materials



The equivalent (von Mises) stress evolution highlights the influence of material strength on bending response. Copper exhibited the highest peak equivalent stress of approximately 539.94 MPa, while Al 5083 and Al 1100 reached peak values of 398.67 MPa and 136.69 MPa respectively.

The higher stress magnitude in copper can be linked to its material stiffness and defined plastic behaviour within the simulation model. During bending, compressive and tensile stresses develop simultaneously across sheet thickness, leading to maximum stress concentration near the inner radius of curvature. The stress–time response indicates that peak stress occurs near maximum punch penetration, where curvature and contact pressure are greatest.

The comparatively lower stress in Al 1100 suggests reduced resistance to deformation, which is consistent with its larger displacement observed in Section 5.1.

5.3 Internal Energy Evolution

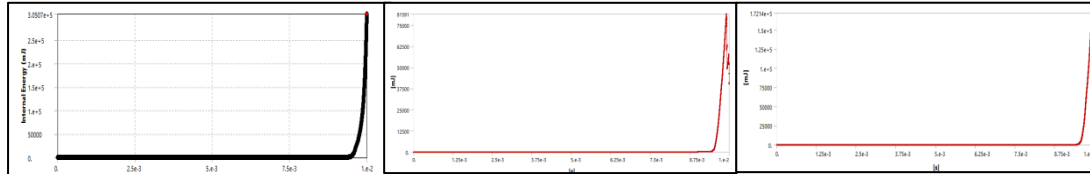


Fig -11: Comparative internal energy–time response during bending

Internal energy accumulation during bending provides additional insight into elastic–plastic work performed on the sheet. The simulation results indicate that copper stored the highest internal energy (305070 mJ), followed by Al 5083 (172140 mJ) and Al 1100 (81519 mJ).

Energy accumulation increased progressively after the onset of punch–sheet contact, reflecting the mechanical work absorbed by the material during plastic deformation. Since springback behaviour is directly related to recoverable elastic energy, higher internal energy storage suggests a stronger tendency for elastic recovery after unloading.

The linear growth pattern observed in the energy–time curves indicates stable contact interaction and absence of numerical instability within the explicit solution.

6. RESPONSE SURFACE OPTIMIZATION

6.1 Design of Experiments

Table of Outline A2: Design Points of Design of Experiments						
	A	B	C	D	E	F
1	Name	P1 - dieangle (degree)	P2 - dielength (mm)	P3 - Equivalent Stress 2 Maximum (MPa)	P4 - Shear Stress Maximum (MPa)	P5 - Total Deform... Maximum (mm)
2	1	90	125	116.67	2485.7	37.052
3	2	88	125	1608.7	3215.6	36.826
4	3	92	125	86.45	1670.5	36.511
5	4	90	124	117.41	2484.2	37.041
6	5	90	126	124.11	2617.4	36.924
7	6	88	124	1617.1	3046.7	36.814
8	7	92	124	83.651	1485	36.59
9	8	88	126	1592.8	6819.1	37.407
10	0	00	126	87.877	1421.2	36.584

Fig -12: Taguchi design points for variation of die angle and die length

Design variables:

- Die angle (88°–90° range)
- Die length (124–126 mm range)

Responses:

- Equivalent stress
- Shear stress
- Total deformation

6.2 Model Validation

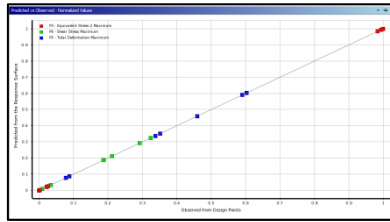


Fig -13: Goodness-of-fit plot showing agreement between predicted and observed values

The regression model exhibited close alignment between predicted and simulated results, indicating acceptable model adequacy.

6.3 Equivalent Stress Response Surface

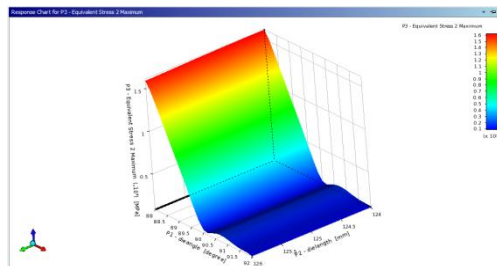


Fig -14: Response surface showing variation of equivalent stress with die angle and die length

Higher equivalent stress was observed in the region:

- Die angle: 88°–88.5°
- Die length: 124–126 mm

Minimum stress regions corresponded to higher die angles.

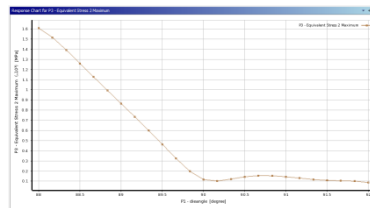


Fig -15: Influence of die angle on equivalent stress

Equivalent stress decreased linearly up to 90° and stabilized thereafter.

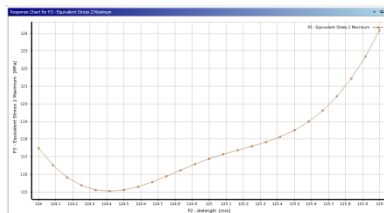


Fig -16: Influence of die length on equivalent stress

Minimum stress occurred near 124.4 mm die length.

6.4 Shear Stress Response Surface

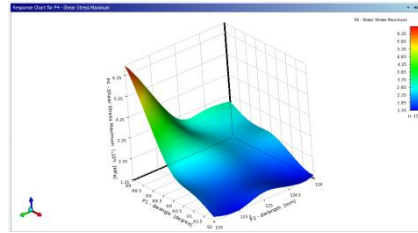


Fig -17: Response surface showing shear stress variation with die geometry

Shear stress exhibited similar sensitivity trends as equivalent stress, indicating die angle as a dominant parameter.

7. CONCLUSIONS

A combined numerical and statistical framework was developed to investigate bending behaviour and geometric sensitivity in sheet metal forming. Explicit dynamic finite element analysis successfully captured transient contact interaction and large deformation response for copper, Al 1100 and Al 5083 sheets under identical loading conditions.

Comparative analysis revealed that Al 5083 experienced the highest overall deformation, whereas copper exhibited the greatest equivalent stress and internal energy accumulation. These variations are primarily governed by differences in material stiffness and plastic characteristics defined within the simulation model. The energy-based evaluation further provided insight into potential springback behaviour, as higher stored internal energy indicates stronger elastic recovery tendency.

Parametric assessment using Taguchi-based design of experiments and response surface modelling enabled systematic evaluation of die geometry influence. Within the investigated range, die angle demonstrated greater sensitivity on equivalent and shear stress compared to die length. Increasing die angle toward 90° contributed to measurable stress reduction, while an optimal die length region was observed near 124.4 mm.

The integration of explicit finite element modelling with statistical optimization techniques provides an efficient approach for analysing bending response and identifying geometry-driven stress variations without extensive physical experimentation.

8. REFERENCES

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