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Energy-Based Evaluation of Springback Behaviour in Sheet Metal Bending Using Finite Element Modelling and Statistical Optimization

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***Abstract*—Accurate estimation of springback in sheet metal bending remains a persistent challenge in manufacturing industries, primarily due to the combined influence of material behaviour, tooling configuration, and process parameters. Conventional approaches largely rely on stress–strain analysis, which, although useful, does not directly represent the fundamental mechanism governing elastic recovery after unloading. In the present study, an energy-oriented approach is introduced to provide a clearer understanding of springback behaviour. A three-dimensional finite element model representing a punch die sheet assembly was developed and analysed using an explicit dynamic formulation to simulate the V-bending process. Three materials Copper, Aluminum 1100, and Aluminum 5083 were examined under identical loading and boundary conditions to evaluate their comparative responses. Unlike traditional methods, this investigation focuses on the evolution of internal energy as a primary indicator of elastic recovery. Internal energy, which reflects the work absorbed and stored within the material during deformation, is directly associated with the extent of springback. In addition, key geometric parameters such as die angle and die length were systematically varied and optimized using Taguchi design of experiments coupled with response surface methodology. The results demonstrate a clear relationship between internal energy accumulation and springback behaviour. Materials with higher energy storage exhibited a greater tendency to recover elastically after unloading. Among the materials studied, copper showed the highest internal energy levels, indicating a stronger springback effect, while aluminum alloys exhibited comparatively lower energy accumulation. The proposed framework offers a more physically meaningful and efficient approach for analyzing and controlling springback in sheet metal forming processes.**

***Index Terms*—Springback behaviour, Sheet metal forming, Energy-based analysis, Finite element modelling, Process parameter optimization, Taguchi method**

I. INTRODUCTION

Sheet metal forming is widely used in manufacturing for producing lightweight and complex components. Among various operations, bending is one of the most commonly applied processes due to its simplicity and flexibility. However, achieving accurate final dimensions is difficult because of springback.

Springback occurs when the material partially returns to its original shape after the removal of the applied load. This behaviour is caused by the release of elastic energy stored during deformation, leading to deviations from the intended geometry. As a result, it becomes an important factor to consider in tool design and process planning.

Most existing studies analyses springback using stress, strain, and deformation parameters. While these approaches describe material behaviour under loading, they do not directly represent the energy-related mechanism responsible for elastic recovery.

Finite element analysis (FEA) has become a reliable method for simulating bending processes, especially with explicit dynamic techniques that handle contact and large deformation effectively. However, the role of internal energy in understanding springback has not been sufficiently explored.

This study proposes an energy-based approach to analyze springback behaviour. By combining finite element simulation with statistical optimization techniques, the work aims to provide a clearer understanding of the influence of process parameters and improve prediction accuracy.

II. ENERGY-BASED PERSPECTIVE OF BENDING

During a bending operation, the external work applied to the sheet is converted into different forms of energy within the material. This energy distribution plays a key role in both deformation and the material's tendency to recover after unloading.

The total work input can be expressed as:

$$W = U_e + U_p$$

where U_e represents the elastic energy stored in the material and U_p corresponds to the plastic energy associated with permanent deformation.

The plastic component leads to irreversible shape change, whereas the elastic portion remains stored during loading. Once the load is removed, this stored elastic energy is released, causing the material to partially regain its original shape this effect is known as springback.

In finite element analysis, internal energy represents the total energy absorbed by the material throughout the deformation process. It includes both elastic and plastic contributions, making it a more comprehensive indicator of material behaviour.

Since only a portion of this energy is recoverable, it directly affects the extent of springback. Therefore, evaluating internal energy provides a more fundamental understanding of elastic recovery compared to traditional stress- or strain-based approaches.

By analyzing how energy is stored and released during bending, it becomes easier to compare material responses and assess the influence of process parameters, ultimately improving the prediction and control of springback.

III. METHODOLOGY

A. Finite Element Model

A three-dimensional model was created to simulate the sheet metal bending process. The system includes three main components: punch, die, and sheet. A V-bending setup was considered to represent practical forming conditions. Symmetry was applied to ensure uniform deformation and reduce computational effort. The selected geometric parameters were chosen to reflect realistic conditions and later used as input variables for optimization.

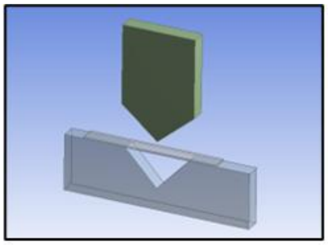
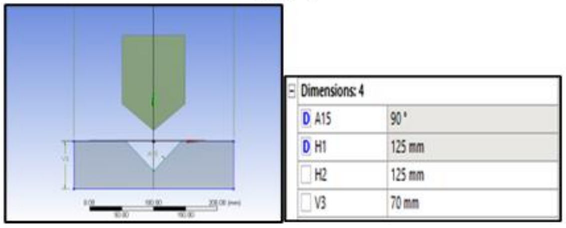
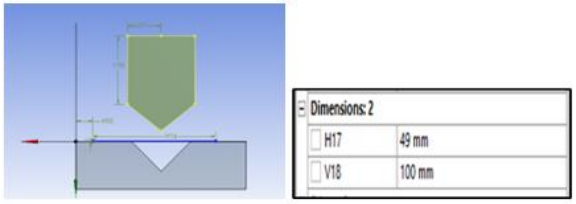


Fig -1



Dimensions: 4	
D A15	90 °
D H1	125 mm
☐ H2	125 mm
☐ V3	70 mm

Fig -2



Dimensions: 2	
☐ H17	49 mm
☐ V18	100 mm

Fig -3

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

B. Mesh and Contact Definition

The model was discretized using finite elements suitable for handling nonlinear deformation. A finer mesh was applied in the bending region to capture stress and strain variations more accurately. Contact between the punch, die, and sheet was defined with a friction coefficient of 0.1 to represent realistic interaction during the forming process.

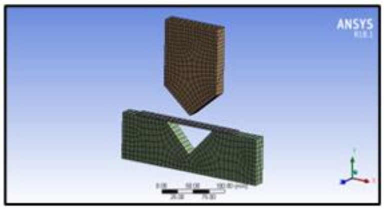


Fig 4: Finite element mesh of punch–die–sheet assembly

C. Boundary Conditions and Loading

The die was fixed in all directions, while the punch was assigned a constant downward velocity of 5 m/s. This velocity-based loading ensured stable and controlled deformation. Contact settings allowed separation between the sheet and tooling after unloading, which is essential for accurate springback prediction.

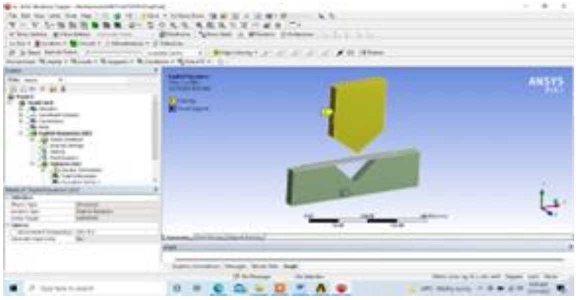


Fig -5: Boundary conditions showing fixed die support and velocity-controlled punch

D. Material Properties

Three materials copper, aluminum 1100, and aluminum 5083 were selected for analysis. These materials represent different mechanical behaviours, particularly in terms of stiffness and deformation response. An elastic–plastic material model was used to capture both permanent deformation and elastic recovery during bending.

	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^-...		

	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 -6: Mechanical properties of copper, Al 1100 and Al 5083 sheet used in simulation

E. Output Parameters

The simulation results were evaluated using the following parameters:

- Total deformation
- Equivalent stress
- Shear stress
- Internal energy

These outputs were used to compare material behaviour and understand springback characteristics under different conditions.

F. Statistical Optimization

To examine the effect of process variables, statistical methods were applied. Die angle and die length were selected as key design parameters. A Taguchi design of experiments (DOE) approach was used to systematically vary these inputs. In addition, response surface methodology (RSM) was employed to develop predictive relationships between input parameters and output responses.

IV. RESULTS AND ANALYSIS

A. Deformation Behaviour

The simulation results indicate clear differences in deformation among the selected materials. Aluminum 5083 shows the highest deformation, which can be linked to its lower resistance to plastic deformation. Copper, on the other hand, exhibits the least deformation due to its higher stiffness. Aluminum 1100 demonstrates moderate behaviour, lying between the two.

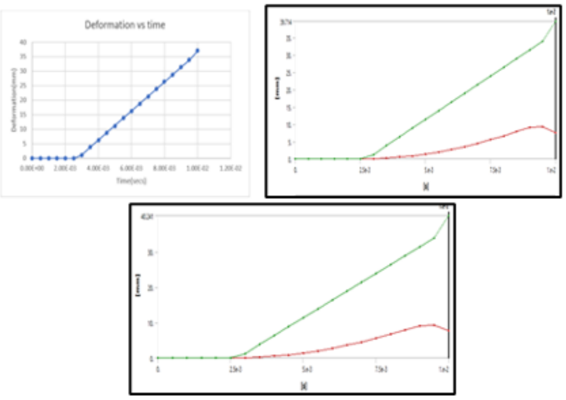


Fig -7: Comparative deformation–time response of copper, Al 1100 and Al 5083 sheets

B. Stress Analysis

The equivalent stress results show that copper experiences the highest stress during bending. This is mainly due to its higher elastic modulus, which increases resistance to deformation. Maximum stress concentration occurs in the bending region where the load is most intense. In comparison, aluminum alloys display lower stress values, indicating their relatively softer behaviour.

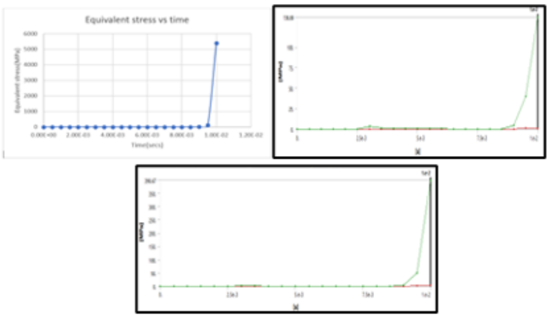


Fig -8: Comparative equivalent stress–time response for three materials

C. Internal Energy Evolution

Internal energy increases progressively throughout the deformation process, representing the total work absorbed by the material. Among the materials studied, copper shows the highest energy accumulation, followed by aluminum 5083, while aluminum 1100 records the lowest values.

This pattern suggests that stiffer materials tend to store more energy during deformation, which contributes to greater elastic recovery. The results highlight internal energy as an important parameter for understanding and evaluating springback behaviour.

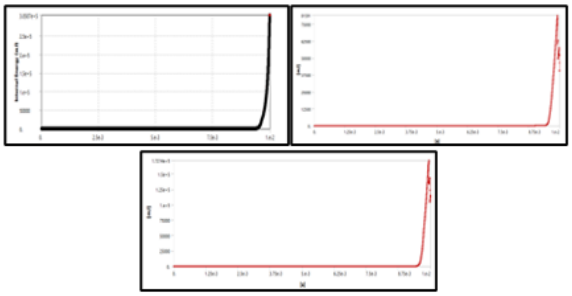


Fig -9: Comparative internal energy–time response during bending

V. PARAMETRIC OPTIMIZATION

A. Design of Experiments

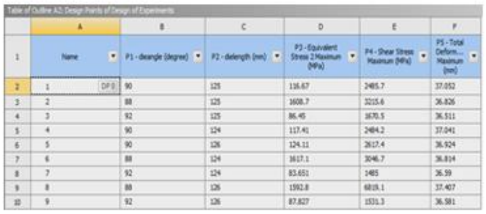


Table of Outline A2: Design Points of Design of Experiments

	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 DP 0	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	9	92	126	87.827	1531.3	36.581

Fig -10: Taguchi design points for variation of die angle and die length

A structured approach was used to study how process parameters affect bending behaviour. Taguchi design of experiments (DOE) was applied to generate different combinations of input variables, as shown in Fig. 10. The main parameters considered were die angle (88°–90°) and die length (124–126 mm). The responses evaluated include equivalent stress, shear stress, and total deformation, which are key indicators of material performance.

B. Model Validation

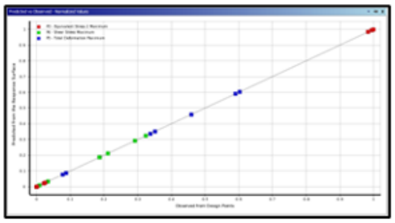


Fig -11: Goodness-of-fit plot showing agreement between predicted and observed values

The regression model developed from the DOE was validated by comparing predicted results with simulation data. As shown in Fig. 11, a strong agreement was observed between predicted and actual values, indicating good model accuracy. This confirms that the statistical model is reliable for analyzing parameter effects.

C. Effect of Die Angle

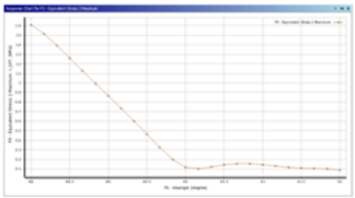


Fig -12: Influence of die angle on equivalent stress

The influence of die angle on equivalent stress is presented in Fig. 12. It is observed that stress decreases as the die angle approaches 90°. This behaviour can be linked to smoother material flow and reduced resistance during deformation. Beyond this range, the change in stress becomes minimal, indicating a stable response.

D. Effect of Die Length

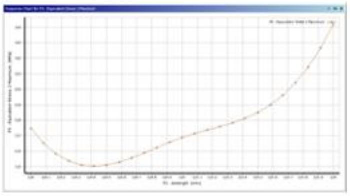


Fig -13: Influence of die length on equivalent stress

Figure 13 shows the variation of equivalent stress with die length. Compared to die angle, its influence is less significant. An optimal value is observed around 124.4 mm, where stress is minimized. Further changes in die length result in only slight variations, indicating lower sensitivity.

E. Response Surface Analysis

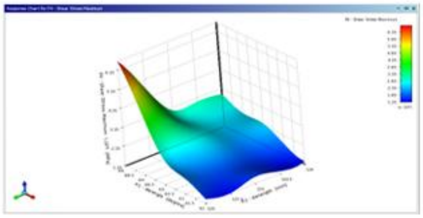


Fig -14: Response surface showing shear stress variation with die geometry

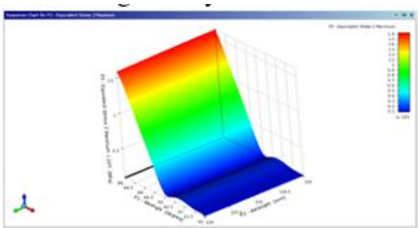


Fig -15: Response surface showing variation of equivalent stress with die geometry

The combined effect of die angle and die length is illustrated through response surface plots (Figs. 14 and 15). Higher stress levels are observed at lower die angles, particularly when combined with larger die lengths. As the die angle increases, stress reduces consistently, indicating improved deformation behaviour. A similar trend is observed for shear stress, confirming that die angle has a dominant influence on stress variation.

VI. DISCUSSION

The findings of this study demonstrate the importance of adopting an energy-based approach for analyzing sheet metal bending. While stress-based methods describe local behaviour during deformation, internal energy provides a broader view of how the material absorbs and releases energy throughout the process.

The comparison of materials shows that copper stores a higher amount of internal energy during deformation, which increases its tendency to recover elastically after unloading. This explains its higher springback behaviour. In contrast, aluminum alloys, due to their lower stiffness, store less energy and therefore exhibit reduced springback.

The parametric analysis indicates that die geometry significantly affects bending behaviour. Among the variables considered, die angle has a strong influence on stress distribution. Increasing the die angle improves material flow and reduces stress concentration. Die length shows a comparatively smaller effect, with only minor changes observed beyond the optimal range.

Overall, combining finite element simulation with statistical techniques proves to be an efficient way to analyse process parameters. This approach helps in reducing dependency on physical trials while still providing reliable insights into bending performance.

VII. CONCLUSIONS

This study presents a combined numerical and statistical approach to analyse sheet metal bending using explicit finite element simulation and optimization techniques. The key conclusions are:

1. Explicit dynamic analysis effectively captured contact interactions and large deformation behaviour during bending.
2. Aluminum 5083 showed the highest deformation, while copper exhibited the highest stress and internal energy.
3. Internal energy proved to be a useful parameter for understanding springback, as higher energy storage leads to greater elastic recovery.
4. Taguchi DOE and response surface methodology provided a structured way to study the effect of process parameters.

5. Die angle was identified as the most influential parameter, with higher values reducing stress concentration.
6. Die length had a moderate effect, with an optimal range minimizing stress variation.
7. The combined FEM–DOE framework offers an efficient method for analyzing and optimizing bending processes with reduced experimental effort.

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