Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

Finite element analysis of incremental sheet metal forming process on complex shapes

To cite this article: Abdulrhman Atef *et al* 2025 *J. Phys.: Conf. Ser.* **3058** 012018

Finite element analysis of incremental sheet metal forming process on complex shapes

Abdulrhman Atef[1], Tamer A Mohamed[1], Hussien Mohamed[2], and Mostafa Shazly[1]

[1] Mechanical Engineering Department, The British University in Egypt, Cairo, Egypt
[2] Mechanical Engineering Department, Helwan University, Cairo, Egypt

E-mail: Abdulrhman.Atef@bue.edu.eg

Abstract. Incremental Sheet Metal Forming (ISMF) is a flexible manufacturing process requiring minimum tooling setup. Practically, this process could be used to manufacture complex parts. However, the existing literature focuses on optimizing the ISMF parameters for simple shapes without considering the part's complexity. In the present work, finite element analysis (FEA) is adopted to investigate the effect of process parameters on the quality produced by ISMF. A finite element model for a conical part is developed and validated against published experimental data. The comparison between the simulation and experimental results confirmed the accuracy and reliability of the developed model. The validated model is then used to check the applicability of the validated process parameters to complex shapes. Results have shown that the complexity of the part significantly affects the forming limit diagram (FLD). Complex shapes consisting of an elliptic part and elliptic then conical part show a median FLD value of 0.37, while a conical part and conical then elliptic part show median FLD values of 0.21 and 0.22, respectively. Results have shown that the success of the proposed process parameters depends on the complexity of the part and the interaction between different process parameters.

1. Introduction

During the last decade traditional metal forming methods, such as stamping and deep drawing, were widely used in many industries. However, traditional methods for metal forming are considered a mass production method as it relies mainly on using rigid dies, which are expensive and time-consuming to design and manufacture. This makes the use of metal forming for custom-designed parts and low-volume production inconvenient since the cost of tooling cannot be justified. On the other hand, ISMF offers a cost-efficient solution by eliminating the need for complex dies. Consequently, the ISMF is considered the ideal solution that suits perfectly the prototyping phase where each part may have unique geometrical requirements.

ISMF was first introduced in the 1960s [1] where CNC was utilized to incrementally deform a sheet metal. Later in 2007, Maidagan and Meier studied the addition of another tool to support the sheet during the forming process [2]. In single-point incremental forming (SPIF), only one tool is in contact with the sheet at any given time and deforms the sheet incrementally based on a predefined tool path. Sometimes this could lead to inaccurate geometries and many researchers attempted to study the tool path definition. In contrast, double-point incremental forming (DPIF) utilizes two opposite tools simultaneously where one of the tools acts as a support to the sheet while the other incrementally deforms it. In either case, the process parameters affect the quality of the product. While the SPIF is considered easier to implement, DPIF offers higher geometrical accuracy [3].

The parameters that affect the process could be classified into two main categories, parameters that are related to the process itself, for example, the tool path, lubrication, and feed rate [4]. Others are related to material formability, such as yield strength, strain hardening, ductility, heat treatment state, and the processing method [4]. Alloys such as aluminum are widely used in ISMF because of their ability to undergo significant plastic deformation without fracturing. On the other hand, materials such as high-strength steels or titanium alloys, despite their high demand in certain industries such as aerospace, have many challenges in ISMF due to their tendency to crack or tear when subjected to localized forces [5]. By optimizing the ISMF process parameters and carefully for a given material, the ISMF could be used in many industrial sectors.

ISMF is considered an attractive option for a diversity of industries due to its ability to form complex, asymmetric geometries without using any dedicated tooling [4]. In aerospace, for example, ISMF is used to fabricate lightweight, custom-designed structural components with complex curves, such as fuselage panels. Likewise, in the medical field, some implants and prosthetics are patient-dependent, therefore ISMF is utilized to manufacture the part with unique anatomical features of the individual [4]. Beyond its flexibility, ISMF also contributes towards a sustainable world. By eliminating the need for large-scale tooling, ISMF offers a huge environmental advantage [4].

The deformation process and materials flow in ISMF is complex and predicting such a behavior is essential to achieve high-quality results. This makes FEA an important tool to simulate the process and predict failure. FEA could predict not only the final shape but also significant factors like stress concentration, thickness variation, and failure locations. This gives engineers the ability to optimize tool paths and other process parameters before committing to physical trials, significantly reducing the costs associated with prototyping.

While the previous literature extensively addressed the manufacturing of basic geometries using ISMF, there was comparatively less focus on the production of more intricate shapes. For example, several authors investigated the accuracy of the ISMF on an elliptical shape using machine vision. This led to the successful modification of the forming tool path, minimizing the discrepancy between the formed parts and the design CAD file [3]. Other researchers focused on analyzing the material of sheet metal used for the forming limit of AA2024 in the case of incremental forming compared to conventional forming processes. Figure 1 shows the forming limit diagram (FLD) for AA2024 for both ISMF and stamping processes ISMF showed higher ductility compared with sheet metal stamping [6][7]. Previous studies often focus on the effect of process parameters of a single shape either experimentally or numerically, leaving a gap in understanding the situation where different shapes are combined and the effect of process parameters on such a case.

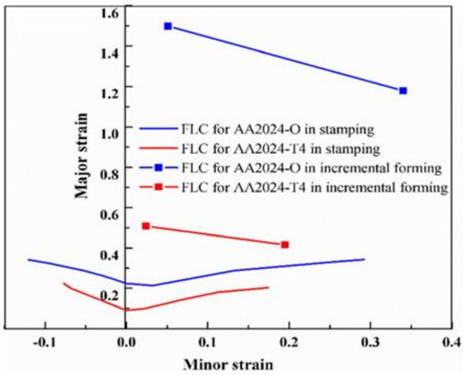

Figure 1. FLD comparison of AA2024 sheet metal stamping and ISMF [7]

2. Methodology

To address the research gap, the authors will first introduce the FEA model and validate it against published experimental work. Secondly, the Analysis of Variance (ANOVA) will be adopted to test the effect of process parameters on forming complex shapes and their interactions on the formability of AA2024. Data required for the ANOVA analysis will be obtained using the validated FEA model.

2.1 Development of the FEA Model

The FEA model was developed using Simulia®/ABAQUS Version 2024 software. Figure 2 shows the tool with a hemisphere end of 10 mm diameter and a length of 20, and the sheet metal with a square of side length 100 mm and a thickness of 1.5mm. The tool was modeled as a rigid part, while the sheet metal was modeled as a shell part. The material is modeled as elastic-plastic isotropic hardening with the von Mises yield criterion. The true stress-strain is shown in Figure 3, while the material's parameters are given in Table 1 [3,7,8]. The quantify the damage, the FLD presented above was used.

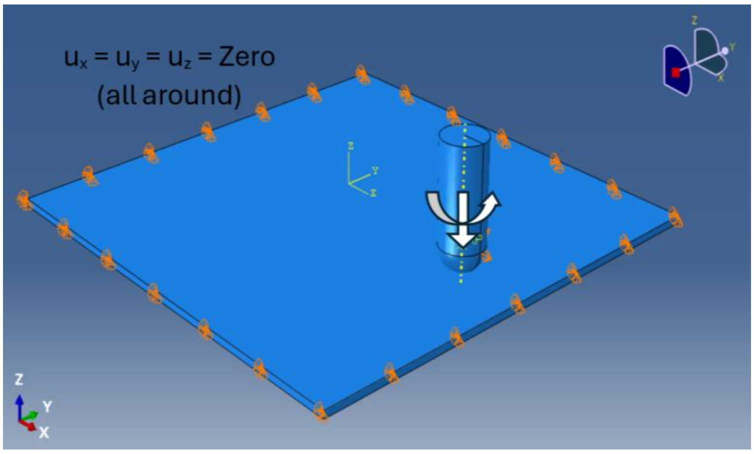

Figure 2. FEM model showing tool and sheet metal along with boundary conditions

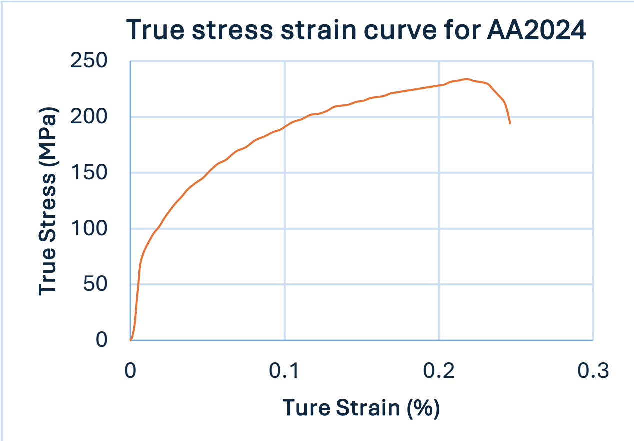

Figure 3. True stress-strain curve for AA2024 [8]

Table 1. AA2024 material properties

Property	Density	Young's Modulus	Yield strength	Ultimate tensile strength	Poisson's ratio
Unit	Kg/m^3	GPa	MPa	MPa	-
Value	2770	72.4	80.24	233.81	0.33

A dynamic explicit solver was used to perform the ISMF with boundary conditions as indicated in Figure 2. The tool position in the x, y, and z directions was defined using a MATLAB script based on the tool path and feed rate. To simulate the machine oil lubricant, the surface-to-surface interaction between the tool and the sheet metal is defined with a friction coefficient of 0.1[3].

Regarding the mesh, a standard 4-node reduced integration conventional shell element (S4R) was used for the sheet metal with an element size of 1 mm, resulting in 10000 elements with an aspect ratio of 1.

2.2 ANOVA design

The ISMF process contains many parameters that may affect the formability of the sheet metal. These include Step Depth, Feed Rate, Spindle Speed, and Shape Complexity. Step depth refers to the incremental vertical distance between two consecutive tool path layers and also known as layer height. The feed rate defines the linear velocity the forming tool moves along the pre-defined tool path. Spindle speed refers to the angular velocity of the forming tool. Shape complexity classifies the part into four main categories, a conical shape, elliptic shape, combined: elliptical then conical, and combined: conical then elliptical.

Both the step depth and feed rate are tested at three levels, on the other hand, spindle speed is tested at two levels only; finally, the complexity of the geometry is tested at four levels as shown in Table 2. The levels of factors like feed rate, spindle speed, and step depth were chosen to cover the same values used in previous studies like Ref. [3], and then the range was widened to cover more range around those values. Regarding the complexity factor, four levels were chosen to study the effect of each shape alone and then the effect of combining both shapes in all possible combinations. The maximum value of FLD was taken as the response for the ANOVA analysis.

Table 2. Factors and their levels.

Parameter	Unit	Level 1	Level 2	Level 3	Level 4
A- Step depth	Mm	0.2	0.5	0.7	-
B- Spindle speed	rpm	1000	1500	-	-
C- Feed rate	$mm//min$	800	900	1000	-
D- Complexity	-	only elliptic	only conical	elliptic then conical	conical then elliptic

3. Result and discussion

3.1 Experimental validation

The experimental data presented in Ref. [3] was used to validate the FEA model. In the developed FEA model, the tool diameter, tool path, step size, feed rate, and spindle speed were used in [3]. Figure 4 shows a comparison of the final part profiles for both the FEA model and the experimental work. To evaluate the difference between the Ref. [3] data and the FEM model the mean absolute error (MAE) was computed. The analysis showed a 0.31 MAE which is less than 10% of the data range, indicating a strong agreement between the model and the literature. Furthermore, the average error percentage between the FEA model and the experimental data was less than 5%, reinforcing the reliability of the results. Hence all results taken from the same setup could be trusted.

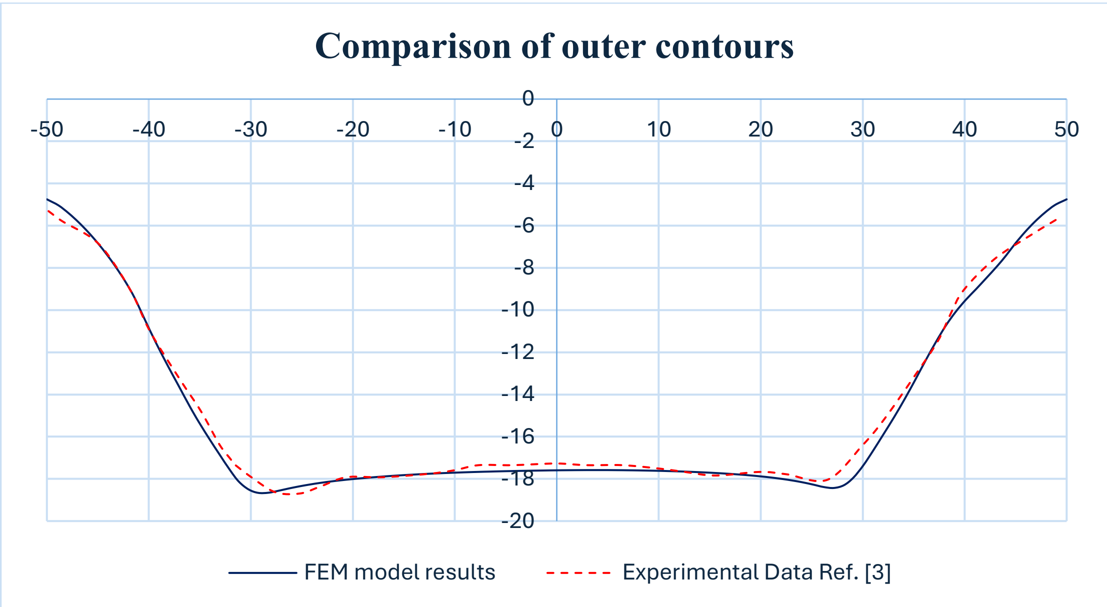

Figure 4. Comparison of outer contours

3.2 ANOVA Results

This section aims to discuss and analyze the four-factorial experiment at multiple levels. Table 3 shows reduced ANOVA based on the significance level of $\alpha = 0.05$ with R2 equals to 0.99, which shows that ANOVA result can be trusted. The spindle speed was found to be not significant and had no effect on the FLD of the sheet metal. On the other hand, the complexity and interaction between complexity and both feed rate and step depth have a significant effect on the response.

Table 3. Reduced ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	675.11	21	32.15	1467.47	<0.0001
A- Step depth	24.62	1	24.62	1123.65	<0.0001
C- Feed rate	3.02	1	3.02	137.92	<0.0001
D- Complexity	628.37	3	209.46	9561.07	<0.0001
AC	1.92	1	1.92	87.8	<0.0001
AD	4.61	3	1.54	70.12	<0.0001
CD	1.97	3	0.6555	29.92	<0.0001
A^2	0.3279	1	0.3279	14.97	0.0003
C^2	0.0984	1	0.0984	4.49	0.0391
ACD	2.86	3	0.9538	43.54	<0.0001
A^2D	7.15	3	2.38	108.8	<0.0001
AC^2	0.167	1	0.167	7.62	0.008
Residual	1.1	50	0.0219		
Cor total	676.21	71			

By referring to the FEA results, the complexity of shapes was found to affect the formability, through utilizing MATLAB software the values were visualized in a boxplot as shown in Figure 5. The elliptic and elliptic then conical shows higher variability and median FLD values which indicate a higher damage in the sheet metal. In both cases the maximum value of FLD was 0.5 while the minimum value was in range of 0.37 and 0.31 depending on the other parameters. On the other hand, conical and conical then elliptic have a maximum value of 0.23 and 0.24 respectively and minimum value of 0.21, that reflect a significantly lower values of FLD and minimal spread.

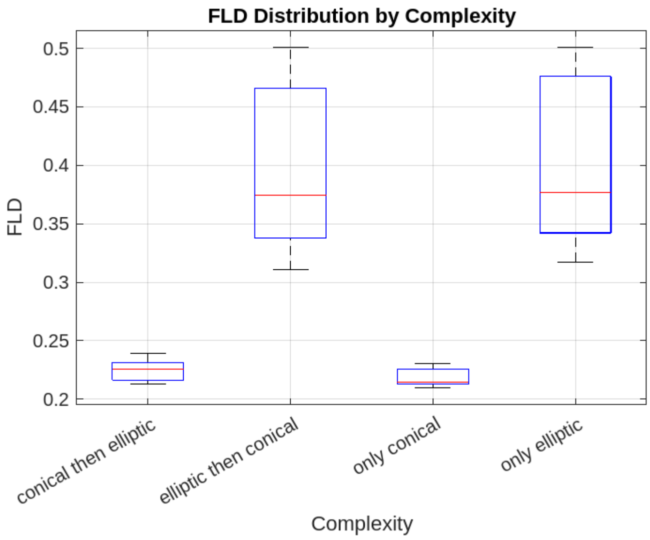

Figure 5. Boxplot for FLD vs Complexity

By checking the FLD contours in ABAQUS software it was found that the reason behind that significant increase was due to elliptic shapes suffer significant damage in the sheet metal at the edge as shown in Figure 6. For the conical shapes, damage at the edges was reduced as shown in Figure 7. Furthermore, the inclusion of conical shapes before the elliptical shape enhances formability and mitigates the challenges associated with forming the elliptical shape, as illustrated in Figure 8.

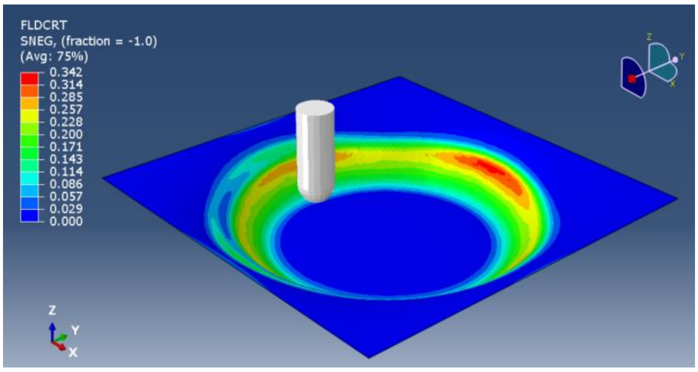

Figure 6. FLD diagram for elliptic shape

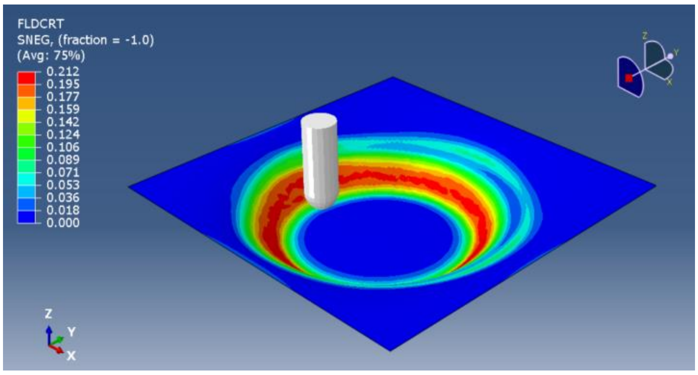

Figure 7. FLD diagram for conical shape

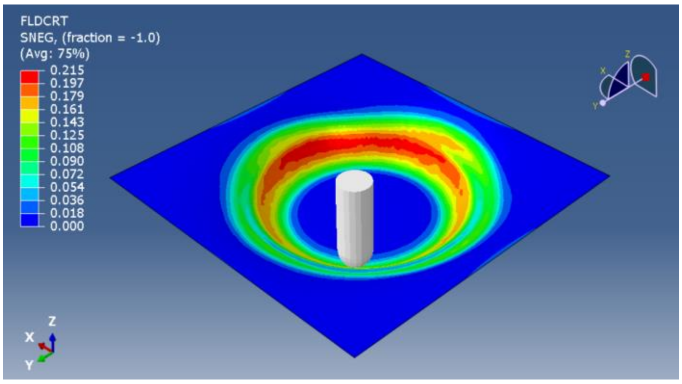

Figure 8. FLD diagram for conical then elliptic shape

It is worth mentioning that regardless of the process parameters, the maximum value of von-Mises stress ranges between 220 MPa and 232 MPa as shown in Figure 9. Although the von Mises values approach ultimate tensile strength of uniaxial tension test, however during the ISMF process, AA2024 undergoes biaxial stressing and can withstand up to 450 MPa [7,9].

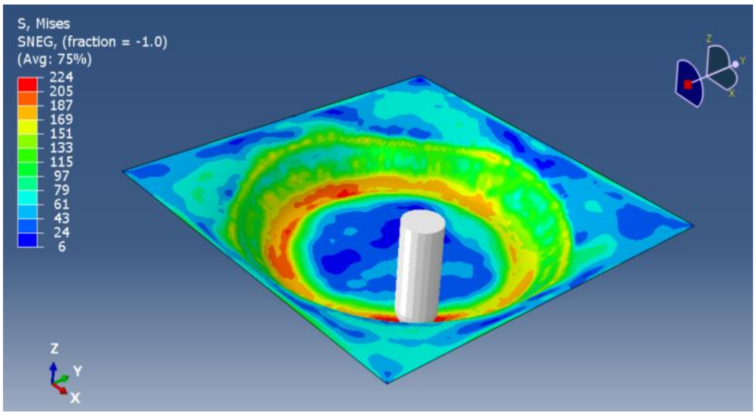

Figure 9. Typical von-Mises stress distribution in ISMF process

Journal of Physics: Conference Series **3058** (2025) 012018 doi:10.1088/1742-6596/3058/1/012018

4. Conclusion

In the present work, an FEA model was successfully built and validated against previously published work. The validated model was used along with ANOVA to examine the impact of process parameters such as step depth, spindle speed, feed rate, and complexity on the formability of the AA2024 sheet metal. The following conclusions can be drawn:

- Spindle speed does not affect sheet formability.
- Shape complexity has significant effects on sheet formability.
- Conical and conical then elliptic have an FLD value ranging from 0.21 to 0.24 for different process parameters
- In the case of an elliptic part and elliptic then conical part, an increase in the FLD value of approximately 50-100% occurs.
- Elliptic shapes significantly damaged the sheet metal at the edge.
- In case of a conical shape, a minimum FLD value of 0.21 was achieved using a step depth of 0.2 mm, spindle speed of 1500 rpm, feed rate of 900 mm/min.

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