



Experimental and Numerical Investigation on the Formability of SUS304 Stainless Steel Sheets in Multi-Stage Single Point Incremental Forming

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Abstract— Multi-Stage Single Point Incremental Forming (MSPIF) has been proposed as an effective strategy to improve the formability of hard-to-form sheet metals in die-less forming processes. This study presents an integrated experimental and numerical investigation into the formability of SUS304 austenitic stainless steel sheets subjected to MSPIF. Controlled forming experiments are conducted to evaluate the maximum achievable wall angle, thickness distribution, and fracture characteristics under different combinations of process parameters. A three-dimensional finite element (FE) model is developed using the Abaqus/Explicit solver, incorporating large deformation kinematics, nonlinear elastic–plastic material behavior, and frictional contact between the forming tool and the sheet. The numerical predictions are validated against experimental measurements in terms of wall angle, thickness thinning, and final geometry. In addition, a Taguchi based design of experiments is employed to quantitatively assess the effects of forming angle increment, vertical tool step-down, tool diameter, and in-plane tool feed rate on material formability. The results demonstrate that MSPIF effectively enhances the forming capability of SUS304 sheets by promoting gradual strain accumulation and reducing strain localization, thereby delaying fracture initiation. Wall angles of up to approximately 84° are achieved without premature failure. Among the investigated parameters, tool diameter and forming angle increment are identified as the dominant factors governing formability. The proposed experimental numerical framework provides valuable insights for optimizing MSPIF processes applied to stainless steel sheets.

Keywords— Incremental sheet forming, Multi-stage single point incremental forming, SUS304 stainless steel, Formability enhancement, Explicit finite element modeling.



I. INTRODUCTION

Incremental Sheet Forming (ISF) has been widely investigated as a flexible and die-less manufacturing technology for producing complex sheet metal components with high geometric adaptability and reduced tooling costs, making it particularly suitable for prototype fabrication and small-batch production [1], [5]. Among the various ISF variants, Single Point Incremental Forming (SPIF) has received considerable attention due to its simple tooling configuration and process flexibility. However, the industrial application of SPIF is often constrained by limited formability, excessive thickness thinning, and premature fracture, especially when forming high-strength metallic materials [1], [3].

SUS304 austenitic stainless steel is extensively used in engineering applications owing to its excellent corrosion resistance, good ductility, and favorable mechanical properties. Nevertheless, under incremental forming conditions, SUS304 exhibits pronounced strain hardening, nonlinear elastic plastic behavior, and complex multiaxial stress states, which significantly restrict the attainable wall angle in conventional SPIF and frequently lead to early failure [7], [13].

To overcome these limitations, Multi-Stage Single Point Incremental Forming (MSPIF) has been introduced as an advanced forming strategy in which the target geometry is achieved through multiple forming stages with gradually increasing wall angles [3], [10]. By distributing deformation over successive stages, MSPIF promotes progressive strain accumulation, reduces strain localization, and enhances overall formability compared with single-stage SPIF [12]. Previous studies have reported notable improvements in achievable wall angle, thickness uniformity, and forming stability through the use of optimized multi-stage toolpaths and stage sequencing strategies [10], [12].

From a numerical perspective, finite element modeling has been extensively employed to analyze incremental forming processes and to predict deformation behavior, thickness thinning, and forming forces [4]-[6]. However, many existing numerical studies focus primarily on SPIF or simplified MSPIF configurations and often rely on idealized material models or symmetry assumptions that may not adequately capture the complex contact conditions and non-axisymmetric deformation inherent in incremental forming [4], [11]. Moreover, the integration of validated finite element simulations with statistical design of experiments to quantitatively assess parameter sensitivity in MSPIF of stainless steel sheets has received relatively limited attention.

Therefore, the objective of the present study is to provide a systematic experimental and numerical investigation of the formability of SUS304 stainless steel sheets under MSPIF conditions. A Taguchi based design of experiments is employed to evaluate the influence of forming angle increment, vertical step-down, tool diameter, and tool feed rate on the maximum



achievable wall angle. In parallel, a three dimensional finite element model is developed using the Abaqus/Explicit solver, incorporating large deformation kinematics, nonlinear elastic plastic material behavior, and frictional tool sheet interaction. The numerical predictions are validated against experimental observations. By combining experimental results, statistical analysis, and finite element modeling, this study aims to clarify the mechanisms responsible for formability enhancement in MSPIF and to provide practical guidelines for process optimization.

II. INVESTIGATION OF THE FORMABILITY OF SUS304 SHEETS USING MSPIF THROUGH SIMULATION

A. Selection of Influential Process Parameters

The formability of sheet metals in the Multi-Stage Single Point Incremental Forming (MSPIF) process is governed by a complex interaction between toolpath geometry, kinematic conditions, and material response under large plastic deformation [3], [5]. To establish a robust and computationally efficient numerical framework, it is essential to identify the dominant process parameters that primarily control deformation behavior and formability outcomes. Accordingly, a preliminary screening of process parameters is conducted based on previous studies, technological considerations, and initial numerical trials [10], [12].

Among the numerous variables involved in MSPIF, four controllable technological parameters are identified as having the most significant influence on the formability of SUS304 austenitic stainless steel sheets: the incremental forming angle between successive stages ($\Delta\alpha$), the vertical tool step-down (Δz), the forming tool diameter (D), and the in-plane tool feed rate (V_{xy}) [3], [10]. These parameters directly affect the evolution of stress strain states, thickness thinning behavior, and deformation stability during progressive forming. Other factors, such as tool rotational speed, lubrication conditions, and clamping stiffness, are maintained constant throughout the simulations to isolate the effects of the selected variables and ensure consistency of the numerical conditions [6].

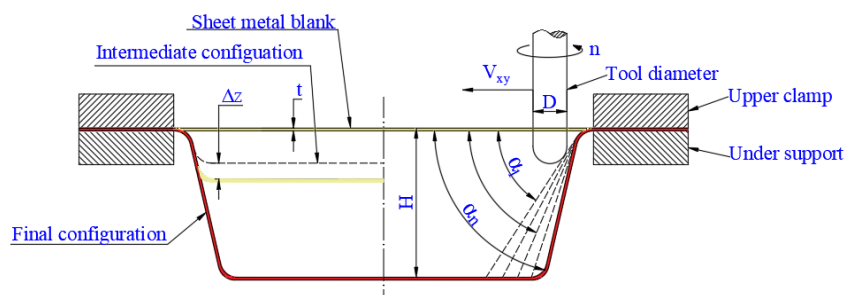


Fig 1. Schematic illustration of the Multi-Stage Single Point Incremental Forming (MSPIF) process, showing the intermediate and final configurations and the definition of key process



parameters, including incremental forming angle ($\Delta\alpha$), vertical tool step-down (Δz), tool diameter (D), and in-plane tool feed rate (V_{xy}).

A schematic illustration of the MSPIF process adopted in this study, together with the definition of the selected process parameters, is shown in Fig. 1. The incremental forming angle $\Delta\alpha$ characterizes the change in wall angle between successive forming stages and plays a critical role in controlling the severity of deformation introduced at each stage. Smaller values of $\Delta\alpha$ promote a more gradual distribution of plastic strain and help mitigate strain localization, whereas larger $\Delta\alpha$ values intensify deformation and may accelerate the onset of fracture [10], [12].

The vertical tool step-down Δz defines the depth of tool penetration per increment and strongly influences local contact conditions, thickness reduction, and stress concentration beneath the tool [13]. The forming tool diameter D determines the contact area and curvature of the tool sheet interface, thereby affecting stress distribution, material flow, and surface integrity; larger tool diameters generally promote smoother stress gradients and improved formability [6], [9]. The in-plane tool feed rate V_{xy} controls the forming speed and forming force level and may influence material response through strain-rate effects, although its impact is typically secondary compared with that of geometric parameters [8].

Based on these considerations, the four selected parameters ($\Delta\alpha$, Δz , D , and V_{xy}) are treated as input variables in the finite element simulations to systematically investigate their individual and combined effects on the formability of SUS304 sheets under MSPIF conditions. Forming performance is evaluated using numerical indicators including the maximum achievable wall angle, thickness distribution, accumulated plastic strain, and forming force evolution.

B. Finite Element Model

The finite element (FE) model of the MSPIF process is developed using the Abaqus/Explicit solver, which is particularly suitable for handling severe nonlinearities associated with large plastic deformation, complex contact conditions, and continuously evolving tool sheet interaction in incremental forming processes [4]–[6]. The model is constructed based on the actual experimental configuration to ensure direct comparability between numerical predictions and experimental observations.

The SUS304 sheet is modeled as a deformable body using reduced-integration shell elements, which are well suited for representing thin sheet structures subjected to combined membrane and bending deformation under large strains [5], [7]. The peripheral edges of the sheet are fully constrained to realistically reproduce the clamping conditions applied in the experiments. A rigid backing plate is introduced beneath the sheet to simulate the supporting surface while minimizing computational cost [6].



The hemispherical forming tool is modeled as a rigid analytical surface and is prescribed with forced displacements in the x, y, and z directions following the helical toolpath employed in the MSPIF process [3], [10]. Frictional contact between the tool and the sheet is defined using a Coulomb friction model, which has been widely adopted in incremental forming simulations and shown to provide reasonable accuracy for predicting forming forces and deformation behavior [9].

In several earlier numerical studies, symmetry assumptions have been employed to reduce computational cost by modeling only a fraction of the sheet geometry [2]. Such simplifications inherently presume symmetric stress and strain distributions, which are generally not satisfied in Multi-Stage Single Point Incremental Forming (MSPIF). Owing to the non-axisymmetric deformation mode and the continuously evolving contact conditions associated with the helical toolpath, symmetry-based models may lead to inaccurate predictions of strain localization, thickness thinning, and the onset of failure [4], [12]. Therefore, a full three-dimensional finite element model is adopted in the present study to accurately capture the spatial evolution of stress, strain, and thickness distribution throughout successive forming stages [5], [11].

C. Material Modeling

Accurate material modeling is a prerequisite for reliable finite element simulation of the Multi-Stage Single Point Incremental Forming (MSPIF) process, in which SUS304 austenitic stainless steel sheets undergo large plastic deformation, severe strain gradients, and complex stress states. The constitutive description must be capable of representing the nonlinear elastic plastic behavior and pronounced strain-hardening characteristics of SUS304 in order to accurately predict formability-related responses such as strain localization, thickness thinning, and the initiation of fracture [7], [11].

Accordingly, the adopted material model in this study is designed to fulfill the following objectives:

- (i) assess the risk of cracking or tearing during progressive forming,
 - (ii) determine the critical forming angle and forming limits of SUS304 sheets under MSPIF conditions, and
 - (iii) provide consistent and physically meaningful material input data for finite element simulations implemented in Abaqus/Explicit.
- Material Selection and Plastic Property Database of SUS304

The material investigated in this study is SUS304 austenitic stainless steel, which conforms to the Japanese Industrial Standard (JIS). Owing to its excellent ductility, high strain-hardening capacity, and favorable strength-to-formability ratio, SUS304 is widely employed in industrial applications and has been extensively studied in incremental sheet forming research [7], [11],



[13]. These characteristics make SUS304 particularly suitable for investigating formability enhancement mechanisms in MSPIF.

TABLE I. MECHANICAL TEST REQUIREMENTS [13]

Type ^A	Tensile Strength, min MPa	Yield Strength ^B , min MPa	Elongation in 2 in. or 50mm, min, %	Hardness, max ^C	
				Brinell	Rockwell B
304	515	205	40	201	92

The chemical composition, mechanical properties, and physical properties of SUS304 in the annealed condition are summarized in Table I, based on standard reference data reported in ASTM A240 / JIS specifications [13]. Among the commonly used grades (SUS304, SUS304L, and SUS304H), the conventional SUS304 grade is selected in the present study due to its widespread industrial usage and availability in thin sheet form.

From Table I, the key mechanical properties of SUS304 are extracted as reference parameters for defining the elastic and plastic behavior in the finite element model:

- Young's modulus: $E = 193 \text{ GPa} = 193\,000 \text{ N/mm}^2$
- Ultimate tensile strength: $F_{tu} = 515 \text{ MPa} = 515 \text{ N/mm}^2$
- Yield strength (0.2% proof stress): $F_{ty} = 205 \text{ MPa} = 205 \text{ N/mm}^2$
- Total elongation at fracture: $\varepsilon_{\max} \approx 40\%$

These values are consistent with commonly reported material data for annealed SUS304 sheets and provide a reliable basis for constitutive modeling in incremental forming simulations [11], [13].

- Ramberg–Osgood Constitutive Model for Elastic–Plastic Behavior

To describe the nonlinear elastic plastic transition and pronounced strain-hardening behavior of SUS304, the Ramberg–Osgood constitutive model is adopted in this study. This model has been widely applied to austenitic stainless steels due to its ability to accurately represent the smooth transition from elastic to plastic deformation and its suitability for large-strain forming simulations [7], [14].

According to the MMPDS-01 standard [14], the total strain–stress relationship is expressed as:

$$\varepsilon = \frac{\sigma}{E} + 0,002 \left(\frac{\sigma}{F_{ty}} \right)^n \quad (1.1)$$



Where ϵ is the total strain, σ is the equivalent stress, E is Young's modulus, F_{ty} is the yield strength at 0.2% offset, and n is the strain hardening exponent.

The strain hardening exponent n is determined based on the uniform plastic strain at the onset of necking. The uniform strain ϵ_{us} is calculated as:

$$\epsilon_{us} = 100 \times \left(\epsilon_r - \frac{F_{tu}}{E} \right) = 100 \times \left(\frac{40}{100} - \frac{515}{193000} \right) \approx 39.73\% \quad (1.2)$$

The strain hardening exponent n is then evaluated using the logarithmic relationship:

$$n = \frac{\text{Ln} \left(\frac{\epsilon_{us}}{0,2} \right)}{\text{Ln} \left(\frac{F_{tu}}{F_{ty}} \right)} = \frac{\text{Ln} \left(\frac{39,73}{0,2} \right)}{\text{Ln} \left(\frac{515}{205} \right)} \approx 5.734 \quad (1.3)$$

The resulting Ramberg–Osgood parameters provide a realistic representation of the strong work-hardening behavior of SUS304, which is critical for accurately predicting thickness reduction, accumulated plastic strain, and forming force evolution during the MSPIF process [7], [11].

- Plastic Stress–Strain Data for FEM Implementation

To accurately represent the nonlinear plastic response of SUS304 austenitic stainless steel in the MSPIF simulations, a detailed equivalent stress plastic strain dataset is established and implemented in the finite element model. The plastic strain values are obtained by subtracting the elastic strain component from the total strain, while the corresponding equivalent (von Mises) stress values are calculated based on the calibrated Ramberg–Osgood constitutive relationship described in above

The resulting plastic stress–strain data span a wide deformation range, which is essential for ensuring numerical stability and reliable prediction of strain localization, thickness thinning, and accumulated plastic strain during multi-stage incremental forming. In MSPIF, the material undergoes progressive and highly localized deformation under complex, non-proportional loading paths; therefore, an adequately extended hardening curve is required to avoid artificial hardening saturation or premature convergence issues in the finite element solution.

The discretized equivalent plastic strain–stress dataset adopted in the present simulations is summarized in Table II.



TABLE II. PLASTIC STRESS-STRAIN DATA OF STAINLESS STEEL SUS304 MATERIAL

ϵ	σ (MPa)
0.001992	205.63
0.003024	221.42
0.004461	237.35
0.006418	253.45
0.009031	269.80
0.012459	286.47
0.016884	303.55
0.022514	321.17
0.029582	339.47
0.038343	358.63
0.049075	378.85
0.062074	400.38
0.077649	423.50
0.096115	448.55
0.117787	475.92
0.142968	506.07
0.171939	539.49
0.204949	576.79
0.242204	618.62
0.283857	665.75
0.330000	719.02

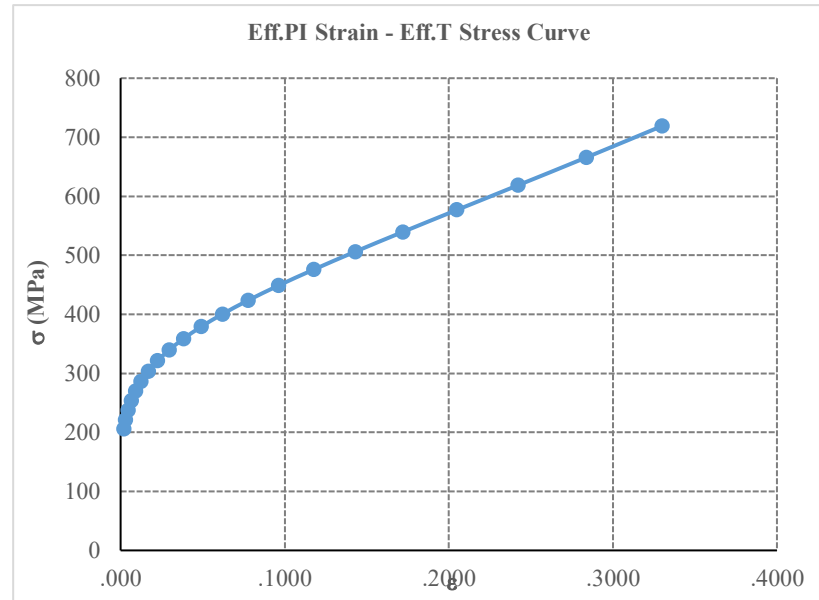


Fig. 2 Stress-strain curve of the plastic region for stainless steel SUS304 material [6]

D. Toolpath Generation and Data Processing for MSPIF Simulation

The toolpath required for the multi-stage single point incremental forming (MSPIF) process is generated using Autodesk Fusion 360, which provides a flexible and reliable CAM environment for defining complex incremental forming trajectories. The overall procedure for constructing the CAM model and generating the MSPIF toolpath is illustrated in Fig. 3.

The initial geometric model of the blank is first created in SolidWorks to ensure an accurate representation of the experimental setup, including sheet dimensions and reference geometry. The CAD model is subsequently imported into the CAM module of Autodesk Fusion 360, where the forming strategy, tool geometry, and process parameters are defined. A helical toolpath is selected, as this strategy ensures continuous and smooth contact between the hemispherical forming tool and the sheet surface, which has been widely reported as an effective approach for incremental forming processes, particularly in MSPIF applications [1], [4], [7].



The forming tool is defined as a hemispherical-ended tool with a diameter of 10 mm (radius 5 mm), consistent with the experimental configuration. The toolpath is programmed to achieve a maximum forming depth of 30 mm through successive incremental passes, corresponding to the multi-stage forming strategy adopted in this study. Upon completion of the toolpath generation, the numerical control (NC) program is exported from Fusion 360 in standard G-code format. An excerpt of the generated NC code is provided to illustrate the structure of the programmed tool motions and coordinate commands.

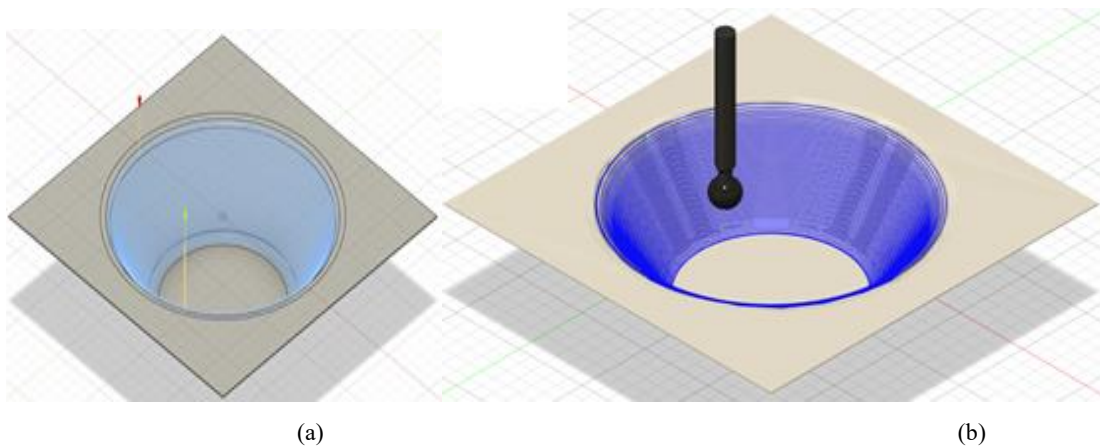


Fig. 3 (a) CAD model of the sheet designed in SolidWorks; (b) CAM model and helical toolpath generated in Autodesk Fusion

E. Toolpath Data Extraction and Time Mapping

To enable direct implementation of the tool motion in the finite element simulation, the generated G-code is post-processed to extract discrete tool coordinates. The NC file is first converted into a point-based trajectory using G-Code Ripper software, which allows the transformation of continuous tool motions into a sequence of spatial coordinates. The extracted tool position data are then imported into Microsoft Excel for further processing and normalization.

Using Excel-based data manipulation procedures, including filtering, string parsing, and unit conversion, the tool displacement coordinates along the X-, Y-, and Z-directions are extracted for each incremental step of the toolpath. These spatial coordinates are subsequently associated with corresponding time increments to construct a time-dependent tool motion profile, which is required for defining prescribed displacements in Abaqus/Explicit simulations.

The total forming time is determined based on the cumulative toolpath length and the prescribed in-plane tool feed rate v_{xy} , and is calculated as:

$$t_{\text{sum}} = \frac{\text{Trajectory length}}{v_{xy}} = \frac{1}{v_{xy}} \sum_{i=0}^N \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2 + (z_{i+1}-z_i)^2} \quad (1.4)$$



where x_i , y_i , z_i denote the tool coordinates at the i -th discretized point along the toolpath, and N is the total number of extracted points.

The processed dataset, consisting of time-dependent tool coordinates, is directly implemented to prescribe the tool motion in the finite element model. This data-driven strategy ensures a high degree of consistency between the experimentally generated toolpath and the numerical simulation, thereby improving the reliability of subsequent comparisons between simulated and experimental results, particularly with respect to forming force evolution, thickness distribution, and formability limits [5], [11].

III. SIMULATION DESIGN BASED ON THE TAGUCHI METHOD

A. Selection of the Orthogonal Array

The objective of the experimental investigation is to quantify the influence of key MSPIF process parameters on the final forming angle α of SUS304 stainless steel sheets. To achieve this objective with a limited number of experimental trials while maintaining statistical reliability, the Taguchi method is adopted. This approach enables efficient exploration of the process parameter space by significantly reducing the number of required experiments without compromising the quality of the analysis.

In this study, four dominant MSPIF process parameters are selected as control factors:

- $\Delta\alpha$: forming angle increment between successive stages,
- Δz : vertical tool step-down,
- D : forming tool diameter, and
- V_{xy} : in-plane tool feed rate.

Each control factor is investigated at three discrete levels, selected based on technological feasibility, preliminary simulations, and consistency with the experimental setup. A full factorial design would require a prohibitively large number of simulation runs, leading to increased computational cost and time consumption.

Therefore, a Taguchi L9 orthogonal array is adopted to efficiently evaluate the relative influence of the selected process parameters on the final forming angle α . This approach enables systematic parameter assessment while ensuring balanced representation of factor levels and practical computational efficiency.

B. Selection of Parameter Levels

The numerical simulations are conducted on SUS304 austenitic stainless steel sheets under multi-stage single point incremental forming (MSPIF) conditions. The levels of the selected process parameters are determined based on preliminary numerical trials, machine capability



constraints, and considerations related to deformation stability and formability. The selected ranges are chosen to avoid unstable forming conditions while remaining representative of practical MSPIF applications.

Four dominant process parameters are selected as control factors, namely the forming angle increment between successive stages ($\Delta\alpha$), the vertical tool step-down (Δz), the forming tool diameter (D), and the in-plane tool feed rate (V_{xy}). Each parameter is investigated at three discrete levels. The selected parameter levels are summarized in Table III.

TABLE III. MSPIF PROCESS PARAMETERS AND INVESTIGATED LEVELS

Parameter	Symbol	Level 1	Level 2	Level 3
Forming angle	$\Delta\alpha$ ($^\circ$)	67	69	72
Downward step of pestle	Δz (mm)	0.5	0.7	0.9
Diameter of pestle	D (mm)	8	10	12
Velocity of pestle	V_{xy} (mm/min)	400	500	600

These parameter ranges enable systematic evaluation of the influence of geometric and kinematic variables on deformation behavior and achievable forming angle, while ensuring numerical stability throughout the MSPIF simulations.

C. Taguchi L9 Simulation Matrix

Based on the selected control factors and their corresponding levels, a Taguchi L9 orthogonal array is adopted to construct the simulation matrix for the MSPIF process. This approach allows efficient exploration of the parameter space while maintaining a manageable number of simulation runs. A total of nine MSPIF simulations are performed on SUS304 sheets, each corresponding to a unique combination of the selected control factors, as listed in Table IV.

In each simulation, the sheet is progressively formed through nine successive stages with increasing wall angles to reproduce the deformation mechanisms inherent to MSPIF. The staged forming strategy enables gradual accumulation of plastic deformation and reduces premature strain localization. The forming process is terminated when either the target geometry is successfully achieved or numerical indicators of fracture initiation or excessive thinning are observed.

To ensure controlled deformation progression, the forming angles at successive stages are defined symmetrically with respect to a reference forming angle α_0 . The maximum achievable



forming angle is identified as the highest forming stage completed without fracture or unacceptable thickness reduction and is taken as the primary response variable for evaluating formability.

TABLE IV. TAGUCHI L9 SIMULATION MATRIX FOR MSPIF OF SUS304 STAINLESS STEEL

No.	$\Delta\alpha$	Δz	D	Vxy	Forming angle between each stage of MSPIF (Perform 9 stages)								
	($^{\circ}$)	(mm)	(mm)	(mm/min)	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9
1	67	0.9	8	600	47	52	57	62	67	72	77	82	87
2	67	0.7	10	400	47	52	57	62	67	72	77	82	87
3	67	0.5	12	500	47	52	57	62	67	72	77	82	87
4	69	0.7	8	500	49	54	59	64	69	74	79	84	89
5	69	0.5	10	600	49	54	59	64	69	74	79	84	89
6	69	0.9	12	400	49	54	59	64	69	74	79	84	89
7	72	0.5	8	400	60	63	66	69	72	75	78	81	84
8	72	0.9	10	500	60	63	66	69	72	75	78	81	84
9	72	0.7	12	600	60	63	66	69	72	75	78	81	84

α_1 – α_4 denote the early-stage forming angles, α_5 represents the intermediate forming angle, α_6 – α_8 correspond to the late-stage forming angles, and α_9 is the final forming angle.

The simulation results obtained from this design matrix provide the basis for subsequent Taguchi signal-to-noise (S/N) ratio analysis and statistical evaluation of parameter significance. These analyses enable quantitative assessment of the relative influence of MSPIF process parameters on the formability of SUS304 sheets and support the identification of optimal forming conditions.



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IV. RESULTS AND DISCUSSION: INTEGRATED NUMERICAL AND EXPERIMENTAL VALIDATION

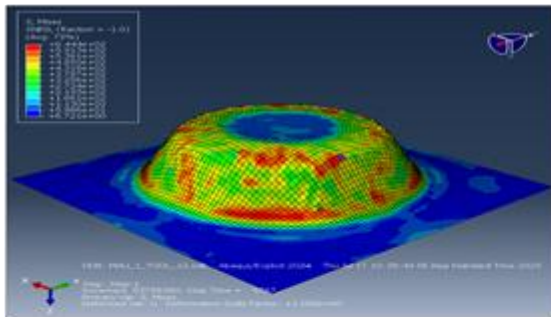


Fig. 4 Model 1. Crack initiation at stage 6 ($\alpha_6 = 72^\circ$): (a) finite element prediction; (b) experimental observation.

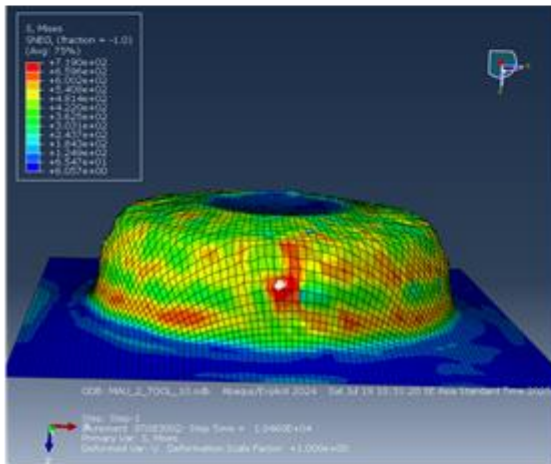


Fig. 5 Model 2. Crack initiation at stage 8 ($\alpha_8 = 82^\circ$): (c) finite element prediction; (d) experimental observation.

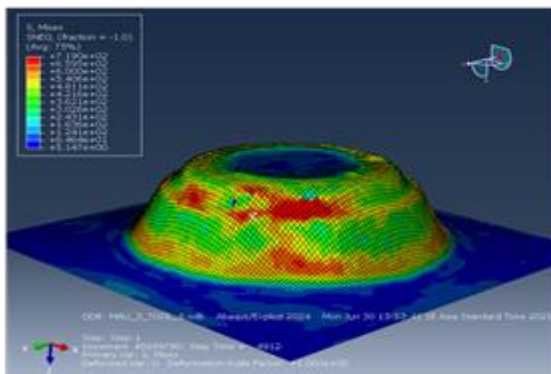


Fig. 6 Model 3. Crack initiation at stage 6 ($\alpha_6 = 72^\circ$): (e) finite element prediction; (f) experimental observation.

A. Integrated Numerical and Experimental Validation of MSPIF on SUS304 Stainless Steel Sheets Using Abaqus and a Three-Axis CNC Machine



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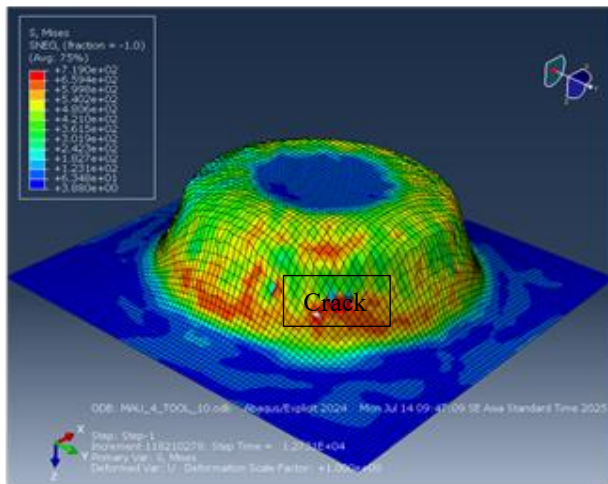


Fig. 7 Model 4. Crack initiation at stage 6 ($\alpha_6 = 74^\circ$): (g) finite element prediction; (h) experimental observation.

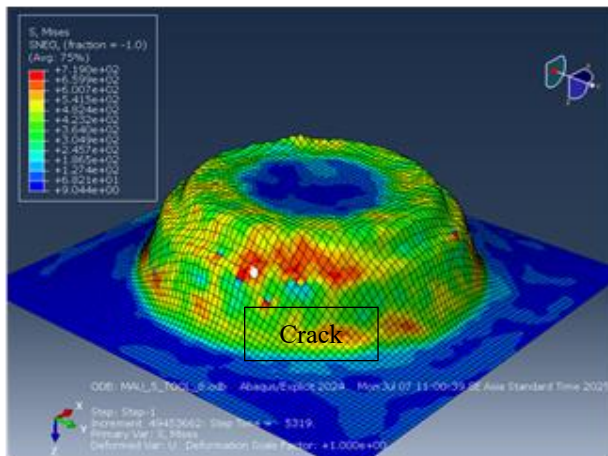
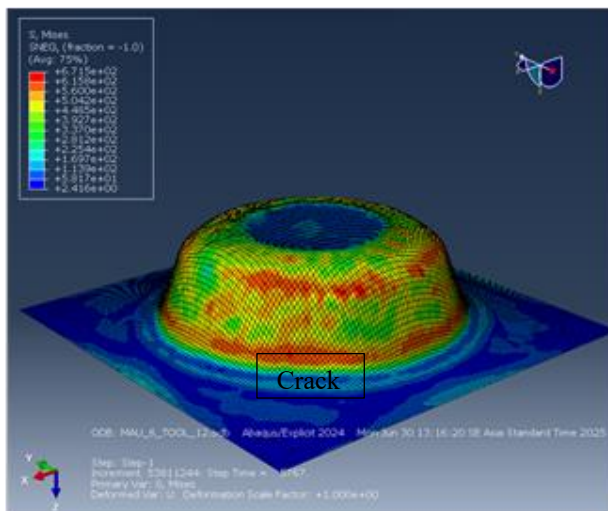


Fig. 8 Model 5. Crack initiation at stage 7 ($\alpha_7 = 79^\circ$): (i) finite element prediction; (j) experimental observation.





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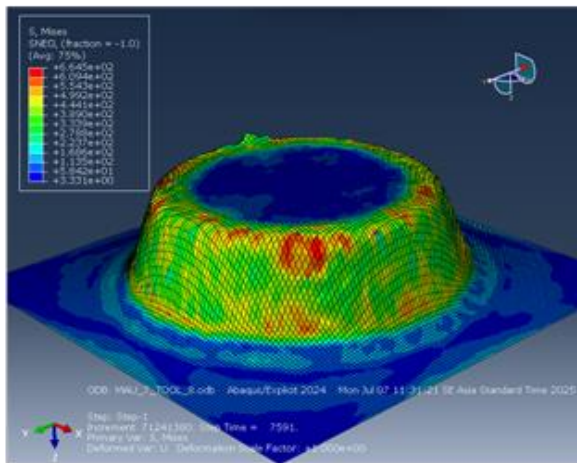


Fig. 10 Model 7. Crack initiation at stage 6 ($\alpha_6 = 74^\circ$): (m) finite element prediction; (n) experimental observation.

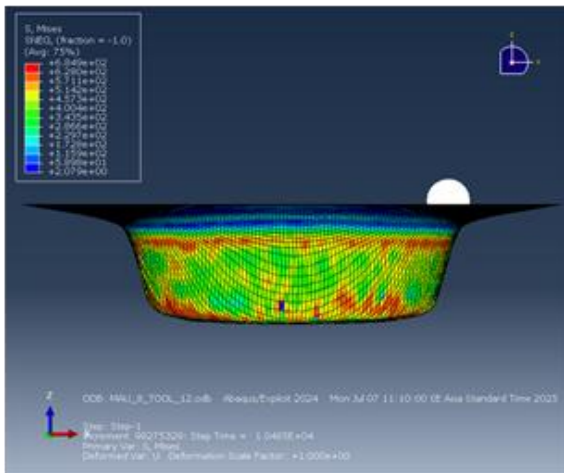
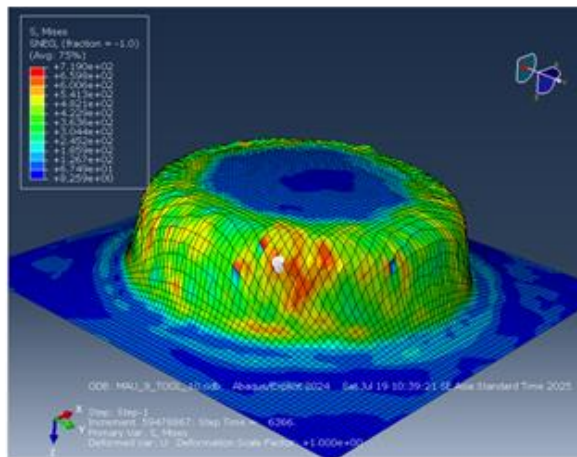


Fig. 11 Model 8. Specimen achieving a forming angle of 84° under the optimal parameter combination: (o) finite element prediction; (p) experimental observation. The sheet was successfully formed to $\alpha_8 = 84^\circ$ without fracture, confirming the consistency between numerical simulation and experimental results.





B. Comparative Analysis of Formability and Failure Stages

The integrated numerical and experimental results obtained from the nine MSPIF models provide a comprehensive assessment of the formability limits of SUS304 stainless steel sheets under different process parameter combinations. The maximum achievable forming angle and the corresponding fracture stage for each model are summarized based on Figs. 4–12.

For Models 1, 3, and 7, fracture initiation was observed at Stage 6, corresponding to forming angles of 72° , 72° , and 74° , respectively. In both the finite element simulations and experiments, crack initiation consistently occurred in the region of maximum thinning near the tool–sheet contact zone. The numerical model successfully predicted the crack-prone zones through localized plastic strain concentration and excessive thickness reduction.

Models 5, 6, and 9 exhibited fracture at Stage 7, with forming angles ranging from 78° to 79° . Compared with the early-failure models, these parameter combinations enabled more stable strain accumulation during the intermediate stages. However, once the wall angle exceeded approximately 78° , a rapid increase in plastic strain localization was observed, leading to crack initiation. The agreement between simulation and experiment in identifying both fracture stage and crack location confirms the predictive capability of the developed FE model.

Model 2 demonstrated improved formability, reaching Stage 8 ($\alpha_8 = 82^\circ$) before fracture. The delayed failure suggests that the selected combination of forming angle increment, tool diameter, and step-down contributed to a more favorable stress distribution and reduced strain concentration.

Among all investigated cases, Model 8 exhibited the highest formability. The sheet was successfully formed to Stage 9 with a final wall angle of $\alpha_9 = 84^\circ$ without fracture, as shown in Fig. 11. Both simulation and experimental observations confirmed stable deformation throughout the entire multi-stage process. The thickness distribution remained more uniform, and no abrupt localization of plastic strain was detected. This result clearly demonstrates the effectiveness of the optimal parameter combination in enhancing formability through gradual strain accumulation.

Overall, the comparative analysis reveals several important trends:

- Fracture consistently occurs after a critical wall angle between approximately 72° and 82° for most parameter combinations.
- Larger tool diameters and moderate forming angle increments contribute to improved deformation stability.
- The multi-stage strategy effectively delays fracture by distributing plastic strain over successive stages.



- The full three-dimensional FE model accurately captures the stage at which failure initiates and the corresponding crack location.

The close correlation between numerical predictions and experimental observations validates the robustness of the proposed simulation framework. Furthermore, the results confirm that MSPIF significantly enhances the achievable wall angle of SUS304 sheets compared with conventional single-stage SPIF, with a maximum successfully attained angle of 84° under optimized conditions.

C. Taguchi Signal-to-Noise Analysis and Parameter Significance

To quantitatively evaluate the influence of MSPIF process parameters on the formability of SUS304 sheets, the maximum achievable forming angle α_{\max} obtained from each model was treated as the primary response variable in the Taguchi analysis. Since the objective is to maximize the forming angle without fracture, the “larger-the-better” signal-to-noise (S/N) ratio criterion was adopted.

The S/N ratio for each experimental run was calculated according to the standard Taguchi formulation:

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{\alpha_i^2} \right) \quad (1.5)$$

where α_i represents the measured forming angle for each run and n is the number of observations. In the present study, the response corresponds to the maximum successfully achieved wall angle prior to fracture.

The Taguchi design was implemented using an L9 orthogonal array with four control factors and nine experimental runs. The calculated response table for the S/N ratios under the “larger-the-better” criterion is summarized in Table V.

TABLE V. RESPONSE TABLE FOR SIGNAL-TO-NOISE RATIOS (LARGER IS BETTER) [14]

Level	X1	X2	X3	X4
1	36.92	37.02	36.82	37.42
2	37.18	37.34	37.87	37.26
3	37.71	37.46	37.14	37.14
Delta	0.79	0.45	1.05	0.28
Rank	2	3	1	4



In Table V, X1, X2, X3, and X4 correspond to the forming angle increment ($\Delta\alpha$), downward step of pestle (Δz), pestle diameter (D), and velocity of pestle (V_{xy}), respectively.

The Delta value, defined as the difference between the maximum and minimum S/N ratios across the three levels of each factor, reflects the sensitivity of the response variable α_{\max} to variations in that factor. A larger Delta value indicates a stronger influence on formability.

As shown in Table V, the pestle diameter (X3) exhibits the highest Delta value (1.05), ranking first in influence. This result indicates that contact geometry and stress distribution beneath the forming tool play a dominant role in controlling strain localization and thickness thinning during MSPIF.

The forming angle increment (X1) ranks second (Delta = 0.79), indicating that staged angular progression significantly affects deformation stability. The downward step of pestle (X2) shows moderate influence (Delta = 0.45), whereas the velocity of pestle (X4) presents the smallest Delta value (0.28), suggesting a comparatively minor effect on formability within the investigated range.

Overall, the ranking of parameter influence is:

$$D > \Delta\alpha > \Delta z > V_{xy}$$

This statistical outcome is fully consistent with the numerical and experimental observations presented in Section IV.B, further confirming that geometric parameters dominate the formability behavior of SUS304 sheets under MSPIF conditions.

To quantitatively assess the influence of each process parameter on the formability of SUS304 sheets, an analysis of variance (ANOVA) was performed on the signal-to-noise (S/N) ratios using Minitab software [15]. This statistical procedure enables evaluation of the relative contribution of each factor to the variation in the maximum achievable forming angle in a systematic and rigorous manner.

Based on the Minitab output, the coefficient of determination of the developed statistical model is $R^2 = 100\%$, exceeding the commonly accepted adequacy threshold ($R^2 > 90\%$). This indicates that, within the investigated parameter space defined by the Taguchi L9 orthogonal array, the selected process parameters fully explain the observed variation in the response variable. The zero residual error arises from the saturated nature of the orthogonal design (total degrees of freedom fully allocated to factors), rather than implying universal predictive capability outside the studied experimental domain.



The detailed ANOVA results are summarized in Table VI.

TABLE VI. ANOVA RESULTS FOR S/N RATIOS

Source	DF	Sew SS	Ad SS	Ad MS
X1	2	0.96557	0.96557	0.482786
X2	2	0.31694	0.31694	0.158470
X3	2	1.74302	1.74302	0.871509
X4	2	0.12204	0.12204	0.061019
Residual Error	0	-	-	-
Total	8	3.14757		

In Table VI, X1, X2, X3, and X4 correspond to the forming angle increment ($\Delta\alpha$), Downward step of pestle (Δz), pestle diameter (D), and Velocity of pestle (V_{xy}), respectively.

The relative contribution of each factor can be estimated from the ratio of its sum of squares to the total sum of squares. Based on the ANOVA results, the percentage contributions are approximately:

- Pestle diameter (X3): 55.4%
- Forming angle increment (X1): 30.7%
- Downward step of pestle (X2): 10.1%
- Velocity of pestle (X4): 3.9%

These results clearly indicate that tool diameter is the dominant parameter governing formability in MSPIF of SUS304 sheets, followed by forming angle increment. The vertical step-down has a moderate influence, whereas the feed rate exhibits minimal contribution within the investigated range.

The ANOVA findings are fully consistent with the S/N ranking analysis presented previously, reinforcing the conclusion that geometric parameters primarily control deformation stability and strain localization behavior in multi-stage incremental forming.

V. CONCLUSIONS

This study presented an integrated numerical–experimental investigation of the formability of SUS304 stainless steel sheets under Multi-Stage Single Point Incremental Forming (MSPIF)



conditions. A full three-dimensional finite element model developed in Abaqus/Explicit was validated through controlled experiments conducted on a three-axis CNC machine. Based on the obtained results, the following conclusions can be drawn:

- The developed FE model accurately predicts deformation behavior, fracture initiation stage, and thickness distribution in MSPIF. Good agreement between numerical and experimental results confirms the reliability of the adopted constitutive model and contact formulation.
- MSPIF significantly enhances the achievable wall angle compared with conventional single-stage incremental forming by promoting gradual strain accumulation and reducing strain localization. A maximum forming angle of 84° was successfully achieved without fracture under the optimal parameter combination.
- Fracture initiation consistently correlates with localized plastic strain concentration and severe thickness thinning near the tool sheet contact region. A rapid increase in forming force is observed prior to crack initiation, indicating that force evolution can serve as a practical indicator of forming limits.
- Taguchi signal-to-noise analysis and ANOVA reveal that geometric parameters dominate formability. Pestle diameter is identified as the most influential factor ($\approx 55\%$ contribution), followed by forming angle increment ($\approx 31\%$). Vertical step-down exhibits moderate influence ($\approx 10\%$), while feed rate shows minimal contribution within the investigated range.
- The statistical model derived from the L9 orthogonal design exhibits $R^2 = 100\%$ due to the saturated experimental structure, indicating complete explanation of response variation within the studied parameter domain.

Overall, the integration of finite element modeling with Taguchi-based statistical optimization provides an efficient and reliable framework for predicting and enhancing formability in MSPIF of stainless steel sheets. The findings offer practical guidelines for parameter selection in die-less incremental forming applications involving hard-to-form materials.

Future work will focus on incorporating advanced anisotropic hardening and damage-based fracture criteria to further improve predictive capability under complex non-proportional loading paths.

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