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Investigation of Formability and Surface Roughness Behavior of Inconel 625 by Single Point Incremental Forming Process

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***Abstract*— Inconel 625's formability and surface roughness are examined using Single Point Incremental Forming (SPIF). Due to its weak ductility and work hardening, Inconel 625 is difficult to form despite its excellent strength, corrosion resistance, and thermal stability. This study examines how tool diameter, step-down size, feed rate, and spindle speed affect material formability and surface polish. To determine the effects of these factors, Design of studies (DOE) studies were performed. Formability was determined by maximum wall angle, and surface roughness by profilometry. Tool diameter and step-down size considerably affect formability and surface roughness, with larger tool diameters improving formability but increasing surface roughness. An ideal process parameter combination balanced good formability and acceptable surface quality. The results provide insights into Inconel 625's SPIF process, guiding aerospace and high-performance production.**

Keywords*— Inconel 625, Single Point Incremental Forming (SPIF), Formability, Surface Roughness, Process Parameters, Tool Diameter, Step-down Size, Feed Rate

I. Introduction

Single point incremental forming

It is an acronym for the single point incremental forming process, which, as the name implies, is a procedure in which the deformation takes place gradually in a single point contact. This process is comparable to the layered engineering process. A derived version of the ISF process is what this is. As can be seen in Fig. 1., the fundamental elements of the process are the sheet, the work-holding fixture, the computer numeric control machine, and the tool that is fashioned like a cylindrical rod. Due to the fact that the process used standardized tooling and holding systems for the operations, this method is appropriate for quick prototyping of complicated forms and low batch production systems. One of the benefits of the procedure is that it allows for greater formability of sheet pieces before they fracture further. There is a significant difference between the magnitude of stresses and those of traditional methods or dome testing [5]. **History**

Deep drawing and stamping process has traditionally influenced sheet metal industries for mass production runs. Bulk amount of parts can be produce quickly with high venture capital [1]. In genesis of any mass production, a prototypes need to be prepared.

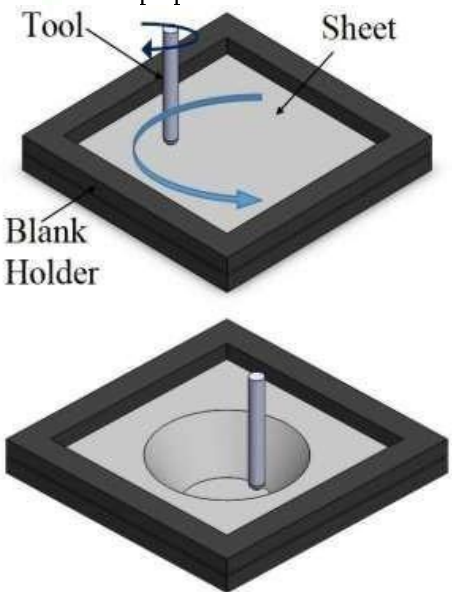

Fig.1: , Elements Process Are the Sheet

A solicit flexible process must exits, which can accomplish with minimum investment [2]. Incremental sheet forming process (ISF) is defined as the flexible manufacturing process where the sheet is deforming locally between tool-sheet interfaces without the aid of die. Incremental sheet forming is classified on the basis of several terms as shown in Fig 2.

Fig 2: Classification of ISF process

In the year 1967, two patents is issued regarding ISF process which are permutation of spinning process. One issued to Berghahn of General Electric and another to Leszak. In the Leszak manufacturing method, the final shape of product is prepared by local bending of rotating clamped sheet through linear displacement by roller tool, while in Berghahn method sheet is deformed through motions in all three directions by the roller tool [3]. Kitzawa and his colleagues pioneered this process into industries and brings revolution in the sheet metal industries [4].

II. LITERATURE REVIEW

S **Kim et al. (2002)** [1] Sheet metal appears to be more formable in incremental forming than in conventional forming. Experiments and FEM studies were used to explore the influence of process factors on formability, including tool shapes, tool size, feed rate, friction at the tool-sheet interface, and sheet plane anisotropy. It was discovered that using a roller tool of a specific size with a slow feed rate and little friction improves formability. The formability varies depending on the tool movement direction due to planar anisotropy.

Martins et al. (2008) [2] This study gives a closed-form theoretical analysis of the principles of single point incremental forming, as well as an explanation of the experimental and simulation results that have been published in the literature in recent years. The concept is based on membrane analysis with bi- directional in-plane contact friction and is targeted at severe modes of deformation encountered in single point incremental forming processes. The scholars' experimental work and data from the literature are used to support the overall analysis.

Hussain et al. (2010) [3] Author proposed new methods to precisely asses the forming limit curves. To meet the conditions of forming limit curve which states that, the curve is drawn by joining different straining conditions; a varying wall angle spiral contour was adopted. They reported, the limiting strain magnitude is higher compared to conventional groove test; along with that the shape of curve appears to be quadratic.

Hamilton et al. (2010) [4]

Orange peel, thickness distribution and microstructure were investigated by incorporating high feed motion and high spindle speed rotation as a process parameters. Full factorial design of experiments is used to investigate the process parameters. They concluded orange peel are highly effected by shape factor and step size; while there is no change in microstructure and thickness distribution of sheet compared to regular single point incremental forming process.

Malhotra et al. (2011) [5] To anticipate fracture in Single Point Incremental Forming, this research combines finite element analysis and a damage-based material model in incremental sheet forming. The fracture envelope is a result of both the hydrostatic pressure and the deviatoric stress state and is represented in the stress space. The tool forces and fracture depths obtained from models and tests are found to be quite similar. An in-depth examination of the deformation reveals that through-the-thickness shear has a substantially greater impact on formability than hydrostatic pressure. The ramifications of this impact on boosting formability in single point incremental forming are also discussed.

Bhattacharya et al. (2011) [6] The ability of incremental sheet metal forming (ISF) to manufacture sophisticated three- dimensional components without a need for component-specific tooling has been proven. The die-less characteristic of incremental forming makes it a cost-effective and efficient way to fabricate low-volume functional sheet components. ISF, on the other hand, has restrictions in terms of maximum formable wall angle, geometrical precision, and component surface quality. The influence of incremental sheet metal forming process factors on maximum formable angle and surface quality is investigated in this paper through an experimental research. For the formability investigation, the Box–Behnken technique is utilised, and for the surface finish study, the complete factorial approach is used. The formability of incremental forming reduces as the tool diameter increases, according to the findings of the experiments; and for good surface quality small tool size and higher wall angles shall be adopted.

III. Research Gaps

T From the above mentioned literature review of single point incremental forming process, it was observed that single point incremental forming has advantages such as generic tooling, low force requirement, and high formability of materials compare to other sheet metal forming processes. Inconel 625 is high strength nickel based alloy. It requires large deformation force at room temperature. According to the literature:

I. Some researchers applied plane compression process, stretch forming, laser solid forming, warm deep drawing, and shear spinning process on Inconel 625 to study the effects of process parameters on the output characteristics; but the effect of single point incremental forming process parameters for the thin sheets of Inconel 625 on the output characteristics such as surface roughness and formability is yet to be reported.
II. Further post processing such as optimization of process parameter and formability reduction percentage between two different sheet thicknesses of same material processed by same process parameters is yet to be reported.

IV. Proposed Methodology

Proposed Methodology

In the early 2000s, several alloys with varying chemical proportions have been developed to solve the engineering problems in order to meet the demand of prominent engineering sectors such as petrochemical industries, automobile industries and aeronautical industries. A great attention is given to nickel based alloys due to its good mechanical properties at harsh environments it is generally categorized under the class of superalloys [7].

Inconel 625 (UNSN06625/W.Nr. 2.4856) is a nickel-chromium-iron based alloy, strengthened by solid solution at their intermetallic phase. It is different from Haste alloy in terms of composition; as in Inconel main constituent is nickel-chromium, while in Hastle alloy its main constituent is nickel-molybdenum. For the present study Inconel 625 sheets of dimension 130 mm x 130 mm x 0.5 mm as shown in Fig 3.

Fig .3: Test specimen

Inconel 625 constituents shown in Table 1. This superalloy also contains carbides like M6C (M is plentiful in niobium and molybdenum), MC (M is plentiful in niobium and molybdenum), and M23C6 (M is plentiful in chromium). The role of constituents in this alloys are as follows. Niobium acts as a strengthener in the Ni-Cr matrix, both chromium and molybdenum act as a hindrance to corrosion; and iron minimizes the cost of the alloy.

Table 1 Inconel 625 composition

Ni	Cr	Mo	Fe	Nb	Co	Mn	Al
58-71%	21-23%	8-10%	5%	3.2-3.8%	1%	0.5%	0.4%

The above defined properties of this superalloy makes it preferable for critical structural engineering applications such as nuclear industries, aerospace industries, marine industries and petrochemical industries [10-11].

Tool path

Single point incremental forming process can be implement on dedicated SPIF machine, or on any numeric control machine. This machine requires coordinates for motion of main spindle or work table. The classification for tool path is shown in Fig 5.

The tool path is considered one of the important factor at pre-experimental stage, because it regulates working time; and also it has governing effects on output parameters such as formability, axial force, and surface quality [3]. The preparation of tool path for the geometry are created using CAD/CAM systems, or any programming languages such as MATLAB, C/C++, Java, Python etc. For the present study, tool paths logic for Profile strategy/Z-level strategy and Helical strategy are created by means of programming language; because these provides flexibility to analyze/visualize data, and easy adaptability in design change.

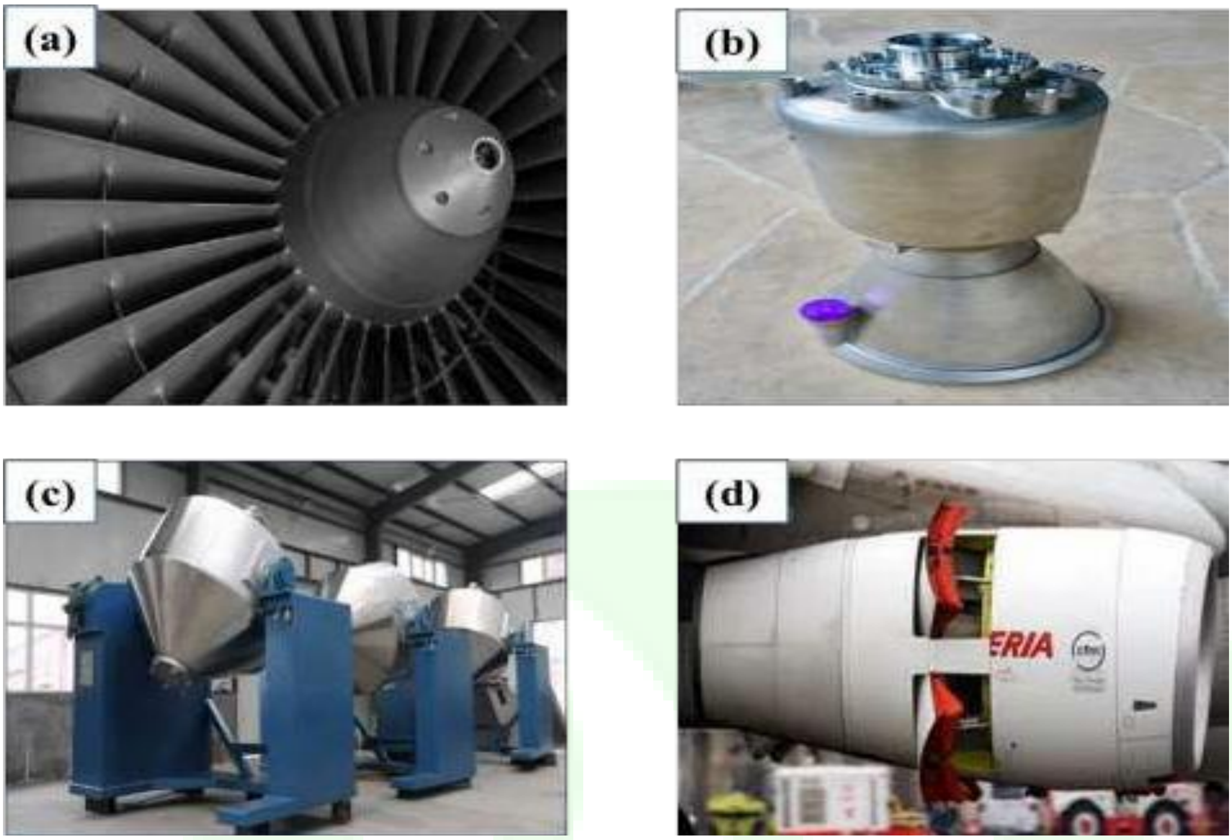

Fig. 4: (a) Jet engine blade [15] (b) Astral engine [17] (c) Chemical mixture equipment [18] (d) Thrust reversal [19]

Java language is used for extracting coordinates of truncated cone geometry, because this language allows user to create modular programs, and code is independent to any compiler specific. Java code compiled in the form of Java byte code and according to the Java virtual machine (JVM) this code is converted to the system specific compiler. The dimension of tool path for obtaining 60° wall angle is as follows Rmajor = 30 mm, Rminor = 15.56 mm, H = 25 mm.

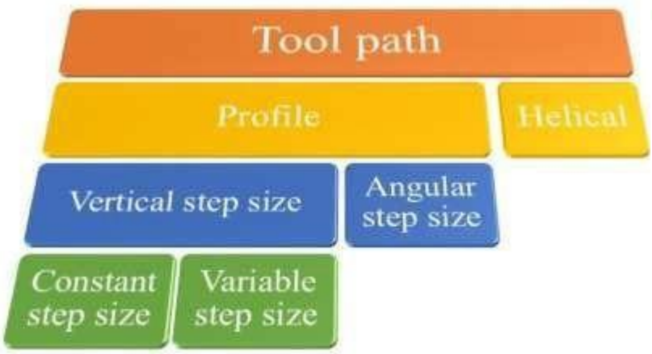

Fig. 5: Tool path characterization

For the present study, tool paths logic for Profile strategy/Z-level strategy and Helical strategy are created by means of programming language; because these provides flexibility to analyze/visualize data, and easy adaptability in design change. Java language is used for extracting coordinates of truncated cone geometry, because this language allows user to create modular programs, and code is independent to any compiler specific. Java code compiled in the form of Java byte code and according to the Java virtual machine (JVM) this code is converted to the system specific compiler. The dimension of tool path for obtaining 60° wall angle is as follows Rmajor = 30 mm, Rminor = 15.56 mm, H = 25 mm.\

Truncated cone from profile strategy

In Z-level strategy path shown in Fig 6 is a discontinuous-type tool path, geometry are divided into series of contour/slicing in the direction parallel to tool longitudinal direction or in axial tool movement direction. In this strategy, tool rams down into axial direction which is equal to the step size provided by the experimenter and then tool travels to the circumferential direction of contour geometry; and after the completion of the contour, the tool rams down again and the course of action replicate [2].

Algorithm

```
For loop (i = 0; i ≤ --n; i++)
{
For (α = 0; α ≤ 360; α++)
{
```


R= Rmajor – {(1/n+1) x (Rmajor - Rminor)} X coordinates = R x cos (α)
Y coordinates = R x sin (α)
}}

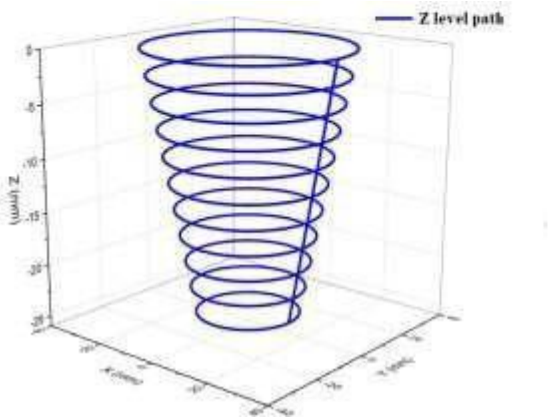

Fig.6: Truncated cone from profile strategy

Several researchers have done relative studies on tool path. They observed that profile tool path produces instability in forces, stretch marks and high magnitude of peak force.

Truncated cone from helical strategy
Helical tool path strategy shown in Fig 7 is a continuous-type tool path. This toolpath is unidirectional in nature; unlikely in Z-level, in helical strategy the tool moves simultaneous in all three principal direction of the contour geometry. The axial motion of the tool is adjusted equal to the step size, for every complete rotation from its initial point; and this course of action repeats itself until the final geometry is incrementally formed. In the previous literatures, the tool path compensation is done with the aid of CAM software's. In the present tool path strategy, tool compensation is accompanied within the code.

Algorithm
For loop (α = 0; α ≤ αtotal; α++)
{
R= Rmajor – {(1/ αtotal+α) x(α)* (Rmajor - Rminor)} - Rcompensation X coordinates = R x cos (α)
Y coordinates = R x sin (α)
}

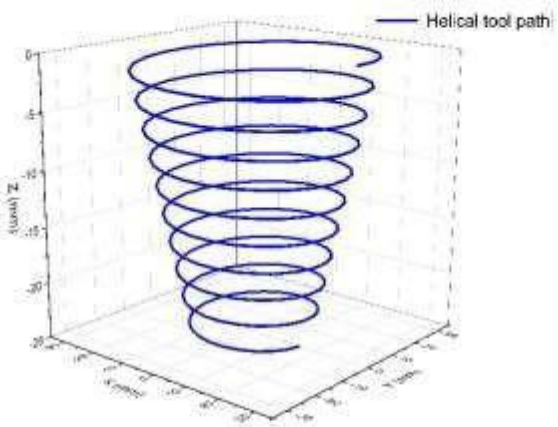

Fig. 7: Truncated cone from helical strategy

Several researchers adapted helical tool path strategy for their study over others; due to obtaining high formability, no tool impression marks, uniform thickness distribution, force stabilization, and lower peak forces.

Truncated pyramid from helical strategy
Fig 8 shows a truncated cone geometry using a helical method. This path follows the same method as the truncated cone geometry, with the only change being the strain path. In a truncated cone, there is only plane strain, but in a pyramid, there is both plane strain (near the wall) and biaxial strain (at the corner). The logic for this tool path is that, the axial movement of tool is subdivided into smaller vertical movement depending on the number of corner present in complete toolpath. In every fourth corner of the contour the tool will undergo axial motion equal to the step size.

Algorithm
For loop (i=0;i<=--n;i++)
{
length=(lma/2-((i*lma/n)*(lma-lmi)/2));
for(count=1;count<=5;count++)
{
if (count==1)

{ X coordinates = length; Y coordinates = length;} else if (count==2)
{ X coordinates = -length; Y coordinates = length;} else if (count==3)
{ X coordinates = -length; Y coordinates = -length;} else
{ X coordinates = length; Y coordinates = -length;} Z coordinates = -i*dh;
}}

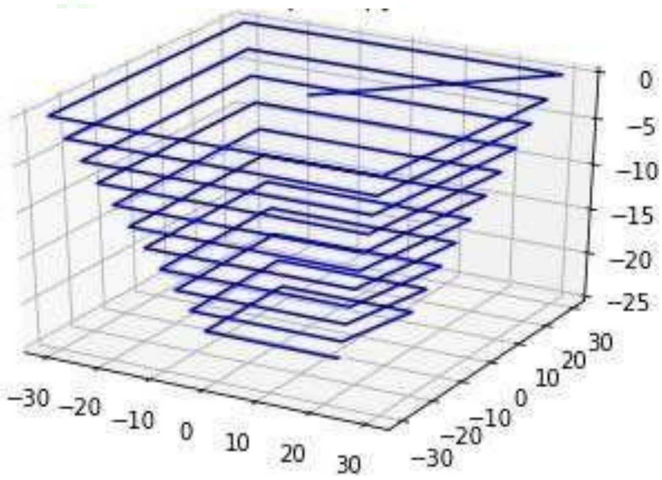

Fig. 8: Truncated pyramid from helical strategy

Design of Experiments
Design of Experiments (DOE) is a statistical method of performing experimentations efficiently and analyzing the results. The design variables and objective function of experiment are equivalent to attribute values and factors in design of experiments. DOE method utilize deterministic model for evaluation of results, the advantage of numerical

method is that it does not have errors and function of response can be approximated accurately. Shown in Fig. 9.

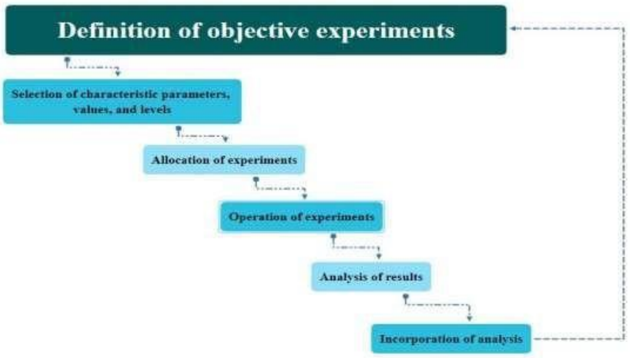

Fig. 9: Design of Experiments layout

Quality loss function

It is a kind of measurement tool to measure the financial loss to the society resulting from poor quality of product or deviation of response from the target value/ mean value. It is defined as

$$L_y = k(y-m)^2,$$

where

$L_y = quality\ loss\ function,$

$k = Constant,$

$y = Actual\ Value,$

$and\ m = taget$ value or mean value

It considers the quality loss occurred inside the deigned limit of Tolerance, irrespective of the loss occurred to user or manufacturer. For these reasons the above equation is represented in the form of continuous and symmetrical as shown in Fig 10. Based on the system requirement, the quality loss function for response variable is defined for three cases namely Smaller is better, nominal is better; and larger is better.

Fig. 10 Quality loss function diagram

Steps of TM

I. Define the problem
II. Identify control variables, noise variable.
III. Define the required level of each variable
IV. Determine the interested response
V. Select the suitable structure of orthogonal arrays
VI. Perform the experiments
VII. Undertake the analysis; and
VIII. Interpret the results.

For the experimentation, the parameters step size, spindle speed, and feed rate is selected to investigate their effects on the surface roughness & fracture depth. Three levels of each parameter are considered as shown in Table 2.

Table 2:Process Parameters

Parameters	Low (-1)	Medium (0)	High (1)
Step size (mm)	0.2	0.3	0.4
Feed rate (mm/min)	250	400	550
Spindle speed (rpm)	0	200	400

Taguchi L9 design is suitable for three tiers and three parameters, according to the orthogonal array selector. For the three parameter design study, the main effects were plotted without considering the interactions between them

Single point incremental forming setup

SPIF process is carried out on dedicated incremental forming machine as shown in Fig 11. It is a flexible manufacturing setup situated in dieless manufacturing center.

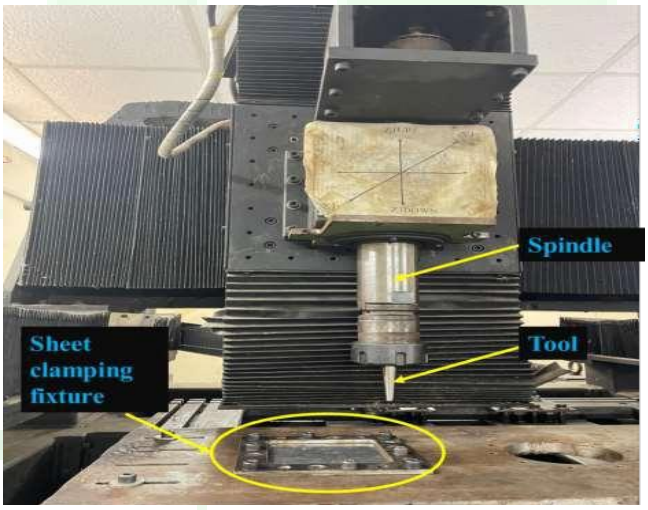

Fig.11 Seven Axis Dieless Forming Setup

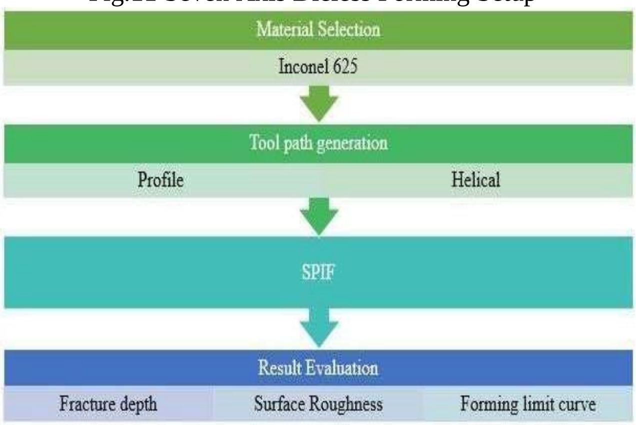

Fig.12: Flow diagram of Experiment

V. Results

All the experimental trials were performed on Inconel 625 sheet with a thickness of 0.5 mm and a tool diameter of 8 mm. Helical tool path technique is adopted for creating truncated cone shape geometry. Total 9 samples were tested as shown in Fig 13 of different tests conditions based on the design of experiments.

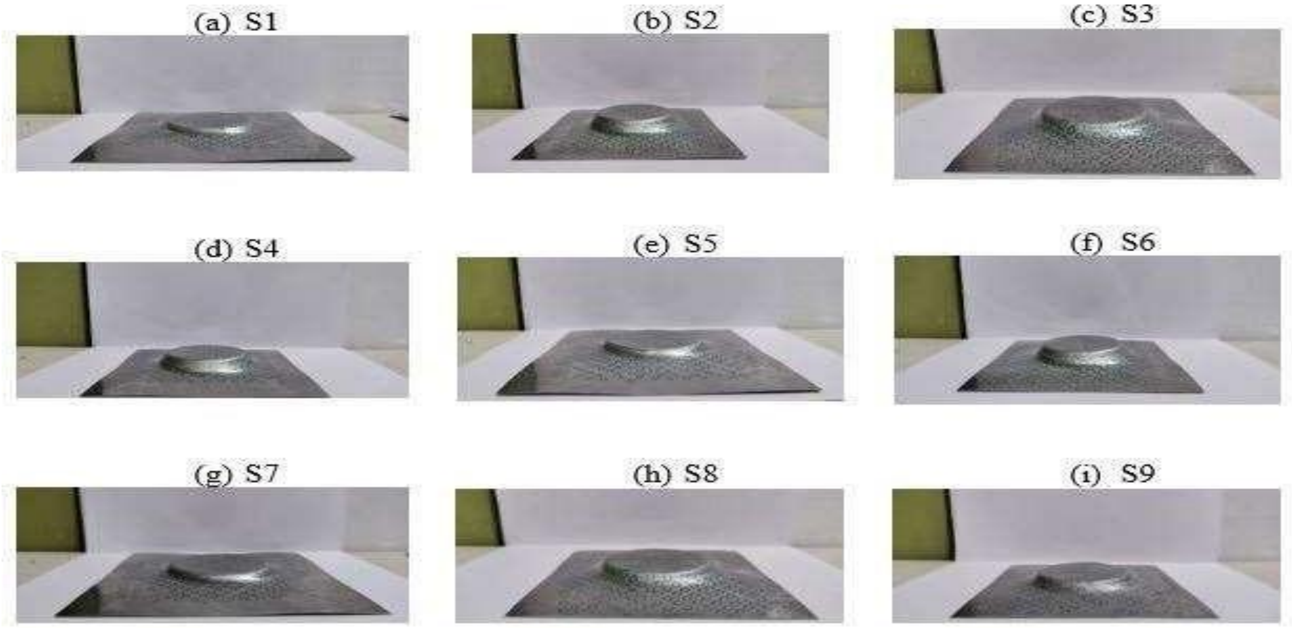

Fig. 13: Taguchi table test specimens

The formability of the sheet metals in single point incremental forming can be expressed in either of maximum achievable wall angle fracture or maximum achievable depth until fracture. For the present study, a constant wall angle tool path strategy approached thus maximum forming depth is the limit of formability. The amplitude of fracture depth was measured using Vernier height gauge as shown in Fig 14.

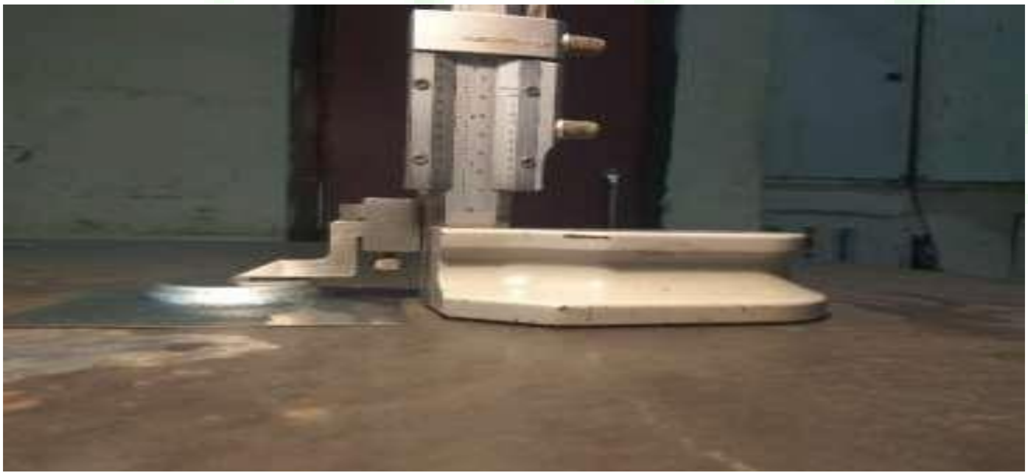

Fig. 14: Fracture depth measurements

The "larger the better" design is opted for formability because it is a desirable factor and need to maximized. The response table for SN ratio for the formability is shown in TABLE 3.

TABLE 3 : Experimental runs for formability

S.	Step size	Feed rate	Spindle speed	Fracture depth
1.	-1	-1	-1	12.16
2.	-1	0	0	12.10

3.	-1	1	1	13.14
4.	0	-1	0	12.56
5.	0	0	1	12.08
6.	0	1	-1	12.74
7.	1	-1	1	12.40
8.	1	0	-1	14.02
9.	1	1	0	12.67

TABLE 4 : Response table for SN ratio (Formability)

Level	Step size	Feed rate	Spindle speed
1	22.91	21.85	22.24
2	21.91	22.07	21.90
3	22.28	22.18	21.96
Delta	0.37	0.33	0.34
Rank	1	3	2

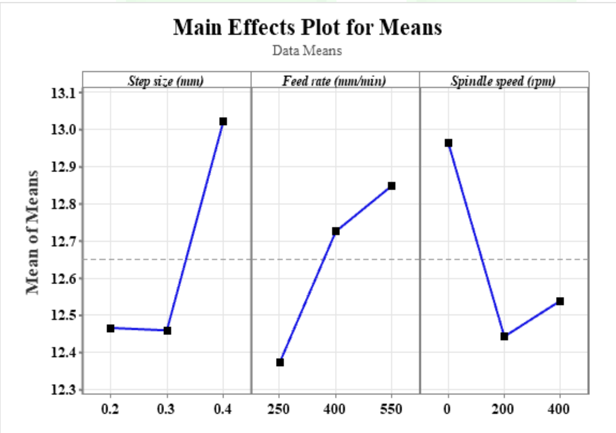

Fig.15: Main Effects Plot For Means (Formability)

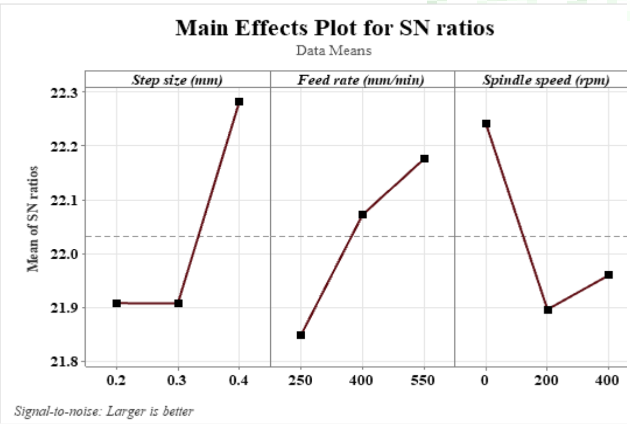

Fig.16: Main effects plots for SN ratio (Formability)

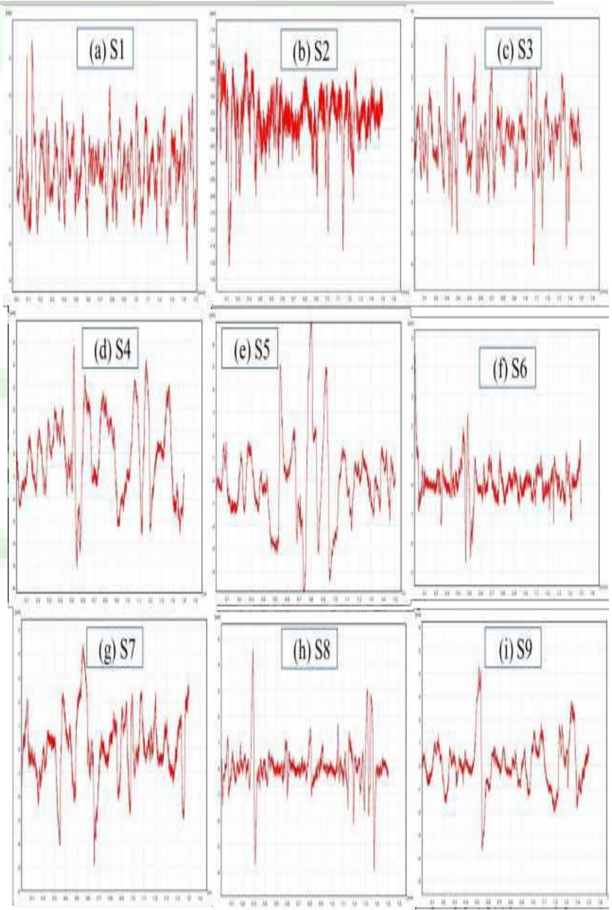

Fig.17: Surface roughness graph

Fig. 18: Forming limit curve for 0.5 mm thick Inconel 625 sheet

VI. CONCLUSION

The Study investigates the impact of process parameters on the formability of Inconel 625 sheets of thickness 0.5 mm. The experiments were conducted using Taguchi L9 design and a spiral tool path strategy for different geometries. The results show that both formability and surface roughness are highly influenced by step size. For step sizes 0.2 mm to 0.3 mm, there is no significant change in formability. However, fracture depth increases with step size due to increased forming temperature. Formability increases with feed value due to less heat dissipation between tool-sheet interfaces. Spindle speed has a negative effect on formability for regions 0 rpm to 200 rpm due to frictional effects. Surface roughness Ra increases with step size due to the staircase effect. The best parameters for maximum formability are 0.4 mm step size, 550 mm/min feed rate, and 0 rpm spindle rotational speed, and for minimum surface roughness, 0.2 mm step size, 400 mm/min feed rate, and 0 rpm spindle speed.

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