FLD Analysis and Optimization of Single Point Incremental Forming on Inconel 625 Sheets

Mohammed Anvar.S[1] Dr. C. Raju[2]
[1,2]Department of Mechanical Engineering
[1,2]Engineering, College of Engineering Trivandrum, India

Abstract— Single Point Incremental Forming (SPIF) of sheet metals is an area where industry can focus due to the extensive opportunities available for automated manufacture of sheet metal parts. Single point incremental forming, sheet metal part is formed in a step by step mode by a CNC guided; rotating, spherical tool without using a supporting die. It is a method to deform the sheet metal into different shapes such as straight groove, cup and cone shaped parts with variable wall angles. It is used for the expansion of small scale batches and reform products at a relatively lower cost. So the process is eminently recommended for fast prototyping implementation, but the slowness of the process is a major disadvantage that prevents industries from applying it on a larger scale. SPIF is an advanced technological process, industrial and manufacturing applications mainly in the aerospace and automobile sectors. The objective of this present work is to analyse the SPIF process of Inconel 625 sheets through Forming Limit Diagram and its optimization using response surface methodology. The Inconel blank sheet is clamped in a fixed blank holder and the form describes the contour of the desired geometry controlled by a regular CNC machine. The Forming Limit Diagram FLD of Inconel 625 sheets are plotted. The sheet when formed at 600 rpm and 0.6 mm vertical step depth shows higher major true strain values. Optimization of process parameters using response surface methodology.

Keywords: SPIF, Inconel 625 Sheets, CNC, FLD, Optimization, Response Surface Methodology

I. INTRODUCTION

Nickel-base alloys are the widely used nowadays in aerospace, nuclear, marine, and automobile sectors due to high corrosion resistance, lightweight, and ability to retain at high temperature, etc [1]. Inconel 625, a nickel-chromium-molybdenum high-performance alloy, is used extensively in extreme environments owing to its high strength, high toughness, good weldability and outstanding resistance to high temperature corrosion and oxidation [2, 3]. Its unique properties arise from the solution strengthening effect of the molybdenum and niobium in the nickel-chromium matrix. Hence precipitation hardening treatments are not required for this alloy, which enables its use for diverse applications over a wide temperature range from -150 °C to 982 °C [2-4]. Inconel alloy 625 can be cold-formed by standard processes. Increased tensile properties can be achieved by cold work for moderate-temperature applications. Tensile strengths of more than 300,000 psi accompanied by good ductility have been developed in 0.010-0.020-in. - diameter wire after 75-90% cold reduction [4].

In recent years, the development of methods for small batch production has attained a global interest. However, most of these technologies require high investments that increase the final cost of the product. In this regard, single point incremental forming (SPIF) process is a relatively economic alternative for manufacturing customized products [5], and one of its most attractive characteristic is the possibility to obtain complex geometries from metal or polymer sheets at room temperature. Besides, the use of simple tools, high energy savings, and easy automation make SPIF a cost effective process for manufacturing customized products [6]. SPIF is a new sheet metal forming technique, which is used to deform the sheet metal into different shapes namely straight groove, cup and cone shaped parts with different variable wall angles. This is a die-less forming process that enables the development of miniature batches and modified products at a comparatively lower cost. SPIF is an advanced technological process and is progressively developing in the direction of industrial and manufacturing applications mainly in the aerospace and automobile sectors [7–9].

Shakir et al. [10] published a detailed review on the current state of incremental sheet forming processes with a focus on the effect of various parameters on incremental sheet forming. The methodical quantitative analysis and literature review was under taken to analyze the effect of various parameters, namely tool shape and type, material thickness, spindle speed and rotation direction, feed rate, tool diameter, step down and a few other parameters [11]. Jewet et al. [12] studied in detail the manufacturing of variety of asymmetric complex shapes with SPIF. In this work, two processes, the single point and multi point IF processes were used, the single point process was for forming and the latter was applied for partial die fill up.

G. Yoganjaneyulu et al.[13] elucidated the forming behavior of titanium grade 2 sheets in terms of the forming limit, fracture limit through spif process. Fracture behavior of titanium grade 2, the limiting maximum fracture strain values were diminished for a maximum speed of 600 rpm and a tool diameter of 12 mm as evidenced from the Fracture Limit Curve (FLC). The Forming Limit Diagram (FLD) also reveals that as the speed and vertical step depth increases limiting major true strain value increases and conversely as the speed and vertical step depth decreases the major true strain values also decreases. Most of the research on SPIF is focused on aluminium, steel and copper and its alloys [14-18]. No such information is available on the SPIF of Inconel 625. Inconel 625 is the most widely used nickel alloys in aerospace, automobile applications and medical implants. Moreover, there is a lack of literature on Inconel 625. The objective of the current research is to analyse the SPIF process of Inconel 625 sheets through Forming Limit Diagram and its optimization using response surface methodology by varying different parameters such as the tool diameter, speed, feed rate and vertical step depth.

II. MATERIALS AND METHODS

A. Characterization of Parent Material

The work material selected for the current study is 0.5 mm thicknesses of Nickel Alloy sheets having a temper designation of IN625 were used. Inconel 625 was selected for its excellent corrosion resistance and formability at elevated temperatures. The chemical composition of the Inconel 625 sheet (as received condition) was Ni-63.03%, Cr-20.05%, Nb-3.59%, Mo-8.61%. Specimens with dimensions as prescribed by the ASTM E08 standards were prepared by laser cutting machine with a gauge length of 25 mm, and tensile testing was done in a computerized electronic universal testing machine (Model: M-100) at a constant strain rate of 0.5 mm/min. Engineering stress Vs engineering strain curve was plotted, as shown in Fig. 1, revealing that the plastic strain occurred in the engineering stress range of 500–824.33 MPa and engineering strain range of 7.67–66.9 %.

These values were converted into true stress and true strain values using the following equations:

$$\varepsilon = \ln(e+1) \quad (1)$$

where ε is the true strain, and e is the engineering strain

$$\sigma = s\,(e+1) \quad (2)$$

Where σ is the true stress and s is the engineering stress.

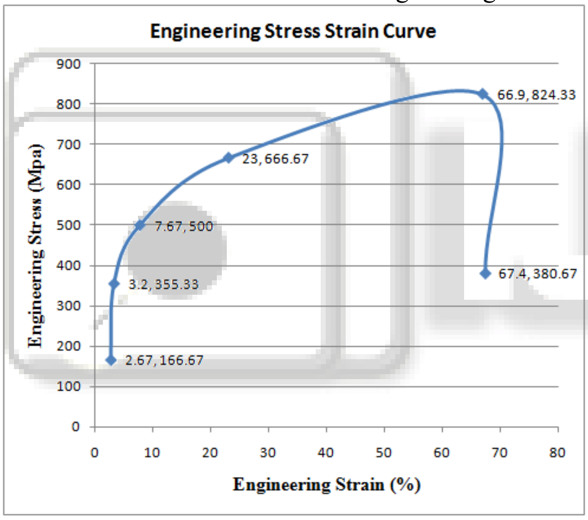


Fig. 1: Engineering stress–strain curve of IN625

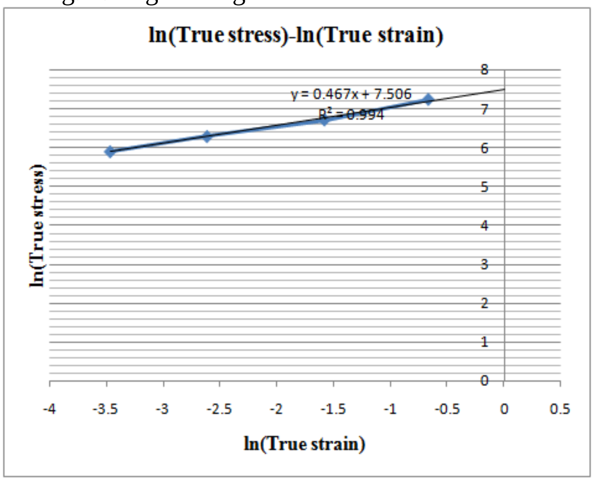


Fig. 2: ln (true stress) versus ln (true strain) graph

A log–log plot of the true stress and true strain values thus obtained is shown in Fig. 2. The slope of the above graph gives the exponent of work hardening, the y-intercept gives the strength coefficient, and the obtained values are shown in Table 1.

The mathematical equation for strain hardening is given by:

$$\sigma = k\,\varepsilon^n \quad (3)$$

where K is the strength coefficient, and n is the work hardening exponent. By using the values obtained from tensile testing, the above equation can be written as:

$$\sigma = 1818.92(\varepsilon^{0.467}) \quad (4)$$

From the true stress and true strain plot, the mechanical properties were analyzed and listed in Table 1.

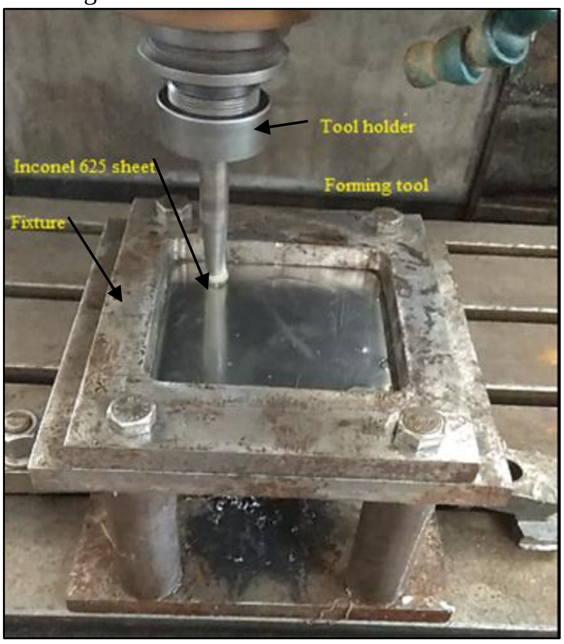
Sl.no	Properties	Values
1	Strength coefficient, K	1818.92 MPa
2	Exponent of work hardening, n	0.467
3	Ultimate tensile strength	824.33 MPa
4	Yield strength	355.33 MPa

Table 1: Mechanical properties of Inconel 625

B. Experimental setup

Inconel 625 sheets were cut into in square array with dimensions of 150 mm (length) X 150 mm (width) X 1 mm (thickness). Circles with 2 mm diameter and 0.05 mm depth were engraved using a laser grid engraving machine on the Inconel 625 sheets [18]. The tool was made up of EN8 steel and hardened steel balls of different diameters (8 mm, 10 mm and 12 mm) were placed at the bottom end of SPIF tool shank using grease.

The SPIF process was carried out at Precision engineering works, Thuvakudi, near Trichy, with a Leadwell Vertical Machining Centre with Fanuc OM CNC milling machine. Coconut oil was used as the lubricant to obtain a good surface finish on the deformed part. A CNC program was coded in the computer control unit of the CNC milling machine for controlling the tool movement at speeds of 300 rpm, 450 rpm and 600 rpm. A feed rate of 300 mm/min, 400 mm/min, and 500 mm/min was maintained for experimental trials while the vertical step depth was varied (0.2 mm, 0.4 mm and 0.6 mm). The SPIF experimental setup and SPIF process operations of Inconel 625 sheet blanks are shown in Fig. 3



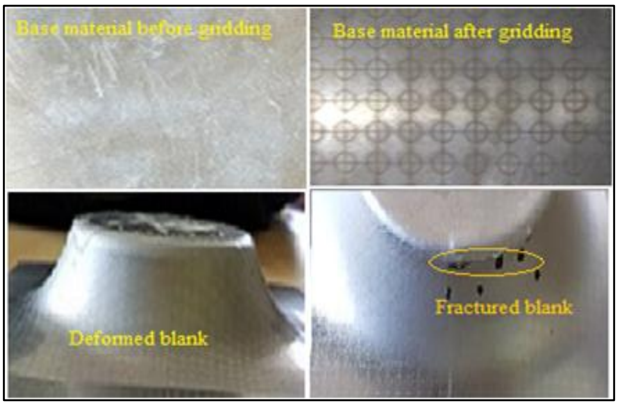


Fig. 3: Shows (a) SPIF process experimental setup and (b) SPIF process operations of Inconel 625 sheets blanks.

The forming tool travels horizontally as well as vertically as per a tool path based on NC part program, and forms a desired frustum cup shape from the sheet metal blank. The sheets were arranged individually one by one to perform the forming process. The straight groove and cup shape were formed, as shown in Fig.3. The major and minor diameters of the deformed circles were measured using a digital USB microscope.

C. Experimental Procedure and Plans

The variable process parameters and its levels used for SPIF of Inconel 625 sheets are shown in table 2.

Process Parameters	Level 1	Level 2	Level 3
Spindle speed(rpm)	300	450	600
Vertical step depth (mm)	0.2	0.4	0.6
Feed rate (mm/min)	300	400	500
Tool diameter (mm)	8	10	12

Table 2: Process parameters

Using a L9 orthogonal array design of experiments, 9 frustum cup shaped parts were made using the different combination of process parameters shown in table 2. The major and minor diameters of the deformed circles already engraved on Inconel 625 sheets were measured using a digital USB microscope. Plot Forming Limit Diagram as major true strain on y axis and minor true strain on x axis.

Major true strain,(ε_{major}) = ln(d_m/d_c).

Where d_m is the major diameter of the ellipse and d_c is the diameter of the circular grid.

Minor true strain,(ε_{minor}) = ln(d_i/d_c).

Where di is the minor diameter of the ellipse.

Optimization of SPIF process on Inconel 625 sheets by response surface methodology using three responses such as Forming time (min) directly from CNC, Formability, spring back(mm).

Formability = Major true strain + Minor true strain.

Spring back (S) = D-d

Where D is depth of formed part till failure as per the CNC program and d is the actual depth of the formed part measured using the coordinating measuring machine.

III. Results and Discussions

A. Forming Limit Diagram (FLD) of Inconel 625 sheet material

The plot of Fig. 4 shows the variation in Forming Limit Diagram (FLD) of inconel 625 sheets formed at various speeds ,vertical step depths and feeds ranging from 300 rpm to 600 rpm and 0.2 mm to 0.6 mm, 300 to 500 mm/min respectively. The sheet when formed at 600 rpm , 0.6 mm vertical step depth shows higher major true strain values. This is due to the fact that when speed increases the rotational shear stress transmitted to the sheet increases and which increases the formability. When the speed is decreased the major true strain values also decreases as evidenced from the FLD. The FLD also shows that as the vertical step depth increases major true strain value increases and conversely as the vertical step depth decreases the major true strain values also decreases. This is due to the fact that as the vertical step depth increases more strain is induced on the material. The Forming Limit Diagram provides a tool for the determination as to whether a given forming process will result in failure or not. Such information is critical in the design of forming processes, and is therefore fundamental to the design of sheet metal forming processes.

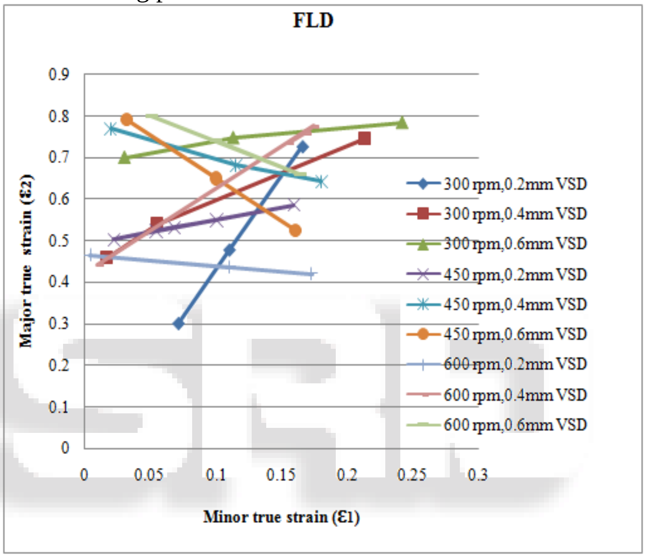


Fig. 4: Plot of Forming Limit Diagram of Inconel- 625 sheet material.

B. Optimization of SPIF process on Inconel 625 sheets

Optimization of SPIF process on Inconel 625 sheets for three responses such as forming time(min), formability, spring back(mm) using response surface methodology. Response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. Target of optimization is minimize forming time and spring back and maximize formability.

Spindle speed(rpm)	Vertical step depth(mm)	Feed rate(mm/min)	Tool dia (mm)
300	0.2	300	8
300	0.4	400	10
300	0.6	500	12
450	0.2	400	12
450	0.4	500	8
450	0.6	300	10
600	0.2	500	10
600	0.4	300	12
600	0.6	400	8

Table 3: shows process parameters and responses.

Forming time (min)	Formability	Spring back (mm)
77.75	0.68125	3.41
38.8	0.68	4.11
20.483	0.882	3.21
61.05	0.6188	3.7
34.583	0.7922	2.79
25.883	0.772	2.36
42.553	0.537	1.95
53	0.805	1.71
17.283	0.813	2.19

Table 4: Process parameters and responses

The optimization plot as shown in fig.5 reveals that the effects of process parameters on SPIF of Inconel 625 sheets also it reveals the impact of process parameters on responses.

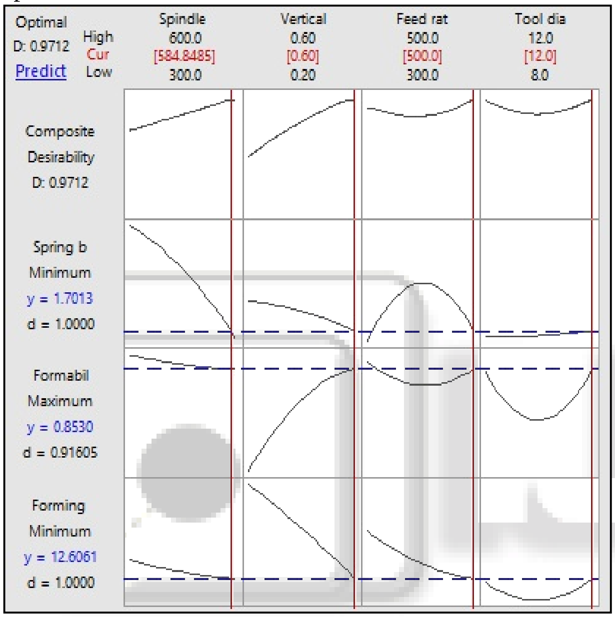


Fig. 5: Optimization Plot

Optimization of SPIF process using response surface method gives an optimal combination of input process parameters, such as spindle speed (585 rpm), vertical step depth (0.6mm), feed rate (500 mm/min), and tool diameter (12mm).

IV. CONCLUSIONS

Single point incremental forming of Inconel 625 sheet material is a promising method of forming due to its advantages over other conventional forming technologies. The effect of SPIF process on various process parameters and responses has been analysed experimentally and also using response surface analysis.

The following points have been concluded from this project:

- The Forming Limit Diagram (FLD) reveals that as the speed and vertical step depth increases limiting major true strain value increases and conversely as the speed and vertical step depth decreases the major true strain values also decreases.
- The sheet when formed at 600 rpm and 0.6 mm vertical step depth shows higher major true strain values.
- The effect of SPIF process parameters on the three responses are analysed and compared. It can be inferred from those comparisons that the parameters selected directly influence the formability and general forming features.
- Optimization of SPIF process using response surface method gives an optimal combination of input process parameters, such as spindle speed (585 rpm), vertical step depth (0.6mm), feed rate (500 mm/min), and tool diameter (12mm).

REFERENCES

[1] Choudhury, M. El-Baradie, Machinability of nickel-base super alloys: a general review, J. Mater. Process. Technol. 77 (1998) 278–284.
[2] B. Geddes, H. Leon and X. Huang, Superalloys alloying and performance, ASM International Materials Park, Ohio: ISBN-13: 978-1-61503-040-8, 2010.
[3] M. Donacihe and S. Donacihe, Superalloys A Technical Guide, 1-18 Second edition, ASM International, 2002.
[4] Special Metals Corporation, INCONEL and INCOLOY are trademarks of the Special Metals Corporation group of companies, 2013.
[5] M.A. Davarpanah, A. Mirkouei, X. Yu, R. Malhotra, S. Pilla, Effects of incremental depth and tool rotation on failure modes and microstructural properties in Single Point Incremental Forming of polymers, J. Mater. Process. Technol. 222 (2015) 287–300.
[6] Said LB, Mars J, Wali M, Dammak F. Numerical prediction of the ductile damage in single point incremental forming process. Int J Mech Sci 2017;131:546–58.
[7] Amino H, Lu Y, Ozawa S, Fukuda K, Maki T. Dieless NC forming of automotive service panels. Proc Conf Adv Tech Plast 2002:1015–20.
[8] Leach D, Green AJ, Bramley AN. A new incremental sheet forming process for small batch and prototype parts. Int Conf Sheet Met Leuven 2001:211–8.
[9] Liu Jie, Mo Jianhua, Shuhuai Huang. Sheet metal die less forming and its tool path generation based on STL files. Int J Adv Manuf Technol 2014;23:696–9.
[10] Shakir Gatea, Hengan Ou, McCartney Graham. Review on the influence of process parameters in incremental sheet forming. Int J Adv Manuf Technol 2016;87:479–99.
[11] Mc Anulty, Tegan, Jeswiet Jack, Doolan Matthew. Formability in single point incremental forming: a comparative analysis of the state of the art. CIRP J Manuf Sci Technol 2017;16:43–54.
[12] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou Joost, Allwood J. Asymmetric single point incremental forming of sheet metal. CIRP Ann Manuf Technol 2005;54:88–114.
[13] G. Yoganjaneyulu, C. Sathiya Narayanan , R. Narayanasamy. Investigation on the fracture behavior of titanium grade 2 sheets by using the single point incremental forming process. Journal of Manufacturing Processes 35 (2018) 197–204.
[14] Narayanasamy R, Narayanan CSathiya. Forming, fracture and wrinkling limit diagram for if steel sheets of different thickness. Mater Des 2008;29:1467–75.

[15] Narayanasamy R, Parthasarathi NL, Sathiya Narayanan C, Venugopal T, Pradhan HT. A study on fracture behavior of three different high strength low alloy steel sheets during formation with different strain ratios. Mater Des 2008;229:868–1885.
[16] Narayanasamy R, Narayanan CSathiya. Some aspects on fracture limit diagram developed for different steel sheets. Mater Sci Eng A 2006;417:197–224.
[17] Vigneshwaran S, Krishna KSVBR, Sekhar KC, Sivaprasad K, Venkateswarlu K, Narayanasamy R. A study on the work hardening and the effect of triaxiality on the fracture behavior of some cryorolled aluminium alloys. Mater Sci Eng A 2016;678:165–77.
[18] Raju C, Narayanan CSathiya. FLD and fractography analysis of multiple sheet single point incremental forming. Trans Indian Inst Met 2016;69:1237–43.