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A Comprehensive Review of Formability and Surface Roughness in Single Point Incremental Forming of Inconel 625

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***Abstract*— This review explores the impact of Single Point Incremental Forming (SPIF) parameters on the formability and surface roughness of Inconel 625, a nickel-based superalloy known for its superior strength, corrosion resistance, and thermal stability. Despite its advantageous properties, Inconel 625 is challenging to form due to its low ductility and high work hardening rate. The review synthesizes findings from various studies investigating the effects of key SPIF parameters, including tool diameter, step-down size, feed rate, and spindle speed, on the material's formability and surface finish. Utilizing Design of Experiments (DOE) approaches, the reviewed studies assess formability through maximum wall angle measurements and surface roughness via profilometry. The analysis reveals that while larger tool diameters enhance formability, they also tend to increase surface roughness. Conversely, smaller step-down sizes and optimized feed rates contribute to improved surface quality. The review identifies optimal parameter combinations that balance high formability with acceptable surface finish, offering valuable guidelines for the aerospace and high-performance manufacturing sectors. These insights aim to advance the understanding and application of SPIF for Inconel 625, ultimately contributing to more effective and efficient forming processes in critical industrial applications.**

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

I. INTRODUCTION

Inconel 625, a high-performance nickel-based superalloy, is renowned for its exceptional strength, corrosion resistance, and thermal stability, making it a critical material in aerospace, marine, and chemical industries. However, despite its advantageous properties, Inconel 625 presents significant challenges in manufacturing due to its low ductility and high work hardening rate, which complicate traditional forming techniques. Single Point Incremental Forming (SPIF) has emerged as a promising solution for fabricating complex geometries from such difficult-to-form materials. SPIF offers flexibility and cost-efficiency by eliminating the need for dedicated dies, thus making it suitable for low-volume and customized production.

The SPIF process involves incrementally forming a sheet material into a desired shape using a tool that moves along a predefined path. The process parameters, such as tool diameter, step size, feed rate, and spindle speed, play a crucial role in determining the outcome of the forming operation. For Inconel 625, the influence of these parameters on formability and surface roughness is of particular interest. Formability refers to the ability of the material to undergo deformation without failure, while surface roughness pertains to the quality and finish of the formed surface.

Previous studies have shown that both formability and surface roughness are significantly impacted by step size and feed rate. Larger step sizes can increase fracture depth due to elevated forming temperatures, while finer step sizes typically enhance surface quality but may affect material flow. Similarly, feed rate affects heat dissipation and tool interaction, influencing both formability and surface finish. Spindle speed further complicates this relationship by affecting friction and heat buildup. This review aims to synthesize existing research on these factors to provide a comprehensive understanding of their effects on the SPIF process for Inconel 625, offering valuable insights for optimizing forming conditions and improving the performance of this critical material.

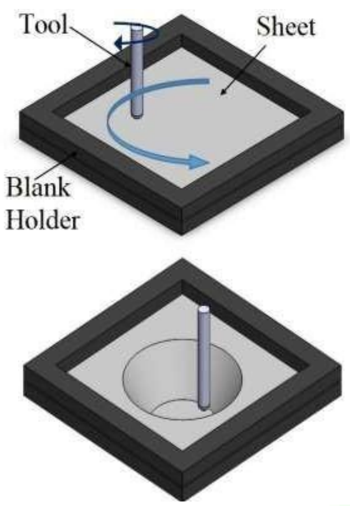

Figure (a)1: Geometry of object

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. 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.1

Figure 1 (b) 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.

Lasunon (2013) [7]

The impact of forming parameters on the average surface roughness (Ra) of aluminium alloy formed using a SPIF method is discussed in this research. Feed rate (12.5, 25 and 50 inch/minute), depth increment (0.015 and 0.030 in), and wall angle (45 and 60 °) are the three factors that were tested. The findings demonstrate that wall angle, step size, and their interaction have a significant impact on surface roughness, whereas feed rate has a minor impact. Feed rate of 25 in/min, step size of 0.015 in, and wall angle of 45° are the best forming conditions for lowering surface roughness.

Radu et al. (2013) [8]

The purpose of this study was to examine the impact of process parameters such as tool size, tool vertical step size, feed rate, and spindle speed on the quality of sheet surface, as measured by roughness and macrostructure, in parts formed by single point incremental forming on Al1050 aluminum grade metal sheets, the analysis was performed. The findings demonstrated that different process parameters had distinct effects on surface quality, with the increase in tool vertical step exerting the most negative impact.

Beltran et al. (2013) [9]

Incremental sheet metal forming (ISMF) is a relatively recent process that deforms a sheet of metal into the desired shape by moving a basic hemispherical ending tool along a specified three-dimensional toolpath. Because ISMF can effectively make ultrathin components beyond the forming limit found in traditional stamping and does not require any geometry-specific tooling, the greater process flexibility and improved formability of ISMF has sparked increased academic and industry interest in this technology. Because of the above-mentioned process features, ISMF is an excellent candidate for adoption into the micro manufacturing scenario. Micro-ISMF is used in this study to see how forces and the frequency of sheet failure alter when the geometric dimensions of ISF are reduced. The fabrication of a highly reproducible micro-ISMF experimental setup is detailed, and tests are carried out to show that in micro- ISMF, a hitherto unknown buckling mechanism of deformation exist that is connected to the structural material properties. The study gives design and understanding recommendations for the micro-ISMF.

Centeno et al. (2014) [10]

The spifability of AISI 304 metal sheets was examined using circle grid analysis. In order to determine the influence of bending in the limit strains, the Characterisation of formability limits in classical Nakazima tests is undertaken and compared to stretch-bending and SPIF. Postponed necking with ductile fracture was the failure mode observed. When comparing the effects of bending on formability above the FLC in SPIF and stretch-bending, it was discovered that the elevation of formability above the FLC in SPIF is substantially larger than in stretch-bending. In actuality, in stretch-bending, the percentage enhancement of formability maintains about 30% for the two diameters studied. The boost in spifability, on the other hand, grew as the tool diameter decreased, reaching values of roughly 150 percent for the smaller tool diameters. It should be noted that, while the bending effect caused by the punch radius is essential in SPIF, it is not the only factor that allows stable deformations much above the FLC.

Nirala et al. (2017) [11]

ISF stands for incremental sheet forming and is a relatively new manufacturing process. Forming is done in ISF by applying deformation force to the clamped sheet metal blank via the movements of a computer numerical control (CNC) single point forming tool. Because no die is required to construct any component, SPIF is also known as a die-less forming process. It is now frequently used for the quick production of sheet metal components. The formability of the SPIF process is improved by incorporating intermediate phases, resulting in the Multi-stage SPIF (MSPIF) method. However, stepped features are generated during the formation stage of the MSPISF process due to intermediary steps. With modelling and experimental results, this work studies the production of stepped features. They reported that, the proposed strategy can successfully eliminate the stepped effect with little discrepancy in geometry accuracy.

Mulay et al. (2017) [12]

In this article, author attempted to determine the process parameter influence and mathematical model on surface finish, and maximum formability (wall angle) of aluminum 5052 sheets. Authors used response surface methodology and analysis of variance for the confirmation tests. They concluded that step size and interaction of step size-sheet thickness influence the formability and for smaller tool diameter the surface finish increases.

Liu et al. (2019) [13]

The study of incremental sheet forming energy usage is vital in evaluating the most energy- efficient process parameters. First, the machine total power is divided down into standby power, feed motion power, and forming power, all of which are theoretically assessed. A theoretical mechanistic model for sheet forming power during the incremental forming process is constructed based on the contact area and sheet flow condition, in addition to the modelling of standby power and feed axis power. The important coefficients of the theoretical model are then determined by tests in the standby condition, idle feed condition, air forming condition, and real processing situation. Furthermore, the processing power prediction model in incremental forming is produced, and the correctness of the estimate is confirmed by experiments. The findings revealed that the power forecast error is less than 5%. Furthermore, the impact of input parameters such as tool size, step size, sheet thickness, feed rate on processing power, power efficiency, processing energy, and energy efficiency is thoroughly investigated.

Sisodia et al. (2019) [14]

An experimental investigation of peak forming force during single point incremental forming operation been conducted. Authors selected tool diameter size, step depth, dummy sheet thickness and geometry wall angle as input parameter for the study. Taguchi and ANOVA design of experiments techniques were used to investigate influence of parameters. It was concluded that peak forming force increases with increase in step size due to high material flow, increases with dummy sheet thickness due to high force requirement for the deformation of target sheet, increases with tool size due to distribution of force, and increases with wall angle due to sine law.

Dodiya et al. (2021) [15]

In this literature, experiments are conducted by applying central composite design using process parameters namely sheet thickness, tool size, step depth, and feed rate to investigate their effect on average surface roughness of aluminum 3003-O grade sheets. Authors concluded that tool size pursued by step depth, feed, and sheet thickness have individual subsiding effect. They also reported that a direct proportional connection between sheet thickness and surface finish.

III. RESEARCH GAPS

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. PROBLEM FORMULATION

1. Problem Formulation

The primary problem addressed in the investigation of formability and surface roughness behavior of Inconel 625 using Single Point Incremental Forming (SPIF) revolves around understanding and optimizing the complex interactions between process parameters that affect the quality and manufacturability of this difficult-to-form alloy. This problem can be formulated as follows:

2. Problem Statement

Inconel 625, a high-performance nickel-based superalloy, is extensively used in industries such as aerospace, nuclear, and chemical processing due to its superior mechanical properties, including high strength, corrosion resistance, and thermal stability. However, these advantageous properties also make Inconel 625 notoriously difficult to form using traditional manufacturing techniques due to its low ductility, high work hardening rate, and tendency to generate surface defects during forming.

Single Point Incremental Forming (SPIF) offers a flexible and cost-effective alternative to conventional forming methods, particularly for low-volume and customized production. However, the application of SPIF to Inconel 625 presents significant challenges, primarily related to achieving high formability without compromising surface quality. The key challenges include:

Formability Limits: Determining the maximum achievable deformation (wall angle) before failure or cracking occurs due to the material's limited ductility and work hardening.

Surface Roughness Issues: Controlling surface roughness, which is critical in applications where surface finish impacts performance, especially under high-stress or corrosive environments.

Parameter Sensitivity: Identifying and optimizing SPIF process parameters—such as tool diameter, step-down size, feed rate, and spindle speed—that significantly affect the material's formability and surface roughness.

Effect of Process Parameters on Formability and Surface Roughness

1 Step Size

Step size is a critical parameter in SPIF, influencing the depth of material deformation per tool pass. The studies reviewed indicate that step size significantly affects both formability and surface roughness:

- **Formability:** For step sizes ranging from 0.2 mm to 0.3 mm, there is no significant change in formability, indicating a stable forming process within this range. However, as step size increases, the fracture depth also increases, primarily due to the rise in forming temperature caused by greater deformation per pass. This temperature rise enhances the material's ductility, allowing for deeper forming without immediate fracture.
- **Surface Roughness:** Larger step sizes increase surface roughness (Ra), attributed to the staircase effect inherent in incremental forming. This effect becomes more pronounced with higher step sizes, as each step leaves a distinct mark on the surface, compromising finish quality.

2 Feed Rates

Feed rate, or the speed at which the tool moves across the sheet surface, plays a crucial role in heat dissipation and the overall forming mechanism:

- **Formability:** An increase in feed rate generally leads to improved formability. This improvement is attributed to reduced heat dissipation at the tool-sheet interface, which maintains higher temperatures during forming. The elevated temperature softens the material, facilitating greater deformation before failure occurs.
- **Surface Roughness:** A moderate feed rate helps achieve a balance between formability and surface quality, though excessively high feed rates can negatively impact surface smoothness due to increased vibrations and inconsistent material flow.

3 Spindle Speed

Spindle speed, or rotational speed of the forming tool, directly influences the frictional forces between the tool and the sheet, thereby affecting both formability and surface finish:

- **Formability:** Lower spindle speeds (0 to 200 rpm) were found to have a negative effect on formability. Increased frictional effects at low spindle speeds contribute to higher resistance against material flow, resulting in reduced deformation capabilities. Additionally, increased friction can lead to localized heating, which, while enhancing ductility in some cases, can also cause premature failure under certain conditions.
- **Surface Roughness:** Operating at 0 rpm spindle speed minimizes friction and heat buildup, resulting in a smoother surface finish compared to higher rotational speeds.

Optimal Parameter Combinations for Formability and Surface Roughness

The review identifies the best combinations of SPIF parameters for achieving maximum formability and minimal surface roughness:

- **Maximum Formability:** The optimal parameters for enhancing formability are a step size of 0.4 mm, a feed rate of 550 mm/min, and a spindle speed of 0 rpm. These settings allow for increased material deformation due to higher forming temperatures and reduced heat dissipation.
- **Minimum Surface Roughness:** For achieving the lowest surface roughness, the optimal parameters are a step size of 0.2 mm, a feed rate of 400 mm/min, and a spindle speed of 0 rpm. These settings minimize the staircase effect and maintain a stable forming process with minimal surface defects.

V. CONCLUSION

This review highlights the significant impact of SPIF process parameters on the formability and surface roughness of Inconel 625. Step size, feed rate, and spindle speed play crucial roles in determining the quality of formed parts, with specific parameter combinations offering a balance between maximum formability and optimal surface finish. These findings provide valuable guidelines for manufacturers looking to optimize the SPIF process for Inconel 625, enabling the production of high-quality components for demanding applications.

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