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An Analytical Review of Incremental Single Sheet Metal Forming Technique

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Abstract: Single Point Incremental Forming (SPIF) has evolved as a flexible and low-cost alternative to conventional metal forming processes, especially for low volume production of complex three-dimensional shapes (complex geometry parts) without using costly dedicated die. This review is focused on process parameters, tool path strategies, tool geometry, and lubrication in SPIF and their combined effects on formability, surface quality and geometric accuracy. The potential use of SPIF in automotive, aerospace and biomedical domains is also considered. The process has some merits including lower tooling cost and shorter design-to-production time, but is also confronted with long forming time, dimensional in precision, and surface defects. In this paper, the advances in the trends on and the optimization of the efficiency and product quality aspects of SPIF are reviewed.

Keywords: CNC machines, Metal forming, Lubrication, Process optimization, Single point incremental forming (SPIF), Tool geometry, Tool path

Introduction

The need for new methodologies in prototyping and low-volume production is stressed. Incremental Sheet Forming (ISF) for small batch production, which is a novel method for sheet metal components manufacture in high-efficiency manufacturing. ISF, originally established in Japan, is a cold-working process designed to accommodate the requirements of the automotive sector (Binamra -Poudel, 2018). This approach uses a smooth spinning tool to create a locally-induced and deformation without costly tooling. It is this trait that causes ISF to be referred to as a die-less forming method. The method enables the complex curvature of different materials to be bent. It offers rapid prototyping capabilities by enabling the direct transformation from a 3D CAD model to a final product without the constraints of conventional tooling (Najm, 2022). Incremental forming produces components with surface roughness issues, geometrical and dimensional imperfections and other issues (Trzepieciński et al., 2022). Sheet forming process characteristics (e.g., vertical pitch, tool diameter, trajectory) cause these defects. Researchers and manufacturers have optimized incremental forming process parameters using diverse ways to improve part geometry and surface quality to prevent defects. For instance, A process known as "forming without a mould" involves gradually shaping sheet metal using a small tool. Leszak patented this approach in 1967 (Edward, 1967; Skjoedt et al., 2007) prior to its practical implementation. It was then modified and used by several researchers (Skjoedt et al., 2007). Actually, two separate forms of asymmetric incremental formation exist as shown in Figure 1:

- Two-Point Incremental Forming (TPIF);
- Single Point Incremental Forming (SPIF).

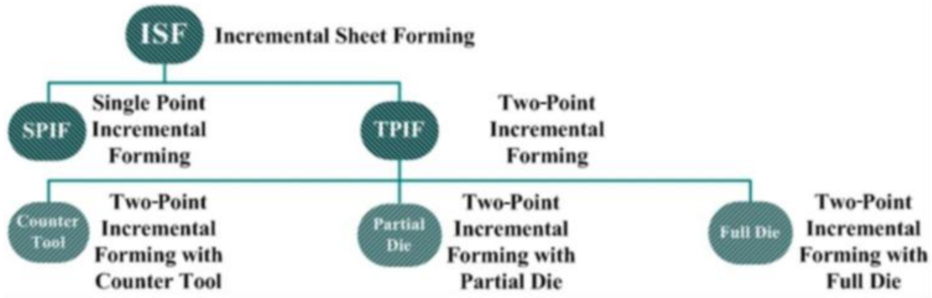


Figure 1. Methods based on the ISF process

Positive forming, or two-point incremental forming, is a local deformation process for sheet metal. By means of a counter tool or a mold, a hemispherical device is moved on the part's convex surface to create full or partial contact with the sheet (Hirt et al., 2004) (Figure 2). The blank holder and the die are capable of vertical movement.

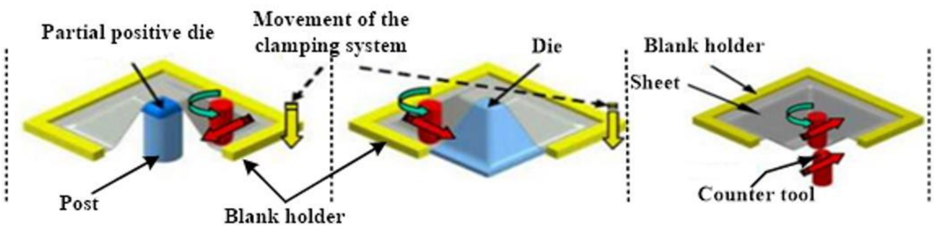


Figure 2. Two-point incremental forming (Jeswiet et al., 2005)

A diminutive hemispherical tip apparatus adheres to a designated path to manipulate sheet metal in single point incremental shaping, similarly referred to as “negative forming” (Azaouzi & Lebaal, 2012) proposed an approach to optimize the tool path in order to achieve the required final geometry (Jeswiet et al., 2005; Kim & Yang, 2000). This method makes use of a blank holder and die in the absence of a counter die (Hirt et al., 2004). An illustrate of SPIF in Figure 3.

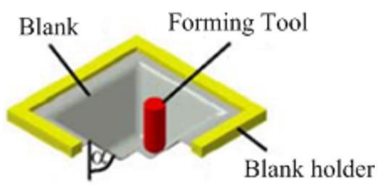


Figure 3. Single-point incremental forming (Hirt et al., 2004)

All of the foregoing procedures have benefits, but researchers and scientists often turn to single-point incremental forming when working with CNC machines or robots to create components of varying geometries (Jeswiet et al., 2008) as well as costs less than two-point incremental shaping (Trzepieciński et al., 2022). Forming sheets asymmetrically. A CNC indenter moves over a sheet of metal in an asymmetric route, commonly contours or a spiral of descending depth, determining the product's shape. Thus, moving the tool along a predetermined path can create a variety of asymmetric products without specific tools. Thus, ‘The term "incremental sheet forming" will be used throughout this article with the implication that it is most commonly related to asymmetric CNC incremental sheet forming methods. The simplest method of asymmetric ISF, identified as single-point incremental forming (SPIF), involves clamping a metal sheet firmly at its edges and using a single indenter to shape one surface (Figure 1).

Working Principle of ISF

Single Point Incremental Forming (SPIF) is a flexible die-less sheet metal forming process where a hemispherical tool incrementally shapes a clamped sheet blank along a programmed trajectory. Mounted on a 3-axis CNC milling machine or similar apparatus, the tool descends gradually in the Z-direction, penetrating the sheet in small vertical steps, while the X-Y plane feed facilitates localized stretching and bending of the material (Bhatt et al., 2016). This coordinated motion results in complex 3D geometries without the requirement of dedicated dies or mandrels.

The geometric path of the tool, which is usually spiral or contour point based, is extracted from the CAD model by CAM software and determines the shape, wall thickness and surface finish of the sheet (Najm, 2022). This synchronised movement produces intricate 3D shapes without the need for specialist dies or mandrels. The tool path, typically created in the form of spiral or contour paths, is derived from the CAD model in CAM software and directly affects not only the finished form, but also the wall thickness, and the surface finish (Najm, 2022). The thickness reduction obeys an analytical sine-law model:

$$t_f = t_0 \cdot \sin(\lambda)$$

Where t_0 is the initial sheet thickness and λ is the wall angle. This incremental layering leads to reduced global stress and enhanced flexibility, allowing for the fabrication of small-batch, complex metal parts efficiently (Abdulrazaq et al., 2019).

Key Parameters and Their Effects

- Z-step size: Smaller steps enhance geometric accuracy but increase processing time; larger steps accelerate failure through thinning (Bhatt et al., 2016).
- Tool diameter: Smaller diameters concentrate deformation and improve formability but may exacerbate thinning and springback (Rauch et al., 2009).
- Path strategy: Spiral or contour paths ensure uniform deformation and smoother surfaces, whereas erratic tool movements can lead to surface defects (Skjoedt et al., 2007).

In a nutshell, SPIF is performed by moving the tool precisely and discretely--which means kind of stepwise (vertically + in generation of form) at the tool's surface-- to locally form the sheet and create complex parts without dies. Thereby, profound knowledge of parameters like Z-step and tool size as well as path guarantees best results regarding distribution of thickness, form and surface.

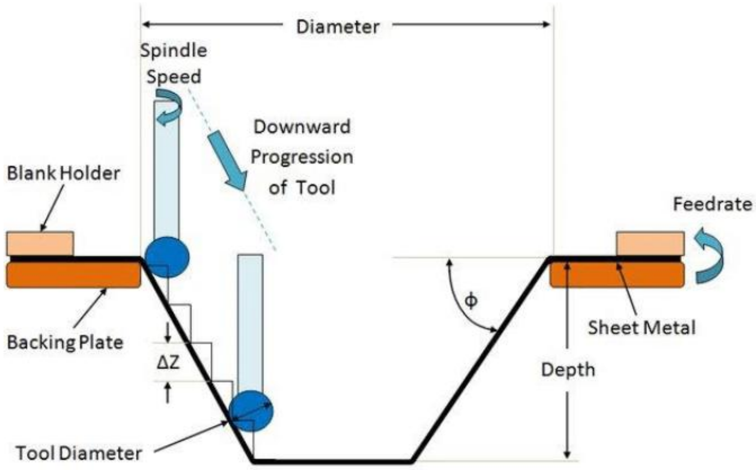


Figure 4. Simulation model of SPIF toolpath (Najm, 2022)

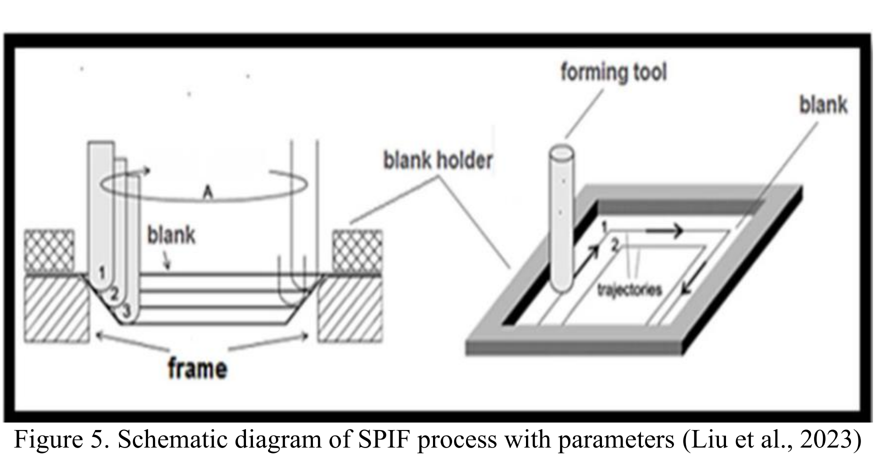


Figure 5. Schematic diagram of SPIF process with parameters (Liu et al., 2023)

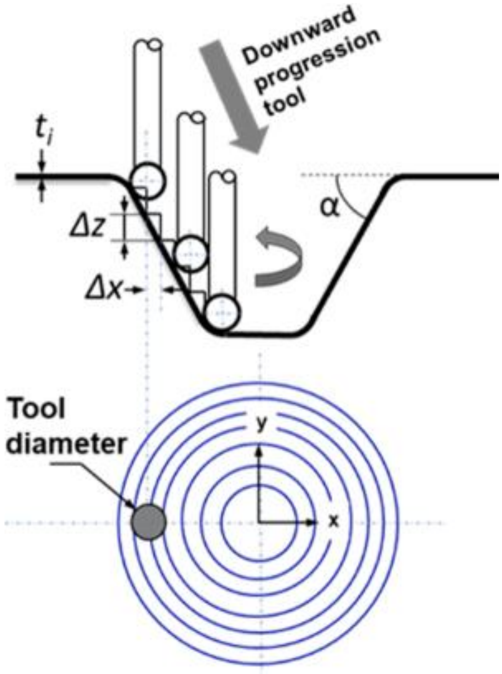


Figure 6. Analytical deformation illustration of SPIF (Abdulrazaq et al., 2019)

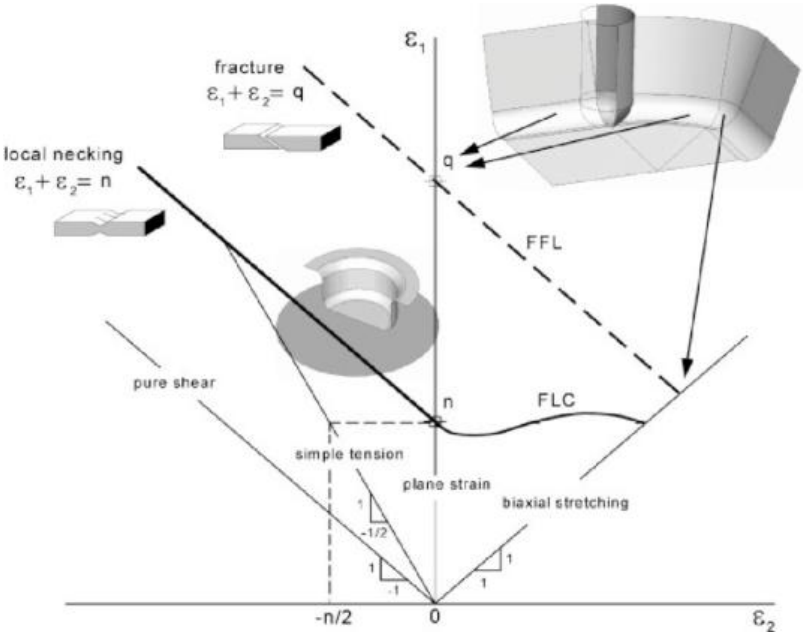


Figure 7. Basic toolpath and shape generation in SPIF (Bhatt et al., 2016)

The basic setup, devised by. Emmers et. al., is a three-dimensional CNC milling machine with manual work piece holding and suitable tool path control. Figure 8 shows that the final geometry was reached using a single rotating tool that moved inward through a defined step from 1 to 3. The clamping of the work piece was done correctly. Sheets are formed by coordinating the motion of tools and hand-operated tables (Iseki et al., 1989). Tool trajectory depended on part shape. Table moves in X and Y and tool stretches sheet in Z (Bhatt et al., 2016).

SPIF is commonly illustrated in Figure 9. A sheet is secured over a backing plate and shaped via a tiny tool executing a series of passes along the perimeter. The ultimate configuration of the component is dictated via the integrated trajectory of the tool, in contrast to the tool's form as seen in conventional stamping. The primary benefit of SPIF compared to other Asymmetric Incremental Sheet Forming (AISF) methods is its utilization of a singular tool without the need for counter tooling or molds, facilitating straightforward implementation in a commercially available CNC machine. Employing a regular machine tool reduces the costs associated with implementing such a method, while also enabling the machining of additional features in situ using standard machine tools and commercial software (Jeswiet et al., 2005; Jeswiet et al., 2015).

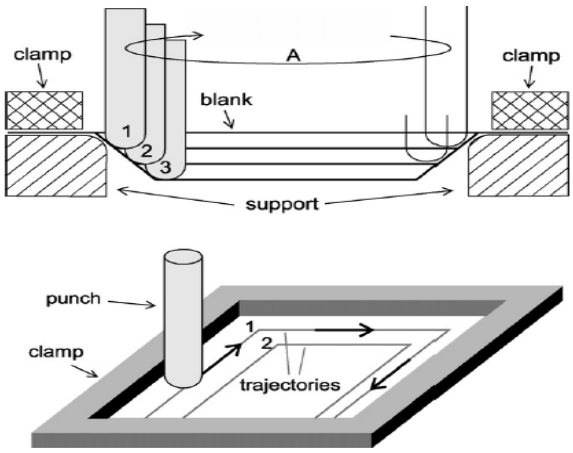


Figure 8. Principle of SPIF for a non-axis symmetric shell (Iseki et al., 1989)

Generally, SPIF provides reduced tooling costs and quicker lead times, but higher cycle durations than classic forming methods like stamping (Table 1). SPIF is best for custom and prototype, but its long cycle durations make it unsuitable for high-volume production.

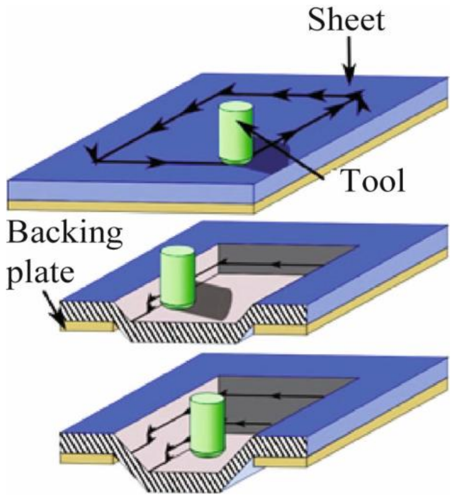


Figure 9. Overview of the SPIF process (Jeswiet et al., 2015)

Table 1 compares single point incremental forming (SPIF) and the conventional sheet metal forming operations including deep drawing, flexibility surface, quality, and tooling in comparison with forming processes as stamping, hydroforming, and roll forming. Production suitability. Source numbers with which to cite each entry are numbered according to the reference list below.

Table 1. Comparison of SPIF with conventional sheet forming processes

Forming process	Tooling requirement	Flexibility	Surface quality	Volume suitability	Source
Deep drawing	High (die + punch)	Low	High	High-volume	(Liao et al., 2009)
Stamping	Very high	Very low	Very high	Mass production	(Jeswiet et al., 2005)
Hydroforming	Moderate	Moderate	Good	Medium/High	(Behrens et al., 2012)
Roll forming	Very high	Low	Excellent	Continuous production	(Behrens et al., 2012)
Single point ISF (SPIF)	Very low (die-less)	High	Moderate	Low-volume	(Jeswiet et al., 2005; Kim & Park, 2002)

Process Parameters of ISF

Incremental Sheet Forming (ISF) provides high degree of flexibility, low tooling costs and can be used for low batch and custom shape production, having a better solution than traditional forming. Unlike die based processes, ISF does not require special tooling, leading to quick design changes and short lead times. Furthermore, it is very flexible for complex geometry and great ease of changing part dimensions. However, the full potential of ISF remains underutilized due to the lack of optimized process parameters, which limits its efficiency and repeatability in industrial applications.

First, we must identify process parameters, then we can understand their effects. The procedure is affected by the following parameters. Metal Incremental Sheet Forming (ISF) mechanics, focused on through-thickness deformation and stresses in copper/aluminum plates during SPIF and TPIF. Their investigation showed that shear strain, which is parallel to the tool direction, accounts for the majority of strain in SPIF and TPIF as a result of tool-workpiece friction, while stretching accounts for the remaining portion of deformation. Tool forces were superior in SPIF than TPIF, corresponding to stress. To measure geometry and accuracy, Coordinate Measuring Machines (CMMs), 3D stereovision systems, and laser scanners have been used in recent studies to ensure precise dimensional analysis and shape validation.

Stereovision systems, while fast, are expensive and scarce. Gages, grids, and stereovision were employed to measure strain. Tool force was measured using a force dynamometer, strain gauges on the tool post, and load cells on the workpiece support. Key findings imply that SPIF causes higher shear perpendicular to the tool direction, generating material accumulation at the plate's center, compared to TPIF (Ambrogio et al., 2004; Gupta et al., 2018). advantages as shown below (Bhatt et al., 2016; Suriyaprakan, 2013):

- Direct manufacturing of usable components from CAD data requires minimal specialized tooling.
- These may consist of either fast prototypes or small-scale production runs.
- The process is die-less, as it does not necessitate the use of either positive or negative dies.
- Nonetheless, a backing plate is essential to deliver a noticeable angle shift at the surface of the sheet.
- Modifications in part design dimensions can be readily and swiftly implemented, providing significant flexibility.
- Creating metal rapid prototypes is typically challenging; however, this process simplifies the task.
- In order to improve formability, the process's incremental features and small plastic zone work together, facilitating the deformation of sheets with low formability.
- A conventional CNC milling machine or lathe is applicable for this procedure.
- The dimensions of the component are constrained solely by the capacity of the machine.
- The forces remain constant because of the small incremental step size and confined contact zone.
- It is possible to improve the component's surface finish.
- There is hardly any noise or background noise throughout the operation.

Conversely, there are several downsides outlined below (Martins et al., 2008; Binamra - Poudel, 2018; Suriyaprakan, 2013):

- SPIF requires a longer formation time than the typical deep drawing technique;
- SPIF exhibits reduced geometric precision, particularly at the bending edge regions and convex radii. In comparison to other incremental sheet metal processes
- The process is constrained by limited production batch sizes;
- Attaining a vertical angle necessitates multi-stage techniques;
- Springback occurs, however it can be mitigated using certain correction algorithms.

Applications for ISF

High precision of the products is required in several areas to ensure the accuracy of performance (Bhatt et al., 2016). Automobile, aerospace, and other industries are beginning to value incremental sheet metal shaping (Jeswiet et al., 2005) and biomedical industries (Ambrogio et al., 2005) as well as for processing recycling panels (Jackson et al., 2008) creating dies/molds fast by complicated sheet metal surfaces created via incremental forming at low cost (Reddy et al., 2015). ISF can make these goods (Suriyaprakan, 2013):

- The aircraft sector employs instrument panels, body panels, and passenger seat coverings.
- Automobile: Inner and exterior doors, hood, engine cover, etc.
- Tailored products: Denture plates, ankle supports, metal helmets, etc.

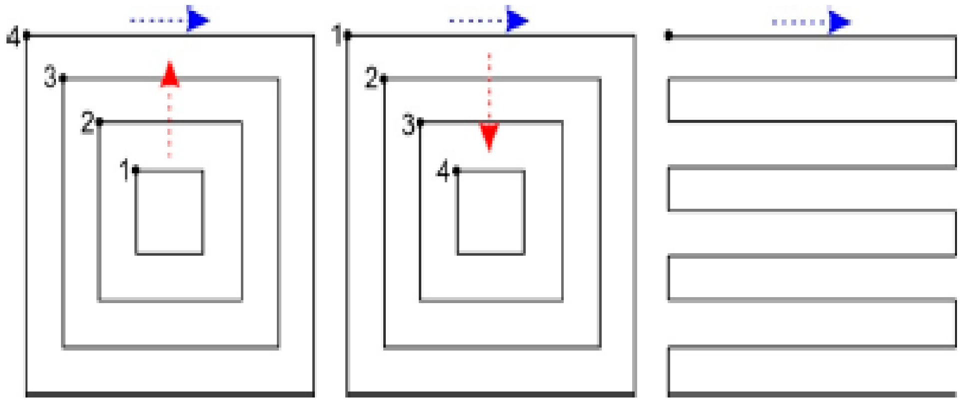
- Mobile telephones;
- Integrated circuit lead frames;
- Electronics;
- Healthcare;
- Miniature fasteners;
- National security and defense commodities;
- Automobile;
- Hard disk drives: Forming the aluminum or magnesium alloy covers of hard disk drives;
- Sensors: producing customized metal casings for pressure or environmental sensors, especially in aerospace or biomedical applications.

Process Parameters Effect on Single Point Incremental Forming

The quality of the surface of the deformed sheet significantly influences the parts acquired through ISF in various applications. Several parameters have a consequence on the manufactured pieces' surface quality.

Tool Path

Single Point Incremental Forming (SPIF) is a sophisticated manufacturing method that utilizes a localized plastic deformation process to transform a metal sheet into a specified geometry (Najm, 2022). Tool path is crucial to part quality and efficiency. Deforming parts requires tool movement on a predetermined trajectory. This path is ISF tool path. To generate the tool path, commercial CAM software needs CAD models. Four tool paths were examined by L. Ben Said et al. (2016): The punch follows a rectangle path with a vertical step size at one corner in this basic method. Two-Type Parallel Contour Paths: A zigzag path was considered as an alternative to parallel contour paths (Said et al., 2016) as shown in Figure 10.



(a) (b) (c)

Figure 10. The three toolpath strategies (a, b) parallel contour and (c) zigzag (Said et al., 2016)

The results showed that the best results in terms of thickness distribution, strain values and geometrical accuracy were obtained by the spiral trajectory allowing better continuous motion without vertical entry points. This path was the most efficient tool path for the cranioplasty plates manufacture, and the tool path used for these purposes was found to be most effective (Said et al., 2016; Trzepieciński et al., 2021). Tool path optimization using FEA, RSM and SQP. You could begin with determining SPIF process variables such as the vertical pitch, toolpath envelope, and sheet thinning. A response surface model that estimates tool path configuration responses is built reasonably by altering these factors in turn.

In this research, the focus is on FEA simulation of SPIF process with different tool paths. These simulations indicate the influence of the secondary channels on the thickness distribution of the produced part; thus the response surface model is improved. Finally, a best toolpath is obtained to reduce the forming time with uniform thickness distribution by SQP algorithm. Linear, spiral, and customized optimized tool paths were compared, as depicted in Figure 11. With path optimization, it is possible to minimize path length and limit variation of minimum sheet thickness (Azaouzi & Lebaal, 2012).

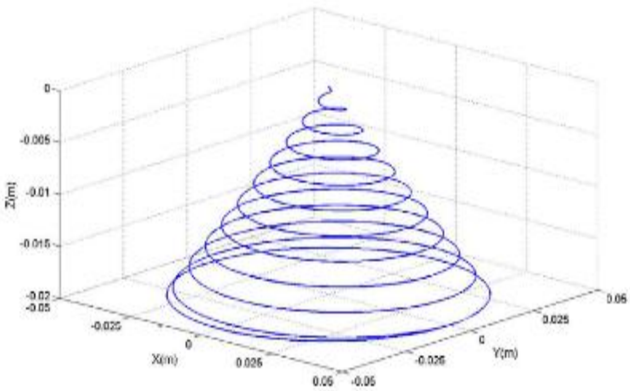


Figure 11. Tool path variation in SPIF process

It was found that the alternate tool path resulted in a significant improvement of the performance of the SPIF process. In particular, the better tool path led to a more uniform thickness distribution over the part and, as a result, a smaller chance of thinning and hence the appearance of defects. The uniform apportioning of material is a requisite for the structural integrity of the formed article. The entire tool path length was reduced by the optimization, which resulted in a reduction in forming time. This is a crucial factor in industrial applications since processing time also reflects in the cost of production. By adjusting the aspect ratio of the vertical pitch and envelope, the authors were able to simplify the tool route. This not only enhanced final item quality, but also raised the efficiency of the entire SPIF process (Azaouzi & Lebaal, 2012), as presented in Figure 12. Tool path optimization in induction heating assisted SPIF of thin Ti6Al-4V sheets at close and above beta-transus temperature (980 °C) using machine learning.

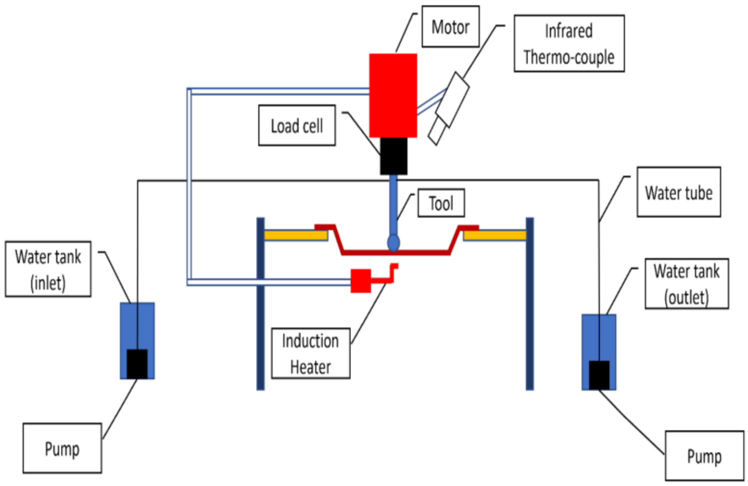


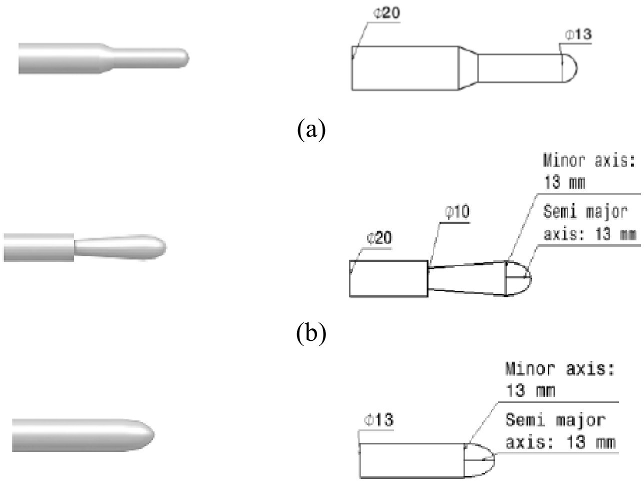
Figure 12. Induction heating SPIF system set-up

The Radial Basis Function (RBF) network, a machine learning method, was used by the authors to improve the tool path in the SPIF process. The RBF network has developed to predict the tool path by using the forming force and the temperature during the exercise along the geometric Coordinates of the experiment data of the RPF network. According to this method, a tool path is optimized, and the spring back can be greatly reduced to 5% or lower. This demonstrates the capacity of the network to improve the tool path with experimental feedback ‘leading to improved forming performances. Material temperature reduction is also presented considering the formed tool path required to control the thermal response and the material deflection. By regulating temperature through an optimized tool path, enhanced geometric profile accuracy is obtained, and improved alignment with the CAD profile is achieved.

The FEM investigation supports these results, showing that the optimized trajectory lead to a temperature distribution and forming force very close to the simulated ideal conditions. It results in the improvement of form accuracy and decrease in the number of defective products. It is revealed from the research that tool path optimization using RBF network and cooling methods can greatly improve the SPIF process efficiency and precision. The optimal tool path of WSM contributes to reducing spring back, control of the temperature of the temperature, and the high accuracy in the process (Li et al., 2022).

Tool Geometry

Single Point Incremental Sheet Metal Forming (SPISF) considering the influence of various tool geometries on formability and deformation forces. The study considered three tool geometries: spherical, elliptic with a straight major diameter, and elliptic with a tapered major diameter. The Tool geometries are illustrated in Figure 13 (a) spherical, (b) elliptical with reducing diameter and (c) elliptical with straight wall.



(c)

Figure 13. Tool geometries utilized (a) spherical (b) elliptical with decreasing diameter (c) elliptical with straight diameter (Pachori & Agrawal, 2017)

Spherical tools need higher force and have lower forming limitations due to their wider contact area. Elliptical tools, especially tapered ones, reduce contact area, lowering deformation forces and increasing forming limits. Simulations confirmed that tapered-diameter elliptical tools are more effective and require less force due to their smaller contact area. According to the study, adjusting tool path and geometry can greatly improve SPISF results (Pachori & Agrawal, 2017). Various sheet metal forming tools are discussed in this table. It includes studies by several writers on tool kinds, dimensions, and the best tool type for optimal results. Table 2 shown forming tools used in manufacturing processes for some authors.

Table 2. Forming tools used in manufacturing processes

Author's name	Year	Type of tool used	Tool dimensions	Best tool type	Reason
Khalil Ibrahim Abass	2016	Spherical, Ellipse, Flat	Tool diameter: 10 mm, Die diameter: 5 mm	Flat	Provides better profile accuracy, lower forming force, and improved formability compared to spherical and elliptical tools (Abass, 2016).
Brendan Cawley	2013	Hemispherical, Parabolic, Flat	Hemispherical: D = 5.08mm, Flat: D = 12.7mm	Flat-end (90°)	Achieved higher forming limits and better surface quality with flat-end tools. Parabolic profiles showed increased smoothness but lower formability (Cawley et al., 2012).
Mohamed Azaouzi	2012	Spherical	Diameter: 30 mm	Spherical	Optimal for tool path control and achieving uniform thickness distribution in ISF. The optimization reduced tool path by 60% while improving sheet thickness (Azaouzi & Lebaal, 2012).

The key takeaway from the table is that flat tools were preferred in many studies as they offered better forming accuracy, required less force, and provided improved formability compared to other tools like spherical or elliptical ones.

Lubricant

It was created a cooling lubricant system for the forming tool by Weining Li et al. as shown in Figure 14 to reduce friction thermal expansion. To decrease geometric error and lubricant adhesion induced by high temperature, The cooling lubricant system performed well with RBF designed tool route to maintain temperature and decrease surface friction and lubricant adherence. Experimental results without cooling lubricant and non-optimized tool paths showed a significant temperature rise, especially toward the end of forming. Due to excessive thermal expansion and surface quality and spring back, geometric accuracy suffered. Optimized tool paths, especially when paired with cooling lubricant, maintain a more uniform temperature, reduce thermal strains, and improve product quality (Li et al., 2022).

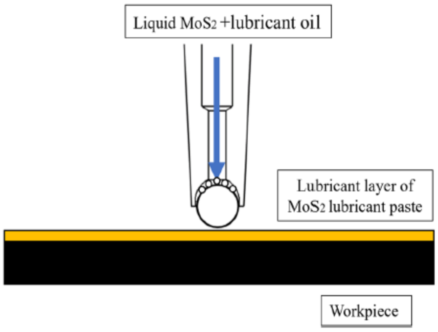


Figure 14. Schematic of the lubricating system

Tomasz Trzepieci et al. 2021 utilized SPIF often uses traditional deep drawing lubricants. Gear and mineral oils are the principal lubricants for producing aluminum alloy sheets. MoS2 and slipped graphite powder are crucial for titanium and its alloys. Although most lubricants are petroleum-based, SPIF is using more biodegradable vegetable oils (Trzepieciński et al., 2021). Table 3 lists lubricants used in manufacturing and sheet metal forming. It lists research studies on lubricants and which ones worked best in practice.

Table 3. Types of lubricants used in manufacturing and forming processes

Author(s)	Year	Type of lubrication used	Best lubrication found
Abed, Bedan, Noori	2017	Polymer, grease, grease with graphite, MoS2 (Molybdenum disulfide), no lubricant	Grease with graphite, polymer (Abed, 2017)
Premika Suriyaprakan	2013	Grease, oil, dry lubrication	Grease (Suriyaprakan, 2013)
Mohammad Honarpisheh et al.	2019	Ti-N lubricant	Ti-N lubricant (Honarpisheh et al., 2019)
Aseel Hamad Abed et al.	2017	Polymer, grease, grease with graphite, mos2, without lubrication	Grease with graphite (Abed et al., 2017)
Afshin Fatemi & Bijan Mollaei Dariani	2023	Hydro-assisted lubrication	Hydro-assisted lubrication found to be effective (Fatemi & Mollaei Dariani, 2024)

Forming Force in Single Point Incremental Forming

To build specialized machinery, use modified equipment, or set up online process control systems, it is necessary to estimate the incremental sheet forming force. Metal sheets can split and lose some of their precision when subjected to forming stress (Li et al., 2017). The outcome of spindle speed, tool diameter, and step down on Single Point Incremental Forming (SPIF) with various wall angle geometry in various bending situations was investigated by Bagudancha et al. (2013). The findings presented that tool diameter increases highest forming force because of a bigger tool-sheet contact area. An axial force of 3581.40 N is possible for a 20 mm tool diameter, however greater spindle speeds diminish it. As the step-down rises, the forming force rises as well because more material must be distorted. A 0.5-mm step down requires 3581.40 N. Lower friction and temperature lower forming force at higher spindle speeds, improving material formability. Maximum axial force at 1000 rpm: 2525.10 N. Last, a fixed spindle speed increases tool-blank friction, which raises forming temperature. To prevent sheet failure, the bending conditions-dependent forming force evolution could be applied (Bagudanch et al., 2013).

Pengyang Li et al. (2016) examined how ultrasonic vibration impacts SPIF forming forces, which improves sheet metal precision and surface quality as depicted in Figure 15 the ultrasonic vibration spindle device. ABAQUS program simulated how ultrasonic vibration frequencies and amplitudes affected forming force. In Figure 16, we can see illustrates the ultrasonic vibration system. To verify simulation results, a US-SPIF experimental setup was created.

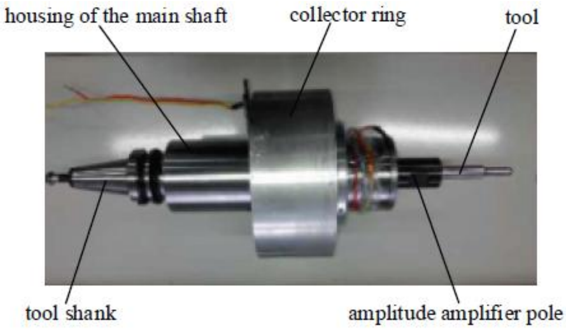


Figure 15. Ultrasonic vibration spindle device

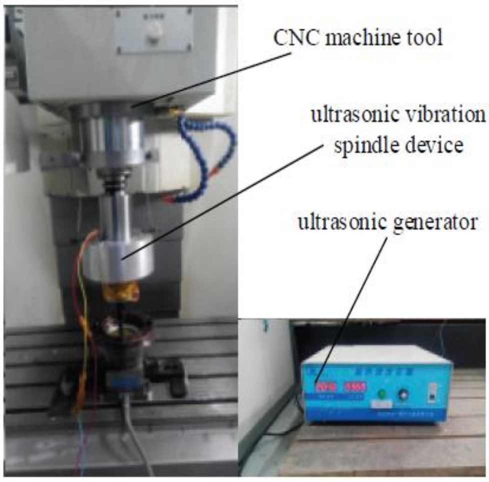


Figure 16 Ultrasonic vibration system

Ultrasonic vibration greatly lowered SPIF formation force. When ultrasonic vibration amplitude rose from 5 to 50 µm, the mean axial force fell by 20-30%. Reduced forming forces increased sheet metal surface quality. The forming force decreased by 15% at 30 µm amplitude and 606 W power, and by 30% at 50 µm and 1203W power. Simulations applied the stress-strain curve of Q235 material, which has a young modulus of 203 GPa and a tensile strength of 391 MPa. This shows that ultrasonic vibration can improve SPIF efficiency and quality by reducing forming forces and enhancing product surface smoothness (Li et al., 2017).

Sheet Material

Researchers are becoming increasingly interested in sheet material due to its efficacy. Formability varies according on the information provided by Fratini et al. Writers have attempted to determine how material qualities affect formability (Tabibian & Najafabadi, 2014). After reviewing the research, for formability and ISF, the most important factors were strength coefficient (k) and strain hardening exponent (n). As material strain hardening exponents vary. Geometry shows that formability increases with hardening coefficient (Bhatt et al., 2016).

An outline of the many facets of ongoing research on SPIF of lightweight materials technology was given by Trzepieci et al. (2021) . The SPIF study focuses on aluminum because of its exceptional formability. Second-class alloys are those made of aluminum. The least studied metals are magnesium alloys and titanium and its alloys. Methods involving high temperatures were able to improve the formability of these materials. There are just two fundamental test object forms that are utilized: truncated pyramids and truncated cones. Most of the time, hemispherical instruments are utilized (Trzepieciński et al., 2021).

Tool Force

Table 4 presents research on Single Point Incremental Forming (SPIF)of metal sheets, concentrating on the optimal operating parameters like rotational speed (rpm), step size (mm), and feed rate (mm/step). It lists the best combinations of these parameters used by different researchers to achieve the superior outcomes in accordance to formability, surface finish, and tool wear reduction. Table 4 also provides reasons for selecting these specific values in each study. Table 4 presents the optimal operating parameters.

Table 4. The optimal operating parameters

Author	Year	Operating speed (rpm)	Feed (mm/step)	Step size (mm)	Best speed and feed	Reason
Skjoedt et al.	2007	35	0.5	0.5	Speed: 35 rpm, Feed: 0.5 mm/step	Dummy plate minimized tool wear and reduced bulging in steel sheets; however, the formability decreased by 5° compared to traditional SPIF (Skjoedt et al., 2007)
Malwad, Nandedkar	2014	1000	1500	0.5	1000 rpm, 1500 mm/min, 0.5 mm	A medium step size helped achieve better formability and surface uniformity for AA8011 sheet metal (Malwad & Nandedkar, 2014)
Ajay Kumar, Vishal Gulati	2018	1000	1000	0.2	1000 rpm, 1000 mm/min, 0.2 mm	Optimal for minimizing forming forces on AA2024-O sheets. A small step size combined with moderate speed/feed helps avoid excessive thinning (Kumar & Gulati, 2018)
Vikas Sisodia, Shailendra Kumar	2018	0	2000	0.7	No spindle speed, 2000 mm/min	The dummy sheet significantly reduced surface roughness while step size had a notable effect; larger step sizes increased roughness (Sisodia & Kumar, 2018)
Pratheesh kumar Sa & Elangovan Sa	2019	100	3000	0.2	3000 mm/min, 0.2 mm	Surface quality and profile precision were both improved by increasing the feed rate and decreasing the step size, balancing rapid stretching with minimal surface imperfections (Pratheesh Kumar & Elangovan, 2019)

Tool Size

Table 5 discusses the consequence of tool diameter in Single Point Incremental Forming (SPIF). It lists different tool diameters used in various studies, identifies the optimal diameter, and explains the reasons for choosing this diameter.

Table 5. Consequence of tool diameter in single point incremental forming (SPIF)

Author's name	Year	Tool diameter diameter used (mm)	Best size/diameter	Reason for best diameter
Ajay Kumar et al.	2020	3 sizes (7.52, 11.60, 15.66 mm)	7.52 mm	Requires the least forming force (Kumar et al., 2020)
Vishal Gulati et al.	2016	2 sizes (8 mm, 12 mm)	8 mm	Provides better formability (Gulati et al., 2016)
Ajay Kumar et al.	2020	7.52, 11.60, 15.66	7.52 mm	Lower forming forces are required for smaller diameters, enhancing process efficiency (Kumar et al., 2020)

Table 5 highlights that smaller tool diameters generally require less forming force, which improves efficiency and process control in metal forming.

Conclusion

Progress in Incremental Sheet Forming (ISF), particularly the Single Point Incremental Forming (SPIF) variant, marks a significant milestone in the evolution of flexible metal manufacturing. SPIF offers notable advantages such as cost-effectiveness, the elimination of dedicated dies, and the ability to produce highly customized and complex geometries directly from CAD models. These features make it particularly suitable for low-volume production in sectors like aerospace, biomedical, and automotive engineering. However, based on the reviewed literature and our own analysis, we believe that SPIF still faces critical challenges that hinder its broader industrial adoption. These include surface roughness, geometric inaccuracies, prolonged cycle times, and a lack of standardized process parameters. Such issues affect repeatability, dimensional control, and scalability, especially in high-volume production contexts.

To overcome these limitations, further research is necessary in the areas of advanced lubrication systems, tool geometry refinement, and toolpath optimization. Additionally, we see the future of SPIF in the integration of intelligent control systems, AI-driven process optimization, and hybrid forming strategies. These developments, in our view, are essential for transforming SPIF from a prototyping-focused method into a robust, reliable solution for industrial-scale manufacturing.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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