ADVANCEMENTS AND CHALLENGES IN INCREMENTAL FORMING: A COMPREHENSIVE REVIEW OF PROCESS OUTPUTS

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ABSTRACT

This paper describes earlier studies on the advantages of the incremental sheet forming process. Types of this process are Single-Point Incremental Forming (SPIF), Two-Point Incremental Forming (TPIF), Multi-Point Incremental Forming (MPIF), Double-Sided Incremental Forming (DSIF) and Incremental Sheet Folding with its advantages and applications. It has been shown that the two types of single-point and two-point operations are the most used by researchers, and this depends on the application. These processes are characterized by the fact that they do not require mold or support, so they are considered one of the best processes for manufacturing complex and small parts within a short period of time compared to traditional forming processes. These processes are suitable for different types of materials, including metals, polymers, and ceramics, but not alone, but rather as a composite material with metals. As a literature review some of the process parameters that affected on process output such as, formability, forming force, accuracy and surface roughness were discussed. Final thoughts on the literature found through this review will serve as the researchers' foundation for added investigation.

Keywords: **Incremental forming process, Formability, dimensional Accuracy, surface roughness.**

NOMENCLATURE

r	tool radius
f	feed rate
z	step over
FE	finite element

ISF incremental sheet forming.

SPIF single point incremental forming

TPIF two-point incremental forming

ANN artificial neural network

CMM Coordinate measurement machines.

3D three dimensional

TG Relational Analysis

RSM Response Surface Methodology

DOE Design of experiment

INTRODUCTION

Incremental sheet metal forming (ISMF) is a manufacturing process used to shape sheet metal into complex geometries incrementally, layer by layer. When comparing the incremental forming process with the rest of the traditional attics, it is distinguished in that it is formed in only one step and does not require added operations, Trzepieciński et al., 2022.The incremental forming process is carried out using a tool of different shapes and sizes that is controlled by a computer. This tool follows a specific path called the tool path. After that, the plate to be formed is placed and firmly fixed on the frame. Then the tool moves on the plate by gradually applying a certain force until it is obtained. To the shape required to be formed. This process is characterized by great flexibility when forming, so it is used to form complex and small parts in large quantities without the need for specific molds. Therefore, it is considered one of the steps to reduce the cost of production compared to other forming processes. Rath et al., 2023.

One of the most important things that distinguishes the incremental forming process for sheet metal from traditional forming processes such as extrusion, deep drawing, and stamping is its many benefits in terms of formation, which can be explained in the following table, table. 1

Table 1: Features of Incremental sheet Metal Forming process.

Feature	Specifics
Versatility and Flexibility	ISF is used to forming prototypes and complex shapes without need to any mold using single tool moved on the suitable tool path, so its time conserving with low-cost production. while conventional forming process required special mold for each shape needed.
Reduced Setup Time and Cost	Because ISF doesn't need any dies this reduces the cost of make dies and time preparing so it’s very beneficial for industries that required different products shapes with low cost.
Material Savings	ISF process reduced material waste because it forms metal sheets step by step without removing a part of metals this contribute to reduced material waste and time saving
Design Iteration and Customization	ISF suitable for design iteration and customization this mean changes for design included directly without need for new die.
Suitable for Low-Volume Production	ISMF is well-suited for low-volume and niche production scenarios, where the cost of developing dedicated dies in traditional methods may not be justified.
No Spring back Issues	In traditional forming methods, materials often experience springback, leading to deviations from the desired shape. ISMF typically shows less springback, resulting in improved dimensional accuracy and reduced need for secondary forming operations
No Wrinkling or Tearing	ISF can deal with materials that have low ductility or thinner sheet so it reduced the risk of tearing and wrinkling and that can be happened in traditional forming processes such as deep drawing
Shorter Lead Times	ISF doesn’t required any dies, so no time required to make mold so turnaround directly to production steps

Complex Shapes with Minimal Tooling	ISMF enables the production of complex three-dimensional shapes with minimal tooling complexity. This makes it ideal for creating prototypes, customized parts, and artistic sculptures

Incremental sheet metal forming has different types, and each type has advantages, characterization, and applications. some of them are summarized in table 2.

Table 2: Types of Incremental Forming, Advantages and Application.

Type of Incremental Forming	**Advantages**	**Application**
Single-Point Incremental Forming (SPIF) Fig. (1)	- Versatility - Low Setup Costs	- Rapid Prototyping - Customized Components
Two-Point Incremental Forming (TPIF) Fig. (1)	- Improved Control - Larger Parts	- Complex Aerospace Components - -Automotive Panels
Multi-Point Incremental Forming (MPIF), Kumar et al., 2023	- Higher Production Rates - Reduced Cycle Times	- Architectural Components - Consumer Goods
Double-Sided Incremental Forming (DSIF), Ullah et al. ,2023	- Symmetrical Parts - Increased Efficiency	- Household Utensils
Incremental Sheet Folding	- Complex Folded Shapes - Reduced Springback	- HVAC Ducting - Furniture Design
Incremental Tube Forming	- Complex Tubular Components - Reduced Material Waste	- Aerospace and Automotive
Hybrid Incremental Forming	- Enhanced Formability - Reduced spring back	- Automotive Body Panels

All things considered, incremental sheet metal forming provides a more flexible, economical, and agile method of producing sheet metal, which makes it a desirable option for businesses looking to streamline operations, cut waste, and react quickly to design modifications and client requests.

Effect of Parameters on Incremental Forming:

Incremental sheet metal forming (ISMF) can be influenced by several factors. The most important factors that affect ISF are:

1. **Feed Rate**: There is an increase in the stress rate at high feed rates, which leads to high deformation and thus affects the geometric accuracy of the final shape.
2. **Tool Path**: The final sample shape is greatly influenced by the tool path, which varies depending on the type of incremental forming process, Ullah et al., 2023.
3. **Tool Shape**: The diameter of the tool, the degree of its curvature, and the point of contact between it and the metal plate greatly affect the shape of the final product , Trzepieciński et al., 2022.
4. **Step Size**: The amount of material that is gradually distorted at each pass of the forming tool is decided by the step size. While smaller step sizes may result in improved dimensional accuracy and surface polish, they may also lengthen processing times.
5. **Material Properties**: How a material reacts to the forming process depends on its properties, including its kind of metal, thickness, ductility, and strain hardening tendency. To obtain the intended effects, some materials can need forming parameter changes, Kharche and Barve, 2022.
6. **Tool Temperature**: Sometimes, during ISMF, heating the sheet metal or the forming tool might help to improve material flow and lessen forming forces, Mohanraj et al., 2023.
7. **Clamping and Support**: Precise shaping and the avoidance of excessive vibrations depend on the clamping and supporting of the sheet metal. The dimensional accuracy of the part might be affected by the kind and stiffness of the clamping mechanism, Kumar et al., 2023.
8. **Lubrication**: To lowering friction between the sheet metal and the forming tool, lubricants can improve surface quality and minimize tool wear, Van Sy and Van Viet, 2022.
9. **Machine Dynamics**: The forming process may be affected by the ISMF machine's dynamic behavior, which includes its stiffness and control system. Stable machine dynamics are a necessary part to obtain regular and correct machining ,Bârsan et al., 2022.

10. **Part Geometry**: The choice of process variables depends on the complexity of the shape of the part to be formed. Some shapes may need significant modifications to prevent cracks and tearing, Frikha et al., 2022.

To obtain products of high quality and geometric accuracy, the variables of the spot forming process must be carefully selected and the characteristics of the effect of each variable on the final product must be known and how to improve them.

Materials Used in the Incremental Forming Process

The incremental forming process is not limited to only metallic materials or those with high ductility. This process has developed greatly, making it possible to deal with many metals and alloys, as well as some non-metallic materials such as plastics and ceramics, which are used as a reinforcement material with metal-based composite materials.

1**. Metals:**

- Aluminum, Trzepieciński et al., 2023.
- Steel, Mohanraj et al., 2023.
- Copper Dizajyekan, et al., 2023
- Titanium, Trzepieciński et al., 2022
- Magnesium, Mohanraj et al., 2023, Magdum et al., 2022.

2. **Alloys:**

- Brass (Marini et al., 2022), (Oraon et al., 2023).
- Bronze
- Stainless steel, Vinoth et al., 2022.

3. **Non-metals:**

- Plastics, such as ABS or PLA, Kharche, and Barve, 2022.
- Composite materials, Rath and Schüppstuhl, 2023.
- Definite ceramics, Pratheesh et al., 2022.

When a material is to be shaped, the extent of its ductility must be taken into account, as this process makes it easy to produce a material with high flexibility, but depending on the rest of the process variables, such as the thickness of the sheet used and the complexity of the required shape, as these variables can be dealt with by changing the path of the tool used to deal with the thickness of the material.

The researchers conducted many tests to decide the extent of the effect of process variables, such as tool diameter, step size, path type, tool shape, and others, on the scientific outcomes represented by formability, geometric accuracy, forces, and others. These studies will be included in the next section as a literature review.

Literature Review in Process Outputs:

In the incremental molding process, formability is the key element, which depends on the desired product design. To form components correctly and securely, it is standard procedure to estimate increased formability of parts formed during the SPIF process. There exist several more rationales for examining the formability of the component, including the verification of formed part quality by the direct correlation between plastic strain and work-piece stress levels and local deformation. Kumar and Gulati, 2018. Although there has been a lot of study done in the last few years, it is still difficult to perfect the SPIF process for better response due to the absence of a thorough insight into the effects of the parameters. Investigating the formability is a very important way to understand how the ISF process deforms. The failures occur when the forming depth of the part is high during incremental forming. As a result, formability can be decided by the forming depth. By examining the forming depth of the parts that formed, Golabi and Khazaali, 2014 looked at the formability of conical frustums. For SS304 sheets, forming depth and wall angle were decided about the effects of tool diameter and sheet thickness. The results showed that the developing depth of conical frustums increased as sheet thickness increased. in fact, that the material is only slightly deformed during this ISF process, the effect of tool diameter on the component's forming depth was determined to be very little. Additionally, it was shown that as feed rate and step size were reduced, formability increased. The effects of angular step size (3, 5 and 7) during TPIF on FeP04 sheets were examined by Fiorentino et al., 2009. Li Y, Liu, Daniel, and Meehan, 2014 used the aluminum sheet type AA7075-O to investigate the effect of tool diameter on forming depth. They find that forming depth is inversely proportional to step size while increasing with an increase in tool diameter. Up until the sheet material fractured, a grove-like shape was formed. Results from experiments and finite element (FE) simulations were compared by Lora, and Schaeffer, 2014. The findings showed great agreement. Lu et al., 2015 expanded an analytical model to investigate the material formability and deformation behavior while accounting for the supporting force during two side incremental process and the relative positions of the main and minor tools. Material formability can also be examined about the forming wall angle of the part. In this method, pieces are molded up until sheet metal begins to fracture. At the fracture depth, the greatest wall angle is measured, Kurra et al., 2015 studied the formability of steel sheets that were previously formed by deep drawing process using incremental forming to create varied wall angle pyramid frustums (VWAPF) of different geometrical shapes. Limiting angle and fracture depth were used to evaluate formability. It was discovered that the elliptical generatrix increased the components' formability.

Warm temperatures can boost the formability of hard-to-form materials, according to certain researchers. Honarpisheh et al., 2016 experimental investigation of the electric hot-assisted SPIF method was supported by numerical outcomes. As a result of the increased contact area between the tool and sheet, this decreased the current density and so the current density. Also noticed formability fallen with rising wall angle, step size, and tool diameter. This resulted in a reduction in heat generation.

For 65Cr2 sheets with 0.5 mm thickness, Duflou et al., 2008 investigated the effects of locally dynamic heating using the laser assisted SPIF technique on the formability of the generated parts. Results showed that using a laser to help SPIF allowed parts to be successfully formed up to a 64-degree wall angle, while a 57-degree wall angle was the maximum for components created using SPIF at ambient temperature. Mohammadi et al., 2016 conducted a study on the impact of various heat treatment settings and warm forming mechanisms on the formability of the forming parts during the SPIF. some researchers used laser as a heating medium one of them are Lehtinen et al., 2015 to investigate material formability at different temperature for various types of materials such as Cu, AL, SS. Kumar et al., 2019 investigated how is formability affected by different parameters, such as tool shape and diameter, tool rotation, formed wall angle, step down size and sheet metal thickness. It was discovered that as tool diameter increased, formability also did so. The formability of the pieces was improved by tools with a flat-end and larger side radii. The decrease in formability was caused by an increase in step size and wall angle. Increased spindle speed and sheet thickness considerably improved the formability, allowing for the successful formation of fracture-free components. Ghorbani-Menghari et al., 2022 presented the impact of tool diameter and forming temperature on spring-back and dimensional accuracy of manufactured parts. It was concluded that spring-back amount fell with increase in tool diameter and when temperature was rose from 25 to 200 while for dimensional accuracy it was concluded that it decreased with the wall depth increase.

Iseki, 2001 was one of the first few scientists to use a straightforward approximated deformation analysis to find the forming forces for a pyramid based on a plane-strain deformation. After that, Jeswiet, Duflou, and Szekeres, 2005. investigated the force magnitudes of the pyramid and truncated cone during SPIF and TPIF. In their force study, Filice et al., 2006 divided tangential force into three groups: monotonically declining, polynomial, and steady-state force. Dabwan et al., 2016 demonstrated that the sheet thickness, followed by tool diameter and step-down size, is the primary factor in predicting the forming force. It has become out that forming force estimation does not depend much on feed rate. According to Duflou et al., 2007, the forming forces rise as sheet thickness, forming wall angle, and step-down size decrease. According to Bagudanch et al., 2013, the bending condition affects the forming force. They also discovered that as spindle speed increases, the forming force reduces. Finite element analysis was used by Arfa et al., 2013 and Henrard, et al.2011 to accurately forecast the SPIF forces. Based on the registered force data, Ingarao et al., 2012 evaluated and estimated the energy usage for the SPIF process. Petek et al., 2009 investigation and localization of the fracture involved a skewness function analysis of the response force. According to the force sensed throughout the forming process, Fiorentino, 2013 offered a different failure criterion. Furthermore, Ambrogio et al., 2006 suggested that failure in SPIF could effectively be preceded by the gradual rise in force necessary to reach its maximum value.

As an alternative to conventional methodologies, the development of models that can analyze the effects of input elements on performance outputs has recently attracted more attention Anwar, 2017 and Do, V. C, 2017. To forecast the forming forces in SPIF, this research suggests a smart process model built on the idea of data collecting. The constraints of this procedure have been overcome by many researchers; however, the end products are of poor quality. To the best of our knowledge, an adaptive-neuro fuzzy inference system (ANFIS) and an artificial neural network (ANN) have not been considered in prior research, but they serve as the foundation for the prophetic model for the forming forces proposed in this literature. To regulate the process quality, a precise model that predicts the forming forces in SPIF is needed. The 2019 study by Ali Alsamhan et al. examined the effects of four distinct process parameters on the maximum forming force: step size, tool diameter, sheet thickness, and feed rate. It was concluded the tool diameter, step size, and sheet thickness have percentage effects of 7.25%, 6.42%, and 8.98% respectively. The effect of some process variables such as plate thickness, feed rate, tool rotation speed, tool diameter and step size on forming force was studied by Maheshwar et al., 2019. They used Taguchi theory to conduct several experiments. The results were as follows: The thickness of the sheet greatly affects the axial forming force, followed by the step size.

Surface roughness during the incremental shaping process is affected by many variables, including the feed rate, the spindle rotation speed, the depth of the step size, the diameter of the tool used, and the property of the metal sheet used. Through some studies, some conclusions were obtained, including: The diameter of the tool and the speed of the spindle greatly affect the surface roughness, as the larger the diameter and the higher the spindle speed, the greater the roughness, in contrast to the small step size and high feed rates, which give a softer and smoother surface. Therefore, balancing is necessary. Between the variables when choosing to obtain a smooth surface, Mohanty et al., 2019 conducted investigations on the effect of step size and feed rate on surface roughness and formability at a certain angle. They built an artificial neural network (ANN) model for forming an aluminum plate of type AA5052-H32 with a thickness of 1.2 mm. It was discovered that the maximum value of Ra is 0.99807 and the expected value is 0.98913, proving a tight relationship for the chosen rate. It was discovered that lowering the forming angle and step depth can reduce surface roughness. Increases in step depth and scallop height result in lines on the portion being left unformed. The feed rate can be kept constant because it has no impact on surface roughness. In comparison to the other two characteristics, step depth has a greater impact on forming time. Although the forming time shortens as step depth increases, surface roughness does not. The forming angle barely affects the forming time. Forming time gets shorter as the feed rate rises. Step depth is a major factor that influences the forming process and surface quality. Mariem Dakhli et al., 2019 to obtain the best possible set of many process parameters, such as step-down size, feed rate, rotation speed, lubrication type and sheet type, the Taguchi Grey Relational Analysis (TG) and Response Surface Methodology (RSM) are used. The main effect graphs show that the level 1 material sheet yields the highest main effect for the grey grade. The SPIF process has a best parameter condition where the sheet material is copper, the rotation speed is 500 rpm, the feed rate is 900 mm/min, the step increment is 0.25 mm, and the lubricant is Oil 1. The process is significantly affected by the feed rate, which also causes Ra to grow. For finding the best parameter for the SPIF Taguchi approach of DOE and its impact on Surface finish and wall thickness, P.B. Uttarwar et al., 2015 used many process parameters (factors) such as wall angle, feed rate, spindle speed, and step increment. For a larger wall angle, more thickness reduction can be obtained. While thickness reduction is dependent simply on wall angle, surface roughness is dependent on both step increment (Depth) and wall angle.

By perfecting process variables such as feed rate, step down, tool diameter, and spindle speed, Echrif et al., 2015 built a prognosis model for minimizing the value of surface roughness. To create a smoother surface by considering the greater tool diameters and lower step down the results were analyzed using ANOVA and DOE that was based on the Taguchi method. The primary parameters that this study specifies are the 30 mm tool diameter and the 0.25 mm step size. The experiment's findings show that tool size, step downsize, spindle speed, and feed rate have the biggest effects on surface roughness. Radu and Cristea, 2013 used DC01, AA1050, and AISI304 as examples of the materials and investigated how step size, tool diameters, feed rate, and spindle speed affected the surface roughness of the components created using SPIF. They decided that the surface roughness has improved after statistically analyzing all the gained results and the main effect charts. It is also possible to consider variables such the largest tool diameters, feed rate, variable spindle speed, and smallest step size. As we mentioned previously, the piece is formed gradually in incremental point formation. Therefore, process variables are carefully selected to obtain the geometric accuracy needed for the final shape. Geometric accuracy is affected by several factors, Terlau et al., 2022, Qadeer et al., 2023, Oraon et al., 2023, Zhan et al., 2022 and Bharti et al., 2022 including:

1. **Tool Deflection**: The force exerted by the forming tool during incremental forming may result in deflection, particularly when working with deep draws or intricate designs. Inaccurate geometries may arise from this deflection, particularly in the workpiece's deep or narrow sections.

2. **Material Springback**: Many of the materials used in incremental forming have a spring-back characteristic, which implies that following deformation, they usually revert to their earlier shape. The springback must be compensated appropriately to avoid a workpiece with inaccurate dimensions and an incorrect finish.

3. **Tool Wear**: Repeated use of the tool may cause wear that resulted from friction between the tool and the workpiece, and thus a correct final shape is not obtained, and errors also occur during the shaping process.

4. **Process Instabilities**: Unstable changes in process parameters such as rotation speed, tool path, and feed rate lead to scientific instability. During shaping, the material expands unevenly or wrinkles because of the instability.

5. **Effects of friction:** High friction between the tool and the plate leads to inaccuracy of the final shape.

6. **Geometry Complexity**: The incremental forming process is characterized by its ability to form metal sheets with sharp angles and complex shapes.

7. **Material Properties**: Materials vary in their ability to be formed, as most metals are characterized by their high plating, which contributes to their ease of formation compared to other materials.

8. **Toolpath**: It is necessary to choose a suitable tool path and plan it well because insufficient planning leads to uneven deformation of the sheet.

9. **Fixture and Workpiece Clamping**: It must be ensured that the workpiece is well fixed before starting work, because poor fixation during the shaping process leads to not obtaining the product with the required accuracy.

To obtain a product with high accuracy, manufacturers rely on the use of simulation programs such as FEA to predict springback and tool wear and corrosion, along with designing an accurate tool path to prevent exposure to machining problems, the most important of which is the accuracy of the final shape. Originally, a few researchers proposed a method of changing hardware that includes adding components to better control material deformation. Attanasio et al., 2008. It was suggested that backing plates be used.

The blank holder was likewise made of epoxy resin, which drastically lowered the production cost and required amount of die material. They worked with a table that features a die-holding frame and a moveable blank holder. Fiorentino et al., 2009, they used a table with a die-holding frame and a moveable blank holder. M. Bambach et al., 2009 They used multistage forming to create a pyramidal part and discovered that it was more accurate than single stage forming. There were three distinct multi-stage techniques found. The pre-form, the intermediate stages, and the final shape are all used in these tactics. Duflou et al., 2008 and Ambrogio et al., 2004 have investigated both the one-stage and multi-stage approaches.

Finally, a small number of researchers concentrated on the third form of customized rolled blank Hirt et al., 2004 or partly cut-out blank Allwood et al., 2010, which is the alteration of the blank stiffness to produce higher geometric precision. Researchers employed two distinct approaches to test the geometric accuracy of the items produced using the ISF process. To measure geometrical correctness, the first tool is a 3D scanning device. Coordinate measurement machines (CMM) come in second, Walaa, 2019.

CONCLUSION

According to several studies, ISF is appropriate for the majority of industrial applications when using a sheet with a thickness of less than 1 mm. However, the time-consuming nature of this process has led many academics to find ways to speed up the formation process. The time it takes to build an idea can be significantly reduced after using the multipoint tool technique, thus creating a multipoint tool is crucial. Although many studies have been conducted, there is still a gap between empirical research and its practical application. Process improvement should focus on speeding up production and reducing process costs in order to overcome such problems through process improvement on speeding up production and reducing process costs. Process parameters like sheet thickness, tool diameter, spindle speed, etc., have a significant impact on forming strength. Only experimentation was used to study this; however, an in-depth examination with physical interpretation is needed. Predicting formation strength using FE simulations is a process that takes a lot of time. In literature, the analytical method is incredibly rare. Therefore, it is necessary to propose a reliable model for the ISF operation.

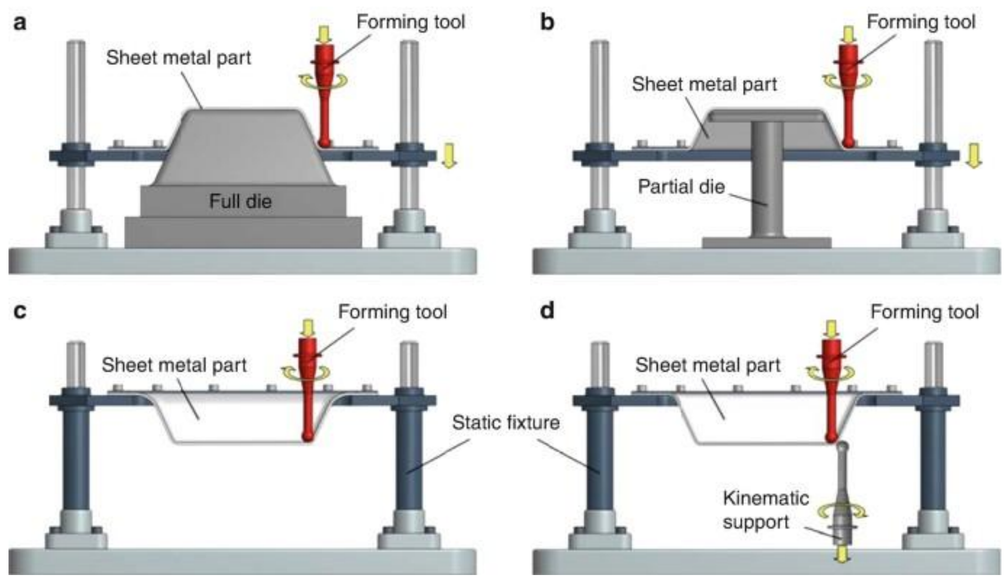

Figure 1: different types of incremental forming process: (a) TPIF full die, (b) TPIF partial die, (c) SPIF and (d) SPIF with counter tool. (Sami et al., 2019).

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