Available on https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.10 Issue 2 Page No 51-58

Enhancing Sheet Metal Forming Through Ultrasonic-Assisted Incremental Techniques: A Comparative Analysis of SPIF and TPIF

[1] Thokale Manoj J, [2] Dr. Neeraj Kumar, [3] Dr. A. Haldar
Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
[1] manojthokale@gmail.com
[2] neeraj.kumar1@mygyanvihar.com

Abstract— This study compares Ultrasonic Assisted Single Point Incremental Forming and Two-Point Incremental Forming processes in sheet metal fabrication. These techniques are gaining popularity due to their flexibility and cost-effectiveness in producing complex shapes without dedicated dies. However, limited formability and surface quality persist, prompting further investigation. This research integrates ultrasonic vibrations into SPIF and TPIF processes and develops a multi-stage tool path strategy to address these challenges. The primary objectives include enhancing formability, improving surface finish, and evaluating the effectiveness of ultrasonic assistance. The study explores the role of ultrasonic vibrations in multi-stage incremental forming, examining their impact on material deformation, stress distribution, and surface integrity. Comparative analysis focuses on forming groove-shaped and spherical components, systematically varying parameters such as number of stages, feed rate, step depth, and frequency amplitude. Insights from this research are expected to advance the field of sheet metal forming by optimizing these techniques for industrial applications, thereby enhancing manufacturing efficiency and product quality. Preliminary findings suggest that UA-TPIF exhibits a significantly greater reduction in forming forces compared to UA-SPIF, possibly due to localized sheet thickness reduction where ultrasonic oscillations are applied. UA-SPIF, on the other hand, allows for membrane vibration of the entire sheet, potentially distributing ultrasonic energy more uniformly across the material. These observations highlight the nuanced effects of ultrasonic assistance on different incremental forming techniques and underscore the importance of optimizing process parameters for achieving desired outcomes in sheet metal fabrication.

Keywords— Incremental Sheet Forming, Single Point Incremental Forming, Two-Point Incremental Forming, Double Sided Incremental Forming

I. INTRODUCTION

Research is currently investigating the effects of ultrasonic vibrations on incremental sheet forming (ISF), a technology utilized in sheet metal fabrication to shape complex surfaces gradually without the need for dies. This process stabilizes the material through a complex stress state, reducing necking and expanding the sheet forming limit compared to traditional methods like stamping and hydroforming. In ISF, a blank holder secures the sheet along its edges. A common tool, which is frequently hemispherical, then deforms the sheet locally along a predefined path to gradually achieve the required final shape. ISF is classified into three main types based on tool configuration. First, SPIF (Single Point Incremental Forming) is known for its simplicity and flexibility, utilizing a single versatile tool to shape sheet metal without the need for specialized dies. This flexibility makes it ideal for small batches or prototypes. Second, Two-Point Incremental Forming (TPIF) utilizes a tool alongside a partial or full die, offering greater control over sheet thickness through adjustments like the squeeze factor.

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

TPIF provides more precise deformation compared to SPIF due to the die's guiding influence. Third, DSIF (Double-Sided Incremental Forming) employs two independent tools to deform the sheet, enabling complex shaping and improved precision by applying forces from both sides. DSIF enhances the ISF process's capability for intricate geometries and higher part accuracy.

A spiral toolpath is commonly employed to shape cone structures. Dieless NC forming, sometimes known as SPIF, was developed in response to the requirement for rapid, adaptable technology for small and medium-sized businesses. Based on a concept by Leszak, Matsubara introduced SPIF to the Japanese market. Originally intended for automakers, it has subsequently grown to include a variety of industries, including the automotive, aerospace, and marine sectors. SPIF's versatility extends to medical applications and allows forming at both cold and elevated temperatures. It is utilized for creating complex shell elements and rapidly producing prototypes through Rapid Prototyping (RP) methods.

Ultrasonic vibration has proven highly beneficial in various manufacturing processes, significantly enhancing efficiency and product quality. For instance, Baghlani et al. [4] demonstrated improved material removal rates, reduced drilling forces, and enhanced surface roughness when applying ultrasonic assistance in deep drilling of Inconel superalloys. Similar benefits have been observed in turning [5] and milling [6], where ultrasonic energy optimizes machining by modifying surface friction and transferring energy to the material, resulting in decreased forming forces [11]. It has proven possible to successfully include ultrasonic vibration into conventional forming processes such as wire drawing, deep drawing, upsetting, and extrusion. When applied to the forming tool, vibration alters the frictional dynamics, particularly when it is parallel to the tool's sliding direction, resulting in a more efficient reduction of friction. Smoother movement between surface features is encouraged by this vibration-induced elastic-plastic deformation of surface imperfections, which improves the quality of the surface finish. In the field of ISF, scholars such as Amini et al.

For SPIF, Vahdati et al. have created attachments for CNC machines that add rotary motion and longitudinal ultrasonic vibration. The principle of ultrasonic softening, initially found by Blaha and Langenecker in 1955, was echoed in their tests on aluminum 1050 sheets, which showed reduced forming forces and increased formability with ultrasonic help. This phenomenon, observed across different alloys, involves a reduction in flow stress during plastic deformation under high-frequency vibrations (20-100kHz) and small amplitudes (1-10μm) [11]. The degree of softening varies with the material system, correlating with ultrasonic vibration amplitude or acoustic intensity [19, 24, 25], affecting material properties temporarily during vibration application and potentially influencing residual hardness or softness after processing [21-23].

II. LITERATURE REVIEW

Recent advancements in Single Point Incremental Forming, as discussed by Daniel Nasulea et al., have focused on enhancing the dimensional accuracy and surface finish of formed parts through innovative tool designs and optimized process parameters. The introduction of circumferential hammering tools has shown notable promise in improving material flow and reducing spring-back, thus enhancing overall part accuracy. Research highlights that the shape and movement of the tool significantly influence forming outcomes, with circumferential hammering tools showing superior performance compared to traditional hemispherical ones. Full factorial designs have been used in experimental research to systematically study the effects of many parameters, including component shape, feed rate, and tool spindle speed. These studies have resulted in the development of accurate mathematical models capable of predicting part accuracy. These models have been validated through practical experiments, demonstrating their reliability and highlighting the importance of ongoing innovation in SPIF technology. Yujing Sun et al. conducted a series of experiments aimed at exploring these effects, providing valuable insights into the mechanisms and benefits of ultrasonic-assisted incremental sheet forming (UA-ISF). The study focused on evaluating how ultrasonic vibration influences surface properties and spring-back effects in symmetrical aluminum alloy sheets. [38],

A study by Shamik Basak et al. used a laboratory-scale setup for plastic deformation of AA6061 sheet metal using single-point incremental forming. Regression models were developed in their study using a Box-Behnken design and response surface methodology (RSM). The purpose of these models was to determine the correlations between mechanical outcomes, such as surface roughness, part depth per unit time, angle of failure, and input process parameters [37].

Ajay Kumar and colleagues examined the effects of tool radius and forming angle interactions on the surface roughness of items produced by SPIF. They discovered that average roughness (Ra) often rises with greater forming angles using a full factorial Design of Experiments (DOE) technique. On the other hand, decreasing surface waviness was ascribed to lower Ra values that resulted from increasing the tool diameter [40].

In an effort to increase prediction accuracy, Yanle Li et al. carried out a comprehensive investigation to comprehend the mechanics underlying the softening effect in Ultrasonic Incremental Sheet Forming (UISF). They first developed a theoretical model based on crystal plasticity theory, which describes the interaction between stress and strain when ultrasonic vibrations are applied. This model specifically integrates acoustic softening effects by adjusting parameters related to thermal activation processes and the evolution of dislocation density. [39]

The incorporation of ultrasonic vibration (UV) into incremental sheet metal forming (ISMF) represents a significant advancement aimed at improving material

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

formability and reducing forming forces. Studies indicate that UV can enhance material flow and minimize spring back through acoustoplasticity effects, altering metal deformation behavior under high strain rates. Research by Khan et al. (2013) and Shin et al. (2010) illustrated that UV-assisted forming results in finer grain structures and reduced residual stresses in formed parts. Shan et al. (2014) discussed the development of acoustoplasticity constitutive models, which enable accurate predictions of material responses under UV conditions. Furthermore, Zhou et al. (2017) experimental and numerical studies supported these models and pinpointed important variables that affect forming performance, such as tool size, feed rate, revolution speed, and vibration amplitude. The findings of this study highlight how UV-assisted ISMF can improve the accuracy and productivity of sheet metal forming procedures.

Understanding residual stresses induced during manufacturing is critical, especially in aerospace applications where only compressive residual stresses are acceptable under external loads. A study using Single Point Incremental Forming (SPIF) was carried out by Isaac Jiménez et al. to evaluate residual stresses in aluminum parts. They used X-ray diffraction (XRD) techniques to assess residual stresses on the inner and exterior surfaces of the manufactured pieces. Bending effects were suggested by the results, which showed a shift in stresses from tensile to compressive. The study revealed significant bending stress patterns based on the yield stress of the material. Variations in sheet thickness were also found to have an impact on the microstructural evolution of aluminum parts and to have an effect on the distributions of bending and residual stresses. This underscores the importance of managing residual stresses to ensure the reliability of SPIF-manufactured components [17].

III. TYPES OF FORMING PROCESSES

A forming process involves transforming raw materials into precise shapes or configurations. In a number of industries, including consumer goods, automotive, aerospace, and electronics, this manufacturing method is crucial. The two main categories into which forming techniques are frequently divided are bulk forming and sheet metal forming. In bulk forming, solid materials like billets or bars undergo plastic deformation to achieve desired shapes. Common bulk-forming methods include forging, rolling, and extrusion. Forging involves shaping materials using compressive forces from hammers, presses or dies, often used for producing components such as crankshafts and gears. Rolling passes materials through rotating rolls to alter thickness or cross-sectional shape, used in making sheets, plates, bars, and wires. Extrusion forces materials through the die to create continuous profiles like pipes and tubes with constant cross-sections. Sheet metal forming processes shape thin metal sheets into complex forms through plastic deformation while maintaining sheet thickness. Key sheet metal processes include Bending, Deep Drawing, and Stamping. Bending deforms metal along a straight axis to form angles or shapes, commonly used in fabricating brackets, enclosures, and automotive parts. Deep drawing transforms flat sheet metal into three-dimensional shapes like cups or boxes by drawing it into a die cavity with a punch, widely used in manufacturing kitchen utensils, cans, and automotive components. Stamping presses sheet metal between dies and punches to create shapes with features such as holes, slots, and flanges, a standard method for producing various industrial parts.

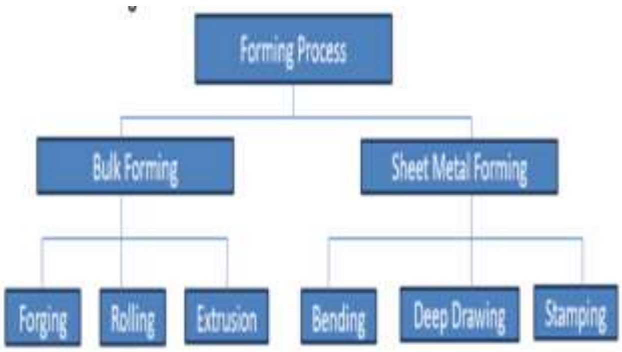

Fig. 1 Forming process

Single point incremental forming:

In contrast to conventional methods that employ fixed dies and punches, incremental forming is a sheet metal shaping process where the part is molded incrementally by deforming the sheet material locally. In this method, the sheet metal is shaped using a tool that is CNC-controlled. A versatile, dieless technique for processing sheet metal that involves non-uniform deformation and localized dynamic loading is called single point incremental forming (SPIF). It overcomes drawbacks like long design times, large space requirements, high development costs, and restricted flexibility inherent in conventional stamping methods with advantages like great flexibility, low forming force requirements, and quick design cycles. However, SPIF encounters challenges such as localized stresses that can lead to sheet instability, wrinkling, and cracking, which have impeded its widespread adoption in industrial applications. Researchers such as Shrivastava and Tandon [4] have utilized advanced techniques like X-ray diffraction (XRD) and electron backscattered diffraction (EBSD) to analyze microstructural features and strain patterns during different stages of Single Point Incremental Forming (SPIF). Their studies have identified common failure modes in sheet metals subjected to biaxial strain conditions. Some alternative forming techniques have been researched in an effort to improve formability and get around some of the shortcomings of SPIF. The techniques include electromagnetic incremental forming, hot incremental forming, double-sided incremental forming, and hybrid approaches. Beyond what SPIF alone can accomplish, these techniques seek to increase the formed sheet metals' efficiency and surface quality.

.

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

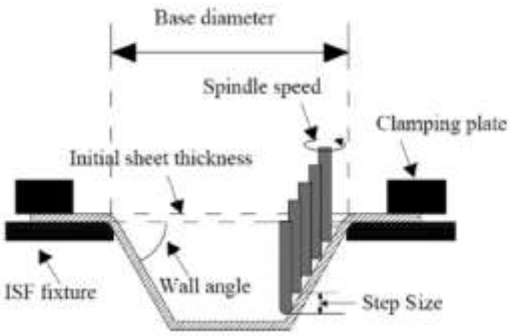

Fig. 2 A diagram illustrating the SPIF process [25]

The incremental forming process begins with setting up a flat sheet metal workpiece, typically made from ductile materials like aluminum or steel, which is securely clamped onto a fixture or movable table capable of multi-axis adjustment. A CNC-controlled forming tool, such as one with a spherical or hemispherical tip tailored to the part's shape requirements, is then employed. This tool moves over the sheet metal surface, applying localized pressure and displacing material according to a pre-programmed tool path in the CNC system. As the tool moves incrementally in small steps, the sheet metal undergoes deformation, involving stretching, bending, and thinning to achieve the desired shape. This process is iterative, often requiring the tool to revisit specific areas multiple times to refine and ensure the accuracy of the part's geometry.

Twin point incremental forming:

The Two-Point Incremental Forming (TPIF) process involves two points of contact: one between the sheet and the forming tool, and the other between the sheet metal and an auxiliary tool or die. Either a whole die (Figure 3c) or a partial die (Figure 3b) can be used by TPIF. In contrast to Single Point Incremental Forming (SPIF) (Figure 3a), TPIF improves the accuracy of components that are created. The shaped sheet's edges are secured with additional movement in TPIF methods (Figure 3b, c), It permits wall thickness adjustment and increases part geometric precision. SPIF involves moving an additional spindle, offset by the thickness of the sheet and positioned opposite the forming spindle, along a corrected trajectory with regard to the main tool using a counter tool (Figure 3d). TPIF with a full die is referred to as positive incremental forming; negative incremental forming refers to the other techniques.

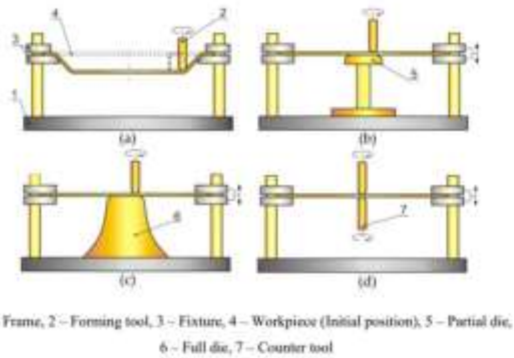

Fig. 1 Processes of incremental forming (a) SPIF, (b) TPIF, (c) TPIF with a full die, and (d) TPIF with a counter tool

Incremental forming provides several advantages over conventional sheet metal forming methods:

Incremental forming offers several advantages over traditional forming processes. Firstly, its flexibility stems from eliminating the need for dedicated dies, allowing manufacturers to efficiently produce intricate and low-volume components. This capability supports rapid prototyping and enables easy modifications to part designs as needed. Secondly, incremental forming significantly reduces setup time and associated costs due to minimal tooling and equipment requirements, making it highly suitable for small-scale production runs. Thirdly, the process promotes material efficiency by minimizing waste and optimizing the use of sheet metal resources, thereby reducing costs and environmental impact. Lastly, the formability of sheet metal is enhanced by localized deformation in incremental forming, making it possible to fabricate parts with complex forms and a range of thicknesses that may be challenging to accomplish with traditional techniques. Overall, these benefits position incremental forming as a versatile and efficient manufacturing technique suitable for a range of applications across industries.

Incremental forming has several limitations:

Incremental forming, despite its advantages, presents several challenges that impact its applicability in manufacturing. Firstly, its slower production speed compared to traditional farming methods results from the incremental movements of the tool, making it less suitable for high-volume production where efficiency is paramount. Secondly, the process is constrained by material thickness limitations, performing best with thin to moderately thick sheet metals up to 7mm thick. Thicker sheets require multiple passes, prolonging processing times and reducing overall efficiency. Thirdly, incremental forming may yield surface finishes that are less smooth than those achieved through traditional methods, necessitating additional finishing operations to achieve desired surface quality

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

standards. These factors highlight considerations that manufacturers must weigh when choosing between incremental forming and other manufacturing techniques based on production volume, material requirements, and desired surface finish.

Depending on how the tool moves and deforms the material, there are two main types of incremental forming:

1. Single-point incremental forming: This approach employs a single tool or stylus to reshape sheet metal by moving methodically across its surface, exerting localized pressure to shape the material. SPIF can be further classified into two subtypes:

a. Conventional single-point incremental forming: Here, the tool moves in a linear or curvilinear path, following the desired contour of the part. The tool typically rotates around a fixed point or follows a predefined path.

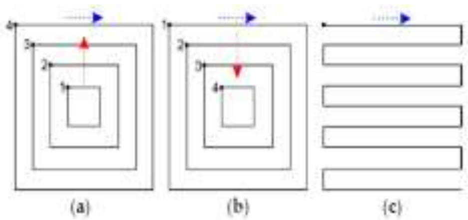

Fig.4 The three toolpath strategies [8]

b. Radial single-point incremental forming: In this subtype, the tool is mounted on a rotating arm that moves radially. The tool follows a spiral path, gradually shaping the sheet metal.

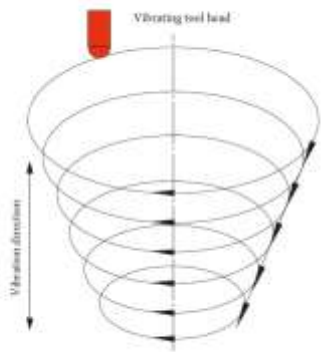

Figure 5. Forming track on radial single-point incremental forming [1].

2. Two-point incremental forming: This method uses two forming tools or styluses. One tool holds the sheet metal in place, while the other applies deformation by pressing against the sheet. The tools may move independently or in coordination to shape the part. TPIF offers better control over the deformation process and can achieve more complex geometries compared to SPIF.

Both SPIF and TPIF have unique advantages and applications. SPIF is simpler in terms of tooling and setup, making it suitable for rapid prototyping, small-scale production, and less complex parts. TPIF provides more precise control and is used for creating parts with higher complexity and tighter tolerances. Incremental forming is a versatile process, and variations and combinations of these methods are continually being explored and developed by researchers and manufacturers to enhance their capabilities and meet specific manufacturing needs.

Ultrasonic Vibration-Assisted Sheet Metal Forming:

Ultrasonic vibration-assisted sheet metal forming combines conventional sheet metal forming techniques with ultrasonic vibrations to enhance metal deformation and shaping. This method improves material flow, reduces forming forces, and enhances the metal's formability. High-frequency vibrations, typically exceeding 20 kHz, are applied to either the forming tool or the workpiece. Ultrasonic transducers or embedded piezoelectric elements within the forming tool are commonly used to introduce these vibrations.

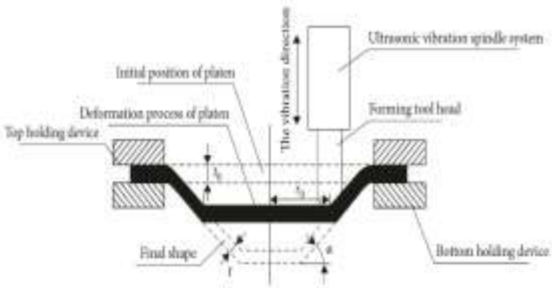

Figure 6. UV- SPIF technology schematic [7]

Advantages:

Ultrasonic vibration-assisted sheet metal forming stands as a major leap in manufacturing technology, providing numerous advantages. Firstly, it improves the formability of sheet metal by decreasing its yield strength and enhancing ductility. This allows for the fabrication of intricate, complex-shaped parts with minimal spring back. Second, applying ultrasonic vibrations reduces forming forces by reducing friction between the workpiece and the forming tool. This lowers the amount of energy used during the shaping process and increases the tools' lifespan. Thirdly, by breaking up surface oxides and reducing interfacial friction, ultrasonic vibrations promote smoother material flow during forming, thereby reducing the occurrence of defects such as wrinkling or tearing. Lastly, these vibrations contribute to an improved surface finish on the formed parts by minimizing surface roughness and tool marks, which is crucial for applications requiring high-quality surface aesthetics and functionality. Overall, ultrasonic vibration-assisted sheet metal forming offers manufacturers enhanced capabilities in producing precise, high-quality components across various industries including automotive, aerospace, and electronics. Ultrasonic vibration-assisted sheet metal forming is utilized in various industries, including aerospace,

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

automotive, electronics, and medical device manufacturing. It is especially valuable for forming challenging materials, such as high-strength alloys or materials with low formability.

Multi-Stage Tool Path Strategy:

A multi-stage tool path strategy, also known as a multi-pass tool path strategy, is a manufacturing technique used in processes like machining and forming to achieve the desired shape or surface finish of a part through multiple sequential tool paths. Instead of completing the entire operation in a single pass, the process is divided into several stages, with each stage progressively refining the workpiece.

Benefits:

Utilizing a multi-stage tool path strategy in manufacturing processes provides several notable advantages. Firstly, dividing the operation into multiple stages enhances control and precision by allowing for incremental material removal. This approach results in more accurate dimensions and superior surface finishes compared to single-pass methods. Secondly, the strategy enables the achievement of smoother surface finishes by progressively reducing tool engagement and step-over distance in each stage. This capability is particularly valuable in applications where high-quality surface aesthetics are critical. Thirdly, the distribution of load across multiple passes in the multi-stage approach reduces tool wear, thereby extending tool lifespan and reducing operational costs associated with frequent tool replacements. Lastly, minimizing cutting forces through reduced material removal rates in each stage helps to diminish vibrations and enhance overall process stability, contributing to improved machining and forming outcomes. These benefits highlight the effectiveness of multi-stage tool path strategies in optimizing manufacturing efficiency, precision, and tool longevity across various industrial applications.

Implementing a multi-stage tool path strategy in manufacturing varies depending on the process and desired outcomes. In machining operations such as milling or turning, this approach may include using increasingly smaller cutting tools, reducing cutting depths, or employing finishing passes. These methods aim to achieve precise dimensions and high-quality surface finishes. In sheet metal forming, such as single-point incremental forming, a multi-stage tool path can gradually shape the sheet metal, with initial stages focusing on rough shaping and subsequent stages refining the geometry for tighter tolerances. In additive manufacturing, a multi-stage tool path strategy can enhance surface quality by starting with thicker layer heights for faster printing, followed by finer layer heights for a smoother finish. The selection and optimization of this strategy depend on factors such as the material, the desired outcome, and the capabilities of the manufacturing equipment. By meticulously planning and executing each stage, manufacturers can achieve greater accuracy, better surface finishes, and overall improved efficiency in their operations.

IV. METHODOLOGY

To achieve the research objectives, the methodology depicted in Fig. 6.1 is implemented. First, the single-point and two-point incremental forming processes with the assistance of ultrasonic vibrations are set up. This configuration consists of attaching a fixture to the VMC machine spindle and integrating an ultrasonic generator. An intricate tool path strategy is created for the component's formation using specialized software. Subsequently, the sheet metal blank is prepared by cutting it to the specified dimensions. The validation of the multi-stage tool path strategy for forming a spherical-shaped component is conducted through experimental testing. Experimental results, including circle grid analysis and thickness distribution, are compared with Finite Element (FE) simulation data. Additionally, an experimental design is created using the (Design of Experiments) method in order to generate a straight groove-shaped component. Experiments are executed based on this plan, with subsequent measurements taken. The obtained experimental outcomes are then compared against the results from FE simulations.

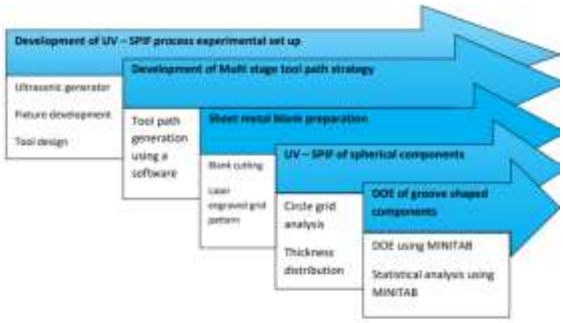

Fig 7 Proposed plan of work

V. CONCLUSIONS

Combining ultrasonic vibrations with SPIF (Single Point Incremental Forming) and TPIF (Two-Point Incremental Forming) marks a substantial progression in sheet metal forming. This study aims to fill crucial gaps in current understanding by investigating the impact of ultrasonic vibrations on SPIF and TPIF processes, focusing particularly on groove-shaped and spherical components. Key findings indicate that ultrasonic vibration-assisted forming improves the deformation and flow characteristics of the metal, resulting in enhanced formability, reduced spring back, and lower forming forces. This study provides important insights into optimizing the forming process for various industrial applications by a methodical investigation of input variables such as forming stages, feed rate, step depth, and frequency amplitude. By

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

comparing ultrasonic-assisted SPIF and TPIF processes, it delineates the unique benefits and constraints of each method, facilitating informed decisions on technique selection according to specific manufacturing requirements. The improved material characteristics and operational efficiency provided by ultrasonic vibration-assisted forming present an attractive solution for manufacturing high-quality, intricate metal components in sectors like automotive, aerospace, electronics, and medical devices. The sheet metal forming technologies are greatly advanced by this research, leading to more accurate, efficient, and flexible manufacturing processes. The research emphasizes how ultrasonic vibration-assisted incremental forming can revolutionize the way complex and high-performing metal components are made, enabling modern manufacturing companies to keep up with changing demands.

REFERENCES

[1] Mingshun, Yang, Bai Lang, Lin Yunbo, Li Yan, Yuan Qilong, and Zhao Renfeng. "Research on the radial accuracy of ultrasonic vibration-assisted single point incremental forming parts." International Journal of Aerospace Engineering 2019 (2019).

[2] Cheng, Randy, Nicholas Wiley, Matt Short, Xun Liu, and Alan Taub. "Applying ultrasonic vibration during single-point and two-point incremental sheet forming." Procedia Manufacturing 34 (2019): 186-192.

[3] Duflou, Joost R., Anne-Marie Habraken, Jian Cao, Rajiv Malhotra, Markus Bambach, Dave Adams, Hans Vanhove, Amirahmad Mohammadi, and Jack Jeswiet. "Single point incremental forming: state-of-the-art and prospects." International Journal of Material Forming 11 (2018): 743-773.

[4] Shrivastava, Parnika, and Puneet Tandon. "Microstructure and texture-based analysis of forming behavior and deformation mechanism of AA1050 sheet during Single Point Incremental Forming." Journal of Materials Processing Technology 266 (2019): 292-310.

[5] Shamsari, Mohsen, Mohammad Javad Mirnia, Majid Elyasi, and Hamid Baseri. "Formability improvement in single point incremental forming of truncated cone using a two-stage hybrid deformation strategy." The International Journal of Advanced Manufacturing Technology 94 (2018): 2357-2368.

[6] Jackson, Kathryn, and Julian Allwood. "The mechanics of incremental sheet forming." Journal of materials processing technology 209, no. 3 (2009): 1158-1174.

[7] Jadhav, Sanjay. Basic investigations of the incremental sheet metal forming process on a CNC milling machine. Shaker, 2005.

[8] Baghlani, V., P. Mehbudi, J. Akbari, and M. Sohrabi. "Ultrasonic assisted deep drilling of Inconel 738LC superalloy." Procedia Cirp 6 (2013): 571-576.

[9] Gallego-Juárez, Juan A., Karl F. Graff, and Margaret Lucas, eds. Power ultrasonics: applications of high-intensity ultrasound. Woodhead Publishing, 2023.

[10] Siddiq, Amir, and Elaheh Ghassemieh. "Thermomechanical analyses of ultrasonic welding process using thermal and acoustic softening effects." Mechanics of Materials 40, no. 12 (2008): 982-1000.

[11] Behera, Amar Kumar, Ricardo Alves de Sousa, Giuseppe Ingarao, and Valentin Oleksik. "Single point incremental forming: An assessment of the progress and technology trends from 2005 to 2015." Journal of Manufacturing Processes 27 (2017): 37-62.

[12] Lu, Haibo, Michael Kearney, Yanle Li, Sheng Liu, William JT Daniel, and Paul A. Meehan. "Model predictive control of incremental sheet forming for geometric accuracy improvement." The International Journal of Advanced Manufacturing Technology 82 (2016): 1781-1794.

[13] Martins, P. A. F., Niels Bay, Martin Skjødt, and M. B. Silva. "Theory of single point incremental forming." CIRP annals 57, no. 1 (2008): 247-252.

[14] Amini, Saeid, Ahmad Hosseinpour Gollo, and Hossein Paktinat. "An investigation of conventional and ultrasonic-assisted incremental forming of annealed AA1050 sheet." The International Journal of Advanced Manufacturing Technology 90 (2017): 1569-1578.

[15] Mingshun, Yang, Bai Lang, Lin Yunbo, Li Yan, Yuan Qilong, and Zhao Renfeng. "Research on the Radial Accuracy of Ultrasonic Vibration-Assisted Single Point Incremental Forming Parts." International Journal of Aerospace Engineering 2019, no. 1 (2019): 9809815.

[16] Al-Ghamdi, Khalid A., and G. Hussain. "On the free-surface roughness in incremental forming of a sheet metal: A study from the perspective of if strain, surface morphology, post-forming properties, and process conditions." Metals 9, no. 5 (2019): 553.

[17] Slota, Ján, Bogdan Krasowski, Andrzej Kubit, Tomasz Trzepiecinski, Wojciech Bochnowski, Kazimiera Dudek, and Miroslav Neslušan. "Residual stresses and surface roughness analysis of truncated cones of steel sheet made by single point incremental forming." Metals 10, no. 2 (2020): 237.

[18] Alinaghian, Mahnoush, Iman Alinaghian, and Mohammad Honarpisheh. "Residual stress measurement of single point incremental formed Al/Cu bimetal using incremental hole-drilling method." International Journal of Lightweight Materials and Manufacture 2, no. 2 (2019): 131-139.

[19] Chang, Zhidong, and Jun Chen. "Investigations on the deformation mechanism of a novel three-sheet incremental forming." Journal of Materials Processing Technology 281 (2020): 116619.

[20] Amini, Saeid, Ahmad Hosseinpour Gollo, and Hossein Paktinat. "An investigation of conventional and ultrasonic-assisted incremental forming of annealed AA1050 sheet." The International Journal of Advanced Manufacturing Technology 90 (2017): 1569-1578.

[21] Bai, Lang, Yan Li, Mingshun Yang, Zimeng Yao, and Zhiyuan Yao. "Influences of Process Parameters

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com

and Vibration Parameters on the Forming Force in the Ultrasonic-Assisted Incremental Forming Process." Advances in Materials Science and Engineering 2018, no. 1 (2018): 5726845.
[22] Trzepieciński, Tomasz, Valentin Oleksik, Tomaž Pepelnjak, Sherwan Mohammed Najm, Imre Paniti, and Kuntal Maji. "Emerging trends in single point incremental sheet forming of lightweight metals." Metals 11, no. 8 (2021): 1188.
[23] Nasulea, Daniel, and Gheorghe Oancea. "Achieving accuracy improvements for single-point incremental forming process using a circumferential hammering tool." Metals 11, no. 3 (2021): 482.
[24] Li, Yanle, Weidong Zhai, Zijian Wang, Xiaoqiang Li, Lingling Sun, Jianfeng Li, and Guoqun Zhao. "Investigation on the material flow and deformation behavior during ultrasonic-assisted incremental forming of straight grooves." Journal of Materials Research and Technology 9, no. 1 (2020): 433-454.
[25] Zhang, Liangchi, Chuhan Wu, and Hossein Sedaghat. "Ultrasonic vibration–assisted incremental sheet metal forming." The International Journal of Advanced Manufacturing Technology 114, no. 11 (2021): 3311-3323.
[26] Jiménez, Isaac, Cecilio López, Oscar Martinez-Romero, Pedro Mares, H. R. Siller, J. Diabb, Jesús A. Sandoval-Robles, and Alex Elías-Zúñiga. "Investigation of residual stress distribution in single point incremental forming of aluminum parts by X-ray diffraction technique." The International Journal of Advanced Manufacturing Technology 91 (2017): 2571-2580.
[27] Gatea, Shakir, and Hengan Ou. "Surface roughness analysis of medical grade titanium sheets formed by single point incremental forming." The International Journal of Advanced Manufacturing Technology 114, no. 9 (2021): 2975-2990.
[28] Alsamhan, Ali, Adham E. Ragab, Abdulmajeed Dabwan, Mustafa M. Nasr, and Lotfi Hidri. "Prediction of formation force during single-point incremental sheet metal forming using artificial intelligence techniques." PloS one 14, no. 8 (2019): e0221341.
[29] Slota, Ján, Bogdan Krasowski, Andrzej Kubit, Tomasz Trzepiecinski, Wojciech Bochnowski, Kazimiera Dudek, and Miroslav Neslušan. "Residual stresses and surface roughness analysis of truncated cones of steel sheet made by single point incremental forming." Metals 10, no. 2 (2020): 237.
[30] Ostaševičius, Vytautas, Vytautas Jūrėnas, Darius Eidukynas, Valdas Grigaliunas, Marius Gudauskis, Ieva Palevičiūte, and Vidmantas Ambrasas. "Peculiarities of the robotised incremental metal and polymer sheets forming." In 2020 International Conference Mechatronic Systems and Materials (MSM), pp. 1-3. IEEE, 2020.
[31] Azhiri, R. B., F. Rahimidehgolan, F. Javidpour, R. M. Tekiyeh, S. M. Moussavifard, and A. S. Bideskan. "Optimization of single point incremental forming process using ball nose tool." Experimental Techniques 44 (2020): 75-84.
[32] Amar, AL-Obaidi, Andreas Kunke, and Verena Kräusel. "Hot single-point incremental forming of glass-fiber-reinforced polymer (PA6GF47) supported by hot air." Journal of Manufacturing Processes 43 (2019): 17-25.
[33] Oleksik, Valentin, Dan Dobrota, Sever-Gabriel Racz, Gabriela Petruta Rusu, Mihai Octavian Popp, and Eugen Avrigean. "Experimental research on the behaviour of metal active gas tailor welded blanks during single point incremental forming process." Metals 11, no. 2 (2021): 198.
[34] An, Zhi-guo, Dong Yan, Jian-jian Qie, Zai-liang Lu, and Zheng-yuan Gao. "Effect of process parameters on formability of a AZ31 magnesium alloy thin-walled cylindrical part formed by multistage warm single-point incremental forming." Frontiers in Materials 7 (2020): 151.
[35] Barnwal, Vivek Kumar, Shanta Chakrabarty, Asim Tewari, K. Narasimhan, and Sushil K. Mishra. "Forming behavior and microstructural evolution during single point incremental forming process of AA-6061 aluminum alloy sheet." The International Journal of Advanced Manufacturing Technology 95 (2018): 921-935.
[36] Basak, Shamik, K. Sajun Prasad, Amarjeet Mehto, Joy Bagchi, Y. Shiva Ganesh, Saurav Mohanty, Ajay M. Sidpara, and Sushanta Kumar Panda. "Parameter optimization and texture evolution in single point incremental sheet forming process." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 234, no. 1-2 (2020): 126-139.
[37] Sun, Yujing, Zhenyun Lu, Chao Li, Rongtao Wang, and Weidong Zhai. "Study on the springback effect and surface property for ultrasonic-assisted incremental sheet forming of aluminum alloy." Symmetry 13, no. 7 (2021): 1217.
[38] Sun, Yujing, Zhenyun Lu, Chao Li, Rongtao Wang, and Weidong Zhai. "Study on the springback effect and surface property for ultrasonic-assisted incremental sheet forming of aluminum alloy." Symmetry 13, no. 7 (2021): 1217.
[39] Kumar, Ajay, Vinay Singh, Sujata Nayak, Amit Kumar, Ankit Tyagi, and Anita Sharma. "Impact of process variables on surface roughness in negative incremental forming process." Materials Today: Proceedings 50 (2022): 930-934.
[40] Zhai, Weidong, Yanle Li, Zinan Cheng, Lingling Sun, Fangyi Li, and Jianfeng Li. "Investigation on the forming force and surface quality during ultrasonic-assisted incremental sheet forming process." The International Journal of Advanced Manufacturing Technology 106 (2020): 2703-2719.

Correspondence to: Thokale Manoj J, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: manojthokale@gmail.com