Hybrid Multi-Axis Forming of Sheet Metals: Toolpath-Driven Innovations for Die-Less Thin-Walled Component Fabrication

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Abstract: Recent advancements in sheet metal forming have unlocked the potential for manufacturing intricate thin-walled components without the use of conventional dies. This paper explores a novel hybrid forming process that integrates deformation machining (DM) with incremental sheet metal forming (ISMF), focusing on multi-axis systems capable of double-sided toolpath execution. A custom-designed 8-axis configuration comprising four axes on both the upper and lower sides, each equipped with spindle rotation, enabled the fabrication of monolithic impeller-type geometries through synchronized top and bottom tooling, achieving high dimensional accuracy and surface quality. The methodology emphasizes algorithm-based toolpath generation, springback compensation, and process parameter analysis. The proposed hybrid process offers a cost-effective and flexible alternative to traditional die-based forming, with significant implications for low-volume production of complex geometries.

Keywords: Hybrid Forming, Deformation Machining (DM), Incremental Sheet Metal Forming (ISMF), Thin-Walled Structures, Multi-Axis Toolpath, Springback Compensation, CNC Forming, Die-Less Manufacturing

I. INTRODUCTION

Recent advancements in sheet metal forming have enabled the die-less fabrication of complex, thin-walled geometries with high flexibility and cost efficiency. Processes such as Deformation Machining (DM) and Incremental Sheet Metal Forming (ISMF)-particularly its variant Single Point Incremental Forming (SPIF)-have emerged as powerful alternatives to conventional forming techniques. These hybrid approaches combine cutting and forming actions, allowing the direct production of intricate components from CAD models using CNC toolpaths, without the need for dedicated dies.

However, the machining of thin-walled structures remains a challenge due to their low static and dynamic stiffness, which leads to deformation, reduced accuracy, and thermal instability. To address these issues,

Recent research has focused on developing toolpath strategies and error compensation methods that mitigate deflection and enhance dimensional precision. A critical review of the literature reveals a growing interest in hybrid forming techniques and toolpath optimization for multi-axis systems, highlighting their potential to revolutionize the manufacturing of complex, lightweight geometries in a single, efficient setup.

Advancements in sheet metal forming technologies have enabled the fabrication of complex, thin-walled geometries without the need for dedicated dies. Several studies have investigated the forming mechanisms, toolpath strategies, and mechanical behavior associated with such geometries. Notably, processes such as Deformation Machining (DM) and Incremental Sheet Metal Forming (ISMF) have gained significant attention due to their flexibility and cost-effectiveness. Hybrid forming-utilizing both machining and forming tools-offers a promising alternative to conventional die-based methods, particularly for complex geometries and low-volume production.

1.1 Background of Incremental Sheet Metal Forming (IMSF)

The Single Point Incremental Forming (SPIF) process was started in 1967 [1]. Started from the year 2001 was evident at the starting point of the research in SPIF. It was in 2004 when Young and Jeswiet (2004) predicted the process and named it SPIF. Later, they distinguished the process from those conventional forming techniques that utilize progressive dies for bulk-forming operations. The deformation mechanisms of both SPIF and TPIF are stretching and shear. The Stretching is in the plane vertical to the tool direction, and with shear in the plane parallel to the tool direction [2], [3], [4]. The history starts with the early research work in 1978–1996; these early developments used only SPIF. Historical second: 1993–2000, this period showed many developments towards modern ISF, including other variants like TPIF. Historical third (2000–2010): This historical period showed increased activities. ISF and spinning are closely related [5]. Studied the force fluctuation, elastic deflection of the sheet metal during the movement of the forming tool, [6]. ISMF simplifies sheet metal forming into a flexible process compatible with any facility using a 3-axis CNC mill. It operates in two modes: single-point forming or dual-point forming with a partial or full die, as highlighted by [7]. The technique holds immense potential for future applications.

1.2 Background of Deformation Machining (DM)

Reported the work on deformation machining as a new hybrid process for producing a thin profile structure using milling machining operations and using ISF forming to obtain the desired thin geometry shape. [8]. A brief review of work on conventional and shear spinning as background for the study of incremental forming processes [9]. They proved that the flexible forming of a sheet metal workpiece is possible by using a hemispherical tool that can be moved along a three-axis CNC mill. [10]. The deformation behavior of an Al–Cu–Mn alloy sheet in uniaxial and biaxial stress conditions was investigated at different cryogenic temperatures [11]. The deformation mechanism of micro-thin-walled structures under mixed boundary states is analyzed [12]. Studies carried out on the significant deformation prediction of mesoscale deformation in milling modeling, micro-thin-wall structure [13]. Propose Deformation Machining (DM) as a rapid manufacturing alternative to conventional techniques, enabling efficient fabrication of customized components during the product development stage by [14].

1.3 Application

Biomedical: Cranial plates, facial and skull implants, orthosis supports, prosthetics (ankle, knee, backseat), [15], [16], [17]. Automobile: Car fenders, taillight brackets, customized and complex thin-walled parts like blades and impellers, [18], [12]. Aerospace & Aviation: Customized structural components, micro-channel cold plates, thin-walled parts (blades, impellers),[8], [19]. Defence: High-precision thin-walled components including impellers, blades, and cold plates, [13,14]. Other Domains: Geometric forms (cones, polygons), flower pot shapes, micro-thin wall constitutive models [20], [21], [13].

Applications of Impeller/Compressor Components

Aviation: Turbojet engine parts – turbine/compressor wheels, blades. Marine & Locomotive: Turbocharger parts – turbine and compressor wheels, diesel engine components. Energy Sector: Gas/steam turbines – wheels, blades, guide vanes. Oil, Gas & Chemical: Pump and compressor parts – various impellers, blower components, guide vanes. Automotive: Car/truck turbocharger parts – turbine/compressor wheels, rotors, blades.

Despite notable progress, substantial work remains in developing integrated machining-forming toolpath strategies for Deformation Machining (DM). [22] Introduced feature-based toolpath algorithms that significantly reduced tool travel distance and thereby shortened the forming time in Incremental Sheet Forming (ISF). These algorithms also yielded a superior surface finish compared to conventional ISF toolpaths. Building on this, [23] Proposed an automatic feature recognition and toolpath generation approach tailored for Double-Sided Incremental Forming (DSIF). Their method employed outline loops to identify and separate features on the component surface, followed by intelligent feature sequencing, which facilitated efficient toolpath planning. Similarly, [24] An advanced novel contour-relation map-based strategy for generating toolpaths for complex multi-feature parts in DSIF. This method enabled effective feature separation and customized forming sequences. To address the tool-sheet contact issues, [25] Introduced a spring-supported mechanism using a pressurized air cylinder to maintain continuous contact between the slave tool and the sheet. This approach improved thickness control and reduced the likelihood of contact loss during forming. These ISF-derived toolpath strategies are highly applicable to the forming stage of DM, where Single Point Incremental Forming (SPIF) principles also apply.

Outline of the literature review

- ISF and DM strategies to obtain thin monolithic geometries
- The significant process and response parameters for DM
- ISF and DM Experimental strategies
- Deformation mechanics and fracture behavior
- Toolpath generation techniques and
- Processes applications of the DM

Several critical research gaps and future directions have been identified in the domain of hybrid sheet metal forming processes, particularly those integrating Deformation Machining (DM) and Incremental Sheet Metal Forming (ISMF):

- Lack of Integrated Process Models: Current studies rarely combine the principles of DM and ISMF into a unified modeling framework, limiting predictive accuracy and process optimization.
- Limited Advancement in Multi-Axis Toolpath Strategies: There is limited research on advanced multi-axis toolpath planning, especially for dual-spindle and synchronized top-bottom forming systems.
- Inadequate Springback and Deflection Compensation: Few studies address real-time or predictive compensation strategies for springback and wall deflection during hybrid forming operations.
- Machining of Low-Rigidity Structures: Complex thin-walled components, especially in aerospace applications, pose significant challenges due to low structural rigidity, requiring tailored forming strategies.
- Forming of Thin-Walled, Low-Stiffness Structures: The machining and forming of low-rigidity components-common in aerospace and precision engineering-pose considerable difficulty due to instability and deformation, requiring novel support and control techniques.
- Need for Intelligent Toolpath Algorithms: An Adaptive algorithm modifies the tool path to partially compensate for the surface profile errors caused by deflection. The surface finish and dimensional accuracy of an ISF part could be improved by using different algorithms to generate the tool path, several types of lubricant, and new tool designs and materials.

This research aims to develop multi-axis toolpath strategies for simultaneous machining and ISF within a single setup, enhancing the efficiency of the Hybrid Deformation Machining (HDM) process. It focuses on reducing component count through monolithic fabrication, exploring HDM-compatible materials for biomedical, aerospace, and automotive applications, minimizing material waste and cost, and formulating analytical models to assess the formability of thin-walled geometries.

II. PROCESS PARAMETERS

Process parameters-including tool geometry, spindle speed, feed rate, and step depth-were carefully selected for both the milling and incremental forming stages to ensure optimal formability and minimal surface roughness. The integration of surface roughness measurement and force monitoring allowed for the comprehensive evaluation and refinement of the DM process.

This section deals with various process parameters related to both incremental forming (IF) for DM processes. Researchers have reported that the formability of the sheet metal increases by decreasing the feed rate of the tool. Ambrogio and Gagliardi [26] state that to enhance the material formability in high-speed ISF an optimal feed rate must be selected to maximize the temperature generated at the sheet tool interface. The spindle speed is the most important parameter as it affects the formability and the surface finish of the formed parts. To date, the effect of various tool sizes and shapes on the ISF process has been studied. This includes the tools with hemispherical, elliptical, ball end, flat end, angled, and parabolic profiles. Surface quality improves with small step depth in the ISF process [27].It is observed from the reported works that the sheet thinning limits the range of possible wall angles to approximately 60° to 65° for most of the applications. Several researchers have reported that the high rotation speed of the forming tool can generate a significant amount of frictional heat. Thus, the friction indicator remains a critical factor that strongly influences the roughness in the forming. If friction increases significantly, it could result in a fracture. The formability of sheet metal is the ability of a material to deform into the desired shape, without exhibiting specific forms of failure. The residual stress distribution is affected by the exerted mechanical and thermal loads on the workpiece during machining. After the forming operation, when the load is removed, an undesirable shape change occurs due to the material's tendency of elastic regaining, which leads to springback. Springback happens during unloading, primarily due to the elastic recovery of the material and leading it to change the shape. Surface roughness is one of the critical response parameters in the ISF and DM processes, and research has been done to find the optimal parameters for minimum surface roughness. Table 1 presents the process and performance parameters of both the Incremental Sheet Forming (ISF) and Deformation Machining (DM) processes. During experiments, the force measurement is carried out for both ISF and DM processes. The deformation forces are measured along the X, Y, and Z directions during the deformation machining of the thin wall structure. There are several ways of measuring the forces in the ISF.

Table 1. Performance parameters of both the Incremental Sheet Forming (ISF) and Deformation Machining

Performance parameters of both the Incremental Sheet Forming (ISF) and Deformation Machining		
Milling machining parameters	**Incremental forming**	
Thin section/ profile machining	Formability	Accuracy
Feed rate (mm/rev)	Tool path	Step size
Stepdown size (Δz)	Feed rate	Tool size
Cutting speed (m/min)	Forming angle	Feed rate
Depth of cut (mm)	Tool size	Spidle speed
Springback effect	Step size	Tool path
Residual stresses	Surface roughness	Blank thickness
Forming force	Forming angle	Dimensional attribute
Milling machining parameters	Step size	Floor thickness
Thin section/ profile machining	Tool size	Floor size
Feed rate (mm/rev)	Tool path	Surface roughness

III. TOOLPATH DEVELOPMENT AND INTEGRATION

To facilitate the Double-Sided Deformation Machining (DSDM) process, two independent toolpaths were developed-one for each spindle (top and bottom) of the 8-axis machine. These toolpaths were designed to perform distinct yet synchronized operations: machining and incremental forming. For each spindle, the corresponding machining and forming toolpaths were integrated into a single, continuous trajectory, ensuring seamless execution during the manufacturing process. Both toolpaths were fed simultaneously to the machine, enabling synchronized top and bottom tool engagement. This dual-sided strategy enhances the uniformity of deformation, improves dimensional accuracy, and reduces residual stresses in the final component. Toolpath generation plays a crucial role in determining the geometric fidelity, surface finish, and overall processing time of the DM process. Therefore, special attention was given to the toolpath development phase. It is also recommended to incorporate angular springback compensation within the toolpath design, particularly in regions with high curvature, to achieve acceptable geometric accuracy after elastic recovery.

3.1 Machining Toolpath Implementation

The initial machining toolpath was generated using Autodesk PowerMILL 2020, offering advanced toolpath strategies for complex geometry. This involved extracting discrete X, Y, and Z coordinates along the arc segments to reconstruct the toolpath using linear movements (G01 commands), ensuring compatibility with the control system while preserving path dependability. Table 2 presents the implementation of machining toolpaths through the generated G-code. This customized approach to toolpath generation allowed for the successful execution of the DM process on the available 8-axis system while maintaining control over key quality parameters such as dimensional accuracy and surface integrity.

Table 2 Illustrates the generated G-code for machining toolpath implementation

Sample G-code is generated using OKUMA OSM postprocessor.	**Extracted coordinates from G-code using Python scripts**
……………………… G03 X19.7281 Y-11.39 I-1.5495 J-1.5257 N4049 G03 X21.0648 Y-14.582 I1.8832 J-1.0873	………………… … X-0.158 Y1.4252 Z1.3064 X-0.1592 Y1.4229 Z1.3064 X-0.1601 Y1.4205 Z1.3064 X-0.1609 Y1.4181 Z1.3064

N4050 G01 X21.2881 Y-14.6137 N4051 G03 X22.1821 Y-14.1141 I0.028 J0.9996 N4052 G01 X23.3142 Y-12.1532 N4053 G03 X23.2999 Y-11.1292 I-0.866 J0.5 N4054 G01 X23.0745 Y-10.8516 N4055 G03 X21.2176 Y-9.9254 I-1.8569 J-1.3984 N4056 G03 X19.2045 Y-13.4123 I0.0 J-2.3246 N4057 G03 X20.935 Y-14.5573 I2.0131 J1.1623 ……………………	X-0.1615 Y1.4155 Z1.3064 X-0.1618 Y1.413 Z1.3064 X-0.1619 Y1.4104 Z1.3064 X-0.1618 Y1.4078 Z1.3064 X-0.1615 Y1.4053 Z1.3064 X-0.1609 Y1.4028 Z1.3064 …………………………… ………

3.2 Toolpath Generation and Visualization: Toolpath generation was carried out using Autodesk PowerMILL, followed by verification and simulation in NC Viewer.

3.2.1 Machining Toolpath Generation and Visualization

Toolpath generation was performed using Autodesk PowerMILL, followed by verification and visualization using NC Viewer. Figure 1 (a-b) shows top and isometric views of the developed toolpath for precision machining of a single fin geometry. These views demonstrate the spatial orientation and trajectory of the tool, highlighting the effectiveness of the multi-axis strategy in achieving accurate and efficient material removal along complex contours. As depicted in Figure 1 (a-b) Both top and isometric views of the toolpath were developed for the machining of a single fin. Building on this, a comprehensive multi-fin toolpath strategy was devised to enable the simultaneous formation of six fins, as shown in Figure 1 (c). To illustrate the coordinated execution, Figure 1 (c) presents an isometric NC Viewer representation, emphasizing the multi-axis synchronized machining operations.

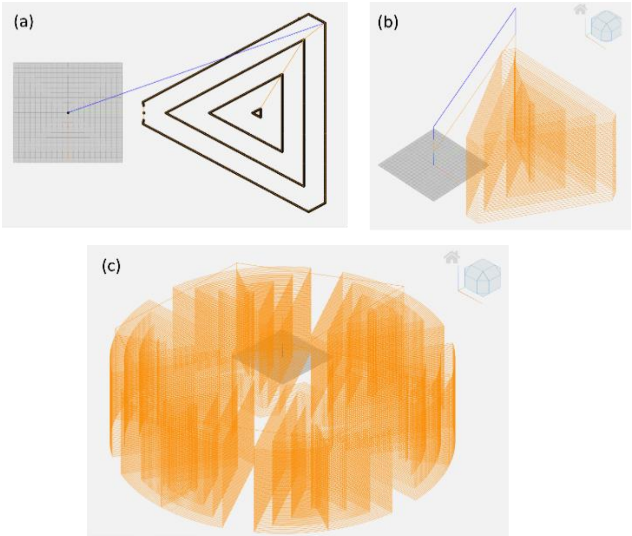

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Figure 1 (a-b). Top and isometric views of the developed toolpath for machining a single fin.

This visualization demonstrates the capability and efficiency of the developed toolpath strategy in generating complex freeform geometries through simultaneous deformation machining using the top spindle.

Figure 1 (a-c) shows the toolpath strategies for machining thin structures to the shapes of preforms, which need to be incrementally formed into the desired shape of the monolithic component. In machining, the tool moves out-to-in and in-to-out alternatively after each depth increment along the top-to-bottom direction. Figure 2 (a-b) Isometric representation of the developed toolpath showcasing synchronized multi-axis machining operations, modeled in CATIA V5.

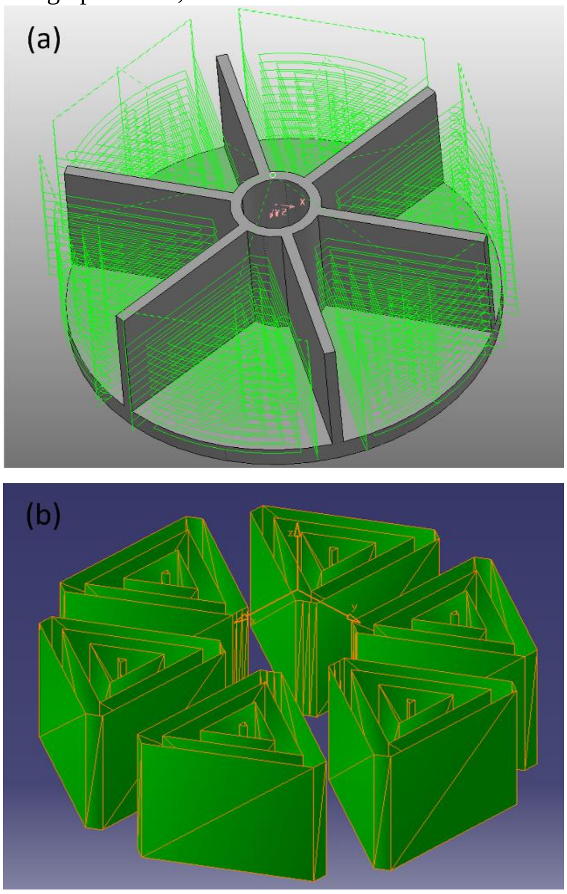

Figure 2 Isometric representation of the toolpath highlighting multi-axis synchronized machining operations developed in CATIA V5

The visualization highlights the coordinated tool movements and spatial complexity involved in generating precise geometries, reflecting the integration of advanced toolpath planning strategies for efficient and accurate material removal. Toolpath generation was carried out using Autodesk PowerMILL, followed by verification and simulation in NC Viewer. A dedicated toolpath was executed in NC Viewer to visualize and assess the machining strategy in detail. Figure 3 (a-b), Isometric wireframe simulation views illustrate the developed toolpath for machining multiple fins using a comprehensive multi-fin strategy. This simulation effectively demonstrates the capability and efficiency of the developed toolpath in generating complex freeform geometries through simultaneous deformation machining using the top spindle.

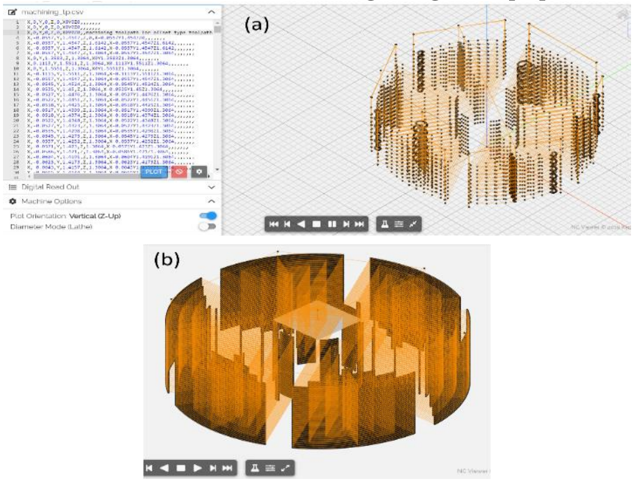

Figure 3 (a-b). Isometric simulation views (wireframe) of the toolpath developed for machining multiple fins using a multi-fin strategy.

3.2.2 Forming Toolpath Generation and Visualization

Toolpath generation for the Deformation Machining (DM) process was carried out using Autodesk PowerMILL, which offers advanced strategies for multi-axis toolpath planning. Figure 4 (a) illustrates the NC Viewer simulation of the toolpath for a single formed fin, showcasing the precise trajectory followed during the incremental forming operation. Figure 4 (b) presents the toolpath strategy for multiple (six) formed fins, highlighting the scalability of the approach for complex multi-feature components. Furthermore, Figure 4 (c) displays the isometric view of the NC Viewer simulation, demonstrating the simultaneous multi-axis execution of both machining and forming operations. This synchronized strategy ensures efficient processing while maintaining the geometric dependability of each fin structure.

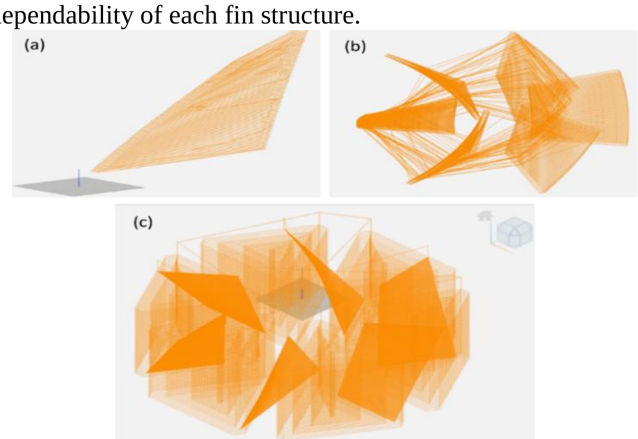

Figure 4 (a-c) Isometric view of multi-axis simultaneous machining and forming toolpath strategies for fin structures, visualized using NC Viewer.

Figure 5 illustrates toolpath strategies of incremental forming (IF) to shape one fin preform into monolithic components with angles of the monolithic components. In the incremental forming operation, the tool moves away from the centre and toward the centre of the component alternatively after each step increment in the bottom-to-top direction. The visualization of the toolpaths for forming toolpath generation and visualization.

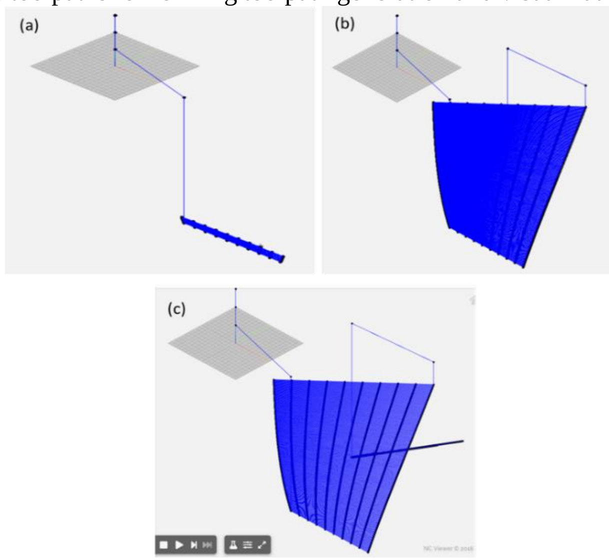

Figure 5 Toolpath strategies for Incremental Forming (IF) to shape one fin preform into monolithic components with angles.

Toolpath generation was performed using Autodesk PowerMILL, with subsequent verification and simulation conducted in NC Viewer. A dedicated toolpath was executed within NC Viewer to visualize and evaluate the forming strategy in detail. As illustrated in Figure 6 the isometric simulation screenshot showcases the toolpath developed for the formation of multiple fins, forming part of a comprehensive multi-fin deformation strategy. This simulation demonstrates the effectiveness and precision of the developed toolpath in shaping complex freeform geometries through deformation machining utilizing the top spindle.

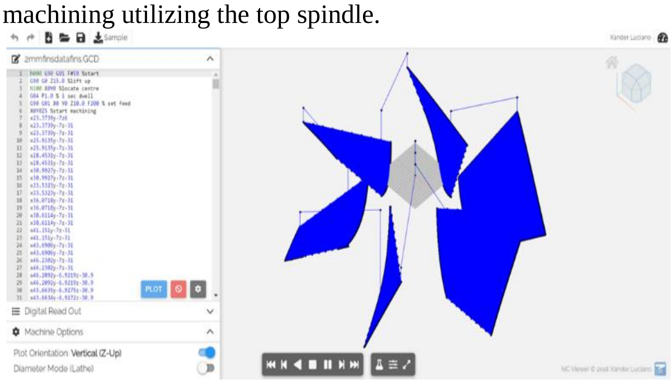

Figure 6 Isometric simulation view illustrating the toolpath developed for forming a multi-fin deformation strategy

IV. METHODOLOGIES

In the Deformation Machining (DM) approach, conventional machining and Incremental Forming (IF) operations are synergistically integrated to connect the advantages of both processes. This integration enables the shaping of complex monolithic components using a single, unified tooling system. The DM technique offers significantly enhanced flexibility over traditional die-based manufacturing, which often faces challenges in producing intricate geometries-especially during the design and prototyping stages. Traditional 3-axis machining systems are inherently limited in their ability to access deep or contoured regions of freeform geometries, making it difficult to generate toolpaths that can produce such features. As a result, conventional toolpath generation techniques are not compatible with the requirements of DM. To overcome these limitations, a novel feature-based, double-sided combined machining–forming toolpath strategy has been developed to enable effective Hybrid Deformation Machining (HDM).

The CAD components fabricated during experimentation simulation include impeller blade-like structures with thin, freeform geometries formed on one or both sides of a monolithic blank. This hybrid approach effectively overcomes the tool accessibility limitations associated with 3-axis systems by leveraging the extended DOF available through IF integration. As shown in Figure 7 (a-b) CAD model and detailed illustration of the custom-designed 8-axis forming machine, developed to perform synchronized multi-axis forming operations. The setup highlights the integration of multiple actuated axes to enable complex deformation paths suitable for forming intricate monolithic geometries

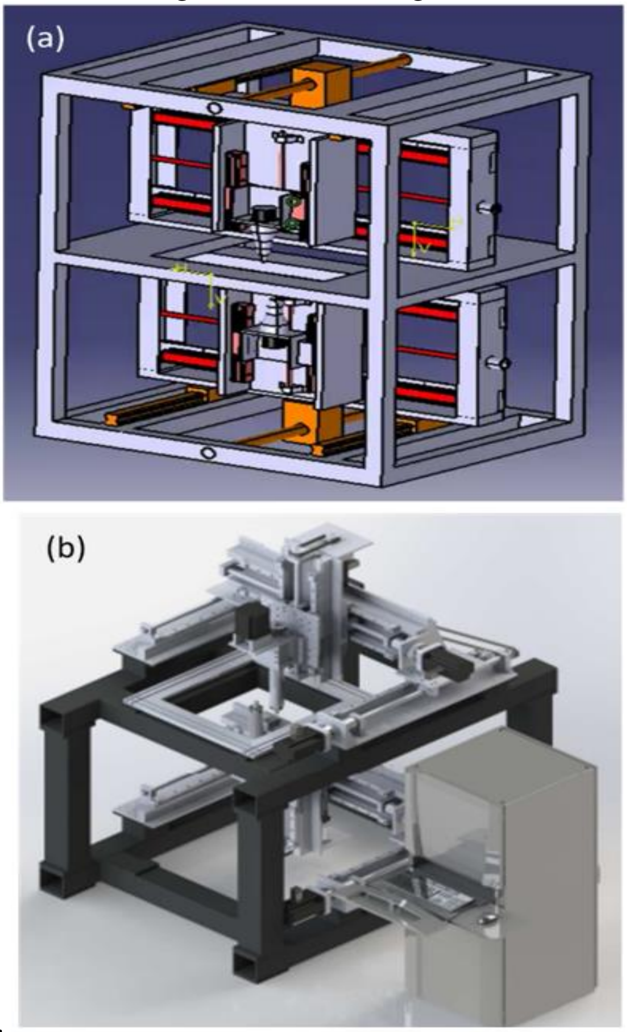

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Figure 7 (a-b) CAD model and illustration of the 8-axis forming machine designed for multi-axis forming operations.

4.1 CAD Geometry Preparation and Toolpath Development:

The CAD geometries of the double-sided impeller-like structure and corresponding preforms, used for toolpath generation, are illustrated in Figure 8 (a-c). In Figure 8 (a), the grey-colored regions represent the final preform geometry obtained after machining. A custom double-sided machining toolpath was generated by slicing the offset surfaces into a tailored section size, shown in tan color. To accommodate an 8 mm diameter milling cutter, the toolpath surfaces were developed by offsetting the internal surfaces of the CAD model by 4 mm, ensuring optimal tool clearance and path accuracy.

Similarly, for the incremental forming (IF) operation, Figure 8 (b) depicts the final formed geometries in grey. For toolpath calculation, the contact surfaces of the blades were offset by a distance equal to the tool radius, allowing accurate determination of tool location points. In this case, an offset of 6 mm was applied to match the 12 mm diameter flat-end forming tool used in the customized IF process. Figure 8 (c) presents the proposed CAD model of the complete impeller-like structure.

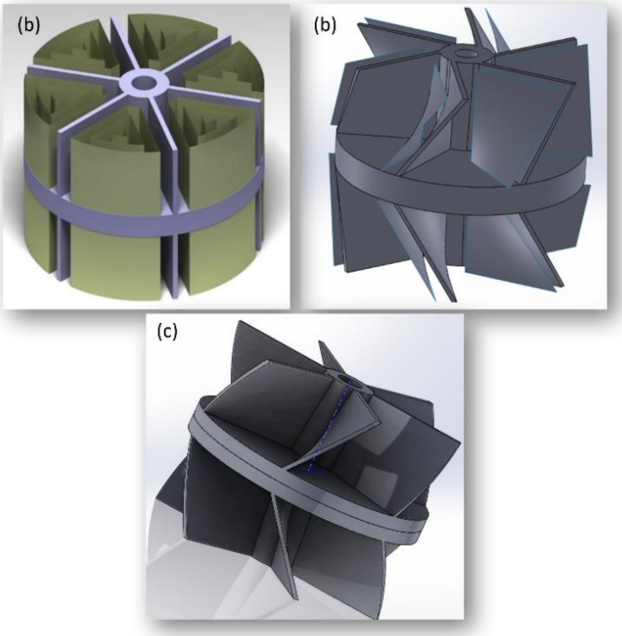

Figure 8 (a-c) CAD geometries related to the double-sided impeller-like component and corresponding preforms used for toolpath generation [28] .

4.2 Rationale for Hybrid Deformation Machining (HDM) of Impeller-Like Structures and Compressor Components:

The manufacturing of impeller and compressor wheel components using Hybrid Deformation Machining (HDM) offers several advantages over conventional techniques, especially for monolithic, complex-shaped parts that traditionally require multi-stage assembly or die casting. The proposed hybrid machining and forming technique offers a high degree of flexibility for the manufacturing of freeform monolithic components. Proposed CAD component with the 12-blade double-sided impellers (6 on each side) with blade thicknesses of 2 mm, experimental simulation with the DSDM technique, is shown in Figure 8 (c). Compressor wheels, including centrifugal and axial types, are typically designed with intake, impeller, and diffuser vanes. These complex features benefit significantly from HDM due to its capacity to precisely form intricate blade profiles on both sides of a disc.

4.3 CAD Modeling of Proposed Impeller/Compressor Components:

The CAD models developed for the proposed components represent both single-sided and double-sided configurations of impeller/compressor wheel structures, optimized for hybrid deformation machining (HDM) operations. As depicted in Figure 9 (a-b), The single-sided configuration illustrates the geometric layout of a monolithic impeller or compressor wheel, featuring radial or backward-curved blades arranged on one surface of the central disc. This configuration is typically used where unidirectional fluid flow or space constraints are dominant factors. The blades are integrated into the top surface, allowing straightforward toolpath development for single-sided deformation machining or incremental forming.

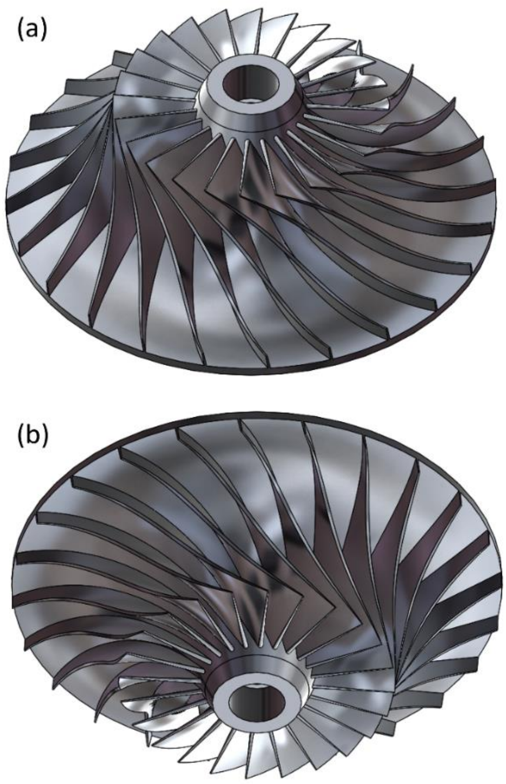

Figure 9 CAD model of the single-sided compressor configuration highlighting key geometric features for efficient airflow.

In contrast, Figure 10 (a-c) presents the double-sided configuration, where impeller blades are symmetrically or asymmetrically distributed on both sides of the central disc. This configuration enables more effective compression and flow control, often required in aerospace propulsion, turbocharging systems, or high-efficiency centrifugal pumps. The double-sided geometry demands a multi-axis simultaneous toolpath strategy, precisely coordinated through both top and bottom spindles to achieve uniform deformation without part distortion or over-thinning.

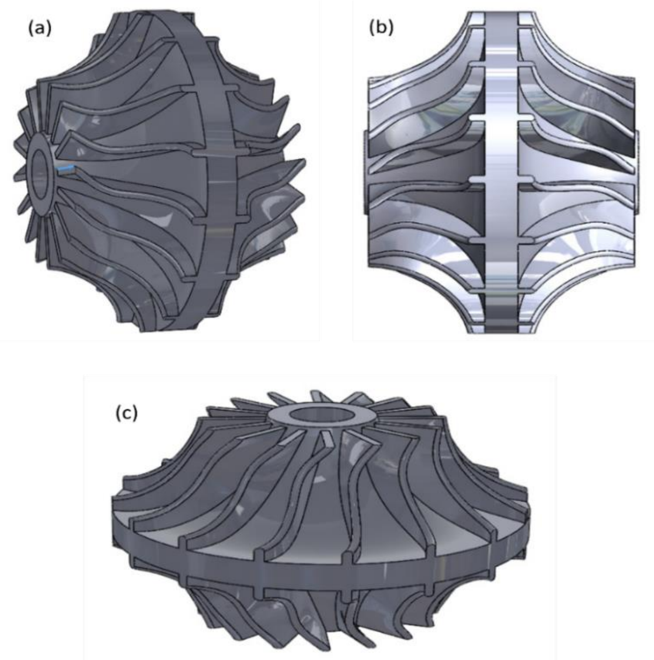

Figure 10 (a-c) CAD model of the double-sided compressor configuration, emphasizing critical geometric features optimized for airflow efficiency and precise toolpath generation

The CAD models were developed considering the tool accessibility, clearance requirements, and minimum wall thickness constraints imposed by the deformation machining process. Blade profiles were defined with smooth curvature transitions and optimized blade angles to maximize aerodynamic performance while maintaining manufacturability through the HDM technique.

This modeling strategy ensures that both single- and double-sided variants can be manufactured without dies, using toolpath-driven forming and machining, thereby reducing lead time, tooling cost, and material waste.

Centrifugal Compressors:

- Comprised of one or two stages using a rotating impeller to accelerate the air and a diffuser to convert kinetic energy into pressure energy.
- Impellers are traditionally machined from forged discs with radial or curved vanes, where HDM can provide double-sided machining and forming to generate the desired aerodynamic profiles.

Axial Compressors:

- Constructed with multiple stages of alternating rotating and stationary blades, compressing air progressively.
- Known for higher mass flow rates and superior pressure ratios, axial compressors demand precise blade geometry- ideal for HDM’s multi-axis, die-less forming capability.

Advantages of HDM for Impeller/Compressor Components:

- Geometric Complexity & Variability: HDM enables the fabrication of highly intricate, freeform geometries with variable sections and blade thicknesses, essential for achieving optimized fluid flow and performance in rotating machinery.
- Monolithic Construction: By producing impellers as single-piece monolithic components, HDM eliminates the need for assembling multiple parts, significantly reducing assembly time, potential joint failures, and material costs.
- Die-less & Furnace-free Process: HDM bypasses traditional die manufacturing and does not require melting of metal or furnace heating, unlike conventional die-casting or forging methods. This results in reduced energy consumption and faster prototyping cycles.
- Design Flexibility & Customization: In conventional methods, modifications or design upgrades require new dies, leading to added cost and delays. HDM, on the other hand, allows for rapid adaptation through toolpath reprogramming, facilitating agile customization without tool rework.
- Wider Range of Shapes & Minimal Waste: HDM supports a broader range of part geometries while maintaining tight dimensional tolerances, without the need for tooling adjustments. This also reduces die-cast waste and material scrap, enhancing sustainability.
- Toolpath-Based Manufacturing: The HDM process is driven by digitally generated toolpaths, which replace expensive and rigid tooling with software-driven flexibility, enabling efficient iteration and optimization.

V. CONCLUSION

Hybrid Deformation Machining (HDM) revolutionizes the manufacturing of complex impeller and compressor components by integrating precision machining and incremental forming through a single, digitally coordinated toolpath. This die-less, furnace-free approach enables the production of monolithic, aerodynamically optimized geometries with high accuracy, reduced material waste, and enhanced customization. HDM shortens lead times, lowers energy consumption, and offers unmatched design flexibility, making it a sustainable and cost-effective alternative to conventional die-based methods. Its advantages position HDM as a transformative solution for the aerospace, automotive, and energy sectors, setting a new standard for agile, high-performance manufacturing in the digital era.

VI. ACKNOWLEDGMENT

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