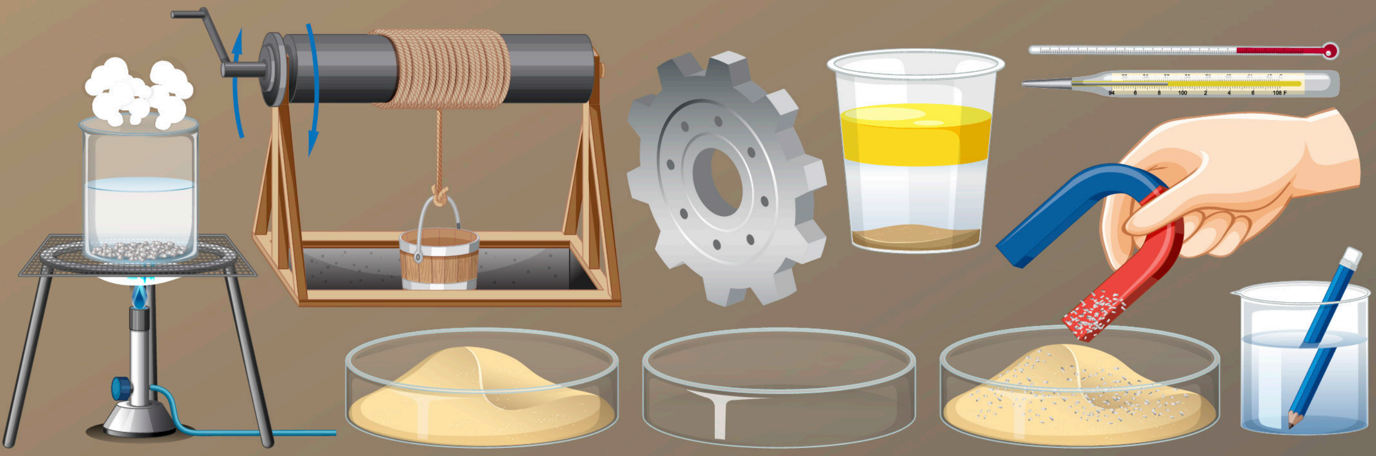
American Journal of Advanced Materials Research (AJAMR)

VOLUME 1 ISSUE 1 (2025)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of
Advanced Materials Research (AJAMR)

Volume 1 Issue 1, Year 2025
https://journals.e-palli.com/home/index.php/ajamr

Comprehensive Study on Enhancing the Forming Performance of Incrementally Forming Sheet Metal

Muhammad Aqib Raza Shah[1*], Agung Shamsuddin Saragih[1]

Article Information

Received: July 20, 2025

Accepted: August 18, 2025

Published: September 14, 2025

Keywords

Customized Heat Treatment, Die-less Manufacturing, Incremental Sheet Forming, Process Optimization, Predictive Modeling

ABSTRACT

Incremental sheet forming (ISF) is a versatile, die-less sheet metal forming process that allows for the manufacture of complex shapes in sheet metals at minimal tooling expense. Its widespread application, however, is hindered by significant limitations such as high forming forces, rapid work hardening, and unfavorable surface finish, especially for challenging-to-beat alloys like stainless steel, high-strength aluminum, and titanium. This review presents recent advances to enhance sheet metal formability. We examine innovative heat-assisted methods, such as local approaches (e.g., laser- and electrical-assisted forming) that accurately soften the deformation zone, and global strategies (e.g., hot air and oil bath heating) that evenly improve ductility, and hybrid strategies with ultrasonic vibrations. The role of hybrid approaches that integrate two or more heating methods to find an optimal balance between energy efficiency and properties of materials is investigated. The impact of significant process factors (temperature, tool geometry, tool rotation, feed rate, and step size) is thoroughly analyzed, and predictive modeling methods (analytical, numerical, and empirical) are presented to formulate robust optimization algorithms. Scalability of the ISF process in industry, considering its applications in aerospace, automotive, and biomedical industries, is also included under the review. This comprehensive study outlines current challenges and proposes avenues for future research to advance incremental sheet forming further towards more efficient, sustainable, and reliable industrial applications.

INTRODUCTION

Incremental sheet forming (ISF) is an innovative technology in modern manufacturing that offers the benefits of flexibility, low-cost tooling, and the potential to produce custom geometries without employing special dies (Smith *et al.,* 2013). Unlike conventional forming methods requiring costly dies and intricate setups, ISF uses a computer-controlled tool path to induce localized deformation, thus making it an economically sound means of manufacturing complex parts (Trzepieciński, 2020). Its prospects have attracted attention across various industries like healthcare, automotive, aerospace, and defense (Gupta *et al.,* 2019). ISF is especially significant in low-volume production, prototyping, and patient-specific biomedical components where precision and customization are crucial (Raabe *et al.,* 2020). It can be applied on a wide range of materials like aluminum alloys, stainless steel, titanium alloys, and polymers, each presenting their own set of challenges (Zhang *et al.,* 2015).

Although numerous advantages, creating high-strength, low-ductility alloys such as stainless steel, high-strength aluminum, and titanium is nonetheless still problematic owing to excessive forces of forming, inhomogeneous thickness distribution, and restricted ductility (Centeno *et al.,* 2017; Kumar *et al.,* 2015). These limitations restrict the amount of plastic deformation under standard ISF, and thus new approaches are needed for enhancing formability (Duflou *et al.,* 2007). Heat treatment techniques have been suggested to modify material properties temporarily so that yield strength is decreased and ductility is increased (Liu, 2018; Pragana *et al.,* 2020). Hybrid processes that combine thermal energy and vibrations further boost the forming performance by relieving residual stresses and providing surface finish improvement (Jiang, 2022; La *et al.,* 2024). Further, improvements in tool design, tool path strategy, and process parameter optimization are vital in controlling material flow, strain distribution, and end-part accuracy (Chang & Chen, 2021; Farahani *et al.,* 2018).

Improvements in computational software such as finite element analysis (FEA), analytical modeling, and empirical methods further refined understanding of ISF mechanics to permit optimal tool path optimization effectively and reduce trial-and-error experimentation (Hussain & Al-Ghamdi, 2017; Li *et al.,* 2013). Future advancement is expected through more powerful hybrid approaches, material-specific process optimization, and the employment of real-time monitoring to provide superior control (Afzal *et al.,* 2021; Qin *et al.*, 2024). This paper will highlight the recent developments in ISF, including process innovation, material-specific challenges, and avenues for future research to spur development of this promising manufacturing technique.

LITERATURE REVIEW

Incremental sheet forming (ISF) is a widely accepted flexible technology over conventional metal forming methods, especially for prototypes, customized, or small lots of parts. ISF has unique advantages of low-cost tooling, flexibility, and the ability to produce complex shapes without the need for expensive dies. These benefits

---

[1] Department of Mechanical Engineering, University of Indonesia, Depok, 16424, West Java, Indonesia
[*] Corresponding author's e-mail: aqibshah535@gmail.com

have made ISF a promising technique for firms forming hard-to-form metals such as stainless steel, high-strength aluminum, and titanium (Jeswiet *et al.,* 2005). Despite its immense potential, the process continues to experience high forming forces, uneven thickness distribution, rapid work hardening, and low surface finishes (Cao & Banu, 2020).

One of the most important advancements has been the addition of heat-assisted incremental sheet forming (HA-ISF). Localized heating methods such as laser-assisted and electric current-assisted ISF have exhibited notable enhancements in formability and reduction in forming forces. Silva *et al.* (Silva *et al.,* 2011) reported laser-assisted ISF reducing forming forces by over 30%, whereas Wang *et al.* (Ao *et al.,* 2024) obtained comparable improvements using electric current-assisted ISF on titanium sheets. Besides, ultrasonic-vibration-aided ISF has found more popularity because of its capability to further reduce forming loads and improve surface qualities through improving material flow (Trzepieciński *et al.,* 2021).

Hybrid ISF processes involving localized heating and ultrasonic vibration have also shown their effectiveness. Experiments by Jagtap and Kumar (2021) found that hybrid processes effectively reduce the surface roughness, minimize springback, and enhance dimensional accuracy. Additionally, Asghar *et al.* (2014) highlighted that hybrid heating processes improve formability as well as tool life through reduction of wear and friction between the metal and the tool.

Global heating methods, such as hot air and oil bath heating, have also been employed for ductility improvement. However, Fan and Gao (2014) reported drawbacks like increased oxidation and challenges in maintaining uniform process control at elevated temperatures. Instead, Singh *et al.* (2023) proposed combining global and local heating arrangements to maximize temperature uniformity and local softening.

Parallel to thermal advances, process parameter optimization remains a priority. Investigations focused on step size, tool rotation, feed rate, and tool pathing have proven their direct influence on the quality of the final product. Analytical and finite element modelling (FEM) approaches have been utilized extensively to predict forming forces, thickness distribution, and residual stresses. Li *et al.* (2023) established the credibility of FEM to simulate complex ISF deformation behavior, while empirical models like those of Chen *et al.* (2018) provided useful process predictions with less computational effort. In recent years, predictive models based on AI and machine learning have emerged as promising tools to improve ISF optimization. Huang *et al.* (2021) proposed the coupling of AI with FEM simulations to improve the accuracy of predictions for hybrid ISF processes, opening new possibilities in adaptive, real-time process control.

Although considerable advancements have been made, some challenges persist in areas such as achieving reliable temperature distribution, reducing tool wear, and scaling ISF processes to industrial-scale use. Overcoming these challenges with hybrid processes, advanced control systems, and AI-based monitoring remains a primary area of future development.

Techniques For Enhancing Forming Performance

Improving ISF's performance for sheet materials is crucial to increasing its industrial usability. This section classifies the main methods used to enhance surface quality and formability.

Customized Heat Treatment Strategies

Localized Heating Techniques

Localized heating methods, such as laser-assisted and electrical-assisted ISF, employ concentrated heat to the zone of deformation to reduce material strength and enhance ductility. By reducing the yield point and activating additional slip systems, these methods reduce forming force and minimize defects like tearing and cracking (Kulkarni & Mocko, 2020; Safari *et al.,* 2020). Laser-assisted ISF uses a controlled laser beam for localized heating, while electrical-assisted ISF uses resistive heating by electric currents. These techniques allow for accurate thermal control, dimensional accuracy, and avoidance of thermal distortion (Göttmann *et al.,* 2013). Therefore, localized heating techniques expand the range of materials to be applied on ISF, improving overall forming capability. These techniques also reduce the likelihood of tool wear through minimizing the forming forces, thus improving tool life, and reducing cost of production. Heating select portions alone also assists in saving energy, thus making ISF more viable for the manufacturing industry.

Global Heating Approaches

Global heating techniques involve uniform heating of the entire sheet by processes like hot air, oil baths, or heated chambers. These processes enhance ductility and reduce forming forces through softening of the material to become more pliable for deformation (Almadani *et al.,* 2023). However, achieving uniform temperatures across the entire sheet may be challenging, potentially leading to non-uniform mechanical properties. Moreover, high-temperature oxidation can also degrade surface quality, for which protective coatings or inert atmospheres must be used to combat such an effect. Although there are such challenges, heating the entire sheet at one time can lead to easier process control compared with localized methods. In some situations, the heating medium (e.g., oil) also acts as a lubricant and reduces friction and further improves surface finish, which is particularly beneficial to produce parts with intricate geometries (Trzepieciński *et al.,* 2024; Zhang *et al.,* 2020). Global heating techniques are most suitably applied to high-strength, low-ductility materials that require extensive thermal assistance to achieve wanted deformation.

Hybrid Heating Methods

Hybrid techniques offer the advantages of localized and general heating or include other sources like ultrasonic vibration to enhance the forming process. By a blend of localized heating with overall material softening, these methods achieve precise thermal control while reducing forming forces and limiting defects (Cheng *et al.,* 2019; Jiang, 2022). Ultrasonic-assisted ISF, for instance, employs high-frequency vibrations on the tool or material, reducing friction and slowing down material failure. These result in improved surface finish and increased tool life. Further, the combination of thermal assistance with mechanical vibrations helps in stress distribution in a more even manner, reducing the possibilities of cracks and surface flaws. Figure 1 illustrates various heat treatment techniques used in hybrid heating processes like hot air heating, electric heating, friction stir heating, and laser heating. These processes provide localized heating, which enhances the formability of the material and minimizes springback effects in forming. The choice of the heating process depends on material properties, accuracy demands, and limitations in manufacturing. Hybrid techniques prove particularly beneficial in working with hard-to-machine materials like high-strength alloys, which typically lack good ductility and require enhanced formability. Although these methods offer numerous benefits, the use may require sophisticated equipment and process control to enable uniform performance, and consequently, may be more applicable to high-tech production plants.

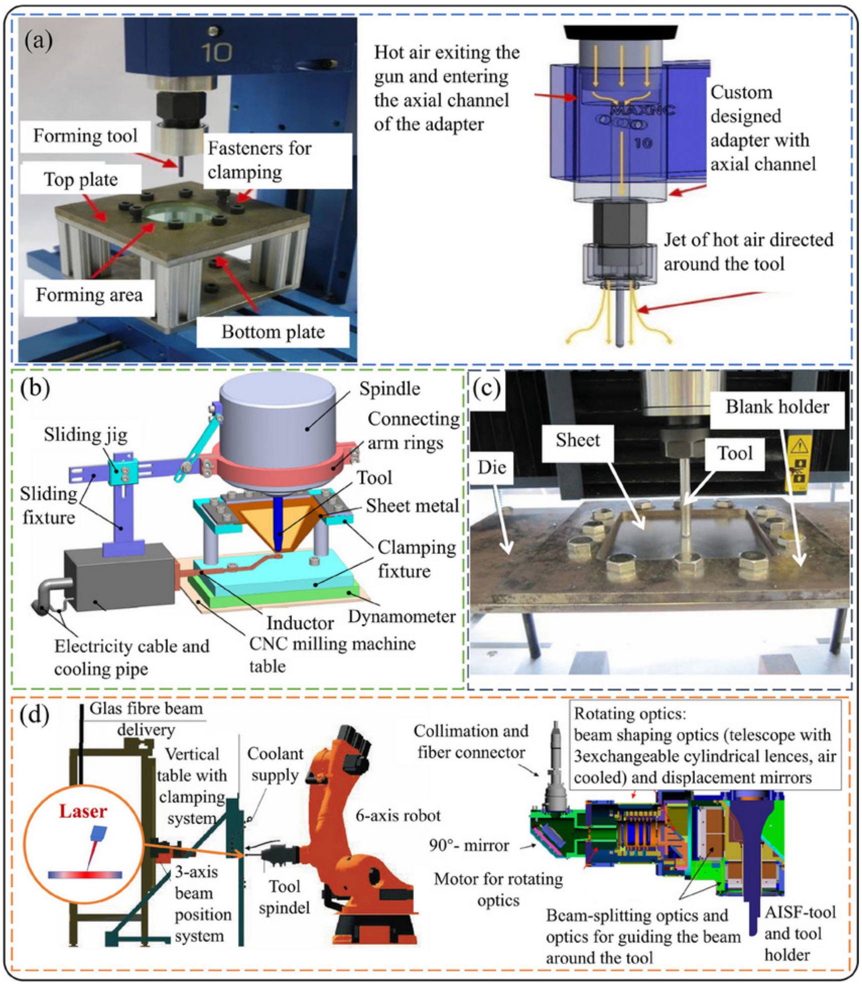


Figure 1: Heat Treatment Strategies: (a) Hot air heating (Mosecker *et al.,* 2013), (b) Electric heating (Gilman, 2000), (c) Friction stir heating (Jiang *et al.,* 2012), (d) laser heating (Heigel *et al.,* 2000; Zhao *et al.,* 2013)

Tool and Process Modifications

Tool Geometry and Surface Modifications

Tool geometry is equally crucial in determining the performance and quality of the ISF process. Hemispherical and ball-end roller tools have been shown to reduce friction and enhance material flow compared to flat-end tools, resulting in smaller forming forces and better surface quality (Yan *et al.,* 2021; Zhao *et al.,* 2021). The tool dimensions and shape also determine the pattern of localized strain, influencing the final shape and thickness distribution of the formed part. In addition, tool surface coatings such as TiN or DLC are employed for wear reduction and reduction of material adhesion, increasing tool life, and maintaining surface integrity (Afonso *et al.,* 2019; Rinschede *et al.,* 2021). Unique tool designs incorporate internal cooling channels or cryogenic cooling to eliminate heat, preventing thermal damage to the tool and material. Proper selection of tool material, based on hardness and thermal conductivity, also enhances process stability and efficiency. By reducing tool design, manufacturers achieve greater formability, better dimension accuracy, and a better surface finish in ISF processes.

Tool Path Optimization

The trajectory of the forming tool is important to ensure uniform thickness distribution, minimize surface defects, and reduce spring back in ISF. New tool trajectories such as helical, Z-level, and parallel line motions have been developed to maximize material flow, improve deformation homogeneity, and minimize residual stresses (Hoang & Nguyen, 2021; Torres *et al.,* 2022). Helical motions ensure smooth transition, avoiding abrupt variations in strain, while Z-level motions provide better control in multi-pass operation. Parallel line tool paths are best to utilize for achieving precise geometric and form accuracy on complex contours. However, improper use of tool paths can lead to surface defects in sample, particularly in non-symmetrical parts. Figure 2 shows a problem of potential surface defect on non-symmetrical components where tool marks on the resulting surface are observed due to accumulated strain and uneven slicing paths. It normally happens whenever the tool path is unable to create equal deformation so that localized stresses form and result in surface irregularities. Finite element analysis (FEA) is also frequently utilized to optimize and examine such trajectories, achieve equal material deformation, and reduce the risk of tool failure. Optimal choice and optimization of tool path enable manufacturers to achieve improved part quality, and dimension accuracy, as well as improved tool life in ISF processes.

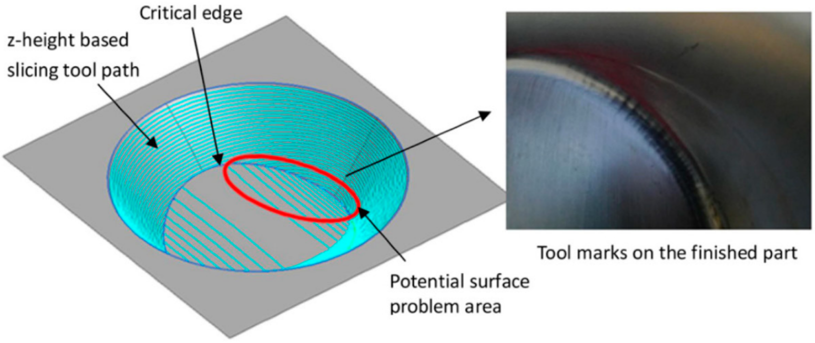


Figure 2: Potential surface problem in non-symmetrical part (reprinted with permission from (Lu *et al.,* 2013).

Process Parameter Optimization

Critical process parameters such as step size, feed rate, and spindle rotation speed play a significant role in determining the quality of the part and the overall process efficiency in ISF. Higher step sizes can minimize cycle times but can increase the forming forces, cause surface roughness, and result in non-homogeneous thickness distribution (Afzal & Buhl, 2022; Patel & Gandhi, 2022). Similarly, higher feed rates can enhance productivity but can compromise the surface finish and lead to tearing. Rotational speed of tools influences frictional heating, and this affects surface finish and material flow. Balanced optimization of the parameters is thus required to achieve a compromise between part quality and efficiency (Riofrio Sabando, 2024; Samoy-Alvarado, 2022). In practice, process optimization will entail numerical simulations or experimental tests to establish the best combination of these parameters for specific part geometries and material types.

Impact of Process Parameters on Sheet Forming

The sheet material forming behavior in ISF is greatly affected by process conditions. This chapter summarizes the effect of temperature, tool geometry, tool rotation, feed rate, step-over distance, and tool path.

Temperature Effects

Increased forming temperatures reduce the yield strength of the sheet material and activate other slip systems, thereby lowering the required forming force and improving formability (Y. Li *et al.,* 2023; Qin *et al.*). Localized heating techniques, such as laser-assisted and electrical-assisted ISF, allow local temperature control and localized material softening with reduced thermal distortion. Global heating methods, including hot oil or air heating, are useful for isotropic improvement of ductility but could lead to complications such as oxidation, temperature gradient, or inhomogeneous distribution of temperature (Jiang *et al.,* 2022; Yang *et al.,* 2023). Although flow of the material is increased with rising temperatures, spring back is reduced. Care should be exercised to avoid excess heating to reduce grain growth, surface degradation, or compromised mechanical properties. The selection of the correct heating method and regulation of optimum temperature levels are crucial for establishing the desired equilibrium between formability and part quality in ISF processes. This idea is further supported by the graph Figure 3, which shows that forming resistance can be successfully decreased by maintaining regulated temperatures, resulting in more accurate and efficient material shaping.

Tool Geometry and Size Effects

Tool geometry plays a crucial role in material deformation, surface finish, and stress distribution in ISF. Reducing tool diameter concentrates frictional heat on the tool–

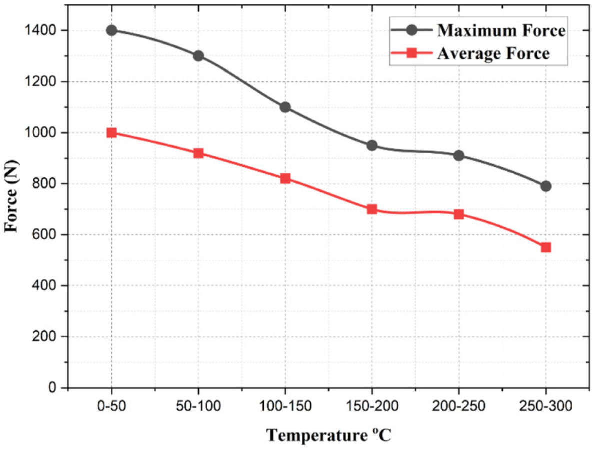


Figure 3: Temperature effect on forming force (Leonhardt *et al.,* 2018)

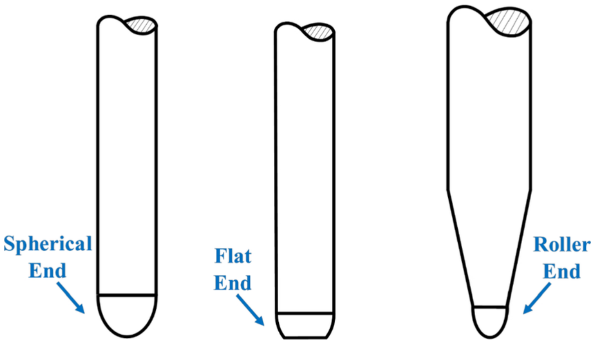


Figure 4: Different tool shape for the deformation process

sheet interface, reducing forming force and enhancing material flow but raises more uniform deformation (Kajal *et al.,* 2023; Singh *et al.,* 2023). Tool shape and profile can affect thickness variation and localized strain distribution. Additionally, specialized surface finishes can minimize wear, friction, and total surface finish. Built-in internal cooling systems ensure a stable temperature, extend tool life, and keep dimensional tolerance (Benmessaoud, 2024; Felinks *et al.,* 2023). Proper tool selection relative to material properties and part complexity is crucial to maximize the process. Different tool shapes for the deformation process as shown in Figure 4.

Tool Rotation, Feed Rate, and Step Size

Tool rotation influences heat generation and friction. As shown by Figure 5, increased rotational speeds can enhance material flow by generating additional frictional heat, which can reduce forming forces and enhance ductility (Jayathunga & Chandana, 2023). However, excessively high speeds can cause surface defects or tool wear (Jayathunga & Chandana, 2023; Kumar, 2024; Zhang, 2023). Moreover, Figure 6, illustrates the effect of step size on the energy consumption, where a smaller step size contributes to a sudden rise in total energy requirements. This implies that while smaller step size improves surface quality and precision, it comes with the cost of higher energy consumption. Similarly, feed rate and step size are also important parameters in forming quality. As evident from Figure 7, higher feed rates have the tendency to increase residual stresses, particularly with spherical-end tools. In the same way, Figure 8, indicates that higher step sizes lead to elevated residual stresses, potentially jeopardizing part integrity (Mandaloi *et al.,* 2022; Singh *et al.,* 2020). A trade-off between these parameters is essential to maximize material deformation, minimize defects, and maintain part quality. Therefore, careful selection of parameter settings based on material properties and desired outcomes is necessary to realize optimum efficiency and effectiveness (Eyers *et al.,* 2022).

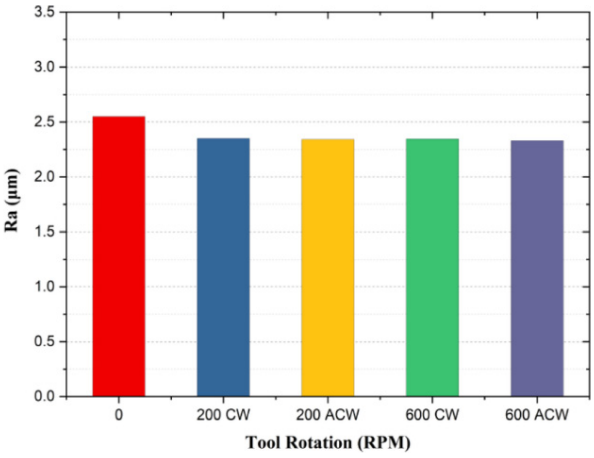


Figure 5: Rotation's effect on surface roughness (Durante *et al.,* 2009).

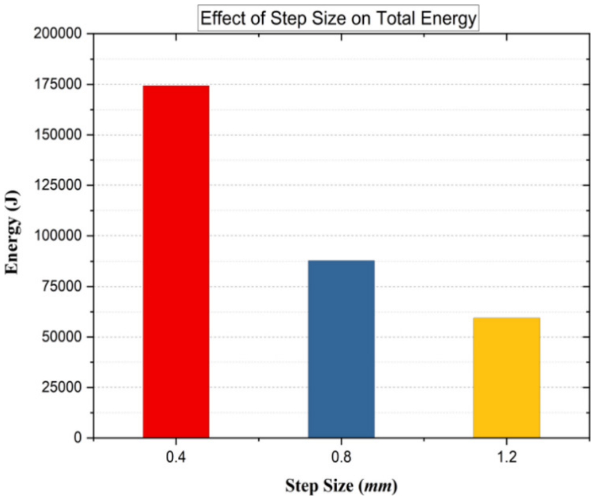


Figure 6: Effect of Step Size on total Energy (Li *et al.,* 2019).

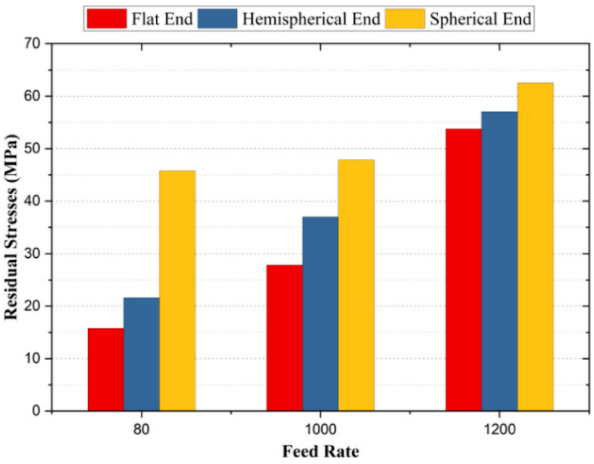


Figure 7: Effect of tool geometry & feed rate on residual stress 550° FA (Conte *et al.,* 2017).

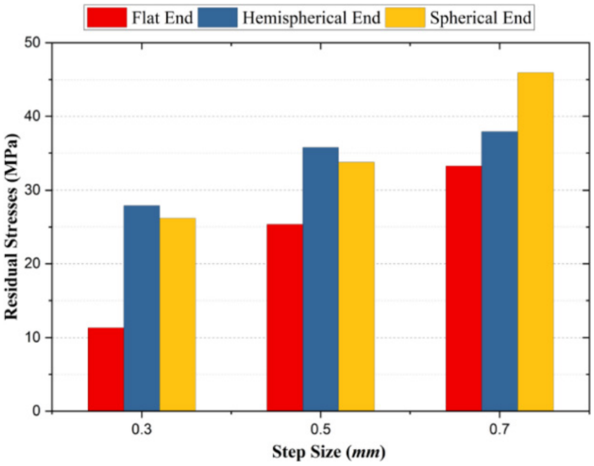


Figure 8: Effect of step size under different tool shape 45° FA (Abdulrazaq *et al.,* 2019).

Tool Path Considerations

Tool path designing is necessary to attain uniform thickness distribution, decrease spring back, and lower residual stresses. Complicated trajectories such as helical, Z-level, and parallel line paths have been determined to reduce localized thinning, improve dimensional stability, and enhance surface quality. These paths allow for efficient control of material flow, enabling more predictable deformation as well as better geometric accuracy. Finite element analysis is a significant component in the calculation of optimal tool paths, optimization of process parameters, and analysis of material behavior of various sheet materials and geometries (Dixit *et al.,* 2011). Tool path choice affects not only part quality but also the overall cycle time and process effectiveness.

Modeling Approaches For Predicting Forming Performance

For ISF process optimization, robust predictive modelling is crucial. This section describes the main modelling techniques.

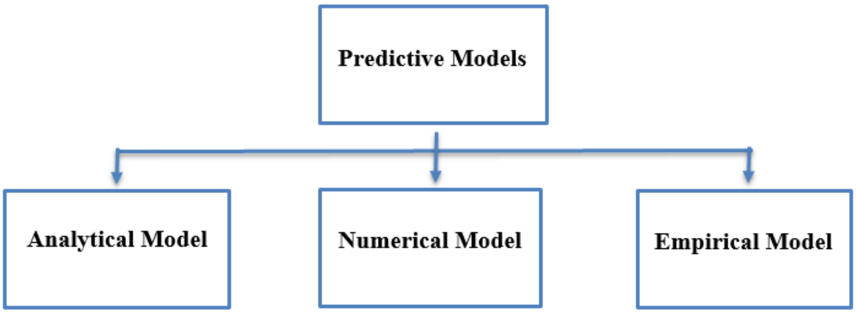


Figure 9: The main modelling techniques

Analytical Models

Analytical models use fundamental concepts of heat transfer, friction, and material mechanics to predict temperature distributions, stress-strain behavior, and forming forces in ISF. Joule heating, frictional energy conversion, and slip line field theory-based models provide initial estimates of thermal and mechanical response of the forming zone (Ramzan *et al.,* 2021). These models help in predicting the influence of process parameters, material properties, and tool geometry on deformation behavior. Despite due to the inherent material behavior under high-temperature conditions, dynamic strain aging, and localized plastic deformation, most of the models are incomplete in capturing the complete behavior of real forming operations (Thornton *et al.,* 2023). Therefore, they are traditionally employed together with experimental facts or numerical modelling to verify and refine them.

Numerical Modeling

Numerical simulation, particularly using finite element analysis (FEA), is used extensively to simulate the ISF process. FEA allows for accurate prediction of stress, strain, temperature profile, and material flow, and thus optimization of tool paths, process parameters, and material selection with fewer trial-and-error experiments (Kyratsis *et al.,* 2023; Sharma *et al.,* 2024). Validation of experimental data enhances the precision of FEA predictions, and therefore it serves as a useful tool for process planning and optimization. However, numerical modelling is time-consuming computationally, requiring huge processing power and time, and highly sensitive to several parameters such as meshing, boundary conditions, and assumptions in material modelling (Panchal *et al.,* 2013; Pietrzyk *et al.,* 2015). Despite this, FEA remains an essential methodology for ISF process understanding and optimization.

Empirical Modeling

Empirical models, derived from regression analysis and statistical analysis of experimental results, provide useful tools for predicting performance like surface quality, thickness distribution, and residual stress (Peng *et al.,* 2020). Empirical models tend to be faster and easier to apply compared to advanced numerical simulations and are well-suited for industrial applications where rapid decision-making is required. However, their reliability is heavily dependent on the consistency and availability of experimental data on which they are calibrated. While they might not have the theoretical depth of physics-based models, empirical models can be optimized and calibrated with growing datasets so that they can be progressively better predictors of behavior and more sensitive to the specific material and process conditions.

MATERIALS AND METHODS

This review systematically collected and reviewed research articles, conference articles, and technical reports on incremental sheet forming (ISF) from 2000 to 2025. Systematic searching of scholarly databases was conducted. The keywords and keyword phrases for the given search strategy were "incremental sheet forming," "heat-assisted ISF," "hybrid incremental forming," "predictive modelling in metal forming," and "tool path optimization." These yielded 70 original research papers of high relevance to developments in the ISF process, and innovations in heating concepts, process parameter optimization, and modelling strategies from an initial yield of over 120 papers. The criteria for selecting privileged studies involving experimental data, numerical modeling, or industrial experience that addressed formability problems, enhanced surface quality, or improved process efficiency in ISF.

These selected studies were then categorized systematically to corresponding groups to analyze and compare. The categories included localized and global heating practices, alteration of tool geometry, process parameter adjustment, hybrid sheet forming methods, and predictive software tools like finite element analysis (FEA), empirical models, and artificial intelligence (AI) systems. All the papers were closely reviewed to ascertain the extent to which each has helped in minimizing forming forces, maximizing thickness distribution, improving surface finish, and optimizing tool life. Comparative research in these areas facilitated the establishment of prevailing trends, technical bottlenecks, and deficiencies in existing literature. Specific emphasis was placed on the incorporation of hybrid processes and real-time control systems because the disciplines showed tremendous potential to take ISF technology to industrial scale and application in demanding areas such as aerospace, automotive, and biomedical manufacturing.

Applications and Case Studies

The enhanced ISF techniques highlighted here have been utilized successfully in various industries, to demonstrate their industrial capabilities.

Biomedical Applications

Customized biomedical implants require accuracy and complex geometry to meet patient-specific demands. High-end ISF processes have been employed to create cranial plates, facial prostheses, and orthopaedic braces from biocompatible sheet materials like titanium, magnesium alloys, and stainless steel (Salmi *et al.,* 2015). These types of materials are chosen for their compatibility with human tissue, corrosion resistance, and mechanical strength. ISF applications within the biomedical field demonstrate significant advantages including less wastage of materials, decreased lead times, and the ability to produce customized geometries appropriate for unique anatomical structures. In addition, surface treatments in ISF are better, allowing the achievement of smooth finishes that completely remove the chance of infection and increase patient comfort.

Automotive and Aerospace Industries

In automotive and aerospace applications, ISF enables fast prototyping and low-volume manufacturing of complex components like body panels, engine covers, and structural reinforcements. ISF's flexibility allows design changes to be incorporated without large-scale retooling, an aspect that is highly desirable in custom or niche applications. The integration of novel heat-assisted techniques and optimization of process parameters has led to improved strength-to-weight ratio and surface finish, and reduced lead times and tooling costs. ISF also enables the incorporation of lightweight materials like aluminium and titanium alloys and is therefore highly suitable for material efficiency- and performance-driven industries (Williams & Starke Jr, 2003).

Discussions and Future Directions

Despite significant advancements, there are still several challenges in the application of ISF on sheet materials. Overcoming these challenges can lead to broader material applicability and industrial scalability:

Uniform Heating and Temperature Control

Uniform temperature distribution throughout the sheet is challenging to achieve, especially through localized heating sources. Temperature gradients result in inhomogeneous material flow, decreased ductility, and inconsistent part quality. For future research, high-end thermal sensing, adaptive control, and hybrid heating processes can be examined to minimize thermal gradients and increase material properties (van Blitterswijk, 2024).

Tool Wear and Surface Quality

Reducing tool wear while maintaining high surface finish is a complex challenge, particularly in long production runs. Severe wear can lead to dimensional error, attachment of material, and manufacturing cost. Investigating new tool coatings, surface finishing, and internal cooling can extend the tool life as well as minimize material attachment while enabling higher dimensional accuracy (Bin Che Ghani, 2013).

Predictive Modelling

Existing models are likely to have problems predicting forming forces, surface finish, and size accuracy under variable conditions due to ISF being dynamic and complex in nature. It becomes impossible to make precise predictions that limit the process as well as control optimization. The development of more comprehensive modelling approaches that involve analytical, numerical, and empirical approaches could lead to more understanding and predictability, hence optimizing the process as well as control (Bikas *et al.,* 2016; Nguyen *et al.,* 2014).

Hybrid Process Integration

Coupling different enhancement methods like induction heating, ultrasonic vibrations, and electrical-assisted techniques holds a promising way to higher efficiency and product quality. These hybrid methods can lower forming forces, enhance material flow, and minimize spring back at the same time, enhancing the versatility of ISF for intricate and hard-to-deform materials. They also lower variability and enhance the versatility of ISF in complex applications (Ben Said, 2022).

Industrial Scalability

Scalability of ISF from pilot-scale laboratory facilities to large industrial production is difficult due to challenges such as increased cycle times, energy requirements, and process stability. Large-scale production requires the development of cost-effective, efficient, and stable systems from small-scale experimentations. Cycle times, energy, and process stability need to be optimized in the future research for higher industrial utilization and economy (Nguyen *et al.,* 2024; Shokrani *et al.,* 2024). Overcoming these challenges is essential to realizing the complete potential of ISF across all industries, innovations, and further applications development of new material forming technologies.

RESULTS AND DISCUSSION

Recent studies have proved that through the application of heat treatment techniques the formability of high-strength sheet metals is significantly enhanced. These treatments decrease the yield strength and enhance ductility, making it possible for materials like stainless steel and titanium alloys to be formed more deeply without fracture. The improved results include increased achievable wall angles and improved thickness distribution. In addition to these thermal processes, hybrid ISF processes with localized electric heating, laser assistance, and ultrasonic vibration have been effective in reducing forming forces by up to 30% and improving surface quality. These benefits, however, depend on precise thermal control to prevent overheating and material degradation (Wang *et al.,* 2005; Zhu & Zeng, 2008). Hybrid methods also reduce springback and enhance geometric fidelity, particularly in low-ductility, high-strength alloys. Such techniques are of utmost significance in aerospace and biomedical applications, where customized properties and accuracy are crucial. Emerging advances, such as temperature-controlled tool heads and feedback-based thermal control, have improved process repeatability. However, broader industrial adoption is discouraged by greater equipment cost and complexity (Shao *et al.,* 2022).

Tool path and tool design techniques are also significant in achieving high-quality and precise ISF components. Literature recognizes the benefits of hemispherical tool shapes, adaptive vertical step sizes, and multi-pass or bidirectional tool paths in minimizing strain localization and improving geometric accuracy. Smoother tool paths also account for reduced thinning and improved surface finish. Moreover, the formability of ISF with a range of materials such as aluminium, stainless steel, titanium alloys, and polymers proves its versatility. However, forming high-strength aluminium and titanium remains problematic due to poor ductility and high forming forces, generally requiring specially adapted process parameters and hybrid enhancements to improve results (Duflou *et al.,* 2005).

Computational modelling with finite element analysis (FEA) is now essential in simulating part geometry, strain behavior, and tool forces in ISF. Optimizing tool paths is enabled through these models while reducing dependence on costly trial-and-error processes. However, limitations in modelling are present, and mainly of getting proper material behavior in hybrid or thermal assisted forming processes. Despite these advances, major research gaps persist in challenges such as real-time monitoring, intelligent process control, and green production. Future research must aim to address industrial scale-up, material-property-based optimization, and experimental protocol standardization for meaningful comparison across studies (Emmens *et al.,* 2010).

CONCLUSION

This review has comprehensively discussed the advancements in enhancing the forming performance of incrementally formed sheet materials. With the addition of specially designed heat treatment strategies—both local and global—and innovative tool design, optimized tool paths, and precisely controlled process parameters, significant gains have been achieved. These advancements have led to the reduction in forming forces, surface defects, enhanced material flow, and better dimensional accuracy. Use of predictive modelling methodologies, including analytical, numerical, and empirical methods, has also enabled further comprehension of the forming process and to provide efficient models for optimization of process parameters.

There are still many obstacles to overcome despite these advancements. The challenges of maintaining consistent temperature control, reducing tool wear, and creating predictive models that can accurately represent the intricate interconnections in the forming process are never-ending. These issues can be effectively addressed by hybrid approaches that combine thermal, mechanical, and vibrational energy inputs to maximize material formability while reducing harmful consequences like excessive thinning or surface flaws. For wider use, novel solutions are needed to reduce cycle times, energy usage, and production costs as controlled laboratory settings give way to full-scale industrial operations.

Future research must prioritize the development of holistic, cross-disciplinary strategies for addressing these challenges. Collaboration among material scientists, engineers, and industrialists can facilitate the development of more efficient, reliable, and scalable ISF processes. Ultimately, resolving these challenges will expand the application of ISF in critical industries like aerospace, automotive, and biomedical manufacturing, opening doors to new possibilities in the production of complex, customized parts with precision and affordability.

Contribution to Knowledge

This review is a valuable contribution by consolidating scattered research on Incremental Sheet Forming (ISF) and streamlining it in a cohesive, structured format. By dividing developments into focused areas, addressing heating strategies, developments in tooling design, process parameter optimization, and predictive modeling techniques, the paper presents a unified knowledge of how these strategies individually and in conjunction influence ISF performance. It is particularly distinguished by its focus on the increased success of hybrid processes, like the coupling of localized heating and ultrasonic vibrations, which have consistently enhanced formability, dimensional accuracy, and reduction of defects. The review further draws attention to the increased application of artificial intelligence (AI) and data-driven predictive models for the optimization of process control and efficiency in real-time processes. Along with summarizing existing knowledge, the paper identifies key gaps in the areas of large-scale process scalability, real-time monitoring integration, and standardized performance testing of ISF components. By recognizing these difficulties and proposing pragmatic, research-based solutions, the paper offers tangible guidance for future research, helping to aid both academic researchers and industrial practitioners in advancing ISF from experimental setups to stable, high-performance production systems.

Fulfilment of Research Gap

While previous reviews of ISF have tended to cover individual topics such as heating methods, die designs, or specific modeling techniques, the literature has been absent a cohesive viewpoint that covers several approaches simultaneously. This review remedies this oversight by taking an overarching view of numerous techniques for enhancing performance, covering how they can be used in concert to achieve optimal outcomes for ISF. In particular, the review demands detailed research that considers the interplay of heating, tooling adaptations, parameter control, and modeling, with a more complete understanding of how these techniques can be integrated to achieve improved results. This integrated approach has been absent in the work done so far, and its consideration is a significant step in advancing ISF technology.

Furthermore, the review identifies primary outstanding areas requiring research, such as the scalability of ISF processes, in-process monitoring in real time, and potential for hybrid heating-vibration integration. These are pressing questions for ISF industrialization, where current knowledge has proved insufficient to surmount the difficulty of translating laboratory findings to full-scale production. The article also underlines the necessity of the integration of sophisticated modeling tools and AI-based control systems that would have the capability to dynamically adjust ISF parameters during the forming process. This integration of tools and technologies is an excellent opportunity for the implementation of ISF process optimization in real-time, which is one of the largest gaps in current research and would allow broader industrial application of ISF. By highlighting these gaps, this review provides a roadmap for future research that will be essential to allowing ISF to evolve as a more practical and efficient large-scale manufacturing technique.

REFERENCES

Abdulrazaq, M. M., Gazi, S. K., & Ibraheem, M. Q. (2019). Investigation the Influence of SPIF Parameters on residual stresses for angular surfaces based on iso-planar tool path. *Al-Khwarizmi Engineering Journal, 15*(2), 50-59.

Afonso, D., De Sousa, R. A., Torcato, R., & Pires, L. (2019). *Incremental forming as a rapid tooling process.* Springer.

Afzal, M. J., & Buhl, J. (2022). Numerical study to promote the residual stresses development during ISF process with improvement in two point incremental die forming. *Key Engineering Materials, 926*, 752-759.

Afzal, M. J., Hajavifard, R., Buhl, J., Walther, F., & Bambach, M. (2021). Influence of process parameters on the residual stress state and properties in disc springs made by incremental sheet forming (ISF). *Forschung im Ingenieurwesen, 85*(3), 783-793.

Almadani, M., Guner, A., Hassanin, H., & Essa, K. (2023). Hot-air contactless single-point incremental forming. *Journal of Manufacturing and Materials Processing, 7*(5), 179.

Ao, D., Zhang, H., Wang, H., Bao, W., Gao, J., & Chu, X. (2024). Investigation of deformation behavior during electric pulse assisted incremental forming of Ti-6Al-4V sheet with a water-cooling system. *Journal* *of Manufacturing Processes, 126*, 165-174.

Asghar, J., Lingam, R., Shibin, E., & Reddy, N. (2014). Tool path design for enhancement of accuracy in single-point incremental forming. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 228*(9), 1027-1035.

Ben Said, L. (2022). The incremental sheet forming; technology, modeling and formability: A brief review. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 236*(6), 2729-2755.

Benmessaoud, R. (2024). Formability and Dimensional Accuracy Enhancement with Controlled Tool Rotational Speed in Stretch Forming Process. *Journal of Advanced Manufacturing Systems, 23*(02), 263-284.

Bikas, H., Stavropoulos, P., & Chryssolouris, G. (2016). Additive manufacturing methods and modelling approaches: a critical review. *The International Journal of Advanced Manufacturing Technology, 83*, 389-405.

Bin Che Ghani, S. A. (2013). *Design and analysis of the internally cooled smart cutting tools with the applications to adaptive machining Brunel University School of Engineering and Design* [PhD Theses].

Cao, J., & Banu, M. (2020). Opportunities and challenges in metal forming for lightweighting: review and future work. *Journal of Manufacturing Science and Engineering, 142*(11), 110813.

Centeno, G., Bagudanch, I., Morales-Palma, D., Garcia-Romeu, M. L., Gonzalez-Perez-Somarriba, B., Martínez-Donaire, A. J., Gonzalez-Perez, L. M., & Vallellano, C. (2017). Recent approaches for the manufacturing of polymeric cranial prostheses by incremental sheet forming. *Procedia Engineering, 183*, 180-187.

Chang, Z., & Chen, J. (2021). Analytical modeling of fracture strain and experimental validation in incremental sheet forming. *Journal of materials processing technology, 294,* 117118.

Chen, S.-L., Chen, J.-H., & Lee, Y. H. (2018). A comparison of competing models for understanding industrial organization's acceptance of cloud services. *Sustainability, 10*(3), 673.

Cheng, R., Wiley, N., Short, M., Liu, X., & Taub, A. (2019). Applying ultrasonic vibration during single-point and two-point incremental sheet forming. *Procedia Manufacturing, 34*, 186-192.

Conte, R., Ambrogio, G., Pulice, D., Gagliardi, F., & Filice, L. (2017). Incremental sheet forming of a composite made of thermoplastic matrix and glass-fiber reinforcement. *Procedia Engineering, 207*, 819-824.

Dixit, U., Joshi, S., & Davim, J. P. (2011). Incorporation of material behavior in modeling of metal forming and machining processes: A review. *Materials & Design, 32*(7), 3655-3670.

Duflou, J., Callebaut, B., Verbert, J., & De Baerdemaeker, H. (2007). Laser assisted incremental forming: formability and accuracy improvement. *CIRP annals, 56*(1), 273-276.

Duflou, J. R., Szekeres, A., & Vanherck, P. (2005). Force measurements for single point incremental forming: an experimental study. *Advanced Materials Research, 6*, 441-448.

Durante, M., Formisano, A., Langella, A., & Minutolo, F. M. C. (2009). The influence of tool rotation on an incremental forming process. *Journal of materials processing technology, 209*(9), 4621-4626.

Emmens, W., Sebastiani, G., & van den Boogaard, A. H. (2010). The technology of incremental sheet forming—a brief review of the history. *Journal of materials processing technology, 210*(8), 981-997.

Eyers, D. R., Potter, A. T., Gosling, J., & Naim, M. M. (2022). The impact of additive manufacturing on the product-process matrix. *Production Planning & Control, 33*(15), 1432-1448.

Fan, G., & Gao, L. (2014). Mechanical property of Ti-6Al-4V sheet in one-sided electric hot incremental forming. *The International Journal of Advanced Manufacturing Technology, 72*, 989-994.

Farahani, B. V., Belinha, J., Tavares, P. J., & Moreira, P. M. (2018). A nonlinear simulation of a bi-failure specimen through improved discretisation methods: A validation study. *The Journal of Strain Analysis for Engineering Design, 53*(8), 616-629.

Felinks, N., Krumme, E., & Biermann, D. (2023, November). Advanced Process Analysis for High Performance Tapping Technology in Aluminum Cast Alloy AlSi10Mg. In *Congress of the German Academic Association for Production Technology* (pp. 707-716). Cham: Springer Nature Switzerland.

Gilman, J. J. (2000). Electro-plastic effect in semiconductors. *Materials Science and Engineering: A, 287*(2), 272-275.

Göttmann, A., Bailly, D., Bergweiler, G., Bambach, M., Stollenwerk, J., Hirt, G., & Loosen, P. (2013). A novel approach for temperature control in ISF supported by laser and resistance heating. *The International Journal of Advanced Manufacturing Technology, 67,* 2195-2205.

Gupta, P., Szekeres, A., & Jeswiet, J. (2019). Design and development of an aerospace component with single-point incremental forming. *The International Journal of Advanced Manufacturing Technology, 103*, 3683-3702.

Heigel, J. C., Andrawes, J. S., Roth, J. T., Hoque, M. E., & Ford, R. M. (2000). Viability of electrically treating 6061 T6511 aluminum for use in manufacturing processes.

Hoang, V. Q., & Nguyen, D. T. (2021, November). A simple method to tool path generation for cone surface on CNC 3 axis milling. In *International Conference on Advanced Mechanical Engineering, Automation and Sustainable Development* (pp. 481-492). Cham: Springer International Publishing.

Huang, Z., Shen, Y., Li, J., Fey, M., & Brecher, C. (2021). A survey on AI-driven digital twins in industry 4.0: Smart manufacturing and advanced robotics. *Sensors, 21*(19), 6340.

Hussain, G., & Al-Ghamdi, K. A. (2017). Empirical modeling and simultaneous optimization of energy efficiency/demand, cost and productivity in incremental forming of metallic clad composite. *International Journal* *of Hydrogen Energy, 42*(31), 20375-20385.

Jagtap, R., & Kumar, S. (2021). An experimental study on geometric accuracy in hybrid incremental sheet forming. *Advances in Materials and Processing Technologies, 7*(4), 684-695.

Jayathunga, J., & Chandana, A. (2023). The Impact of Friction Force and Parabolic Arc Patterns on the Initial Acceleration Interacting with Block Start Obliquities: 100m Sprint. In: Sabaragamuwa University of Sri Lanka.

Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., & Allwood, J. (2005). Asymmetric single point incremental forming of sheet metal. *CIRP annals, 54*(2), 88-114.

Jiang, Y., Tang, G., Shek, C., Xie, J., Xu, Z., & Zhang, Z. (2012). Mechanism of electropulsing induced recrystallization in a cold-rolled Mg–9Al–1Zn alloy. *Journal of Alloys and Compounds, 536*, 94-105.

Jiang, Z. (2022). *Process Understanding of Hybrid Multi-Step Incremental Sheet Forming* [Northwestern University].

Jiang, Z., Ehmann, K. F., & Cao, J. (2022). Prediction of forming temperature in electrically-assisted double-sided incremental forming using a neural network. *Journal of materials processing technology, 302*, 117486.

Kajal, G., Tyagi, M., & Kumar, G. (2023). A review on the effect of residual stresses in incremental sheet metal forming used in automotive and medical sectors. *Materials Today: Proceedings, 78*, 524-534.

Kulkarni, S. S., & Mocko, G. M. (2020). Experimental investigation and finite element modeling of localized heating in convective heat-assisted single-point incremental forming. *The International Journal of Advanced Manufacturing Technology, 107*, 945-957.

Kumar, A. (2024). Critical state-of-the-art literature review of surface roughness in incremental sheet forming: a comparative analysis. *Applied Surface Science Advances, 23*, 100625.

Kumar, H., Barman, P., & Singh, R. R. (2015). Effect of size and shell: enhanced optical and surface properties of CdS, ZnS and CdS/ZnS quantum dots. *Physica E: Low-Dimensional Systems and Nanostructures, 67*, 168-177.

Kyratsis, P., Tzotzis, A., & Davim, J. P. (2023). *3D FEA Simulations in Machining*. Springer.

La, N.-T., Ngo, Q.-H., Vu, V.-D., Mai, T.-H., & Ho, K.-T. (2024). Optimization of Ultrasonic-Assisted *Incremental Sheet Forming. Materials, 17*(13), 3170.

Leonhardt, A., Kurz, G., Victoria-Hernández, J., Kräusel, V., Landgrebe, D., & Letzig, D. (2018). Experimental study on incremental sheet forming of magnesium alloy AZ31 with hot air heating. *Procedia Manufacturing, 15*, 1192-1199.

Li, J., Geng, P., & Shen, J. (2013). Numerical simulation and experimental investigation of multistage incremental sheet forming. *The International Journal of Advanced Manufacturing Technology, 68*, 2637-2644.

Li, J., Li, Y., Yuan, H., Cheng, Z., Yu, Y., Ghafoor, S., & Li, F. (2023). Multi-stage finite element modeling of the deformation behavior during ultrasonic-assisted incremental sheet forming. *Journal of Computational Science, 72*, 102077.

Li, Y., Liu, F., Xu, C., Zhai, W., Zhou, L., Li, F., & Li, J. (2019). Investigation of the effect of process parameters on energy consumption in incremental sheet forming. *Procedia CIRP, 80*, 50-55.

Li, Y., Zhao, G., An, D., Chen, J., & Zhao, G. (2023). A novel macro-micro integrated incremental sheet forming process for fabricating parts with functional surface microfeatures. *Journal of materials processing technology, 320*, 118130.

Liu, Z. (2018). Heat-assisted incremental sheet forming: a state-of-the-art review. *The International Journal of Advanced Manufacturing Technology, 98*(9), 2987-3003.

Lu, B., Chen, J., Ou, H., & Cao, J. (2013). Feature-based tool path generation approach for incremental sheet forming process. *Journal of materials processing technology, 213*(7), 1221-1233.

Mandaloi, G., Nagargoje, A., Gupta, A. K., Banerjee, G., Shahare, H. Y., & Tandon, P. (2022). A comprehensive review on experimental conditions, strategies, performance, and applications of incremental forming for deformation machining. *Journal of Manufacturing Science and Engineering, 144*(11), 110802.

Mosecker, L., Göttmann, A., Saeed-Akbari, A., Bleck, W., Bambach, M., & Hirt, G. (2013). Deformation mechanisms of Ti6Al4V sheet material during the incremental sheet forming with laser heating. *Key Engineering Materials, 549*, 372-380.

Nguyen, A.-T., Reiter, S., & Rigo, P. (2014). A review on simulation-based optimization methods applied to building performance analysis. *Applied energy, 113*, 1043-1058.

Nguyen, G. T., Iftekhar, M. S., Ratnasiri, S., Roiko, A., & Beal, C. D. (2024). Supply, demand and the economic effectiveness of urine-diverting technologies and products: A systematic literature review. *Water Research*, 121478.

Panchal, J. H., Kalidindi, S. R., & McDowell, D. L. (2013). Key computational modeling issues in integrated computational materials engineering. *Computer-Aided Design, 45*(1), 4-25.

Patel, D., & Gandhi, A. (2022). A review article on process parameters affecting Incremental Sheet Forming (ISF). *Materials Today: Proceedings, 63*, 368-375.

Peng, H., Dong, P., Cheng, X., Zhang, C., Tang, W., Xing, Y., & Zhou, X. (2020). Semi-empirical prediction of residual stress distributions introduced by turning Inconel 718 alloy based on Lorentz function. *Materials, 13*(19), 4341.

Pietrzyk, M., Madej, L., Rauch, L., & Szeliga, D. (2015). *Computational Materials Engineering: Achieving high accuracy and efficiency in metals processing simulations. Butterworth-Heinemann.*

Pragana, J. P., Cristino, V. A., Bragança, I. M., Silva, C. M., & Martins, P. A. (2020). Integration of forming operations on hybrid additive manufacturing systems based on fusion welding. *International Journal of Precision Engineering and Manufacturing-Green Technology, 7*, 595-607.

Qin, Z., Gatea, S., & Ou, H. Spindle speed effect on the ISF processing of materials with different thermal conductivities. *Materials Research Proceedings, 41*.

Raabe, D., Sun, B., Kwiatkowski Da Silva, A., Gault, B., Yen, H.-W., Sedighiani, K., Thoudden Sukumar, P., Souza Filho, I. R., Katnagallu, S., & Jägle, E. (2020). Current challenges and opportunities in microstructure-related properties of advanced high-strength steels. *Metallurgical and Materials Transactions A, 51,* 5517-5586.

Ramzan, M., Dawar, A., Saeed, A., Kumam, P., Watthayu, W., & Kumam, W. (2021). Heat transfer analysis of the mixed convective flow of magnetohydrodynamic hybrid nanofluid past a stretching sheet with velocity and thermal slip conditions. *Plos one, 16*(12), e0260854.

Rinschede, T., Biermann, D., Iovkov, I., & Bücker, M. (2021). Development of a concept for the use of low-temperature emulsion in drilling of Inconel 718. *Procedia CIRP, 104*, 774-779.

Riofrio Sabando, M. I. (2024). Toward sustainable metal forming: cost and environmental evaluation of single point incremental forming.

Safari, M., Alves de Sousa, R., & Joudaki, J. (2020). Recent advances in the laser forming process: A review. *Metals, 10*(11), 1472.

Salmi, M., Partanen, J., Tuomi, J., Chekurov, S., Flores, I., Björkstrand, R., & Lehtinen, P. (2015). *Tekes projekti SuperMachines loppuraportti.*

Samoy-Alvarado, A. (2022). *Intravital Two-Photon Microscopy and the Glymphatic System: Settling the Bulk Flow Debate* [The University of Arizona].

Shao, W., Rong, Y., & Huang, Y. (2022). Image contrast enhancement and denoising in micro-gap weld seam detection by periodic wide-field illumination. *Journal of Manufacturing Processes, 75*, 792-801.

Sharma, M., Alkhazaleh, H. A., Askar, S., Haroon, N. H., Almufti, S. M., & Al Nasar, M. R. (2024). FEM-supported machine learning for residual stress and cutting force analysis in micro end milling of aluminum alloys. *International Journal of Mechanics and Materials in Design, 20*(5), 1077-1098.

Shokrani, A., Arrazola, P., Biermann, D., Mativenga, P., & Jawahir, I. (2024). Sustainable machining: Recent technological advances. *CIRP annals, 73*(2), 483-508.

Silva, M. B., Nielsen, P. S., Bay, N., & Martins, P. (2011). Failure mechanisms in single-point incremental forming of metals. *The International Journal of Advanced Manufacturing Technology, 56*, 893-903.

Singh, G., Kalita, B., Vishnu Narayanan, K., Arora, U. K., Mahapatra, M. M., & Jayaganthan, R. (2020). Finite element analysis and experimental evaluation of residual stress of Zr-4 alloys processed through swaging. *Metals, 10*(10), 1281.

Singh, R. P., Kumar, S., Pande, S., Salunkhe, S., Ragab, A. E., Singh, P. K., Meraz, M., & Davim, J. P. (2023). Robot-assisted cold and warm incremental sheet forming of aluminum alloy 6061: a comparative study. *Metals, 13*(3), 568.

Singh, S., Agrawal, V., SAXENA, K. K., & Mohammed, K. A. (2023). Optimization on manufacturing processes at Indian industries using TOPSIS. *Indian Journal of Engineering and Materials Sciences (IJEMS), 30*(1), 32-44.

Smith, J., Malhotra, R., Liu, W., & Cao, J. (2013). Deformation mechanics in single-point and accumulative double-sided incremental forming. *The International Journal of Advanced Manufacturing Technology, 69*, 1185-1201.

Thornton, E.-L., Zannoun, H., Vomero, C., Caudill, D., & Schoop, J. (2023). A review of constitutive models and thermal properties for nickel-based superalloys across machining-specific regimes. *Journal of Manufacturing Science and Engineering, 145*(8), 080801.

Torres, S., Caldeŕon, E., Ortega, R., & Acosta, P. (2022). Sustainability in terms of energy consumption in processes of incremental forming and stamping. *Materials Today: Proceedings, 49*, 175-180.

Trzepieciński, T. (2020). Recent developments and trends in sheet metal forming. *Metals, 10*(6), 779.

Trzepieciński, T., Oleksik, V., Pepelnjak, T., Najm, S. M., Paniti, I., & Maji, K. (2021). Emerging trends in single point incremental sheet forming of lightweight metals. *Metals, 11*(8), 1188.

Trzepieciński, T., Szpunar, M., Ostrowski, R., Ziaja, W., & Motyka, M. (2024). Advanced FEM Insights into Pressure-Assisted Warm Single-Point Incremental Forming of Ti-6Al-4V Titanium Alloy Sheet Metal. *Metals, 14*(6), 619.

van Blitterswijk, R. H. (2024). *Adaptive Model Predictive Control for Microstructure Control in Laser Material Processing* [University of Waterloo].

Wang, L., Lian, J., Wu, X., & Jia, X. (2005). A new rolling force model for dry thick temper rolling strip mill. *Journal of materials processing technology, 170*(1-2), 381-384.

Williams, J. C., & Starke Jr, E. A. (2003). Progress in structural materials for aerospace systems. *Acta materialia, 51*(19), 5775-5799.

Yan, Z., Hassanin, H., El-Sayed, M. A., Eldessouky, H. M., Djuansjah, J. R. P., A. Alsaleh, N., Essa, K., & Ahmadein, M. (2021). Multistage tool path optimisation of single-point incremental forming process. *Materials, 14*(22), 6794.

Yang, Q., Xu, Y., Tong, X., Hu, T., Liu, Y., Chakraborty, T. C., Yao, R., Xiao, C., Chen, S., & Ma, Z. (2023). Influence of urban extent discrepancy on the estimation of surface urban heat island intensity: A global-scale assessment in 892 cities. *Journal of Cleaner Production, 426*, 139032.

Zhang, S.-H., Chen, S.-F., Ma, Y., Song, H.-W., & Cheng, M. (2015). Developments of new sheet metal forming technology and theory in China. *Acta Metallurgica Sinica (English Letters), 28*, 1452-1470.

Zhang, S., Tang, G., Wang, W., & Jiang, X. (2020). Evaluation and optimization on the formability of an AZ31B Mg alloy during warm incremental sheet forming assisted with oil bath heating. *Measurement, 157*, 107673.

Zhang, Z. (2023). *Assessing sustainable development in industrial* *regions towards smart built environment management using Earth observation big data* [Curtin University].

Zhao, X., Qin, H., & Feng, Z. (2021). Influence of tool edge form factor and cutting parameters on milling performance. *Advances in Mechanical Engineering, 13*(4), 16878140211009041.

Zhao, Y., Ma, B., Guo, H., Ma, J., Yang, Q., & Song, J. (2013). Electropulsing strengthened 2GPa boron steel with good ductility. Materials & Design, 43, 195-199.

Zhu, D., & Zeng, Y. (2008). Micro electroforming of high-aspect-ratio metallic microstructures by using a movable mask. *CIRP annals, 57*(1), 227-230.