

## Recent Advances And Research In New Hybrid Technique Deformation Machining

P L Parmar<sup>1</sup>, P M George<sup>2</sup>

Research Scholar, Mechanical Engineering, Gujarat Technological University, Gujarat, India<sup>1</sup>

Professor, Mechanical Engineering, Gujarat Technological University, Gujarat, India<sup>2</sup>

<sup>1</sup>[plparmar221@gmail.com](mailto:plparmar221@gmail.com)

<sup>2</sup>[pmgeorge02@gmail.com](mailto:pmgeorge02@gmail.com)

**How to cite this article:** P L Parmar, P M George (2024) Recent Advances And Research In New Hybrid Technique Deformation Machining. *Library Progress International*, 44(3), 14484-14492.

### ABSTRACT

Deformation machining is a hybrid process where material is first plastically deformed, and then machining operations (such as milling or turning) are used to refine the shape or surface finish. This hybrid approach leverages the advantages of both plastic deformation—typically seen in processes like forging, bending, or stamping—and precision machining, enabling the production of complex, lightweight, and high-performance parts. This technique is especially useful for industries requiring high precision and strength, such as aerospace, automotive, and medical device manufacturing. Deformation machining combines two emerging manufacturing processes, machining of thin structure and single point incremental forming (SPIF). Single point incremental forming creates sheet metal parts without dies by deformation of local point. Starting from plate stock, thin features are created by machining operations. Then using forming tool SPIF process is used to create deformations of the thin sections in two different ways, by bending or by stretching. It enables the creation of structure that have geometries that would be difficult or impossible to create by other processes. The parts manufactured are lighter in weight and also less expensive than the replaced parts. Components which were previously made by assembling sheet metal can now be made as monolithic machined component. And this reduces assembling time and precision is also improved. This paper focused on the work that has been carried in the area of deformation machining.

**Keywords:** Thin structure manufacturing, Deformation Machining, Incremental Forming

### Introduction

Deformation machining is an advanced manufacturing process that combines elements of both deformation (plasticity-based forming) and material removal (machining) to achieve complex geometries, enhance material properties, or create lightweight structures. Below is a review of this process, touching upon key principles, methodologies, applications, and challenges. In many application areas such as aerospace, it is desirable to have thin metallic structures. The machining of such thin components can be done by deformation machining process and this can replace large number of assembly operations. Research in this area is related to feasibility of the process and the related tooling requirement for the process. The process time, forces generated during the process, geometry of the part produced and the responses of different material are the areas which are still open to work on.

### **Fundamental Principles:**

**Plastic Deformation:** During deformation machining, a workpiece undergoes plastic deformation under controlled conditions, which leads to shape changes while preserving or enhancing the internal structure. This results in improvements in material properties such as hardness, ductility, and fatigue resistance.

**Material Removal:** After deformation, excess material is removed using traditional machining processes. This may involve high-precision techniques like milling, turning, or grinding, depending on the desired surface finish and dimensional accuracy.

**Strain Hardening:** Deformation machining often induces strain hardening, a phenomenon where the material's strength increases due to dislocation movements within the microstructure. This is particularly advantageous when producing parts that require high mechanical performance.

### **Methodologies in Deformation Machining:**

**Incremental Sheet Forming with Machining:** One of the common methods in deformation machining is incremental sheet forming (ISF), where a sheet metal part is formed incrementally using a tool path similar to that in CNC machining. After forming, excess material is machined away to achieve the final geometry and tolerances.

**Surface Deformation and Machining:** In some processes, deformation is applied selectively to enhance specific surface properties, such as increasing hardness or inducing compressive residual stresses. This is followed by precision machining to achieve the final dimensions and surface finish.

**Combined Deformation and Machining for Lightweight Structures:** By strategically deforming the material, internal cavities, channels, or ribbed structures can be created to reduce weight while maintaining structural integrity. This is followed by machining to finalize the external geometry, making it a valuable process for aerospace and automotive applications.

### **Recent Advances and Research**

Recent research in deformation machining focuses on several fronts:

**Process Optimization:** Efforts are being made to optimize tool paths, cutting forces, and deformation parameters using artificial intelligence (AI) and machine learning algorithms. This helps reduce the need for trial-and-error approaches in process design.

**Advanced Materials:** Studies on materials such as composites, functionally graded materials, and high-entropy alloys explore how deformation machining can be adapted for next-generation manufacturing materials.

**Additive Manufacturing Integration:** There is growing interest in integrating deformation machining with additive manufacturing (AM) techniques, creating a hybrid approach where parts are additively built, deformed for enhanced properties, and finally machined for precision finishing.

**Sustainability:** Deformation machining is also being studied for its potential to reduce material waste and energy consumption, which are critical factors in sustainable manufacturing. The reduction in material removal, due to the deformation phase, could lower the overall environmental footprint of the process.

Preliminary results in feasibility study of the process are encouraging, and point to a broad range of industrial applications. Starting from plate stock, thin features like walls, floors, or even pins are created by machining operations. Then using a forming tool SPIF process is followed to create deformations of the thin sections in two different ways, either bending or stretching the features. By switching between the cutting tool and the deformation tool, it is possible to make interesting features which are thinner, lighter, or less expensive than the structures they replace. In addition, it is possible to produce geometries that would be difficult or impossible to create using other processes. The two modes of deformation machining process are shown below:

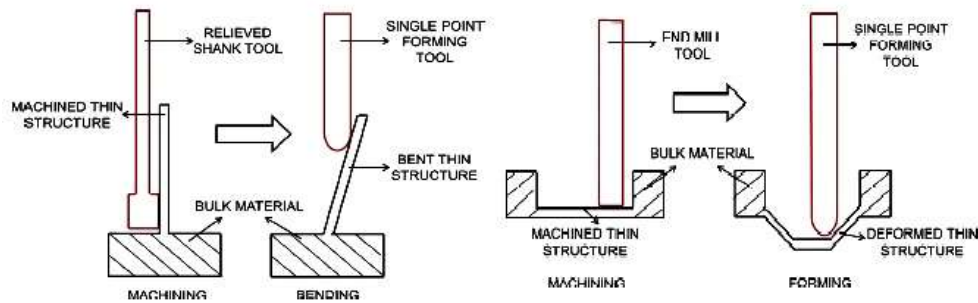


Figure.1 Schematic of Deformation Machining Bending and Stretching Mode[5]

S. Smith et al.[1] describes a novel hybrid process, deformation machining. Two large target classes of part (1) those where primary deformation is perpendicular to the axis of the tool resulting in a forming operation i.e. bending of the wall or floors and (2) where deformation is along the axis of tool resulting in stretching of wall or floor. Goal was to explore the potential benefits and limitations of using a single 3 axis CNC machine tool to create complex parts using combination of thin part machining and SPIF. Forces were measured in both the case while manufacturing different component made of AA 7050 T7451 widely use in aerospace industry and collected data shows that this process is within the capability of existing machine tools, and deformation forces are similar in magnitude to cutting forces.

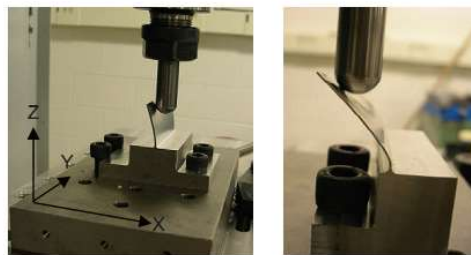


Figure.2 Measurement of the deformation force on a thin wall showing force data sign conventions and setup.[1]

S. Smith et al.[2] filed a patent on deformation machining systems and methods. The thin Wall/floor structure may be bent to form any type of lip or overhang, a C-channel, a U-channel, or selectively and progressively bent along its transverse direction to form an impeller blade or the like and the possibilities the same are virtually endless.

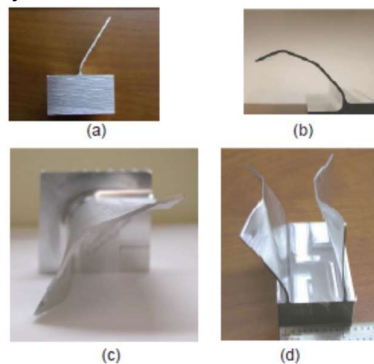


Figure.3 (a) A thin wall with a single bend (b) thin wall with multiple bends (c-d) Interesting thin wall geometries. [2]

Agrawal et al.[3] study indicates that DM process is not providing tight tolerances like standard milling process. This may be due to the spring back and local variations in material properties which influence the yield strength and results in spring back. However, the components created by this process found more repeatable compare to similar components

created with sheet metal using SPIF, but less repeatable than components created by conventional bending of sheet metal. The other objective of the work was to investigate whether components fabricated using the DM process can be considered for fatigue critical applications. Studies were performed to experimentally compare the fatigue life of components fabricated by DM process with sheet metal components made by single-point incremental forming and conventional bending. Results of the study indicates that sheet metal SPIF components under the loading conditions have significantly longer fatigue life of approximately 3900-5500 cycles, compared to DM and sheet metal conventionally bent components with approximately equal fatigue life of 2200-3900 cycles. However, it is notable that the repeatability of the DM bending mode process appears to be significantly better than for SPIF of sheet metal.

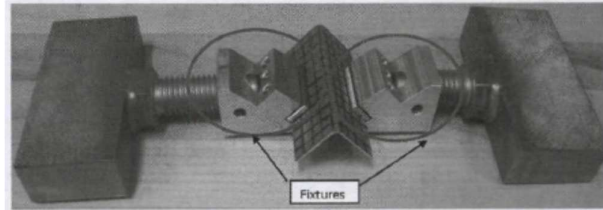


Figure.4 Photograph of the fixture used to hold the specimen [3]

Arshpreet Singh et al. [4] had compared dimensional repeatability and accuracy for deformation machining stretching mode with sheet metal component. Ten components were fabricated by Deformation Machining stretching mode, and measured at various forming depth using on CMM for repeatability of the process. The dimensional repeatability of the process largely depends on the accuracy of the machined floor, and other factors affecting are elastic deformation, residual stresses, spring back and highly localized yielding. For DM components raw material billet was firstly machined to component size of 90X90X12mm to be held in fixture and then floor of 1 mm thickness with diameter 70mm were machined. After that machined floor was formed incrementally into conical frustum using single point tool of hemispherical end. For SPIF and conventionally formed component sheet metal of the same alloy was prepared and formed using single point tool. The results evident that the dimensional accuracy of the conventionally formed components is the best with the average variation of 1.875 mm from the actual required dimensions. Average variation of the measured diameter from the required diameter across forming depths for DM components and SPIF components is comparable with the magnitude of 6.430 mm and 5.982 mm respectively. The poor repeatability of the components produce by DM and SPIF could be attributed the uneven redistribution of residual stresses; however this could not be confirmed conclusively. The role of residual stresses in this process could be seen as a new research scope.

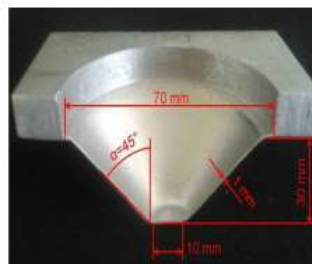
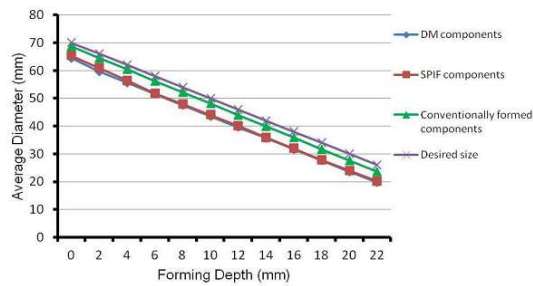


Figure.5 Geometry of conical frustum [4]

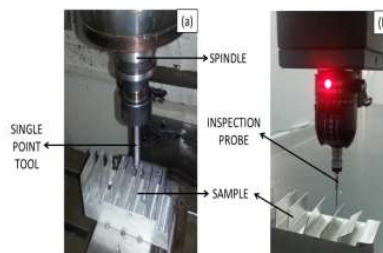
Diameter of the formed cone was measured at 0 mm up to 22 mm depth with an interval of 2 mm. Variation on the diameters at different points across the depth of conical frustum for all the similar components made was recorded. The average of ten diameters at different point is shown in figure below.



**Figure.6 Average diameter of ten components of respective process V/S forming depth[4]**

Poor dimensional accuracy for DM and SPIF is attributed mainly due to bending effect at the start of bending and elastic spring back effect in incremental forming. The future work to this is developing good strategy to counter these problems.

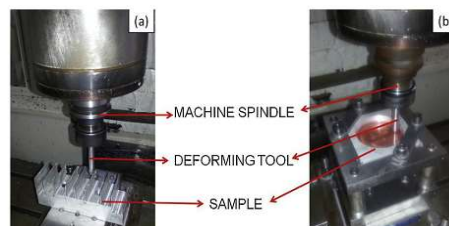
Arshpreet Singh et al. [5] had experimentally investigated the elastic spring back in deformation machining bending mode. The nano-indentation technique shows the generation of compressive surface residual stresses during machining and tensile surface residual stresses during forming operations, and it is also observed that there is a significant variation in the surface residual stresses with varying machining and forming parameters. Due to the elastic recovery during unloading dimensional inaccuracy becomes a major concern. The material used Al 6063 –T6 (50mmX50mmsquare bar) commonly used material in aerospace and marine industry. Firstly samples were machined to thin structure and then bent incrementally using a single point forming tool. Elastic spring back and other dimensional inaccuracies were measured on CMM. Reduction of compressive surface residual stresses was observed at different forming depths on DM stretching mode components. It is found that increase in incremental step size, incremental angle, and forming feed rate results in decrease of surface compressive residual stress generated machining.



**Figure.7a) Fabrication of samples on CNC Machines b) Inspection on CMM [5]**

The results shows that feed rate, dimensional attributes like wall thickness, bent angle, H/L ratio have significant bearing on the elastic spring back. The future scope is to develop correlations with the various aspects of elastic spring back and developing holistic experimental model, incorporating wide range and levels of parameters for accurate prediction of spring back.

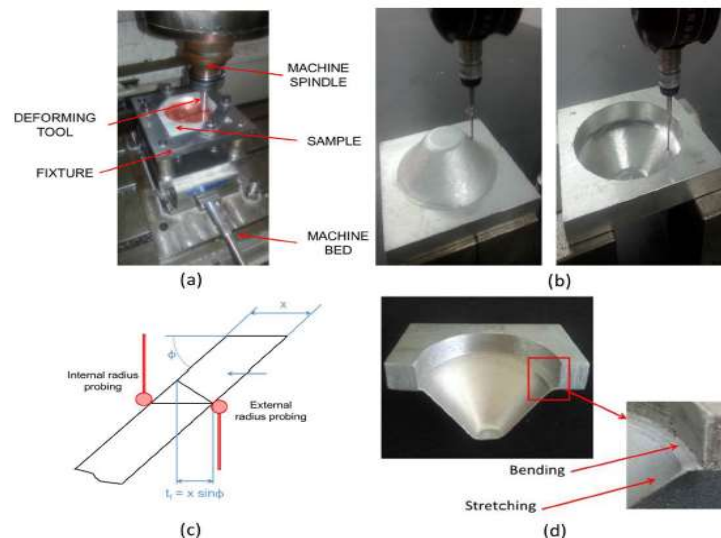
Arshpreet Singh et al. [6] investigated residual stress distribution in deformation machining process for Al 6063-T6 bending mode and stretching mode. This stresses have significant effect on fatigue life, strength, corrosion resistance and overall product life of component. Residual stresses are induced in the component by deformation machining during the machining as well as forming. Study of this work shows the amount and distribution of the residual stresses.



**Figure.8 Experimental setup for a) DM Bending mode b) DM Stretching mode [6]**

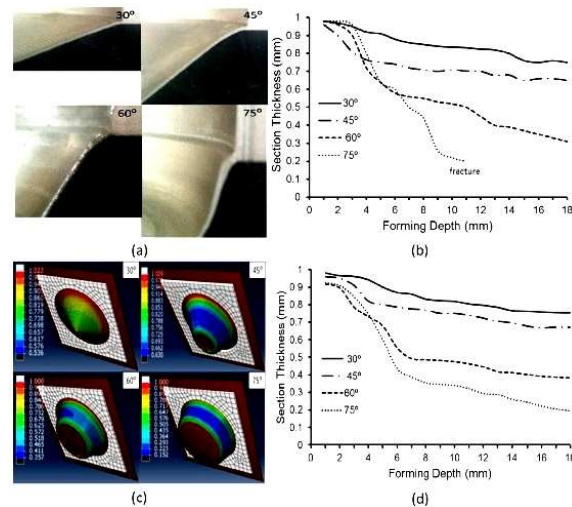
Incremental bending resulted in lessening of compressive residual stresses on the tensile face and increase in compressive residual stresses on the compressive face of the DM bending mode components. Reduction of compressive surface residual stresses was noticed at different forming depths on DM stretching mode components. Increase in incremental angle, incremental step size and forming feed rate also results in decrease of surface compressive residual stress generated by prior machining. Overall, stresses in DM bending and stretching mode component were compressive in nature due to the dominating effect of compressive surface residual stresses generated during the thin section machining.

Arshpreet Singh et al.[7] compared deformation forces, residual stresses and geometrical accuracies of deformation machining with conventional forming and single point incremental forming. Substantial reduction in deformation forces in deformation machining and single point incremental forming was found over conventional forming. The work provides initial insights to commercialize the process as a replacement of conventional forming. Deforming forces were recorded using a Kistler 9257B six component force dynamometer mounted on the machine bed along with a Kistler 5070 8-channel charge amplifier. The samples were inspected for geometrical inaccuracies on a coordinate measuring machine (CMM). After the recording of deforming force and inspection on the CMM, the samples of size  $10 \times 10$  mm were cut with EDM wire cut and Buhler IsoMet low speed saw for surface and core residual stress calculation. The samples were cut from actual bending zone from tensile as well as the compressive side of the bent structure. The stretch forming samples were cut within the forming depth of 10 mm. Thereafter, the samples were cold mounted in epoxy resin. Each sample was ground with different grades of abrasive paper and polished with Buhler EcoMet 250 to achieve desirable surface finish for nano-indentation. Respective raw material specimen were also cut and grounded to desired finish and taken as a reference for nano indentation.



**Figure.9(a) Fabrication of samples on CNC machine; (b) inspection of external and internal radii on CMM; (c) schematic of thickness measurement (d) Actual sample. [7]**

Arshpreet Singh et al.[8] worked on structural thinning and compensation stratagem in deformation machining stretching mode. The material used in the present study is AA 6063-T6, a commonly used aerospace and aviation alloy. A  $12 \times 100$  mm aluminum flat was used as a raw material. A fixture was designed and fabricated, for mounting and clamping the samples. The samples were radially measured at 20 locations across the depth. Experimental and FE simulation results reveal considerable thinning in the formed section along with highly non uniform thickness profiles. Desired formed thickness along with considerable uniform profile across the forming depth was achieved by employing a varying thin section machining compensation strategy, prior to incremental forming. This would probably enhance the formability limits and strength of the formed monolithic components. Future work in structural thinning and compensation would be its extension to varied profiles, geometries with variable forming angles.



**Figure.10 (a) Cross sectional images of thin formed components; (b) experimental variation of section thickness along the forming depth at varying forming wall angles; FE simulated section thickness profiles; (d) simulated variation of section thickness along the forming depth at varying forming wall angles.[8]**

Arshpreet Singh et al.[9] Prepared experimental force modeling for deformation machining stretching mode for aluminum alloys. The results of this study indicate that average resultant force during DM process primarily depends on floor thickness to be deformed and incremental depth in the tool path. Among these two, the floor thickness is observed to be the most significant parameter. Whereas the effect of tool diameter, deforming wall angle, and floor size were found not as significant. The model has been compared and validated for different aluminum alloys at varied levels of parameters, within an error range from 2.5 to 11.4%. The influence of shape of the formed component on the average resultant forces has also been studied and found to be dependent on the geometry. Forces have been carried out and were observed to be more during DM process. It could be due to the work hardening of the component during machining, prior to deformation.

Arshpreet Singh et al.[10] Investigated the parametric effects on geometrical inaccuracies in deformation machining process. A comprehensive study covering a wide range of process parameters on the geometrical inaccuracies in deformation machining process. The results show that dimensional attributes such as bent angle, wall height to length ratio, and wall thickness have a significant effect on the average spring back in DM bending mode components in comparison to the process parameters such as tool diameter, incremental bending angle, and bending feed rate. Bending error due to curvature increases significant with increase in the bent angle. Inclination at the free end of the bent structure increases at increased bending angle and wall thickness. Process parameters such as forming tool diameter, forming angle, and incremental depth have a significant effect on the average radial error in DM stretching mode components in comparison to dimensional attributes like floor thickness and floor size. This study would help in calculating the necessary compensation or over draft for a wide range of process parameters involved in deformation machining employing conventional machining modules for the tool path generation. The future work in this direction could be finding different ways and techniques to eliminate the geometrical discrepancies in order to achieve acceptable level of accuracy.

#### Applications

**Aerospace:** Deformation machining is used to produce lightweight yet robust components, such as turbine blades, structural components, and thin-walled parts. The ability to control the microstructure and enhance material properties during deformation is critical for meeting the stringent performance requirements in aerospace applications.

**Automotive:** In automotive manufacturing, deformation machining helps in the production of high-strength, lightweight parts like suspension components, engine blocks, and structural frames. The reduced material usage while maintaining strength contributes to fuel efficiency and performance.

**Biomedical:** Medical implants, such as bone plates, screws, and prosthetics, benefit from deformation machining due to the high precision and customization potential it offers. Additionally, the process can improve biocompatibility through surface treatments and precise finishing operations.

**Energy Sector:** Components used in oil, gas, and renewable energy systems, such as turbine casings or pipeline fittings, require excellent mechanical properties and precision, which can be achieved through deformation machining techniques.

### Challenges in Deformation Machining

**Process Control:** A significant challenge in deformation machining is maintaining tight control over the deformation process to avoid defects such as wrinkling, tearing, or excessive strain hardening, which could compromise the material's performance or final geometry.

**Tool Wear:** The hybrid nature of the process, especially when machining high-strength materials, often leads to increased tool wear due to the residual stresses and strain hardening induced by the deformation phase. High-performance tooling materials and coatings are required to mitigate this.

**Complexity of Simulation and Modeling:** Modeling deformation machining processes can be complex, as it involves the interaction of both plastic deformation and material removal mechanics. Accurate finite element analysis (FEA) simulations are necessary for predicting outcomes like stress distributions, strain rates, and temperature effects, but they are computationally intensive.

**Material-Specific Challenges:** Different materials exhibit varying responses to deformation and machining, making process optimization difficult for a broad range of materials. For instance, harder metals like titanium and Inconel may benefit from deformation machining but require careful control to avoid excessive tool wear and surface damage.

### Conclusion and Recommendations for Future Work:

Deformation machining offers significant advantages in producing complex, lightweight, and high-performance parts by combining plastic deformation and machining. Deformation machining is a new hybrid manufacturing process which combines two process namely, thin part machining and SPIF. Starting from stock material, thin features like walls, floors, or even pins are created by machining operations. After this, SPIF is used to form the thin sections in different ways, by bending or by stretching. By switching between these two processes it is possible to make interesting features which are thinner, lighter, or less expensive than the structures they replace. It is also possible to create geometries that would be difficult or impossible to create using other processes. The collected force data shows the process within the capability of existing machine tools. While challenges like tool wear, process control, and material variability remain, ongoing research and technological advancements are addressing these issues. The application of deformation machining is expanding, particularly in high-demand industries such as aerospace, automotive, biomedical, and energy. As simulation tools, process optimization techniques, and material science continue to evolve, deformation machining is poised to play an even more critical role in the future of manufacturing. Thickness variation, hardness and surface finish of the formed geometries are still the open area for the improvement in the process.

### REFERENCES

- G. S. Smith, B. Woody, J. Ziegert, and Y. Huang, "Deformation machining - A new hybrid process," CIRP Ann. - Manuf. Technol., vol. 56, no. 1, pp. 281–284.
- U. States, "United StateS (12)," no. 12, 2004.
- A. Agrawal, J. Ziegert, S. Smith, B. Woody, and J. Cao, "Study of Dimensional Repeatability and Fatigue Life for Deformation Machining Bending Mode," J. Manuf. Sci. Eng., vol. 134, no. 6, p. 061009, 2012.
- A. Singh and A. Agrawal, "Comparison of Dimensional Repeatability and Accuracy for

Deformation Machining Stretching Mode with Sheet Metal Components,” no. AIMTDR, pp. 1–5, 2014.

A. Singh and A. Agrawal, “Experimental Investigation on Elastic Spring Back in Deformation Machining Bending Mode,” no. April, 2015.

A. Singh and A. Agrawal, “Investigation of surface residual stress distribution in deformation machining process for aluminum alloy,” *J. Mater. Process. Technol.*, vol. 225, no. April, pp. 195–202, 2015.

A. Singh and A. Agrawal, “Comparison of deforming forces, residual stresses and geometrical accuracy of deformation machining with conventional bending and forming,” *J. Mater. Process. Technol.*, vol. 234, no. April, pp. 259–271, 2016.

A. Singh and A. Agrawal, “Investigations on structural thinning and compensation stratagem in deformation machining stretching mode,” *Manuf. Lett.*, vol. 9, pp. 1–6, 2016.

A. Singh and A. Agrawal, “Experimental force modeling for deformation machining stretching mode for aluminum alloys,” *Sadhana - Acad. Proc. Eng. Sci.*, vol. 42, no. 2, pp. 271–280, 2017.

A. Singh, “Investigation of Parametric Effects on Geometrical Inaccuracies in Deformation Machining Process Investigation of Parametric Effects on Geometrical Inaccuracies in Deformation Machining Process,” no. June, 2018.

S. Smith and D. Dvorak, “Tool path strategies for high speed milling aluminum workpieces with thin webs,” *Mechatronics*, vol. 8, no. 4, pp. 291–300, 1998.

J. Tlustý, S. Smith, and W. R. Winfough, “Techniques for the Use of Long Slender End Mills in High-speed Milling,” *CIRP Ann. - Manuf. Technol.*, vol. 45, no. 1, pp. 393–396, 1996.

R. Malhotra, N. V. Reddy, and J. Cao, “Automatic 3D Spiral Toolpath Generation for Single Point Incremental Forming,” *J. Manuf. Sci. Eng.*, vol. 132, no. 6, p. 061003, 2010.

Rahul Jagpat, Sachin Kashid, Shailendra Kumar & H.M.A. Hussein, " An experimental study on the influence of tool path, tool diameter and pitch in single point incremental forming(SPIF),"

Ambrogio G, Gagliardi F, Filice L (2013) On the high-speed sin-gle point incremental forming of titanium alloys. *CIRP Ann* 62(1): 243–246.

Silva MB, Skjoedt M, Bay N, Martins PAF (2009) Revisiting single-point incremental forming and formability/failure diagrams by means of finite elements and experimentation. *J Strain Anal Eng Des* 44(4) :221 – 234.

Jeswiet J, Dufloy JR, Szekeres A, Lefebvre P (2005) Custom manufacture of a solar cooker – acasestudy. *Adv Mater Res* 6–8:487–492.

Ambrogio G, Gagliardi F, Bruschi S, Filice L (2013) Robust de-sign of incremental sheet forming by Taguchi’s method. *Procedia CIRP* 12:270–275.

Azaouzi M, Lebaal N (2012) Tool path optimization for single point incremental sheet forming using response surface method. *Simul Model Pract Theory* 24:49–58.

Bhattacharya A (2014) Studies on incremental forming to enhance accuracy and geometric complexity, PhD Dissertation, IIT Kanpur

Lu B, Chen J, Ou H, Cao J (2013) Feature-based tool path gener-ation approach for incremental sheet forming process. *J Mater Pro c es s Technol* 21 3(7): 1221 – 1233.