A REVIEW ON DEVELOPMENT OF TOOLPATH STRATEGIES IN INCREMENTAL SHEET FORMING

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Abstract—Incremental sheet forming is one of the promising technology which is appropriate for rapid prototyping and diminutive batch production. ISF technology produces green and efficient products which satisfy customer’s diversified demands. The above novel approach increases global efficiency in production process. There are various process parameters which influence the responses of Incremental Sheet Forming but the most critical process parameter is toolpath strategy. Different toolpath strategies have significant effect on different responses used in dieless forming. So an extensive development and variation to toolpath strategies have been made to bring the responses within the possible limits according to the requirement of customers. The study of influence of different toolpath strategies have been made on various responses like surface finish, formability, wall thinning and geometric accuracy in this literature review.

Keywords—Dieless Forming, Toolpath strategies, Formability, Surface Finish, Geometric Accuracy, Wall Thinning, Model Predictive Control (MPC)

I. INTRODUCTION

Incremental Sheet Forming also known as dieless forming as it does not requires die due to which useful for prototyping concept. It is a flexible manufacturing process which uses a blunt moving forming tool (stylus) along a sheet material along a predefined toolpath to produce a desired shape/ geometry without and dedicated die [1].

Incremental sheet forming consists of main elements like Sheet metal, blank, Forming tool, Fixture, and tool path generation software. The basic process parameters are spindle speed, feed rate, tool diameter, tool type, toolpath, toolpath strategies, wall angle, step size, preheating temperature, etc. The different responses in incremental sheet forming are surface finish, geometric accuracy, formability, wall thinning and forming time. There are different tool types i.e. hemispherical, flat, roller ball, ellipsoidal, etc. to be used in incremental sheet forming. Also different materials like Titanium, Aluminium alloys, Steel, Polymers, Composites, etc. can be used according to its application. Different toolpaths can be used like contour, spiral, bidirectional, combined toolpath, etc. Out of which, the most commonly used toolpath type is contour [1].

In incremental sheet forming, toolpath is generated in any CAM software and then it passes to CNC milling machine and forms the desired shape. So it is flexible manufacturing process which does not require any specialized machine. Incremental Sheet Forming can be classified according to number of forming tool: Single and Double Point Incremental Forming. According to forming technique: Negative and Positive. In comparison to conventional sheet forming process, Dieless Forming has some advantages like no die, formability higher, strain reduces, compatible with CNC milling machine. But this novel approach has some disadvantages also like limited to small and batch production, limited to form at 90 degree wall angle, higher forming time, and higher geometric error [1].
Incremental sheet forming has found its wide applications in automotive, transportation, medical implants, prototypes and custom made products.

![Personalized Hood of a Honda Car](image1)

![Hand Wash Stand](image2)

![Original and two replicates of denture base](image3)

**Fig 2. Applications of ISF Process [2]**

**II. INCREMENTAL SHEET FORMING METHODOLOGY**

The methodology begins with customer requirements, then according to application it goes to selection of material. Afterwards geometric modelling and toolpath generation using software and then production takes place. The detailed methodology is shown in below figure.

![Detailed Methodology of ISF Process](image4)

**Fig 3. Detailed Methodology of ISF Process [3]**

**III. LITERATURE REVIEW**

Dai et al. (2018) [4] incrementally formed a non-axisymmetric part which includes stepped features using specific intermediate configuration (i.e. 3 passes were considered). Through multi pass incremental forming, geometric accuracy increases and decreases the force in stepped features. Without toolpath, with multi pass geometric deviation reduces by 60 % and with toolpath compensation, it reduces to 70 %. For bidirectional protruding features to be formed, there was a difficulty in forming.

![Three-pass incremental forming of the stepped feature](image5)

**Fig 4. (a) Three-pass incremental forming of the stepped feature (b) Compensation scheme of the intermediate configuration for each pass [4]**
Zhu et al. (2018) [5] developed a toolpath planning for Double Sided Incremental Forming. Wang et al (2018) [6] proposed a new toolpath strategy based on equal diameter spiral toolpath. Also spiral tool directions i.e. along right hand and anti right (left hand) spiral direction were utilized. Also spiral diameters were varied. For one entire toolpath, the spiral diameter was kept constant. The formability increases as spiral lead decreases and spiral diameter increases. Along anti right hand direction, the formability is higher than the right hand direction. With increase in spiral lead, the surface finish decreases. The formability is higher with equal diameter spiral toolpath as compared to common ISF process.

Fig 5. Equal diameter Spiral Toolpath [6]

Fig 6. Surface indentation Schematic [6]

Elford et al. (2018) [7] had developed a dedicated ISF software package known as ‘ISF Toolkit’, and compared with AMINO DLNC-PC ISF. Shape used was a truncated geodesic polyhedron (TCP). Good correlation with numerical and experimental results. Grimm et al. (2018) [8] developed a wavy toolpath even without losing its contact to the surface of part. The objective is to improve surface finish of the part. Wavy toolpath generated due to different amplitudes of ultrasonic vibrations. With wavy toolpath surface variability improves.

Boudhiaouia et al. (2017) [9] developed a spiral toolpath strategy and experimental and FEM analysis was conducted. Spiral toolpath shows a higher surface finish and acceptable geometric accuracy. Also, FEM shows better results in agreement with the practical or experiment ones. A fractal toolpath used in 3D printing and FDM was utilized in ISF by Nirala et al. (2017) [10] for a square cup. Maximum forming depth was obtained using FGBIT with 10mm. With FGBIT, formability is higher than conventional incremental toolpaths. For FGBIT, fracture occurs at corner of a square cup. Nirala et al. (2017) [11] developed a multi stage incremental forming in order to reduce strain hardening effect which is predominant in case of SPIF. Stepped features were removed using developed strategy.

Bensaid et al. (2016) [12] developed three toolpath strategies using CAM software and two numerical treatments were performed using Explicit code and user material subroutine. Also CPU time better than strategy A (normally used ISF strategy).

Fig 7. Three tool path strategies developed by CATIA V5R17 [12]
Hartmann et al. (2016) [13] developed an automated process from a digital model using an ANN architecture, which is capable of reducing geometrical accuracy and also can produce any complex shapes.

Lu et al. (2016) [14] developed a two dimensional MPC control algorithm in vertical and horizontal direction used to control and correct the toolpath. A comparison was made between horizontal and vertical direction toolpath. With two directional toolpath MPC model, the geometric accuracy changes from ±3mm to 0.3 mm. The springback measured along horizontal direction gives more uniform than in along vertical direction. Wen et al. (2016) [15] developed a multi directional Incremental Sheet Forming for hole flanging, curling, hollow profiles and localized forming of planar sheets. A method for automatic feature recognition was developed by Lingham et al. (2016) [16], from free form components in which features are sliced using horizontal, inclined or offset strategies and mixed strategy. Automatically toolpath are selected according to feature geometry characteristics.

Li et al. (2015) [17] performed an experiment for a multi stage Double Point Incremental Forming and it was found that as forming stage increases, the thickness increases initially and then decreases. For increase in plastic deformation area, more uniform thickness is needed. Fiorentino et al. (2015) [18] developed an iterative algorithm based on artificial cognitive system for a non-axisymmetric part using different toolpaths and materials. An intelligent system was developed which learns and correct itself without a priori knowledge.

Zhang et al. (2015) [19] developed mixed toolpath strategy for double side incremental forming. Mixed toolpath strategy includes Accumulate Double Sided Incremental Forming (ADSIF) and DSIF. With the ADSIF, as step size decreases, geometric accuracy increases, forming time reduces with ADSIF. Step depth was optimized for shape state feedback during forming process by Lu et al. (2015) [20]. A Model Predictive Control (MPC) strategy using feedback control strategy and a comparative study was performed for formed parts in both controlled and uncontrolled ISF process. Geometric accuracy improved at bottom area and also at walls of parts.

Behera et al. (2014) [21] developed a feature specific partial toolpaths and the features were identified using neighbouring and using graph method. Also human face was developed with less than ±0.5mm tolerance.

Behera et al. (2013) [22] projected a solution to the geometric accuracy by utilizing Multivariate Adaptive Regression Splines (MARS). For continuous error prediction, two features i.e. ruled and planar and two combination of feature-planar and ruler combination. Also accuracy compensation in complex 3D shapes can be method. Junchao et al. (2013) [23] introduced a multistage incremental forming for a car taillight bracket. An area division multi pass incremental forming has been included. In comparison to conventional multi pass strategy modified or proposed multi pass strategy, without any major defects and thinning was also reduced to about 25%.

Fig 8. Flow chart showing 3D neutral network [13]

Fig 9. Methodology for generation of training sets containing accuracy data for building MARS models [23]
A user friendly procedure which simplifies the design phase in order to optimize thickness distribution along profile was developed by Filice et al. (2011) [24].

An algorithm was developed which minimizes the difference between sine law and actual thickness. A decremental slope was introduced which shows better results than single slope method. Fei et al. (2011) [25] built a closed loop control model for controlling springback and dimensional accuracy. A wavelet transform with Fast Fourier transform was used. A profile correction algorithm was developed. The developed control model is combined with numerical method in order to reduce springback. This method enhances the dimensional accuracy of workpiece.

Hao et al. (2011) [26] applied a model predictive control (MPC) method for solving online process at each sampling instant. A fourth order degree polynomial was applied for tool trajectory. The error was upto ±0.2mm. Contour toolpath was optimized to get improved results for final shape accuracy. Geometrical error was greatly reduced using this method. Hao et al. (2011) [27] developed a closed loop control system and a comparison is made between open and closed loop control system. Error was greatly reduced in closed loop control as compared to open loop control system.

Li et al. (2011) [28] performed a multi stage Double Point Incremental Forming using experimentally and simulation model. As compared to single pass, the maximum thinning rate reduces and largely in double pass. Malhotra et al. (2011) [29] performed an experiment on Double Sheet Incremental Forming by developing a squeezing toolpath in which sheet material is squeezed between two tools. FEM analysis and experiment was performed. It was found that there occurs elimination of distortion of component with DSIF as compared to SPIF. In comparison to SPIF, geometrical accuracy is higher in DSIF.

Allwood et al. (2009) [30] developed an online feedback control for part geometry by creating a linear process model around a preplanned toolpath with a spatial impulse response. With an involvement of proper online feedback control system, the geometric accuracy improves as compared to contour toolpath. Mobile toolpath was utilized. Geometric accuracy within ±0.2mm can be produced. For axisymmetric cone, there would be single impulse while for symmetric cone; there would be more than one impulse for each contour.
Attanasio et al. (2006) [31] manufactured an automotive part by Double Point Incremental Forming with an assistance of full die. A blank holder shapes comparison was held. Two fixture shapes were utilized- one flat and other which fits the part geometry. Surface quality improves with decrease in step size and scallop height. Maximum thickness results were terrible for flat sheets as compared to performed sheets. Geometric accuracy found accurate at higher step depth and higher scallop height.

A path-correcting methodology was developed by Ambrogio et al. (2005) [32] and performed mathematical formulation, numerical and Experimental method to bring the geometric accuracy within 70 %. In comparison to previous methodology, dimensional accuracy improves by adapting path correcting methodology. The optimized profile was developed.

IV. CONCLUSIONS

Till date many toolpath strategies were developed for Incremental Sheet Forming. There are various process parameters which influence the responses of Incremental Sheet Forming but the most critical process parameter is toolpath strategy. So an extensive development and variation to toolpath strategies have been made to bring the responses within the possible limits according to the demand of customers. The study of influence of different toolpath strategies have been made on various responses like surface finish, formability, wall thinning and geometric accuracy. Various closed loop feedback control algorithms have been developed in order to improve responses. Following conclusion have been made from the above literature review:

1. Model Predictive Control (MPC) with online control reduces geometric error. With two directional toolpath MPC model, the geometric accuracy changes from ± 3mm to 0.3 mm.
2. With the application of equal diameter spiral toolpath, formability is higher in comparison to common used toolpath in ISF process.
3. The fixture shapes which fits to the part geometry gives better results than fixture with flat shape. Path correcting methodology improves geometric accuracy.
4. Geometric accuracy is higher in case of DSIF as compared to SPIF. Geometric error greatly reduced in closed loop control system as compared to open loop system. A profile correction algorithm reduces springback and improves geometric accuracy. Mixed toolpath strategy for DSIF improves geometric accuracy as compared to DSIF toolpath strategy.
6. Maximum thinning rate reduces in case of multi pass strategy as number of passes increases. A decremental slope method shows better results for maximum wall thickness as compared to single slope.

REFERENCES


