

A review of various Parameters of Incremental Sheet Forming Process and their effects

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Abstract: ISF (Incremental Sheet Forming) is a new metal forming technique which does not have the punch and die & achieves better dimensional accuracy. This technology is especially helpful for small and medium-sized batch manufacturing and prototyping since it is less expensive than traditional sheet metal forming procedures. Design adjustments can be made fast and easily because it can be done on a standard CNC machine. The components can be manufactured straight from the CAD file. One of the biggest advantages of Incremental Sheet Forming process is the strain hardening effect involved during plastic deformation of product can be minimized. To ensure the applicability of ISF, guidelines describing the relationship between input parameters and process formability are required.. The paper includes the review of various researchers on how the parameters like tool diameter, step size, thickness, forming angle, wall angle, temperature, spindle speed etc. The effects of post process parameters like roughness & spring back are also mentioned based on the results of various researchers.

KEYWORDS: ISF, Process parameters, Modeling, Spring back, CAD, CNC, heat assisted

1. INTRODUCTION

Incremental Sheet Forming, a kind of Sheet Forming technique that involves deforming of sheet mainly metal sheet. Material is deformed beyond their elastic limit to change the shape permanently under sheet forming processes. Conventional sheet forming operations such as shearing, blanking, bending, stretch forming etc. consumes a lot of time and money in making the punches and dies.

ISF is a novel and recent method which can solve the problems associated with the conventional sheet forming processes. ISF can process the complex geometries which are not difficult to achieve when manufactured using other kind of sheet forming techniques. Also, ISF can be performed by any production facility having CNC machine tools that are employed with technologies such as CAD/CAM, applicable for profile generations. The product is deformed step by step (incrementally) to get the final shape.

The Principle followed by process, the tool does localized deformation through gradually advancing tool which follows different trajectories according to the requirement of operator on the machine. This also makes is easy for the tool to process the materials having low formability.

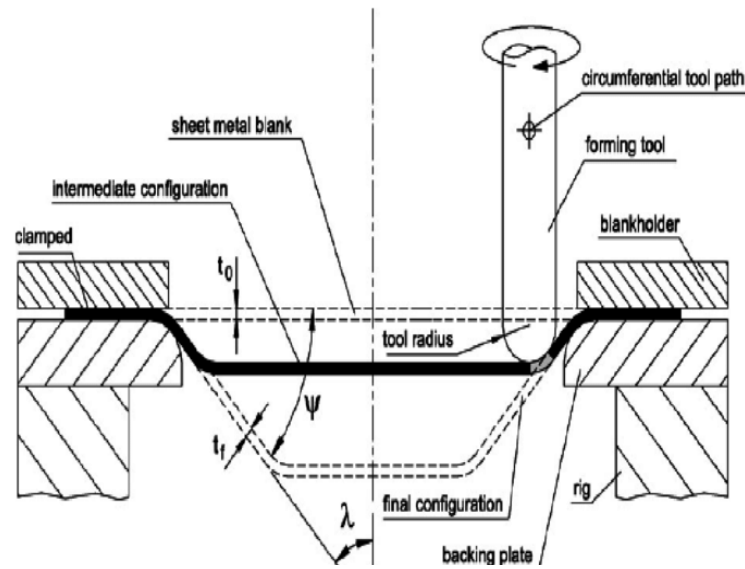


Fig 1: Incremental sheet forming [46]

1.1 Mainly ISF is classified into two types:

(1) Conventional ISF and (2) Hybrid ISF.

Traditional/Conventional Incremental sheet forming is sub-arranged into following classes: Single point incremental forming (SPIF) and Two point incremental forming (TPIF). Fig 2 shows the SPIF process.

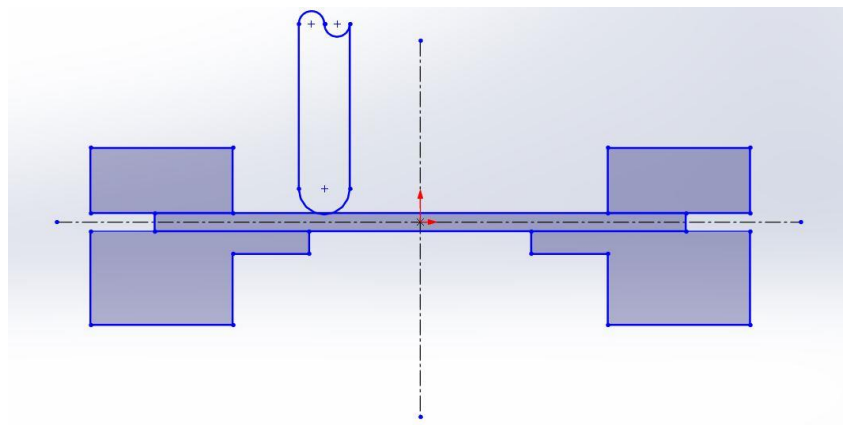


Fig 2: Single Point Incremental Forming [46]

Single Point ISF as the name suggest, here one single tool moves on the specified trajectory and no backing support is provided to the material under deformation. Whereas considering the Two Point ISF, here apart from the tool moving on one side of the surfaces, backing support is also provided to deform the sheet material. It is named as TPIF because it includes two tools i.e. deforming tool (DT) & supporting tool (ST) are being used (see fig 3).

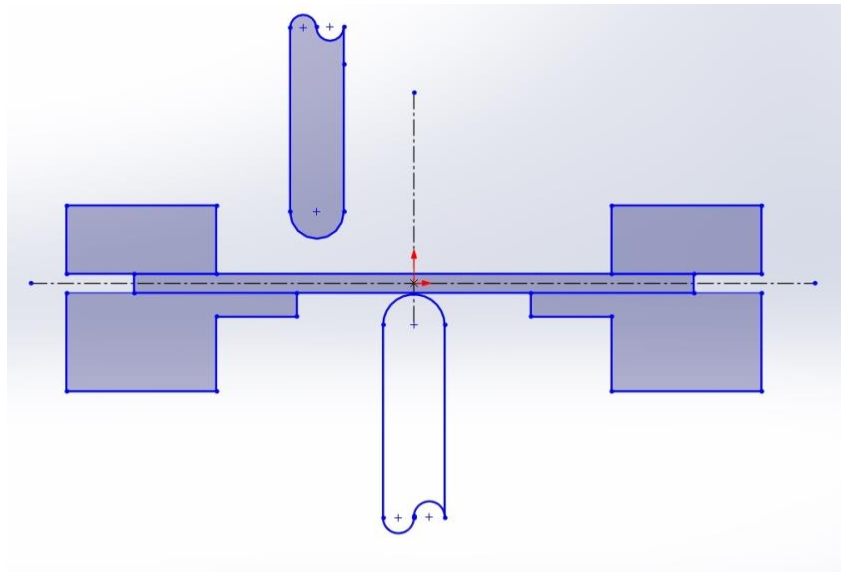


Fig 3: Two point incremental forming [46]

Nowadays, Hybrid ISF (modified ISF process) is also being used. It is different from earlier ISF techniques because here hydraulic pressure (instead of solid supporting tool) is provided to support the deformation (see fig 4). Hybrid ISF is more close to TPIF as here also hydraulic pressure is involved to work as backing tool to the sheet being deformed.

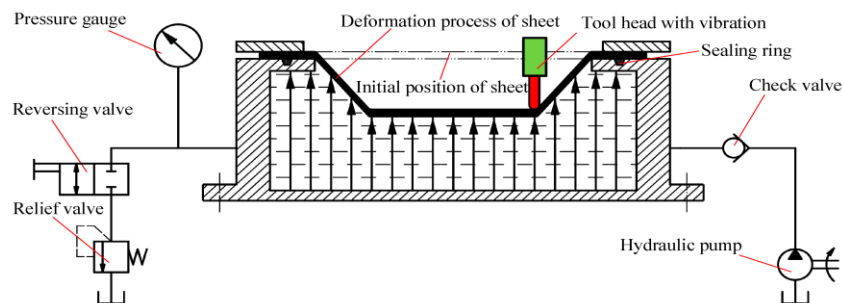


Fig 4: Incremental Hydro-Forming at a Single Point [46]

1.2 Sub Category of TPIF:

a) TPIF with partial die: The supporting tool provided here is not the replica of the product which is to be formed. It is used only to attain desired impression as shown in the fig 5.

b) TPIF with full die: Full die means here the die used is the replica of the final product to be formed. Because it holds the trajectory of a part that will be created, the die utilized here work as a form tool itself. (see fig 5).

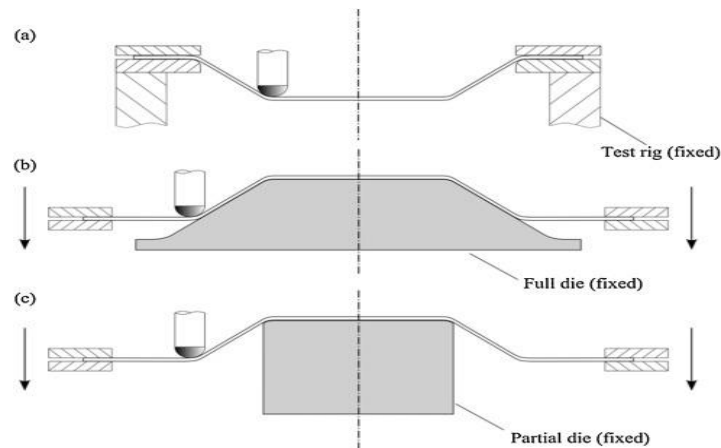


Fig 5: TPIF with Partial and Full Die [46]

2. Process parameters of ISF & their effects

2.1 Tool diameter

Tool diameter plays a very vital role during forming in ISF. Many researchers had performed the studied the effect of change in tool diameter during forming. Written below are some of the conclusions that we can get from their studies.

Bagudanch et al. [1] & Duflou J.et al.[32]while studying the forming forces resulted that there is an increase in maximum forming force with corresponding increase in tool diameter. G. Vishal et. al. [2] while experimenting with Al2024-O observed that formability increases with tool diameter &with large side radius of flat end tool (see fig 6).Considering the heat assisted ISF heating of product with current is done by Fan G. [6] to inc. the formability of materials. Results showed that increase in diameter can decrease temperature and thus formability. Tool diameter can affect the geometric accuracy as well; results of Pacheco P. et al.[25] showed that inc. in dia. causes tool to inc. heat transfer which ultimately reduces the accuracy of geometry. An interesting fact noticed by Zhang S. et al.[36] that tool diameter was an insignificant factor while evaluating and optimizing the formability of an AZ31 (Mg alloy) during hot ISF assisted with oil bath heating. Maxi. forming angle gets significantly affected by the change in dia. of tool, as shown by Ham H. et al.[39]

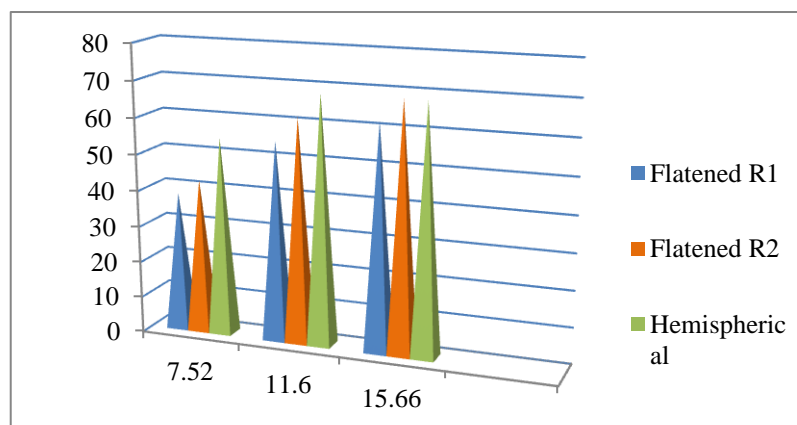


Fig 6: Effect of tool dia. (x-axis) & shape of tool (y-axis) on forming depth[2]

2.2 Step size

It is another very important factor in Incremental Sheet Forming. The conclusion that can be drawn from the literature review, an increase in step size will reduce the formability of the material to be formed by ISF (see fig 8). Also forming forces required to form can be decreased by decreasing the step size as shown by Bagudanch et al. [1] Ismail N. et al. [8] while analyzing the surface characteristics of heat affected zone in robot based ISF revealed how step size can affect Heat affected zone because of the area of contact b/w tool used for forming and w/p. Appropriate step size selection can lead to achieve the maximum forming angle (up to 90°) along with increase in formability as concluded by Kumar Y. et al.[21]; they have developed an analytical model for modified MSMS (multi stage multi step) forming strategy. Interesting results were developed by Duflou J. et al.[33] which showed that vertical step size variation has least effect on the forming force on Al3003-O, can therefore ΔZ be increased in favor of lower 'part production time'. Considering Mg alloy as sheet material Zhang S. et al. conclude how formability of Mg alloy was most affected by forming temp. followed by step depth & sheet thickness.

2.3 Thickness

Thickness of the sheet material is something which should be taken into account while forming by ISF. As we all know the material to be formed has to have enough formability to sustain the different forces; thickness plays a considerable role in the formability of the sheet material. The results of experiment by G. Vishal et. al. [2] proved how formability of Al2024-O showed positive response while dealing with thicker sheets (see fig 7). Also the forming forces required to form material showed proportionality with the thickness of the sheet, as shown by Duflou J. et al.[32] Also the Mg alloy's formability can be increased by an inc. in sheet thickness. Ham H. et al.[39] showed that maximum forming angle is effected by the thickness of material.

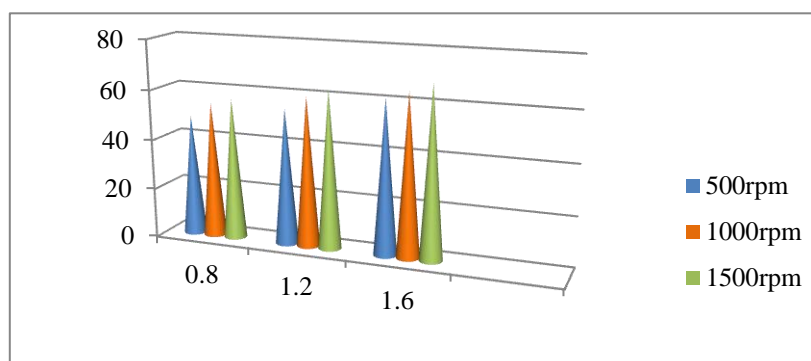


Fig 7: effect of thickness of sheet (x-axis)&speed of spindle(y-axis) on forming depth[2]

2.4 Forming angle (α), drawing angle, wall angle

Several researches have been carried out to determine how forming angle is important criterion for forming. Forming angle is dependent on the shape that we are required to give to the work piece. Although ISF is very useful in forming parts with complex shapes, to achieve high forming angle has always been challenging in ISF. Various researches have been done

to analyze how the forming angle can be increased. Below written are some of those results which I have collected while reviewing the literature.

Again considering the work done by G.Vishalet. al.[2] showed some positive response performed the formability increases with increase in forming angle (fig 8). It is very difficult to form a part with high forming angle in a single stage, multi stage strategy had been proposed by S. Martin et. al.[3] to produce a cup with 90° drawing angle. Also Kumar Y. et al. [20] proposed an analytical model for modified MSMS (multi stage multi step) forming strategy which showed possibility to attain forming angle up to 90° due to hydrostatic support at other end. Duflo J. et al.[32] showed the increase in forming angle increased the forming forces accordingly however the statement is not true for all the materials, as the same guy while experimenting on Al3003-O comes through an interesting fact that for 60°=wall angle, due to the neck of the lock, the force required for deformation will decrease. This situation occurs in parts where the angle of the wall is close to the maximum achievable limit. While measuring the forces in cones & truncated pyramids from AA3003-O, maximum forces were noted in the area where failure occurred at maxi. draw angle which also signifies that forming forces are higher in the area of higher forming angle. When forming with Robot based ISF Parameters like wall angle & step size effect HAZ because of the are of contact between forming tool & work piece. In Electric assisted ISF, forming angle had the most considerable effect on the temp. control using electric current as proposed by Min J. et al.[20] Researches have been done to induce more than one tool to increase the maximum forming angle, the experiment of Meier[23] is an example of this. Tool diameter, step size & material thickness were varied by Ham H. et al.[38] It shows that the step size did not affect the maximum angle of formation largely, while other parameters such as material thickness, the tool dia. and the interaction of material thickness and tool size gave a notable impact on the maxi. angle of training.. Dynamic re crystallization is a strategy which can be employed to achieve larger draw angles; Buffa G. et al.[41] concluded that maximum draw angle inc. of 7.5°,10°,12.5° w.r.t. traditional SPIF was found for AA1050-H24, AA1050-O & AA6082-T6 respectively while forming by employing localized sheet heating.

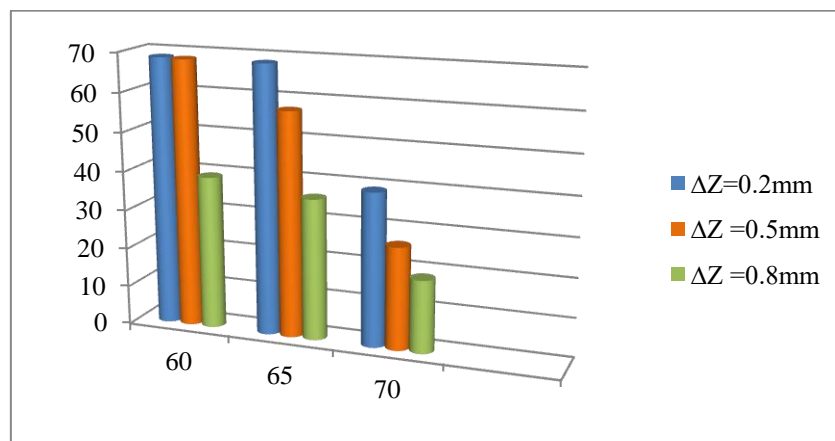


Fig 8: effect of wall angle (x-axis)& step size on forming depth (y-axis)[2]

2.5 Temperature

Temperature is an important parameter while forming. Temperature is something that can change the grain structure (micro-structure) which in turn can effects the properties like ductility, formability, hardness etc. This forced the

researchers to analyze the effect of temperature or thermal treatment to forming. Effect of heat treatments on post forming micro-structural & mechanical properties of Laser assisted SPIF formed parts (AA2024-T3) were reported by Moheemadi A. et al.[13] & Duflou J. et al.[14] showed that as the temperature increases Forces decreases & spring back behavior is improved, thus reduces unwanted deformation & geometrical errors. Formability increases due to local heating along with decrease in residual stresses. Degree of deformation of high strength steel alloy can be increased by Induction heating as shown by Al-obaidiA. et al.[15] Joule heating of dynamic forming zone on Ti6Al4V by Mangus S. et al.[19] provided many positive response in the form of increase in formability, reduced forming zone, decrease in further deformation of areas which are already formed & decrease in spring back. Thermoelectric ISF is an effective method to reduce the force required to form, but because of the thermal characteristics of the process, geometrical accuracy gets reduced; to improve geometric accuracy 'preheating' is employed to EH-ISF (Pacheco P. et al.[25]). Formability of Mg alloy is poor at room temp. so here hot fluid is used by Galdos L. et al.[35] to increase the temperature & thus the formability. To investigate the impact of temperature on the limit of forming, plain strain along with asymmetric stretching test were done by Ji H. et al.[38] at 20°C, 100°C, 150°C, 200°C

2.6 Spindle speed (N)

Consideration of spindle speed is important because of the fact that there will a direct contact between tool tip and the work piece, so there will friction and the thermal stresses development takes place while forming. These factors can drastically affect the temperature, geometrical accuracy, roughness etc. Bagudanch et al.[1] showed how the increase in spindle speed can lower down the forming force required at the interface. Various researchers such as Ham H. et al.[39], G. Vishal et. al.[2] have proved how the inc. in spindle speed can improve the formability of the material (see fig 7). Xu D. et al.[17] examined how incorrect combination of tool rotation speed & feed rates limits performance of frictional stir ISF.

2.7 Tool path

It includes the trajectory of tool along with the no. of stages & passes which has to be followed for forming the sheet into desired shape. Proper selection of tool path is required to reduce the chances of fracture besides improving the surface finish and geometrical accuracy. Production time greatly depends on the tool path followed by the tool. S. Martin et. al.[3] used a multi pass strategy which make it possible to process a cup with 90° drawing angle which has not been possible with single pass strategy. Here, two strategies are performed; DDDU (Down Down Down Up) gave the product without fracture whereas DUDD strategy employed resulted in fractured product (see fig 9). Another parameter 'Sheet thinning' is a defect which impedes the process's wide application, a multi stage forming process was proposed by Junchao et. al.[42] to effectively deal with this problem. Cerro et. al.[4] showed how the no. of stages can be increased to distribute the deformation, thus in turn decrease the chances of fracture. Ismail N. et. al.[8] made a very good comparison between helical and straight paths of tool, forming tool remained uniformly contacted to w/p in curved path compared to that in straight path. Junchao et. al.[9] examined how complicated shaped taillight of car which cannot be formed by traditionally by multi pass forming divided into several region k/s 'Traditional model' and then formed satisfying thinning rate of <= 25%. Suresh K. et al.[30] proposed a methodology to produce the necessary device way for mathematical recreations straightforwardly from the NC part program created utilizing the CAM bundle. Aiming to minimize the error due to spring back effect Fu Z. et al.[31] an iterative algorithm of closed loop control was proposed. Correction algorithm for tool path

was based on 'Fast Fourier' & 'Wavelet Transforms'. Duflou J. et al.[32] concluded that discrete orientation changes in tool paths ought to be considered, since they prompted nearby pinnacles and drops in power segments.

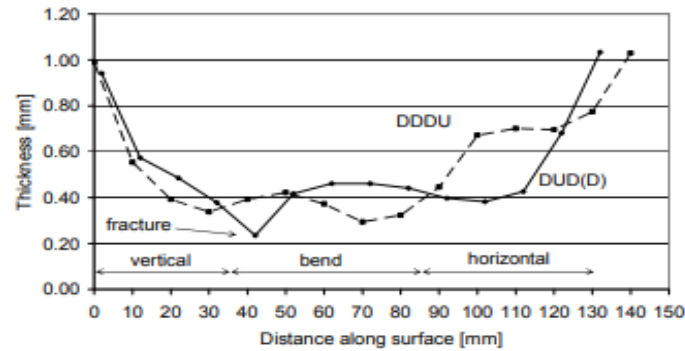


Fig 9: Thickness v/s distance along the surface for the two methodologies DDDU and DUD(D). [3]

2.8 Lubricant

Lubricant has been a matter of concern while forming with ISF as it can change the effective viscosity as well as coefficient of friction between the contacting surfaces. Gill N. et. al.[12] has experimented to assess the impact of the kind of grease utilized in SPIF. Results showed that greater the hardness of material to be formed, lower the necessity of viscosity of lubricant. Also it was noticed that lubricant performance depend upon the material too as the lubricants which guaranteed good results in Al were not up to the mark for steel & vice-versa. But lubricant played no role in reducing the spring back phenomenon in their experiment.

2.9 Sheet material

By reading various research paper it has been observed how sheet material can effects the formability, surface finish, maximum forming forces required, roughness, fracture limits etc. Therefore appropriate combination of feed rate, spindle speeds, lubricant, thermal conditions are required to be selected for a given material to be formed. Taking an example of the work of Gill N. et. al.[12] , it can be examined how a lubricant which is best for Al showed worse results for steel & vise-versa. Moheemadi A. et. al.[13]&Duflou J. et al.[14] had used Heat assisted processes to change the micro structure of materials to improve the mechanical properties of the sheet to get better results.

2.10 Tool shape or tool geometry

Hemispherical tipped instruments delivered better formability when contrasted with that created by the Flat end tools as suggested by the results of G. Vishal et. al. [2] Experimental test was carried out by Li Y. et al.[34] to make a straight groove with 4 diff. tools of which 1 is roller ball while other three were sliding tips; roller tip provided better surface finish integrity compared to the sliding tip. Work done by Meier [23] defines how more than one tool can help to give better surface finish as well as of the part formed.

Post Process parameters

2.11 Roughness

Cerro et. al.[4] study explained how roughness of material can be reduced by a decrease in axial step size. Gill N. et. al.[12] intended to assess the impact of the sort of grease utilized in SPIF. Surface roughness tests were conducted, lubricants which gave better results with regards to Al proved to be worse for steel and vice-versa. Meier showed how surface quality & accuracy can be improved by implementing more than one tool for forming. Tool geometry plays a key role when considering the surface quality of a product, roller tip provided better surface finish integrity in comparison to the sliding tip in the study of Li Y. et al.[34] Geometric accuracy & surface finish was improved by Xu D. et al.[37] using E-DSIF.

2.12 Spring back

Spring as we as a whole know is the mathematical change made to a section toward the finish of the framing cycle when the part has been delivered from the powers of shaping instrument. And in ISF spring back phenomenon has been observed which adds to one of the drawbacks of ISF. Researches have been done to detect its effect and tried to minimize its effect to inc. the geo. accuracy of the final part. Dynamic heating through radiation by using LB Duflou J. et al.[7] to deal with undesired plastic deformation in locality of contact area of tool, spring back effects & inaccuracy in geometry. Another method i.e. an analytical model has been developed by G. Ambrogio et al.[23] to minimize the geometrical error, namely both spring back & pillow effect. Fu Z. et al.[31] showed how a tool path correction algorithm can be effective in minimizing the spring back effect.

Use of models in ISF

Modeling is very important to solve a complicated problem. A set of equations is developed for analysis or physical arrangement can be developed for experimentation under modeling to solve a given problem.

Bouffionx C. et. al.[10] used an analytical formula (i.e. $F_{z,s}=0.0716.R_m.t^{1.57}.dt^{0.41}.\Delta h^{0.09}.\alpha.\cos\alpha$ [10]) to calculate the axial force while forming. Apart from that Li Y. et. al.[11] study aimed at establishing an effective model for prediction of force in tangential direction. Aerens R. et al.[16] work also led to an analytical formula to calculate the axial force. To calculate the heat while comparing Frictional stir and electric hot assisted ISF, Xu D. et al.[17] used an analytical formula.

Experimental results & FEM (numerical method) results are compared by Cerro et. al.[6]& concluded that FEM results were quite close to that of experimental results. Bambach et al.[43] aimed to provide a smooth tool path definition & of a strategy to control error in explicit FE simulations of SPIF. Pacheco et al.[26] used numerical model to distribute temp. in welding in straight line.

Another type of model k/s Empirical model is used where the problem is too complicated for the mathematical model to solve and time consuming while solving using numerical model. Ambrogio G. et al.[27] developed Empirical model for predicting relation between temperature & other parameters. Sine law (empirical modeling) was used by Hagan E. et al.[28] for the calculation of sheet thickness. Cosine law (empirical) was used by He S. et al.[29] to compare experimental results which showed good agreement.

Summarized effects of parameters:

Table 1: Effect of various parameters		
1.	Tool Dia.	Formability and maxi. Forming forces showed direct proportionality with tool dia.
2.	Step Size (ΔZ)	Inc. in step size resulted in increase in forming force. Formability showed mixed behavior towards change in step size
3.	Thickness	Forming forces showed proportionality with the thickness of sheet. [32]
4.	Forming angle(α), drawing angle, wall angle	Forces required to form material inc. with inc. in forming angle [32] ; also to form high forming angle parts, multi stage strategy was employed. [3]
5.	Temperature	As temp. increases, forming forces decreases. [14] Degree of deformation can be increased by use of Heat Assisted ISF techniques. [15,19]
6.	Spindle Speed (N)	Increase in speed resulted in decrease in forming forces and also an improved formability. [1,39]
7.	Tool path	Correct path minimized the chances of failure. [4] Complicated shapes can be formed by right tool path planning. [3,4,9,31]
8.	Sheet material	Surface finish, forming forces, roughness, fracture limit etc. dependent on the types of sheet material. Lubricant behavior depends largely on the sheet material. [12]

3. Direction for future research

The work done by some of the researchers have left some gap or we can define as literature gap, someone can find these points helpful for doing further research.

M. Silva et. al.[44] proposed enhancement of multistage SPIF strategy was proved to be successful for producing the flat, cylindrical cups with vertical walls but enhancement is needed in other shapes. Another very important parameter 'production time' was not analysed by most of the researchers so work would be done by taking time as a factor to be tested. To control the wearing of tool to reduce the cost of process & for controlling the quality of product consistently, findings of Ismail N. et. al.[8] would be helpful to recognition the pattern of tool condition. In Al-obaidi A et al.[15] work further experiments are required to decrease the deflection value to increase dimensional accuracy. Cui Z. et al.[45] while comparing the analytical model with experimental results showed good agreement for small forming angles but further research could be done to improve results of analytical model at large forming angles. Very little study has been done to analyze the effect of lubricant on forming so further detailed study on lubrication can be performed.

Although researches were very keen to find the effects of tool shape and geometry but the contact interface between tip of tool & material of sheet would be taken into account to develop an analytical model for the calculation of forces while forming & to check the influence of different parameters on these forces.

4. CONCLUSION

Formability of sheet material seems to be increasing with decrease in step size & wall angle; and with increase in speed of spindle & sheet thickness. To form sheets with high wall angle, multi stage or multi stage multi step (MSMS) strategy of forming is helpful. Heat Assisted Incremental Sheet Forming can be used to form hard materials as the heat could be employed to improve the mechanical properties of sheet material. How a lubricant behaves depends largely on the material properties which have to be formed. Also it seems like lubricant has little or no role in reducing the spring back phenomenon in experimentation. Use of models can be done to develop a set of equations or physical model, to solve complicated problems as the results from the models developed by various authors showed good agreement with experimental results.

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