International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 02 - Issue 03 || March 2017 || PP. 35-43

A brief review of Incremental sheet metal forming

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Abstract: Sheet metal products are used extensively in aerospace and automobile industries due to their relatively easiness and low manufacturing cost of the product. In last one decade, there has been a continuous increase in study of Incremental sheet metal forming (ISF) process among various sheet metal forming processes due to their ability to deform a metal sheet to a higher degree compared to other conventional forming operations. A brief review of different methods of ISF, deformation mechanisms in ISF, effect of different parameters on formability in ISF has been discussed.
Keywords: Incremental Sheet Forming, SPIF (Single Point Incremental Sheet Forming)

1. Introduction

ISF is the process in which a sheet metal blank is simply clamped with the help of blank holder and the numerically controlled tool with hemispherical end forms the sheet incrementally into desired shape which actually contains series of locally deformed zones. Actually the idea of incrementally forming sheet metal with a single point tool, called 'die less forming', was patented by Leszak in 1967 well before it was technically feasible. Requirement of numerically controlled tool can easily be fulfilled by CNC milling machines, though people are using robots sometimes. In addition to that ISF also has been tried with modern machining processes like water jet forming and LASER forming [1]. Some researchers have developed special purpose machines to carryout ISF.

ISF is carried out in mainly four different ways which is also considered as process principles and can be represented as mentioned in the Fig.1 As we can see in the given figure, part (a) represents Single Point Incremental sheet Forming (SPIF) in which rotating tool moves over the clamped sheet and produce the desired shape. SPIF is able to create asymmetric parts therefore sometimes it is called Asymmetric Incremental sheet Forming (AISF) Part (b) represents Accumulative Double sided Incremental Sheet metal Forming (ADSIF) in which a counter tool is moved on the other side of sheet in synchronization with forming tool; this trick is applied to achieve higher dimensional accuracy. Above mentioned both process is also known as positive ISF, as metal is formed in the downward direction i.e. in the direction of tool motion. Part (C) represents Two Point Incremental sheet Forming (TPIF) in which partial support is provided to the sheet being formed. It is very suitable when ISF is carried out with a robot. Part (D) also represents TPIF but full die is used in this case. Thus TPIF can be considered as negative ISF, as metal is formed in the upward direction i.e. in the opposite direction of tool motion. The article contains brief overview of methods of ISF, historical background of ISF, Deformation mechanisms in ISF, effect of various process parameters on ISF, forces in ISF,etc.

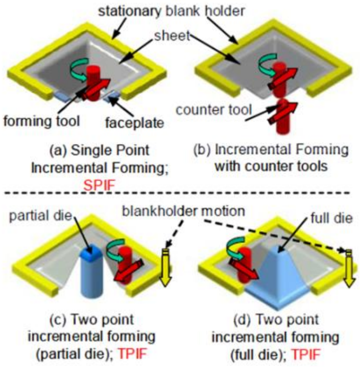

Figure 1 Process principles of ISF [1]

1.1 Applications of ISF

- As ISF does not require dedicated die and punch, it is suitable for small batch production in aerospace and automobile industries.
- As localized deformation in ISF has resulted in increased formability, it can be effectively used in forming lower strength material.

- Use of numerically controlled tool in ISF allows user to follow any complex path and hence complex geometrical parts can be formed with relative ease than any other conventional forming process.
- Now a days ISF is also used for rapid prototyping of metallic parts.
- ISF is successfully being used to produce biomedical implants.
- One interesting application of ISF is that it can be used to recycle the sheet metal parts by converting it into flat sheet without much harm. This results in reduction of carbon dioxide which could have been generated in melting those sheets.

1.2 Limitations of ISF

- ISF is a time consuming process, as small diameter tool is used, forming time is quite high. Thus it is not suitable for mass production.
- Dimensional accuracy of the parts prepared by ISF is not up to the mark, as spring back occurs locally at each tool/sheet interface, when tool moves ahead from a particular position.
- Surface roughness is also not as per requirement, as tool leaves its marks on the sheet.
- The most crucial fact about ISF is that localized deformation is so complicated that its deformation mechanism is still little understood. Thus behavior of any new material that is not available in literature cannot be predicted perfectly.

2. Historical background of ISF

History of ISF starts with the early work started by Mason in 1978 and continuous upto the present date. The need of design flexibility of sheet metal parts used in automotive industries make them focus on ISF. The boundray between spinning and ISF is very thin. In the 20th century many patents has been issued as the varients of spinning. Two of them both from 1967 can be regarded as ISF or very close to that. One issued to Leszak and one to Berghahn of General Electric. Leszak proposel is using bending against an elastic medium to provide final shape. Berghahn proposal uses XYZ motion of a rollor to carry out required product. Thus it is very close to ISF as per its one of the sevaral definiitions “A family of sheet forming processes where the deformation is highly localized, without drawing in of material from a surrounding area and using a fully clamped blank, where the final shape is determined by the xyz movement of some tool part without the need for a die.” [2]

Though it had been noticed that Berghahn was very close to ISF , it had not actually started the present developments of modern ISF, this credit goes to Mason of the Uni. Of Nottingham. In 1978 he has proposed a process using single sphere, in which numeric control of this sphere along xyz directions is enough to form required part geometry. He used lathe, i.e. rotating blank to perform the operation. Taking reference of Mason’s work Iseki has formed first asymmetric part in 1989 on stationary blank. Kitzawa presented his work in 1993, he did it both way, i.e. with stationary as well as rotating blank. Matsubara has presented Two Point Incremental sheet Forming (TPIF) for the first time in 1994. After that many patents were filed by various automotive industries like TOYOTA, HONDA, etc. In 2001 luttgeharm has filed a patent as a variation of spinning process [2].

In 2003 another patent was filled by okada and coworkers in which TPIF apparatus additionaly equipped with a local heating device to reduce the amount of springback. Park had attained temperatures upto 400K by using friction of the fast rotating punch to create local heating. Amino and Matsubara filed a patent request to overcome the thinning normaly encountered in ISF. Tuominen of Twincam OY, Finland filed a patent in 2002, describing various configurations, including the use of two robots. A robot has in general a lower stiffness [2].

The automotive industries like Honda, Toyota, BMW, Daimler, etc are using ISF to produce their own specific parts. For example, Honda applied ISF to manufacture replacement parts for the S800 sports car in collaboration with Amino in 2002. In this case Amino had manufactured ISF machines as per requirements of Honda. Some of the universities and research institutes that have patented their work for various reasons [2].

3. Different methods of ISF

Four different principles of ISF have already been discussed, now the setup required to carry out the process is presented. Among those four, SPIF and TPIF with partial die are discussed in detail. Moreover, ISF with LASER is also presented. People have also tried with PLASMA as it is cheaper, but study of that process is in primary stage. Water jet incremental sheet forming has also been done but it requires 50MPa pressure to form 0.5mm sheet of an Al alloy [1].

3.1 SPIF (Single Point Incremental Forming)

SPIF can easily be carried out on a CNC milling machine. Thus as shown in Fig. 2 basic elements required for SPIF can be listed as under [1]:

- A CAM software package for tool path planning
- A hemispherical forming tool having small diameter
- A CNC milling machine to automate the tool motion
- A blank holder
- A sheet metal blank

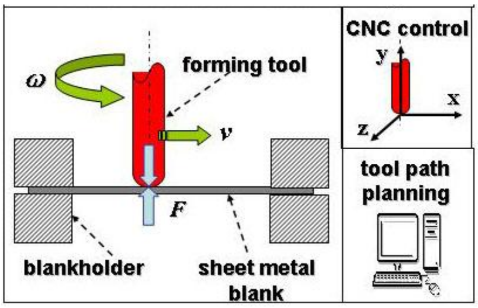

Figure 2 Basic elements of SPIF [1]

In addition to these basic tools, sometimes CAD software package is also required in case of difficult geometry, as it is easy to generate tool path from a CAD model in that situation. Generally cold die steel, high speed steel, cemented carbide; plastic, etc are used as tool material [1]. While copper, HSS, mild steel, brass, Al alloys, stainless steel, gold, silver, platinum etc are used as blank material [1]. Ti alloys can be used as blank material when LASER is used in ISF. Schematic representation of SPIF can be shown as mentioned in the Fig. 3

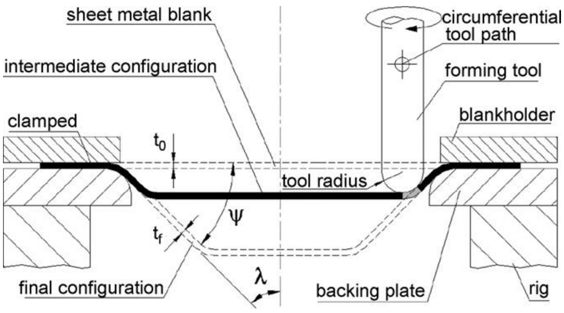

Figure 3 Schematic representation of SPIF [3]

Where, t_f = Final sheet thickness ψ = Wall angle
t_i = Initial sheet thickness λ = Half cone angle

3.2 TPIF (Two Point Incremental Forming)

Matsubara has carried out TPIF using his own setup. In this process partial die is used. TPIF is generally applied to the special purpose machines prepared to carry out ISF. In this process supporting frame moves down on guide posts gradually and pneumatic cylinders maintain the required pressure during the forming [4].

3.3 LASER forming

The basic elements of LASER forming are as under [5]:

1. Numerical control
2. Diode laser
3. Optic connected to the spindle sleeve
4. Additional driver unit
5. Collimation and fiber connector

LASER forming is generally used to form the material which is not easily formable at the room temperature, for example Ti alloy. Temperatures up to 400°C can be obtained with the help of LASER beam. The position of the LASER beam is so set that it heats the material just before tool reaches the point [5].

3.4 SPIF using Stewart platform

This technique requires a computer and a dedicated machine which forms the sheet incrementally. Ethernet TCP/IP link is the mode of communication between these two. This facility allow them to work even they are not at the same location [6].

In addition to these methods many other special purpose machines are made to study ISF. ISF is also carried out with the help of robot instead of NC controlled tool. As stiffness of the robot is less than robust CNC setup its use is very limited [6].

4. Comparison of Forming Limit Diagram (FLD) (conventional forming / ISF)

The FLD gives the values of safe strains to which material can be formed safely, beyond this limits failure occurs due to necking [7]. Therefore FLD is generally considered as a material property and it is same for a material formed by different forming processes. There are some assumptions made while preparing FLD of any particular material as mentioned on the next page [8]:

- Material should be deformed under proportional loading and in the absence of bending.
- Through thickness shear should be negligible i.e. a state of plane stress should be there.

Under all above mentioned assumptions conventional FLD of any material lies generally under the region as shown in the Fig. 4.

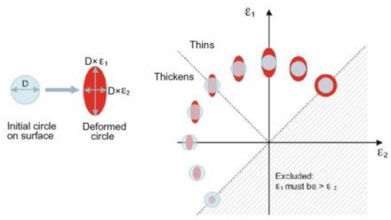

Figure 4 the conventional forming limit diagram [7]

One very interesting and yet not clearly understood fact about ISF is its increased formability. The localized deformation in ISF is so difficult to understand that it is still a point of discussion among the researchers. Experimental results conclude that ISF can achieve three times higher strains than it can achieve during conventional forming process like deep drawing [9]. Some researchers have claimed that failure in ISF is not due to necking and hence fracture occurs due to damage [3]. Therefore forming limit in ISF should be represented by Fracture Forming Limit Diagram (FFLD) and not by FLD. This fact can be plotted as shown in the Fig. 5.

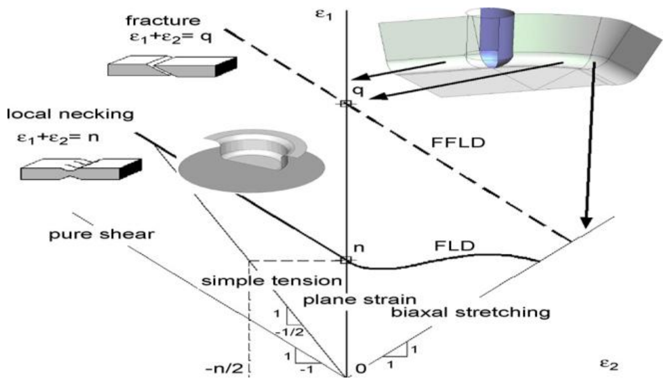

Figure 5 Schematic representation of the forming limits of SPIF against those of stamping and deep drawing [3]

5. Experimental study of increased formability in ISF

Jeswiet et al, has aggressively studied the FLD in ISF by forming different shapes of the same material as well as forming the same shape of different material. Filice and Micari have also plotted the FLD for truncated cone (Al 3003-O). Jeswiet et al has taken five different shapes as under for the same material i.e. Al 3003-O [9].

1. Cone 2. Hyperbola 3. Dome 4. Pyramid 5. Lob shape

Jeswiet et al, has found that formability has been increased significantly for truncated cone when he has compared his results with Filice and Micari. The reason of this difference is mentioned by Jeswiet, that grid used by Filici et al has made stress concentration while the grid used by him was a silk-screen layer [9]. From the results he has clearly proved that 300% strain can be achieved with SPIF [9].

Apart from these Jeswiet has also studied the FLD of different material using ISF, which shows that brass and AA6114 has very low strain even when formed by ISF [1].

6. Factors affecting formability in ISF

There is ample amount of literature available describing effect of different process parameters on the formability of sheet metal. The different process parameters can be listed as under:

Wall angle, Tool diameter, Tool velocity (Feed rate), Tool RPM, Vertical pitch, Plastic anisotropy

In addition to these process parameters material properties like yield strength, young modulus, etc are also affect the formability, thus different materials have different formability. Sheet thickness also affects the formability to a great extent. Generally increase in sheet thickness results in increased formability.

6.1 Effect of Wall angle

As deformation mechanism is not easy to understand in ISF, many a times this wall angle is used as a formability benchmark. The maximum angle to which a specific thickness of a given material can be formed is known as maximum draw angle. By knowing maximum draw angle of any given material for a particular thickness, a designer can decide that required geometry can be done in a single pass or it should require multi-pass. Therefore it is clear that increase in wall angle results in decreased formability.

Matsubara [4] has shown from the experimental results that as half apex angle of the formed part increases formability increases. He has studied various Al alloy like A1050-O, A1050-H and A5083-O. The result shows that formability decreases as wall angle increases (because wall angle is the complementary to the half apex angle of the formed part) [4].

Junchao Li et al [10], has showed that increase of wall angle results in increased equivalent plastic strains which results in increased plastic deformation of blank. The material used was DC56, 1mm thick. If it is increased beyond certain limits it causes non homogeneous deformation and even fracture can occur. Maximum plastic stress shows the same trend. While in case of axial force required to form the material increases with decrease in wall angle. Thus they have concluded that decrease in wall angle provides uniform thickness distribution.

E HAgun and Jeswiet [11] has studied effect of wall angle on Al3003, they found increase in yielding and neck stress for increasing wall angle. They have formed the parts ranges from 20°-60° with an equal interval of 10°. A reasonable size of flat portion from each finished part having different wall angle is used for tensile test and then all data is analyzed. The result shows that strain hardening exponent decreases with increase in wall angle, while strength coefficient decreases up to certain value then starts increasing gradually with increasing wall angle. Major and minor strains increase with increasing wall angle.

Silva et al [3], has studied on AA1050-H111 sheets having thickness of 1.5mm. They have derived an equation to find the maximum draw angle.

$$\psi = (\pi/2) - \{(\sigma_Y/\sigma_\phi) - 1\} \times (r_{tool}/(k * t_o))$$

Where, ψ = maximum wall angle, σ_Y = circumferential stress, σ_ϕ = meridional stress

r_{tool} = tool radius, t_o = initial sheet thickness, k = constant 1 or 2, for plane strain and bi-axial stretching respectively

It is obvious from the equation that maximum draw angle increases with increase in initial sheet thickness and decreases with increasing tool radius.

6.2 Effect of Tool diameter

Matsubara [4] has mentioned that if the radius of the forming hemispherical tool is less than three times the sheet thickness, galling of the sheet takes place. Therefore, it is advisable to use tool radius about five times higher than sheet thickness.

Junchao Li et al [10], has showed that increase of tool diameter results in increased equivalent plastic strains. The material used was DC56, 1mm thick. Thus formability decreases with increasing tool diameters. At the same time increased tool diameter deforms more material resulting in higher requirement of axial force to form the material. Therefore, axial forming force increased with increase in tool diameter.

Hussain et al [12], presented study on AA-2024O aluminum sheet ranges from 0.9mm-3mm thickness. The tool radius has been varied from 3.5mm-10mm. He observed that with least sheet thickness the lowest tool radius shows the higher formability while at highest thickness the tool having highest radius shows higher formability. He has then concentrated on the ratio of tool radius to initial sheet thickness (r/t_o).

6.3 Effect of Tool velocity (Feed rate)

Tool velocity is very crucial process parameters for manufacturers. As increase in feed rates not affecting the formability adversely, they are allowed to carry out ISF at higher feed rates, which results in less production time. Generally feed rates in ISF ranges from 100 mm/min to 10,000 mm/min. Matsubara [4] has mentioned that feed rates 100 m/min are also viable in recent trends.

Baharudin et al [13] presented the effect of feed rate on a stainless steel sheet when stretched on a CNC lathe. They have also observed that the surface quality slightly increased when feed is gradually increased, while very high feed rates deteriorate the surface quality due to friction and vibrations [13].

6.4 Effect of Tool RPM

Effect of tool rpm is very important because it also affects the friction between the tool/sheet interfaces. Increasing RPM results in higher friction and hence metal forms at higher temperature with increased formability [14].

Many times free rotation to the spindle is also applied to avoid friction and increase in temperature. Jeswiet has presented the equation for minimum spindle speed to avoid sliding friction during the process [1]. Baharudin et al [13] presented the effect of spindle speed on a stainless steel sheet when stretched on a CNC lathe.

E Hagan and J Jeswiet [15] has studied the surface roughness of Al3003 material they have found that surface roughness for a particular RPM is lower. The clear variation in surface roughness is justified by the fact that tool forming the sheet has surface defects.

6.5 Effect of Vertical pitch

Pitch is the vertical displacement of the tool for a contour in case of ISF. Generally it is correlated with wall angle, as increase in pitch results in increased wall angle. However, to form at higher angle does not necessitate increase in pitch. Therefore, it is considered as a separate parameter affecting formability. It is very clear that increase in pitch results in decreased formability.

Junchao Li et al [10], has showed that increase in pitch results in increased equivalent plastic strains, thus smaller pitch results in reduced strain and more uniform deformation. The material used was DC56, 1mm thick. Increase in plastic stress with increased pitch is thus obvious. Forming forces required to form the material also decreased with smaller pitch. Therefore, it is clear that increase in pitch results in decreased formability [10].

6.6 Effect of Plastic anisotropy

As in case of ISF deformation zone is localized, the effect of anisotropy of material is not significant on formability. Though Kim and Park[1] has showed that formability along transverse direction is higher when small diameter tool is used, while in case of large diameter tool formability is higher along rolling direction.

7. Forming Forces in ISF

During ISF operation three orthogonal forces come into picture: Radial force “Fr”; Tangential force “Ft”; and Axial force “Fa”. Most of the forming energy goes into pushing down because Fa, the axial force is much higher thanFb, the resultant of Ft and Fr [1].

8. Process mechanics and FEM strategies for ISF

Generally, a numerical model of any process is able to give the state of stress, strain and forming limits. Numerical simulation is carried out either with implicit or explicit method, in some cases both are used. For example in ISF, first part of process is carried out with explicit and the last part is carried out with implicit to calculate springback accurately. Here, the results of FEM concludes that [1]

- The plastic strain increases stepwise under the action of the tool and
- Each increase in plastic strain is accompanied by compressive stresses.

Carlos Felipe Guzmán and Anne Marie Habraken have recently used triaxiality to predict fracture in SPIF [16]. They have concluded that the influence of the Lode angle over damage development should be considered when studying rupture in SPIF. They found negative triaxiality during the process. The governing deformation mechanism of ISF is in controversy among the researchers.

9. Dimensional accuracy in ISF

Bramley [1] reports an accuracy of ±1.5 mm for symmetrical and ±2 mm for asymmetrical parts produced by SPIF using a tool path from a milling oriented CAM. For TPIF of mild steel parts Hirt et al[1], report deviations of order of magnitude ±2 to 3mm. Probable causes of deviation from the theoretical workpiece shape, that correspond to the programmed toolpath are springback and geometric distortion due to stress propagation.

Jeswiet and Ham[17] has carried out study of forty-six parts which includes mean and standard deviations error from reference, as well as the maximum and minimum errors and the probability of points within one and three standard deviations. 15% of the parts have maximum errors less than ±1 mm, 48% of the parts are within 2 mm, 76% are within 3 mm and all parts are within ±4 mm. The overall average mean is 0.13 mm and all parts have a mean error of less than 1 mm.

10. Various deformation mechanisms proposed for ISF

The main objective of studying deformation mechanism is to justify the stabilization of material during ISF. Emmens et al [8] has presented an overview of stabilizing deformation mechanisms in ISF. He has proposed some of the possibilities responsible for increased formability or restriction of neck growth:

Effect of shear, Cyclic effects, Effect of bending under tension, Restriction of neck growth, Hydrostatic pressure, Effect of contact stress

10.1 Effect of shear

Unlike deep drawing, in ISF product is made without the flow of material from blank holder area [8]. Sawada(2001) was the first to investigate in detail the forming of the sheet around the punch contact. Bambach(2003) has also noticed the occurrence of shear in his simulation of ISF, and observed that the level of shear depends both on the punch head diameter and the vertical pitch. Jackson(2007) has detected the presence of through-thickness shear in the direction of punch movement experimentally by measuring the relative displacement of both surfaces of a sandwich panel in SPIF.

10.2 Cyclic effects

In a practical ISF operation the punch passes a certain material point several times, up to a few dozen. Each pass causes bending and unbending with possible strain reversal so the material is subjected to cyclic straining. Bambach has noticed this cyclic straining which was presented by eyckens et al in 2007 [8].

10.3 Effect of bending under tension

BUT is a true dynamic phenomenon, it only occurs when the material is actually moving around the punch. The mechanism predicts an additional stabilizing effect proportional to t/R, which in good agreement with the experimental observations of ISF [8]. W.C.Emmens has studied cyclic stretch bending; he noticed that the fibres at the concave side are in compression in the direction of major straining. Eventually he finds similarities between formability in ISF, and formability created by cyclic stretch-bending [1].

10.4 Restriction of neck growth

Martins has examined fractured ISF products and noticed that there was no sign of an actual neck. He then proposed that the absence of a neck is due to the fact that necks do not have the ability to grow (Martins et al, 2008) [8].

10.5 Hydrostatic pressure

Bambach has stated that considerable back stresses are expected from the elastic surroundings which suppress the neck formation. Martin has related the increased forming limits in SPIF as compared to conventional stamping to the reduced triaxiality ratio [8].

10.6 Effect of contact stress

Bambach (2003) has observed high levels of contact stress in his simulations and concluded that it may be of influence on the occurrence of hydrostatic stress in ISF. Huang has also presented a direct relation between the enhanced formability in ISF and the presence of contact stress with reference of work done by Smith (2008). Silva [3] has presented an elaborate analysis of the ISF process based on membranes (2008). The contact stress is introduced in this model by stretching of the sheet over the punch radius. Examination of Silva's formulae reveals that the yield stress in tension is reduced by the contact stress. The model is based on membrane analysis with bi-directional in-plane contact friction and is focused on the extreme modes of deformation that are likely to be found in single point incremental forming processes.

He has also differentiated conventional FLD from Fracture Forming Limit Diagram (FFLD). The FFLs in SPIF can be characterized by means of ductile damage mechanics based on void growth models. He has concluded based on the experimental observations that fracture is not preceded by localized necking and that crack propagates under tensile meridional stresses acting under stretching modes of deformation [3].

Silva et al (2009) [18] has then presented the experimental and numerical simulation to validate their theory. They have used truncated conical shape and pyramid shape for study. They have also shown that the meridional stress is lower than the yield stress and its value decreases along the inclined wall. They have also concluded that governing mode of deformation is stretching in ISF, and the formability is limited by fracture without previous necking.

Silva et al (2010) [19] has again presented strategies and limits in multi-stage SPIF. The strain paths are linear in the first stage and highly non-linear in the subsequent stages. The overall level of strains achieved in multi-stage SPIF is much higher than the experimental values of necking currently found in conventional sheet metal forming.

Smith et al (2013) [20] has presented deformation mechanics in Accumulative Double Sided Incremental Forming (ADSIF). They have concluded that ADSIF causes the sheet metal to be subjected to greater plastic strains, through-the-thickness shear strains and greater hydrostatic pressure than in SPIF. Moreover, formability in ADSIF is more than SPIF.

11. Research opportunities and challenges in ISF

- Dimensional accuracy of the parts formed with ISF, is not up to the mark.
- Fracture Forming Limit Diagrams for different combinations of materials and sheet thickness.
- Compensates for springback needs to be taken care.
- Work needs to be done in making ISF more viable for mass production.
- A comprehensive study on deformation mechanism of localised zone (tool/sheet interfaces) during ISF, is needed.

12. Summary

- ISF does not need any dedicated die, so it can be used for rapid metal prototyping and small batch production.
- Forming forces during ISF are very low which allows large shapesto be formed on the machines having low capacity of forces.
- Formability of material has increased greatly while being formed with ISF in comparison of conventional forming i.e. deep drawing or stamping.
- Increased formability in ISF is mainly due to localised deformation.
- Deformation mechanism of ISF is still not properly understood.

13. Acknowledgement

I am very greatful to Prof. H K Raval and Prof. AsimTewari for providing an opportunity to work at IIT Bombay for my M.Tech dissertation. I would also like to thank Prof. VivekBarnwal for introducing me to Incremental Sheet Forming.

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