

## CHAPTER 1

### Introduction and literature survey

**Abstract:**

*The field of sheet metal forming has witnessed a significant transformation with the emergence of Robot Assisted Incremental Sheet Forming (RAISF), an innovative technique that enables the deformation of sheet metal into complex three-dimensional shapes without the need for dedicated dies. This research project delves into a promising variant of RAISF, known as Robot Assisted Incremental Sheet Hydroforming (RAISHF), which introduces the application of hydrostatic fluid from the back of the sheet during the forming process. The integration of fluid support from the sheet's rear surface holds the potential to significantly enhance strain distribution and overall forming quality.*

*This thesis represents the culmination of six years of intensive research and analysis, comprising seven comprehensive chapters. The structure of the dissertation is as follows: The thesis commences with a meticulous review of the existing body of knowledge, providing a concise definition of the Incremental Sheet Forming (ISF) process and a comprehensive survey of prior research endeavors related to ISF techniques. This introductory phase sets the stage, elucidating the significance of RAISHF within the broader context of sheet metal forming, and highlighting the motivation for its study.*

*Chapter 2 of the thesis presents an experimental setup meticulously designed and implemented for executing RAISHF and traditional RAISF processes. An integral aspect of this research involves the optimization of critical input parameters, including tool speed, tool diameter, and step depth. This optimization is achieved through a well-structured design of experiments (DOE) approach, ensuring the efficiency and efficacy of the forming*

operations. A pivotal component of the thesis involves the development and presentation of a sophisticated mathematical model which is presented in chapter 3 of the thesis. This model serves as a fundamental tool for understanding the intricate mechanical dynamics underlying the RAISHF process. It enables the calculation and prediction of various force components and deformations, facilitating in-depth analysis and optimization of the forming process. Central to this study is a comprehensive comparative analysis between RAISF and RAISHF. Utilizing a range of advanced mechanical and metallurgical characterization techniques, including tensile testing, surface roughness profiling, microhardness assessments, X-ray diffraction (XRD), and electron backscatter diffraction (EBSD), the thesis rigorously evaluates and discerns the mechanical and metallurgical attributes of these sheet metal forming methodologies. In addition to the comparative study, this research extends its scope to scrutinize the differences between single-stage and multi-stage RAISHF processes. The investigation primarily revolves around the evaluation of surface quality and thickness distribution in the formed products, providing invaluable insights into the advantages of multi-stage RAISHF for specific applications. The research also encompasses an in-depth comparative assessment of cold and warm RAISF and RAISHF processes. Various mechanical and metallurgical characterization techniques are systematically employed to assess and contrast these processes, revealing their distinct advantages, challenges, and applicability. The thesis concludes by summarizing the key findings, insights, and contributions derived from this extensive research endeavor. It also contemplates the future prospects and potential research avenues within the rapidly evolving fields of RAISHF and RAISF, underscoring the transformative potential of these technologies in advancing customized 3D part fabrication and sheet metal forming. This thesis, thus, serves as a vital and comprehensive resource for researchers, engineers, and practitioners in the domain of sheet metal forming and manufacturing technology.

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## 1.1 Introduction

Metals are widely used in all fields of manufacturing and production. They are typically shiny, ductile and malleable. Metal Forming is a process which has been carried out since the inception of mankind. It is a manufacturing process which is used to plastically deform metals into desired shapes using different states of stresses. Today forming process has become extremely important for almost all manufacturing industries. The major industries using metal forming processes are Aerospace, Automobile, Steel, Medicine, and Non-ferrous metal industries, Nuclear and thermal plants, Biomedical sectors etc. [1-3]. The inclination of the manufacturing industry towards the forming in recent years is due to certain advantages it has over all the other manufacturing processes. The constancy of volume is a general characteristic of forming operation, due to which material can be saved, which can ultimately contribute towards sustainability. Additionally, certain phenomena associated with metal forming, such as strain hardening, contribute towards enhancement of mechanical properties of formed parts. During forming, there is alignment of fibre lines along the loading direction, which is not observed in machining and casting, hence the strength and other properties can be enhanced in forming processes.

Some of the advantages of forming over other mechanical processes are:

1. More raw materials saving can be done because volume remains constant before and after forming.
  2. Increased strength of the formed part can be obtained as a result of strain hardening and better grain flow.
  3. Improved wear resistance in the formed part can be obtained.
  4. Better dimensional tolerances can be obtained.
  5. High production volume can be achieved.
  6. Better surface finish in processes involving cold working can be obtained.
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7. Improved fatigue properties can be obtained in comparison with other manufacturing processes.

The fracture limit of the material depends on the stress state. During forming operations involving compression, a high level of hydrostatic compressive stress squeezes the voids and slows down damage development [4]. So, forming processes involving compressive stresses (like rolling and press working etc.) can create large strains without damage. Because of the advantages mentioned above, metal forming finds its place in almost all manufacturing fields today.

## 1.2 Classification of forming process

Forming process can be broadly classified in terms of bulk forming and sheet metal forming. Sheet metal forming can be further classified in terms of conventional and non-conventional sheet metal forming. A broad classification of forming process is displayed in Figure 1.1.

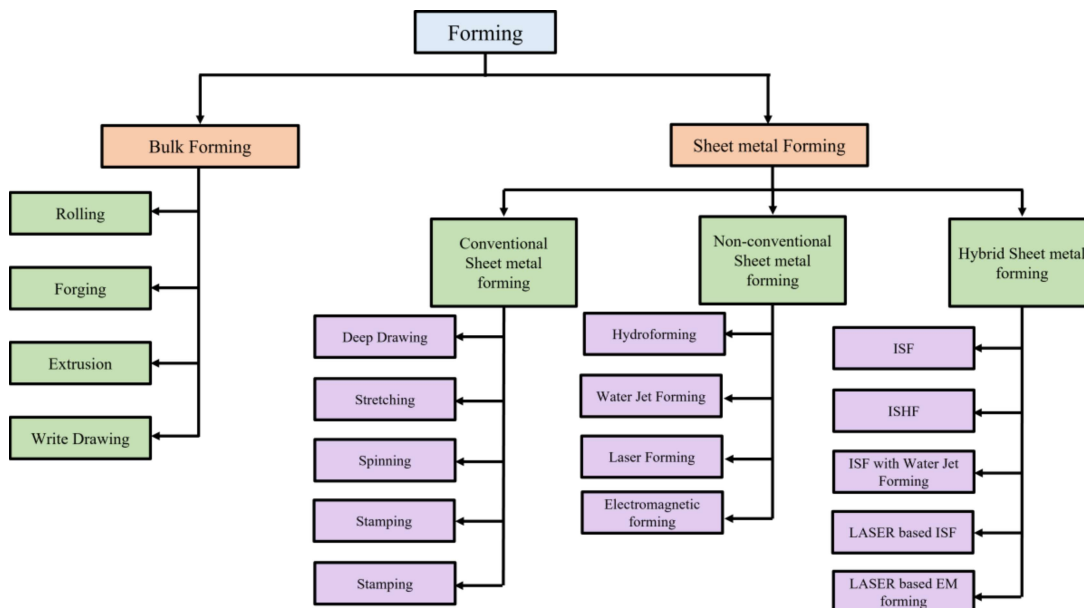


Figure 1.1: **Broad classification of metal forming processes.**

### **1.2.1 Conventional sheet metal forming**

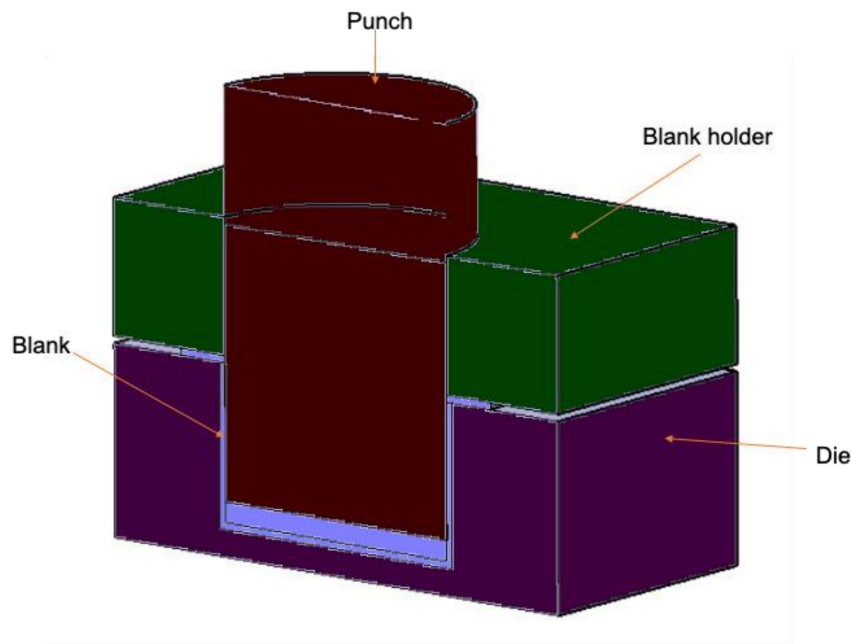
Sheet metal forming and working are the most frequently used production techniques in industries. The volume to surface area ratio is much smaller in sheet metal forming than in the bulk mechanical forming processes. Automotive bodywork, aeroplane frames, home appliances, housings, and construction fixtures are the areas in which large sheet metal parts are readily used in bulk application. However, there are several uses where tiny sheet metal components, such as washers, beer cans, kitchenware, utensils and pots. Use of dedicated dies and punches is one of the common characteristics of all conventional sheet metal forming processes. The geometry of the part to be formed follows the die geometry with required tolerances, and sheet metal is pressed against dies using machines and tools. Different factors, including tools, equipment, material qualities, and tribology, have major impact on the cost and quality of sheet metal forming processes. Some of these variables have direct effects on one another. A sheet metal part's ability to be formed depends on a variety of elements, including material properties, forming technique used, and process parameters. Standard material parameters, such as tensile yield strength, ultimate elongation, breaking strength etc. can be used to assess the material qualities. Finding the most efficient and cost-effective approach to form a part using the available machinery and forming techniques has been the key difficulty. The following is a description of various sheet metal forming procedures that are frequently used in the area of production.

#### **1.2.1.1 Deep Drawing**

Deep drawn parts are characterized by the depth of the parts being is more than half of the part diameter. In this procedure, sheet metal is clamped by the blank holder over the die, which contains a cavity in the outside shape of the part. The sheet metal is pushed downward by the punch and drawn into a die cavity. The sheet deforms plastically into a cup-shaped component as a result of the force being applied to it. A blank, blank holder,

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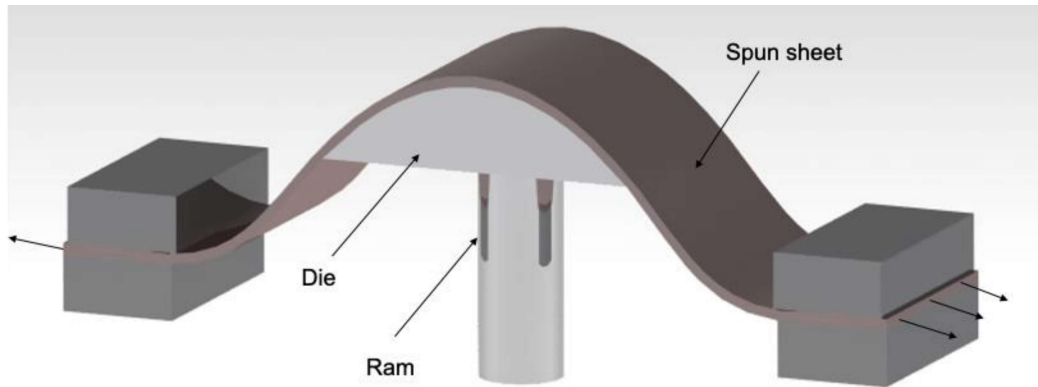
punch, and die are needed for this technique. The blank holder controls the sliding of the sheet during the process and prevents wrinkling of the sheet. The complete setup for deep drawing process is shown in Figure 1.2.



*Figure 1.2: Setup for deep drawing.*

### **1.2.1.2 Stretching**

This is yet another form of sheet metal forming. In this process, punch is brought down, and the sheet is allowed to deform and take the shape of the die while being clamped at its perimeter over the die chamber. The sheet metal stretches and thins as it is formed because it is clamped around the edges. Radial strain is used to obtain the sheet's deformation. Stretch-formed components are generally large and have bends of large curvatures. Anything can be formed, from a simple curved surface to intricate non-uniform cross sections. Stretch forming can be used to form sheets with high levels of accuracy and smooth surfaces. The labelled diagram of setup for stretch forming is shown in Figure 1.3.



*Figure 1.3: Labelled diagram of stretch forming setup.*

Stretch forming and deep drawing are the two most commonly used sheet metal forming processes. The main difference between the two processes is that in deep drawing, the material is allowed to deform under blank holder, whereas in stretch forming, the material is prevented to deform under blank holder.

### **1.2.1.3 Spinning**

In this process, a rigid tool is used to push a flat circular sheet against a rotating mandrel. Mandrel and sheet metal are fastened between the lathe's headstock and tailstock using clamps so that the spindle can rotate them at high speed. A tool applies force to the sheet as the sheet and mandrel are rotating, causing the sheet metal to flow and deform against the mandrel, which has the shape of the finished product. Metal spinning can be used to fabricate three-dimensional seamless, asymmetrical designs out of flat metal using rotational motion and force. The labelled diagram of setup for shear spinning is shown in Figure 1.4.

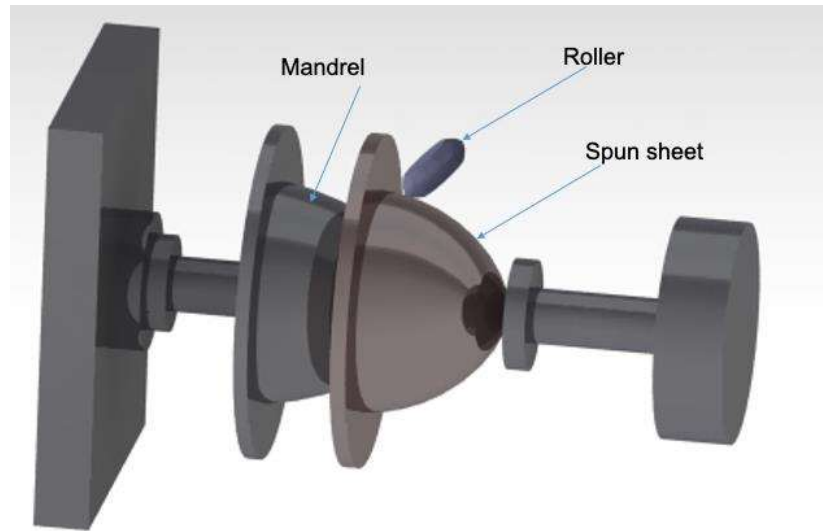


Figure 1.4: Labelled diagram of spinning machine.

During spinning the sheet thinning occurs the initial and the final sheet thickness are related by equation  $t_f = t_0 \sin \alpha$  where  $t_f$  is final sheet thickness and  $t_0$  is initial sheet thickness and  $\alpha$  is wall angle of the formed cone.

#### 1.2.1.4 Stamping

It is a cold forming process used to form shallow parts in a press by stretching the sheet over a shaped punch and die set. The required shape is stamped out of the metal using a stamping tool, often called a die, in a press. The die is pressed into or through the metal with force in the order of tons. The sheet is clamped at the edges by the blank holder, which holds the sheet in such a manner that it can be drawn inwards against the clamping action but develops sufficient tension so that sheet can be stretched over the punch. If some re-entrant shape needs to be made, then it can be made by some counter punch, as shown in Figure 1.5.

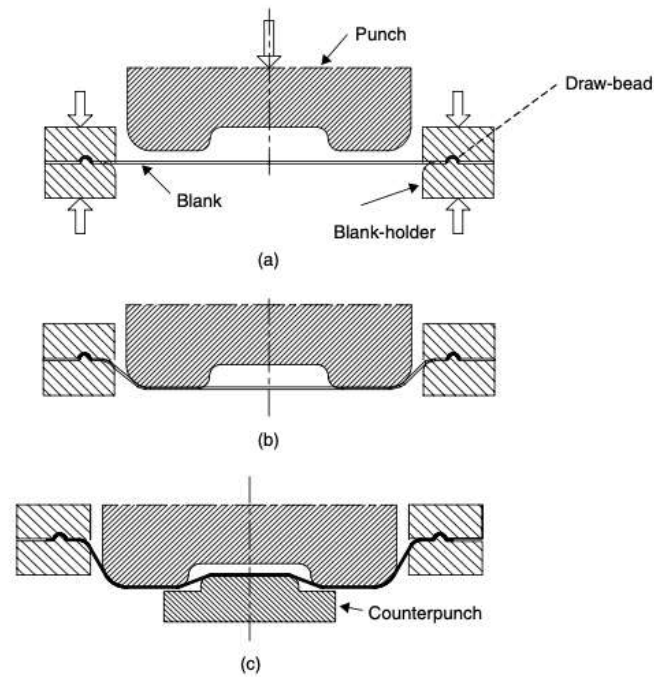


Figure 1.5: Schematic diagram of simple stamping process [3].

### 1.2.1.5 Bending

Bending along a straight line is one of the most common sheet metal forming processes. It can be done by forming along a complete bend within a die, by wiping, folding or sliding the sheet over a die radius. In order to make structural stamping elements like braces, brackets, supports, hinges, angles, frames, and other non-symmetrical sheet metal parts, bending is typically done on a sheet of metal. As shown in Figure 1.6(a) and (b), during bending, the compressive stress increases from the neutral axis to the inside of the bend, while the tensile stress on the outside of the bend begins to diminish and becomes zero at the neutral axis. Although there is significant plastic deformation during bending, the middle portion of the bending zone functions as an elastic zone; therefore, elastic recovery occurs after unloading. Because of this elastic quality, sheet metal tends to spring back partially after bending. In order to get the desired shape and bend angle, the sheet metal must be precisely overbent. Depending on the product shape required, there are various

ways of bending. Every time a sheet of metal is bent, a punch provides force to the sheet of metal, causing it to deform into the shape of the die while being supported by a die. In each instance, a separate punch and die will be utilised to bend the metal.

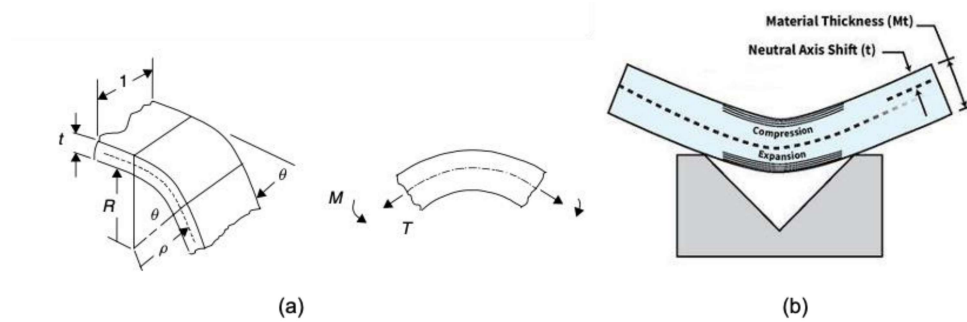


Figure 1.6: (a) A continuous strip bent along a line [3] (b) Sheet metal bent against a V-die [5].

## 1.2.2 Non-conventional metal forming

In this class of forming operations, traditional tool and die setups are minimized or eliminated by employing flexible tools such as metallic foams, rubber, viscous fluids, semi-solid materials, and oils to shape components into their final forms. Unlike conventional rigid dies, these flexible tools offer greater adaptability and cost-effectiveness, enabling the production of complex and customized shapes while reducing the need for dedicated tooling. This approach is particularly valuable in industries requiring flexibility, small production runs, or rapid prototyping, as it streamlines the forming process and minimizes tooling-related expenses.

Some of these processes are explained in fore coming sections:

### 1.2.2.1 Hydroforming

Hydroforming is an advanced sheet metal forming process that utilizes high-pressure hydraulic fluid to shape metal components [6, 7]. It offers advantages such as reduced material waste, enhanced design flexibility, and the ability to produce lightweight yet

durable parts. The pressurized fluid from back forces the sheet to take the desired shape and get fabricated. Hydroforming has found applications in various industries, including automotive and aerospace, where it is used to produce components like automobile frames and aircraft fuselages [8, 9]. As sustainable manufacturing practices gain prominence, hydroforming's capacity to reduce material waste and enhance part performance makes it an area of continued research and innovation, with potential applications in emerging industries seeking both efficiency and environmental responsibility.

#### **1.2.2.2 Water jet forming**

Water jet forming is a specialized manufacturing process that utilizes high-pressure streams of water, often mixed with abrasive particles, to form such as metal, plastic, and composites. This technique offers several advantages, including the ability to form intricate shapes with minimal heat generation, resulting in reduced material distortion and stress [10]. Consequently, it finds applications in industries ranging from aerospace and automotive to architecture and art, where precision forming, and environmentally sustainable practices are essential [11].

#### **1.2.2.3 Laser forming**

Laser forming is a non-contact manufacturing process that utilizes high-intensity laser beams to heat and deform metal components. It operates on the principle of thermal expansion, where localized heating causes the material to expand or contract, leading to desired shape changes [12]. This innovative technique offers several advantages, including precision in shaping complex geometries, minimal tool wear, and the ability to form materials that are traditionally challenging to work with [13]. Laser forming finds applications in aerospace, automotive, and microelectronics industries, enabling efficient and flexible production processes while reducing material waste and tooling costs [14].

### **1.2.3 Hybrid sheet metal forming process**

In the past few years, sheet metal forming operations combining conventional and non-conventional forming operations have been used. Such processes can be categorised as hybrid sheet metal forming operations. Some of the examples of hybrid sheet metal forming operations are incremental sheet forming (ISF), ISF combined with hydroforming, water based ISF, Laser based ISF, and Laser based electromagnetic forming. Since incremental sheet forming (ISF) is the scope of this research, it will be discussed here, being the main scope of current research work.

### **1.3 Incremental sheet forming**

Incremental sheet forming (ISF) is the method of forming sheets into a programmed shape with a dedicated forming tool and without use of any dedicated dies or with use of a partial die only. In this process, a sheet is formed in a stepwise manner without use of any dedicated dies. This is the reason why this process is also called Dieless forming. The sheet is deformed in stepwise incremental manner where a small area is under deformation at a time and the area of deformation is moved over the entire product. Hence, the nature of the deformation in ISF is gradual, localised, and incremental, which are found to be responsible for increased limiting strain. Additionally, due to small contact with tool, the friction is also found less, which can also contribute towards more strain before the onset of necking.

Patented in 1967 by Edwards Leszek under the invention titled ‘Apparatus and process for incremental Dieless forming’, the process has attracted the eyes of aerospace, automotive fields, and biomedical sectors for manufacturing complex sheet metal components [15, 16]. The idea of incremental forming the sheets came from the two already existing processes.

(a) Metal Spinning

(b) Shear forming

In metal spinning, the blank is swept on a rotating tool (mandrel) and the deformation takes place, as already shown in Figure 1.4. The blank takes the shape of the rotating mandrel pressed by roller. In shear forming operation, the workpiece is mounted on the rotating mandrel and is subjected to rollers which apply the force in the shear direction so that the workpiece takes the final shape, as shown in Figure 1.7(a). No radial displacement of material occurs in the ideal Shear forming process. From this assumption, it may be concluded that sine law can be used to predict the final thickness of the blank which is depicted in Figure 1.7(b) [17].

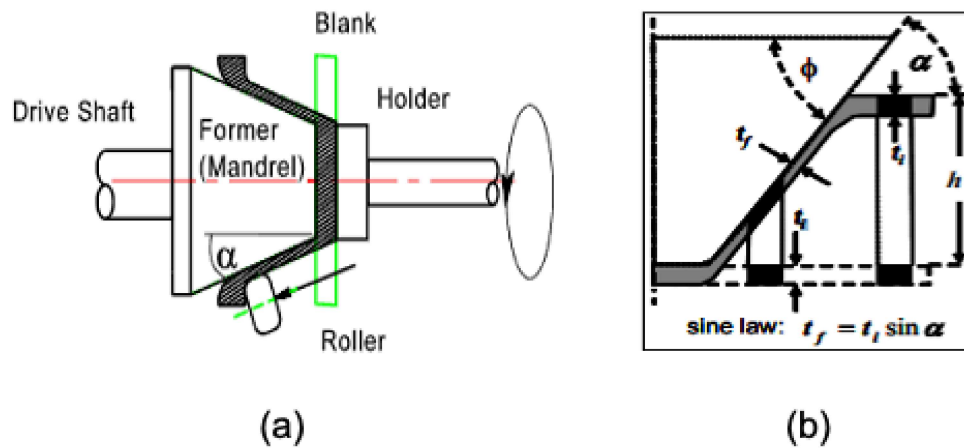


Figure 1.7: (a) Shear forming process (b) Sine law for thickness prediction [16].

ISF can be considered as the combination of above mentioned two processes without use of any mandrel or any other type of dedicated dies or with use of partial dies only. In the initial years of ISF, the mechanism behind the deformation was assumed to be predominately shear. So, sine law can be used for prediction of final sheet thickness axis-symmetric cones. In 2006, Jeswiet et al. [16] presented a review article on ISF and gave a broad categorisation of ISF processes.

The process was used by Iseki et al. [18] for small batch production of non-symmetrical shallow shells using path-controlled spherical rollers in the last two decades, the process of

ISF has been seen as a potential sheet metal forming which can be used in small batch production of customized parts as in ISF, necking is either suppressed or delayed due to which higher strains can be induced than in conventional stamping, deep drawing, and stretching processes [19]. In addition to this, the process of ISF has different other advantages over conventional forming processes. These can be summarized as

- (a) As the process does not require dedicated dies, the setup cost can be largely reduced.
- (b) The degree of flexibility of the process is quite high as different shapes can be achieved by changing the tool path. Merely changing the programming for tool path can lead to production of new shapes.
- (c) The deformation zone in the ISF is confined, due to which stress gets localized, which leads to enhanced formability in ISF. The uniformity of thickness throughout the deformed region is one of the key factors in improving the formability in the sheet metal forming processes. Moreover, Kim and park demonstrated that shear deformation is one of the factors for the improved formability of the product [17, 20].
- (d) The process of ISF forms the basis for rapid prototyping because of its stepwise deforming nature.
- (e) The process is energy efficient and the products can be recycled. So it becomes a very strong candidate to be used in small batch production in automotive, Aerospace and biomedical sectors.

### **1.3.1 Classification of ISF**

Different variants of ISF have been used by different researchers worldwide to make the process more efficient and less time-consuming. The major classification of ISF is given in Table 1.

Table 1.1: Broad classification of ISF

Basis of Classification	Distinguished property
Nature of tool-sheet contact	<ul style="list-style-type: none"> <li>• Single point incremental forming</li> <li>• Two-point incremental forming</li> </ul>
Die used	<ul style="list-style-type: none"> <li>• No die used</li> <li>• Use of partial die from back of the sheet</li> </ul>
Symmetry of parts produced	<ul style="list-style-type: none"> <li>• Symmetric ISF</li> <li>• Asymmetric ISF</li> </ul>
Nature of flexible back medium from back	<ul style="list-style-type: none"> <li>• Incremental sheet hydroforming using Static Fluid pressure.</li> <li>• Incremental sheet hydroforming using rubber pad.</li> <li>• Incremental sheet forming using metallic foam.</li> <li>• Incremental sheet forming using viscous medium.</li> </ul>
On the basis of tools used	<ul style="list-style-type: none"> <li>• Single tool ISF</li> <li>• Multi tool ISF</li> <li>• ISF with vibrating tool</li> </ul>
On the basis forming temperature used	<ul style="list-style-type: none"> <li>• Cold incremental sheet forming (Forming Temperature <math>\approx</math> room temperature, Friction coefficient = 0.1 to 0.3)</li> </ul>

	<ul style="list-style-type: none"> <li>• Hot incremental sheet forming (Forming Temperature <math>&gt; 0.6</math> melting temperature, Friction coefficient = 0.3 to 0.6)</li> <li>• Warm incremental sheet forming (Forming Temperature <math>&lt; 0.6</math> melting temperature, Friction coefficient = 0.2 to 0.4)</li> </ul>
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Some of the commonly used variants of ISF with schematic representation are given in Figure 1.8(a) to (d).

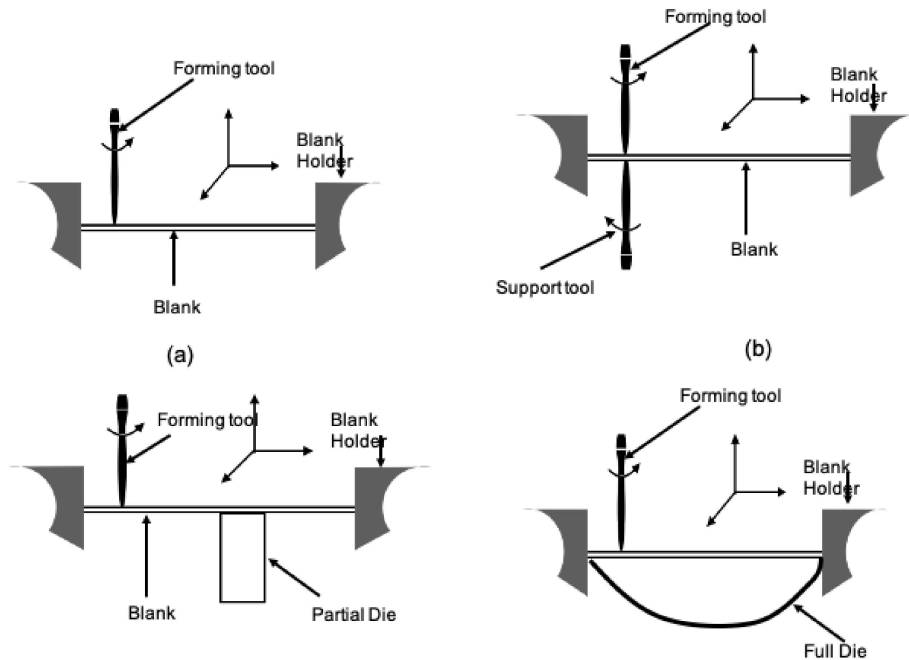


Figure 1.8: Some commonly used ISF methodology (a) Single point ISF (SPIF) (b) Two point ISF (TPIF) (c) ISF with Partial die (d) ISF with full die.

## 1.4 General Apparatus of ISF

The setup for ISF has following important components such as:

### 1.4.1 Controller machine

In the initial years of ISF, the process was carried out using a 5/6 axis NC/ CNC machine. The forming tool is mounted on the machine and is programmed to follow certain path to achieve deformation. In the recent times 5/6-axis industrial robots are being used as driver machines in ISF, the process being called as robot assisted incremental sheet forming (RAISF). In 2003 Timo Tuominen [21] filed a patent for ISF using six axis industrial robots under the title “Method and apparatus for forming three-dimensional shapes in a sheet metal”. A CNC-based ISF and industrial robot based ISF setups are shown in Figure 1.9(a) and (b) respectively.

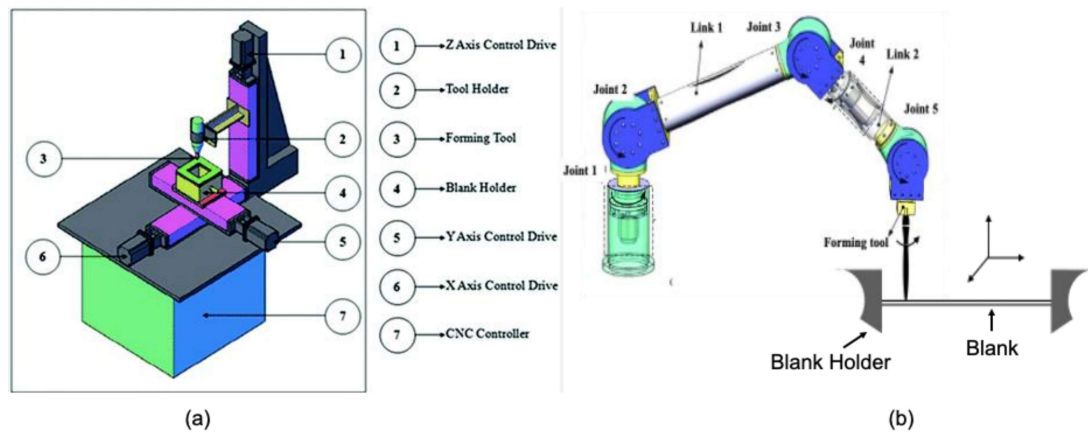


Figure 1.9: (a) CNC machine-based ISF machine [22](b) Robotic arm-based ISF machine.

### 1.4.2 Forming tool

Forming tool plays the most crucial role in the ISF. It is mounted on the machine. There are many types of forming tools which are used. The most common of them is the hemispherical ball tool. Two types of hemispherical ball tools are used which are fixed ball tool and rolling ball tool. In rolling ball tool, nature of friction between sheet and tool is

static, whereas limiting friction occurs between sheet and tool in case of fixed ball tool. The most common materials used for the tools are HSS, CBN, Cemented Carbide, and steel and Ceramics etc. The contact geometry of the hemispherical ball tool at the tool sheet interface can be understood by the following Figure 1.10 (a).

At any instant, a part of the tool is in contact with the sheet as can be seen from Figure 1.10 (a), only a fraction of tool radius makes contact with the sheet. The fraction of tool radius staying in contact with the sheet can be termed as contact radius and can be mathematically determined from the following relation:

$$r' = r \times \sin\Theta$$

Ziran et al. [23] studied the effect of hemispherical and flat end tool as shown in Figure 1.10(b) on profile accuracy of fabricated U-shaped channel and formability of the sheet. It was found that flat end tools can offer superior formability and profile accuracy than hemispherical end tools. Additionally, compared to hemispherical end tools, flat end tools needed a considerably lower forming force [23]. Lu et al. [24] achieved better surface quality, and formability along with lower forming forces through reduced friction by using an oblique roller-ball tool shown in Figure 1.10(c).

Apart from this, some other types of tool configurations have also been used depending upon their profile and have been shown in Figure 1.10(d). Cawley et al. [25] studied the effect of various tool shapes on the formability and surface finish of the fabricated part. It was concluded that tight curvatures near tool tip can give rise to larger forming angle than larger curvatures. However, surface finish in case of tight curvature is inferior to that of larger curvatures. It was further proposed that parabolic tools can give the best combination of high forming angle and high surface finish [26].

Similarly, Vanhove et al. [27] used asymmetric elliptical tool for performing ISF and reported better formability in aluminium 5XXX alloy. Different types of forming tools as used by different researchers are shown in Figure 1.10 (e).

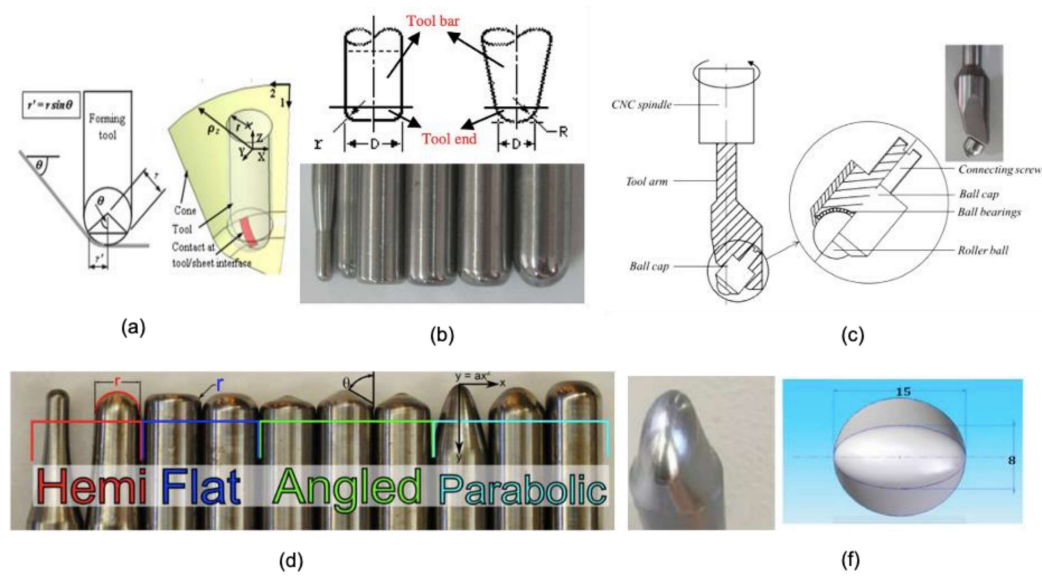


Figure 1.10: (a) Tool-sheet interface geometry [28], (b) Flat and hemispherical tools used by Ziren et al. [23], (c) Roller tool used by Lu et al. [24], (d) Different forming tools used by Cawley et al. [25], and (e) Elliptical tool used by Vanhove et al. [27].

In addition to this, Yoon and Yang [29] presented a new set of punch having centre punch with two pairs of lower punches for forming doubly curved sheet metal as shown in Figure 1.11 (a). Wang et al. [30] used a multi-head tool for making frustums from 2024-O Aluminium plate and found it to have good forming efficiency and surface finish. Panjwani et al. [31] devised multi bolt system called Flexible Bolt System (FBS) for shaping asymmetric shapes. L and M shapes were fabricated using FBS system. Punch used by Yoon and Yang and FBS system is shown in Figure 1.11(c).

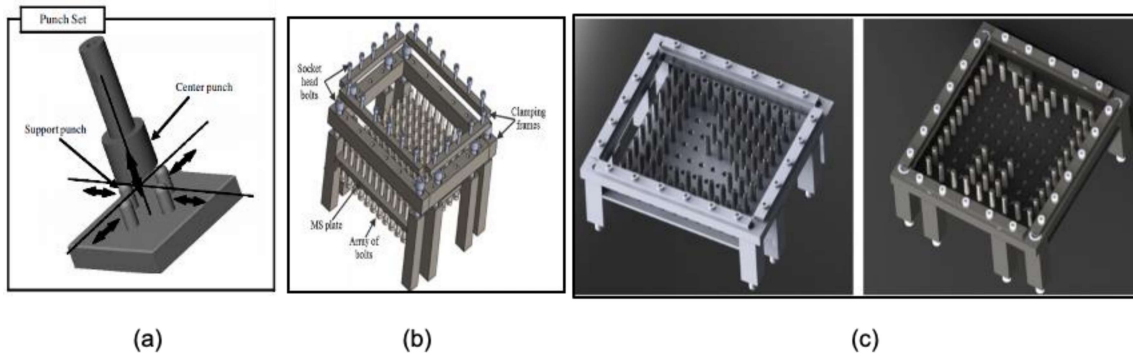


Figure 1.11: (a) Punch set with counter punch used by Yoon and Yang [29] and (b) FBS system (c) FBS system with removed bolts for making L and M shapes [31].

In the recent past use of so many modifications in forming tools have been reported in ISF. Daniel and Oancea [32] used a circumferential hammering tool shown in Figure 1.12 (a) to achieve better part accuracy. Similarly, tools with ultrasonic vibration have been reported in the recent past. Liu et al. [33] drew titanium wires without lubrication, at room temperature with the assistance of longitudinal and torsional vibration and found that both vibrations were beneficial as they decreased drawing force and increased surface finish for drawn wire. Similarly, Hu et al. [34] investigated the ultrasonic volume effects (reduction of flow stress due to ultrasonic vibration) in terms of stress superposition, acoustic softening and dynamic impact using 60 kHz longitudinal ultrasonic-assisted compression test system. The tests had been carried out on AA1000. Zhou et al. [35] studied the effect of ultrasonic vibration on the plasticity of Al and titanium alloys using an Ultrasonic assisted compression test based on nano indentation and EBSD. It was concluded that, ultrasonic vibration (UV) can induce plastic deformation and refine the grains for both aluminium and titanium samples. Amini et al. and Vahdati [36, 37] used ultrasonic vibration-assisted ISF(UVAISF) and deployed it on the AA1050 sheet. Ultrasonic vibration of high frequency and low amplitude was employed with the help of vibratory tool consisting of an ultrasonic head with a vibration frequency of 20 kHz and was attached to the CNC machine. It was found that the forming force decreased up to 36 % in the straight groove test. It was also discovered

that formability can greatly increase, with a maximum value of 48 % obtained in the straight groove test. It was shown that ultrasonic vibration is a viable solution for dealing with the spring back problem. The best results come in terms of forming force, formability, and spring back when ultrasonic vibrations are combined with the right lubricant. Pengyang et al. [38] used ABAQUS to perform FEA analysis of UV-SPIF to simulate and analyse the influence of frequency and amplitude on forming forces. It was found that the use of ultrasonic (frequency 50 kHz) vibration can decrease the mean axial force and can also improve the surface quality with a larger amplitude of vibrations. The arrangement for forming tool and complete setup is shown in Figure 1.12 (b) and (c) respectively. Li et al. [39] used FEA modelling to examine the effect of ultrasonic vibration in ISF on AA1050 and AA5052 and found that forming forces were reduced, especially at the later stages in the process and introducing US vibrations also induced sheet softening. Sun et al. [40] used USAISF to fabricate aluminium sheets and found that the spring-back effect can be reduced by using ultrasonic vibration. With increasing ultrasonic amplitude, the surface waviness of aluminium alloy is reduced, and the surface topography becomes smoother. In addition, the application of ultrasonic vibration can reduce the surface hardness and promote the surface residual stress distribution to be more uniform. Zhang et al. [41] did the numerical modelling of UVAISF and validated their constitutive model with experimentations. The impacts of essential factors such as tool size, tool revolution speed, feed rate, pitch, and tool vibration amplitude on forming force, maximum sheet thickness reduction, and spring back were also examined.

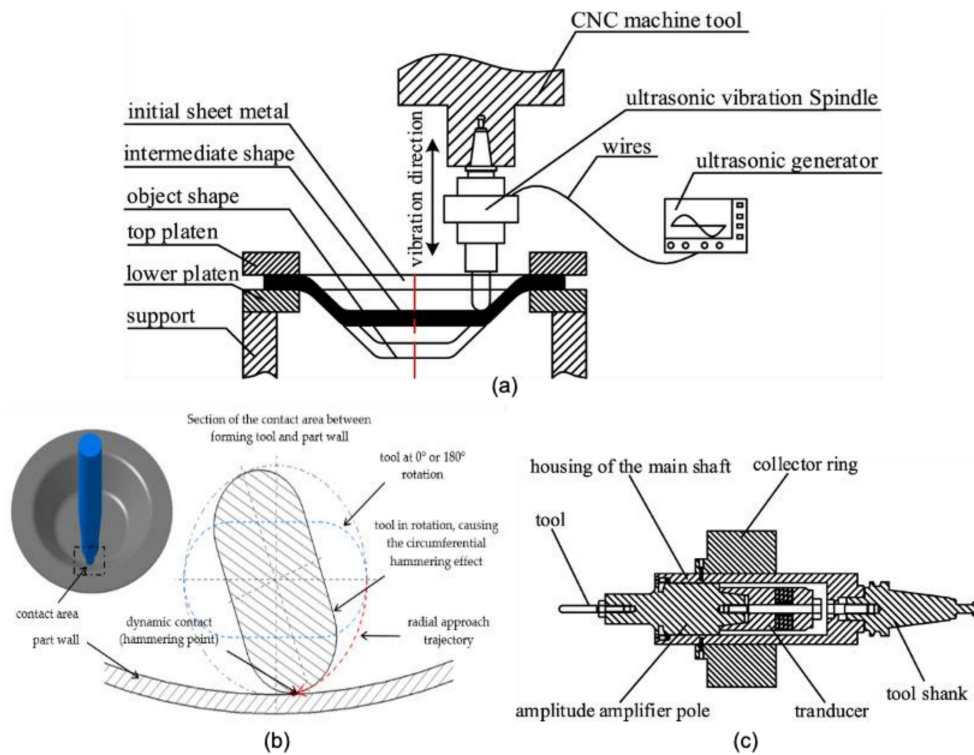


Figure 1.12: (a) CNC-based ISF machine with a vibrating tool, (b) ISF with circumferential hammering tool [32], and (c) Ultrasonic vibration assisted tool [38].

### 1.4.3 Interface for generating Tool path in ISF

The fabrication of the parts in ISF depends on tool path. Choosing the right tool path is the most crucial part in fabricating a given shape. The accuracy of the formed components depends on the acquired tool path and the strategy. The tool path generation on a CNC based ISF can be broadly done in two ways:

(i) *Pocketing with constant step depth:* This is also called Contour milling tool path which is mainly characterized by constant step depth ( $\Delta Z$ ). In such strategy, the tool moves from top to the bottom in a series of consecutive contours with fixed step depth. The main disadvantages of such strategy are:

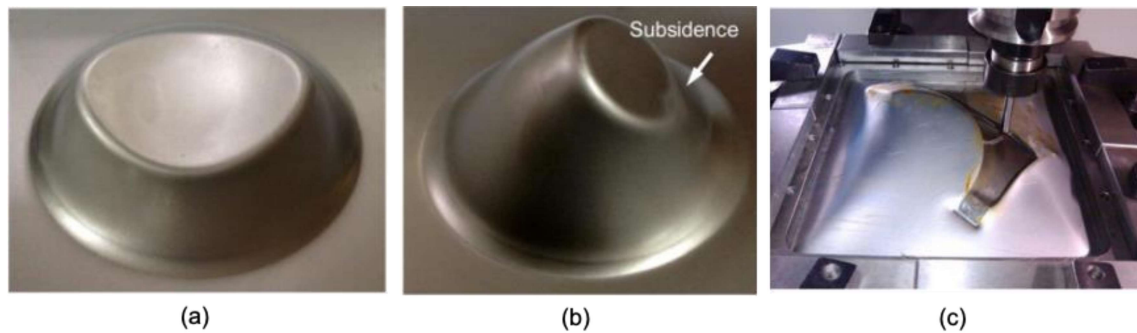
- (a) A marking appears on the sheet at the transition point between consecutive layers.
- (b) For high value of  $\Delta Z$ , the quality of flat or near to flat surface becomes poor.

(ii) *Pocketing with constant “scallop height”*: It is the tool path programming in which step size  $\Delta Z$  varies in order to keep the scallop height constant. This type of tool path leads to reduction of 1<sup>st</sup> type of disadvantage encountered in tool path with constant step depth strategy.

Attanasio et al. [42] used different combinations of constant step and constant scallop height and recommended the maximum step depth of 0.2 mm and maximum scallop height of 0.02 mm as the best combination to get the best combination of surface quality, geometric accuracy and thickness profile. Jeswiet et al. [16] used a spiral tool path, where the path is characterized by the value of pitch between two consecutive circles. Kim and Yang [19] compared ISF done by single pass, double pass and by linear blending method which was proposed by Cho in 1997 [43]. In linear blending method, the predicted shapes are then blended together to create a final shape. This is typically done by using a linear interpolation between the predicted shapes. It was found that the formability achieved in double pass method was better than the rest two for forming ellipsoidal and clover cups. Lingam et al. [44] presented a strategy based on saddle points and silhouette loops for tool path strategy making and also gave the sequence to be followed for choosing a certain tool path (horizontal, vertical or inclined slicing) depending upon the geometry of the component for double sided incremental forming DSIF. Rauch et al. [45] suggested that basic CAM tool paths are not suitable for carrying out ISF applications. It was recommended that that intelligent CAM tool path planning should be adopted to achieve desired shape by ISF. Basic tool paths were generated by CAM software and were sent to the CNC machine. Then, during the running of the program, tool paths were optimized by the CNC controllers as per real-time process data evaluation. Azaouzi and Lebaal [46] used FEA with a surface response method and sequential quadratic programming algorithm and optimised tool path for fabrication and applied it to minimise forming time and homogenize

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thickness distribution. Lu et al. [47] used feature-based tool path generation algorithm to generate tool path according to the specified critical edges. The generated tool path was used to produce an axis-symmetric cone with double bottoms, a non-symmetrical cone and a car fender, as shown in Figure 1.13(a), (b) and (c) respectively.



*Figure 1.13: (a) Cone made with twin bottoms, (b) non-axis-symmetric cone, and (c) car fender [47].*

Chang et al. [48] used a quadratic spiral tool path for the generation algorithm. A quadratic interpolation between two contours was chosen, as shown in Figure 1.13(a). Chang et al. [49] used a modified point contact tool path strategy where they chose an offset tool path and simulated the same in order to avoid circumferential friction for forming less ductile sheets. Han et al. [50] built closed loop control model for compensating spring back and hence increasing accuracy of the formed product. FEA was used for prediction of spring back and used wavelet with fast Fourier transform for devising the closed-loop algorithm of the trajectory profile. Gahbiche et al. [51] used circular interpolation for translating the G code in to a file which can be used for FEA simulation using ABAQUS. This can be used for producing general shapes on CNC milling machines and also for feeding tool motions as X, Y, Z amplitudes in FEA simulations. It can be said that several attempts have been made in the field of tool path planning for ISF to make the parts more precise and accurate and to reduce spring back.

In the past few years, machine learning (ML) and artificial intelligence (AI) has been used to make the tool path more accurate. Machine learning has been also used for predicting the temperature and spring back during the process. An online adaptive shape forecasting model was created by Wang et al. [52] to forecast the forming geometry inside each incremental step. In order to reduce geometric error and optimise the prospective step that may deliver a precise tool path to increase geometric accuracy, the model was incorporated into a coupled constrained control algorithm. To optimise tool path generation, Li et al. [53] applied a machine learning technique. Similar experimental conditions were used in the initial training trials' design. In order to create an optimised tool path, the obtained geometric coordinates, temperature, and forming force data were then input into the machine learning system. Nagargoje et al. [54] processed point cloud data (set of X-Y coordinates on 3D space), and identified and extracted the geometrical features by developing an algorithm for the same. Pham et al. [55] used the material response experimentally determined by an ISF V-shape test to establish an ML-based calibration method for hardening law parameters of aluminium alloy sheets. The reference hardening law established using the FEM approach and experimental data from a uniaxial tensile test were compared with the calibrated flow curves. Finally, an ISF simulation of a truncated cone was used to validate these curves.

### **1.5 Deformation mechanism in ISF**

The strain obtained in case of ISF is well above what can be achieved by conventional forming technique of stamping and deep-drawing. The process is not limited by instabilities that limit common forming operations. The localized nature of deformation is commonly used to explain higher strains obtained in the process. However, the underlying reason behind localized deformation and the fact that process is not limited by instabilities has

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always attracted the researchers to find proper explanation. Since the establishment of the process, there have been numerous attempts to establish the mechanism of ISF. Shim and Park [56] used finite element analysis (FEA) to study the deformation mechanism of ISF and concluded that Near Biaxial Stretching occurs in the closed loop and near plane strain occurs along the straight line. They further concluded that Forming Limit Curve (FLC) for ISF is quite different from that of conventional forming. The FLC as a straight line with a negative slope in the positive direction of minor strain was observed as shown in fig. 1.14(a). A straight groove test was recommended as a standard test for plotting FLC for ISF as shown in fig. 1.14(b). In straight groove test a straight groove is made in the sheet using forming tool. The depth of groove gives an idea of formability achieved in the process.

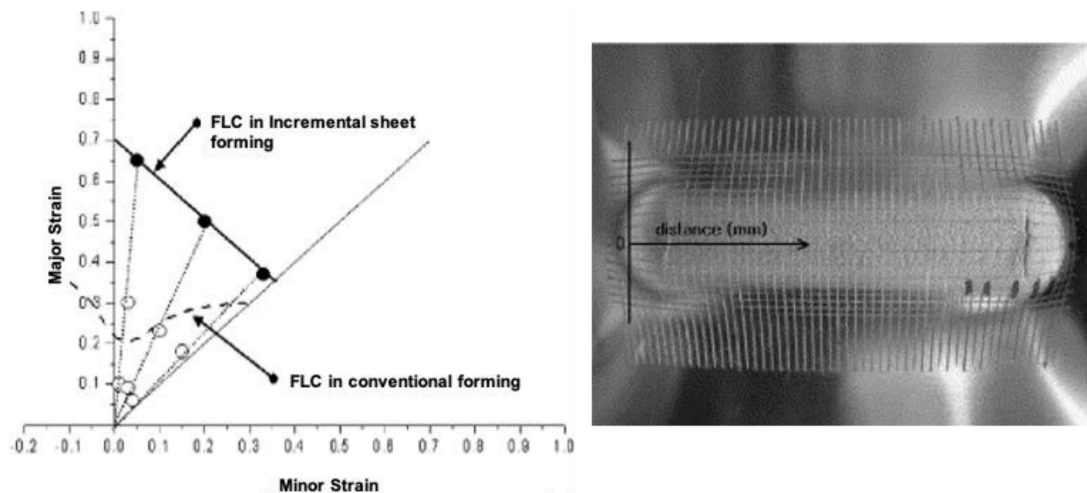


Figure 1.14: (a) Comparison of FLC of conventional forming and ISF (b) Sample for straight groove test.

Kim and Park [57] predicted the same results by performing a series of experiments to produce various shapes. Further, near uniaxial strain has been observed by Bambach et al.

[58] for a straight-sided pyramid and by Fratini et al. [59] for a truncated cone. The sheet thickness in ISF process can be approximated by the famous sine law  $t = t_0 \sin \theta$ , where  $\theta$  is the wall angle in the formed conical part. Since, the thickness in the case of shear spinning is also given by the same sine law, the underlying deformation mechanism as established by Avitzur and Yang [60] and demonstrated mathematically by Kim et al. [17], which was initially considered to be pure shear through the thickness of the sheet and plane strain in the plane parallel to the undeformed sheet. Jackson et al. [61] found the presence of through-thickness shear along tool movement by measuring relative displacement in the sandwich panel. Two pieces of 3 mm thick copper sheet were taken and their cross section were engraved with square mesh and were brazed. The method was adopted from the work suggested by Kalpakcioglu [62]. After deformation, mesh configuration was analyzed and of through-thickness shear was found in the tool direction [61]. The presence of out of plane through-thickness stresses can lead to improved formability in the case of ISF as suggested by Ma and Wang [63]. It was further suggested that the conventional M-K model which includes in-plane stresses only, needs to be extended which should also consider the through-thickness shear stresses. Allwood and Shouler [64] proposed a generalized forming limit diagram (GFLD) which considered the out of plane stresses.

These studies have been dedicated to understand the underlying deformation mechanism of ISF which leads to enhanced formability. Emmens and Boogaard [65] gave an overview of the mechanisms responsible for higher strain in the single-point incremental forming (SPIF) process. It was suggested that there are various factors responsible for higher strain in the ISF process and hence was concluded that factors like state of contact stress, bending under tension, shear, cyclic straining, and the geometrical inability of the neck to grow due to localised deformation and hydrostatic stress are responsible for higher strains in the ISF

process [5]. Eyckens et al. [66] through finite element modelling demonstrated presence of shear in the direction of tool movement but a little shear in the perpendicular direction. In addition to shear in the tool direction bending under tension (BUT) also plays a role in the enhancement of formability [59]. Sawada et al. [67] performed a numerical study of stretch forming and ISF and found that bending and unbending occur along the meridional line, and shear occurs along the circumferential direction. It was also concluded that necking is induced on the part of the sheet which is in contact with the sheet and stops after the punch surpasses the necking point. Recently, Li et al. [68] used FE model to affirm that the deformation mechanism in ISF is a combination of bending, stretching and shear.

After so much attempt, the underlying deformation mechanism for the process is still not clear due to the evolution of the complex stress state during the process. But it can be said with affirmation that the presence of out-of-plane through-thickness shear stress in addition to in-plane stresses and the presence of bending can be important factors contributing toward enhanced formability in the case of ISF.

### **1.6 Nature of Forces in ISF**

The forces acting in ISF are

- (a) Axial force  $F_z$ : This force acts in the direction along the tool axis as shown in Figure 1.15(a).
- (b) The force in x-y plane acts in the plane of the undeformed sheet and can be resolved into two components: (a) force in the radial direction ( $F_r$ ), and (b) force along the tangential direction ( $F_\theta$ ). The vector diagram of forces appearing during the process is given in Figure 1.15(b) and (c).

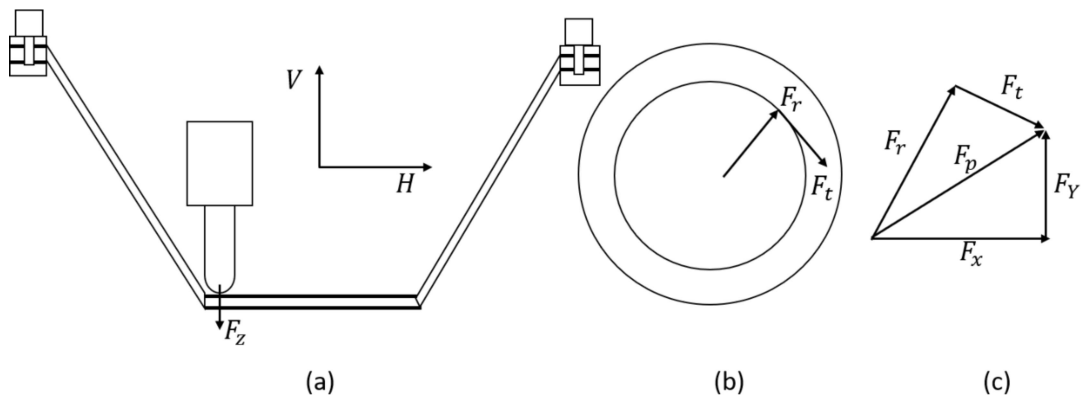


Figure 1.15: (a) Schematic diagram and (b) Vector diagram of forming forces applied in ISF.

The experimental measurement of forces acting during the deformation is done by dynamometer which is attached on the tool. Apart from this, there have been numerous attempts based on different models considering various deformation mechanisms for calculation of forces and other parameters like strain, thickness etc. during the process. Different models and methods used for calculation of forces and other parameters are presented in Figure 1.16.

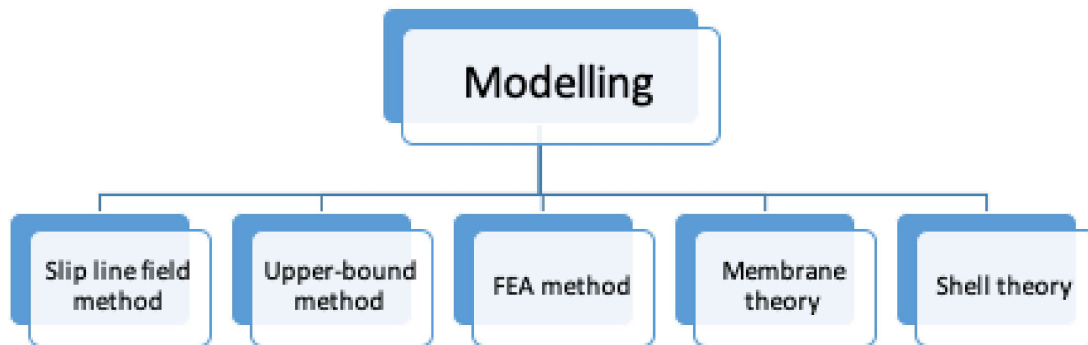


Figure 1.16: Different methods of modelling in ISF.

However, most of these works include development of empirical formulae based on experimental results and developing regression models to calculate average and peak forces appearing during the process. Duflou et al. [69] presented a model based on regression

equations for force prediction during cone forming by SPIF which was a function of step size, wall angle, tool diameter and sheet thickness. Aerens et al. [70] performed a large set of experiments to form empirical relations for the calculation of force components for five different materials AA3033, AA5754, DC01, AISI 304, spring steel 65Cr<sub>2</sub>.

Flores et al. [71] used FEA simulation of SPIF and studied the effects of constitutive laws on force prediction. It was concluded that the selection of constitutive laws plays a vital role in force prediction, as the results were different for elastoplastic laws with isotropic and kinematic hardening. Henrard et al. [72] used FEA simulation to predict the forces for 20° and 60° cones using Lagamine model, first order brick element model for various simulation parameters and inverse method for material data fit. Experiments were also conducted for the validation of results obtained from FE modelling. Jeswiet et al. [73] used a dynamometer based on strain gauge Wheatstone bridges for force measurement for both SPIF and TPIF of 3003-0 Aluminium sheet of thickness 1.21 mm. Similarly, Petek et al. [74] performed ISF on DC01 sheets and studied the influence of wall angle, tool speed, vertical step size, tool diameter, and contact lubrication on the forming forces in ISF. It was concluded that wall angle, vertical step size, and tool diameter affect force requirement for ISF, whereas the tool rotation and lubrication do not significantly influence the force requirement however, these parameters affect the quality of the product formed.

Iseki [75], in his paper, used the equilibrium of the shell element to model bulge height, strain and load during the process. FEA analysis was used for validation of the results of the theoretical model. Silva et al. [76] proposed membrane analysis to consider the friction between the tool and sheet for analysis of the small plastic zone created during forming axis symmetrical shapes in SPIF. It was proposed that the friction stress at the tool-sheet contact can be assumed to be made of a couple of in-plane components viz. meridional

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component ( $\mu_\phi \sigma_t$ ) and circumferential component ( $\mu_\theta \sigma_t$ ). Thickness, meridional and circumferential direction were taken as principle directions as shown in Figure 1.17(a) - (c) and gave the equation for corresponding stresses. The equations obtained are as follows:

$$\sigma_t = -\frac{\sigma_Y t}{(r_{tool}+t)} \quad (1)$$

$$\sigma_\phi = \frac{\sigma_Y r_{tool}}{(r_{tool}+t)} \quad (2)$$

$$\sigma_\theta = \frac{\sigma_Y (r_{tool}-t)}{2 (r_{tool}+t)} \quad (3)$$

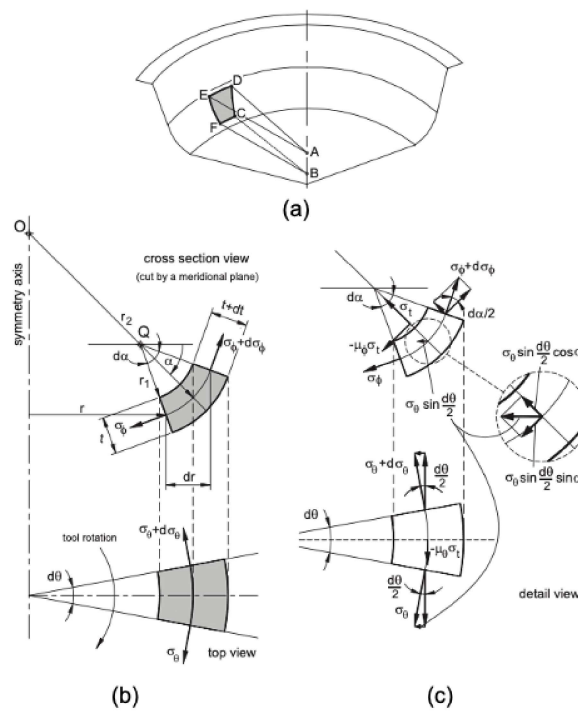


Figure 1.17: Rotational symmetric single point incremental forming: (a) Schematic representation of the shell element in perspective; (b) Schematic representation of the shell element after being cut by an axial meridional plane and as it is seen from the top; (c) Acting stresses.

Bansal et al. [77] used the above equations for force equation for force calculation for single-stage and multi-stage ISF by modelling the contact area and validated obtained results with experiments and the formula given by Duflou et al. [69]. Further, Chang et al. [78] used membrane analysis for analytical modelling of single pass and multi-pass incremental sheet forming process (MPIF). Similarly, Fang et al. [79] did the analytical modelling of the process and validated obtained results with numerical modelling and also studied the fracture behavior of the sheet in ISF. Similarly, Liu et al. [80] modelled the process in 3D polar coordinate system to calculate forming forces using the model and validated the obtained results by experimental results.

From the above literature review, one can say that prediction of forces appearing during the process of ISF is an area of research due to the complex nature of stresses appearing at the sheet-tool interface. However, using different assumptions and models, forming forces can be predicted and hence prediction of forming forces is a matter of further research.

### **1.7 Formability in ISF**

In sheet metal forming operations, the formability achieved is restricted by plastic instability that occurs most likely because of sudden growth of a local neck which leads to the tearing. The analysis of necking in case of perfect and imperfect strip for uniaxial and biaxial stretching is given in Appendix 1.

During uniaxial stretching of the specimen, two phenomena take place: (a) Reduction of cross-sectional area tending to decrease the strength of specimen (b) strain hardening tending to increase the strength of the specimen. At some stage, these two effects balance each other and thus the load in the sheet becomes maximum.

Using Considere's condition [1] for maximum load in a strip, it can be concluded that strain at maximum load is  $\epsilon^* = n$ . This is the condition for onset of diffused neck in a tensile strip. However, in a perfect strip the diffused neck in one region cannot occur as all the strips in a perfect strip behaves identically. Hence, in a real strip an imperfection in form of groove is considered. For a sheet under biaxial stretching of the perfect strip as shown in Figure 1.18(a), when tension is maximum it can be established (Appendix 1) that strains at maximum tensions are related as  $\epsilon_1^* + \epsilon_2^* = n$ . However, the experimental strain at the maximum tension obtained on real strip is found to be coincident with the theoretical strain in the second quadrant only. It is observed that in the 1<sup>st</sup> quadrant where both the principal strains are positive, necking occurs but larger strain than that of maximum tension is obtained in the direction perpendicular to that of major tensile stress as shown in Figure 1.18(b). So a pre-existing imperfection is considered on the sheet in form of a groove as shown in Figure 1.18(c). This was proposed by Marciniak and Kuczyński [81] widely regarded as M-K model. It can be found that the strain in the groove is larger than that in the uniform region of the sheet. If the principal strains in the imperfection, before the onset necking is plotted then it coincides approximately with the actual forming limit curve as shown in Figure 1.18(d).

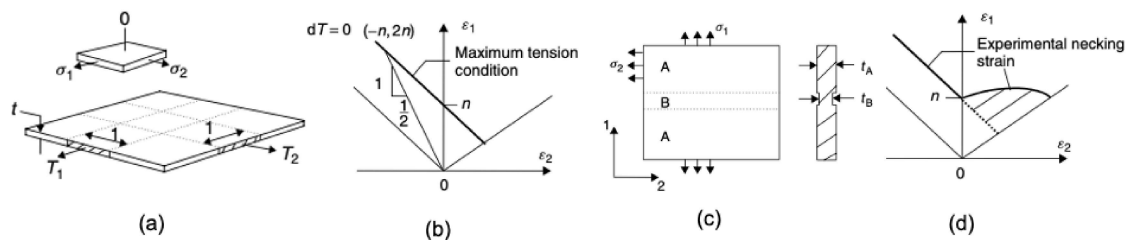


Figure 1.18:(a) Uniform sheet in plane stress process, (b) FLC obtained on perfect sheet,

(c) Sheet with imperfection, and (d) FLC on a sheet with imperfection.

## 1.8 Grid marking methods to plot FLC

FLC is a graph of the major strain ( $\epsilon_1$ ) at the onset of localized necking for all values of the minor strain ( $\epsilon_2$ ), as shown in Figure 1.19(b). Grid marking is one of the commonly used strain measurement methods for strain analysis in sheet metal forming processes due to the relative simplicity. Ozturk et al. [82] presented different methods suitable for grid marking and measurement in order to predict sheet formability. The flow diagram of evaluation of sheet formability is shown in Figure 1.19(a).

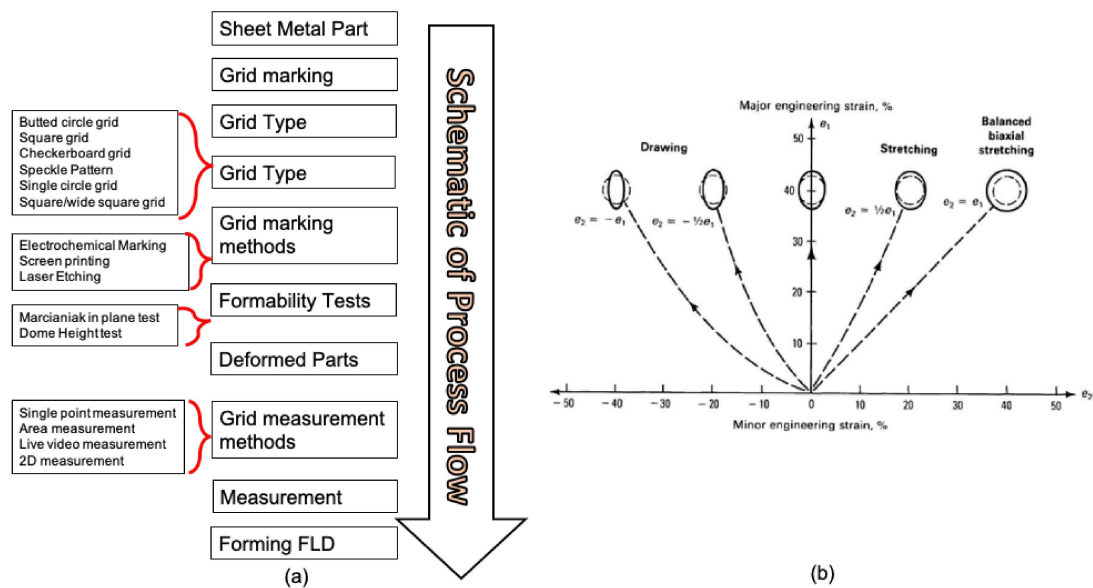


Figure 1.19: (a) Schematic diagram of process of grid marking (b) FLD for various sheet metal forming processes [82].

The forming process causes the line patterns to deform by an amount which depends on the local deformation experienced by the sheet metal [16, 17]. After the sheet metal is formed, the circles will become an ellipse unless deformation is pure biaxial stretching as shown in Figure 1.19(b). The longest dimension of the ellipse is the major axis and the dimension perpendicular to the major axis is called as the minor axis. The utilized grid pattern should be very precise in order to obtain accurate results from the strain analysis. For measurement

of major and minor axes of the final ellipses, different measuring techniques are used as shown in Figure 1.19(b). These include both manual and automated measurement methods. The formability in ISF can be given by maximum formable wall angle in fixed wall angle cone. Steeper wall angle is directly linked to more formability. However, computing forming limit by forming fixed wall angle cone can be time consuming and can cause large material consumption. For the formability analysis, variable wall angle conical frustum (VWACF) and variable wall angle pyramidal frustum (VWAPF) proposed by Hussain et al. [28] can be used. The geometry and details of VWACF and VWAPF are shown in Figure 1.18(a), (b) and (c).

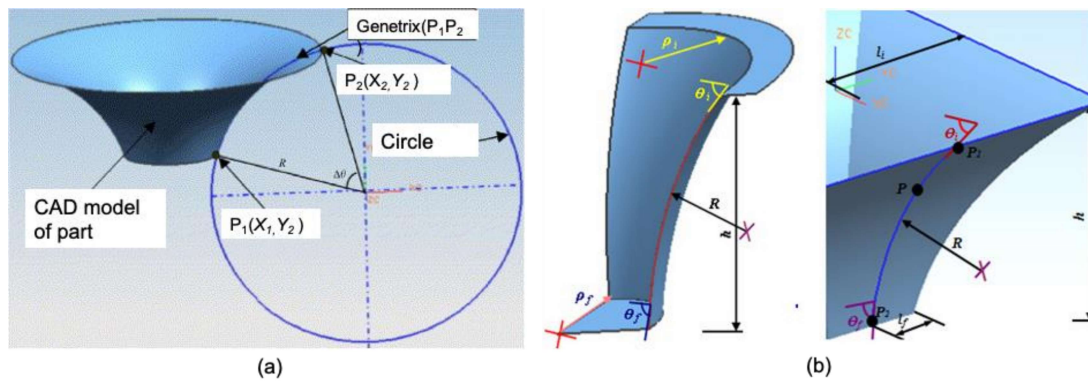


Figure 1.20: Geometries for formability test (a) Genetrix details of VWACF, (b) sectioned view of VWACF, and (c) sectioned view of VWAPF

### 1.9 Factors affecting product quality and forming forces in ISF

There are several factors which affect the extent of the maximum achievable forming angle, forming force and surface finish in the formed cone. As a critical product quality constraint, surface roughness is regarded as a weak point in incremental sheet forming (ISF) due to direct continuous motion of tool over the sheet. McAnulty et al. [83] gave a comprehensive review of process parameters affecting the formability obtained in ISF. The most prominent factors which affect the formability of ISF are:

- (a) Forming tool geometry (b) Step size (c) Spindle speed (d) Forming temperature

Ham and Jeswiet [84] in their work performed ISF on aluminium ally 3003 and concluded that with increasing tool size the maximum forming angle decreases. Smaller forming tips allow concentration of friction heating at the forming tool tip giving rise to increased formability. Additionally, as the tool size is reduced, more forces act on the material to cause deformation since the tool has a smaller surface area. Similar results were obtained by Bhattacharya et al. [85] who also concluded that the surface finish of the formed product decreases with increasing tool diameter. Recently Azpen et al. [86] also demonstrated that tool diameter significantly affects the surface finish of the formed product. Similar results were obtained by Echrif et al. [87] by using Taguchi analysis who demonstrated that tool diameter and vertical step are the most prominent factors affecting the surface finish of the formed cone.

### **1.9.1 Effect of step size**

The effect of step size on the formability of the sheet in ISF is still debatable. Ham and Jeswiet [84], proposed that the step size has little effect on the maximum forming angle. Liu et al. [88] used ISF to fabricate sheet of aluminium alloy 7075-0 and found that increasing step depth can increase formability obtained in ISF. Kim and Park [57] performed ISF on aluminium alloy AA1050-O sheets and concluded that increasing step depth can have negative effect on formability. The same trend was observed by Ham and Jeswiet [84] while performing ISF on AA3003-O and AA5754 where it was found that greater formability was obtained when performing ISF with smaller step depth. The same result was validated by Shanmuganatan and Senthil [89] for Aluminium alloy 3003. Some other researchers also reported that step depth can have a negative impact on formability of products formed on ISF while working on sheet of metals other than Aluminium alloy [74, 90, 91]. It can be concluded that more work needs to be done in order to find out if formability varies monotonically with step depth. It can be a good idea to apply design of

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experiments DOI to optimize the step depth for one's experiments. Hussain et al. [92] examined the impact of several parameters on the formability of AA 2024 sheet and concluded that the formability can change with an increase in step size, depending on the tool radius chosen. In order to improve the sheet's formability, the combination of these two parameters should be selected carefully.

Liu et al. [88] used response surface methodology to study the effect of step depth on surface finish and optimize the surface quality of the product formed. The step depth of 0.39mm was used for optimal surface quality. Zavala et al. [93] plotted SPIFed Stribeck curves for the soybean and corn oils lubricants and concluded that small hydrodynamic span regime changes for an increasing step-size forming process. Xu et al. [94] investigated the impact of various parameters on the internal surface roughness of the manufactured product. A controlling function for roughness of interior surfaces was proposed as  $\frac{d \sin \theta}{2pt}$  (where  $d$  is the tool diameter,  $\theta$  the forming angle,  $p$  is the step size, and  $t$  is the sheet thickness). The AA1060 and Cu/Steel composite materials were used to validate this combination. A factor of  $d/2p$  followed by  $1/t$  is shown to have the highest contribution to the roughening of surfaces in the controlling function for roughness. Additionally, it was recommended to maintain this combination's value low in order to create components with a high level of finish.

It can be concluded that, the effect of step depth on formability and surface finish is still not clear and further work is needed in this direction.

### **1.9.2 Effect of spindle speed**

The tool speed plays a significant role in ISF. As spindle speed increases, the production time in ISF decreases and the process becomes faster, but tool speed also affects the other output parameters in ISF. As spindle speed increases there is friction heating which leads

to softening of the blank and hence the sheet formability increases [95-97]. Ham and Jeswiet [84] in their work on Aluminium alloy 3303 sheet, found increased formability with increasing speed. Xu et al. [94] investigated the mechanism of localized heating due to relative motion at the tool-workpiece interface resulting from tool rotation. A series of experiments were conducted with increasing speed from 0-7000 RPM on AA5052-H32 sheet and it was found that friction is the dominant factor in low tool rotation speed range (0-1000 rpm), whereas in higher speed regions, dynamic recrystallization effects dominate. Due to these reasons, improved formability can be observed when ISF is carried out at higher spindle speeds. Buffa et al. [98] performed ISF at higher speeds on AA1050-O, AA1050-H24, and AA6082-T6 and found better material formability for all materials. However, to exploit the potential of localized heating by tool speed, the ISF needs to be carried out at higher speed. Petek et al. [74] performed ISF on DC01 sheet at relatively lower speeds (0-40 rpm) and found that in this speed range the tool does not significantly affect the formability obtained in ISF. Additionally, tool speed has been also reported to have affected the surface quality of the formed product [99]. Mulay et al. [100] performed high speed ISF of AA5754 H22 and DC04 steel sheet and assessed various parameters such as geometrical accuracy and non-homogenous thickness distribution and process slowness. They further investigated the effect of step depth, forming wall angle and feed rate to assess the ISF feasibility at higher speeds when forming the AA5754-H22 aluminium alloy and DC04 steel and used the optimal combination of the process parameters to obtain better formability. Further Hamilton and Jeswiet [101] studied the effect of high speeds on external non-contact surface roughness (orange peel effect). A model to predict the orange peel effect in SPIF was also provided.

It can be concluded that increasing spindle speed can fasten up the process and can also improve formability. As higher spindle speed induces local heating at tool-sheet interface,

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the formability can be increased but it can also affect the surface quality of the product. The surface quality can get deteriorated while performing ISF at high speeds.

### **1.9.3 Effect of temperature**

The effect of temperature in incremental sheet forming (ISF) is an important parameter that can significantly influence the material behaviour, forming accuracy, surface quality, and production rate of the process. Temperature can significantly affect the material behaviour during the ISF process. Higher temperatures can lead to increased material ductility and reduced flow stress, making the material easier to fabricate and form. This can result in improved formability, reduced forming forces, and lower tool wear. Conversely, lower temperatures can result in increased material strength and reduced ductility, making the material harder to deform and form. This can result in higher forming forces, increased tool wear, and reduced formability.

On the basis of temperature, forming operations can be categorized in three forms.

- (1) Cold forming: In this type of forming operation, forming is done at room temperature.
- (2) Hot Forming: In this type of forming operation, forming is done at temperature above recrystallization temperature which is  $0.6T_m$ , where  $T_m$  is the melting point of the material.
- (3) Warm Forming: In this type of forming operation, forming is done at temperature above room temperature but below recrystallization temperature.

Several works have been carried out to deform sheets in warm and hot conditions. In such processes the setup is provided with an additional heating arrangement to achieve better formability. Duflou et al. [102] developed a laser-assisted ISF machine in which arrangements were made for local heating of the sheet using a 500 W ND-YAG laser. It was discovered that both forming force and spring back were reduced. In addition to these, the residual stress is also found to be reduced in the case of laser-assisted ISF. Similarly, Gottmann et al. [103] used a 10 kW fiber-coupled diode laser emitting laser light coaxially

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aligned with the forming tool, and the deformation was performed with simultaneous heating of the sheet. The sheet of Ti-6Al-4V was deformed at higher temperature, and the final depth was more than that of cold forming. Fan et al. [104] used an electric current heating system to deform magnesium alloy. A maximum formability of 64.3° at a current value of 500 A and at a feed rate of 1000 mm/min was observed. Too low a feed rate causes sheet burning, whereas, at too fast a feed rate, there is not enough time to soften the sheet. It was also found that with a small tool diameter (<6 mm), the heat causes localized burning of the sheet, and with a large tool diameter, heat spreads, and proper heating of the sheet does not occur.

Palumbo and Brandizzi [105] used static heating with high spindle speeds to deform Titanium (Ti) sheets. High spindle speed was found to stabilize the neck. A Ti sheet was deformed at a temperature of 400 °C and was used for manufacturing the car doors. Similarly, Najafabady and Ghaei [106] used hot incremental forming (HISF) to deform the Ti-6Al-4V sheet to a basic conical and pyramidal shape, and observed the effect of different process parameters on the dimensional accuracy, surface quality, and work hardening of the fabricated workpieces. There was a deviation from the ideal geometry, which was found to be maximum at the tip and considerably decreased a few millimetres away from the tip. The roughness of the inner surface, where the tool contacted the workpiece, was greater than that of the outer surface. Micro-hardness showed that the hardness increased from the flange to the vertex of the workpiece, where more considerable plastic deformation, and hence, more work hardening is expected to occur.

Similarly, Al-Obaidi et al. [107] used the setup with induction heating to deform DP 980 sheet, DC04 steel sheet, and 22MnB5 steel to achieve a high degree of deformation. Ambrogio et al. [108] used HISF on AA2024-T3, magnesium alloy AZ31B-O, and titanium Ti6Al4V alloys. The molybdenum disulphide MoS<sub>2</sub> was used as a lubricant in all the

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experiments. An increase in the formability by local heating of the sheet was noticed. As a result, the formability of the aluminium AA2024-T3 increased from  $30^\circ$  to  $60^\circ$ , the final formability of magnesium AZ31B-O was found to be  $40^\circ$ , and the formability of Ti6Al4V rose from  $20^\circ$  to  $45^\circ$ . The surface finish was found to get reduced with the increase in wall angle. Singh et al. [109] used radiation heating to locally heat the AA1050 sheet. A delay in fracture and intensification of the formability with the elevated-temperature incremental forming process compared to that of the incremental forming process at room temperature was observed. Wankhede et al. [110] fabricated an AA2016-T6 sheet at an elevated temperature of  $250^\circ\text{C}$  using a coil for local heating and found a 956% rise in sheet formability. Kumar et al. [111] used radiation heating to perform ISF on CP titanium grade 2 sheet, along with an FE simulation and experimental work were used to investigate the process capabilities of a CP-Ti Grade-2 sheet formed through warm incremental sheet forming (WISF) in terms of thickness distribution, forming forces, geometrical accuracy, and surface roughness. Increased formability, reduced forming forces, and better thickness distribution in the case of ISF at an elevated temperature of  $100^\circ\text{C}$  was reported.

Hot ISF (HISF) has advantages over cold ISF in terms of reduced force and better formability due to reduced flow stress. It can be used for Ti and Mg sheets whose formability at room temperature is less. However, performing ISF at high temperatures has some associated drawbacks; hot ISF requires sophisticated arrangements to be mounted on the ISF setup. Performing ISF at high temperatures can affect the surface qualities of the formed product. While forming sheets of lower strength, it can be helpful to perform Warm ISF to take advantage of both cold and hot ISF. Recently, WISF has been used to exploit its full potential. Ghiotti and Bruschi [112] used WISF to fabricate Mg alloy AZ31B at  $150^\circ$  and  $250^\circ$  and found that fabricated parts had better formability. Azpen et al. [86] used friction stir ISF on 6061-T6 aluminum alloy sheets and concluded that tool diameter

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influences surface roughness. Zhang et al. [112-114] used oil bath heating to perform WISF on the AZ31B sheet. It was found that the most significant factors affecting the formability are forming temperature, step depth, and sheet thickness in decreasing order. Bouhamed et al. [115] also discussed the formability of functionally graded materials formed by single-point incremental forming. Said et al. [116] discussed the numerical simulation and their single-point tool path generation incrementally formed shapes.

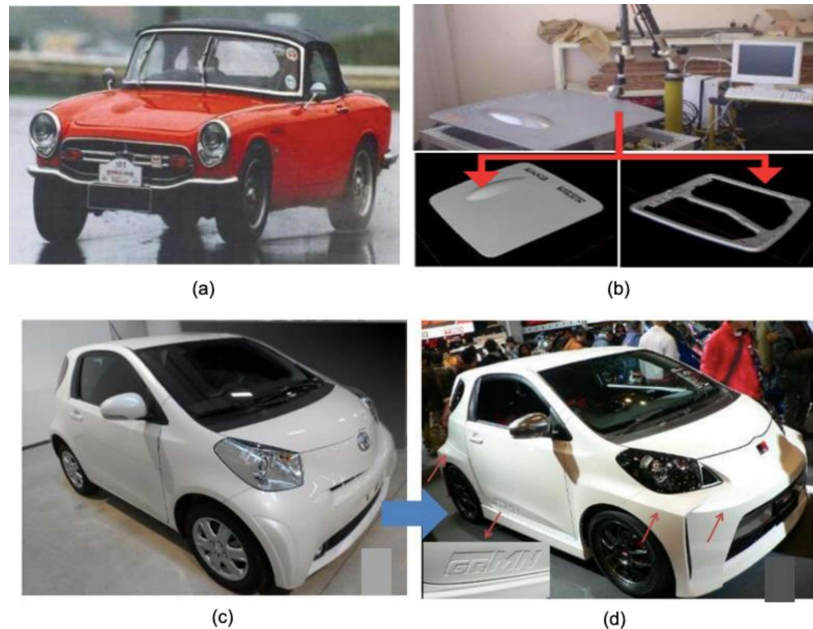
In contrast, tool diameter is a non-significant factor in WISF. The same trend was observed for spring back as well. Recently, Mohanraj et al. [117] performed WISF on magnesium AZ31 and aluminum 6061 alloys and achieved better formability and an exact shape at 300 °C.

Based on above discussion, it can be concluded that forming temperature is one of the most influential parameters in ISF. It can affect the process by reducing the forming force, flow stress and subsequently increasing the formability of the formed product. However, performing ISF at high temperature can adversely affect the surface quality of the formed product and can also decrease the strength of the formed product. Some appropriate heat treatments can be given to restore the mechanical properties in case of HISF and WISF [118].

### **1.10 Applications of ISF**

Iseki et al. [18] reported 1<sup>st</sup> industrial application of ISF, since then, there have been several applications of ISF especially in the field of small batch customized production of sheet metal forming. Especially ISF has been widely adopted in research institutions and prototyping laboratories as a flexible and cost-effective method for creating prototypes and experimental parts. That allows researchers to quickly iterate and test different designs without the need for specialized tooling or high-volume production capabilities. The main areas in which ISF has found industrial application are

(a) Automotive industry: ISF has found applications in the automotive sector for producing various parts, including car body panels, engine covers, and exhaust components. It allows for the production of complex shapes and prototypes without the need of expensive dies, making it suitable for low-volume production and customization. In 2000 Honda Motor Co., Ltd. and Amino Corp. jointly began work to utilize dieless forming as possible production method for automotive replacement panels [119]. The entire car bonnet was formed by ISF process. The old bonnet was taken and was scanned to produce the required tool path to fabricate the new bonnet. The car with bonnet and the scanned part are shown in Figure 1.19 (a) and (b). Similarly, in 2012, Toyota Motor Corporation and Amino Corporation [119] worked together on a project to provide specialty panels to low volume niche vehicles. The purpose to use incremental forming on existing stamped panels to add features or style for special edition vehicle as shown in Figure 1.21 (c) and (d).



*Figure 1.21 Applications of ISF in automotive industry (a) Car with incrementally formed bonnet, (b) scanning of car bonnet, (c) Regular Toyota model, and (d) Limited edition model reshaped with ISF.*

(b) Medical devices: ISF has been used in the production of medical devices and implants, such as prosthetics, orthopaedic components, and surgical instruments. The ability to create patient-specific and complex shapes with minimal tooling makes ISF a suitable technique for manufacturing medical devices. Vanhove et al. [120] produced the laboratory prototype of clavicle implant by ISF as shown in Figure 1.21 (a). Similarly, Eksteen et al. [121] fabricated unicondylar knee arthroplasty implant using ISF as shown 1.21 (b).

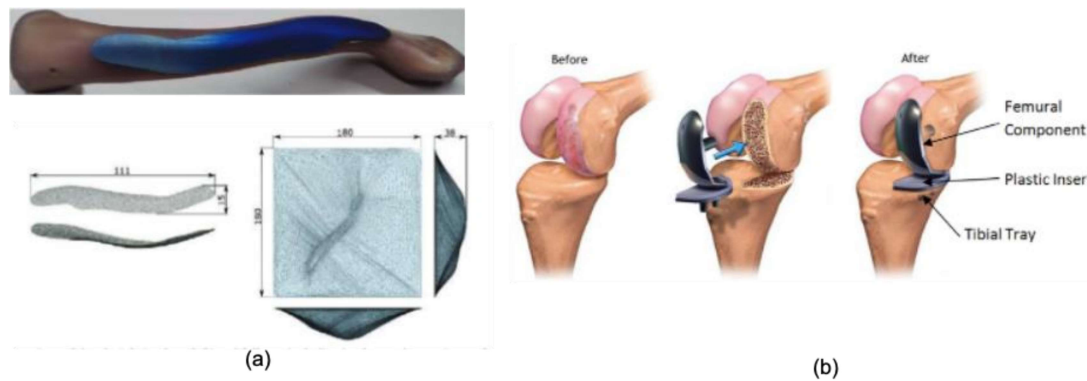


Figure 1.22: (a) Clavicle implant designed by Vanhove et al. [120] and (b) Unicondylar knee Arthroplasty implant using ISF [121].

(b) Aerospace Industry: ISF finds applications in the aerospace sector for manufacturing components of complex geometries, such as turbine blades, engine casings, and aircraft panels. The ability to produce custom-designed parts with reduced lead time and cost makes ISF suitable for aerospace prototyping and small batch production.

### 1.11 ISF with flexible medium support

In the recent past, use of flexible medium such as fluid, rubber pad, metallic foam etc. from the back of the sheet in ISF has been reported by researchers. Better formability and more uniform strain distribution are obtained in comparison with the process not involving any flexible medium from back. Yu et al. [122] used compressed nickel foam support from the

back of the sheet and found that better geometric accuracy can be achieved by using flexible medium of back. One such process is ISF under static fluid pressure from the back, called incremental sheet hydroforming [123]. Hydrostatic pressure does not lead to plastic deformation; however, hydrostatic pressure increases ductility and formability of metals and alloys due to pressure induced ductility [124-126]. Khalifa et al. [127] conducted an experiment using controlled gas pressure from the back and made a concave-convex part. Singh et al. [128] performed ISF on the six-axis industrial robotic arm on an AA6061 sheet under static fluid pressure and found that thickness was more uniform in the case of ISF assisted by static fluid pressure. The same result has been reported by Küçüktürk et al. [129], who found better formability and more uniform thickness distribution in case of ISF under controlled pressure. Kumar et al. [130] used ISF with fluid pressure to produce high-angle cones. Similarly, Shang et al. [131] performed an FEA simulation of the ISF with static pressure for forming high wall angles and validated the same with experimentation.

### **1.12 Summary of literature survey**

It can be concluded from the above literature survey that since its inception, ISF has attracted eyes of researchers and industries due to its high degree of flexibility and low tooling cost. Several studies have been carried out to establish the deformation mechanism of the process. Additionally, several works have been carried out to study the effect of various parameters on outputs of ISF mathematically, numerically, and experimentally. Further, various innovations have been made in ISF to improve process capabilities and ensure better products formed. One such innovation is Incremental sheet forming assisted with hydrostatic fluid pressure from the back of the sheet which is in the purview of this thesis.

### 1.13 The research gaps

Based on literature survey it can be said, that there are following existing gaps in the research areas of ISF.

- Numerous works have been carried out in the area of forming force, there is a lack of comprehensive analytical model to calculate forming forces. In most of the analytical models developed, circumferential, meridional and z-direction have been considered as principal direction which is not necessarily the case.
- Although ISF coupled with static fluid pressure has been promising area to ensure better strain distribution and mechanical properties, very limited work has been done in the area of incremental sheet hydroforming.
- Very limited work has been carried out in the area of Warm ISF for Aluminium Alloys.

### 1.14 Scope and aim of thesis

Based on literature survey and existing research gap, the current work was aimed to achieve following phase wise objectives.

#### 1.14.1 Phase 1: Development of experimental setup

This phase of work was dedicated towards developing experimental working setups for Robot assisted incremental sheet forming (RAISF) and Robot assisted incremental sheet hydroforming (RAISHF). The setup for both the processes was aimed to be developed from scratch, which included establishing 6 axis industrial robotic arm equipped with forming tool, dynamometer and fluid chamber. Design of experiments (DOE) had to be applied for parameters optimization and finally tool path planning had to be generated for fabricating different shapes.

**1.14.2 Phase 2: Analytical and numerical modelling of RAISF**

This phase of current study aimed to generate the analytical and numerical model for RAISF and validated it with experiments performed on the existing setup. The analytical model had to be generated in cylindrical co-ordinate system and numerical model was to be conducted on ABAQUS.

**1.14.3 Phase 3: Final experiments and comparison of various results**

This phase of current study aimed at conducting various experiments for RAISF and RAISHF and comparison of the two processes based on mechanical and metallurgical characterisation techniques. Further, effect of warm RAISF had to be studied.

**1.14.4 Phase 4: Conclusion**

The results obtained in various aspects were concluded in this phase and future scopes of current work were determined.

Development of a setup to carryout various experimental research for RAISF and RAISHF is necessary for innovation and studying the characteristics of a new class of ISF to apply knowledge for industrial application. This is given in the next chapter.

Based on the research gap analysis, the following objectives have been defined for current work.

1. Development of working setup for RAISF and RAISHF.
2. Tool path planning to generate various shapes on the robotic arm
3. Development of Analytical and Numerical model of ISF.
4. Experimentation and comparison of RAISF and RAISHF.
5. Comparison of RAISHF with conventional forming by Limiting Dome Height test.
6. Comparison of Cold RAISF and warm RAISF.

