CHAPTER 1

INTRODUCTION

1.1 SHEET METAL FORMING

Modern continuous rolling mills produce large quantities of thin sheet metal at low cost. If the sheet is thin, it is generally coiled after rolling; if thick, it is available as flat sheets or plates, which may have been decoild and flattened. A substantial fraction of all metals is produced as thin hot-rolled strip or cold-rolled sheet; this is then formed through secondary processes into automobiles, domestic appliances, building products, aircraft, food and drink cans and a host of other familiar products. Sheet metals parts have the advantage of high elastic modulus and high yield strength so that the parts produced can be stiff and have a good strength-to-weight ratio. (Marciniak et al 2002).

Sheet metal forming involves work pieces with a high ratio of surface area to thickness. The materials used in boilers, bridges, ships and nuclear power plants are sheet metals, since they have smaller ratios of surface area to thickness (Kalpakjian & Schmid 2007). There are wide varieties of sheet forming processes available to manufacturing industries. Each process has specific characteristics and uses different types of hard tools and dies as well as soft tooling such as rubber. The sources of energy typically involve mechanical means, but also include various other sources of energy, such as hydraulic, magnetic and explosive. Press working or stamping is the most important metal working process.
The products made by sheet-forming processes include a large variety of shapes and sizes, ranging from simple bends to double curvatures with shallow or deep recesses. Before a part is formed, a blank of suitable dimensions is first cut or removed from a large sheet. The removal is usually done by a shearing process; however, there are several other methods for cutting sheet and plates. Laser cutting has become an important process and is used with computer controlled equipment to cut consistently a variety of shapes.

Forming of sheet metals is generally carried out by tensile forces in the plane of sheet; otherwise, the application of compressive forces could lead to buckling, folding and wrinkling of the sheet. In bulk deformation processes such as forging, rolling, extrusion and wire drawing, the thickness or the lateral dimensions of the workpiece are intentionally change, whereas in most sheet-forming processes, any change in thickness is due to stretching of the sheet under tensile stresses. As the mechanics of all sheet forming basically consists of the processes of stretching and bending, certain factors significantly influence the overall operation (Henry E Theis 1999). The major factors are elongation, yield point elongation, anisotropy, grain size, residual stresses, spring back and wrinkling (Paul DeGarmo et al 2003).

In recent times, the need for achieving intricate shapes through metal forming at low costs is ever growing fast. Necessity to use new materials, demanding functional requirements and miniaturization have led to evolution of modern manufacturing processes (Velayudham, A 2007). Improvement of the existing metal forming processes becomes imperative for accomplishment of complex shapes at reduced cost.
1.2 CLASSIFICATION OF METAL FORMING PROCESSES

Metal forming is the technology used for shaping metal (alloys) into useful products. It encompasses a wide variety of techniques, which make use of suitable force, pressure or stresses, like compression, tension and shear or their combination to cause a permanent deformation of the raw material to the required shape. These processes are also known as mechanical working processes and are mainly classified into two major categories i.e., hot working processes and cold working processes. In these processes, no material is removed; however, it is deformed and displaced using suitable stresses into different shapes. Cold forming can be defined as the plastic deforming of metals and alloys under conditions of temperature and strain rate. (Sharma 2005, Nagendra Parashar 2006, Prakash Dixit & Uday Dixit 2008). Some of the cold working processes are: (1) Cold forging, (2) Cold rolling, (3) Cold heading, (4) Cold drawing, (5) Wire drawing, (6) Stretch forming, (7) Sheet metal working processes such as piercing, punching, lancing, notching, coining, squeezing, deep drawing, bending etc (Roy Lindberg et al 2009). Figure 1.1 shows the various types of metal forming process.

Figure 1.1 Various types of metal forming

Some of the major metals forming processes are discussed below.
1.2.1 Roll Forming

Roll forming is a continuous bending operation in which a long strip of sheet metal is passed through sets of rolls mounted on consecutive stands, each set performing only an incremental part of the bend, until the desired cross-section of the profile is obtained. Roll forming is ideal for producing parts with considerable lengths and complex shapes having constant cross-sections. It provides good surface finish and has high production rates. Figure 1.2 shows the roll forming operation.

![Figure 1.2 Roll forming operation](image)

1.2.2 Stretch Forming

Stretch forming is the shaping of a sheet or part, usually of uniform cross section, through application of suitable tension or stretching and subsequently forming the sheet around or over a die of the desired shape. This process is suitable for large sheet metal parts with shallow contours in limited numbers of quantity. It has high labour stretch and the tooling costs which depend on part size. Figure 1.3 shows the stretch forming operation.
Since most of the deformation is induced by tensile stretching, the forces on the tool are relatively less than those encountered in bending or forming. Consequently the spring back is less and the workpiece conforms closely to the shape of forming tool. Since the stretching invariably creates bending or wrapping over forming tool, wrinkles are pulled out before they occur. This process is quite popular in aircraft industries.

1.2.3 Drawing

Drawing is a metalworking process which uses invariably tensile forces to stretch the metal. It can be classified as sheet metal drawing wire, bar, and tube drawing. It is suitable for shallow or deep parts with relatively simple shapes. In deep drawing a flat sheet metal blank is formed into a cylindrical or box-shaped part by means of a punch that presses the blank into the die cavity. Figure 1.4 shows the deep drawing operation.
1.2.4 Stamping

Metal stamping is the process of placing a flat sheet metal in a stamping press where a tool and die surface forms the metal into a net shape. It includes a variety of operations, such as punching, blanking, embossing, bending, flanging, and coining. Simple or complex shapes can be formed at high production rates.

1.2.5 Punching

Punching is a metal forming process that uses a punch press to force a tool, called punch, through the workpiece to create a hole by means of shearing. The punch often passes through the work into a die. Figure 1.5 shows the punching operation.

![Figure 1.5 Punching operation](Kalpakjian & Schmid 2007)

1.2.6 Rubber-pad Forming

Rubber pad forming (RPF) is a metalworking process where sheet metal is pressed between a die and a rubber block, normally made of polyurethane. Under pressure, the rubber and sheet metal are driven into the die and conform to its shape, forming the part. The rubber pads can have a
general purpose shape, like a membrane. Figure 1.6 shows the rubber-pad forming operation.

![Rubber-pad forming](image)

**Figure 1.6 Rubber-pad forming** (Kalpakjian & Schmid 2007)

### 1.2.7 Superplastic Forming

Superplastic forming is a metalworking process based upon the principle of superplasticity. By producing sheet material with ultrafine-grain size performing deformation at low strain rates and elevated temperatures, higher elongation can be retained. The superplastic alloy should possess ultrafine, equiaxed and stable grains of size approximately between 10 and 20 μm. In this process, the material can elongate beyond 100 percent of its original size and produce essentially neck-free elongations in metallic materials. This superplastic behavior can be made to form the material into large complex-shaped products with corresponding converts. Superplastic forming requires two components: a superplastic alloy as well as a special, high temperature, relatively low strain rate forming process. During the forming process the metal gets plastically deformed into the desired shape as the stress crosses the elastic limit. Figure 1.7 shows the superplastic operation.
(a) heating and clamping   (b) hot drawing stage   (c) gas forming stage

**Figure 1.7(a-c) Superplastic forming process** (Kalpakjian & Schmid 2007)

### 1.2.8 Explosive Forming

Explosive forming is a high energy metal forming process in which an explosive charge is used to induce the deformation (Taylan 2012). Figure 1.8 shows the explosive forming operation.

**Figure 1.8 Explosive forming operation** (Kalpakjian & Schmid 2007)

It can be used on materials for which a press setup would be prohibitively large or require an unreasonably high pressure, and is generally much cheaper than building a large enough and sufficiently high-pressure press; on the other hand, it is unavoidably a batch process, producing one product at a time and with a long setup time.
1.2.9 Magnetic-pulse Forming

Electromagnetic forming (magneto forming) is a type of high velocity, cold forming process. This method is useful to form the electrically conductive metals, most commonly copper and aluminium. The workpiece is reshaped by high intensity pulsed magnetic fields that induce a current in the workpiece and a corresponding repulsive magnetic field. The workpiece can be reshaped without any contact from a tool. This technique is sometimes called high velocity forming or electromagnetic pulse technology. Figure 1.9 shows the magnetic-pulse forming operation.

![Figure 1.9 Magnetic-pulse forming operation](Kalpakjian & Schmid 2007)

1.2.10 Electro-Hydraulic Forming

Electro-hydraulic forming is a type of metal forming in which an electric arc discharge in liquid is used to convert electrical energy into mechanical energy and change the shape of the workpiece. A capacitor bank delivers a pulse of high current across two electrodes, which are positioned a short distance apart while submerged in a fluid (water or oil). The electric arc discharge rapidly vaporizes the surrounding fluid creating a shock wave. The workpiece, which is kept in contact with the fluid, is deformed into an evacuated die. Figure 1.10 shows the Electrohydraulic forming operation.
1.2.11 Hydro Forming

Hydroforming is a specialized type of die forming that uses a high pressure hydraulic fluid to press a working material into a die at room temperature. Figure 1.11 shows the hydro forming operation.

**Figure 1.11 Hydro forming operation** (www.jmpforming.com/hydroforming)
Hydroforming requires placing a sheet inside a negative mold that has the shape of the desired result. High pressure hydraulic pumps then inject the fluid at very high pressure inside the sheet which causes it to expand until it matches the mold. The hydroformed sheet is then removed from the mold. Hydroforming allows forming of complex shapes with concavities, which would be difficult or impossible with standard solid die stamping. Hydroformed parts can often be made with a higher stiffness-to-weight ratio and at a lower unit cost than traditional stamped or stamped and welded parts. Virtually all metals which are capable of cold forming can be hydroformed, including aluminum, brass, carbon and stainless steel, copper, and high strength alloys.

1.3 SHEET METAL FORMING PROCESSES WITH INCREMENTAL APPROACH

There are many different processes in metal forming that use an incremental approach. With this approach, the deformation of the material is carried out incrementally and as a consequence, less forming loads are required as compared to the conventional processes. Some of these processes worked as the basis of SPIF. With this in mind, it follows a short overview of sheet incremental forming technologies (João Luís Padrão 2009).

1.3.1 Hammering

One of the oldest processes in sheet incremental forming is hammering. This process was initially done manually but, with technological developments, it can be done in a modern CNC. During hammering the tool moves and punches the sheet, clamped in a support frame, in circular trajectories descending step by step in each round. Figure 1.12 shows the hammering operation.
1.3.2 Multi-Point Forming (MPF)

The production of a panel by Multi-point Forming (MPF) technology is very similar to the forming process with solid dies. The MPF technology replaces the solid die by a matrix of several punches with specific geometry that are adjustable in height by means of linear actuators (Li et al 1999, Li et al 2002) in order to be able to change to diverse kind of shapes in a relative short period of time. Figure 1.13 shows the multi-point forming operation.
1.3.3 Shot Peen Forming

Shot Peen Forming is a die-less process performed at room temperature (Figure 1.14), whereby small round steel shot impacts the surface of the work piece. Every piece of shot acts as a tiny peening hammer, producing elastic stretching of the upper surface and local plastic deformation that manifests itself as a residual compressive stress. The combination of elastic stretching and compressive stress generation causes the material to develop a compound, convex curvature on the peened side. The shot peen forming process is ideal for forming large panel shapes where the bend radii are reasonably large and without abrupt changes in contour and is widely used in aircraft industry.

![Figure 1.14 Shot peen forming](www.metalimprovement.co.uk)

1.3.4 Laser Forming Process

Laser Forming Process, is based on thermal stresses that are induced on the blank (clamped in a structure) by laser irradiation on the sheet metal (Duflou 2007, 2008). The thermal stresses induce plastic strains resulting in bending or buckling of the material. This process can also be used to make repairs or modifications in sheet metal components (Geiger et al 1993, 1994. The costs of the forming stand, the need of qualified personnel,
the high energy consuming, the need of personal safety protection equipments and the need (sometimes) of pre-coating of the metal sheet in order to enhance the absorptive coupling are the main disadvantages of this process. Figure 1.15 shows the laser forming operation.

![Figure 1.15 Laser Forming](www.keytometals.com)

1.3.5 Water Jet Forming

Water jet forming is similar to laser forming, replacing the laser by a water jet as shown in Figure 1.16. The major advantages are higher flexibility, better surface integrity, smaller tooling requirements, lower equipment costs and lesser environmental impact. In the other hand, water jet forming is less accurate, consumes more energy and takes more time than the other incremental metal forming processes.
1.3.6 Spinning

Metal spinning, also known as spin forming or spinning, is a metalworking process by which a disc or tube of metal is rotated at high speed and formed into an axially symmetric part. Spinning can be performed by hand or by a CNC lathe and the parts have a good surface finish. Figure 1.17 shows the spinning operation. In Conventional Spinning (Figure 1.17 a) axisymmetric parts are gradually formed over a mandrel using a rounded tool or roller. The tool applies a localized pressure to deform the blank by axial and radial motions over the surface of the part. The tool can be actuated manually or mechanically actuated and its tool production costs are low being suitable for producing small series because usually involves a sequence of steps. Shear Spinning (Figure 1.17 b) is quite similar to Conventional Spinning and the difference is the action which is stretching instead of bending.
1.3.7 Incremental Sheet Forming Process (ISFP)

Matsubara (1994) has developed the Incremental backward bulge process, where the blank is clamped in a rig that allows downward movement, the blank center is supported by a support post and the forming tool controlled by CNC. The rotation movement that describes the trajectories needed to obtain the desired part is shown in Figure 1.18. This process allows the production of symmetrical and non-symmetrical shapes.

In Stretch Expanding, as in Spinning, only rotational symmetrical shapes can be formed, although, in this case, the deformation is done through
the relative rotation of the blank (along with the rotational head) and the tool without using a mandrel, as shown in Figure 1.19.

![Diagram of Incremental Stretch Expanding Process](image)

1.19 Incremental stretch expanding process (Matsubara 1994)

The ISMF processes can be further divided into three different classifications: The Single Point Incremental Forming (SPIF), the Incremental Forming with Counter Tool and the Two point Incremental Forming (TPIF).

1.4 SINGLE POINT INCREMENTAL FORMING

Incremental sheet metal forming is a promising flexible process in which 3D shapes are formed from sheet metal using a simple rotating tool moving along the correctly defined path on the surface of the sheet by a progression of localized plastic deformations (Rajiv Malhotra et al 2012). The process is flexible as specialized tooling such as dies are not required. Incremental sheet forming is accepted as a significant forming process over conventional forming process such as deep drawing and stamping for small batch production.

Single Point Incremental Forming (SPIF) gives a new important contribution to incremental forming processes like spinning and stretch expanding as it is capable of manufacturing non-axisymmetric parts. The form describes the contour of the desired geometry controlled by a regular CNC machine as shown in Figure 1.20.
1.5 DIFFERENCE BETWEEN CONVENTIONAL AND INCREMENTAL SHEET METAL FORMING

In early days, different shapes were formed on sheet metal as per the customer requirements using minimal tooling. Due to the flexibility of sheet metal forming, the process has acquired worldwide interest for the researchers and industries. Most manufacturing industries develop prototypes prior to the development of a new product or improvement of an existing one. The prototypes are essential as they allow a preliminary evaluation of the product during the design stage, and also a reduction in the product development time. Generally automotive industries need to form about 40-50 critical panels for each model of a car (Figure 1.21). This requires at least 150-200 dies for stamping process. Thus, a huge amount of work is involved in the prototype manufacturing process.
Moreover the tryouts in the course of manufacture of die and scaled models for testing, progresses at a much slower rate, depending heavily on trial-and-error method and the experience of skilled workers. This consumes a lot of time in addition to the high cost of dies during prototyping and parts manufacturing using conventional processes. Increasing competition demands productivity improvements and reduction of manufacturing cost as well as product-cycle reduction.

Facing up to these requires, the manufacturing companies to adopt a new environment which requires more flexible operations to satisfy different market segments. Consequently, innovation of shorter production cycles combined with a significant reduction in development times is necessitated.

Incremental sheet forming technology (ISF) using CNC machine has made inroads into conventional technology with the aim of reducing the
investment costs and lead-time of tooling development. The major advantage of ISF technology is represented by the possibility of manufacture sheet parts (both metal and polymer sheet) which is difficult to form with traditional processes in a rapid and economic way without expensive dies and long set-up times. In IF, the tooling is usually a simple frame for the sheet metal clamping, while the deformation is realized by using a tool that is moved along a predefined path by a CNC machine or a robot. Although the process can be rather slow in comparison to the traditional processes, the IF process for sheet materials represents the best way to manufacture prototypes and complex components produced in small batches for aeronautical, automotive and medical applications (Charles et al 1997). During prototyping, these parts are currently formed using conventional dies which prove costly during their design and fabrication (Attanasioa 2008, Joost Duflou 2007). This can be avoided by using Incremental Forming, a recently developing die less sheet metal part production technique (Kopac 2005).

Incremental forming has been successfully applied to form a variety of simple shapes, though unresolved issues still exist in aluminum alloys (Ambrogio et al 2007, Mori et al 1996, Capece Minutolo et al 2007, Micari et al 2007) magnesium alloys (Ji & Park 2008) and pure titanium sheets (Hussain 2008). The process though requires precise digital computer aided design that represents the part to be manufactured involves low manual work. Thus the repeatability of the process is very good.

1.6 ELEMENTS OF INCREMENTAL FORMING

The incremental sheet metal forming technology uses the computer numerically controlled generic tool stylus to produce a 3D shape from the flat sheet metal. Through this approach a new product can be transformed from CAD modeling and with careful tool path programming to finish the product to finish the part (Figure 1.22) within a short span of time. While commercial
CAM software can be used for tool path generation, they are designed to generate tool paths for machining applications and are unable to meet the SPIF specific requirements. Hence they cannot be used to automatically generate 3D spiral tool paths with constraints on geometric accuracy and surface finish. The tool path designer thus has two options in either specifying arbitrarily small incremental depths, which may increase the forming time, or perform a number of trials with different incremental depths based on experience to obtain the desired geometric accuracy and surface finish with the least possible forming time (Rajiv Malhotra et al 2010). The basic elements of Incremental Sheet Metal Forming (ISF) system include developing a part model, generating the NC code, fixing sheet metal on the fixture in conventional CNC machine and performing the ISF process.

**Figure 1.22 Steps of incremental forming process**

The process involves the use of a single hemispherical end tool to carry out progressively the local deformation on the sheet metal with three-axis CNC machine (or more axis CNC machine), the sum total of the local
deformations giving the sheet its final shape (Michael Beltran et al 2013). The movement of the forming tool based on NC technology is generated from normal CAM system. The absence of dies or special tools makes the ISF process more attractive, which reduce the lead times, causing higher flexibility and lower cost for small batch production applications. However, for complex products, a simple support is needed to reinforce the stability of the system.

1.7 INCREMENTAL FORMING PROCESS

Incremental forming is a die-less sheet metal part production technique in which the necessary part is obtained by gradually tracing its contours on a sheet of required thickness using progressive increment tool indents.

Initially, the sheet is clamped to a simple fixture using clamps on both sides and tightened with nuts and bolts. The edges of the sheet blank remain usually fixed in the horizontal plane. A computer numerically controlled tool path is developed based on the layered manufacturing principle, where the required shape is divided into horizontal slices. The process is usually performed on a vertical CNC milling machine. A spherical shaped forming tool is moved downwards along the developed CNC controlled tool path till it contacts the sheet. Then the tool indents the sheet, following the contour of the desired part. The next contour is drawn by further indentation of the tool on the sheet metal, until the full part is formed. Thus the sheet metal part is formed in a stepwise fashion by a computer numerically controlled (CNC) rotating spherical tool without the need for a supporting die. The process as described above is shown in Figure 1.23.
1.8 TYPES OF INCREMENTAL FORMING PROCESS

The two types of incremental forming techniques used are shown in Figure 1.24. Incremental sheet forming may be classified based on the forming method, the part geometry, the forming path and tool path strategy, the type of tool used, etc. However the typical classification is made with respect to the forming method namely, single-point, two-point and hybrid processes.
Single-point incremental forming (SPIF) is also called as negative incremental forming. In this process the blank is formed into final shape without the aid of any counter tool or the dies.

The two-point incremental forming (TPIF) is also termed as positive incremental forming that requires either dies or counter tools to transform the sheet metal into the required product. Negative Incremental Forming is the most preferable incremental forming technique as it is more accurate and flexible.

1.9 CHARACTERISTICS OF INCREMENTAL FORMING

Incremental forming process is characterized by

(i) Increased material formability and process mechanics is characterized by a small localized plastic zone that is limited to a small area between tool and work.

(ii) Deformation is close to plane strain into almost pure stretching.

(iii) Use of solid small size forming tool.

(iv) Sheet metal forming process invariably used for light gauge metals.

(v) Does not use large expensive dedicated dies.

(vi) Forming tool having continuous contact with the sheet metal.

(vii) Tool moves in 3D spaces is controlled through the CNC programme to induce localized deformation.

(viii) Yet, a significant impediment in the industrial adoption of this process is the accurate prediction of fracture during the forming process. (Rajiv Malhotra et al 2012).
1.10 INCREMENTAL FORMING PROCESS PARAMETERS

Some of the major controlling process parameters of incremental sheet metal forming are:

- **Sheet thickness**: The thickness of the sheet is an important input parameter during incremental forming. Thinner sheet is invariably used in incremental forming as the amount of force required is less.

- **Tool radius**: The radius of the hemispherical and of the tool is vital as it plays a major role in the roughness of the formed surface.

- **Speed of the tool**: The rotational speed of the tool during incremental forming affects the quality of the formed surface as it influences both hardness and roughness.

- **Feed of the tool**: The tool feed also influences the hardness and the roughness of the formed surface.

- **Step Depth**: The incremental step depth for incremental forming influences the final shape of the part without defects like tearing, wrinkling etc.

1.11 TOOL PATH STRATEGIES IN INCREMENTAL FORMING

The performance of incremental forming can be done through the use of various methods to generate the tool paths using the CAM system (Sanjay Jadhav 2004). Each generated tool paths has their own characteristics. The surface finish, forming time, etc. of the formed shape depends on the type of the tool path selected.
1.11.1 Unidirectional Profile Tool Path

The forming tool starts at any point on the outer edge of the part to be formed. It then moves in the same horizontal plane till it reaches the initial point, thus completing a cycle as shown in Figure 1.25 (a-b).

![Pyramid shape](https://via.placeholder.com/150)

(a) Pyramid shape (Amar Kumar Behera et al 2013)

![Cone shape](https://via.placeholder.com/150)

(b) Cone shape (Le Van Sy 2009)

**Figure 1.25 (a-b) Unidirectional profile tool path**

The tool then indents down along the profile surface for the specified step depth increment value. After moving to next plane of motion, the tool continues in the same direction as in the previous cycle.
This unidirectional motion of the tool is maintained till the final shape is obtained.

### 1.11.2 Helical Tool Path

Helical tool path is generated with a continuous helical motion, in which the tool starts at a point on the flat outer edge of the component. Instead of reaching the initial point at the end of the first cycle it transits towards the centre by maintaining a gradual helix along with the step depth increment as shown in Figure 1.26. The type of helix generated is based on the shape of the part such as pyramid or cone. The step depth from a point in the cycle to the consecutive point in the next cycle is constant.

![Helical profile tool path](Sanjay Jadhav 2004)

### 1.11.3 Bidirectional Profile Tool Path

The bidirectional tool path is used for the removal of the twisting tendency obtained in the unidirectional and helical tool paths. The operation in this tool path is similar to the unidirectional tool path. However in this case, once the tool completes a cycle, it starts moving in the opposite direction for the next cycle. The forming is completed by the combination of two directional motion of tool.
1.11.4 Tool Paths as per the Deformation Patterns

The parts achieved after incremental forming sometimes does not accurately match with the desired shapes. This occurs due to the deviations from the intended tool path owing to the factors such as sheet spring back, twisting, etc. The geometrical inaccuracies resulting from the tool path deviations can be rectified by realigning the tool path. The observed deviation governs the type of realignment of the tool path. If a convex shape deviation is observed on the formed shape, it is suitably compensated by a concave realignment in the tool path using CAD models and vice versa.

1.12 THE MECHANICS OF INCREMENAL SHEET FORMING

Incremental sheet forming allows sheet metal to be stretched much further than in conventional stamping operations, well beyond the common Forming Limit Curve (FLC) (Iseki et al 2001). The mechanics of the deformation of incremental sheet forming influences the forming limits that can be achieved and it is vital when designing the experimental setup and finite element models of the process (Figure 1.27).

Often, the enhanced formability is simply attributed to the localized character of the deformation. However any metal that is continuously being deformed will finally fail. The continuous deformation creates more and more dislocations that move through the material, interact with each other and create voids that finally result in a crack. Forming processes operating largely in tension like conventional stamping can also be limited by another phenomenon: instabilities.
Instabilities do create a situation that the deformation gets concentrated into a small region (the neck) with the result that the remainder of the product does not deform any further. This limits the amount of deformation that can be generated in a practical forming operation, the limit is conveniently called the necking limit. Because of the small size of the neck, even small extra displacements will generate large additional strains and the material will soon reach the fracture limit and fail. The experience is that, for most ductile metals, the necking limit is much lower than the fracture limit. Hence the formability of a material in a forming operation can be increased significantly if one is able to get rid of the instabilities. The system used in incremental sheet forming and the tool movement are shown in the Figure 1.28 and 1.29.

Incremental sheet forming as a practical sheet metal forming process, works if the deformation is localized into a small zone and, within that zone a special situation exists that suppresses or retards necking. At the same time, outside that zone the situation must be such that if a neck that is generated inside the zone it will not grow. This effect of stabilization can be
achieved in two ways: the stress at the location of the neck is reduced to below the level that is required for further growth, or the situation at the originated neck is changed such that the stress needed to develop the neck any further is raised above the level of local stress. The latter phenomenon requires reversibility of the effect of the mechanism that causes localized deformation.

Figure 1.28 System used in incremental sheet forming (William & Rodbert 2011)

Measurements and numerical simulations of SPIF have shown that, for a tool path along straight or gently curved sides, the material does not move significantly in the original plane of the undeformed sheet, but moves mainly normal to this plane. Hence, strains on the surface of the sheet are zero or negligible parallel to the tool direction and positive perpendicular to the
tool direction, and these directions correspond to the minor and major directions of surface strain, respectively (Kathryn & Allwood 2009).

The deformation mechanism has sometimes been described as plane-stress, i.e. analogous to that of pressing and, on some other occasions, had been described as pure shear in the plane normal to the direction of tool travel, i.e. analogous to shear spinning. Idealized deformation mechanism of pure shear has sometimes been associated with single point incremental forming. During incremental forming a fundamental study of material characterization, forming limit diagrams, development of suitable tool path strategies and development of optimal machine configurations needs to be carried out. It has been experimentally verified that the process follows the sine law \((t_f = t_i \sin \alpha)\).

In terms of stability, a simple shear would completely avoid necking, because no tensile force is applied in the plane of the sheet. However of more relevance is shear superposed on stretching of the sheet. An additional shear stress will lower the yield stress in tension. If a sheet is stretched to a level just below the flow stress, even a relatively small additional shear stress may be sufficient to start plastic deformation. This shows that an additional shear stress is capable to localize deformation. If the shear stress is caused by a tangential displacement, e.g. by tool movement, the shear stress cannot be sustained if a neck starts to grow. Without a shear stress, the in-plane yield stress increases again and the deformation mechanism is stable until the in-plane stress is high enough to deform the sheet plastically even without additional shear stress. The result of this stabilizing effect is that it raises the necking limit; the latter defined as the length strain at the onset of necking. This has been shown by Allowood in an elaborate analysis (Allwood & Tekkaya 2007).
1.13 ADVANTAGES OF INCREMENTAL FORMING

1. The chief advantage of incremental forming process as compared with the conventional forming techniques is the absence of dies and the ease of flexible process control through CNC programme.
2. The elimination of the dies reduces the tooling cost.
3. The formability is better than in the conventional deep drawing due to the localized deformations in incremental forming.
4. Modification in design can be easily and quickly performed;
5. The forces required for forming are relatively less in the incremental forming process.
6. Good surface finish of the part can be achieved.

1.14 LIMITATIONS OF INCREMENTAL FORMING

1. A major drawback of incremental sheet metal forming process is its relatively long forming time. Consequently, it is feasible in prototype and small batch productions only.
2. The forming of the part at right angles cannot be achieved in this process.
3. Spring back occurs, although it can be minimized using some correction algorithms.
4. Smaller product accuracy, particularly in convex radii and bending edges areas.

1.15 ORGANIZATION OF THE THESIS

This thesis is organized as follows.

Chapter 2 provides a literature review on the need for incremental forming process. In addition it explains the work carried out so far in
incremental forming of different steel alloys. The influence of various parameters during incremental forming is also discussed.

Chapter 3 presents the experimental setup for incremental forming of steel alloys. Fixture and tool fabrication are discussed. The various standards used in the preparation of room temperature tensile specimens are given. The input parameters varied and the outputs monitored are listed.

Chapter 4 provides the aspects of the theoretical and finite element analysis used in incremental forming of steel sheets. The principle of the theoretical element and its analysis aspects using Abacus are described in this chapter. Optimization of process variables using Design Expert is also provided.

Chapter 5 gives the results and discussion in detail. The influences of incremental forming process variables on mechanical and surface properties are given. Investigations on formability and its characteristics during incremental forming of steel sheets are provided. The studies of microstructure of formed specimens are dealt with in this chapter.

Conclusion and scope for future research are presented in Chapter 6.

1.16 SUMMARY

An overview of various sheet metal forming techniques are provided. In this section an outline of incremental forming, various types of tool-paths and the mechanism involved are provided. An overview of the process parameters involved and the advantages, limitations and applications of incremental forming are listed.