INCREMENTAL SHEET FORMING METHOD

Bachelor's thesis

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ABSTRACT

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Subject Robotic Incremental Sheet Forming

Supervisor(s) Jussi Horelli

ABSTRACT

The aim of this thesis was to collect information on a new type of sheet forming method: Incremental Sheet Forming (ISF). This thesis was commissioned by Jussi Horelli, HAMK. The main objective was to examine the feasibility of this ISF method, its working environment and necessary conditions. This thesis briefly introduces the concept of sheet metal along with its various functions or uses and gives an insight to the different types of forming operations. Out of many other incremental forming processes, Single-Point Incremental Forming (SPIF) is mainly emphasized in this thesis, as it is better and more common than other incremental forming processes. All these incremental forming process need a robotic hand and a hammering punch for deformation, so this is also called robotic incremental sheet forming method.

This thesis includes the process of ISF, development of its hammering tool, generating a tool path and influencing factors as well as the parameters. The thesis work was done using literature review and a collection of different information through electronic media and literature published in the field.

Keywords Sheet metal, robotics

Pages 42 pages including appendices 2 pages

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1 INTRODUCTION

Metal has been a versatile substance from the very beginning of its existence. It is used very widely in almost all the fields around the globe. The main reason behind its versatility is the metal forming process, that stretches the metal parts and changes their geometry to meet the desired shape. Metal forming is the backbone of modern manufacturing industry. Millions of tons of metals go through metal forming processes each year, throughout the world. Talking about the GDP of industrialized nations, about 15-20 % of GDP comes from the metal forming industry. Metal forming industry produces a major amount of semi-finished and finished goods. So, it is important to conduct large scale research and development projects on this method, because even a small saving per ton, adds up to significant sums. (Narayanan & Dixit, 2015.)

Though there are different types of metal forming processes, incremental sheet forming process with an industrial robot is innovative and feasible method to comply with today's generation of products. In this modern generation, technologies are being advanced day by day and different types of complex shapes need to be produced. Conventional methods of forming performs quite poorly when producing complex shapes and they require more funds too. On the other hand, robotic incremental sheet forming is built for complex shape forming and as no special die is required in forming different types of shapes, this method requires a low budget too. Robotic Incremental Sheet Forming is a forming process in which sheet metal is moulded step-by-step to a desired shape by a robotic hand when a predefined set of commands is followed by the robot. The word 'incremental' itself means gradual change. So, this might be a slow process, but it is smoother and more flawless process than any other forming method.

2 SHEET METAL

Figure 1 Sheet Metal (Sheet Metal Inspection| Physical Digital®, 2018).

Sheet metal is simply a metal formed into thin and flat pieces by an industrial process. It is generally found in the form of rolled coils or flat plates as shown in Figure 1. Due to the flexibility of sheet metal for being cut and bent into a variety of shapes, it is one of the most commonly used forms in many metal working process globally. Countless objects that we use every day are constructed with sheet metal. (Lodhi & Jain, 2014)

The thickness of sheet metal is generally categorized into two parts. Extremely thin metal pieces are considered as foil or leaf and pieces thicker than 6mm are considered as plate. Many metals such as aluminium, brass, copper, steel, tin, nickel and titanium can be made into sheet metal. Also, expensive metals like gold, silver and platinum are formed for decorative uses. Car bodies, airplane wings, medical tablets, roofs for buildings, various household items and for many other purposes, sheet metals are widely used. There is no doubt that sheet metal plays an important role in the constructional and technological aspect of our modern society. Rather than metals being in their original state, forming them into sheet can make them durable and easy to use in different applications. (Lodhi & Jain, 2014)

2.1 SHEET MANUFACTURING

Figure 2 General view of electric furnace (Stellman, 1998).

Various metals such as aluminium, steel, copper, brass, nickel, tin, sterling, silver and titanium can be formed into sheet metal. The first step is to melt the metal in an electric furnace (Figure 2) along with a container called crucible, regardless of any type of metal. This metal heating process generally requires 8 to 12 hours of intense heat. After the metal is completely melted, it is poured out of the crucible and tipped into an oblong mould. While pouring the mould, one thing must be kept in mind: the liquid metal must be kept hot so it does not begin to harden outside of the mould. After the completion of the cooling process, a rectangular block of solid metal known as an ingot is taken out of the mould. (Miley, 2018.)

The next step is pickling, in which the ingot is dipped into a mixture of chemicals to clean the ingot and remove the impurities. Once the ingot has been cleaned, it is placed in a press that consists of two large rollers that thin out the metal. The press rollers are moved closer and the rolling is done again. This process must be done several times until the ingots forms into a sheet of desired thickness. Also, heating of metal and pickling it up might have to be done several times throughout the rolling process which is called annealing. During this annealing process, metal is only warmed up, it is not melted again. This rolling process toughens the metal, so it cannot easily break and able to withstand more stress. After the sheet of desired thickness is made, it is either shipped flat or rolled into a coil. (Miley, 2018.)

2.2 HISTORY

One of the most important developments during the metal production era, was the invention of sheet metals. No one knows about the exact date, when the sheet metals were first produced and made applicable. But, it is known to us, during the prehistoric time, people used to work with ductile materials like copper, silver and gold, hammering them with stones until desired sheets were attained. These subtle sheets were used for making jewellery items, making household materials, coating the wood shields, fabricating the armour parts and various other purposes. Since Iron needed intense heat and pressure, desired shape and thickness of iron couldn't be attained at that time. (redazione, 2014)

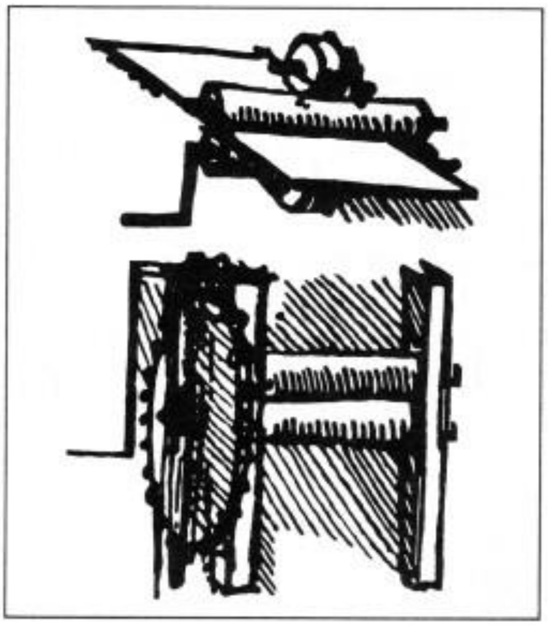


Figure 3 Design of rolling mill by Leonardo da Vinci (redazione, 2014)

The breakthrough occurred when the design of rolling mill was introduced by Leonardo da Vinci during 1485 as illustrated in Figure 3 in one of his designs. In the year 1590, the first rolling mill was invented, and it was the real turning point in the history of sheet metal production. After that other rolling mills also began to originate, with different types of purpose. There were reports of two rolling mills in the sixteenth century that were used to obtain gold sheets for making gold coins and to cut sheets into stripes also. These rolling mills invented during the earlier period were not so advanced that the thickness couldn't be obtained as desired. Later, cold rolling procedure was introduced which allowed variations in thickness with the use of hydraulics. In this process, rather than using heat, pressure would be used instead, so that the produced sheets could be thinner as possible, and the strength and hardness could increase also. The driving force used in the rolling mill evolved; first it was hydraulic wheel, then the steam engine and now the electric motor. While looking through the history, it is observed that the advancement in sheet metal production took place gradually, according to the demand of ages such as lead sheets were highly requested in 1600, rails and semi-finished steel products were needed in 1700 and so on. Changes in this rolling mill technology were made according to the demand of ages and now we have now varieties of advanced sheet producing technology. So, while giving credit for the invention of sheet producing technology, it cannot be given to a single inventor, but can be considered as a fruit of dozens of continuous improvements that have led it to be the most used process in metal working. (redazione, 2014)

3 SHEET METAL OPERATIONS

Sheet metal is very common in the metal working industry because of its flexibility of being bent and cut into different shapes and sizes. As seen on Figure 4, there are various types of operations that can be done on sheet metal to generate desired shape and sizes. Before carrying out these operations, we must consider whether sheet metal can withstand the deforming force applied on it without failure. Usually, sheet metal can be found as flat rectangular sheets of standard sizes or thin and longer sheets in the form of roll. So, to perform the sheet metal operations, the first step is to cut the correct shape and sized blank from a larger sheet. Generally, sheet metal operations can be divided into two categories: Shearing operations and Forming operations.

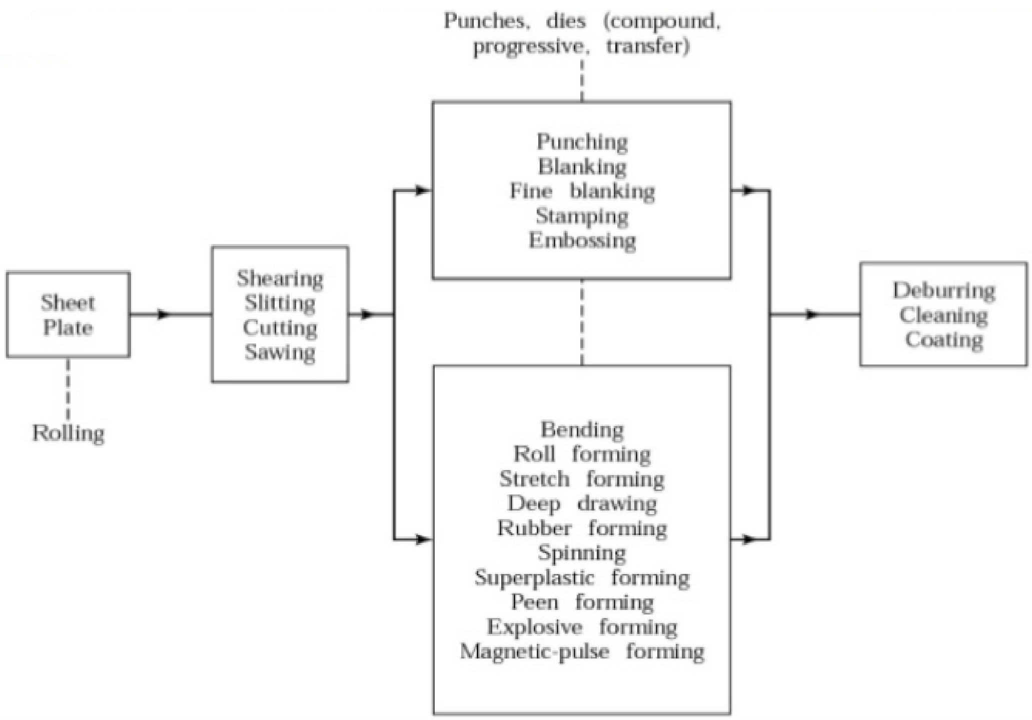


Figure 4 Diagram categorizing different sheet metal operations (GATE Mechanical notes for Punching Operation, 2018).

3.1 SHEARING OPERATIONS

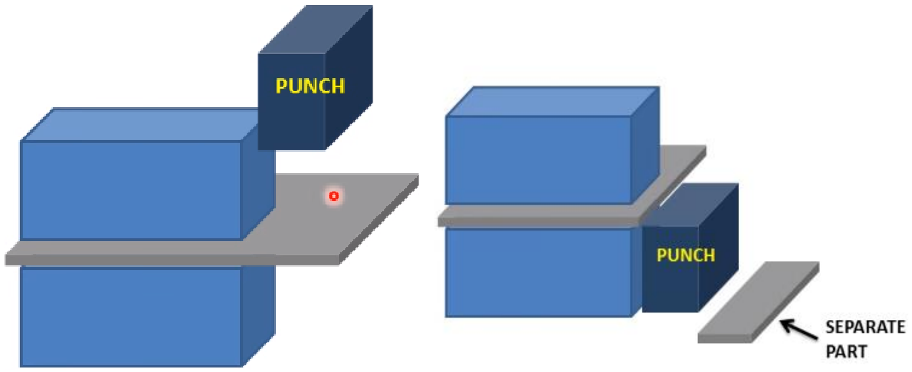


Figure 5 Shearing of Sheet metal (Sheet metal operations - part-1 ! learn and grow, 2018).

Shearing means separating material into two parts. As shown in the Figure 5, the sheet metal is pressed tightly between the dies leaving aside the part that needs to be sheared. Then the punch presses with a force greater than ultimate shear strength of the metal and cuts away the desired part.

3.1.1 BLANKING

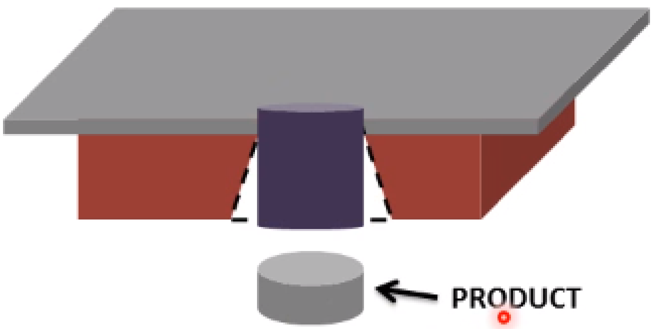


Figure 6 Blanking (Sheet metal operations - part-1 ! learn and grow, 2018).

A piece of sheet metal is removed from a larger sheet and that removed part is the desired product. As shown in Figure 6, the sheet is placed on top of a red die which has a hole so that the blue punch can press the sheet metal through that hole and the required product will be achieved.

3.1.2 PUNCHING

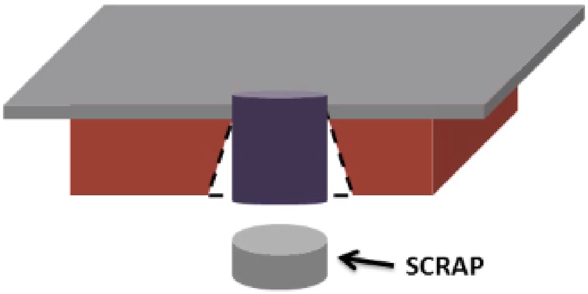


Figure 7 Punching (Sheet metal operations - part-1 ! learn and grow, 2018).

Punching process is similar as blanking process. In this case also die has a hole for the punch to get through as illustrated in Figure 7. The only difference is the removed material is the scrap and remaining material is the product.

3.1.3 PIERCING

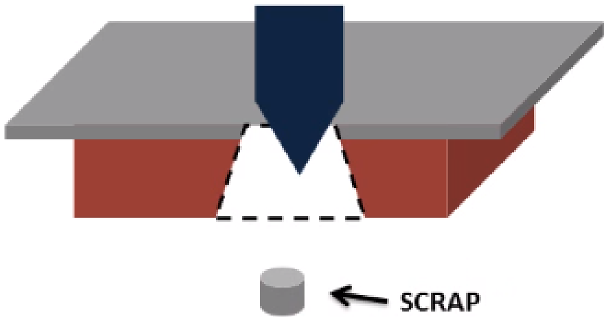


Figure 8 Piercing (Sheet metal operations - part-1 ! learn and grow, 2018).

Piercing is same as punching. Only the shape of the tool is different; piercing uses bullet like punch for making holes, as shown in Figure 8. Also, the scrap material in this process is extremely less than in punching.

3.1.4 TRIMMING

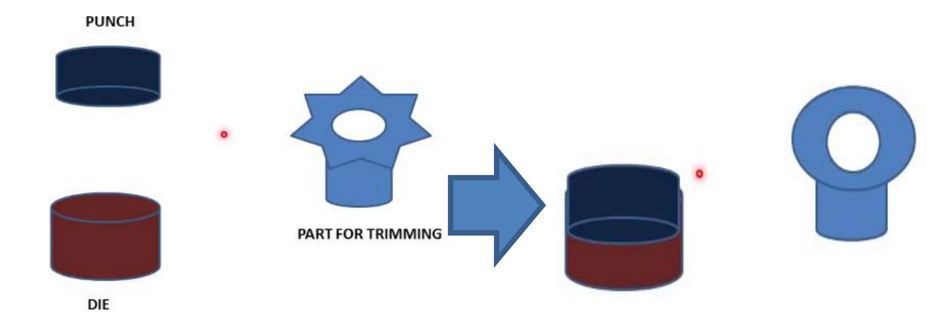


Figure 9 Trimming (Sheet metal operations - part-1 ! learn and grow, 2018).

Trimming means punching away extra material from the perimeter of a part. As shown in Figure 9, a star shaped plate's perimeter is removed to make it a circular shape by using a punch and a die.

3.1.5 SLITTING

Figure 10 Slitting (Sheet metal operations - part-2 ! learn and grow, 2018).

Slitting means cutting straight lines in a sheet without removing scrap using a sharp blade that rotates very fast. Figure 10 describes the process clearly.

3.1.6 NIBBLING

Figure 11 Nibbling (Sheet metal operations - part-2 ! learn and grow, 2018).

Nibbling means punching a series of overlapping slits or holes along a path as shown in Figure 11.

3.1.7 PERFORATING

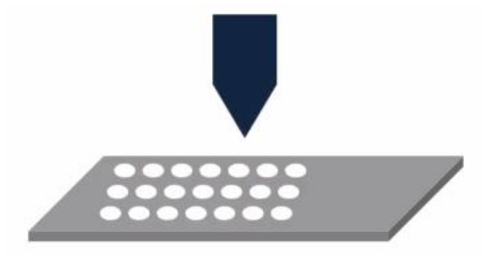


Figure 12 Perforating (Sheet metal operations - part-2 ! learn and grow, 2018).

Perforating is like nibbling method. It can be described as punching a close arrangement of large number of holes as illustrated in Figure 12.

3.1.8 NOTCHING

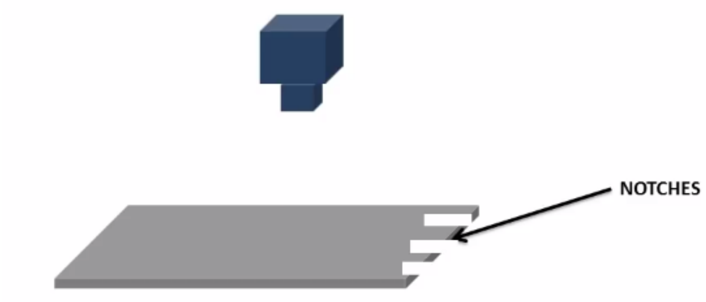


Figure 13 Notching (Sheet metal operations - part-2 ! learn and grow, 2018).

Notching means punching the edge of a sheet and form a notch as shown in Figure 13.

3.1.9 SHAVING

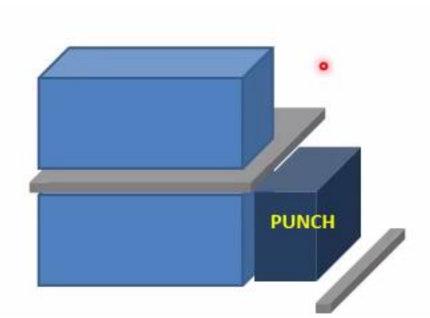


Figure 14 Shaving (Sheet metal operations - part-2 ! learn and grow, 2018).

Shaving can be described as shearing away small material from the edge of a sheet as illustrated in Figure 14.

3.1.10 DINKING

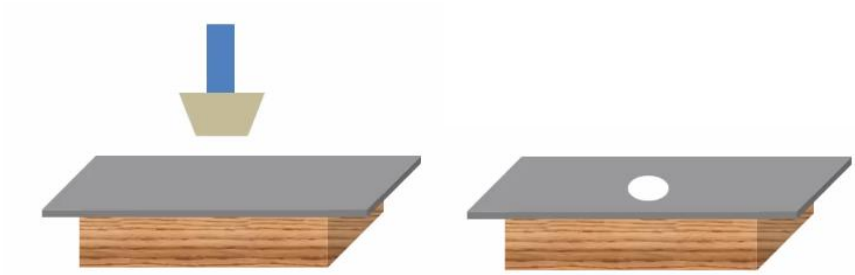


Figure 15 Dinking ("SHEET METAL OPERATIONS - PART-2 ! LEARN AND GROW", 2018).

Dinking is a special type of punching only for soft metals and uses hollow shaped punch as shown in Figure 15.

3.2 **FORMING OPERATIONS**

Forming operations are those procedures in which force is applied to a sheet metal so that the shape and geometry is modified without removing any material. The applied force is more than the yield strength, that causes plastic deformation, but it shouldn't exceed the ultimate shear strength. The advantage of this plastic deformation is that the sheet could be bent or stretched into variety of complex shapes. (Sheet Metal Forming, 2018.)

3.2.1 BENDING

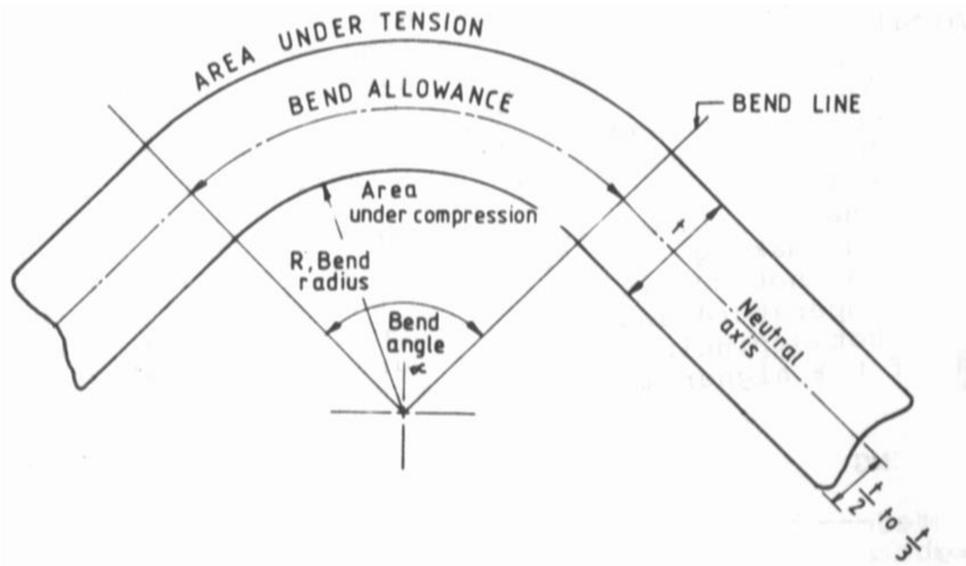


Figure 16 Stretched and Compressed part while bending (Editing K factor, 2018).

Bending is a metal forming process in which a force is applied to a piece of sheet metal around a straight axis, causing a plastic deformation and bend permanently to form a desired shape. Bending is generally done on a sheet metal to produce structural stamping parts such as braces, brackets, support, hinges, angles, frames, channel and other non-symmetrical sheet metal parts. During bending, tensile stress on the outside bend starts to decrease and becomes zero at the neutral axis while the compressive stress starts to increase from neutral axis to the inside of bend, which has been clearly illustrated in the Figure 16. Although there is large plastic deformation while bending, the mid-section of the bending zone acts as an elastic zone, so on unloading elastic recovery occurs. Due to this elastic property, sheet metal tends to spring-back partially, immediately after bending. So, it is necessary to over-bend the sheet metal a precise amount to obtain the desirable shape and bend-angle. There are different types of bending, depending on the shape of the product required. In every bending, there is a die which supports the sheet metal, and a punch, that applies force to the sheet metal and deforms into the shape of the die. The shape of punch and die used in the bending will be different in each case. (Sheet Metal Forming, 2018.)

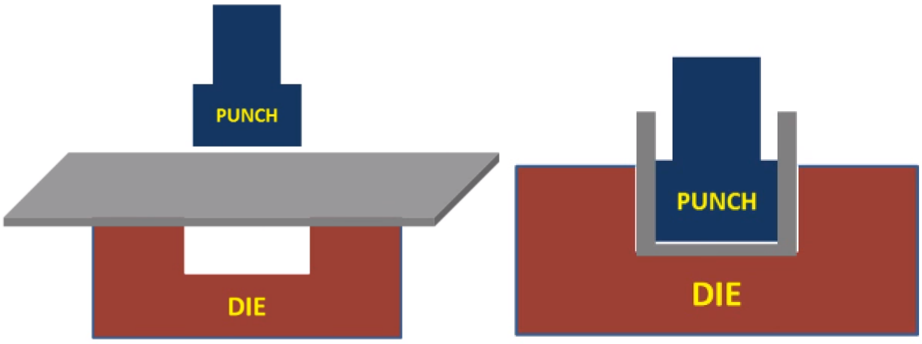


Figure 17 Channel Bending (Sheet metal operations - part-1 ! learn and grow, 2018).

Figure 17 clearly describes how a channel bending is done. A channel shaped die is used here, along with a punch, that has similar characteristics to the shape that fits the die. For the bending, sheet is place on top of the die, and the process is followed by the punch pressing the sheet into the die. Then, sheet is deformed into a channel shape.

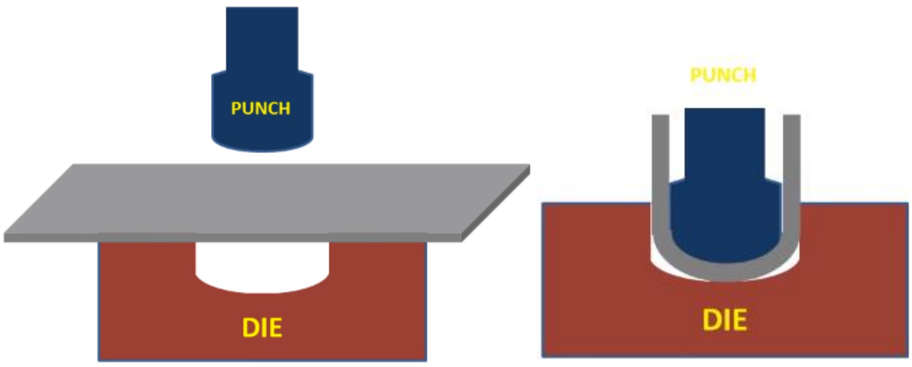


Figure 18 U-Bending (Sheet metal operations - part-1 ! learn and grow, 2018).

Figure 18 clearly describes how a U-bending is done. A U-shaped die is used here, along with a punch, that is like the shape that fits the die. For the bending, sheet is place on top of the die, and the process is followed by the punch pressing the sheet into the die. Then, sheet is bent and formed into a U shape.

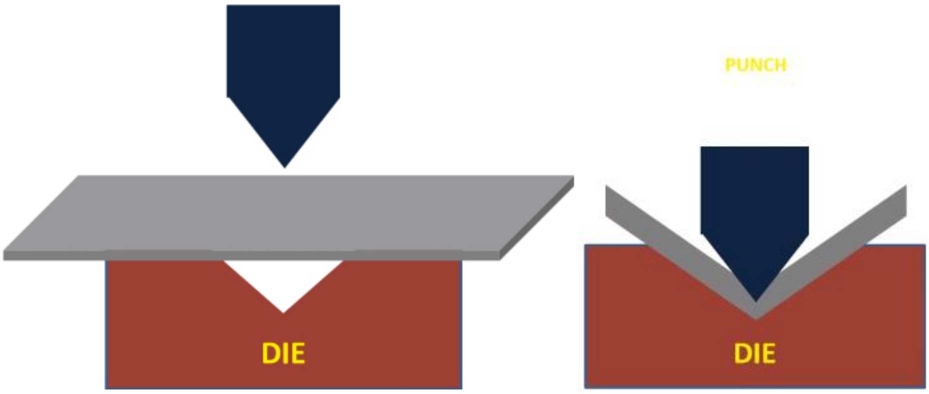


Figure 19 V-Bending (Sheet metal operations - part-1 ! learn and grow, 2018).

Figure 19 clearly describes how a V-bending is done. A V-shaped die is used here, along with a punch, that has similar shape that fits the die. For the bending, sheet is place on top of the die, and the process is followed by the punch pressing the sheet into the die. Then, sheet is bent and formed into a U shape.

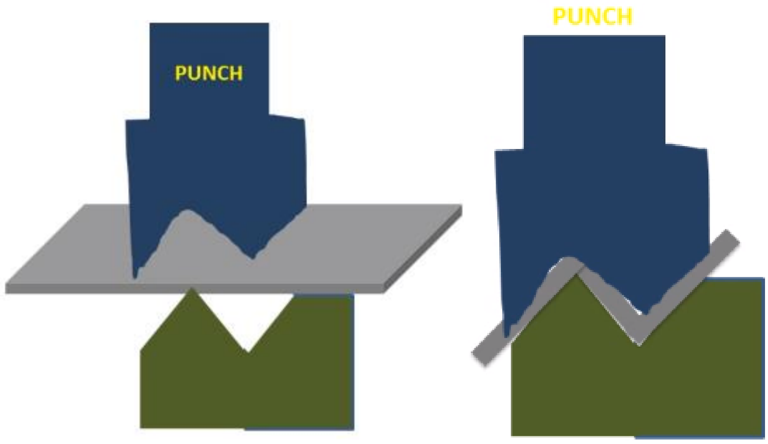


Figure 20 Offset Bending (Sheet metal operations - part-1 ! learn and grow, 2018).

In Figure 20, the process of an offset bending is clearly described. Generally, offset bending is two equal bends in opposite direction. A N-shaped die is used here, along with a punch, that has similar shape that fits the die. For the bending, sheet is place on top of the die, and the process is followed by the punch pressing the sheet into the die. Then, sheet is bent and formed into a N shape.

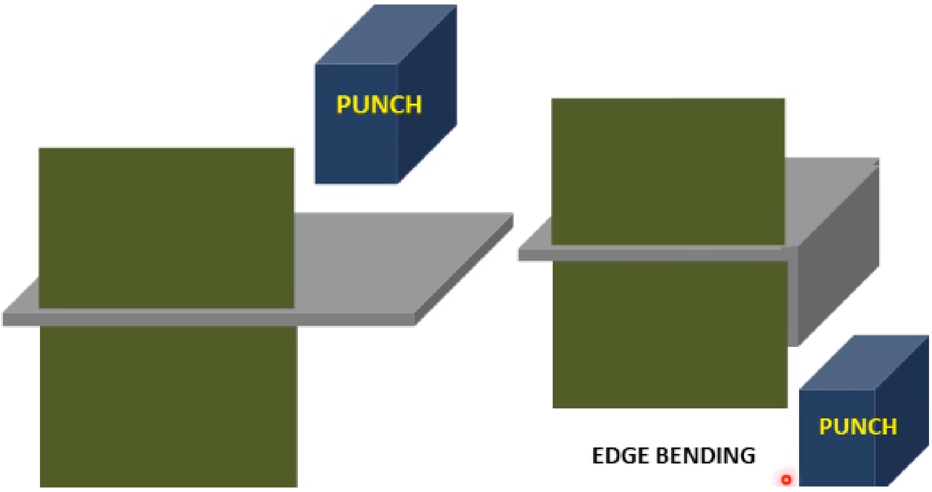


Figure 21 Edge Bending (Sheet metal operations - part-1 ! learn and grow, 2018).

Edge bending simply means bending the edge of a sheet metal in desired angle. As shown in Figure 21, a sheet metal is hold tightly between two dies and a punch is used to create force onto the sheet's edge causing it to bend.

3.2.2 DEEP DRAWING

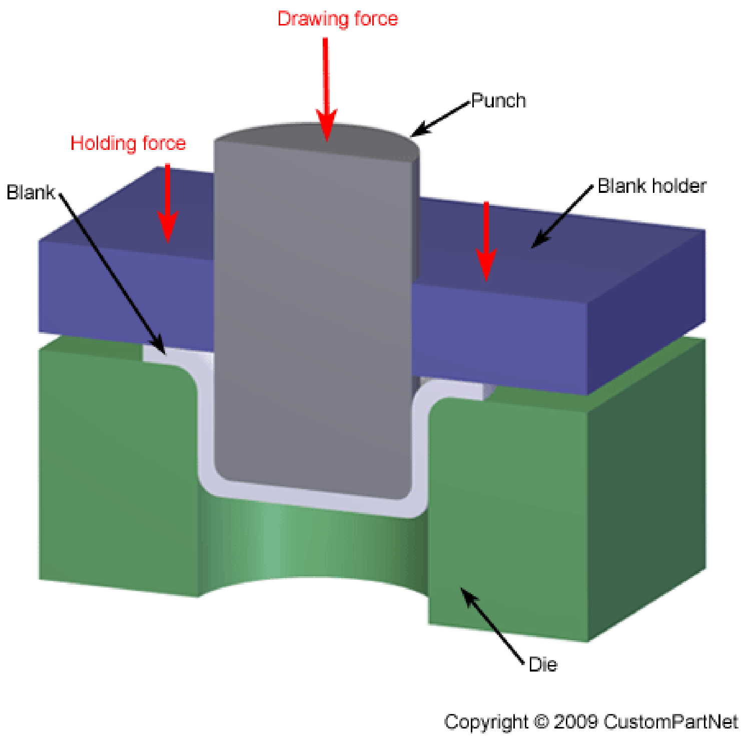


Figure 22 Deep Drawing of Sheet metal (Sheet Metal Forming, 2018).

Deep drawing is a metal forming process in which a tool applies downward force to a sheet metal and pushes the sheet, forcing it into a die cavity in the shape of the desired part. Figure 22 clearly describes the process. The sheet is plastically deformed into a cup shaped part by the tensile force applied by the tool. The depth of a deep drawn part is usually more than half of the diameter of the part. Although cylindrical or rectangular parts are the most common deep drawn parts, these parts can also have a variety of cross sections with straight, tapered or even curved walls. Ductile metals like aluminium, brass, copper and mild steel are most effective for deep drawing. Deep drawn parts are most used in automotive bodies and fuel tanks, making cups, cans, kitchen sinks, pots, pans and many more. (Sheet Metal Forming, 2018.)

The deep drawing method includes a blank, blank holder, punch and a die as shown in Figure. The blank is a piece of sheet metal which is generally disc or rectangular shape, that bears the tensile force and plastically deforms into the desired part. A tool called punch uses the hydraulic force to apply enough force to the blank, stretching it into the die cavity. As the die and punch both experience wear during this process, so they are made from carbon steel or tool steel. This process of drawing parts can be done through a series of operations, called draw reductions. In each step, the punch presses the part into different die, stretching the part to greater depth each time. After a part is completely drawn, the punch and blank holder can be raised, the part can be removed finally and the flanged part around the drawn part could be trimmed off. (Sheet Metal Forming, 2018.)

3.2.3 SPINNING

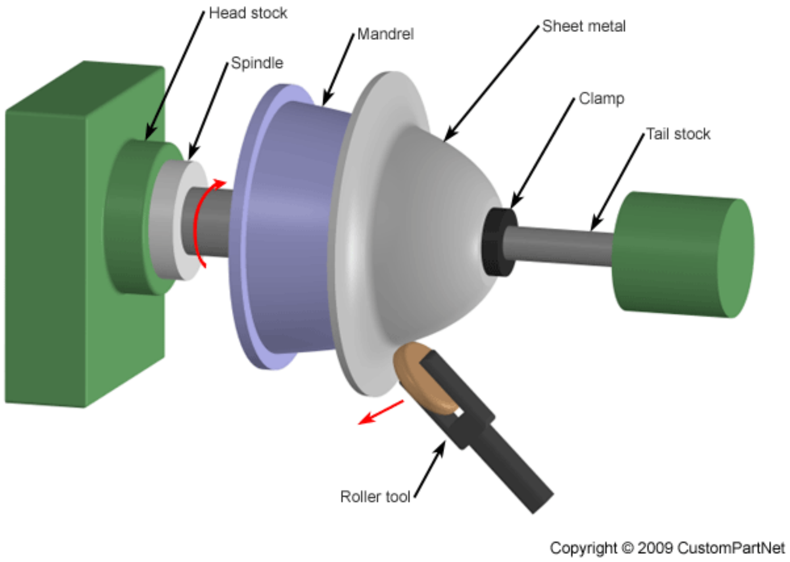


Figure 23 Spinning Process ("Sheet Metal Forming", 2018).

The process of forming sheet metal into a cylindrical part by rotating the sheet metal piece and applying forces to one side, is known as spinning or spin forming. There is a roller tool that presses the fast spinning metal disc against a tool called mandrel, to form the desired shape as shown in Figure 23. One great advantage of this method is that the spun metal parts have a rotationally symmetrical hollow shape, that are used in technological fields like satellite dishes, hubcaps, rocket nose cones and used in cookware and musical instruments too. Typically, this method is performed on a manual or CNC lathe and the basic requirements is a blank, mandrel and roller tool. Here, blank means the sheet metal which is cut into disc-shaped, very suitable shape for this forming method. Mandrel is a solid part which resembles the desired part, against which the blank will be pressed. Sometimes, multi-piece mandrels are used for the complex parts. Since the mandrel doesn't experience much wear during spinning, wood or plastic mandrel could also be used. But, for the high-volume production, metal mandrel is used in general. The head stock and tail stock clamps mandrel and plank together. Then, the spindle starts the rotation and makes mandrel and blank to rotate along. During this rotation, tool applies force to the blank sheet, causing it to bend and form around the mandrel. Generally, this tool is a roller wheel attached to a lever. These rollers which are inexpensive and experience little wear, can be available in different diameters and thickness, and are usually made from steel or brass. (Sheet Metal Forming, 2018.)

3.2.4 STRETCH FORMING

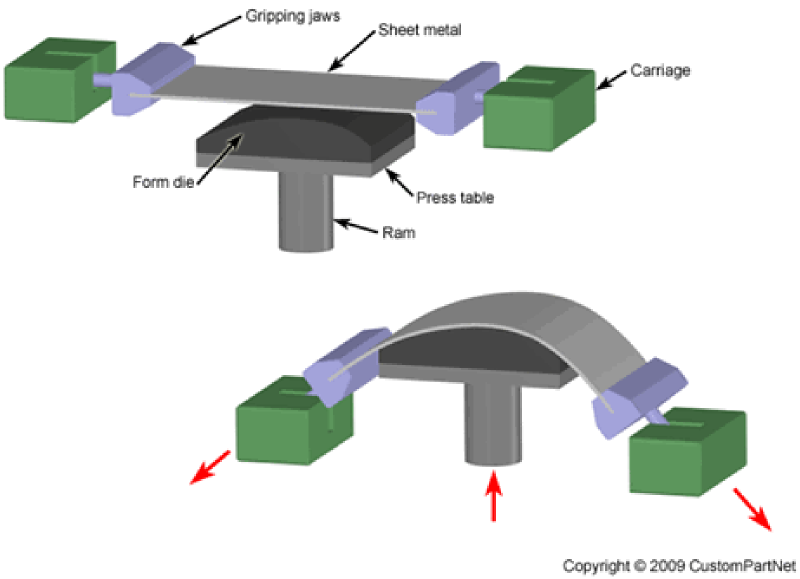


Figure 1 Stretch Forming (Sheet Metal Forming, 2018).

Stretch forming is a metal forming process in which sheet metal is stretched and bent simultaneously supporting over a die to form a large contoured part. As shown in Figure 24, stretch forming is performed on a stretch press, which contains gripping jaws that grips the sheet metal securely along its edges. Gripping jaws, which are attached to the carriage, are pulled together with the support of pneumatic or hydraulic force, so the sheet could be stretched. A solid contoured piece known as form die, is used to support the sheet metal while stretching. Usually, most of the stretch forming presses are oriented vertically, in which the form die is placed on a press table that can be easily raised into the sheet by a hydraulic ram. As the form die applies vertical upward force onto the tightly clamped sheet, the tensile force increases, and the geometry of the sheet is modified. Stretched formed parts are typically large and possess large radius bends. Variety of shapes can be produced from this method from a simple curved surface to a non-uniform cross section. Stretch forming is capable of shaping parts with high accuracy and smooth surfaces. Ductile materials like aluminium, steels, and titanium are preferable for this method. The stretched part, formed from this method, are usually large which are used for big structural part such as door panels in cars or wing panels on aircraft. (Sheet Metal Forming, 2018.)

3.2.5 ROLL FORMING

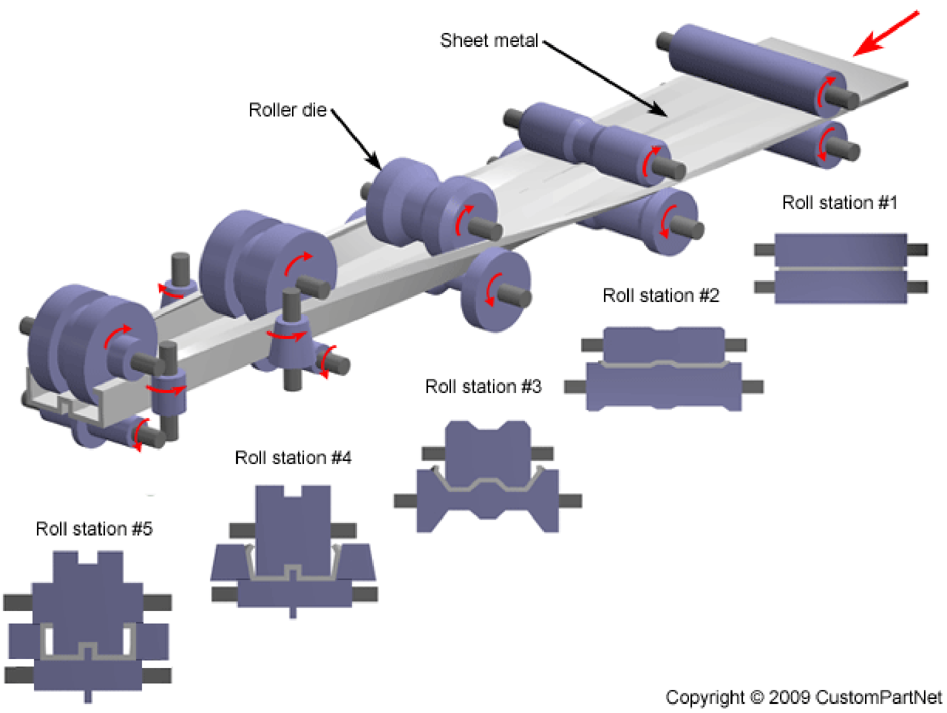


Figure 2 Roll Forming (Sheet Metal Forming, 2018).

Roll forming is a continuous bending operation in which a sheet metal passes through a series of rolling cylinders that change the shape of the sheet. The process is performed on a roll forming line in which a sheet metal goes through a series of roll stations for deformation. In each station, there is a pair of roller die, positioned on both sides of the sheet.

This is clearly illustrated in Figure 25. The shape and size of the roller die may be unique or may contain identical roller dies in different position. Also, the position of roller die may vary; it may be above and below the sheet, along the sides or at an angle. As the sheet passes through the roller dies in each roll station, it plastically deforms and bends. Each roll station performs their own task of bending and the final roll stations completes the finishing stage of bending to form the desired part. Roller dies are often lubricated to reduce friction between the die and the sheet, which also reduces the tool wear. Lubricant also helps for higher production rate, which also depends on the material thickness, number of roll stations, and radius of each bend. Other sheet metal fabricates operations like punching or shearing could be done before or after the roll forming. A wide variety of cross-section profiles can be formed from roll forming. The most common is open profile but closed tube-like shape could also be created. The formed part doesn't require a uniform or symmetric cross-section along its length as the final form is achieved through undergoing a series of bends with different roll stations. A very long sheet metal parts with typical width of 1-20 inches and thickness of 0.004 – 0.125 inches, are made from roll forming. Sometimes, wider (up to 5ft) and thicker (up to 0.25ft) sheets, can also be formed. This method can produce parts with tolerance as tight as ±0.005 inches. The formed parts like panels, tracks, shelving, etc. are commonly used in industrial and commercial buildings for roofing, lighting, storage units, and HVAC applications. (Sheet Metal Forming, 2018.)

3.2.6 EMBOSSING & COINING

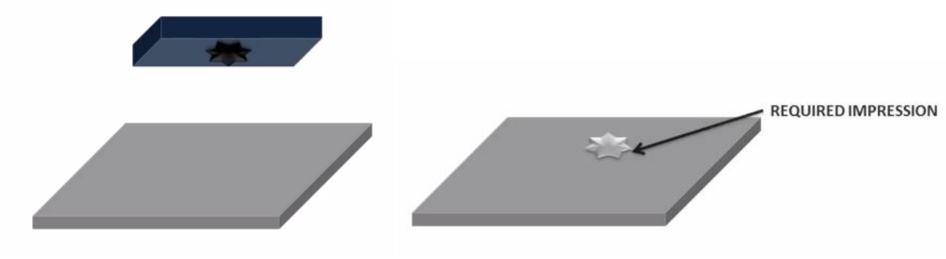


Figure 26 Embossing (Sheet metal operations - part-2 ! learn and grow, 2018).

A certain design is to be embossed on the metal plate and a punch with such design presses the metal, embossing the design on the plate as shown in Figure 26.

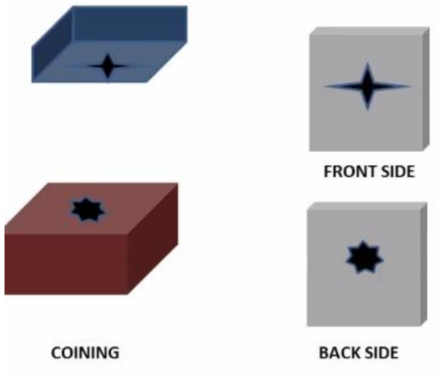


Figure 27 Coining (Sheet metal operations - part-2 ! learn and grow, 2018).

Coining is like embossing but on both side of the metal. As shown in the Figure 27, the punch and die both have different designs, so that when the metal is pressed together, impressions are obtained on both sides of the sheet metal.

4 INCREMENTAL SHEET FORMING METHOD

With the increasing pace of development and introduction of new products to the market suitable for the customer's desires, it is necessary to get into the international pressure of competition. Through an increasing number of developments, therefore reducing time and costs of manufacturing prototypes, one can handle the industrial competition. Today, sheet metal forming requires decisive methods because it's not only about economically beneficial but also manufacturing high quality functional and flexible parts which are challengeable but necessary. Nowadays, when we look at the trend in automobile production, more complex part geometries are made and requires a faster introduction of new products using sheet metal prototypes. Moreover, the demand of new innovative products that is producible only in small lot sizes, are increasing. (Kimura, Mitsuishi & Ueda, 2008.)

Several tests were done to meet the challenges of today's manufacturing prototypes. Depending upon the geometry of the tool, the flexibility of forming several geometries were restricted. First, the construction of a robust forming machine with high forming capacity is very expensive and second, the repeated use of the tools doesn't reduce the cost so much. (Kimura, Mitsuishi & Ueda, 2008.)

The limits of increasing the flexibility of conventional sheet forming process were overcome by developing a new forming method. This new process works on the principle of repeating local forming and producing the desired geometry. As the forming process happens step by step, this method is called incremental forming process. In this process, the forming capacity needed is much smaller than the conventional method of forming, because of the small plastic deformation area. Due to this factor, tool size is also smaller comparing it with other conventional forming methods. Overall, the advantages of using incremental forming method is a higher deformation degree, a possible deformation of materials with reduced ability and higher strength. (Schafer & Schraft, 2005.)

Although, there are so many advantages of incremental forming process, industries barely use those process. It is so because the tool with a flexible shape isn't good with the forming of complex geometries. It was favourable only with a simple geometry. While working on complex geometries, a die plate is still needed for this incremental forming process, so other existing process are chosen because of their shorter process time. Also, the cost for technical equipment of existing incremental forming processes is too high to produce prototypes and limited-batch production. (Schafer & Schraft, 2005.)

To overcome this problem and to take the advantage of incremental forming processes even in complex geometries, a new incremental forming process was developed at the Fraunhofer Institute for Manufacturing Engineering and Automation. This new method characterizes two aspects: first, this process can work without any die plates and second, the forming tool can be moved by an industrial robot, so that the investment costs for the mechanical equipment are low. (Schafer & Schraft, 2005.)

4.1 TYPES OF INCREMENTAL SHEET FORMING

Due to the advancement in computer-controlled machine, symmetric single point forming (spinning) and the development of tool path processors in CAD software packages, new metal forming techniques have been developed in the last few years. Incremental sheet forming is one significant outcome of this technology that could form asymmetric shapes at low cost, without the need of any special expensive dies. The typical characteristics of an incremental forming processes are:

- requires a solid, small-sized forming tool
- doesn't need large, dedicated dies
- forming tool is in continuous contact with sheet metal
- ability of tool to move under control in three dimensional spaces
- can produce asymmetric sheet metal shapes

This last characteristic completely separates the incremental forming from spinning process. ISF processes are a result of the introduction of CNC mills and CAD software with tool path postprocessors. Although, the idea of die-less forming was first introduced in a patent in 1967, there were no further developments because the foregoing tools were not available at that time. Generally, sheet metal parts can be made with either a machine specifically designed for the process or a 3-axis CNC mill with a software attached that generates machine tool paths. There are various types of asymmetric incremental sheet forming (AISF). A simple description of all those types of AISF are described below with figures included so that one process described cannot be confused with other process. (Nimbalkar & Nandedkar, 2013.)

4.1.1 Single Point Incremental Forming (SPIF)

Figure 28 Single Point Incremental Forming Process (What is Roboforming?, 2018).

SPIF is a popular and mostly used incremental forming method than any other types of incremental forming in the recent years. It has gained a lot of attention because of its flexibility in forming method. SPIF process was developed from sheet metal spinning, sheet metal shear flowing and hammering with included CNC technique to control the forming tool movement. In this process, blank holder secures the flat sheet of metal tightly and allows the sheet to be deformed by the forming tool. This method doesn’t require any die and forming takes place through a single tool containing hemispherical tip with the support of a backplate on the opposite side of the tool (Figure 28) to reduce the effect of spring back. The main advantage is this technique allows a relatively fast and cheap production of prototypes or small series of sheet metal parts and has a capability to manufacture a variety of irregular-shaped, axisymmetric components and highly customized medical products in small batches. (Ali, 2014.)

4.1.2 Two Point Incremental Forming (TPIF) with Partial Die

Figure 29 Two Point Incremental Forming process with Partial Die (What is Roboforming?, 2018).

This is a two-point incremental forming in which the deformation takes place through two points; tool and partial die. The die is located on the opposite side of the sheet from the forming tool as shown in the Figure 29. Partial die means that the shape of die is not exactly as the desired geometry. Both the blank and the partial die are movable and are forced together at the same time in the opposite direction respective to each other. This method increases the accuracy at the apex of the form unlike SPIF, which increases accuracy mostly at the periphery of the shape. (What is Roboforming?, 2018.)

4.1.3 Two Point Incremental Forming (TPIF) with Complete Die

Figure 30 Two Point Incremental Forming process with Complete Die (What is Roboforming?, 2018).

Unlike partial die, a complete die is used for this method on the opposite side of the sheet from the tool, allowing the metal to be formed according to the die’s shape which is clearly illustrated in the Figure 30. Although this method enables higher geometric accuracy, the production costs are much higher and takes longer manufacturing time for each part. (What is Roboforming?, 2018.)

4.1.4 Duplex Incremental Forming with Peripheral Supporting Tool (DPIF-P)

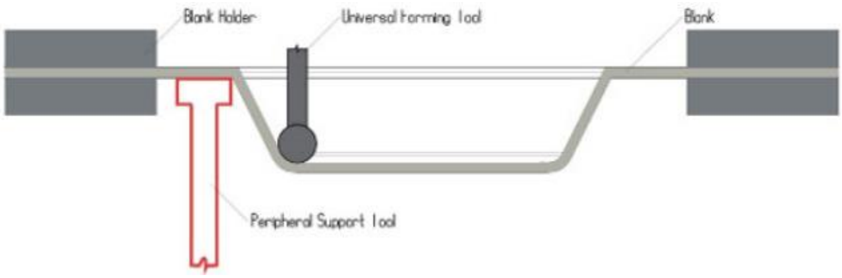


Figure 31 Duplex Incremental Forming with Peripheral Supporting Tool (What is Roboforming?, 2018).

Two industrial robots are placed on the either side of the blank sheet secured in a sturdy frame. The ‘master’ robot holds the forming tool and the ‘slave’ robot holds a support tool which is shown in Figure 31. This forming tool pushes incrementally on the sheet, forming the sheet in the shape of the tool-path whereas the peripheral tool moves along the boundary of the part, acting like a backplate, providing leverage on the opposite side of the sheet for the master robot to push against. (What is Roboforming?, 2018.)

4.1.5 Duplex Incremental Forming with Locally Supporting Tool (DPIF-L)

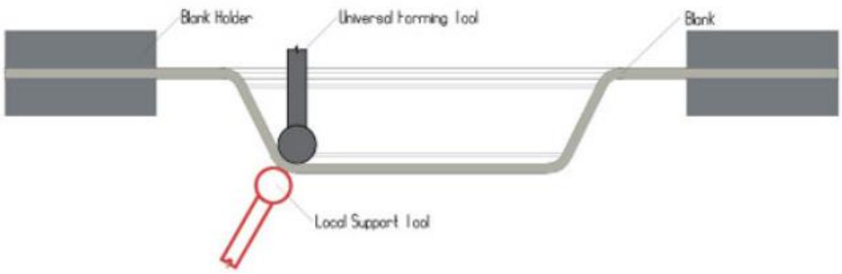


Figure 32 Duplex Incremental Forming with Local Supporting Tool (What is Roboforming?, 2018).

In this process also, sheet secured between two robots containing universal forming tool in a sturdy frame. The ‘slave’ robot supports the ‘master’ robot. The ‘master’ robot pushes incrementally on the sheet, forming the sheet in the shape of the tool-path. Following the ‘master’ robot, ‘slave’ robot also continues to support from the opposite direction, creating a forming gap between the tools. Figure 32 makes the whole process clear. By interchanging the ‘master’ and ‘slave’ roles of robots, concave and convex forms can be shaped within the same part. (What is Roboforming?, 2018.)

4.2 **PROCESS**

The incremental sheet forming works based on deforming of a sheet metal by a great amount of sequentially executed hammer punches through a hammering tool, which is moved by an industrial robotic hand over the plate. Comparing the tool of robotic incremental sheet forming with conventional forming method like deep drawing, the dimension of the hammering tool is very small. A suitable flange is used to install this hammer tool on the last axis of the robot. The overall steps necessary for performing a robotic incremental sheet forming process is shown in Figure 33. (Schafer & Schraft, 2005.)

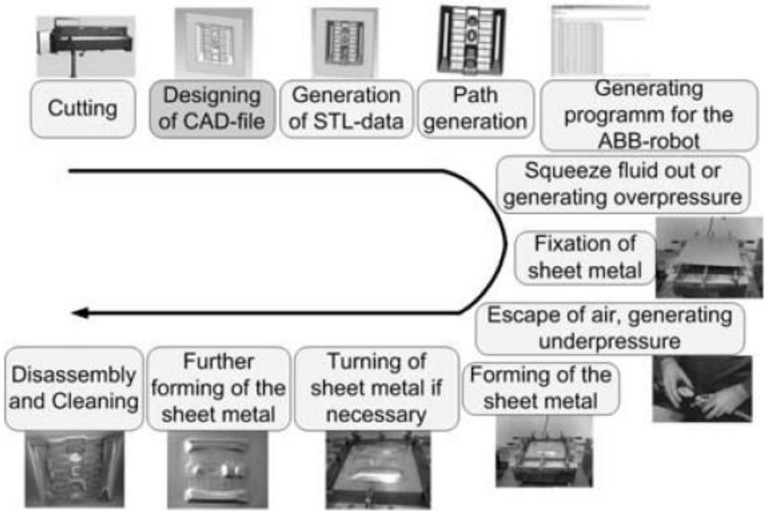


Figure 33 Current single steps needed for ISF by Hammering (Kimura, Mitsuishi & Ueda, 2008).

First, the sheet metal is clamped onto a frame. Then, position of the frame is calibrated and given to the numeric control of the robot. This numeric control, programs the hammering tool to follow along the calculated path and eventually forms the desired shape. Generally, the hammering tool moves along the xy-plane and after forming each circle, it repositions by Δz. The principle of this incremental forming is quite simple, which is shown in the figure 34. (Kimura, Mitsuishi & Ueda, 2008.)

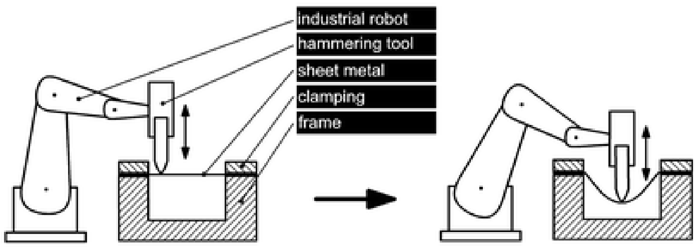


Figure 34 Principle of the incremental hammering by an industrial robot (Schafer & Schraft, 2005).

(Schafer & Schraft, 2005.) stated that hammering principle has these main advantages in comparison to other incremental forming processes:

- “Only small reaction forces affect the handling equipment since deformation forces are generated by the inertia forces of the punch and not by handling the equipment itself. Thus, a commercially available industrial robot can be used for the movement of the forming tool.”
- “The area of deformation is smaller because of the inertia of the sheet metal near the deformation zone. Therefore, a deformation without any die plate under the sheet metal can be realized.”

- "Since hammering tool retracts from the sheet metal after each punch, no friction forces occur in the feed direction. Hence, there is no undesired deformation of the workpiece."

5 DEVELOPMENT OF A HAMMERING TOOL

Generally, there are two principles of hammering, for the incremental forming process. One principle relies upon the energy of moving part while other principle relies on a predetermined movement. Several hammering tools were constructed for both principles with different kinds of complication. (Schafer & Schraft, 2005.)

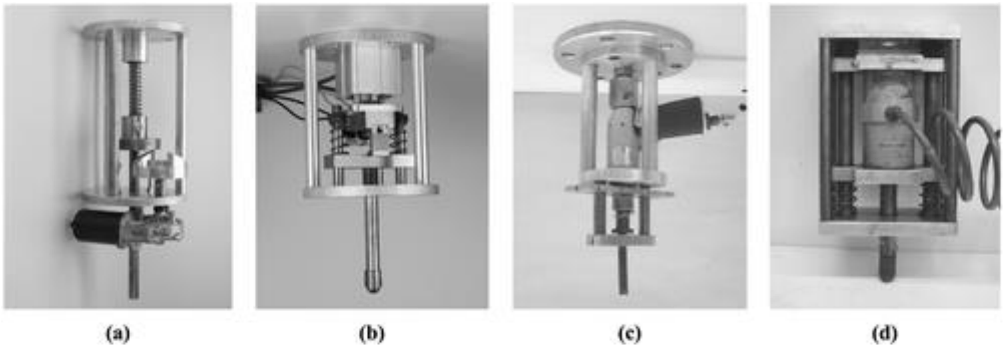


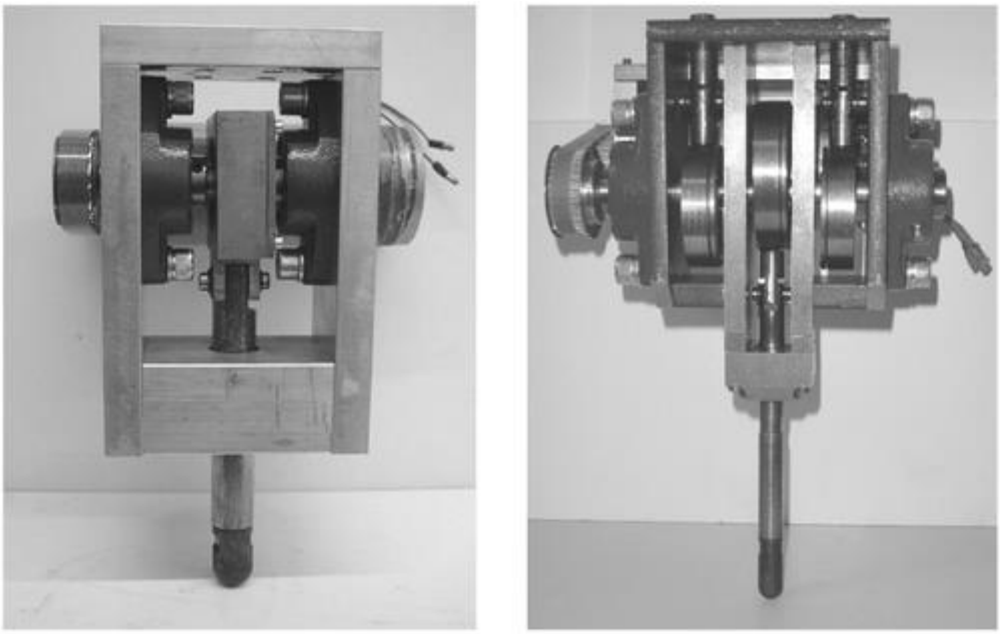
Figure 35 Hammering tools based on the energy of the moving mass (Schafer & Schraft, 2005).

In Figure 35, four different hammering tools can be seen that works on the principle of relying upon the energy of the moving punch. Figure 35(a) shows the simplest tool. The punch is raised by the rotating cam disc and concurrently the spring is compressed. The punch is raised by the rotating cam disc and concurrently the spring is compressed. The punch falls after a quarter turn and the spring is relaxed. The potential energy of the punch and the energy of the spring together makes the forming energy. But, this type of hammering tool is not suitable for incremental forming as the forming energy of the tool is too low and a higher forming energy would cause high friction losses between the cam disc and the moving mass. (Schafer & Schraft, 2005.)

So, a second forming tool was constructed, which is also based on the same energy principle, shown in Figure 35(b). Comparing this with first tool, the vertical movement in this tool is caused by a strong pneumatic cylinder. A strong forming energy without higher friction losses can be achieved by using stiffer springs. Sadly, this type of forming tool is also not useful because of the low number of punches (2.5 punches/s). (Schafer & Schraft, 2005.)

A new hammering principle with faster hammering sequences had to be developed. The required tool was achieved [Figure 35(c)] by integrating a commercial riveting hammer into a robot tool. Unfortunately, during the testing phase, it was found that this tool couldn't be used for incremental forming process. The reason is the uncertainty in punching time, as the movement of released punch to retain its original position lasts longer movement of the internal moving mass. A constant hammering is needed in incremental forming, which is unsupported by this forming tool principle. (Schafer & Schraft, 2005.)

Also, a fourth hammering tool was constructed based on pneumatic principle, shown in Figure 35(d). The robot tool was integrated with a commercial vibrator. Unlike the case with riveting hammer, the internal moving mass of the vibrator doesn't hit against an external punching tool, but it is used for the movement of the whole vibrator which is connected to the external punch. The vibrator is simply supported by four springs to provide the movement. However, this type of tool also proved negative. Since the sheet metal behaves like a spring, coupled oscillations arose during the incremental forming process which results to the change in amplitude and the frequency of the moving punch of the time. (Schafer & Schraft, 2005.)



(a) (b)

Figure 36 Hammering tools based on the predetermined movement of the moving mass (Schafer & Schraft, 2005).

Sadly, these developed hammering tools, based on the energy of moving mass, didn't support the incremental forming method. So, two additional tools were constructed that had eccentric drive and based on predetermined movement of the tool. An eccentric is a circular disk solidly fixed to a rotating axle with its centre offset from that of the axle. Figure 36(a) shows the first type of eccentric driven tool where an electric motor drives a shaft through a driving belt. The eccentric used in this tool has an amplitude of 2 mm that contributes to the up and down movement of the punching mass. Workpiece with a dimension of 100 x 100 mm or larger was able to be produced for the first time with this hammering tool that had a frequency of about 60 hits/s. (Schafer & Schraft, 2005.)

A second type of eccentric-hammer was developed [Figure 36(b)] to increase the number of punches/s. As the frequency increases, the force of inertia also increases. So, it was necessary to balance the moving masses of the hammering tool. After so many concepts of hammering tool, finally this simple concept that allowed a complete mass balancing was created. This hammering tool consists of 1 eccentric moving the punching mass and two eccentrics moving smaller masses for counter balancing. (Schafer & Schraft, 2005.)

6 TOOL PATH GENERATION

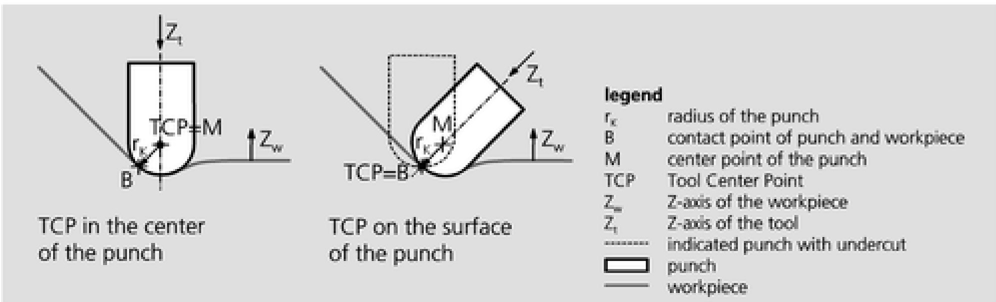


Figure 37 Possible definitions of the TCP (Schafer & Schraft, 2005).

Incremental Forming Process are generally identified as having a complicated tool path generation. As the die plate itself cannot produce desired complicated shape, the 3D information of the desired shape must be expressed by a CAD model, a point cloud or a mathematical function. There are 2 options to define the Tool Centre Point (TCP) using a punching tool with a spherical tool tip as shown in Figure 37. The first option is to define the TCP in the middle of the spherical tip and the second option is to define the TCP in the point in which the Z-axes of the forming tool intersects with the surface of the punch. The hammering tool must be perpendicular to the desired geometry in case of second option. It is effective to use this vertical orientation of hammering tool all the time as the main forming direction in the described incremental forming process is always in the direction of z-axes of the work-piece coordinate system. Thus, the first option is used. The perpendicular orientation of the punch doesn't restrict the possibilities of the incremental forming process as the maximum gradient angle of the producing surface is about 60 degrees. (The limit of the gradient angle exists because the thickness after deformation depends on the local gradient angle of the surface. In all stretch forming process, this gradient angle limit needs to be considered as cracks appear on the sheet metal when the limit is reached.) After the TCP has been defined in the middle of the spherical tool tip, there are 2 ways to calculate the path of the TCP, as shown in Figure 38. (Schafer & Schraft, 2005.)

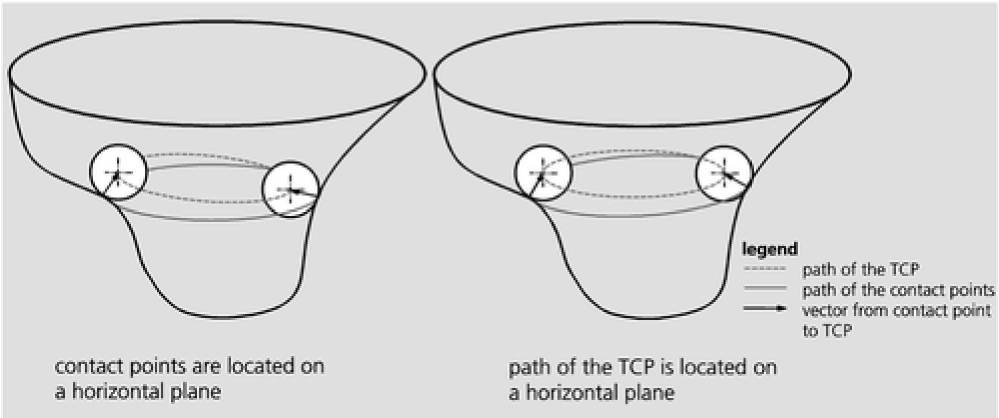


Figure 38 Path of the TCP depending on its generation (Schafer & Schraft, 2005).

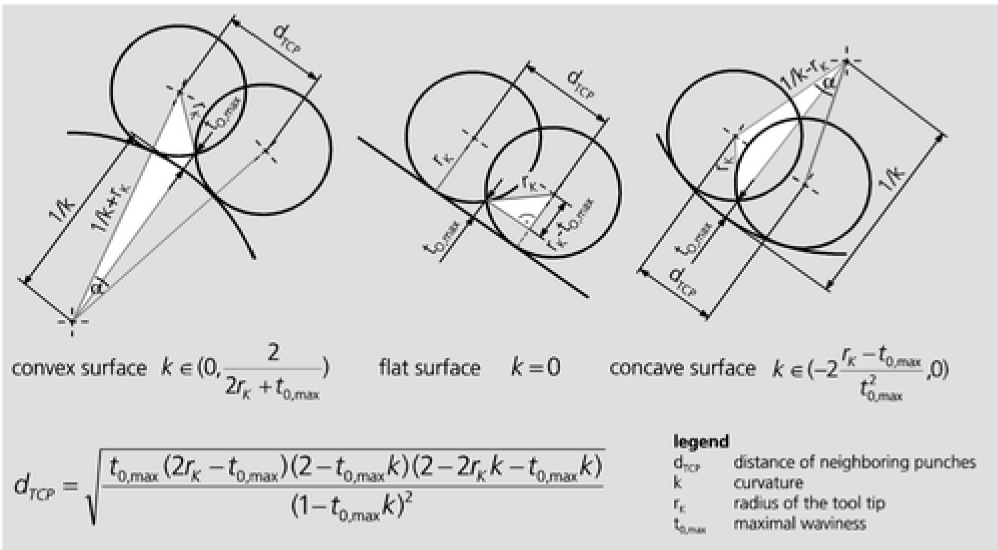


Figure 39 Calculation of the valid distance of neighbouring hammering paths (Schafer & Schraft, 2005).

One way is to make sure that the contact points between the spherical tool tip and desired surface are in a horizontal plane. Another way is to situate the path of the TCP in such a horizontal plane. Using the first method, hammering tool will move in the vertical direction during one circulation. But, a vertical movement of hammering punch cannot be allowed during one circulation. But, a vertical movement of hammering

punch cannot be allowed during one circulation because the desired incremental process works in horizontal layers. So, second way of calculating the path of TCP is to be applied. (Schafer & Schraft, 2005)
Let desired surface be known as a function:

$F: z_F = f(x_F, y_F);\ x_F\ \varepsilon\ |x_{F,min}, y_{F,max}|,\ y_F\ \varepsilon\ |y_{F,min}, y_{F,max}|$ .... (1)

Then the offset surface where the paths of the TCP are located could be expressed as the vectorial equation:

$F^*: \vec{x}_{F^*} = \vec{x}_F + r_k \vec{n}_F$ .... (2)

Where, X_F is the position vector, r_k is the radius of the spherical tool tip and n_F is the standardized normal vector. The desired paths of the TCP are received by slicing the calculated surface F* with horizontal planes. The distance between the hammering positions must be observed carefully during the slicing process, so that a certain surface quality can be guaranteed. Figure 39 shows a formula that can calculate the valid distance between two neighbouring punches using the local curvature, the maximal waviness and the radius of the tool tip. Contrarily to milling with a spherical cutter, the distance between neighbouring hammering paths depends on the distance between neighbouring punches of the paths. A conventional CAD-CAM program can be used, if the distance between neighbouring punches is nearly zero. (Schafer & Schraft, 2005.)

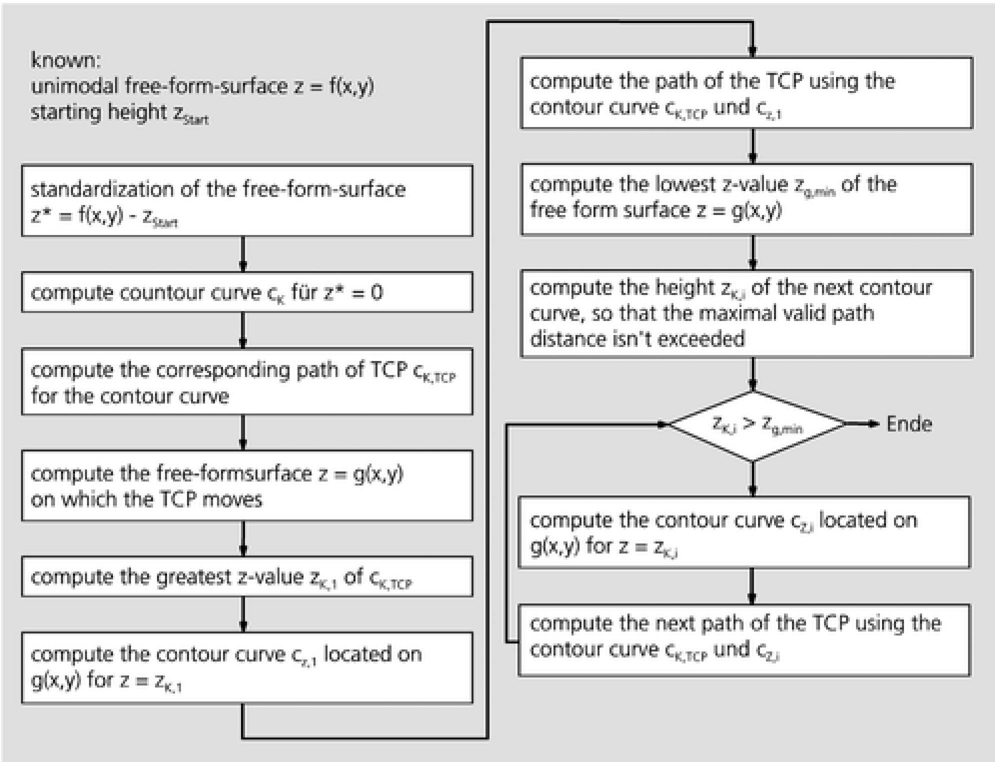


Figure 40 Generation of the tool paths (Schafer & Schraft, 2005).

A flowchart of the developed path generation is shown in Figure 40, that concerns the valid distance between the hammering positions and the radius of the used tool tip. The workpiece expected to be produced is known as a unimodal free-form-surface and a boundary is given in a certain starting height. According to the algorithm, the first step is standardization of the free-form surface. The next step is to calculate the contour curve on the free-form-surface which corresponds to the given boundary. The corresponding path of the TCP can be found using this contour curve. Next, with the help of equation (2), free-form-surface on which the TCP moves during the deformation process is figured out. Then, a new contour curve is found with the greatest z-value of the TCP path and the calculated free-form-surface. The first tool path can be calculated by combining this contour curve with the given boundary. Again, a new contour surface is calculated on the free form surface on which the TCP is located considering a maximum valid path distance. Combining it with the known boundary, next tool path is calculated. This process is repeated several times and the whole tool path is generated until the deepest point of the surface is reached. (Schafer & Schraft, 2005.)

7 EQUIPMENT USED IN THE INCREMENT FORMING

Basically, the equipment used in incremental forming is merely a forming tool and the machinery to move that forming tool in a controlled manner. However, a further description of the overall equipment is included below:

7.1 3-axis CNC machine

CNC stands for Computer Numerical Control in which a computer converts design into machine readable codes that is further used by the machine to control the shaping of the material. Generally, CNC system consists of the 6 elements; Input device, Machine control unit, Machine tool, Driving system, Feedback devices and Display unit. The overall working system of these elements is shown in Figure 41.

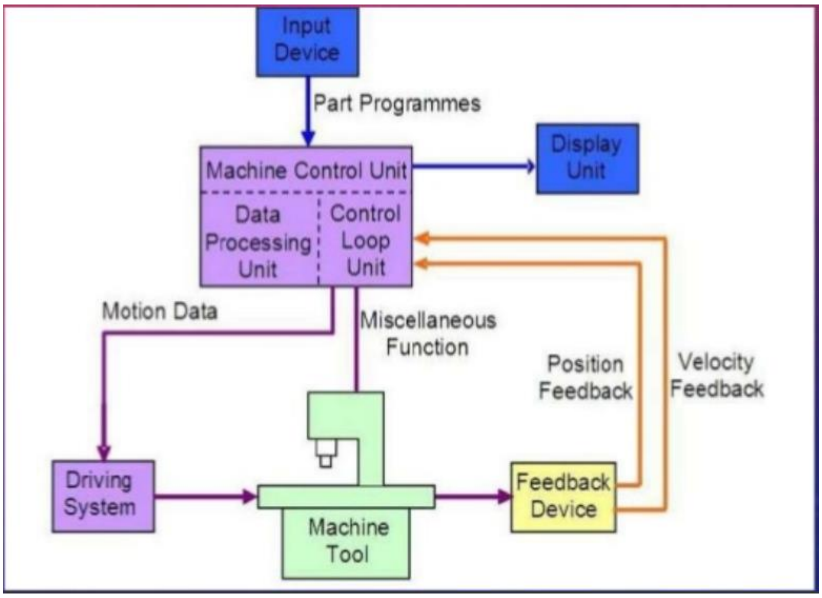


Figure 41 Operating Process of a typical CNC machine (Dhut, 2018).

Normally, CNC machine's operation is controlled through number values and co-ordinates, also called G and M codes. Each of these codes is assigned to a specific operation. The design of the required shape is given through the input device to machine control unit. Here, data processing takes place and the task performing code is generated. Driving system reads these codes and makes machine tool to carry out the operation. There is a feedback device that checks the position and make sure that the machine tool is performing operation accurately and sends the information to the control loop unit in machine control unit. This machine control loop unit sends the whole information about the operation to the display unit which shows progress on the task completion. To perform incremental sheet forming method, CNC machine should have at least 3-axis control system i.e. X, Y and Z coordinates. In contradictory to high maintenance costs, CNC machines are easier to program, very safe to operate, increases production throughout, easy to work with complex products and improves the quality and accuracy of manufactured parts. (Dhut, 2018.)

7.2 Solid Forming Tools

Figure 42 Sample of Tools used in Incremental Forming (Nimbalkar & Nandedkar, 2013).

Forming tools play a vital role in incremental sheet forming process. For assuring a continuous point contact between sheet and forming tool, a solid hemispherical head containing tool is used which is shown in Figure 42. Smaller tool is effective to use at very steep wall angles rather than sphere diameter, so that the contact between shank and sheet metal is avoided. Tool shape must be considered into account while generating the toolpath. After the establishment of tool shape, usually a specific radius with a hemispherical ball-head, tool materials must be chosen. In most cases, ball-head tools made from tool steel are suitable. In addition, tool head could be coated or made of cemented carbide to reduce friction and to increase tool life time. (Nimbalkar & Nandedkar, 2013.)

7.3 ISF Clamping System

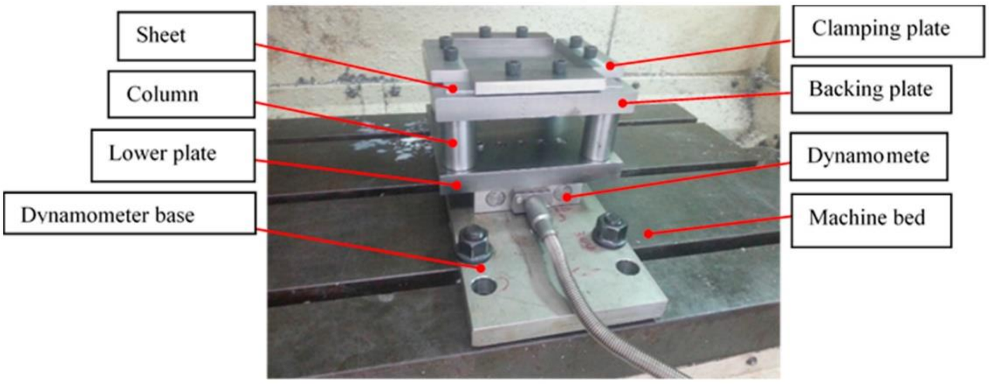


Figure 43 Clamping System of a typical Incremental Forming method (Baharudin, Azpen, Sulaima & Mustapha, 2017).

Clamping system is necessary in ISF for holding a sheet metal into a fixed position and make the working environment ready to carry out the operation. Clamping system generally consists of a clamping plate, backing plate, four columns and a lower or a base plate, as shown in the Figure 43. Lower base plate with four columns, also called ‘fixture’, should be fixed securely on the table of operating area. Deformation in fixture may cause geometrical intolerance. So, simulation of fixture should be done using Ansys for analyzation of proper location of the supports where maximum bending moments are occurred. After the setup is ready, sheet metal is fixed between the two clamping and backing plates. Also, the lower plate could be mounted to the dynamometer, for measuring the forming process. Clamping system needs to be carefully planned as there is a chance of spring-back after the clamping devices are unclamped which results to the geometric inaccuracy in final product. In ISF, spring-back of the formed parts may involve following four components:

- Local deformation during the forming process
- Spring-back after unloading the forming tool or tools

- Global spring-back after releasing the formed parts from the clamping devices
- Spring-back induced by the trimming process

Introduction of the annealing method to the incremental forming process can significantly reduce the spring-back related problems. There have been some experiments done for heat assisted incremental forming using laser, electricity or heating globally by putting the furnace below sheet metal which reduced the spring-back effects. (Zhang et al., 2016.)

8 INFLUENCING FACTORS IN ISF

There are many influencing factors related to Incremental Sheet Forming (ISF). Generally, tool size, wall angles, and the shape of fixture affects the most. The smaller the tool size, the lower the forming capacity of sheet metal will get. This may lead to the perforation of sheet metal. Commonly, tool diameter for forming experiments is 10mm, which results in a minimum edge radius of 5mm for formed parts. Designated wall angles are limited by material and thickness. One can reach wall angles up to 70 degrees for stainless steel, depending on the influencing factors and the forming strategies. While doing further practical tests, it can be found that maximum wall angles of 75 degrees for deep drawing steel and up to 85 degrees for geometry features of depth smaller than 10mm. The plastic deformation area of hammering is very small and limited to the contact between hammering tool and the sheet metal. So, deformation is close to the plain strain condition for incremental forming processes. To find the steepest wall angle in terms of the material thickness, we can use the sine law:

$$\mathbf{S1} = \mathbf{S0}.(\mathbf{1} - \mathbf{sin\alpha}) \quad \text{............ (3)}$$

Here, ‘S1’ is the thickness of the formed shape, ‘S0’ the original material thickness and ‘α’ the designated wall angle. (Kimura, Mitsuishi & Ueda, 2008.)

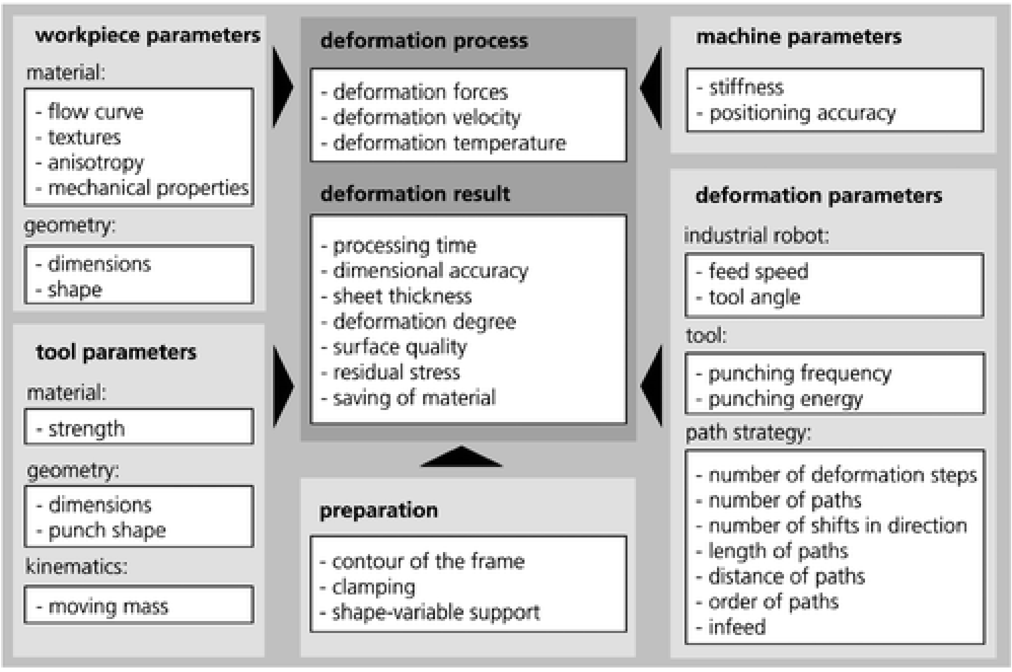


Figure 44 Influencing factors of incremental hammering (Schafer & Schraft, 2005).

Figure 44 shows all the possible influencing parameters of incremental forming. First, the material is itself an influencing parameter. Textures, anisotropy and mechanical properties of the material and its geometry has also a great impact in deformation process. Next comes the tool parameters. The deformation process gets influenced by a) the kind of material, a tool is made b) the geometry of the tool and c) how fast and regular motion, the tool can achieve. The preparation done while carrying out the forming process is also an influencing factor. The contour of the frame, clamping system, shape-variable support and their arrangement can be a great influence on the deformation process. Machine parameters like stiffness and positioning accuracy also influence the deformation process. Similarly, the speed in which the robot operates, angle of the tool while punching, the punching frequency and the force in which punching occurs have a great influence in deformation process. Every small thing matter in this incremental forming process and they can have some influence in deformation process. The number of deformation steps, number of paths, number of shifts in direction, length of paths, order of paths, infeed and even the operating temperature have influence on deformation and should be taken care into account. These all influencing factor may affect the processing time, dimensional accuracy of the final product, thickness of the sheet, deformation degree (wall angles), surface quality, residual stress and even the saving of material.

8.1 **Lubrication**

Figure 45 Lubricants used in Incremental Forming (Alves de Sousa, 2015).

Lubricants are another influencing factor for the ISF process. Lubrication is very essential part in ISF method for giving tools a longer life by reducing friction and wear, improving heat distribution and removing waste materials. There are variety of lubricants in high number and number of distinct products with different characteristics, some of which are also shown in Figure 45. R. Alves de Sousa with his fellow scientists conducted an experiment to determine the significant role played by a lubricant in ISF specifically for steel (hard metal) and aluminium (soft metal).

Table 1. List of lubricants studied (Alves de Sousa, 2015).

Lubricant	Type	Viscosity at 40ºC [mm^2/s]	Density [kg/l]	Melting Point [ºC]
Repsol SAE 30	Mineral Oil	105	0.884	215
Total Finarol B 5746	Mineral Oil	9.75	0.904	150
Moly Slip AS 40	Paste		1.76	190
Weicon AL-M (allround)	Paste	185	0.92	
Moly Slip HSB (high speed bearing)	Paste	N/A	N/A	195

Table 2. List of pastes components (Alves de Sousa, 2015).

Lubricant	Base	Solid Lubricant
Moly Slip AS 40	Petroleum oil	MoS2 (40%)
Weicon AL-M (allround)	Mineral oil	MoS2/Li
Moly Slip HSB (high speed bearing)	Lithium	MoS2/Molysplip special / E.P compounds (9%)

Table 3. Sheet materials (Alves de Sousa, 2015).

Material	Density [g/cm^3]	Young Modulus [MPa]	Tensile Yield Stress [MPa]	Hardness [HV]
Aluminum AA1050	2.7	70000	250	40
Steel DP780	7.8	210000	780	258

Table 4. Initial sheet roughness (Alves de Sousa, 2015).

Material	Ra [μm]	RzD [μm]	Rt [μm]
Aluminum AA1050	0,205	1,012	1.545
DP780 steel	0.710	3.817	5.205

Tables 1 and 2 show a variety of lubricant's properties (both oil and greases/pastes) with different viscosity and density that are to be used in this experiment. The aluminium sheets used were 1mm thick sheets of 1050 aluminium series. Also, high strength dual phase steel DP 780 was used. Their mechanical properties are better described in Table 3. Also, the roughness of the sheets in initial condition before forming was measured in terms of arithmetic mean roughness (Ra), the total height of roughness profile (Rt) and the mean roughness depth (RzD). This is illustrated in Table 4. (Alves de Sousa, 2015.)

Figure 46 SPIF-A Incremental Forming Machine (Alves de Sousa, 2015).

The SPIF-A machine as shown in Figure 46 was used for performing the incremental forming. The machine was designed to support compressive and lateral loads of 13kN and 6.5kN respectively, with a working area of 1000mm x 1000mm and a maximum vertical displacement of 400mm. The task was to incrementally form a truncated cone, 40mm deep, diameter 1200mm and wall angles of 45 degrees. Rather than forming other complex geometries, cone was decided to be formed, due to its simplicity, faster execution time and more straightforward analysis. (Alves de Sousa, 2015.)

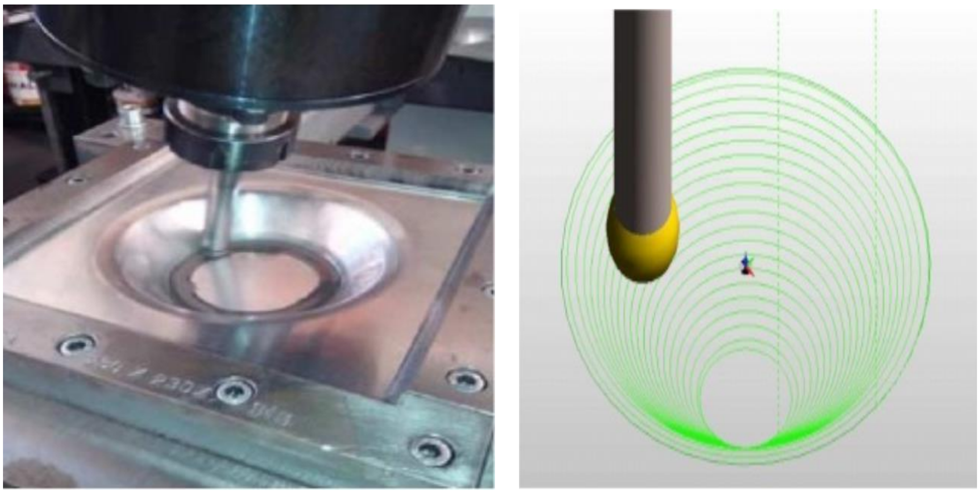


Figure 47 Incrementally formed conical part and its toolpath (Alves de Sousa, 2015).

Figure 47 shows the process of cone forming being done. The tools used in this test was made from a cold working steel (X210CrW12), a very suitable material for incremental forming. The tool was also heat treated for increasing hardness to 58 HRC. The tool consists of spherical tip with a 6mm radius. The trajectory performed by the tool consists of spirals (Figure 47) with a vertical increment of 0.3mm and a control scallop 0.1mm. This type of toolpath prevents the occurrence of peak forces by allowing vertical increment along the geometry of the part. (Alves de Sousa, 2015.)

Figure 48 Instrument measuring surface roughness (Alves de Sousa, 2015).

In all the tests, the lubricant was applied directly on the sheet surface right in the beginning of the forming process. A small amount of lubricant is required when the sheet is placed horizontally, and the lubricant naturally follows the toolpath by gravity during the forming process. After the forming process is completed, the sheet is unclamped, and the roughness tests are conducted using an electrochemical Hommelwerke T1000 rugosimeter as shown in Figure 48. (Alves de Sousa, 2015.)

Table 5. Average roughness values for formed aluminium 1050 (Alves de Sousa, 2015).

Lubricant	Ra [μm]	RzD [μm]	Rt [μm]
AL-M	0,995	4,955	7,014
AS-40	1,128	5,672	7,492
HSB	1,043	5,275	8,672
SAE30	0,873	4,417	7,485

Table 6. Average roughness values for formed DP780 steel (Alves de Sousa, 2015).

Lubricant	Ra [μm]	RzD [μm]	Rt [μm]
AL-M	0,368	1,850	2,490
AS-40	0,215	1,285	1,910
HSB	0,295	1,788	2,415
SAE30	0,473	2,688	4,405
Finarol	0,210	1,230	2,055

The roughness parameter was measured for each lubricant. Parameters measured were according to DIN4768 standard and the values calculated were Ra, Rt and RzD. Results are summarized in Table 5 for Aluminium sheet and Table 6 for Steel sheet. Observing the results, it is found that lubricant SAE30 oils yields the best surface finish for 1050 Aluminium. But, for the DP780 steel, Finarol B576 delivered the smoothest roughness, with AS-40 grease giving very similar values. The results show an obvious relation between the lubricant viscosity and hardness of formed material that concerns the surface finish quality. So, lubricant with high viscosity provides better result for surface quality softer materials and vice versa. (Alves de Sousa, 2015.)

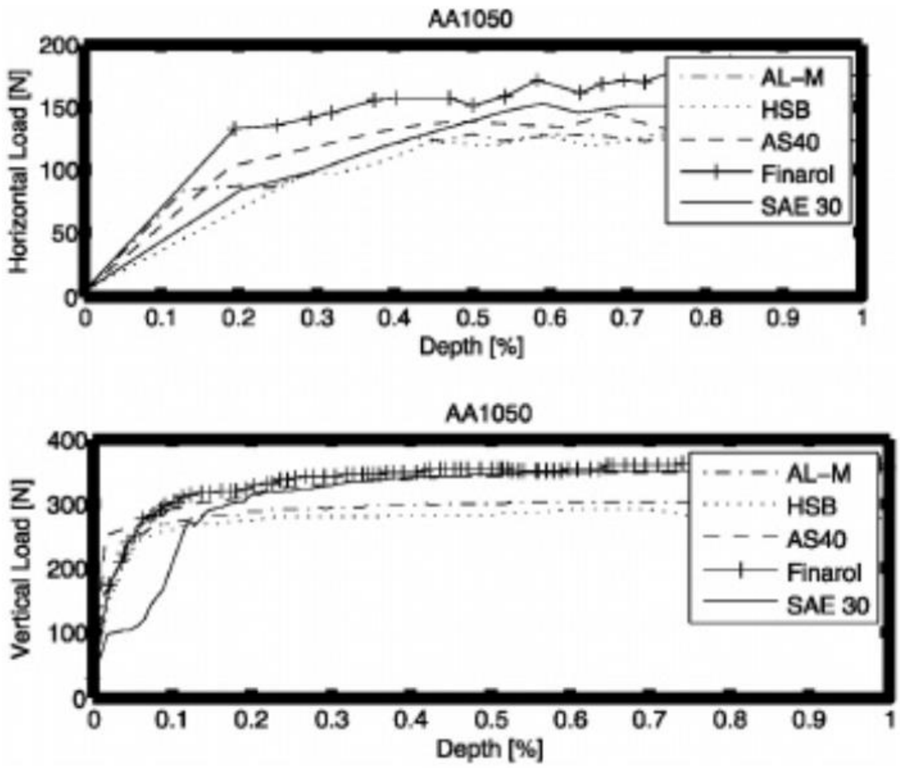


Figure 49 Distribution of vertical and horizontal forces as a function of forming depth (in percentage value) for AA1050 (Alves de Sousa, 2015).

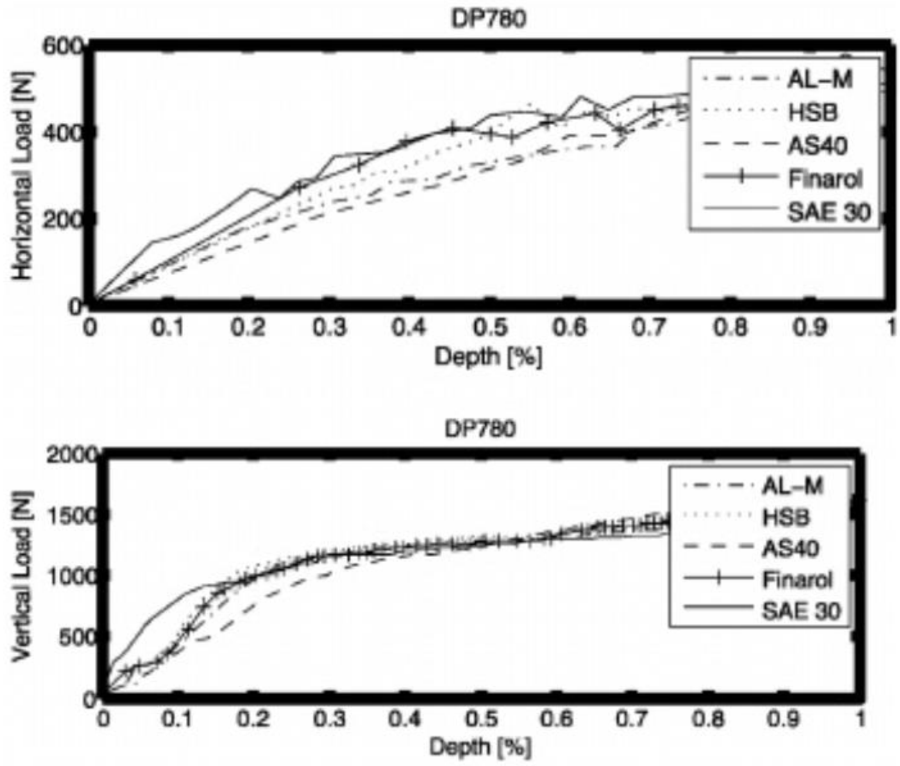


Figure 50 Distribution of vertical and horizontal forces as a function of forming depth (in percentage value) for DP780 steel (Alves de Sousa, 2015).

For any type of forming process, it would be economical if the amount of forming forces be minimized. So, to know the effect of lubrication on this aspect, forming force was also studied. Both horizontal forming force and vertical forming force were calculated for each sheet and graphed into a diagram as shown in Figure 49 and 50. Analysing Figure 49, two levels of vertical forces were observed. One was 280N that corresponded to the tests with HSB and AL-M lubricants. Regarding horizontal forces, highest value was approximately 170N and lowest around 120N. Finarol B5746 corresponded to the highest forces in both directions and the worst finish for aluminium sheet AA1050. However, a clear relation between forming forces suffered and final quality of the surfaces couldn’t be deduced. Observing Figure 50, forming force values were much higher for steel than for aluminium, but the trend of the force curves for steel and aluminium are quite alike. There may be some relation between compressive forming force, hardness of the material and the surface finish itself. But, spring back phenomena is significant for incrementally formed parts and lubricant play no role to reduce it. Even if the machine, the toolpath strategy and the geometry to obtain are the most influencing parameters, the use of a suitable lubricant may significantly improve the surface finish quality, reduce forming forces and prevent tool wear. (Alves de Sousa, 2015.)

9 CONCLUSIONS

While studying the process of Robotic Incremental Sheet Forming, it can be concluded that this is a highly flexible method and does not require expensive tools for manufacturing complex parts. Hence, this process costs less in comparison with other conventional forming. During the project, it was found that a hammering tool with an eccentric drive should be used for the effective forming in this process. One excellent fact about this forming technique is that complex geometries can be produced with good surface quality finish without using any die plates. As a robotic hand is used in the forming process, parts can be produced directly from the CAD file after the proper machine setup and the operation are performed in a conventional CNC machine as well.

There may be some limitations to this process such as geometrical errors: spring-back, pillow effect and sheet bending. In comparison to the deep drawing process, forming time takes much longer in this incremental forming process and is limited to small size production batches. It is difficult to form a sharp corner and an edge with this method because crack easily occurs. Also, multi-stage strategies should be used for the forming of right angles. However, the Incremental forming method is very suitable for rapid prototyping or small volume production. Design changes can be easily and quickly performed with this method. As the nature of this forming method is incremental, the deforming force required is very small, comparing to other forming methods. The material's formability could also be increased with this incremental forming method. The key point, that differs this method from any other type of forming method is its toolpath. The whole process can be operated with cost-effective equipment. Mainly, small and medium-sized enterprises can benefit from this new technology.

REFERENCES

Ali, M. (2014). *Single Point Incremental Forming*. Presentation, University of Kufa/College of Engineering.

Alves de Sousa, R. (2015). Lubrication Aspects during Single Point Incremental Forming for Steel and Aluminium Materials. *INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING*, *16*(3), 1-7. Retrieved from http://www.academia.edu/32101943/Lubrication_aspects_during_Single_Point_Incremental_Forming_for_steel_and_aluminum_materials

Baharudin, B., Azpen, Q., Sulaima, S., & Mustapha, F. (2017). Experimental Investigation of Forming Forces in Frictional Stir Incremental Forming of Aluminum Alloy AA6061-T6. *Metals*, *7*(11). Retrieved from http://www.mdpi.com/2075-4701/7/11/484/htm

Dhut, P. (2018). *ppt on cnc*. *Slideshare.net*. Retrieved 17 April 2018, from https://www.slideshare.net/PankajDhut/ppt-on-cnc

Editing K factor. (2018). *Nirvanatec.com*. Retrieved 1 April 2018, from http://www.nirvanatec.com/support/bend/kfactor.html

GATE Mechanical notes for Punching Operation. (2018). *Geekvis.com*. Retrieved 28 March 2018, from https://geekvis.com/post/gate-mechanical-notes-on-punching-operation

Kimura, F., Mitsuishi, M., & Ueda, K. (2008). *Manufacturing Systems and Technologies for the New Frontier* (pp. 421-422). Guildford, Surrey: Springer London.

Lodhi, V., & Jain, A. (2014). A Review of Experimental Study of Spring Back Effect of Aluminum Sheet Metal. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *3*(4). Retrieved 27 March 2018, from http://www.academia.edu/6995908/A_Review_of_Experimental_Study_of_Spring_Back_Effect_of_Aluminum_Sheet_Metal

Miley, M.(2018). *How is Sheet Metal Made?*. Retrieved 27 March 2018, from https://sciencing.com/how-does-4899623-how-sheet-metal-made.html

Narayanan, R., & Dixit, U. (2015). *Advances in Material Forming and Joining* (pp. 29-30). New Delhi: Springer India

Nimbalkar, D., & Nandedkar, V. (2013). Review of Incremental Forming of Sheet Metal Components. *Int. Journal Of Engineering Research And Applications*, *3*(5), 39-51.

redazione. (2014). A short sheet metal history - Metal Working World Magazine. Retrieved from http://www.metalworkingworldmagazine.com/a-short-sheet-metal-history/

Schafer, T., & Schraft, R. (2005). Incremental sheet metal forming by industrial robots. *Rapid Prototyping Journal*, *11*(5), 278-286.

Sheet Metal Forming. (2018). *Custompartnet.com*. Retrieved 1 April 2018, from http://www.custompartnet.com/wu/sheet-metal-forming

Sheet Metal Inspection| Physical Digital®. (2018). Retrieved from http://www.physicaldigital.com/knowledge-base/sheet-metal-measurement-and-inspection/

SHEET METAL OPERATIONS - PART-1 ! LEARN AND GROW. (2018). *YouTube*. Retrieved 28 March 2018, from https://www.youtube.com/watch?v=L0YgSmfwzWY&t=406s

SHEET METAL OPERATIONS - PART 2 ! LEARN AND GROW. (2018). *YouTube*. Retrieved 1 April 2018, from https://www.youtube.com/watch?v=c-G98EJvxoE

Stellman, J. (1998). *Encyclopaedia of occupational health and safety* (4th ed.). Geneva: International Labor Office

What is Roboforming?. (2018). *Alexjfischer.com*. Retrieved 4 April 2018, from http://www.alexjfischer.com/what-is-roboforming/

Zhang, Z., Zhang, H., Shi, Y., Moser, N., Ren, H., Ehmann, K., & Cao, J. (2016). Springback Reduction by Annealing for Incremental Sheet Forming. *Procedia Manufacturing*, http://dx.doi.org/https://doi.org/10.1016/j.promfg.2016.08.057