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The Impact of CAM Strategies on Incremental Sheet Forming for DC04

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ABSTRACT: Incremental sheet forming (ISF) is a sheet metal forming technique. A sheet is formed into the final workpiece by a series of small incremental deformations. However, studies have shown that it can be applied to polymer and composite sheets too. Generally, the sheet is formed by a round-tipped tool, typically 5 to 20mm in diameter. The tool can be attached to a CNC machine, a robot arm, or similar indents into the sheet by about 1 mm and follows a contour for the desired part. It then indents further and draws the next contour for the part into the sheet and continues to do this until the full part is formed. A pilot study shows that not much study has been done on the effect of CAM strategies for Incremental sheet forming. This research project involves CAM strategies made up of method of deformation, cut pattern, percentage step over, tool shape and part shape. Seventy-two different CAM strategies are possible by combining these parameters. All these strategies will be tested and analysed with the help of simulation software, but before that, a part will be generated in modelling software followed by a tool path. Programming will be required to convert the tool path into a simple (x, y, z, t) file for simulations. After the simulation, dominant strategies will be selected for physical experimentations based on simulation results and data interpretation. A decision will be taken based on sheet thickness uniformity, spring back, fatigue strength, and run time. After successful experiments, simulation results will be validated, followed by documentation. This project aims to determine optimal strategies for the foremost quality of parts produced by incremental sheet forming. This project also requires the knowledge of modelling, tool path generation (N.C. files), simulations and programming.

KEYWORDS: Incremental Sheet Forming, CNC Machine, CAM, Robot Arm, Metal sheet

I. INTRODUCTION

Many techniques, equipment, and machines have evolved into manufacturing items that make life easier and more enjoyable since the dawn of time. Many evolutions have occurred in the twentieth century in order to address the production problems posed by newer needs, materials, tools, and cost restrictions, and the quest continues. Make-to-order manufacturing is frequently required by improvements and breakthroughs in the aerospace, automobile, marine, medical, and many other sectors, and newer improved technology is necessary to meet this challenge. These manufacturing systems require autonomous, flexibly integrated, and adaptable processes that can respond swiftly to changing demands while maintaining real-time shop floor control. For these conditions, incremental sheet forming is an emerging modern manufacturing method that is one of the top trending areas of research in sheet material manufacturing for the cost-effective production of custom objects. Manufacturing is a complex activity that involves converting raw materials into finished products with desired properties, shape, and size through the use of a wide range of processes, machinery, tools, and other equipment, with or without automation, the use of computers, robots, sensors, and other special equipment; it also demands people with a broad spectrum of skills, knowledge, and expertise in multiple disciplines. The flexibility and agility of a production method, as well as its viability for a specific application, determines its effectiveness and efficiency.

To carry out a manufacturing activity, we require five Ms, viz. Men, Materials, Machines, Money, and Methods. Methods refer to the manufacturing processes that are used to create the intended products in a cost-effective and timely manner, with expected quality and adaptability to changing needs and technological advancements. Furthermore, understanding manufacturing processes necessitates knowledge of diverse materials, tools, machine tools, accessories, manufacturing processes, metrology, and testing instruments for inspecting materials or products.

II. LITERATURE REVIEW

1. An attempt was made by Mulay et al.[1] to find out the influence of parameters affecting formability in Incremental Forming of AA5032 H32. At a higher value of step depth, the Deformation was non-localized, and excessive stressing

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of sheets lead to the early failure of the metal. The higher formability was found with smaller step dept and vice versa. The large tool would acquire more materials, leading to non-localized Deformation. Therefore, as tool diameter increases, formability decreases. Higher sheet thickness leads to higher formability due to more material flowing under the same loading condition. The experimental results showed that the small step depth, along with the moderate level of feed rate, results in higher formability and process found to be more sensitive towards step depth. At a constant feed rate, the $Ø_{max}$decreases with an increase in step depth. Increase in $Ø_{max}$ with the decrease in step depth at constant sheet thickness. The results reveal that the increase in $Ø_{max}$with the increase in sheet thickness at constant step depth. Besides, lowering the step depth and increasing sheet thickness improves part formability.

2. The paper by Mulay et al.[2] aimed to understand the effect of feed rate and vertical step depth on formability and microhardness. An increase in sheet thickness resulted in enhanced formability due to more material could flow under the same load. The graphs for AA5754 H22 alloy and DC04 steel parting formability and the non-formability region were found. An increase in forming angle and step depth leads to a fracture point in the deformed region. The forming force increases with an increase in step depth because more material needs to be pushed down in a single stroke, which leads to higher local Deformation of the sheet. While applying immense step value, metal deforms by the combination of tool and pulling force due to the non-localized resulting increase in formability.
3. Melania et al.[3] have proposed several strategies regarding formability behavior along with the implementation of CAD/CAM for the SPIF process. The workpiece is constructed by two layers of DC04 steel and AA6016 Aluminum alloy. The single-stage method using Archimedes' spiral strategy showed an acceptable reduction in sheet thickness and uniformity. Two directional cracks were observed in the finishing stage in the two-stage process strategy (roughening followed by finishing stage using toolpaths oriented at 0° with regards to X-axis). The best result was obtained in the same approach but with an angle of 20°. The low Von mises strains were observed in a single-stage strategy than a two-stage. The distribution of strain was uniform in the Two-stage approach compared to the Single-Stage approach.
4. Raju and Narayan[4] have attempted to investigate the best possible combination of input parameters like feed rate, step depth, speed, tool diameter on the accuracy, surface roughness, formability, and wall angle. The multiple sheets decrease the formability due to an increase in tool radius and longitudinal stresses, followed by an increase in hydrostatic pressure. The percentage contribution calculated for individual parameters showed that the feed rate, step depth, and tool diameter are dominant parameters for the formability. Interaction plots showed that the interaction between a number of sheets and vertical step depth is predominant over the interaction between feed rate and tool diameter.
5. Khazali and Fereshteh[5] presented a study on incremental forming at higher temperatures due to the low formability of Mg alloy AZ31 at room temperature. A significant increase in formability was observed with the rise in ductility (faster slip plane movement) above the Transition temperature (T_f= 160^{0}C). Below the transition temperature,the higher the vertical pitch or tool diameter lower would be drawing depth. Effect of process parameters like vertical depth and tool diameter reversed above T_f. Above 160^{0}C, it has found that the larger the vertical pitch or tool diameter greater would be the drawing depth. This was due to the Deformation resulted from tool penetration instead of plastic bending.
6. Barnwal et al.[6] presented a paper to understand the macro and microstructural behavior of AA6061 Al-Mg-Si based alloy. The direction of major true strain was observed to be always perpendicular to the tool path due to the flow of material in the normal course of tool movement. The Zigzag nature of the Major vs. Minor strain graph shows higher formability of the SPIF process over conventional forming (Fig. 2.1). Higher Taylor's factor showed considerable resistance towards Deformation in the SPIF process. They claimed that the more accurate result could have obtained by the fine meshing of the cone frustum model in the FEM model.
7. The formability was studied by Gipiela et al.[7]for concentric and spiral profiles in SPIF and compared with the conventional Nakajima Test for HSLA 440. The concentric and spiral profile could sustain much more strain than the Nakajima Test. Hence the fracture limit curve of material is needed over a conventional forming limit curve. The spiral profile is slightly more sensitive than a concentric profile to fracture at higher strain.
8. Mercedes et al.[8] attempted to study the effect of a single staged and multi-staged SPIF process on formability, sheet thickness, and sheet thickness distribution. An increase in formability and uniform sheet thickness was observed in the multistage process compared to a single stage. However, for the processed region, the single staged process is more advantageous for uniformity of thickness. All of the results are solely based on experimental outcomes without any theoretical bases.
9. The experimental analysis was performed to evaluate the effect of process parameters such as feed, speed, vertical step depth, and lubrication for the SPIF process on AA5052-H32 in rolling, transverse, and angular direction. Lubrication affects the most in all three directions. Speed and depth were found to be more sensitive in rolling and angular direction with a negligible effect in the transverse direction. A sheet was rolled before the experiment, due to which lubrication became the most significant parameter. Uniform Deformation without strain hardening was observed by increasing the speed[9].

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10. Chang and Chen[10] proposed the study of three sheets of incremental forming (TSIF) and compared it with a conventional incremental forming process (CISF) in terms of formability and forming limit curve for AA2024 and AA7075. The stress triaxiality is a ratio of hydrostatic pressure or means stress to von mises equivalent stress. The higher triaxiality values observed in TSIF compare to CISF. This is due to an increase in Hydraustatic pressure from Auxilary sheets preventing or/and confining crack propagation, increasing fracture strain which ultimately increases the formability.
11. Jagtap and Kumar[11] investigated minimum thickness and formability by varying the wall angle, preforming tool radius, and performing depth for AA-105 for Hybrid incremental sheet forming (HISF). The process is more sensitive towards the wall angle, and hence with an increase in wall angle results in a considerable reduction in minimum thickness as proposed by the sine rule of thinning. Improved minimum thickness was observed with an increase in performing tool radius due to increased contact area between tool and blank. The experimental data showed improved formability for higher wall angles which makes the process suitable for components having vertical walls.
12. Kumar et al.[12] investigated the influence of tool diameter, sheet thickness, tool shape, wall angle, step size, spindle speed on formability for AA-2024-O Aluminium alloy. An increase in tool diameter and tip radius helps to improve formability due to an increase in contact area resulting in lower stress and strain levels. For a large step size, the high force needed to form the material resulting in an increase in stress and lowering the formability. An increase in wall angle reduces formability justified by the sine rule of thinning. The higher spindle speed of the tool generates a significant amount of Friction, an increasing temperature which leads to improved ductility and formability. An increase in sheet thickness allows more material to flow under the same force, and hence formability increases.
13. Mostafanezhad et al.[13] carried out an experimental study to find out the effect on forming force in regards to wall angle, tool nose diameter, initial sheet thickness, step depth for Two-point incremental forming on AA1050. Formability can be interpreted in terms of forming force; higher the forming force required to lower the formability. A higher forming force was required as more material has to be formed with an increase in sheet thickness and step depth. A higher wall angle causes more lateral surface contact between tool and sheet, resulting in a higher forming force. However, the forming force generated due to the increase in wall angle was less significant compared to the forming force generated due to the increase in step depth and sheet thickness.
14. The effect of metal layer arrangement and metal properties on forming process and difference between solid metal sheet and bimetal (Cu-Al) composite sheet deformation illustrated by Liu and Li[14] for the SPIF process. The effect of layer arrangements with layer thickness, feed rate, and tool diameter showed higher formability for Al/Cu compare to Cu/Al. The thicker but weaker layer of Al forces cracks propagation of thinner but stronger layer of Cu in the case of Cu/Al.
15. Wang et al.[15] studied Friction Stir incremental sheet metal forming (FS-ISF) to achieve better surface roughness and formability for A.A. 2024-T3 and AA5052-H32. Experimental data showed an increase in formability (in terms of wall angle) for optimal region compare to a safe zone (Fig. 2.2). The flat end tool with high spindle speed generates higher temperature at the tool-sheet interface due to more contact area resulting increase in ductility and therefore increase in formability.

III. PROPOSED METHODOLOGY

There could be thousands of ISF strategies; nevertheless, based on the following literature, we have devised a handful. ISF's forming strategy entails a number of steps in the process of forming the final shape of the components. ISF techniques can be divided into two categories based on their forming strategy: single-stage forming and multistage forming.

ISF can be divided into four types based on their forming processes:

a) Single-point incremental forming

b) Two-point incremental forming

c) Double-sided incremental forming

d) Hybrid forming

For this project work, we have selected Single-point incremental forming.

3.1 Single-stage forming

SPIF is a fully die-less process for creating material sheet components and is a simple variation of ISF technology. With the help of a CNC milling machine or industrial robots, SPIF can be easily implemented. The blank is simply clamped into a hollow fixture around its perimeter, and a simple formingtool (usually of spherical shape) is moved horizontally over the sheet with a definite feed and predetermined toolpath[33]. N.C. instructions, which are generally generated using proper CAM software, control the route of the forming tool (Del-CAM, UG-NX, etc.). After finishing each contour along the horizontal plane, the sheet is pressed vertically downward by the formingtool. The SPIF approach is depicted in

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Figure 4.1. The step-down size refers to how much the sheet is pressed after each contour. This parameter (step-down size) is critical in defining the component's formability and geometrical accuracy[12].

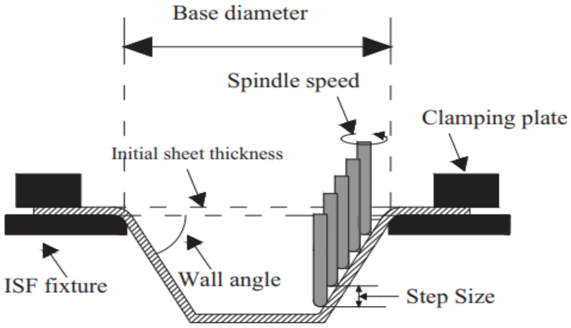

Figure 4.1 SPIF technique

Because just one point of the sheet comes in contact with the forming tool, this type of forming is known as SPIF. As the sheet is stretched into the support or fixture, this process is also known as "negative incremental forming." At the contact zone, the forming tool produces local Deformation. The sheet's lower surface is not in contact with any partial or full supports. During the deformation process, various stress and strain patterns are seen. The following are the essential characteristics of SPIF:

- Purely die-less process
- Produces concave shapes.
- Produces both axisymmetric and asymmetrical shapes.
- Suitable for low-volume production and prototyping.
- Negative incremental forming.
- Only one point of the sheet remains in contact with deforming agents (i.e., forming-tool).
- Greater formability.
- Smaller formingforces required.
- Quick change in design possible with the same hardware.
- Highly flexible and agile process.

Although SPIF has several of the aforementioned critical elements that boost the process' flexibility and agility. Nonetheless, researchers have identified some difficulties that hinder the commercialization of this die-less technique. The following are some of the problems that arise during the SPIF process:

- Geometrical inaccuracy
- Unwanted sheet-bending
- Greater spring-back effect

Researchers, however, worked to resolve the aforementioned concerns. Adaptive control techniques and changed toolpaths can improve geometrical accuracy during the SPIF process. But, these methods are insufficient to address the issue of dimensional inaccuracy and spring back. By installing a backing plate to the clamping fixture, unwanted sheet bending can be avoided. Again, because the backingplate must be changed for each target geometry, this approach limits the process' versatility.

3.2 ISF parameters

The ISF is influenced by a variety of factors. These variables have an impact on the ISF process and are divided into three categories, as indicated in Figure 4.1: workpiece parameters, machine parameters, and process parameters. Material parameters and geometrical parameters are split into two groups in the workpiece parameters. Figure 4.1 also shows the parameters for each group. The focus is on process parameters while dealing with CAM (computer-assisted manufacturing) methods.

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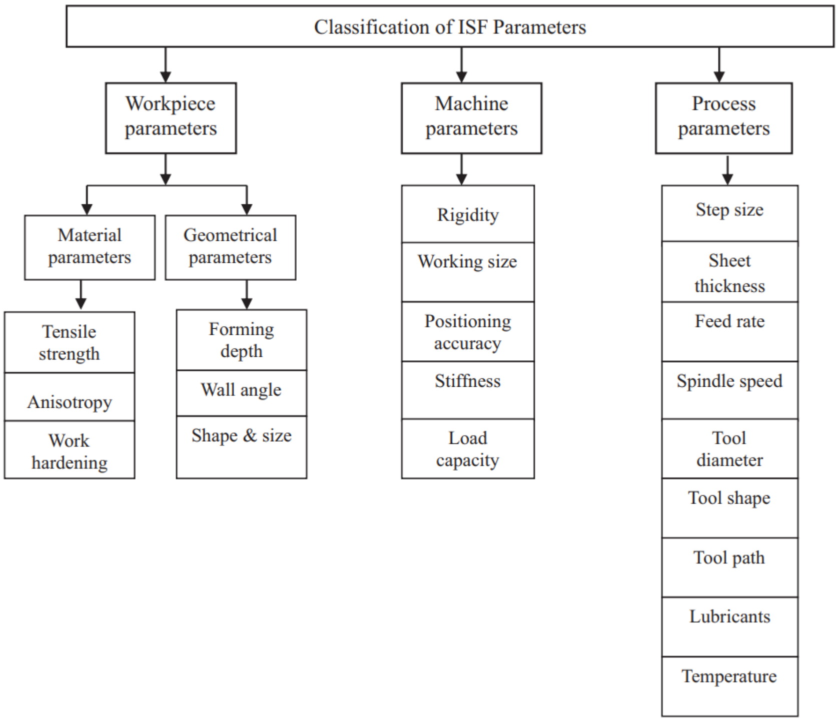

Figure 4.2 Classification of ISF parameters

3.3 classifications of parameters affecting ISF

ISF is majorly dominated by several parameters. These parameters are classified into three major categories: Workpiece parameters, machine parameters, and process parameters, as shown in Figure 1. The workpiece parameters are further divided into two sub-categories as material parameters and geometrical parameters. The parameters in each category are shown in Figure 1, but only the significance of the process parameters is explained in the following sections.

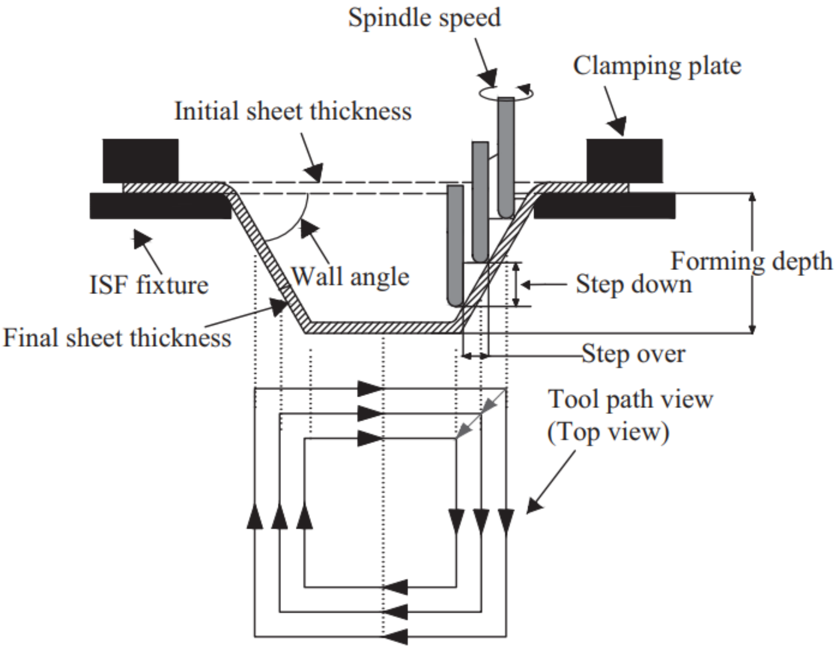

Figure 4.3 Illustration of some parameters of ISF

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3.4 process parameters

The third category of ISF parameters is the process parameters of the ISF process, which plays the most critical role in carrying out the ISF process safely and successfully. The requirements of the forming instruments and formingtools are also directly related to the process parameters of this novel die-less process[33]. In addition, the ISF process parameters yield flexibility to the ISF process designers and engineers in controlling the ISF process[34][27]. The different process parameters (see Figure 1) and their influences are discussed below.

(1) Sheet thickness

Sheet thickness is also a critical process parameter of the ISF process. By sheet thickness, we mean the initial thickness of the sheet to be formed into the desired shape. There are several experiments already performed by varying sheet thicknesses and materials ranging from 0.5 mm to 2.0 mm during the ISF process. Sheet thickness governs the formingforce required, formability, dimensional accuracy, and surface roughness of the formed components

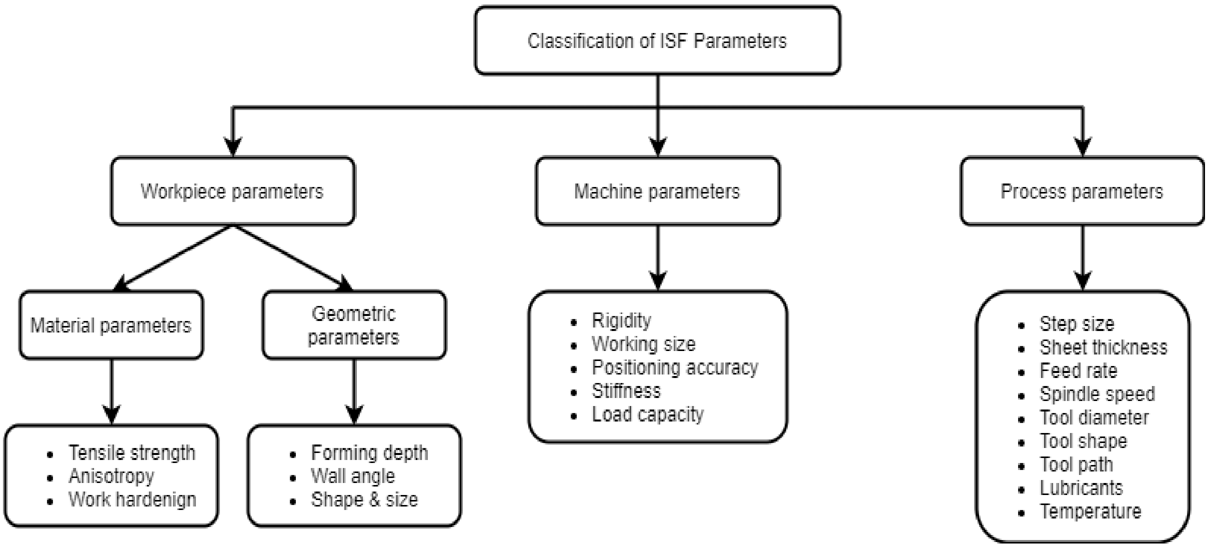

Figure 4.4 Classifications of ISF parameters

Significantly. For example, the higher the sheet thickness greater the formingforce required to produce plastic deformation of the material. However, A higher thickness enhances the formability of the material. According to the sine law*, When the wall angle increases during the forming process, the thickness of the sheet decreases; as a result, at the critical wall angle, the sheet material cracks because the thinned sheet material is unable to withstand the applied force. As a consequence, excessive sheet thinning causes the sheet material to fail.

(2) Feed rate

The feed rate is the rate at which the tool moves relative to the sheet in a given amount of time. During the ISF operation, it is the rate at which the formingtool moves on the stationary surface. The feed rate is another significant process parameter that affects component forming time. A higher feed rate means less formation time or cycle time for formed materials and vice versa. In ISF, the feed rate is usually expressed in mm/min and can vary from very low (200 mm/min) to very high (5000 mm/min).

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*$tf = ti * \sin\left(\frac{\pi}{2} - \alpha\right)$

tf = final sheet thickness; ti = initial sheet thickness; α = wall angle

(3) Speedle speed

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The spindle speed is the rotational speed of the tool at its axis during the formation process, and it is an important process parameter in the ISF process. The formingtool, which is mounted in the ISF machine's spindle, will rotate at different speeds as follows:

• Set the spindle speed to zero and lock it for rotation (No rotation).
• Allow the spindle to rotate freely, i.e., the spindle rotates in response to the tool–sheet interaction.
• The spindle rotates at a specific speed.

The friction at the tool–sheet interface increases in the last instance. Increases in spindle speed increase friction at the tool–sheet interface, which leads to an increase in sheet temperature, which leads to an increase in material ductility, which requires lower forming forces to deform the material[26]. As a result, smaller equipment may be used to perform the ISF process. At higher spindle speeds, the formability of the components improves as well.

(4) The geometry of Forming tool

Since the formingtool deforms the sheet material contour by contour, its shape and size (geometry) are critical process parameters that influence the component material's formingforce, formability, dimensional accuracy, thinning limit, and microstructure. The formingforce increases as the tool diameter increases due to a greater contactzone between the tool and the sheet in traditional ISF. A larger tool diameter, on the other hand, reduces the component's cycle time substantially without compromising the part's surface quality[35].

(5) Tool path

In the ISF method, the toolpath is the path or contour along which the formingtool is driven to achieve the desired shape of the object, layer by layer. The toolpath or contour is a critical parameter in the ISF process since it specifies the component's dimensional accuracy. Furthermore, the tool path specifies the necessary forming force, which is useful in deciding the ISF machinery requirements. Besides that, selecting the right tool path improves the formed component's formability, surface finish, and dimensional accuracy, as well as the processing time[35]. The toolpath for the ISF process can be obtained using CAM software for manufacturing operations[36][23][37]. Toolpaths can be divided into two groups, as seen in Figure 1, the profile toolpath and the helical toolpath.

The tool is given a step-down and moves in a plane until it reaches its initial location in the profile toolpath; then, it is given a step-over followed by a step-down (see Figure 3a). This process is repeated until the entire shape has been created. A constant Z-level toolpath is also known as a profile toolpath. In the case of the helical toolpath, the tool travels along the periphery of the finished part in a helical path with a pitch equal to step down, retaining the prescribed gradual helix along the vertical
direction as shown in Figure 3b.

Researchers have explored the effects of a constant Z-level toolpath (profile toolpath) versus a helical toolpath and

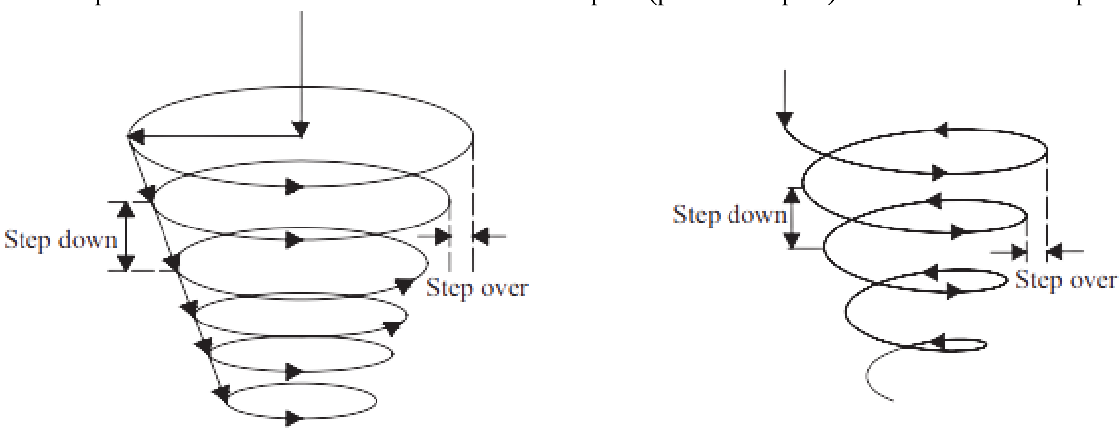

Figure 4.5 (a) Profile tool path (b) Helical tool path

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discovered that the helical toolpath successfully shaped the target geometry, while the constant Z-level toolpath cracked the sheet before reaching the target depth[38][39]. Furthermore, the tool's force is more stable during the helical toolpath, and there is no sudden force drop in the vertical direction[40][23].

The helical toolpath, also known as the continuous toolpath, offers forming-force stability while also enhancing component surface consistency. The profile toolpath, on the other hand, is also known as the discontinuous toolpath because it creates stretch marks after each contour and causes force signal instability during the ISF process[23][40][35].

The following two types of profile toolpaths can be defined:
• Straight step down
• Angular step down

The tool moves inwards by necessary step over before moving in the axial direction with constant step down after each contour in the straight step down toolpath. The tool moves in constant angular steps after each contour in the angular step down toolpath. In the ISF process, angular step down has not been found to be as effective as a vertical step down.

The following two forms of the straight move down can be defined:
• Constant straight step-down size
• Variable straight step downsize or constant scallop height step size

Constant straight step down is a step-down direction where the forming tool travels from top to bottom, contour by contour. Stretch marks are left at the transition points between consecutive contours in this type of toolpath, resulting in low surface quality with high step-down values (more than 0.5 mm). Variable straight step down, also known as constant scallop height step size, is a step-down path in which the forming tool follows a sequence of consecutive contours with variable step down to sustain the scallop height value. This method of moving the tool over the sheet's surface prevents stretch marks and improves the surface consistency of the formed components[41].

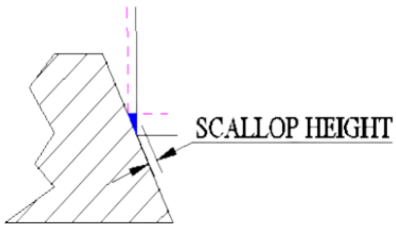

Figure 4.6 Scallop height

The constant straight step-down toolpath can be implemented in one of two ways:
• Unidirectional
• Bidirectional

The unidirectional toolpath is the most basic type of the profile toolpath (for a pyramid-shaped component). The tool travels in a single plane to its initial point, then takes a step down in a straight direction before completing the next contour in the same direction. The unidirectional profile toolpath leaves scratch marks along the line where the tool reduces in size. It also causes the workpiece to twist. A bidirectional profile toolpath can be used to prevent twists in the workpiece, which is similar to the profile toolpath except that the tool changes the direction of motion in each subsequent step, minimizing twists and improving geometric accuracy of the shaped part[42].

The following are two methods for executing the unidirectional and bidirectional profile toolpaths:
• With distributed increments
• Without distributed increments

With or without distributed increments, the unidirectional and bidirectional profile toolpaths can be executed. When using distributed increments, the tool completes one cycle and then adds a quarter of the toolpath cycle before moving on to the next, resulting in scar marks that are not apparent on the surface. In addition, forming forces are distributed

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uniformly around the geometry's edge, improving the part's geometric accuracy[42]. These kinds of toolpaths aren't usually included in commercial CAM software.

To avoid local deformation in the corner region, Wu et al.[43] suggested a method of distributed increment in which the tool travels downward along the diagonal direction of the truncated pyramid wall surface after forming each layer.

(6) Lubricants

The quality of components and the viability of the ISF process are determined by the lubricant selection. Product quality, tool wear, deformation mechanics, and requisite formingforces are all affected by the material-to-material friction between the tooltip and the workpiece surface, which has an effect on the production cost. Lubrication is used in the ISF process to minimize friction between the tooltip and the workpiece. It can be applied as a paste or spray coating on the blank to achieve self-lubricating results, or it can be applied in liquid form with the formingtool and blank submerged in lubricant. The lubricant must be able to withstand forming temperatures and not be squeezed out in order to ensure the presence of lubricant between the tool and blank during the ISF process[44]. Lubrication has an effect on the formed component's surface quality, defects, and formability. The right lubricant can minimize friction at the tool–sheet interface, resulting in lower forming forces during the ISF phase, increased heat dissipation, and reduced tool wear, all of which can extend tool life[45][46][47]. Reduced forming forces necessitate smaller, more cost-effective devices, as well as material flow optimization by reducing the number of stages required to form the final shape. Furthermore, effective lubrication can result in inhomogeneous deformation and reduced internal residual stresses in informed sections. The majority of lubricants serve as thermal insulators at the contact zone, extending tool life[48].

(7) Temperature

The temperature of the sheet is an important factor in the ISF process because it affects the component's forming force, formability, dimensional precision, surface morphology, tension, and strains.ISF may be done either cold or hot, depending on the temperature of the forming process. The cold formation is the process of forming materials at a temperature lower than the material's recrystallization temperature. The majority of the time, cold formation is done at room temperature unless the temperature of the specimen has to be raised to the recrystallization temperature. Various methods and equipment are used to keep the temperature of the specimen higher than the recrystallization temperature during hot formation.

VI.RESULTS AND DISCUSSION

Ideally, the sheet material process should not produce a change in the sheet thickness of the sheet material product produced, but, in some situations, the product may require different thicknesses at different sections of the component. Structural simulation of the part may be performed to determine the required sheet thickness for a given material for the desired product properties. Here, in this project total of seventeen experimental simulations (Table 5.1) were performed, and responses like Sheet thickness reduction, stress-induced, and stress triaxiality were extracted. The results of these responses were analyzed and optimized by a Design expert.

All the experiments were performed with the constant blank size of 222 mm x 222 mm x 0.8 mm, major diameter of 120 mm, minor diameter of 30 mm, total step depth of 30 mm, tool diameter of 10 mm, and incremental step depth of 0.8 mm. The material used for the experiment is DC04 (UTS = 270-350 MPa). Percentage step over, tool shape, and tool path are variable parameters of this project.

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Table 6.1 List of experiments

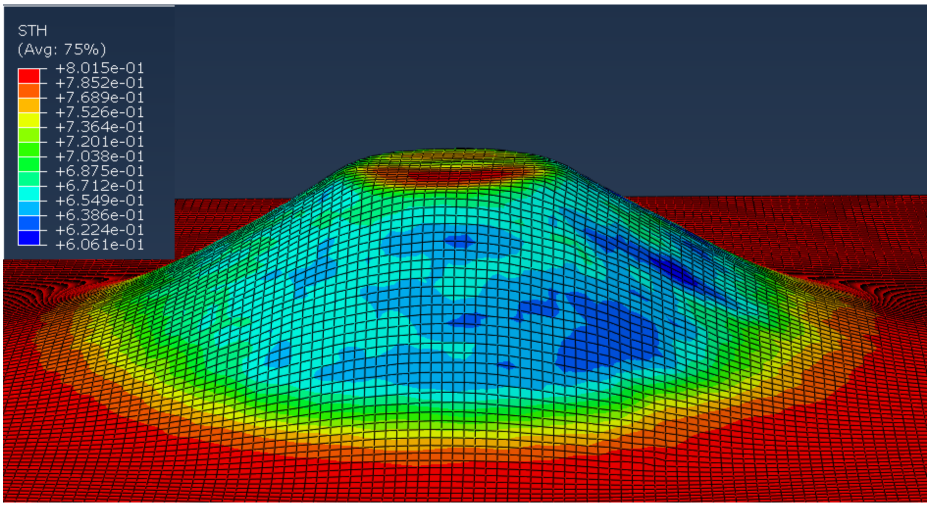
Experiment No.	Step over (%)	Tool shape	Tool path
1	40	Flat	Trochoidal
2	60	Flat	Trochoidal
3	40	Elliptical	Trochoidal
4	60	Elliptical	Trochoidal
5	40	Spherical	Constant Z level
6	60	Spherical	Constant Z level
7	40	Spherical	Zig with contour
8	60	Spherical	Zig with contour
9	50	Flat	Constant Z level
10	50	Elliptical	Constant Z level
11	50	Flat	Zig with contour
12	50	Elliptical	Zig with contour
13	50	Spherical	Trochoidal
14	50	Spherical	Trochoidal
15	50	Spherical	Trochoidal
16	50	Spherical	Trochoidal
17	50	Spherical	Trochoidal

6.1 Sheet thickness distribution

Ambrogio et al. [65] depicted that stretching conditions prevail in the SPIF process and significant thinning of sheets occurs. The maximum allowable thinning of the sheet is an important response to the ISF process. It is mandatory for a process engineer to know the allowable thinning of sheet material without fracture for successful ISF [66].

The final sheet thickness of the component for a particular wall angle in the deformed area varies as per the sine law. The final thickness of the sheet tends to decrease with the increase in wall angle and become zero with a 90° wall angle, which results in sheet fracture.

If the material of the sheet can be considered incompressible, then the sheet is deformed at the expense of thickness. Hence, thickness reduction, thinning limit, and thickness distribution can be considered as important criteria to predict the feasibility of the ISF process [67]. The sheet thickness at which failure occurs is known as the "thinning limit" of the sheet material.



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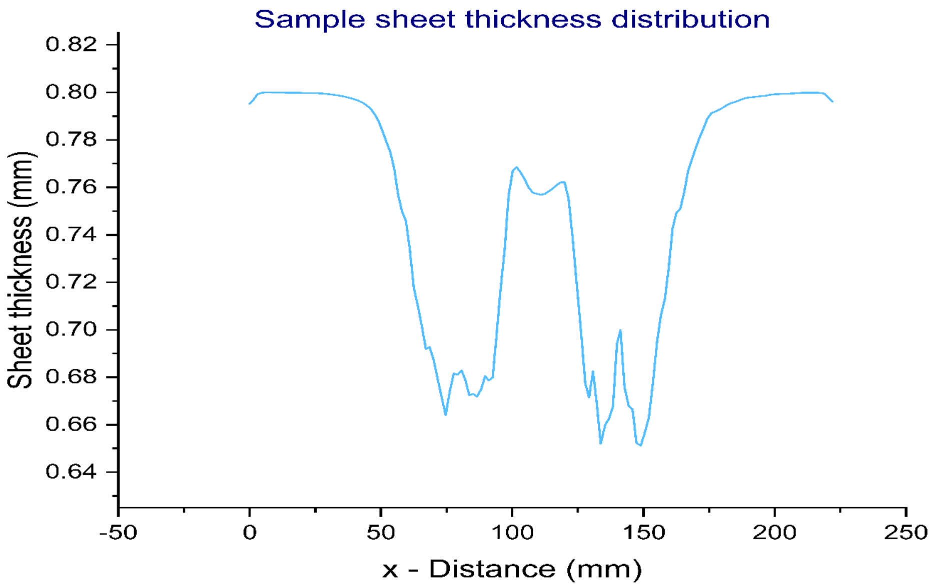

Figure 6.1 (a) Contour plot of typical sheet thickness distribution (b) Sheet thickness vs. x-Distance plot (Exp 11)

Typical sheet thickness distribution is shown in Figure 1. The sheet thickness is unaffected in the zone where the sheet is clamped. As we move towards the center of the frustum, thickness starts reducing as the material flows from edges to center once the sheet starts deforming. Maximum thickness reduction happens at the wall of the frustum due to the stretching, shearing, and squeezing of sheet material. In many types of research, it has been found that up to 80% of sheet thickness reduction is possible without failure. Again, the base of the frustum is unaffected as there is no contact between tool and sheet depending upon the tool path.

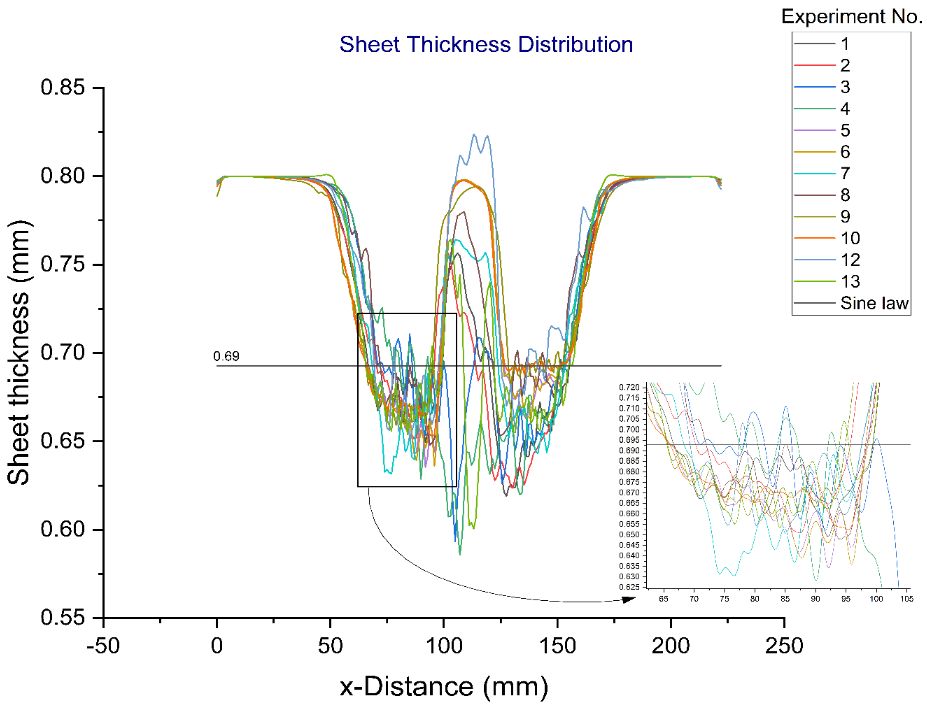

Figure 6.2 Comparison of Sheet thickness distribution

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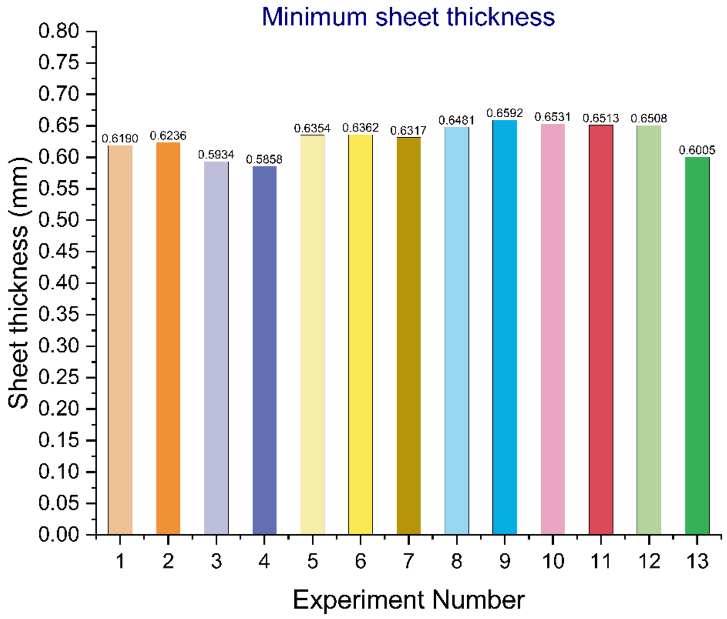

Figure 6.3 Comparison of minimum sheet thickness

Figure 2 presents an interesting comparison of sheet thickness distribution over the entire length of the conical frustum. The figure also shows constant sine law thickness (0.69). Sine law only accounts for wall angle, but that is not the only parameter that affects the final sheet thickness. All experiment follows a similar pattern of thickness distribution except the base of the frustum. The reason base of conical frustum follows a different pattern for different experiments is different types of tool paths. Tool paths like zig with contour and trochoidal make contact with the entire portion of the conical frustum, while tool path constant Z level only makes contact with walls of the frustum.

Figure 3 shows the comparison of minimum sheet thickness. A maximum sheet thickness of 0.6592 mm was observed in experiment 9, which had variable parameters 50% step over, a flat tool with a corner radius of 1 mm, and a constant Z level tool path. While, minimum sheet thickness of 0.5858 mm was recorded in experiment 4 with variable parameters of 60% step over, elliptical tool, and trochoidal tool path.

6.2 Effect of process variable parameters on sheet thickness distribution

While, Figure 2 and Figure 3 provide a brief idea of the effect of thickness distribution with regards to the combination of variable parameters, this section tries to analyze the effect of individual variable parameters on the sheet thickness distribution.

6.2.1 Effect of tool paths on the sheet thickness distribution

In this project, three types of tool paths were considered; two of them are non-conventional – Trochoidal and Zig with contour, while Constant Z level or widely known as profile tool path, is a conventional tool path.

The above plots compare the results of sheet thickness distribution for each of the tool paths. Figure 4(a) shows the sheet thickness distribution comparison for the non-conventional trochoidal tool path. This figure presents an interesting view, as experiments follow two different patterns. It was observed that experiment 1 & 2 follow close to typical distribution, experiment 3, 4 & 13 shows completely different distribution pattern. Experiment 3, 4 & 13 shows that minimum thickness is observed at the base rather than typically observed at the walls. This is because the trochoidal tool path starts contact at the canter of the contour and expands to the walls. Due to this, the direction of material flow is inward to outward, while in the conventional tool path, it is outward to invert. It may look like that this tool path gives a maximum reduction of sheet thickness, but by observing carefully, it is clear that thickness reduction at walls is much lesser than the base. This is because of the flow of material.

VII.CONCLUSION

In this experiment, the effect of non-conventional parameters, i.e., percentage step over, tool profile, and non-conventional tool paths, were analyzed for sheet thickness distribution and sheet thickness reduction. Apart from this, the generated von-mises stress

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in the sheet metal and the triaxiality were analyzed. ANOVA analysis was also done for sheet thickness distribution and stress distribution. The concluding remarks for the experiment are as following:

- Among all the parameters analyzed, i.e., percentage stepover, tool profile, and non-conventional tool paths, the effect of the non-conventional tool path is dominant, which is being followed by the tool profile.
- The maximum sheet thickness was observed in tool path zig with the contour in experiment number 9 (50% step over and flat tool with corner radius of 1 mm). This is due to the material being flowed from the center of the frustum to the walls because of the nature of the tool path.
- The minimum sheet thickness was observed in tool path trochoidal in experiment number 4 (60% stepover and elliptical tool profile). Unlike conventional tool paths, here, the material flows from the center of the frustum to the wall of the frustum. Due to this, even though the overall minimum thickness is low at the base of the frustum, wall thickness is relatively high.
- It was observed that the effect of percentage stepover is not significant for the thickness reduction but the uniformity of the thickness distribution. Higher the tool stepover, lower the uniformity of the distribution.
- The stress generated in the sheet metal while deforming the material is lowest in the conventional constant Z level tool path. At the same time, it is maximum for the zig with contour too path, which has maximum contacting length among all the tool paths analyzed.
- The stress distribution pattern greatly defers from the conventional stress distribution pattern for trochoidal and zig with contour tool path. This is due to the nature of the tool paths. In the trochoidal tool, path material starts deforming from the center, while in zig with contour, it starts from the edge and then moves inwards horizontally.
- The stress distribution is simpler for the zig with contour tool path, while it is clumsy for the trochoidal tool path due to its complex nature. This can be an important factor for the overall geometric accuracy and quality of the formed part.
- The effect of the formed part in the stress triaxiality wasanalyzed. In all the experiment the value of stress triaxiality factor do not cross 0.7 (<2-3), which ensures good overall formability.
- ANOVA analysis for this experiment produces P values less than 0.05, which ensures that the modeled simulation is significant.
- Simualtion time for the non-conventional tool paths is significantaly higher than the conventional tool paths.

VIII.FUTURE SCOPE

The effect of non-conventional tool path over sheet thickness distribution and stress distribution shows great potential for future study. Furthermore, several types of non-conventional tool paths can be generated for the incremental sheet forming. It is important to analyze the effect of individual paths on parameters like formability, surface roughness, geometrical accuracy, and fatigue strength. The effect of such a non-conventional tool path can also be analyzed for non-conventional ISF processes like TSIF and hybrid incremental forming.

It is equally much important to establish the relationship between percentage tool stepover with uniformity of sheet thickness distribution. Here, only three percent of tool stepover were analyzed; for the higher accuracy and uniform sheet thickness distribution, it can be as low as 10%. The effect of tool profile is important for surface roughness and geometrical accuracy. Though several researchers have already performed experiments to assess the effect of tool profile on surface roughness and geometrical accuracy, rarely any studies have been done combined with non-conventional tool paths.Simulation time is significantaly higher for non-conventional tool paths due to substantial contact length, which can be the limitation. In this project, the effect of all the parameters wasanalyzed with the help of simulations; it is important to validate the results with the help of physical experimentation.

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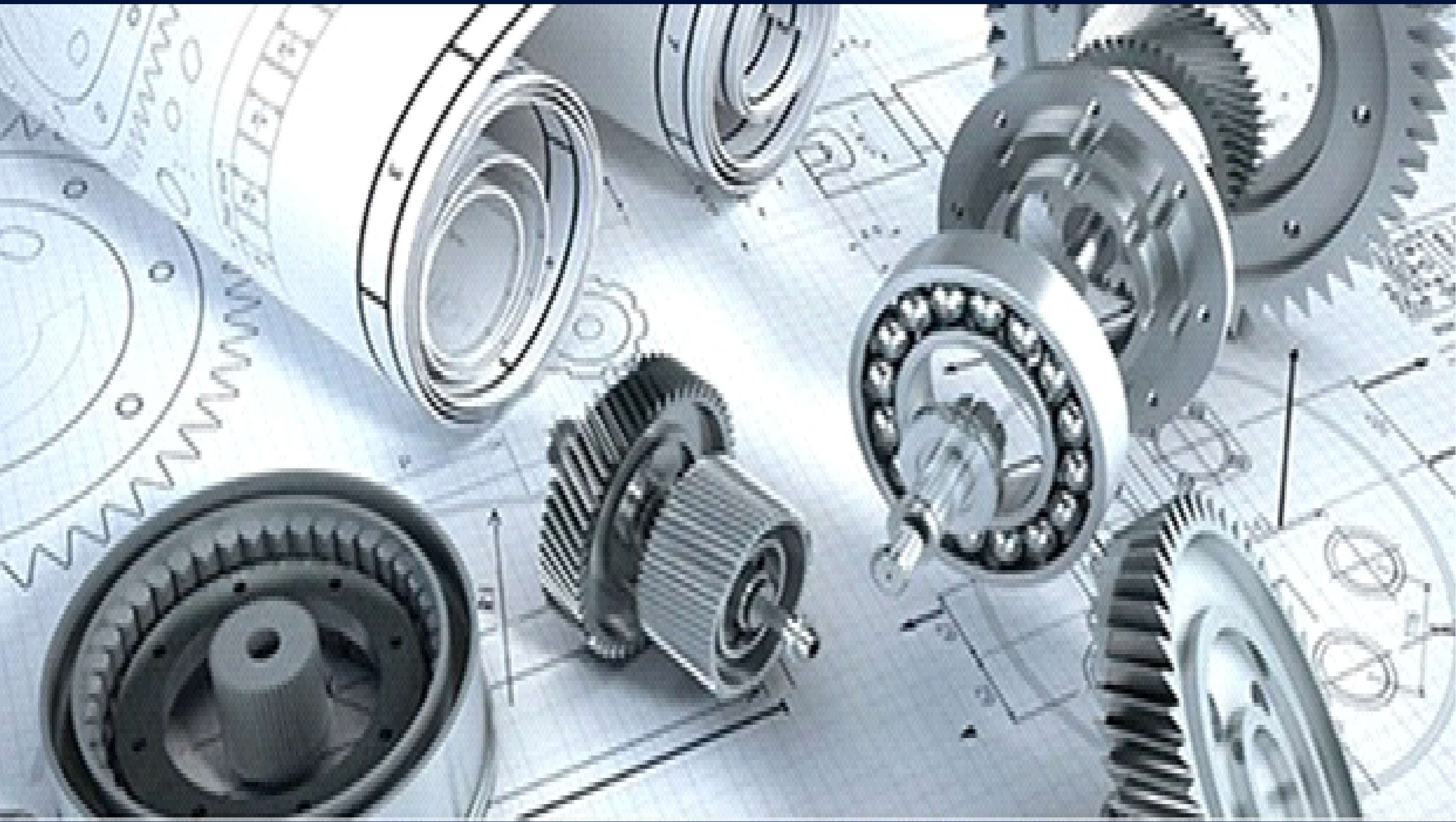

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