Experimental Investigation and Optimization of Incremental Sheet Metal Forming Process Parameters for Al6063 Alloy Using Computerized Numerically Control Machine

Asfawwesen Yalew Marye

A Thesis Submitted to the Department of Mechanical Engineering

School of Mechanical, Chemical, and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Manufacturing Engineering

Office of Graduate Studies
Adama Science and Technology University

Jun, 2023
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DECLARATION

I declare that this thesis entitled "**Experimental Investigation and Optimization of Incremental Sheet Metal Forming Process Parameters for Al6063 Alloy Using Computerized Numerically Control Machine**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Asfawwesen Yalew Marye	______________	______________
Name of Student	Signature	Date

RECOMMENDATION

I, the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Excremental Investigation and optimization of ISMF process parameters for Al6063 alloy using CNC machine" prepared under my guidance by Asfawwesen Yalew Marye. Submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Manufacturing Engineering.

Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedure.

Dr. Moera Gutu (Associate professor.)	______________	______________
Main Advisor	Signature	date

APPROVAL SHEET

I, the advisor of the thesis entitled "Excremental Investigation and optimization of ISMF process parameters for Al6063 alloy using CNC machine" developed by Asfawwesen Yalew Marye. hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Moera Gutu (Associate professor.)	____________	____________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Asfawwesen Yalew Marye have read and evaluated the thesis entitled "Experimental investigation and Parametric Optimization of tungsten inert gas welding process parameters during welding similar and dissimilar metals" and examined the candidate during the open Défense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Manufacturing Engineering.

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Finally, I would like to thank all my friends for their advice and help throughout the thesis.

Contents

List of Abbreviations

AL	Aluminum
AA	Aluminum Alloy
AISF	Asymmetric Incremental Sheet Forming
ANOVA	Analysis of Variance
ASR	Average surface roughness
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerically Controlled
DOE	Design of Experiment
DOF	Degree of Freedom
2D	Two Dimensions
3D	Three Dimensions
MM	Millimeter
M0S2	Solid graphite
Ra	surface roughness
RSM	Response Surface Methodology
OA	Orthogonal Arrays
SB	Smaller the Better
S/N	Signal-to-Noise
SIMF	Single Incremental Metal Forming
SPIF	Single Point Incremental Forming
S	Speed
TM	Taguchi Method
TPLF	Two Point Incremental Forming
TR	tool radius
T	Time
V	Velocity

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ABSTRACT

AA6063 alloy sheet materials are widely used in various industrial products, including aerospace, automotive, and biomedical applications. However, recent market demands have shifted from mass production to small batch production, leading to the need for specialized tools and longer lead times. Single Point Incremental Forming (SPIF) sheet metal process techniques can be used to form various sheet metal components in small batches and prototypes at a cheaper cost without the need for specialized tooling. The process designer can alter parameters such as step size, spindle speed, feed rate, tool diameter, lubrication, and tool shape. to increase SPIF compatibility on an industrial scale, a thorough research on process parameters has been conducted. The Taguchi-based experimental investigation was designed to optimize the procedure for forming AA6063 sheets. The finalized L18 orthogonal array has six parameters, with six levels. The surface roughness value of produced components was measured using the VOGEL model of roughness tester. The experimental inquiry showed that spindle speed, angle, step size, feed rate, and tool diameter enhance forming hardness, while increasing lubricant lowers it. Average part roughness is influenced by lubrication, feed, step size, and angle, but not by speed or tool diameter. This work sheds light on how SPIF technology for difficult-to-form materials will develop going forward. The results from confirmatory trials at the optimum values of input parameters validate the expected outcomes derived from studying responding characteristics, including forming force and surface roughness.

Keywords: Single point incremental forming, Aluminum Alloy 6063, Process parameters, Forming hardness, Surface Roughness.

Chapter -1

Introduction

1.1. Background of the study

One of the most important industrial subsectors for companies is sheet metal forming. There have been a number of technological developments made to the sheet metal forming process over time. Examples include deep drawing, stamping, and other conventional sheet metal forming methods. In order to perform the shaping process, these techniques need for the development of elaborately shaped dies. Therefore, the cost of tooling and die-making can only be justified when these processes are employed in mass production. Small batch production results in a higher variety and complexity of the products.

The low manufacturing volume cannot support the cost of tooling and die-making. The tools, dies, and punches also take up room in the inventory while not in use. Therefore, a variety of novel procedures must be developed in order to fulfill the demands of cost justification and the complexity of the sheet metal forming process in small batch manufacturing.

Incremental sheet forming (ISF), which is presently used in the sheet metal forming industry, was developed to overcome all of the aforementioned problems. Incremental sheet forming (ISF) is a versatile manufacturing technique that employs a single tool to create a variety of regular and complex forms without the need for separate dies. Additionally, because it does not require pricey dies or punches, it is more cost-effective when used in the production of complicated components using basic equipment than other standard sheet metal forming techniques, such as extrusion, hydroforming, and deep drawing (Tomaž & Zlatko, 2001). Additionally, it is utilized as a basic tool to gradually create the required pieces from sheets. However, it takes a lot of time, making it useless for bulk production.

The ISF technique can be divided into two classes: single-point incremental forming (SPIF), which does not require a specific die, and two-point incremental forming (TPIF), which requires a partial die as a support for the sheet during the process (Jeswiet J, et al., 2005). The current focus is on SPIF, where the sheet is molded into the appropriate forms using a tiny hemispherical tool that is controlled by a computer numerical control (CNC) machine along a specified tool path created by computer-aided manufacturing software. A fixture is used to clamp the sheet's edges.

This method enables the cost-effective production of prototypes and the small-batch production of complicated parts. Incremental forming (IF) is one of the most promising methods due to its various applications. Intricate external shapes and profiles in sheet metal may be produced with the Single Point Incremental Forming (SPIF) technology by using a hemispherical tool that is controlled by a CNC milling machine. It is especially well suited for rapid prototyping since complex shapes may be created without the need of dies or punches.

The tool moves along the predetermined path, shaping the sheet into the desired shape. Components It may be employed in a range of applications thanks to its versatility and inexpensive tooling, which are two notable advantages. It has the ability to create a large variety of extremely complex irregular components and highly specialized medical components. Forming Numerous studies looked at a variety of factors related to metal forming, including spindle speed, tool feed, and step size. The objective of this study is to improve the properties of metal forming, including sheet thickness and surface roughness after forming. The incremental sheet forming (ISF) process, used for low-cost small batch production, has steadily helped to solve them. Incremental sheet forming on a CNC milling machine gradually deforms sheet metal while doing away with the necessity for numerous manufacturing tools (dies and punches). By layer-by-layer controlled tool movement, involved sheet deforms into a three-dimensional contour. The surface quality of the formed parts, which is directly related to a variety of elements, including the forming process, the lubrication, and the materials used, is one of the most important features of metal sheet forming.

The main factors that affect the roughness in connection to the incremental sheet forming technique are the vertical depth, zd tool radius, TR the wall angle, and the relative motion between the tool and produced area.

Incremental Sheet Forming

In accordance with its objectives, the ISF process can be divided into a number of categories. The classification of this process is determined by a number of ISF variables and variants. ISF is classified as Single Point Incremental Forming (SPIF), Double Sided Incremental Forming (DSIF) or Two Point Incremental Forming (TPIF), and Hybrid Forming based on forming techniques. SPIF is also referred as negative incremental forming. It is really die-less forming technology, In the SPIF process, the lower surface of sheet does not come in contact with any kind of support, and various stress-strain patterns can be seen during the deformation ne between the sheet metal and the forming tool, and the other between the sheet metal and a support item such as a die or an auxiliary tool (Araghi, et al., 2009). presented a hybrid approach that combines stretch forming with incremental forming to generate a spherical cap with circumferential grooves. Using this method, the forming time can be cut in half or even more.

Additionally, two other approaches—single stage and multiple stages—can be used to carry out the ISF procedure. In single-stage forming, the forming sheet is secured in the fixture and then deformed one contour at a time in the horizontal plane using a rigid tool. After each contour, a vertical step down is carried out. Due to the constraint of the sine law, which states that "thickness would become zero and strain would become infinite at a 90° wall angle", SPIF is not practical for manufacturing components with 90° wall angle (Petek, A, et al., 2009). In general, employing SPIF with a single stage method, aluminum and steel alloys can be produced up to a 70° wall angle (Duflou, et al., 2009). By adopting multistage forming techniques, the challenge of constructing a 90° wall angle in a single stage strategy can be eliminated, and various attempts have been noted in the literature for the same (Centeno, et al., 2014)Further, ISF process is also carried out with assistance of laser heat, Electric heat, Induction heat, Water jet, Ultrasonic and, Friction heat for hard to form material.

Single Point Incremental Forming (SPIF) Process

The TPIF process requires partial or full dies in order to form the required shape. Similarly, DSIF requires a counter or slave tool at the back side of the sheet, which makes the process complex. SPIF is enhanced with process flexibility and can do away with storing expensive dies of components to be made, it can be preferable to TPIF and DSIF processes. For instance, replacing the fuselage components of old and outdated aero planes is a challenge for the aerospace industry. These kinds of unique parts typically do not have forming dies that are readily available in the required form. A technique like SPIF can solve those problems since it uses the least amount of energy to build the components. Although a large amount of work has been performed in SPIF, still it could not have been employed in manufacturing sectors (Yoganjaneyulu, et al., 2018).

The SPIF method is a wholly die-less process, in which a simple spherical tool moves over the blank sheet along a tool path managed by a Computer Numerical Control (CNC) machine to form a part. It is based on locally deforming the sheet layer by layer at a time. A three-axis CNC milling machine is capable of carrying out this process. The sheet is initially fastened in the hollow fixture that is directly installed on the machine table. The forming tool is mounted to a tool holder that is typically installed on the spindle of a CNC milling machine. The basic elements of SPIF system are CAD system (Computer Aided Design), CAM system (Computer Aided Manufacturing), CNC machine (Computer Numerical Control). The parts to be produced are designed, and solid model is created (CAD system) and this part-model is transferred to CAM platform to generate Cutter Location data (CL data). NC part programming is a vital task carried out on a CAD/CAM system. The NC part program transferred to CNC machine through Direct Numeric Control (DNC). Specifying the tool path and defining the part geometry are the two primary jobs in computer-assisted programming.

The Solid model used to define the part geometry includes all of the geometric, dimensional, and material characteristics for the component. The choice of the cutting tool step size is initial step in determining the tool path. In order to calculate tool-offset, this enables the tool diameter and other dimensions to be entered automatically. The next step is to define the tool route. The various CAD/CAM systems have varying capabilities, which leads to varied methods to generate the tool path. Part program transferred to the CNC machine, the CNC controllers moves the tool relative to the machine table in the definite tool path as prescribed by the program. So that the part geometry is formed which is replicated on the real part. The part is removed from the clamping system and send for inspection. By using Co-ordinate measuring machine and part geometry and dimensional values are verified.

Step size, diameter of the tool, feed rate, rotational speed, thickness of the blank, tool shape and size, friction between the punch and sheet, lubrication and tool path are some of the important process parameters in SPIF process. These parameters can have a significant effect on formability, surface roughness and final quality of products. Thus, a systematic study is essential to understand the effect of process parameters on forming to produce the product with required quality. Several experimental studies have been performed to understand the effect of process parameters on various aspects of ISF process and are described in subsequent chapters.

1.2. Rationale of the study

Technique As metal-forming technology develops at an increasingly rapid rate; a wide variety of industrial goods is being developed and produced in novel ways. One of these methods is incremental sheet metal forming, a more recent innovation that employs a progressive, sequential forming method. ISF This study proposed to demonstrate forming a dish product with a 100 mm x 100 mm square based truncated pyramid shaped using ISF because it can be used to form many complex shaped products for different applications in different manufacturing sectors like the automotive, aerospace, and sheet forming industries. Additionally, to examine the impact of chosen process parameter optimization on output response for the formation of pyramidal dishes rather than cone-shaped products Some SPIF settings have conflicting and sometimes disputed effects on the surface roughness of produced elements.

1.3. Statement of the problem

The necessity of technology advancement is very much needed when the complexity of product increases. The complexity and variety in the product nature have brought new sheet metal forming techniques. Among many sheet metals forming process operations, incremental sheet metal forming (ISF) is one of farming fabrication processes in sheet metal industries. Using this operation, the prototype and small batches which are used for the industries like automobile, aerospace, marine, etc. like other forming process, ISF also having many process parameters which have to be choose before forming any sheet metal. The most important research problems that can be minimizing process complicity is through proper forming parameters optimization. Among ISF process parameters, surface roughness is a critical parameter that is related to the surface quality of industrial products. Apart from its relationship with the correct functioning of the product, it has a significant impact on the aesthetics of the final product. Based on this idea, the present works are carried out. In addition, the research focused on the product defect such as roughness, crack, and irregular thickness

1.4. Objective of the study

1.4.1. General Objective of the study

The general objective of this thesis research is the effect of forming parameters on product quality and optimizing incremental Sheet Forming process on AA6063 alloy sheet metal.

1.4.2. Specific objective of the study

To achieve the main objective of this thesis the following specific objectives were designed

1. To identify the effect of incremental sheet forming parameters like speed, feed, inclination angle of the work piece and tool diameters on surface roughness.
2. To Optimization of most influencing process parameters on surface quality of formed sheet using Taguchi experimental design.

3. To Investigation product quality like surface roughness using contact surface profilometer.
4. To Investigation of micro hardness of formed sheet for different processes parameters.

1.5. Scope of the Study

The primary goal of the research is to evaluate various key parameter combinations to improve a process, identify the parameters that have the biggest impact on the outcome based on the result, compare each parameter concerning the product's surface quality, and assess the product's formability by focusing primarily on the production of truncated pyramid dish products.

1. The goal of the current work is to ascertain how different factors and how they interact affect the formability and surface quality of components made from AL6063 using SPIF.
2. Thus, AL 6063 can explore material properties and process mechanics for employing single-point incremental forming to perform a parametric study

1.6. Significance of the study

The significance of this study is to control the effect of the Process Parameter in the incremental forming process by determining any kind of incident; the proposed system can also be input for a better control design world in the CNC machine forming process that requires such efficient working service. It can be provided as a pre-step in other related studies. For instance, the result of the controlled forming technique is taken as input other than work their study on forming process way. This thesis is helpful for manufacturing industries due to the technology is easy and adaptable to 3-axis milling machines, and this technology aid society in better using different manufacturing various equipment.

The followings are some of the beneficiaries of the proposed work: -

- For the high-production company such as sheet-forming industries.
- To increase the surface quality of the formed product
- For the researchers as a reference.

1.7. Research Motivation

Incremental sheet forming is a relatively new technology and the physical phenomena behind the forming process have not yet been explained appropriately. ISF eliminates the use of a die which is required in almost all the conventional forming processes like deep drawing, stamping, etc.

Various research works have been successfully performed on incremental sheet forming using various materials and different methodologies.

The Incremental sheet forming as a potential process is presented to increase the variety of sheet metal parts. However, this process suffers from some drawbacks such as low surface quality and the high possibility of sheet failure. in this study simulation and modeling is used to design and applied to determine the significant effective parameters in this sheet forming process and also find the optimum values of the parameters concerning the maximum sheet thickness distribution and higher surface quality than current studies.

1.8 Thesis Organization

Chapter 1: The present chapter emphasizes the importance of ISF process in the current manufacturing scenario and motivation of present research work. It describes ISF introduction, input parameters, advantage, and, application of process. The remaining chapters of this thesis are summarized as under:

Chapter 2 reveals relevant systematic review on state-of-the-art in ISF. It includes process under various combinations of impact factors and optimization of input factors. From literature review, research gap is identified and objectives of the current research work are reported.

Chapter 3 describes preparation of experiment set up to perform experiments during SPIF process. Selection of sheet material and lubricants are also explained. It also described the methodology to define helical-spiral tool-path for experiments of pyramid shape geometry.

Chapter 4 deals with the application of TM for selecting the DOE and analysis of the surface roughness of the components formed during SPIF. Equipment used for measuring surface roughness has been explained. The effect of process parameters on surface roughness has been studied. Optimal levels of process parameters and confidence intervals for surface roughness are determined. focuses on the application of TM for selecting the DOE and analysis of the forming hardness. Equipment used for measuring forming hardness has been explained. Experimental work has been performed to study the impact of input factors on forming hardness

Chapter 5 summarizes the overall conclusion of the entire research work. The specific contribution of this work to the research community has been discussed. Some scope of future work related to this work also been enumerated at the end of this chapter.

CHAPTER 2
LITERATURE REVIEW

2. Introduction

The history of sheet forming and the sheet forming procedure have influenced how incremental forming is done now. The history, steps, and process of single-point incremental forming, as well as two-point and multi-stage incremental forming, are covered in this chapter. The conventional sheet forming process has drawbacks like high cost of tooling and high setup time in the case of small batch production. Over a period of time, these have been overcome by the incremental sheet forming (ISF) process which is being used for small batch production at low cost. Incremental sheet forming, eradicates the use of different types of production tooling (dies and punches), uses a spherical forming tool to carry out deformation in sheet metal progressively on CNC milling machine.

2.1.Sheet Metal Forming:

Process approaching Incremental Forming This part presents an overview of sheet incremental forming, there are many processes of sheet metal forming that have incremental approach technologies such as Hammering, Spinning, Multi-Point Forming, Stamping, Laser Forming Process and Water jet Process.

2.1.1. Hammering

It's considered one of the oldest Incremental Sheet Forming processes; it is traditionally a manual process. However, with the technologies involved, it could be processed with CNC machines and nowadays using robot arm technology nowadays to help control tool movement

2.1.2. Single Point Incremental Forming (SPIF)

SPIF is a type of Asymmetric Incremental Sheet Forming (AISF) described by (Jeswiet, et al., 2005) as "die less forming" of sheet metal using single point tool patented by (Emmens WC, et al., 2010) discussed about history of development of incremental sheet forming in which distinct difference is mentioned about patent claimed by team of Walter Berghahn of General Electric Company and Edward Leszak. The modern AISF was first described and developed by Mason in 1978 as small batch size sheet metal forming process. Asymmetric Single Point Incremental Forming (AISF) can be performed by holding sheet blank rigidly against the movement of tool establishing contact with sheet blank as shown in Fig. 2.1.

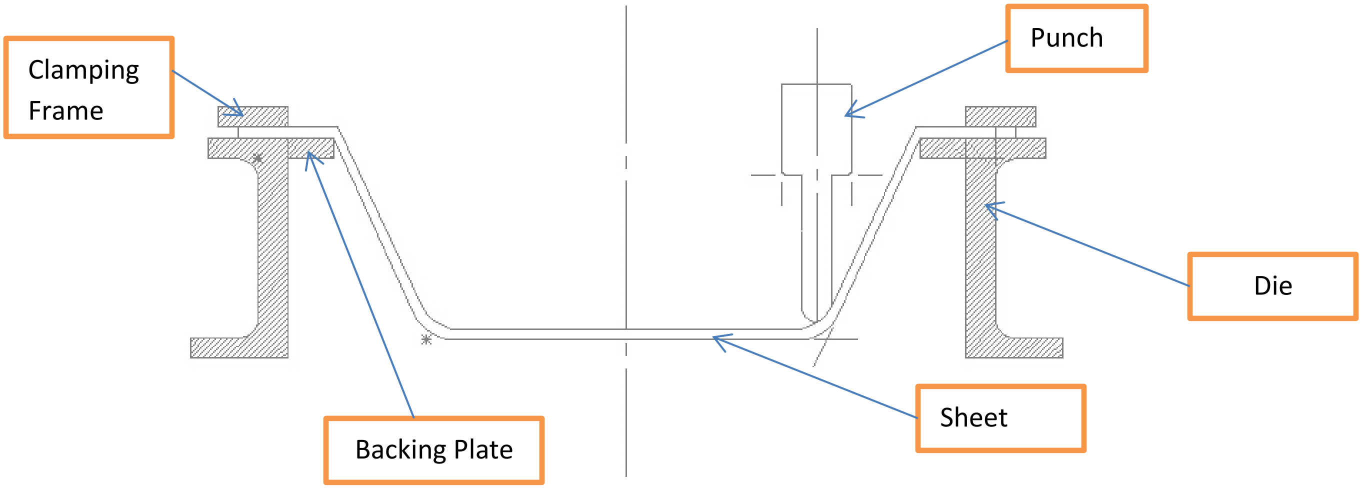


Figure 2. 1 Schematic diagram of Single Point Incremental Forming Process with equipment's(Micari F, et al, 2007)

2.2. Surface Finish

As a critical product quality constraint, surface roughness is regarded as a weak point in incremental sheet forming. It is of great importance to identify the impact of forming parameters on the surface roughness and optimize the surface finish at the production stage**.**

2.2.1. Surface Finish in ISF

Surface roughness is another challenging issue in the ISF process, which necessitates the investigation of the effect of forming variables on surface roughness and finish optimization (Hagan, E & Jeswiet J, 2004), performed surface roughness tests on incrementally formed Al3003 sheet using various tool depth increments and spindle speeds. It was concluded that the surface finish could be created using large waviness due to tool path and also small roughness because of large size surface strains. For incrementally made titanium parts (Cawley, et al., 2012). Reported a poor surface finish as all conventional lubrication squeezed out of the contact region of the sheet and tool. As a solution, a mixture of a sheet coated with microarc oxidation and lubricant of MoS2 paste was utilized. In a study on SPIF process, Allan and Hamilton proposed a model to provide instruction for improvement of the outer surface quality by selecting decent process variables.

A statistical method for surface metrology was proposed for deformed surfaces in SPIF process by (Powers, et al., 2010). It was concluded that when the roll marks are perpendicular to the forming direction, surface roughness parameters are greater (Powers, et al., 2010). In another study on the roughness of the deformed surfaces in SPIF process, an analytical approach for assessing the roughness was introduced regarding amplitude and also spacing related to the slope angle, tool radius, and step-down size. A good match between experimental and predicted values was obtained with an acceptable error (M. Durante, et al., 2010). In another study on using lubrication to decrease the friction in contact region of sheet and tool in the ISF method, (Azevedo, et al., 2015).

Found that the required viscosity for the lubrication decreases by increasing the hardness of the sheet material (Azevedo, et al., 2015), modeled surface roughness in the SPIF process of EDD steel using three different methods i.e., ANN, SVR and GP. In these approaches, diameter of the tool, feed rate, step-down size, angle of wall, and the type of lubricant were assumed as input parameters, and arithmetic mean values of surface roughness (Ra) and highest peak to valley height (R_z) were utilized as response parameters for finding the formed part surface roughness. Between these three methods, GP model was able to produce explicit relation among output and input parameters. This approach was used to optimize R_a and R_z To obtain the minimum surface roughness in SPIF, the optimum process parameters were obtained and validated by the experiments within 10% error (Kurra, et al., 2015), found that the interacting area of the tool affects the type of wear. On the tool tip, adhesive effects were observed due to the high contact loads, while the high stresses and the relative displacement of the work piece material on the edge of the tool caused abrasive wear, leaving marks and outbreaks on the tool edge. Because of these two wear mechanisms and the crack propagation due to the material fatigue, the tool life is limited.

As a solution, they used CrAlN coating with the filigree structure, which resulted in a 2.5 time longer tool life compared to the uncoated samples (P. Sieczkarek, et al., 2016). In a study by mineral oil was reported as the best lubrication to decrease the surface roughness in the SPIF process of copper sheet. None of the lubrication conditions reported in this study affected the grain size or shape in the material formed by the SPIF process. In addition, they reported that tungsten-carbide tool should be utilized in SPIF of copper to prevent adhesion of copper on the forming tool (K. Jawale, et al., 2017)in another study conducted by a new approach was introduced to improve the surface quality, in which a sheet is added between sheet and tool, as an interpolator to increase the contact region (X. Li, et al., 2017).

2.2.2. Effects of Process Parameters on Surface Finish

It is (Hagan, E & Jeswiet J, 2004) performed surface roughness tests and analyzed the influence of several forming variables, such as step-down size and spindle speed, on surface roughness. They concluded that the surface finish can be viewed as a resultant of large-scale waviness created by the tool path and small-scale roughness induced by large surface strains. With step-down sizes decreasing, the morphology of surfaces transforms from waviness to strict roughness without waviness (Powers, et al., 2010). Investigated the surface metrology through a SPIF case analysis. The effect of sheet rolling mark direction and analysis direction on surface topology in SPIF considering two process variables (feed rate and forming direction) first studied. The results showed that surface roughness R z is greater with rolling marks perpendicular to the forming orientation (Lasunon O.U, 2013), assessed the effects of three process parameters on the surface roughness in SPIF by a factorial design. The results showed that wall angle, depth increment and its interaction play an important role on the surface roughness, while feed rate has little effect.

2.2.3. Predictive Modeling for Surface Finish

Science as (Durante M, et al., 2010), described a model for evaluating the roughness both in terms of amplitude and spacing depending on three parameters: the slope angle, the vertical step and the tool radius. Analytical and experimental results were compared in terms of surface roughness in SPIF. The roughness values Ra, Rz, and the mean spacing between profile peaks were evaluated as the output of the models. The prediction and experimental results showed that a good agreement can be achieved with an error below 10% (Hamilton K & Jeswiet J, 2010), investigated the influences of tool feed rates and spindle rotation at high speeds during forming on the non-contact side roughness (i.e. orange-peel effect). A model for the orange peel prediction in SPIF established, which provided some guidelines for the improvement of external surface quality by choosing desirable process parameters during forming.

2.3. Surface Roughness

One of the essential factors in the field of sheet metal forming processes is the component's surface roughness. There has been a lot of research in the last several years, there is still lack of clarity about the surface roughness of parts created by SPIF process. This knowledge is essential for understanding and optimizing the process for improved response characteristics.

Al 3003 sheet was formed into a conical frustum with a 45° wall angle, in order to investigate the impact of tool rotational speed and step size on surface roughness (mean peak-to-valley height) in incremental forming process (Hagan & Jeswiet, 2003) The mean peak-to-valley height was observed to rise exponentially with step size, whereas

2.3.1. Important Parameters for SPIF in SPIF

each parameter mentioned below; sheet material, tool size dimension, forming angle, step size, feed rate, spindle rate, sheet thickness and lubricant; have their own influence on the process in different ways such as part accuracy, formability, maximum forming angle, thickness distribution etc. Hence it is important to notice what parameter has the most effect on the result in order to obtain perfect desired parts.

spindle speed had relatively little impact. Authors presented an analytical model based on a shear forming equation to forecast the peak to valley height (Rt) in CNC incremental forming.

The impact of tool path on surface quality and dimensional accuracy in two-point incremental forming was investigated by (Attanasio, et al., 2008). For this investigation, Authors have selected two alternative tool paths: (a) constant step depth and (b) variable step depth with imposed restrictions on scallop height. It was revealed that step depth and maximum scallop height have a significant impact on surface waviness. Lower step sizes with constant scallop height results in less surface waviness.

examined by (Hussain, et al., 2008). From his studies of surface roughness, it was noticed that the surface-hardened, high speed steel (HSS) tool with molybdenum disulphide (MoS_2) and petroleum jelly in a specified proportion has produced good surface quality. (Durante, et al., 2009) investigated the effect of tool rotating speed and its direction, on force, friction, surface roughness and temperature on AA7075-T0 sheets. When spindle rotation varied from non-revolving to rotating conditions, the roughness of the surface was found to decrease, It was also revealed that the tool's rotational direction had no impact on surface roughness.

(Hamilton & Jeswiet, J. , 2010)examined the impact of high feed rates and otational spindle speeds on the external non-contact sheet blank of surface roughness (orange peel effect), thickness distribution, and microstructure. Authors have presented a mathematical model, that makes use of measured roughness values as well as forecast the orange peel effect in ISF process by considering forming parameters.

By forming a pyramid frustums with AA7075-T0 aluminum alloy, (Durante, et al., 2014)compared maximum roughness (Rz) and average roughness (Ra) estimated from the analytical model with experimental values models. There was a strong association between experimental result with analytical model observed with 10 percent maximum error. Ra and Rz surface roughness value were found to increase as step size increased, but to decrease as tool diameter increased.

The influence of tool diameter, initial surface roughness Ra value of tool, and the friction coefficient (0.08, 0.15) between the sheet and punch on Ra and Rz of the inner surface of produced components were examined by (Oleksik, et al., 2010). Ra and Rz values were observed to rise with increase in tool diameter, initial surface roughness Ra value of tool, and friction coefficient. Additionally, Ra value of formed components was more than initial surface of blank (0.25 μm).

Cavaler et al., (2010) studied the effect of surface coating of the tool, tool radius, and step size on forming of AISI304 steel sheets. It was observed that the forming tool slipped in initial stages of forming. After a certain depth, the punch started to rotate due to rise in the friction between tool and sheet interface which was the effect of the larger contact area. It was reported that surface roughness decreased as step size and tool diameter increased. Compared to uncoated tools, coated tools generated better surface finishes.

In single point incremental forming of Al-5052, (Bhattacharya, et al., 2011) Bhattacharya et al., (2011) investigated the impact of process parameters on formability and surface finish. For all step depths, it

was noticed that surface roughness decreased with increasing tool diameter and with increasing wall angle. When step depth was increased up to a given wall angle, surface roughness first increased and then reduced.

The effects of the step down and two different lubricants (MoS2 and graphite) on Ti - 6Al -4V sheets were examined by (R & Treurnicht , 2012). It was also shown that surface roughness decreased as step size increased. Additionally, it was observed that the work material adhered to the tool's tip during the dry run, which decreased tool life and surface quality.

The effects of step size, feed rate and tool rotational speed on surface quality of deep drawing IS513Cr3 steel sheets were examined by (Babu & Kumar, 2012). As a result, the sheet surface being rough due to an increase in temperature at the tool-sheet interface. It was observed that surface roughness increased with tool rotational speed and lower surface roughness was achieved by increasing the feed rate and step size.

The effects of tool diameter, rotation speed of tool, feed rate, and step size on AA1050 sheet forming were investigated in SPIF process by (Radu & Cristea, 2013). In contrast to step size, the Ra was shown to decrease with an increase in punch diameter, rotational speed, and feed rate. Lower step sizes were used to provide better surface quality without affecting forming time by increasing feed rate.

(Liu, et al., 2014)used the Response Surface Method (RSM) as a DOE strategy to optimize the effects of punch radius, sheet thickness, feed rate, and step size. It was observed that sheet thickness was the most significant factors influencing surface roughness followed by tool diameter and feed rate. The formed component's outside surface roughness was shown to be larger than its inner surface roughness.

The impact of feed rate, step size, punch radius, and tool rotation on AA1050 - O sheets was optimized by (Echrif, et al., 2014). It was revealed that surface roughness decreased with an increase in punch radius but increased with an increase in speed of tool rotation, step size, and feed rate. The fine surface finish was produced by reduced step size because the waviness was reduced.

By analyzing the input parameters on AA6063 sheets, (Gulati, et al., 2016). optimized the SPIF process. The results indicated that as step size, sheet thickness, and feed rate increased, more roughness was observed. The lubrication is the most significant factor on surface roughness of formed part.

Electrically assisted double-sided incremental forming was employed by (Xu, et al., 2016) to test the dimensional accuracy and surface roughness of AZ31B magnesium sheets (EDSIF). The results indicated that the E-DSIF technique improves dimensional accuracy and surface finish.

In a two-point incremental forming process, (Asghari, et al., 2017). analyzed the impact of incremental forming parameters on the surface roughness of the formed part made aluminum

1050. The results indicated that, surface roughness of formed parts decreases with increased tool nose diameter and speed, while increases at larger wall angle and step size value. Additionally, it is found that 15 mm tool nose diameter, 63° wall angle, 800 r/min spindle feed, and 0.2mm deep step are the best parameter settings, that result in 63 % improvement in the overall quality characteristic from the initial parameter setting.

In order to evaluate the formability, surface quality, tensile strength, and micro-hardness, (Liu, 2017) carried out experiments on truncated funnel and pyramid frustum made of 7075-O aluminums alloy sheets using friction stir incremental forming. Experimental findings revealed that, surface roughness at the tool-workpiece contact surface increases as rotation speed rises in both the horizontal and vertical directions. When the tool is rotated at higher speeds (0–2000 rpm), the roughness initially rises and subsequently falls as the rotation speed rises (2000-7000 rpm) in the horizontal direction. As rotation speed increases in the vertical direction, roughness value decreases.

(Wei, et al., 2019). investigated, how the forming of an aluminum sheet affected the friction indicator at the tool/sheet contact and the roughness of inner surfaces. As the friction indicator rises, the roughness generally rises linearly as a result of rising sheet abrasion. The roughness of interior surfaces is found to be controlled by a set of parameters, dsinα/2pt (where d is the tool diameter, α is the forming angle, p is the step

size, and t is the sheet thickness). The factor d/2p followed by 1/t is found to have the highest contribution to the roughening of surfaces in this combination.

By utilizing the Taguchi approach and analysis of variance (ANOVA), (Kumar & Gulati, 2019) evaluated the impact of various input parameters on the surface roughness of formed components. In accordance with the findings, the ideal experimental conditions for average roughness have been identified as tool diameter (15.66 mm), tool shape (hemispherical), viscosity of the forming oil, sheet thickness (0.8 mm), wall angle (60°), feed rate (1500 mm/min), step size (0.2 mm), and spindle rotation (1000 rpm). Some studies, aside from actual investigations, concentrated on the accurate modelling and forecasting of surface topography.

(Kumar & Ethiraj,, 2020) examined the impact of the tool radius and the forming angle on surface roughness, and concluded that, the average roughness rises with a larger forming angle and falls with a larger tool diameter.

The influences of single-point incremental forming control factors on surface profile accuracies were studied by (Dabwan, et al., 2020). To understand and evaluate the findings, the analysis of variance was performed. In terms of minimizing waviness, circularity, and side angle errors, the results showed that larger tool diameter, thinner and softer materials produce enhanced profile accuracy and surface quality.

Prior to the forming process, (Xu, et al., 2020) applied an atmospheric plasma spraying (APS) self-lubricating coating to pure titanium substrates to enhance the lubrication state. When employing the self-lubricating coating instead of conventional mineral oil as the lubricant, it was observed that friction is greatly reduced throughout the forming process. The enhanced lubrication between the forming tool and TA1 sheet led to a better exterior surface finish of formed parts after coating.

A reliable high-frequency induction heating-assisted SPIF system was proposed by (Li, et al., 2022). High geometric accuracy and surface quality were attained by integrating rapid localized heating (600 °C and 700 °C) with a synchronized Inconel 625 Nickel alloy ball-roller forming tool. The results showed that the lubricant was dispersing as the forming tool passed through the center and lower area of the workpiece, which caused

2.4. Formability

Investigation of formability of material is an important aspect to be studied in the field of SPIF process. It is known that the material behavior and formability in SPIF process can be described by the maximum forming angle, maximum forming depth and forming limit diagrams. It has been well understood that heavy strains are responsible for local fracture of the components. Moreover, parts geometry and process parameters decide the degree of thinning and fracture in the sheet material. Therefore, research into how process factors affect part formability would provide assurance of component formed safely during ISF.

(Mulay, et al., 2017) investigated the impact of SPIF process parameters including step depth, feed rate, tool diameter, and sheet thickness on maximum forming angle while forming of high strength AA5052-H32 alloy sheet. In terms of the aforementioned parameters, a mathematical model is created using response surface methodology (RSM) and the Box-Behnken design. ANOVA tests showed that step depth and tool diameter significantly affect surface roughness and formability. Furthermore, the interaction between step depth and sheet thickness has a significant impact on the formability of AA5052 H32 sheet.

(Yoganjaneyulu, et al., 2018). investigated the fracture behavior (void coalescence) and dependence on different process parameters of titanium grade 2 sheets employing the SPIF process. The largest tool diameter (12 mm) was revealed to have the highest deformation fracture strain. The Forming Limit Diagram (FLD) also shows that the major true strain values increase with increasing speed and vertical step depth, and decreases with decreasing speed and vertical step depth.

(Khazaali & Fereshteh-Saniee, 2018) studied the influence of some important process variables, namely the initial sheet temperature, tool diameter and vertical pitch, on forming limit, thickness reduction, drawing depth and the final sample temperature. Based on the Taguchi and analyses of variance, the vertical pitch is shown to be the most

effective parameter for different objective variables, except the final temperature where the tool diameter is the most influencing variable.

The impacts of wall angle and step size on the formability of conical frustums cone were examined by (Xiao, et al., 2019). Result shows that lower step size and lower wall angle together produced a noticeable improvement in formability.

(Xiao, et al., 2019) examined the mechanical characteristics of an incremental sheet forming process using 1.0 mm thick AA7075-T6 sheet at various temperatures (ISF). According to the results, when the temperature increased, formability increased significantly. But as the vertical step depth increases, the formability decreases.

The effects of step size and wall angle on formability, geometrical accuracy, and thickness reduction while employing warm incremental forming were examined by (Mohanraj & Elangovan, 2020). Based on the findings of the experiments, it was discovered that titanium grade 2 sheets formed at a temperature of 300 °C and an incremental depth of 0.1 mm show higher formability. Experimental work is used to verify the predictions of the thermal model, and it has been shown that the experimental findings and the thermal model correspond quite well.

2.5. Tools used in SPIF

The tools used in SPIF are most often a solid hemispherical shape. Tool diameters commonly range from less than 6 mm to 25 mm or greater. Developments on tooling have included flat-ended designs (Ziran Xu, et al., 2009), non-cylindrical tools (Allwood J.M. & D.R. Shouler, 2007) and a tool with a free rolling spherical end to reduce friction (Jeswiet, et al., 2005). It has been shown that the diameter of the tool has a considerable effect on the forming limits of a given part and material, with smaller tools forming higher wall angles. The increased formability of small tools is generally explained by the more localized strain distribution, resulting in suppressed neck formation (P a F Martins, et al., 2008).While smaller tools can offer improved formability due to suppressed neck formation; smaller tools can also produce higher surface friction, as evidenced by spelling and high surface roughness. Studies by (Cavaler L C C, et al., 2010) found that the increased friction may be due to a larger angle of wrap around the tool due to indentation. Using a tool that is too small can result in degradation of the inner surface due to spelling and adhesion, as well as reduced maximum wall angle due to the increased tangential stress. In one extreme case during the work performed in this thesis a very small tool caused a buildup of material, forming a solid wall that starved the tool of lubrication and eventually caused failure of the tool, shown in Figure 2.6. Using Avery small tool results in conditions approaching that of cutting with an extremely dull tool. Some work has been done to investigate the performance of non-hemispherical tool sin SPIF. (Ziran Xu, et al., 2009) studied the effects of using flat-end and hemispherical tools for SPIF and found that by using flat tools with radiuses corners, both formability and shape retention could be improved. Particularly, the bottom surfaces of parts could be made flatter than with hemispherical tools as the tools supported the sheet better than a hemispherical shape.

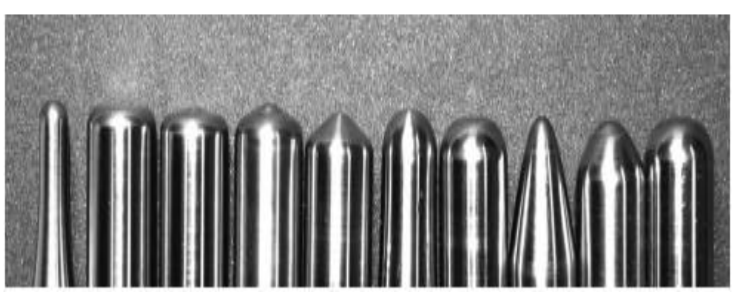


Figure 2. 2 Example of forming tools used by **(Ziran Xu, et al., 2009)**

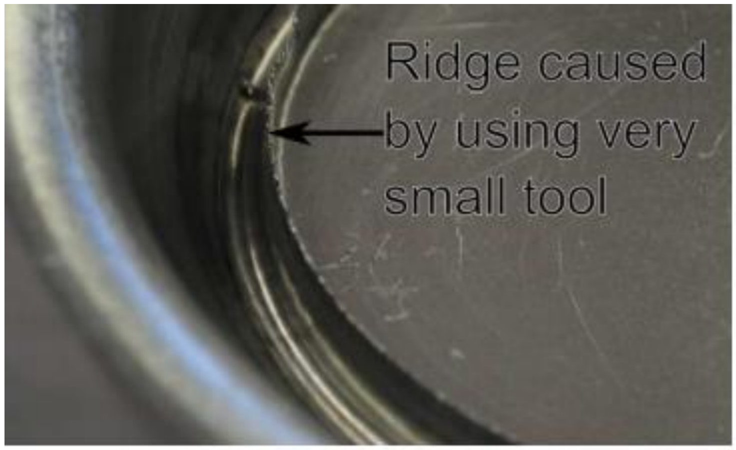


Figure 2. 3 Buildup of material on the inside of the part observed while using a very small diameter.

2.6. Feed rate and Spindle Speed

Because this is no chip load as in conventional machining, the spindle speed and Feedrate do not have the same large effects in SPIF as they do in conventional machining. They do, however, have an effect on the energy efficiency and carbon footprint of the process. (Branker K, et al., 2011), found that increasing the feed rate and step size for a given part reduced the total energy consumed by 69% as well as a substantial reduction in the net CO 2 production. The spindle speed does, however, affect the amount of friction at the tool/sheet interface. In general, more friction leads to a worse surface finish and lower forming limits, in addition to higher energy consumption. It has been shown, however, that high spindle speeds may result in an increase in formability (Jeswiet, et al., 2005), (Durante M, et al., 2010), speculated to be as the result of heat from friction reducing yield stress of the material. Experimentation by (Palumbo G & Brandizzi M, 2012), revealed that high spindle rotation speed had a stabilizing effect on necking.

2.7. Lubrication

The importance of lubrication in SPIF cannot be understated, particularly in the case of the electrically assisted work done in this thesis. Lubrication reduces friction at the tool/sheet interface, and to some extent cools the process. The impact of various lubricants and tribological conditions is an ongoing area of study within SPIF. The performance of a lubricant is therefore perhaps best described by its ability to stay within the contact area (Adams D & Jeswiet J, 2012) found that while using a variety of gear oils of slightly different grades there very little difference in the power consumed by the mill. When using a grease based lubricant, however, the grease squeezed out of the contact area and not able to flow back into place. The result a drastic increase in power consumption (visible in Figure 2.4 as the tool became starved of lubricant, and premature failure of the part as well as very poor surface quality. Found that while forming commercially pure Titanium, the lubricant and application method used had a large effect on interior surface quality of a part (G. Hussain, et al., 2008). The best method found to be micro-arc oxidization and anodic oxidation to create pores in the surface of the sheet to retain MoS2 lubricant. A similar lubrication method employed by (Guoqiang Fan, et al., 2010). It has also been observed that the tool shape has a direct impact on the lubricant performance. (Cawley, et al., 2012), Observed that angled tools produce a lubricant trail that corresponds to a non-constant contact patch. Further (Adams D & Jeswiet J, 2012), found that small tools can create a buildup of chips that certain lubricants are not able to flow back over, eventually starving the tool of lubricant. The viscosity of a lubricant can therefore become important in SPIF not just due to the lubrication properties but the ability to flow back into the contact area after it has been pushed out of place by the tool.

the bule line represente the energe used for a will lubricated run, the red line represente the energe used for a grease lubrication that resulted in an nulubricated state,

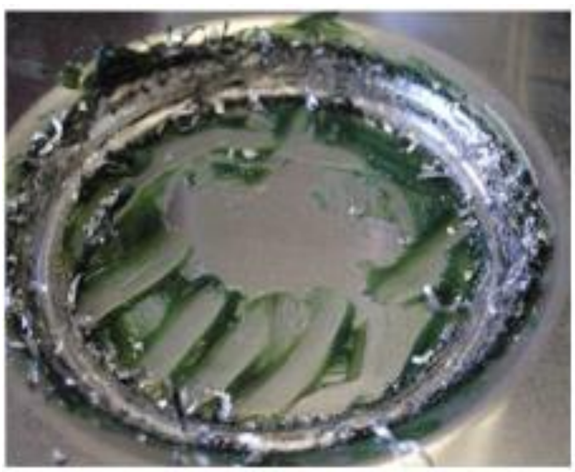


Figure 2. 4, Failed part made with grease lubrication. Note the chips created by firiction, the poor sureface quality, and the forming area where all of the lubricant has been squeezed out

Table 2. 1 Literature summery made Many researchers have contributed towards the process parameter optimizations. For instance

Name	Material and method	Finding
Ham and Jeswiet (2010)	AA3003 and SPIF	showed that step size has little effect on the maximum forming angle, while material thickness, tool size, and the interaction of material thickness and tool size have a significant impact on maximum forming angle. Depth and diameter have no effect on forming a part, and faster spindle rotation speeds improve formability.
Alves et al 2016	Plastic material and SPIF	Concentrated on experimental inquiry for geometric correctness and surface quality and came to the conclusion that the thickness of the plate, the wall angle, and the usage of dummy sheet had an impact on the formability and surface quality of the components.
Sarraji et al 2017	Hared material and ISMF process	Four process factors were examined for their effects on the thickness variation aspect of the ISF process, and the results demonstrated that the tool's travel direction in relation to the rolling direction had the biggest impact on the thickness variation.
Cavaler, et al 2019	AISI 304l stainless steel Sheets and SPIF	Investigated roughness; Senthil and Babu concluded that an increase in spindle speed raises the roughness levels by modifying the input parameters. Additionally, increased spindle speeds and step depths produced information about chips on the surface of the created pyramid, whereas Cavaler confirmed for an AISI 304 austenitic stainless steel that roughness decreases as the vertical depth is increased.

2.8 Literature Gap

Effects of process parameters on surface roughness during incremental forming, like tool radius, sheet thickness, step size, tool rotational speed, feed rate, and lubrication were investigated by different researchers. Formability and surface roughness have been taken into consideration for optimization because these were crucial output factors. However; few researches has been focused on the evaluation of overall surface roughness.

In addition, the impact of roll mark orientation of metal sheets on surface roughness was clarified when the surface roughness measurement was carried out along the step down direction. Although this aspect has been less considered in two processes factors which may limit the findings. Therefore, this thesis research focused on further investigation of process parameters like tool speed, fed rate, work inclination angle and effect of tool diameters on the quality of formed sheet surface roughness. Optimization of most affecting parameters was also included since few r research findings on those parakeets were conducted specially for Aluminum 6063 with thickness of 1 mm.

Few studies devoted to the influence of lubrication on the surface quality of the final product, still there is scope to investigate effect of different lubricants on surface quality of different soft to form work material.

CHAPTER- 3

MATERIALS AND METHODS

3.1. Introduction

In the first section of this chapter, material characterization is described and used to create a fracture forming line (FFL) utilizing a number of in-depth mechanical tests. Before beginning an experiment, it is crucial to establish the FFL since it can forecast both the behavior of a material during incremental formation and fracture. The next section will go through the experimental setup utilized in this work as well as every piece of equipment that was employed. At the conclusion of the chapter, single point incremental forming component inspection employing a variety of data-gathering approaches will also be covered.

3.2. Experimental Setup

An essential piece of equipment utilized in this experiment are described in the experimental set up section, along with details on the sheet metal, forming tool, CNC machine, backing plate, clamping system, and lubricants.

3.2.1. Sheet Material

The material used is Aluminum Alloy A16063 in a thickness of 1 mm. According to Fig. 3.1, the initial sheet is 250 × 250 mm in size. Due to the fact that this aluminum alloy is quickly bent, sheet metal must be kept secure after cutting to prevent any surface flaws. The results of the thickness inspection and roughness test are extremely similar to the actual value.

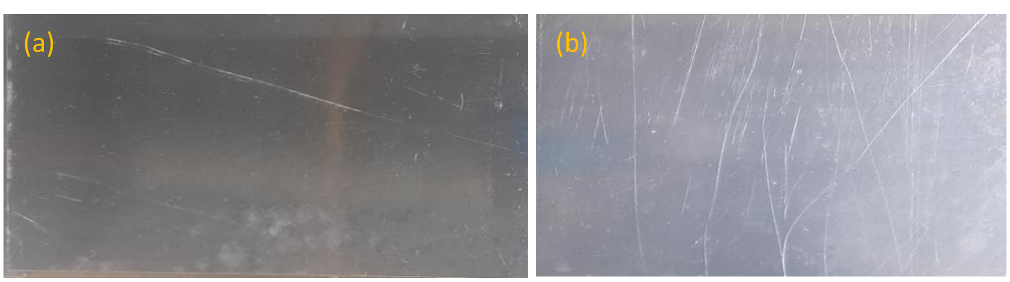


Figure 3. 1 (a) & (b) 250 x 250 Aluminum 6063 sheet for SIF manufacturing

According to Table 3.1, Aluminum Alloy Al6063 is a mixture of various elements, but 97.5% Aluminum stands out as the most significant one. As a result, this alloy is virtually entirely composed of aluminum. The material chosen for this thesis is Al6063 aluminum alloy due to limited works done previously on this material. Al 6063 is a formable material with moderate strength to weight ratio due to which it is largely used in the automotive and part profiles for architectural. Among all the variations of Al 6063 alloy, Al 6063-T5 are chosen for the current work because it is known to have good formability. Therefore, Al 6063-T5 sheets of 1 mm thickness are used in this thesis. The chemical composition and Mechanical properties of Al 6063 are as shown

Table 3.1 The composition of Al6063:

Component	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Wt%	97.5	0.1	0.1	0.5	0.45-0.9	0.1	0.02-0.6	0.1	0.1	0.15

Table 3.2 Mechanical Properties of Al 6063:

Properties	Metric Units
Density	2.70 g/cc
Hardness no. Brinell	60
Ultimate tensile Strength	186 Mpa
Tensile yield strength	145 Mpa
Modulus of Elasticity	68.9 Gpa
Poisson’s ratio	0.33
Fatigue strength	68.9 Mpa

The size of the blanking sheet are selected for this research is 200 x 200mm out of this the working area is 100 x 100mm in which the ISF is performed.

3.2.2. Forming Tool

The tool will have a hemispherical end and a cylindrical design. To execute a sample simulation, we employ two different diameter tools, measuring a hemispherical shape with tips that are 8mm, and 16mm in diameter are used as forming tools. While ball tip tools are used for multi-stage incremental forming of vertical walls, hemispherical tools are utilized for single point incremental forming and outward forming. Using a hemispherical tool, The tool's vertical portion rises 16 mm above the tip. Both tools are composed of PM300 tool steel, which has undergone a standard hardening heat treatment to boost its hardness and wear resistance level (ISBN 0-8493-9013-3). Fig. 3.2 show the tools. The College of General Wingate poly technic college manufacturing technology machine shop produced of the tools. In this instance, the entire production process is completed with just one forming tool. Tool has properties according to Table 3.3.

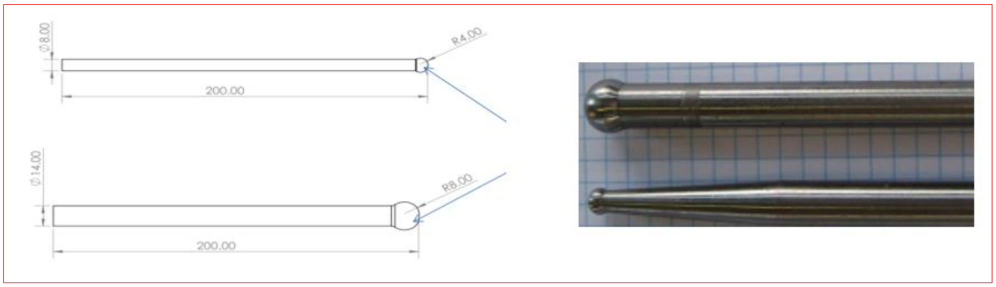


Figure 3. 2 Hemispherical simple forming tool (a) Geometry (b) Pictorial view (All the dimensions are in millimeter).

Table 3. 3 Forming tool properties

Properties	Value
Density	7.85 g/cc
Hardness	310 HB
Specific Heat Capacity	28 W/m-K
Thermal Conductivity	12.8 m/m-C
Major Component Element	94.52% Fe

Table 3.3: Forming tool properties

For a good surface finish and accurate finished component, the most crucial properties of a forming tool are having strong hardness and good wear resistance. As a result, the forming tool in this project has to be well-treated to improve the necessary qualities. Free spindle speed of the forming tool is assisting in this production by ignoring the friction between the tools and the sheet metal, hence boosting formability. Additionally, utilizing a ball head tool is more formable than a hemispherical head tool.

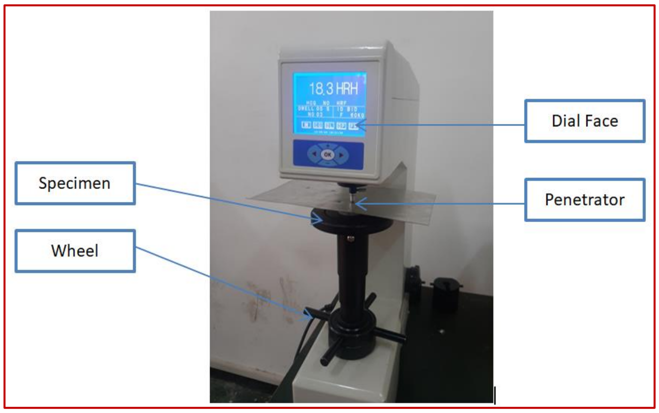


Figure 3. 3 Hardness test Machine for tool

3.2.3. CNC Machine

For manufacturing experimental parts, FANOC MV- 40VA 3 axis vertical CNC machine in Fig. 3.4 was used to perform the operation. It is located at the Department of Mechanical Engineering workshop of the College of General Wingate poly technic college.

Figure 3. 4 CNC optimum 30 milling machine

Table 3. 4 Optimum 30 milling machine CNC machine's specification

CNC Fanuc milling machine	
Machine type	milling machine
Control	CNC
Number of Axes	3
X Axis Travel (mm)	209.250
Y Axis Travel (mm)	260.350
Z Axis Travel (mm)	433.870
Motor Power (kW)	15kw/22kw
Max. Tool Storage Capacity	V8
Machine Speed (mm/min)	24000rpm

3.2.4. Backing Plates and Clamping System

Jig must be used to hold sheet metal while the process is being done to clamp it. Twelve screws are placed all around the sheet to secure it in place. Depending on the final shape, each Jig has a separate backing plate that is either round or rectangular. Backing plates have the purpose of helping to achieve desired geometry as well as preventing significant deformation of the sheet during forming. This clamping system from INEGI was created specifically for incremental shaping on an **FANUC** CNC machine.

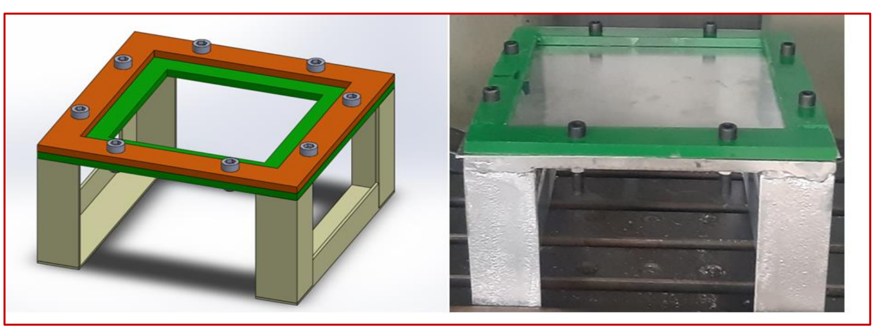


Figure 3. 5 Rectangular backing plate

3.2.5. Lubrication

The lubricant TOTAL FINAROL B5746 [see Fig. 3.6], which is utilized for traditional stamping processes, is used to lubricate sheet metal. Every ISF experiment will use the same lubricant. Applying lubricant is important to facilitate tool movement, lessen final surface roughness, minimize tool wear, and reduce heat produced by friction between the forming tool and the sheet metal.

Figure 3. 6 different lubricant

Small quantities of lubricant are applied continuously to the surface that the tool travels over. When there are plenty of debris floating in the lubricant, it needs to be cleaned and reapplied to avoid creating an unfavorable surface roughness.

3.3. Methodology Procedure

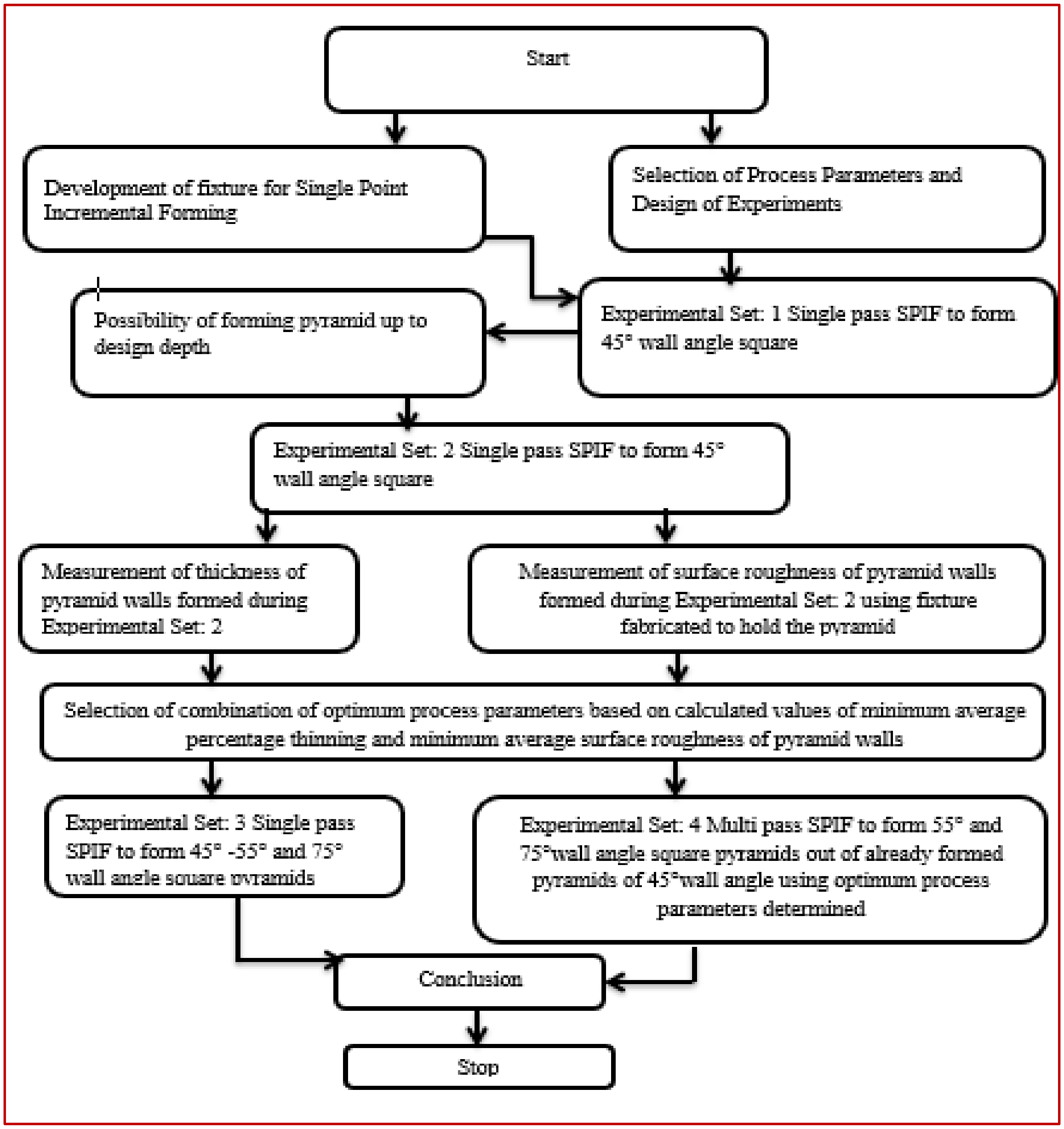


Figure 3. 7 Methodology Procedure

3.4. PROCESS PARAMETERS

Numerous Incremental Sheet Forming process parameters, including feed rate speed (f), rotation speed (S), step-down (z), tool radius (R t), type of lubrication employed, and process temperature, affect the strength needed to create each process, the material's formability, surface finishing, and accuracy of the final product. The essential parameters of the SPIF Incremental Sheet Forming process are shown in Fig.3.8 The primary variables of the SPIF Incremental Sheet Forming method

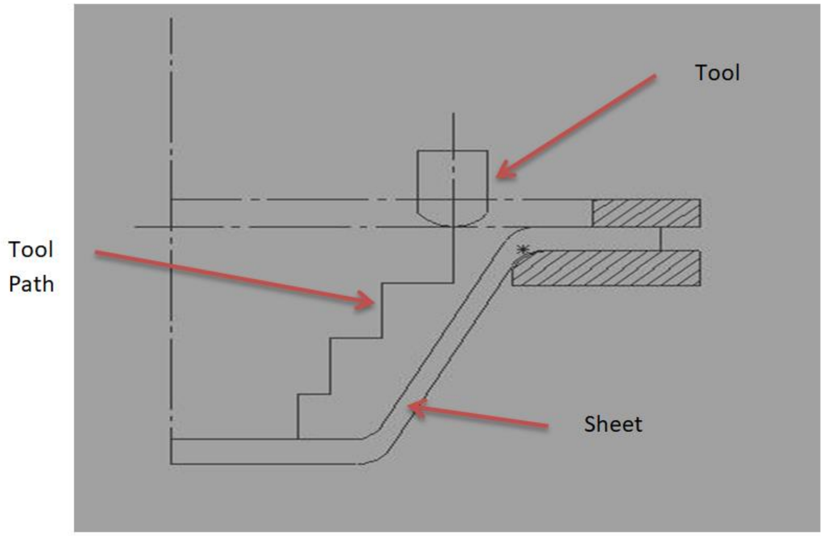


Figure 3. 8 Indicate ISF tool bath mothed(Mulay et al 2017)

The ultimate shape of the produced sheet is decided by the tool's path, which reduces the starting sheet thickness to the final thickness in accordance with the wall angle employed (45), which is determined by the value of the lateral increment.

3.4.1. Forming Speed and Feed

The influence of forming speed, both rotational spindle speed (RPM): speed at which tool rotate about its axis and feed rate: speed at which tool moves over the blank sheet are important regarding the SPIF process. The heat produced by friction is directly proportional to the relative motion of the tool and sheet. Although it is commonly accepted that heating effects cause increase in formability at higher speed, where there are a number of tradeoffs and unfavorable effects that may arise such as, higher tool wear rates and surface roughness. Tool Diameter: Tool size significantly influences the surface quality and formability of the formed component through SPIF process. Greater contact zone and better sheet support while forming are characteristics of larger tools. The diameter of the hemispherical ends of the tool is vital as it plays a major role in the roughness of the formed surface.

3.4.2. Step Size

This is an important parameter in the SPIF process. In this process the tool forms the part layer by layer. When the tool moves from one layer to the next, the tool has to move downwards. The amount of depth, the tool has to move downward is called the incremental depth or step size.

3.4.3. Tool Diameter

Tool size significantly influences the surface quality and formability of the formed component through SPIF process. Greater contact zone and better sheet support while forming are characteristics of larger tools. The diameter of the hemispherical ends of the tool is vital as it plays a major role in the roughness of the formed surface.

3.4.4. Wall angle (α)

Forming angle refers to the angle that a part's side walls make with the horizontal XY plane. The thickness of the sheet and the material's characteristics are the key determinants of wall angle. However, formability is also measured in term of the maximum forming angle, which a material can be formed without incurring catastrophic failure in a single forming pass controls SPIF parts.

3.4.5. Lubrication

In SPIF, lubrication is used to improve surface quality, reduce tool wear, and trends toward friction reduction. Tool wear is not a major concern because the forming process is rather slow, but in warm forming, lubrication is crucial to controlling surface roughness.

3.5. Programming Procedure for ISF Experimental

3.5.1. Solid work geometry design

Own general geometries exist, including the pyramid. Geometries built in the Solid work application [see Fig. 3.26] all start with a 45-degree forming angle, are followed by integrated forming angles, and end with 75-degree angles. Angle variation is necessary to identify each material's maximum forming angle for the first time.

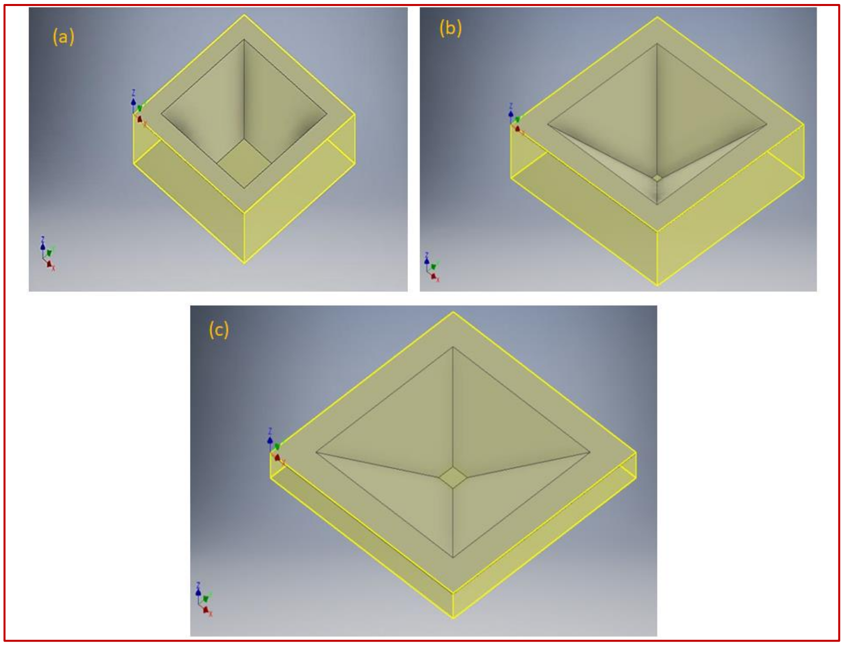


Figure 3. 9 Solidwork geometry design die (a) for 45^0, (b) Solidwork geometry design for 55^0 and (C) Solidwork geometry design for 75^0

The pyramid's greatest depth is 40 mm, and its bottom end features a vertical wall that is 30 mm deep. The breadth of the pyramid's upper square is 140 mm, while its lower square is 62.39 mm wide. Because the Inventor CAM software lacks incremental forming functionality, in order to implement a tool path on a CAD/CAM program, the portion must be rectangular and pyramid in shape, not a sheet metal shape. To accomplish incremental shaping instead of cutting or milling, we employ the same tool path but a different sort of tool. To utilize a Solid work component with Inventor CAM, an IGES file type must be saved.

3.5.2. CAD/CAM program

Uploaded to Inventor CAM and used to determine the tool route. The Inventor CAM program is used to create the CNC program codes for each shape's operational conditions. Geometry from the Solid works IGES file is shown in Table 3.5.

Table 3. 5 Specification condition of creating Mastercam code (1001)

Parameters (unite)	Feed rate (mm/min)	Spindle rate	Angle of °C	Step depth	Tool diameter (mm)
value	300,350 and 400	1000,2000, 2500	45°C,55°C 75°C	1, 1.5 and 2	8, 12 and 16

Except for outward movement toolpath, which needs area clearance of surface high speed toolpath, contour surface finishing mill toolpath must be chosen in order to conduct a code of pyramid shape. all variables in Table 3.9 are common for pyramid shape but surface area selected could be different. The tool is programmed to descend spirally with 0.18 mm steps. Because the tool won't be rotating in this situation due to a particular area of contact with the sheet, the spindle rate is set to zero. In the initial forming process, only the tool tip contacts the sheet. Depending on the geometry, a tool may rotate more quickly at a particular location, such as a wall with a greater angle than 45 degrees.

3.5.3. Numerical code eliminated program

Numerical code parts that are in front of the code on every line must be removed once the final code has been created since they won't be highlighted in red by the CNC machine during production. In order to be utilized in code splitting later on with another program, the Renum program [Appendix] is necessary to assume responsibility for deleting the numerical element, and the final code [Appendx] should be stored as a PRO file type.

3.6. Incremental Forming Experimental Procedure

3.6.1. Pyramid Geometry

For pyramid shape, all parameters and equipment used are similar to conical shape as a mean of fix parameters. All the procedure for this shape is also similar to conical shape as well. The reason of making two different shapes is to observe the influence of shape on SPIF. Even though, both shapes required different range of code for CNC machine. Final part of Pyramid shape is shown is Fig. 3.13.

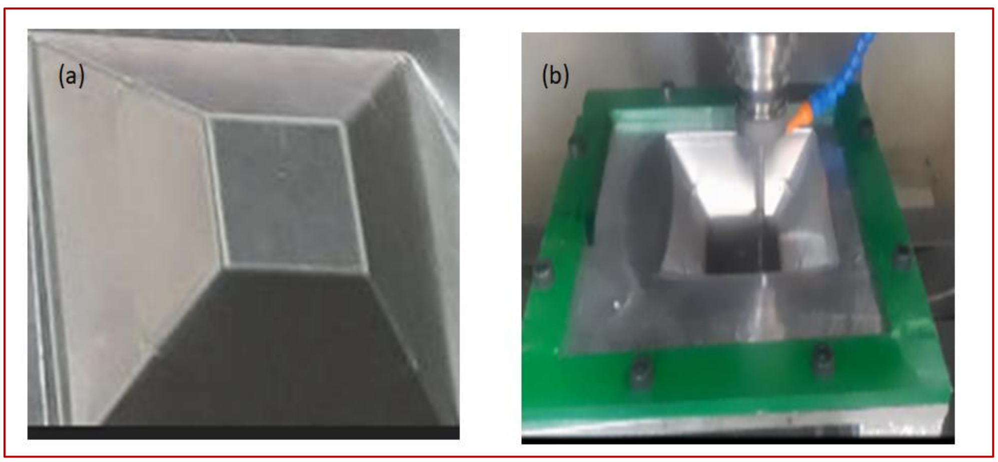


Figure 3. 10 SPIF of pyramid Geometry

3.7. Experimental Equipment and Validation Methodology

In this section, an overview of the experimental equipment and validation methodology used in this thesis is introduced. More details can be found in the Al 6063.

3.7.1. SURFACE ROUGHNESS MEASUREMENT

The most important factor in the machining process is surface roughness because is thought to be the foundation of product quality. It gauges how it gauges how inadequately refined the surface damage caused by wear, corrosion. Improves fatigue strength, reduces creep failure and increases productivity &economics or the industry, the surfaces produced using conventional and non-conventional machine is important. The effectiveness of the surface for preventing wear and corrosion can also be influenced by the quality of a part roughness can be defined in a variety of ways. The average surface roughness. However, ra also known as the arithmetic average (AA) or the center line average (CLA) is a measure of surface roughness that is frequently used in industry for mechanical components. For mechanical components. For this reason, Ra was employed in this study to produce surface roughness.

The German-made VOGEL surface roughness tester which is depicted in figure 3.14, was used to measure surface roughness. The micrometer (m) value of surface roughness is displayed on this tester. The VOGEL surface roughness tester 65711 measures between 0.02 and 50 micro meters. The surface imperfections of the work piece will be traced using a stylus attached to the tester's detecting unit. The instrument's liquid crystal display digitally displays the vertical stylus movement that occurred during the trace after being processed.

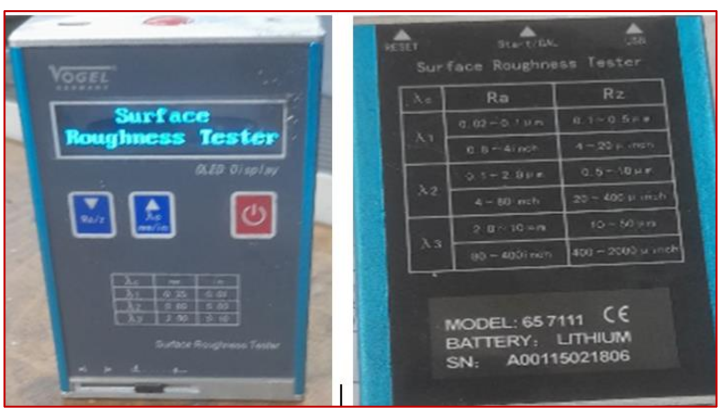


Figure 3. 11 Surface Roughness Tester

3.7.2. SPECTROMETERS

Numerous metals and alloys' elemental compositions can be easily determined by spectrometry analysis. The chemical makeup of AL6063 aluminum material was tested using Txc02 type spark spectroscopy equipment.

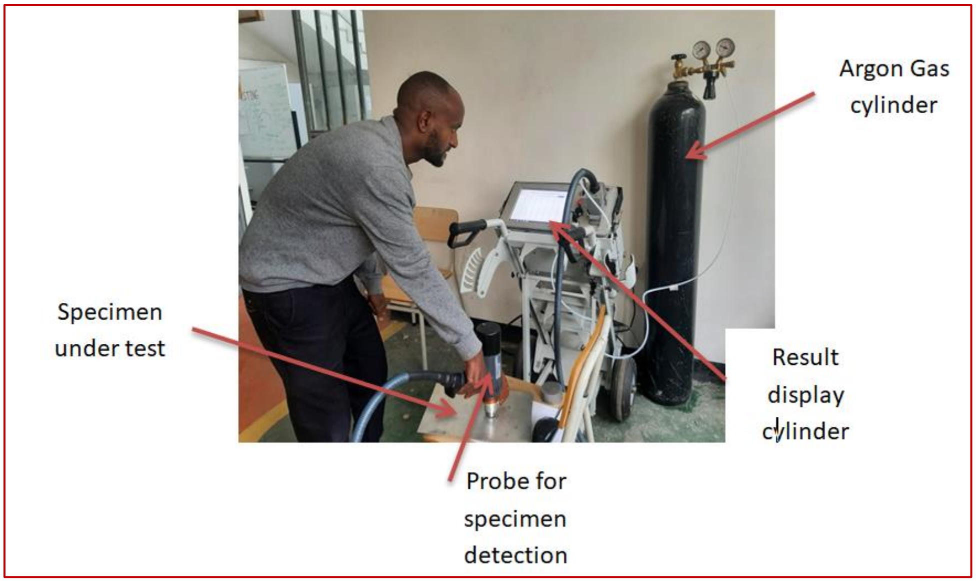


Figure 3. 12 composition tester

3.7.3. micro-hardness testing

The microstructure and micro-hardness of this study were computed at ethiopa federal TVET ininustitut laboratory., and fractural mechanisms testing of the raughenes was used at the biology laboratory. Micro-hardness testing using Vicker's hardness testing machine at the manuachering engineering laboratory. For each test, a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen.

3.8. Process Investigation on experimentation methodology

The defined objectives for the present investigation demanded appropriate methodologies for experimental investigation. In this context, this chapter presents various experimental methods and analyze the raw data-set. Present study attempts to determine the effects of various input parameters on the SPIF process' response characteristics. It also requires necessary optimization and modeling techniques to understand behavior of SPIF process operational sustainability and hardware safety. Design of experiments (DOE) has been employed for proper planning for the experimental investigations. The collected experimental results are used for process optimization. The optimization of SPIF process has been carried out by single response optimization as well as multi responses optimization using statistical tools.

3.8.1. Introduction to Design of Experiment (DOE)

For proper planning of experimental trials, it is necessary to collect the raw data, analyze the results and deduct the conclusions to achieve objectives. The design of experiments (DOE) is an effective method for organizing experiments such that the data collected can be analyzed to generate objective results. The design of experiments can be used to accelerate the design process, the need for less raw materials and labor complexity, providing the most leverage to lower design costs, minimizing process variation and minimizing scrap, rework, and inspection to save manufacturing costs. These are accomplished using the design of experiment tools.

The DOE can be used to:

- Reduce the number of experimental tests for analyzing the effects of parameters.
- Identify the process factors which regulate the performance of the process to be studied.
- Evaluate the optimal combination of the input factors.
- Qualitative prediction of the input factors
- Predict the error produced during experimentation.
- State the trend of effects of input factors on the responses of the process.

3.8.2. Taguchi Approach to Design of Experiments (DOE)

Genichi Taguchi developed the fraction factorial design concept to optimize the process of engineering experimentation. Taguchi gave an excellent philosophy for quality control in the manufacturing industries. It is based on three basic, straightforward ideas (Roy, 1990; Ross, 1996) .

- Quality ought to be planned for the product.
- Losses should be calculated systemically and the cost of quality should be calculated as a function of deviation from the standard.
- Best quality is achieved by minimizing the deviations from the target.

Instead of attempting to check the quality of a product as it moves down the manufacturing line, Taguchi developed an "offline technique for generating quality improvement. As per Taguchi observation, the processes of inspection, screening, and recovery cannot enhance bad quality. The number of parameters can influence the quality characteristic or the responses of the process/product. The parameters can be classified in the following two classes (Phadke, 1995).

The Taguchi method is best suited when the number of variables vary from 3 to 50 (usually) and then there exists few interactions between these variables, but only limited variables contribute significantly. Based on Taguchi method, the best level of conducted experiments is determined using orthogonal array. TM suggests Orthogonal Array (OA) with a definite combination of input factors for conducting experiments. A unique matrix known as an orthogonal array contains entries at several levels of input parameters, with each row representing a different treatment condition. The DOE assigns most suitable OA according to number and levels of input factors using linear graphs and triangular tables. The selection of array facilitates to design identical DOE for all the experimenters (Roy, 1990). TM can be analyzed experimental results in order to obtain following objectives (Ross, 1996):

- ✓ To define the optimal situation for the process or the item to be studied.
- ✓ To predict the contribution of an individual factor.
- ✓ To predict the output characteristics under the optimal situation.

The optimal situation can be noticed from the main effects plot of the input factors. The normal trend of the effect of each factor is identified from the main effects plot. Percentage contribution of every factor with a given confidence level, that can be easily calculated by performing the analysis of variance (ANOVA) to the experimental results. In addition, ANOVA tables permit to define the state of control of the factors. Therefore, a guideline of the contribution of individual factors decides the state of control of the process to be studied (Ross, 1996). According to TM, two approaches can be used to carry out full analysis. In the first approach, ANOVA and main effect analysis are performed on the results of single trial or average of repetitive trials. On the other hand, several trials are performed to use Signal-to-Noise (S/N) ratio for ANOVA and main effect analysis. TM strongly suggests the second approach of analysis for better output. S/N ratio of the raw data is the concurrent characteristics and associated with the loss function (Barker, 1990). S/N ratio calculates the most robust combination of factors taking a variation of results into account. Higher the S/N ratio, lower the loss is. Additionally, TM recommends employing outer OA to incorporate the noise variance into the experiment (Ross, 1996).

The first step of DOE is to select input parameters and its level for investigation of their effects on output parameters. Material parameters, geometrical parameters, and process parameters should be used to group various input parameters that have an impact on the process. Due to several process constraints, little or no change is made to geometrical factors like component shape, wall angle, and sheet thickness as well as material properties like Young's modulus, work hardening exponent, and anisotropy of material. On the other hand, process designer has the choice of altering the input parameter like, rotational speed, feed rate, step size, tool diameter, lubrication, and tool shape etc.

3.10. Preliminary Experimentation

3.10.1 Experimentation Plan

Table 3. 6 Variable parameters for preliminary experimentation

Factor	Machining parameters	Levels		
		L1	**L2**	**L3**
A	Tool radius (mm)	8mm	16 mm	-
B	Inclination wall angle	45°	55°	75°
C	Lubrication	Grease	Coolant	Dry
D	Step Depth	1	1.5	2
E	Spindle speed (rpm)	1000rev/min	2000rev/min	2500rev/min
F	Feed rate (mm/min)	300mm/min	350mm/min	400mm/min

The objective of preliminary experiment is to check the feasibility of AL6063-alloy sheet forming using friction heat method and evaluate the critical parameters. Variable parameter and its levels are selected as shown in Table 4.1. While constant parameters are considered as a workpiece material, sheet thickness (t) = 1 mm, hemispherical end shape tool made of tungsten carbide, tool path- Z-level, geometry as a truncated cone with 46 mm maximum diameter and 15 mm design depth.

Further, L18 dash (OA) Taguchi-Mixed design is select for experimentation as shown in Table 3.8. Formability in term of maximum fracture depth of frustum cone is considered as a response parameter. The maximum fracture depth is the depth of sheet metal formed part before fracture during the forming process. It is reported directly as a Z- coordinate data in mm from the computer screen display of CNC-machine and it is also measured by Vernier height gauge, which is stated in Table 3.8. Fig 3.16. shows formed specimens for preliminary experiments.

Table 3. 7 Layout of L18 orthogonal array

	Coded values						Original values					
Run	A	B	C	D	E	F	A	B	C	D	E	F
1	1	1	1	1	1	1	8	45	Grease	1	1000	300
2	1	1	2	2	2	2	8	45	Coolant	1.5	2000	350
3	1	1	3	3	3	3	8	45	Dry	2	2500	400
4	1	2	1	1	2	2	8	55	Grease	1	2000	350
5	1	2	2	2	3	3	8	55	Coolant	1.5	2500	400
6	1	2	3	3	1	1	8	55	Dry	2	1000	300
7	1	3	1	2	1	3	8	75	Grease	1.5	1000	400
8	1	3	2	3	2	1	8	75	Coolant	2	2000	300
9	1	3	3	1	3	2	8	75	Dry	1	2500	350
10	2	1	1	3	3	2	16	45	Grease	2	2500	350
11	2	1	2	1	1	3	16	45	Coolant	1	1000	400
12	2	1	3	2	2	1	16	45	Dry	1.5	2000	300
13	2	2	1	2	3	1	16	55	Grease	1.5	2500	300
14	2	2	2	3	1	2	16	55	Dry	2	1000	350
15	2	2	3	1	2	3	16	55	Coolant	1	2000	400
16	2	3	1	3	2	3	16	75	Grease	2	2000	400
17	2	3	2	1	3	1	16	75	Coolant	1	2500	300

18	2	3	3	2	1	2	16	75	Dry 1.5	1000	350

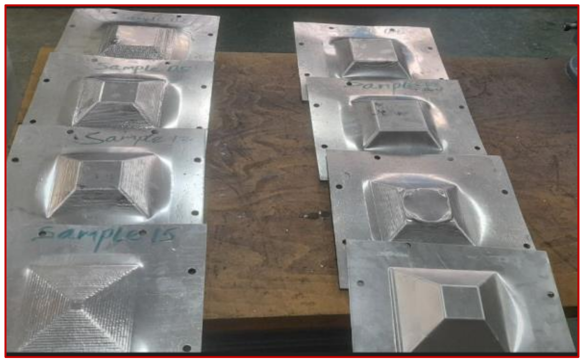


Figure 3. 13 Preliminary experimentation formed components

3.11 Orthogonal Array

Before choosing the orthogonal array, estimate the minimum number of experiments to execute based on the total number of degrees of freedom. The total degrees of freedom provided must be more than the number of experiments required to study the factors (Krishnaiah & Shahabudeen, 2012). In this study, the number of layers of various factors was used to identify which orthogonal array to use. six factors were chosen for the experiments, each having three levels.

DOF=P* (L-1) (1.)

Where, DOF= degree of freedom,

P = number of factors and,

L = number of levels

DOF= 6(3– 1) = **17** (OA≥ DOF, So OA has **18** experimental runs)

After calculating the Degree of Freedom (DOF), the number of experimental runs was chosen from an orthogonal array. The total number of orthogonal array (OA) experiments should be larger than or equal to the computed value, hence the L18 orthogonal array was chosen for the experiment design.

3.12 Signal to noise ratio (S/N ratio)

The Taguchi technique emphasizes the value of evaluating response variation using the signal-to-noise ratio, which reduces the effect of uncontrollable parameter variation on quality characteristics. The desired value (mean) for the output characteristic is referred to as signal, while the undesired value (deviation, SD) is referred to as noise in the Taguchi method. As a result, the S / N ratio equals the average to SD ratio. Taguchi used the S / N ratio to assess the quality attribute that deviates from the desired value. There are numerous S / N ratios available depending on the type of characteristic; smaller is better, nominal is best, and larger is best (Karna & Sahai, 2012; Ross, 1996).

A. Larger the better (Maximization)
B. Smaller the better (Minimization)
C. Nominal the best

Standard S/N ratio formula:

$$\frac{S}{N}\text{ratio} = -10\log\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{Yij^2}\right] \quad (2.)$$

Where 'i' is the number of a trial; 'Yi' is the measured value of quality characteristic for the i^{th} trial and j^{th}experiment, 'n' is the number of repetitions for the experimental combination.

3.13 ANOVA (Analysis of variance)

This is a statistical tool, which is used to analyze the results of the total run of orthogonal array experiments. For ANOVA, following terminology is required to calculate.

1. Grand total sum of squares is determined by sum of the squared value of experimental data of response

$$Grand\ total\ sum\ of\ squares = \Sigma_i^n = 1\left({}^{S}/_{N_i}\right)^2 \quad (3.)$$

Where n = total number of experiments runs.

2. Total Sum of Squares or Total Variation (ST)

$$S_T = \Sigma_i^n = 1\left({}^{S}/_{N_i}\right)^2 - \text{CF} \quad (4)$$

Where; Correction Factor, $$CF = \left(\Sigma_i^n = 1\ {}^{S}/_{N_i}\right)^2 - CF \quad (5)$$

3. Sum of square for a factor (SF)

$$SF = \frac{F_2^2}{N_{F_1}} + \frac{F_2^2}{NF_2}\frac{+F_3^2}{NF_3} - CF$$

(43)

Where; F1, F2, F3 are sum of S/N ratio of level 1, 2, 3 respectively. N= number of repetition of the factor in orthogonal array.

4. Mean Square of Factor (Variance),

$V_F = S_F \ / \ DOF_F$

(^%)

5. Mean Square Error (Se)

$$V_F = S_E \ / \ DOF_F \qquad (6)$$

Where SE = sum of square due to error; DOFF = degree of freedom due to error.

6. F – Ratio = V_F/V_{FE}

From the ANOVA process, it is to determine the most significant parameter to specific response of SPIF process. The statistical significance of each individual parameter is shown by the p-value. The p-value should be less than 0.05 for the 95 percent confidence level, according to Genichi Taguchi et al., (2005). The trial version Minitab- 17 software are used to carry out ANOVA.

CHAPTER – FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Surface Roughness (SR)

Since the SPIF method involves a continuous tool movement on the sheet as it is being formed under high pressure, a scratch mark is often left on the component surface. It is measured by an actual surface's vertical divergence from an ideal shape. Surface roughness has been assessed in the current experiment using a touch-type stylus. A profile (line contact) may be used to compute the roughness value. According to the literature, Ra is the parameter that is most frequently employed to gauge surface roughness. The arithmetic mean of the absolute values is known as Ra. It is measured in height units (m).

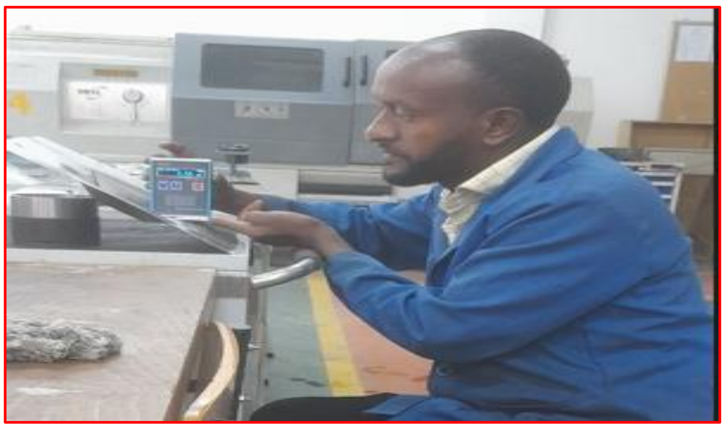


Figure 4. 1 Surface roughness measurement set up

In the current study effort, Ra is used to express the average surface roughness. The Mitutoyo SJ-400 is used to measure surface roughness, as illustrated in Fig. 4.1. The stylus was used to connect the component to the detector. To calculate the surface roughness value, a stylus is pushed horizontally across the component's surface. The roughness measurement findings are presented on the machine unit's display panel.

The Ra value of each specimen is measured on both sides of the wall to improve the statistical correctness of the data, as seen in Fig. 4.2 The surface roughness of the specimen's four side walls is then used as the response parameter. Table 4.1 provides a summary of the additional surface roughness VOGEL testing settings.

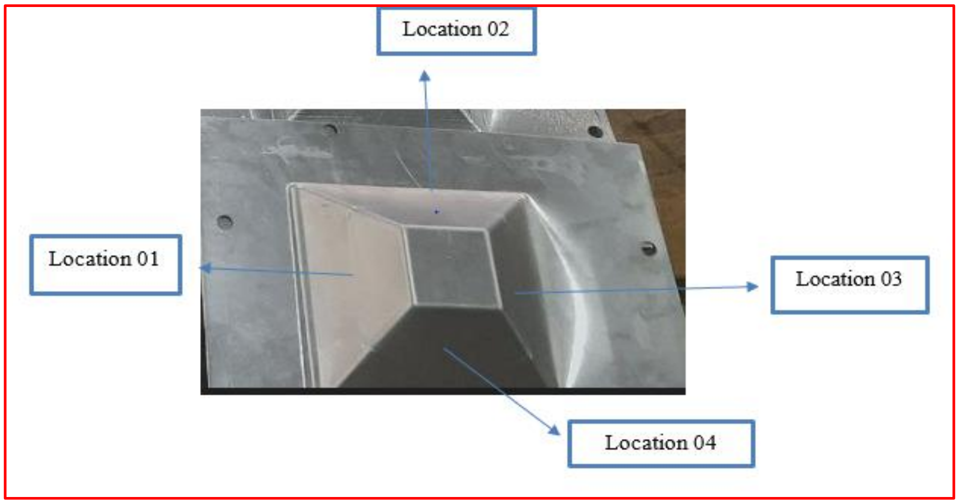


Figure 4. 2 Surface roughness measurement at four locations on wall surface

Table 4. 1 surface roughness (SR) Ra-values of final experimentation

	Surface Roughness Ra(µm)			
Exp. No.	Location 01	Location 02	Location 03	Location 04
01	0.32	0.3	0.26	0.276
02	3.31	3.31	2.38	3.11
03	2.23	3.43	3.77	2.99
04	0.51	0.57	0.69	0.48
05	3.07	3.2	3.46	3.87
06	3.07	3.2	3.46	3.95
07	1.86	2.25	1.64	2.1
08	2.83	1.71	2	2.33
09	3.32	3.8	2.43	3.1
10	1.86	2.25	1.64	1.99
11	1.21	1.69	1.5	1.9
12	1.21	1.69	1.5	1.89

13	0.73	0.58	0.48	0.88
14	3.05	3.21	2.34	2.99
15	3.18	4.82	5.08	4.39
16	0.68	0.75	0.88	0.9
17	1.72	1.52	1.31	1.2
18	3.18	4.82	5.08	4.12

4.1.2 Experimental Results for Average Surface Roughness

The surface roughness value is measured at four different surface locations of formed component wall (Fig. 4.3). Finally, Average Surface Roughness (ASR-µm) is computed for purpose of analysis, which is shown in Table 4.1.

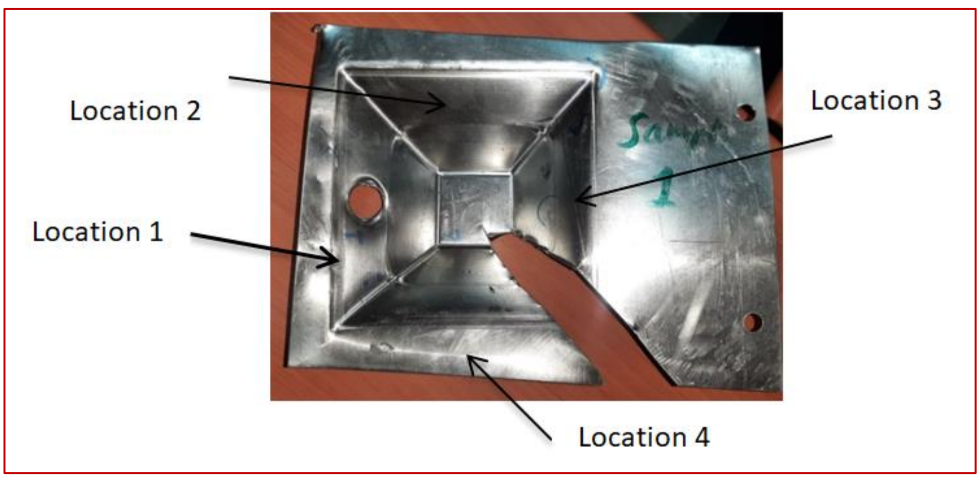


Figure 4. 3 conformation test formed part at optimal set parameters for ASR

Table 4. 2 Average surface roughness (ASR) Ra-values of final experiments

	Surface Roughness Ra(μm)				
Exp. No.	Location 01	Location 02	Location 03	Location 04	Average Surface Roughness ASR (μm)
01	0.32	0.3	0.26	0.276	0.289
02	3.31	3.31	2.38	3.11	3.027
03	2.23	3.43	3.77	2.99	3.105
04	0.51	0.57	0.69	0.48	0.5625
05	3.07	3.2	3.46	3.87	3.4
06	3.07	3.2	3.46	3.95	3.413
07	1.86	2.25	1.64	2.1	2.025
08	2.83	1.71	2	2.33	2.175
09	3.32	3.8	2.43	3.1	3.1625
10	1.86	2.25	1.64	1.99	1.935
11	1.21	1.69	1.5	1.9	1.575
12	1.21	1.69	1.5	1.89	1.5725
13	0.73	0.58	0.48	0.88	0.6675
14	3.05	3.21	2.34	2.99	2.8975
15	3.18	4.82	5.08	4.39	4.3675
16	0.68	0.75	0.88	0.9	0.8
17	1.72	1.52	1.31	1.2	1.4375
18	3.18	4.82	5.08	4.12	4.3

Total 18 combinations of input factors are analyzed. Design of experiment (DOE) and analysis are performed using Minitab statistical software. Surface roughness is taken in to account for analysis of the results. Further, Fig 4.4 shows the Average Surface Roughness (ASR) value verses corresponding the experiment's number for all specimens of SPIF process.

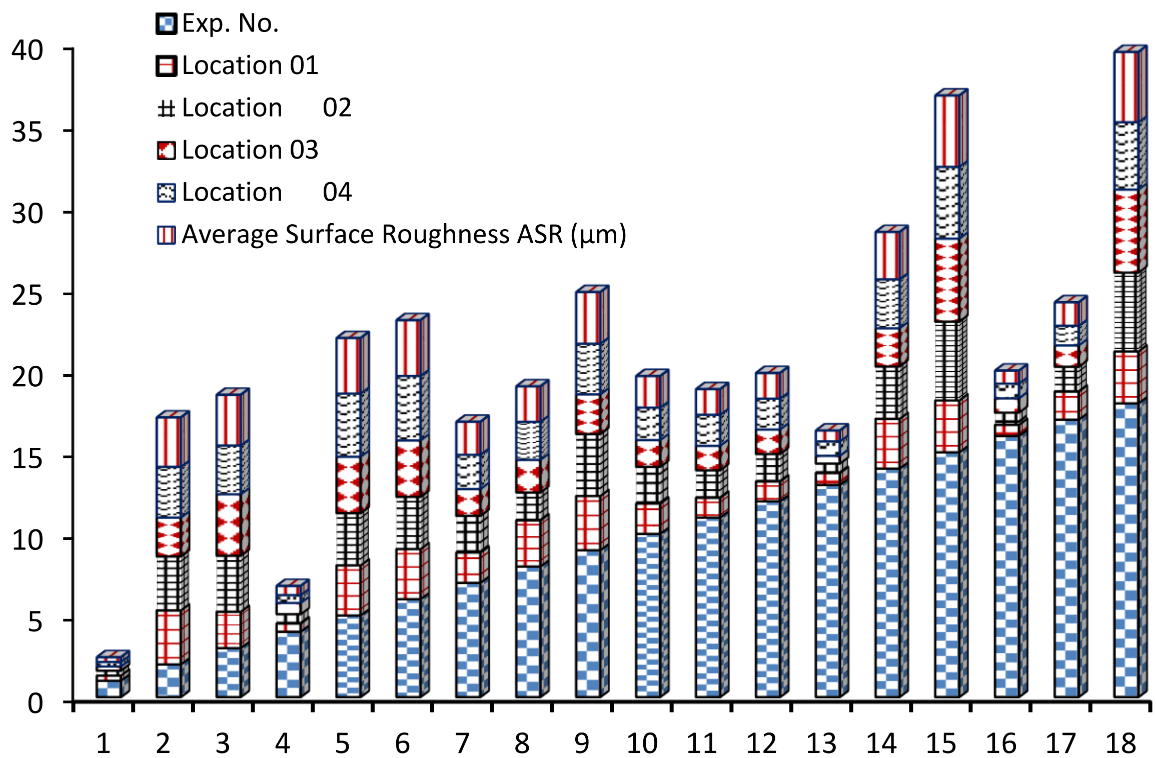


Figure 4. 4 Average surface roughness Vs experiment number

4.2 Analysis and Result discussion for Average Surface Roughness

In this part, the effect and optimization of the chosen individual SPIF process input variables on the average roughness of the formed components are explored. From experimental raw data, the S/N ratio of Ra for each input factor at various levels is calculated (Table 4.2). In order to impact particular process variables on surface roughness, the main effects diagrams (response curves) is used for both raw data and S/N data. Response tables are also employed for raw data and S/N data to select the ranking of the input factors. Analysis of variance (ANOVA) of measured values is also carried out in order to assess the importance of the influence of particular input parameters on average surface roughness. The main effects diagrams and analysis of variance (ANOVA) table is used to select optimum values of all input factors in terms of average surface roughness. S/N ratios have additionally been used to evaluate the variation in the quality feature (Ra, in this case). The lowest Ra variation is produced by the highest S/N ratio, its leads to an optimum condition of the process. Furthermore, the smaller the average surface roughness, the "smaller better" type quality response; thus, a lower value of Ra is generally considered to be ideal.

4.2.1 Effects of the Process Factors on Average Surface Roughness (ASR)

The S/N ratios of the experimental Ra data are derived as indicated in Table 4.2 in order to identify the variables affecting the surface roughness. To explore factor effects, the smaller-the-better feature of the Taguchi technique is chosen for average surface roughness (ASR),

Table 4. 3 S/N ratio experimental average surface roughness

	Process Parameters						Response Parameter	
Sr. No	Tool Diameter (mm)	Inclination wall angle	Lubrication	Step Depth	Spindle speed (rpm)	Feed rate (mm/min)	Average Surface roughens (µm)	S/N of Average Surface roughens (dB)
01	8	45	Grease	1	1000	300	0.289	10.78204
02	8	45	Coolant	1.5	2000	350	3.027	-9.62025
03	8	45	Dry	2	2500	400	3.105	-9.84123
04	8	55	Grease	1	2000	350	0.5625	4.997549
05	8	55	Coolant	1.5	2500	400	3.4	-10.6296
06	8	55	Dry	2	1000	300	3.413	-10.6627
07	8	75	Grease	1.5	1000	400	2.025	-6.1285
08	8	75	Coolant	2	2000	300	2.175	-6.74919
09	8	75	Dry	1	2500	350	3.1625	-10.0006

10	16	45	Grease	2	2500	350	1.935	-5.73362
11	16	45	Coolant	1	1000	400	1.575	-3.94561
12	16	45	Dry	1.5	2000	300	1.5725	-3.93181
13	16	55	Greis	1.5	2500	300	0.6675	3.510975
14	16	55	Dray	2	1000	350	2.8975	-9.24047
15	16	55	Coolant	1	2000	400	4.3675	-12.8047
16	16	75	Greis	2	2000	400	0.8	1.9382
17	16	75	Coolant	1	2500	300	1.4375	-3.15216
18	16	75	Dray		1000	350	4.3	-12.6694

Using the Minitab-17 software, the response table for the S/N ratios of average surface roughness is computed and display in Table 4.3. According to statistics delta values as shown in Table 4.4, Lubrication, with a delta of 11.546 has the greatest impact on surface roughness, followed by feed, speed, Step Depth, wall angle, Spindle speed and tool diameter, with delta value of 5.344, 4.361, 2.412, 1.613, and 0.203 respectively.

Table 4. 4 Response table for average surface roughness

Level	Tool radius (mm)	Inclination wall angle	Lubrication	Step Depth	Spindle speed (rpm)	Feed rate (mm/min)
1	-5.317	-3.715	1.56	-2.354	-5.311	-1.700
2	-5.114	-5.805	7.223	-6.578	-4.362	-7.044
3		-6.127	9.985	-6.715	-5.974	-6.902
Delta	0.203	2.412	11.546	4.361	1.613	5.344
Rank	6	4	1	3	5	2

The main effects of plot of Ra is derived from the response Table 4.3 and is depicted in Fig 4.7. It is observed that the S/N ratio decreases with an increase in the speed, feed and step size. Where in the ratio is increases with an decrease in tool diameter from 8 to 16 mm.

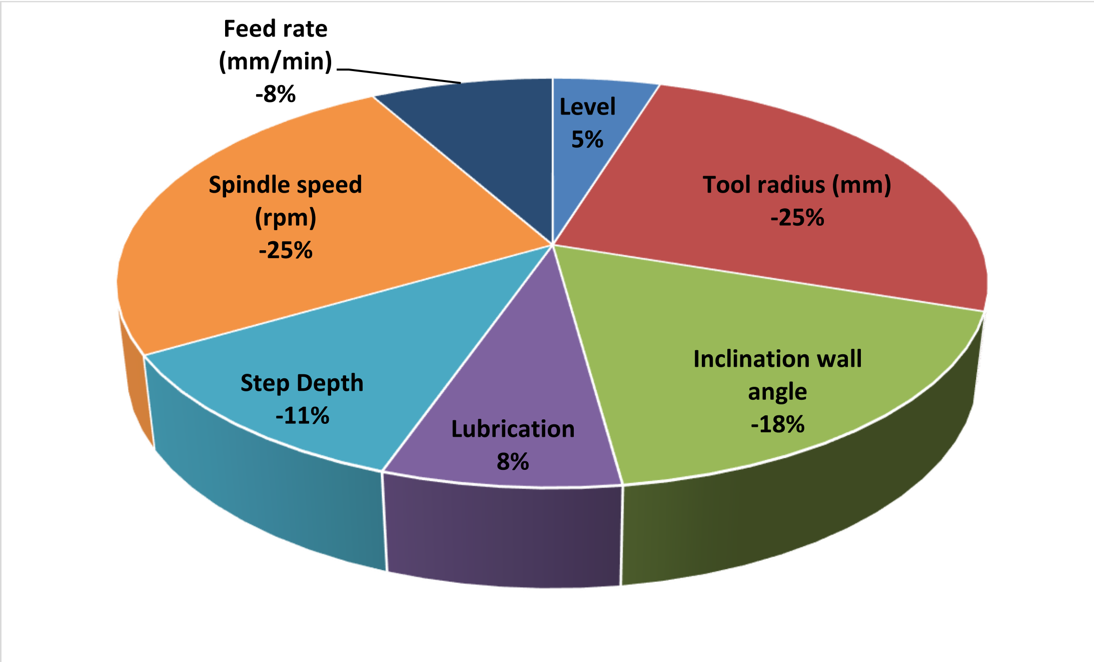


Figure 4. 5 Statistics delta value for SR

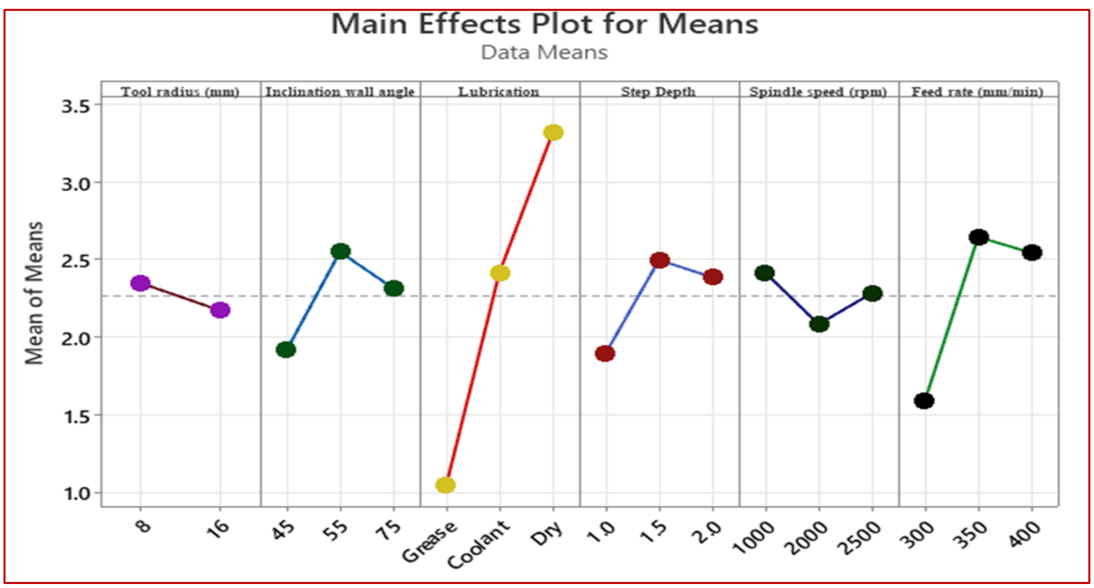


Figure 4. 6 Main effect plot for of mean of means average surface roughness

The main effect of the variable plot demonstrates that surface roughness increases as step size increases. This might be a result of increase surface waviness due to increasing step sizes. The reason for increased waviness of surface is due to increase in scallop height at larger step size.

Increased deep step size during the incremental forming process result in increased axial force and penetrating action. Because of this, a deeper valley forms in the sheet metal's micro-surface and more area is involved in tool sheet interface, resulting in a surface with a lower surface quality with lining pattern. A lower step size greatly reduces the friction resulting in a polishing impact on the sheet's surface roughness, hence it will lower surface roughness.

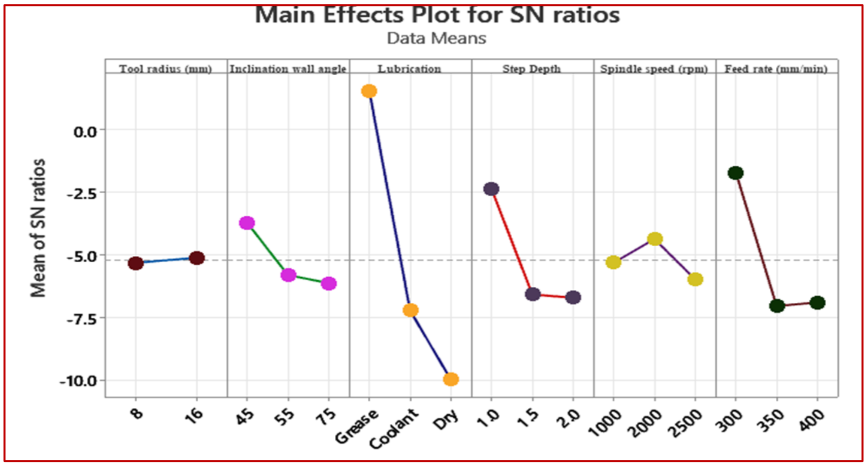


Figure 4. 7 Main effect plot for S/N ratios of average surface roughness

The feed rate (mm/min) is the distance covered by the forming tool across the material's surface in a predetermined amount of time. Consequently, managing how quickly the tool goes over the surface also manages the heat produced by friction. It is observed from Fig 4.7, average surface roughness increases as feed rate increases. This is due to tool is more advance per unit time, results into large amount of frictional heat at tool/sheet interface. Lubricant loses its viscosity that may lead to direct metal to metal contact, hence no polishing effect on sheet surface during process. Further, the higher feed during forming may induce undesired vibrations which further lead to the poor surface finish.

Response curves for S/N ratios (Fig.4.7 shows that average roughness decreased with the rise in tool diameter. Better surface quality is achieved by reducing waviness at the tool-sheet interface When the tool diameter rises, the tool's penetrating action causes the asperities to spread out across a broader region, widening the furrows on the surface of the sheet metal, which lowers the Ra (average surface roughness) value. In addition, when the tool nose diameter increases, the contact pressure drops, flattening the surface peaks and bringing down the surface roughness. When compared to the tool with the larger diameter, the smaller diameter forming tool may have produced a poor surface finish due to excessive sheet wear during the forming process. It is also differential in the amount of wear at the two tools' contacting tips. When compared to bigger tools, the smaller tool causes more sheet wear because contact forces act on a smaller surface area, causing higher stresses.

Further, surface roughness value increases marginally with increases in tool rotating speed from 1000 rpm to 2200 rpm. As the speed increases, friction and heat both are increases at tool- sheet interface cause of higher relative speed. At higher friction at tool interface, Hence the surface roughness value of sample will be increased.

4.2.2 Selection of the Optimal Levels of Factors for Average Surface Roughness

From Fig. 4.8, highest value of S/N ratios for surface roughness (Ra) are attained at the first level of lubricant(grease) (C1), the first level of angle (B1) the first level of speed (E1), the first level of feed (F1), the first level of step size (D1), and the second level of tool diameter (A2). Hence, the optimum set of parameters and its level are A2B1C1D1E1F1 for average surface roughness. The S/N ratio findings in the response table also indicate the same levels for the variables. Further, it evident that the step depth is the most significant parameter, followed by feed, speed and tool diameter.

Table 4. 5 Selection of the Significant Factors for Average Surface Roughness

Factor	DF	Sum of square	Mean of square	F - Value	Adj SS	P - Value	% of contribution
A: Tool Diam (mm)	1	0.1434	0.1434	0.20	0.1434	0.66854	0.53%
B: Inclinational angle	2	1.2333	0.6167	0.87	1.2333	0.46555	4.57%
C: Lubrication	2	15.7291	7.8646	11.11	15.7291	0.00962	58.31%
D: Step Depth	2	1.2213	0.6107	0.86	1.2213	0.46862	8.53%
E: speed (rpm)	2	0.3364	0.1682	0.24	0.3364	0.79568	4.25%
F: Feed (mm/min)	2	4.0633	2.0316	2.87	4.0633	0.13357	20.06%
Error	6	4.2490	0.7082		4.2490		3.75%

Total	17	26.9758	100.00%

Model Summary: R-sq 96.25% , R- sq(adj) 85.37%

is carried out to identify the important factors and the percentage contribution of each component to the response average surface roughness. At the 95 percent confidence level, it can be deduced from the table that Lubrication has the biggest percentage contribution (58.31%), followed by feed (20.06%), Inclinational angle (4.57%), Step Depth (8.53%), speed (4.25%) and Tool Diameter (0.53%). Furthermore, the Lubrication is the only significant factor because its p value is less than 0.05. The high R values support the validity of this model by showing that it can account for 96.25 percent of the variability,

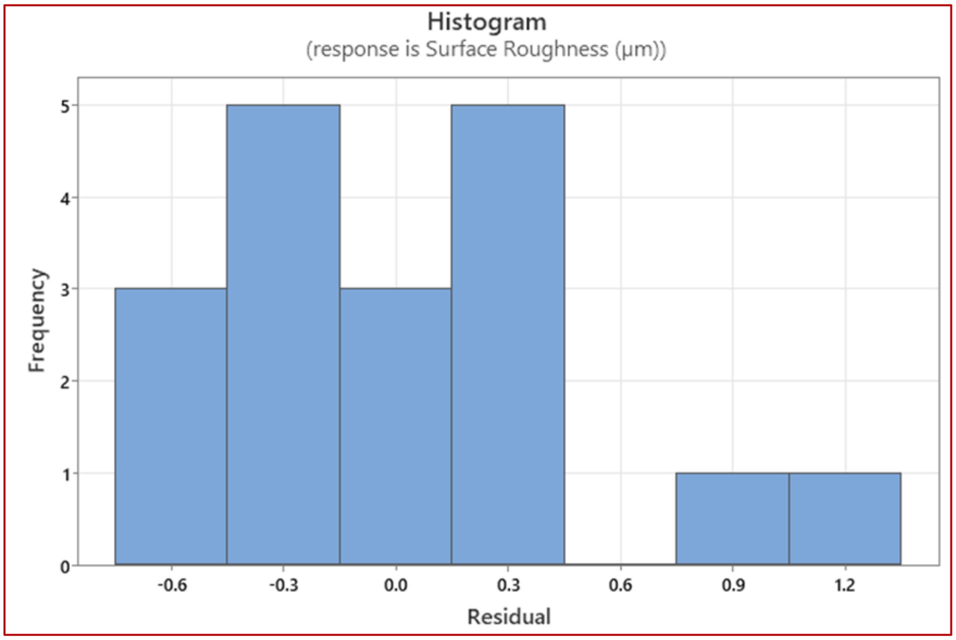


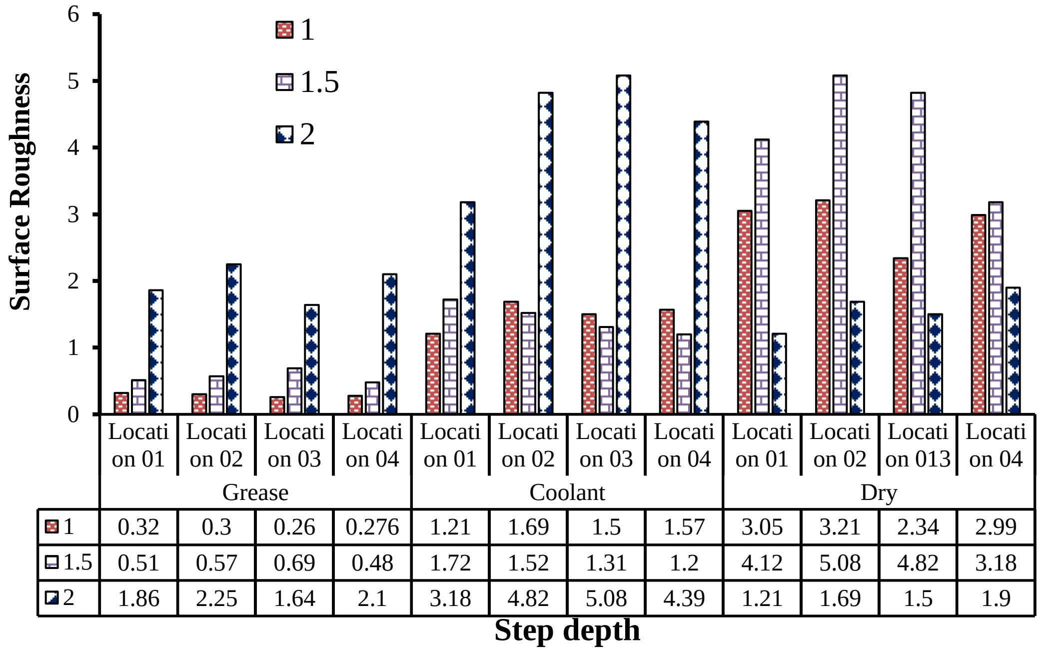
Figure 4. 8 the Optimal Levels of Factors for Average Surface Roughness diagram

is carried out to identify the important factors and the percentage contribution of each component to the response average surface roughness. At the 95 percent confidence level, it can be deduced from the table that Lubricants has the biggest percentage contribution (58.314%), followed by feed (20.06%), tool diameter (0.53%), and speed (4.25%), step size (8.53%) and angle (4.57%) Furthermore, the Lubricant is the only significant factor because its p value is less than 0.05. The high R values support the validity of this model by showing that it can account for 96.25 percent of the variability.

Confirmation experiment is performed at optimum combination of parameters(A2B1C1D1E1F1) for average surface roughness. The specimen formed for conformation test is shown in Fig 4.7 and, the result obtained is presented in Table 4.4. It has been observed that average surface roughness obtained for optimum combination of parameters has within the predicted range at 95% confidence level and closed to predicted value.

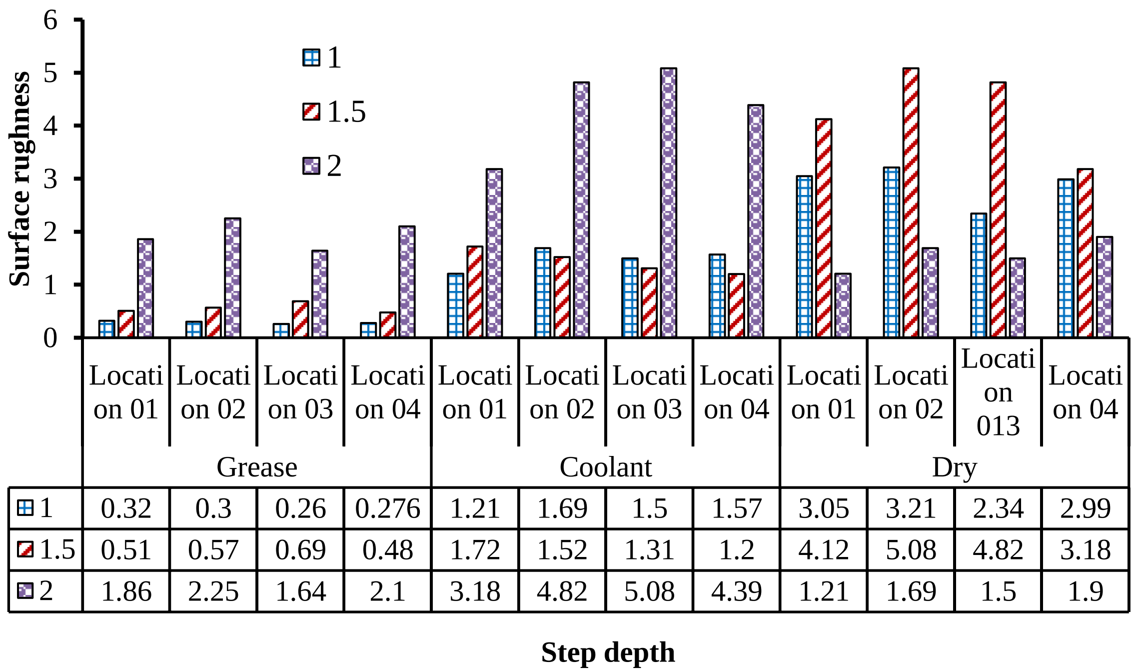
4.2.3 Effect Optimize step increment, will minimum surface roughness

It would need to be analyzed in order to optimize surface roughness and forming process speed, where surface quality should be enhanced per millimeter. When a trade-off between surface quality and forming time is important, a step increment value optimization is required. performed a single replication of each experiment to evaluate various step increments for the aluminum alloy (AA 6063). They discovered that surface roughness reduced with a reduction in step increment. On aluminum Al 6063, evaluated various step increments. They looked at how surface roughness grew initially up to a specific amount with increasing the step increment, following this, step depth increased as surface roughness decreased. Numerous articles in our survey made assumptions about how step increment affects surface roughness. It appears that increasing surface polish and significantly affecting forming time with reducing step down. Optimizing surface quality and forming process speed, where surface quality should be enhanced per millimeters, may be crucial in specific circumstances. For instance, would need to be assessed.



	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
1	0.32	0.3	0.26	0.276	1.21	1.69	1.5	1.57	3.05	3.21	2.34	2.99
1.5	0.51	0.57	0.69	0.48	1.72	1.52	1.31	1.2	4.12	5.08	4.82	3.18
2	1.86	2.25	1.64	2.1	3.18	4.82	5.08	4.39	1.21	1.69	1.5	1.9

Figure 4. 9 Effect Optimize step increment on tool 8 diameters will minimum surface roughness

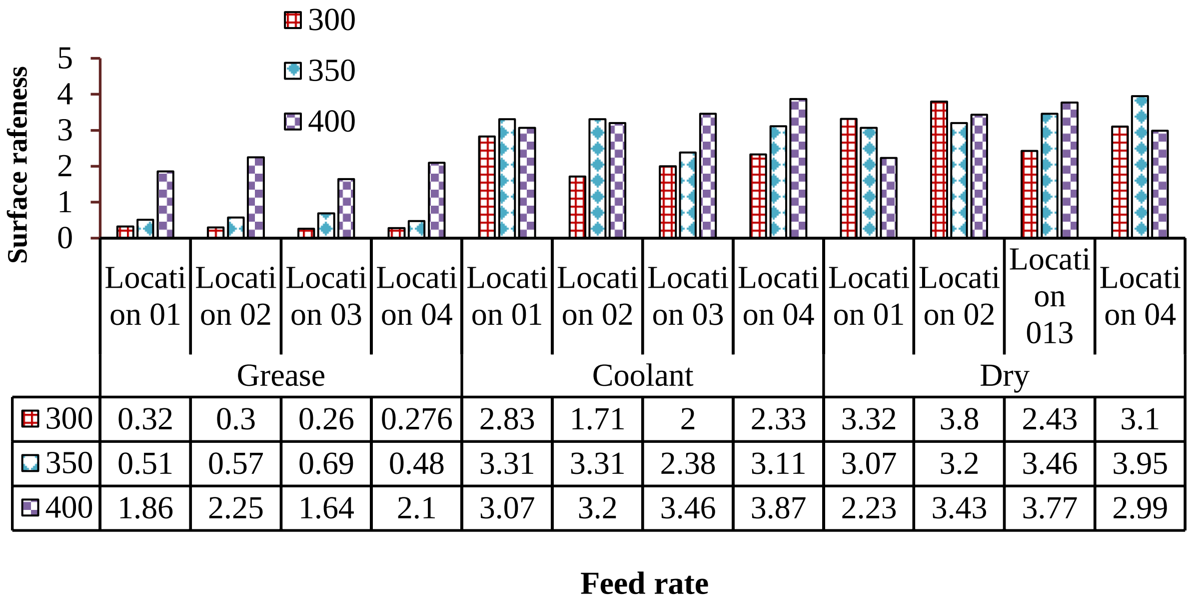


	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
1	0.32	0.3	0.26	0.276	1.21	1.69	1.5	1.57	3.05	3.21	2.34	2.99
1.5	0.51	0.57	0.69	0.48	1.72	1.52	1.31	1.2	4.12	5.08	4.82	3.18
2	1.86	2.25	1.64	2.1	3.18	4.82	5.08	4.39	1.21	1.69	1.5	1.9

Figure 4. 10 Effect Optimize step increment on tool 16 diameters will minimum surface

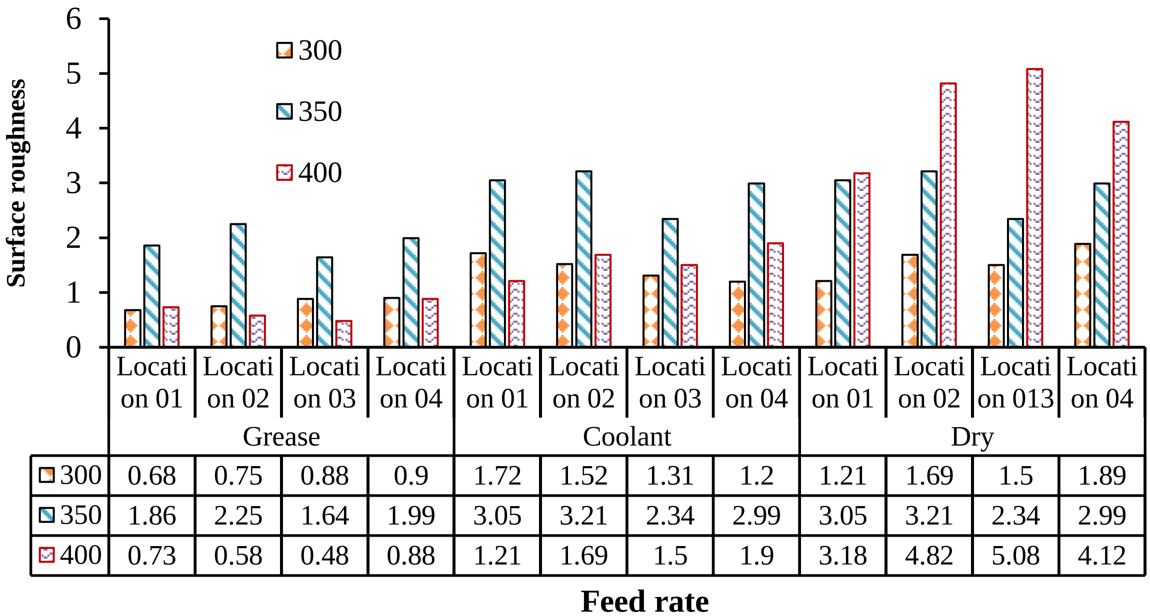
4.2.4 Effect of feed rate on surface roughness at optimum

The effect of feed rate on surface roughness. As, with increase in feed roughness rate surface roughness decreased at some extent the surface roughness increased. Investigated aluminum alloy (AA 6063) sheet metal under different feed rate 300, 350 and 400 mm/rev with 3 replications of each experiment. They suggested that with decrease in feed rate surface roughened decreased. More over smaller feed rate increased forming time.



	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
300	0.32	0.3	0.26	0.276	2.83	1.71	2	2.33	3.32	3.8	2.43	3.1
350	0.51	0.57	0.69	0.48	3.31	3.31	2.38	3.11	3.07	3.2	3.46	3.95
400	1.86	2.25	1.64	2.1	3.07	3.2	3.46	3.87	2.23	3.43	3.77	2.99

Figure 4. 11 Effect of feed rate on tool 8 diameter surface roughness at optimum



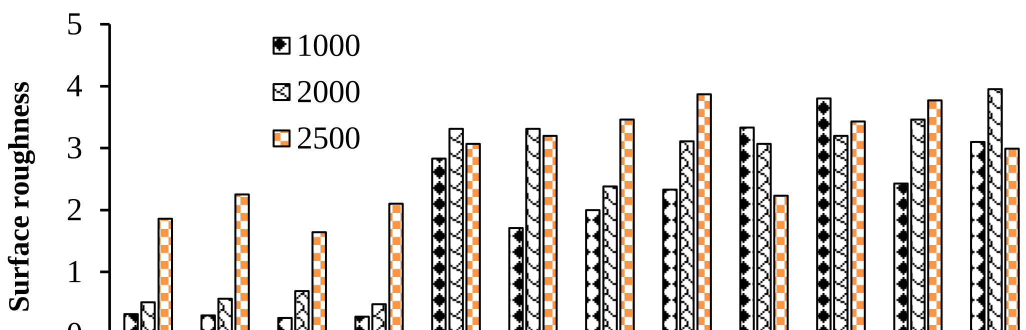
	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
300	0.68	0.75	0.88	0.9	1.72	1.52	1.31	1.2	1.21	1.69	1.5	1.89
350	1.86	2.25	1.64	1.99	3.05	3.21	2.34	2.99	3.05	3.21	2.34	2.99
400	0.73	0.58	0.48	0.88	1.21	1.69	1.5	1.9	3.18	4.82	5.08	4.12

Figure 4. 12 Effect of feed rate on 16 diameter surface roughness at optimum

It is clear that the effect of feed rate depends on the sheet material produced during incremental sheet formation. The forming time is influenced by feed rates in conjunction with step increment. However, there is a trade-off between forming time and surface roughness. It would be necessary to optimize these forming process parameters. For the improvement of surface quality when feed rate decreased, information about the impact of feed rates on different materials would be required.

4.2.5 Effect of spindle speed on surface roughness at optimum

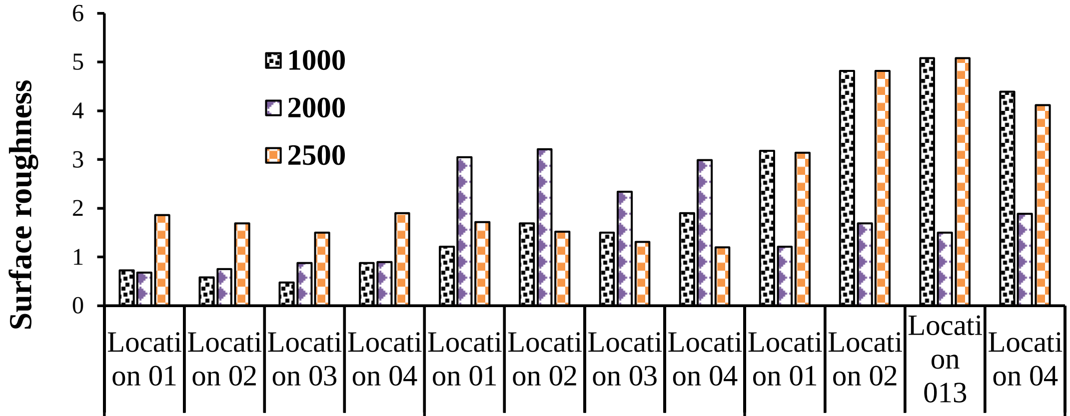
spindle speed has insignificant effect on surface roughness. Figure 4.13(14), shows the effect of spindle speed on surface roughness. As, with increase in spindle speed surface roughness decreased. Desai tested aluminum (Al 6063) sheet blank at constant feed and step increment and varying spindle rotational speed and investigated their effect on surface roughness. developed design of experiments in order to investigate the effect of spindle rotation speed on surface roughness. They tested aluminum (Al 6063) at 1000, 2000 and 2500 rev/ min with three replications of each of each experiment. They found that spindle rotational speed in fluence the surface roughness n both perpendicular and parallel direction. They suggested that with decrease in spindle speed surface roughness decreased.



	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
1000	0.32	0.3	0.26	0.276	2.83	1.71	2	2.33	3.33	3.8	2.43	3.1
2000	0.51	0.57	0.69	0.48	3.31	3.31	2.38	3.11	3.07	3.2	3.46	3.95
2500	1.86	2.25	1.64	2.1	3.07	3.2	3.46	3.87	2.23	3.43	3.77	2.99

Spindle speed rpm

Figure 4. 13 Effect of spindle speed on tool 8 diameter surface roughness at optimum



	Grease				Coolant				Dry			
	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 03	Location 04	Location 01	Location 02	Location 013	Location 04
1000	0.73	0.58	0.48	0.88	1.21	1.69	1.5	1.9	3.18	4.82	5.08	4.39
2000	0.68	0.75	0.88	0.9	3.05	3.21	2.34	2.99	1.21	1.69	1.5	1.89
2500	1.86	1.69	1.5	1.9	1.72	1.52	1.31	1.2	3.14	4.82	5.08	4.12

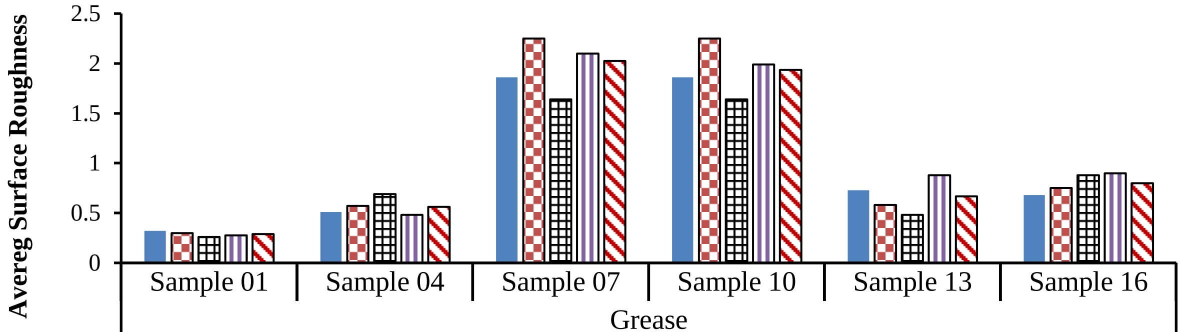
Spindle Speed

Figure 4. 14 Effect of spindle speed on tool 16 diameter surface roughness at optimum

Surface roughness is not significantly impacted by spindle speed. The impact of spindle speed on surface roughness is seen in Figure 4.13(14). Surface roughness reduced when spindle speed was increased. Desai evaluated an aluminum (Al 6063) sheet blank with variable spindle rotational speed, constant feed, and step increments to see how they affected the surface roughness. devised an experiment design to look into how spindle rotation speed affects surface roughness. At 1000, 2000, and 2500 rev/min, they examined aluminum (Al 6063), with three replications of each experiment. They discovered that the surface roughness was affected by spindle rotating speed in both parallel and perpendicular directions. They claimed that surface roughness decreased when spindle speed was reduced.

4.2.6 Parameters comparison on surface roughness

Bar graph shown below in Figure 4.15(16)(17),analyzes the total amount of every process parameter lubricant on the grease highest the number on the paper, in Step increment had highest number of papers, followed by tool tip diameter and feed rate. Few papers were found about spindle rotation speed, sheet thickness and forming tool types. There are some possible causes for limited research in this direction. The factors could have smaller to insignificant effect that was seen in case of spindle rotation direction, or it could be new research. As an example, using different forming tools geometries. It could be due to deficiency of knowledge about the process parameters about in depth for example, forming tool types (using only rigid hemispherical Table).

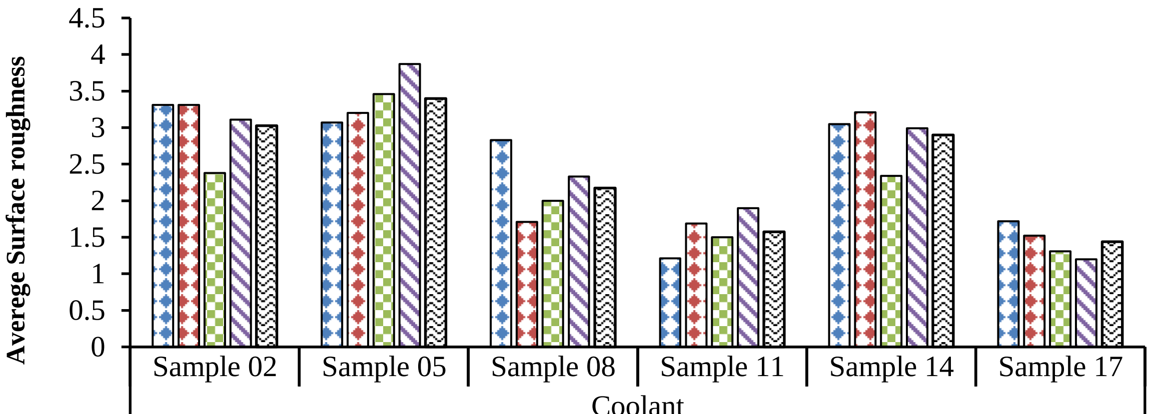


	Sample 01	Sample 04	Sample 07	Sample 10	Sample 13	Sample 16
Series1	0.32	0.51	1.86	1.86	0.73	0.68
Series2	0.3	0.57	2.25	2.25	0.58	0.75
Series3	0.26	0.69	1.64	1.64	0.48	0.88
Series4	0.276	0.48	2.1	1.99	0.88	0.9
Series5	0.289	0.5625	2.025	1.935	0.6675	0.8

Grease

N.B; Series 1 is the sample Location part one Series 1 is the sample Location part two Series 3 is the sample Location part there, Series 4 is the sample Location part Four, Series 5 is the sample Location part at the all ASR.

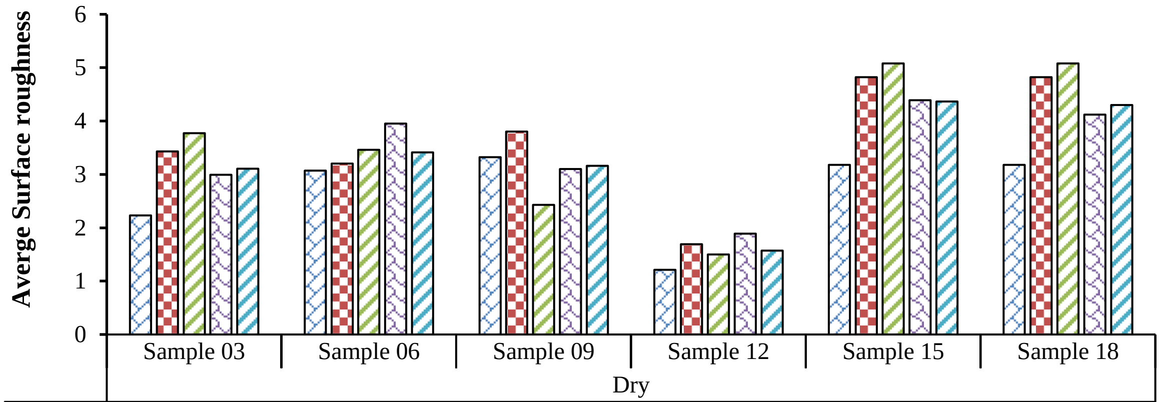
Figure 4. 15 Parameters comparison on tool 8 diameter for grease surface roughness



	Sample 02	Sample 05	Sample 08	Sample 11	Sample 14	Sample 17
Series1	3.31	3.07	2.83	1.21	3.05	1.72
Series2	3.31	3.2	1.71	1.69	3.21	1.52
Series3	2.38	3.46	2	1.5	2.34	1.31
Series4	3.11	3.87	2.33	1.9	2.99	1.2
Series5	3.027	3.4	2.175	1.575	2.8975	1.4375

Collant

Figure 4. 16 Parameters comparison on tool 8 diameter for coolant surface roughness



	Sample 03	Sample 06	Sample 09	Sample 12	Sample 15	Sample 18
Series1	2.23	3.07	3.32	1.21	3.18	3.18
Series2	3.43	3.2	3.8	1.69	4.82	4.82
Series3	3.77	3.46	2.43	1.5	5.08	5.08
Series4	2.99	3.95	3.1	1.89	4.39	4.12
Series5	3.105	3.413	3.1625	1.5725	4.3675	4.3

Dry condition

Figure 4. 17 Parameters comparison on tool 8 diameter for Dry surface roughness

4.2.7 Experimental Results for Average Micro Hardness

the application of Taguchi Method (TM) for selecting design of experiment (DOE) and analyses the result of forming hardness. Experimental work is performed to study the impacts of input factors on micro hardness developed during SPIF process.

Table 4. 6 Combination of input factor micro hardness are analyzed

Micro hardness(kg)				
Ex no	Location 1	Location 2	Location 3	Average hardness(kg)
1	47.8	58.6	49.2	51.9
2	55.9	48.5	43.7	49.4
3	44	50	51.1	48.4
4	66.8	60.6	66.7	64.7
5	52.3	53.1	46.1	50.5

6	42	47	40	43
7	67.5	61.8	67.1	65.5
8	46.2	46.9	60.5	51.2
9	40	41	43	41.3
10	46.1	54	45.6	48.6
11	69.7	47.7	46	54.5
12	54	46	46	48.7
13	69.7	72.7	66.7	69.7
14	51.9	59.96	51.7	54.5
15	50	42	43	45
16	43	41	38	40.7
17	48	50	42	46.7
18	50	44	40	44.7

Total 18 combinations of input factors are analyzed. Design of experiment (DOE) and analysis are performed using Minitab statistical software. Micro hardness is taken in to account for analysis of the results. Further, Fig4.16 shows the Average micro hardness (AMH) value verses corresponding the experiment's number for all specimens of SPIF process.

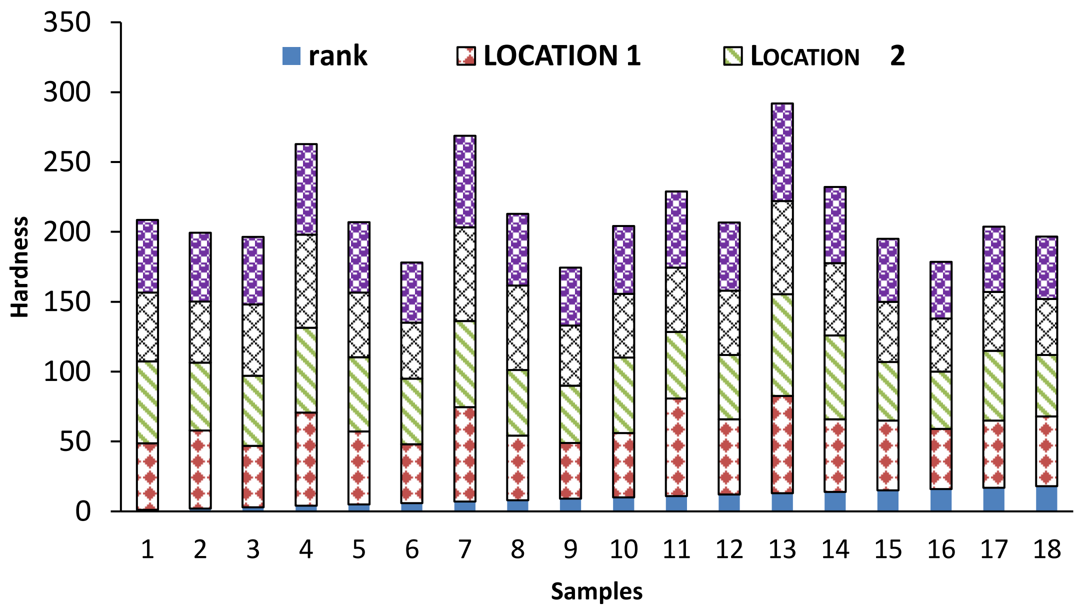


Figure 4. 18 Average Hardness

4.2.7 Selection of the Input Factors to Orthogonal Array

In the present study, six input factors have been investigated. Three parameters have been varied at six levels and one parameter, the tool diameter which has been varied at two levels as shown in Table 4.5. L1, L2 and L3 represent the code for the first, second. third, fourth, five and six level of input factors respectively. The value of each levels is selected based on literature study, preliminary and secondary experimentations. According to Taguchi Method (TM), a four- level parameter has three Degree of Freedom (DOF) and two-level parameters has one DOF. The total DOF for all parameters can be calculated as [6 × (3- 1)] + [5-1] + 1 = 17. An Orthogonal Array has been developed to investigate the effects of the process' input parameters. According to TM, the total DOF of the chosen array should be more than the process's minimum needed DOF, which in this case is 18. The nearest mixed level OA satisfying this condition is L18, which has 17 DOF. As a result, columns with the levels of each input parameter have been provided for a mixed level L 18 OA and are displayed in Table 4.7.

Table 4. 7 Input factors and their coded values with the different levels

Level	Tool radius (mm)	Inclination wall angle	Lubrication	Step Depth	Spindle speed (rpm)	Feed rate (mm/min)
1	34.18	34.01	34.94	34.00	34.29	34.19
2	33.94	34.60	34.16	34.64	33.88	33.98
3		33.57	33.08	33.53	34.01	34.01
Delta	0.25	1.04	1.85	1.11	0.41	0.21
Rank	5	3	1	2	4	6

Table 4. 8 Experimental L18 OA plan and cross ponding ASR value with its S/N ratio

Process Parameters							Response Parameter	
Sr. No	Tool Diameter	Inclination wall angle	Lubrication	Step Depth	Spindle speed	Feed rate (mm/min)	Average hardness(kg)	S/N of Average

	(mm)				(rpm)			hardness(kg)
01	8	45	Grease	1	1000	300	51.9	34.29777
02	8	45	Coolant	1.5	2000	350	49.4	33.86868
03	8	45	Dray	2	2500	400	48.4	33.69092
04	8	55	Grease	1	2000	350	64.7	36.21809
05	8	55	Coolant	1.5	2500	400	50.5	34.06583
06	8	55	Dray	2	1000	300	43	32.66937
07	8	75	Grease	1.5	1000	400	65.5	36.3204
08	8	75	Coolant	2	2000	300	51.2	34.1854
09	8	75	Dray	1	2500	350	41.3	32.32601
10	16	45	Grease	2	2500	350	48.6	33.72677
11	16	45	Coolant	1	1000	400	54.5	34.72262
12	16	45	Dray	1.5	2000	300	48.7	33.74463
13	16	55	Grease	1.5	2500	300	69.7	36.86466
14	16	55	Dray	2	1000	350	54.5	34.73112
15	16	55	Coolant	1	2000	400	45	33.06425
16	16	75	Grease	2	2000	400	40.7	32.18477
17	16	75	Coolant	1	2500	300	46.7	33.38014
18	16	75	Dray		1000	350	44.7	32.99967

4.2.8 Experimental Results for Hardness

Using a tool dynamometer, experimental test results of various process factors on micro hardness are obtained. These values are presented as indicated in Table 4.7. Analysis has been done on a total of 18 combinations of input factors. Minitab17 statistical software is used throughout the current study for all analyses and design of the experiment. Analysis has been done while accounting for hardness forming.

4.2.9 Analysis and Result discussions of Hardness Forming

In this section, the impact and optimization of selected individual SPIF process input parameters have been investigated. From experimental raw data, the mean value and S/N ratio of hardness formation forces for each input factor at various levels are calculated Table 4.7. In order to explain the impact of specific process variables on hardness, the major effects diagrams (response curves) are used for S/N data. To choose the order of the input components, response tables are used for S/N data. Analysis of variance (ANOVA) of measured values are also carried out in order to determine the importance of the influence of the chosen process variables on Hz max. By using main effects diagrams and an analysis of variance (ANOVA) table, the optimal values of all input factors in terms of harness forming is chosen. Additionally, S/N ratios are used to assess the variation in quality feature (Hz-max, in this case). The process is at its optimal outcome when the S/N ratio is highest because it results in the least amount of variation in the hardness forming. Moreover, forming hardness is considered as a “Smaller the Better" type quality response; because it is generally accepted that a smaller value of force in during the forming process. Hence, the power consumption is the lower.

4.2.10 Effects of Process Factors on Forming Hardness

FH experimental data are transformed into S/N ratios using the statistical program Minitab -17 software. The response table for the S/N ratio’s delta statistics is used to identify the dominant control factors. The difference between the highest and lowest average value for each factor is used to calculate the delta statistics. According to the delta value, ranks are allocated. The highest delta value, which stands for the main factor affecting FH, is given the top rank. The Lubrication is the factor that has the greatest influence, according to the response Table 4.8, with a delta value of lubricant 1.85. Step Depth is the second-largest contributing factor, with a delta value of 1.11, followed by Inclination wall angle, Spindle speed, Tool D and feed.

Table 4. 9 Input factors and their coded values with the different levels

Level	Tool D(mm)	Inclination wall angle	Lubrication	Step Depth	Spindle speed (rpm)	Feedrate (mm/min)
1	34.18	34.01	34.94	34.00	34.29	34.19
2	33.94	34.60	34.16	34.64	33.88	33.98
3		33.57	33.08	33.53	34.01	34.01
Delta	0.25	1.04	1.85	1.11	0.41	0.21
Rank	5	3	1	2	4	6

The major effects plot for S/N ratios is derived from the responses in Table 4.8 and is depicted in Fig.4.20. According to the plot's trend, changes in Lubrication have a significant impact on FH. From the findings of result, hardness response quality improves as speed increases as can be seen from Fig. 4.20 that, the S/N ratios for FH have been on a sharp increasing. With increased spindle speed during the SPIF process, an FH is observed to reduce significantly. One possibility seems that the increased friction at the tool-sheet interface is caused by the higher rotational spindle speed. This higher friction raises the heat at the contact area, which enhances the material's ductility. As a result, the value of the axial peak forming force tends to decrease as spindle speed increases. These results are consistent with the technical literature.

The feed plot demonstrates a rise in the S/N ratio from 300 mm/min to 350 mm/min value of feed, whereas the feed is increased from 350 to 400mm/min, the value of S/N ratio subsequently declines significantly. With an increase in feed rate, which takes in to account the fact that more material must be pressed in a given amount of time due to the nature of the process' deformation, hence, a trend toward decreasing the S/N ratio of forming hardness is observed. This is clearly a result of local material ductility declines brought on by a reduction in temperature at the tool sheet interface. Hence, FH increases with increase of feed from level-2 to level-3. Further, contradiction of forming hardness is found to increases marginal when feed rate is decreased from level-1 to level -2, these is due to interaction effect of other parameters with feed.

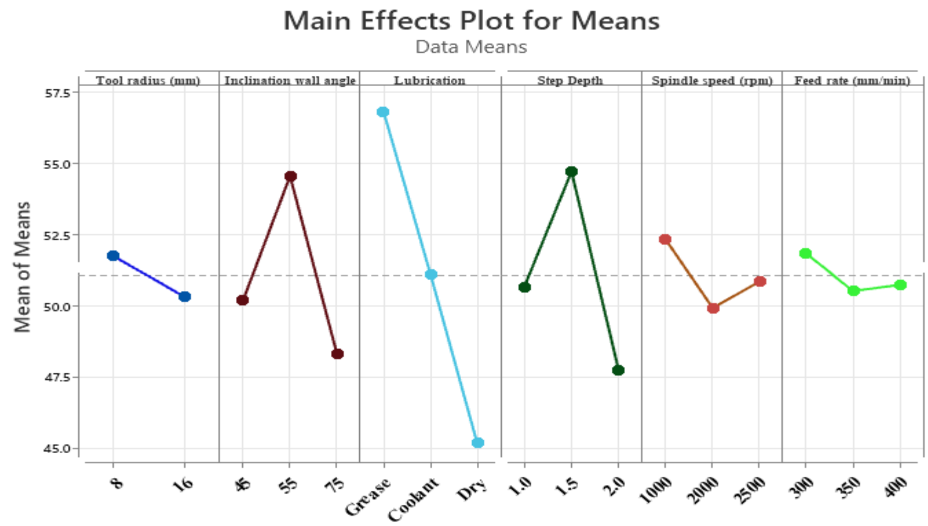


Figure 4. 19 Main effect of plot mean of means for forming hardness

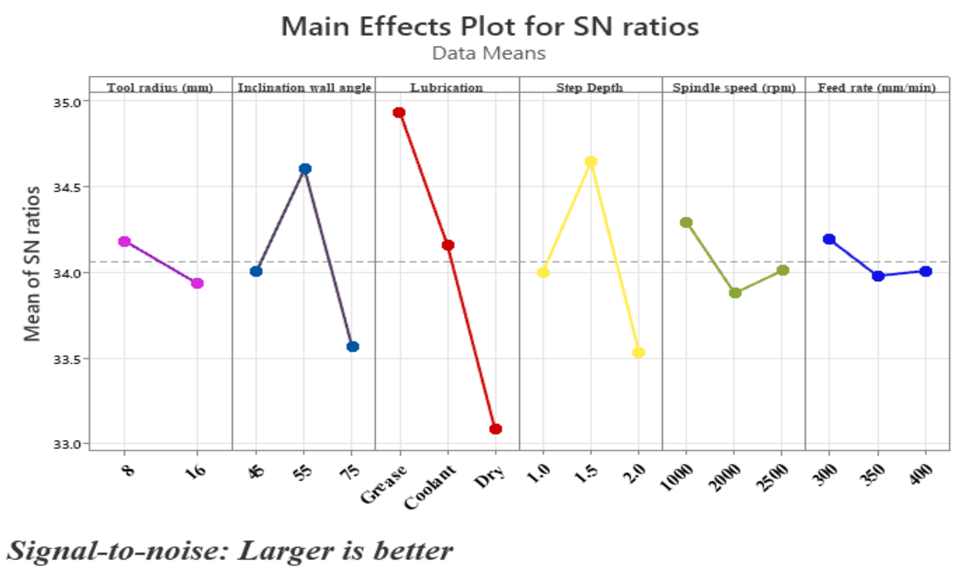


Figure 4. 20 Main effects plot for S/N ratios of micro hardness

The plot of step size shows a decrease of the S/N ratio from 1 to 1.5 mm and 1.5 to 2 mm. The increase in the values of the step size causes an increase in the forming hardness. To complete the part, the tool needs to travel continuously inside the profile and this required more pushing of the material for local sheet deformation during forming. The reaction of the material will be greater with high step size values, finally increasing the forces. But, the value marginally increases when the step size is increased from 1 to 1.5 mm due to interaction effect of another parameter.

Similar to step size, increasing tool diameter, increases the amount of force needed to form a specimen. In Fig. 4.20, the relationship between tool diameter and S/N ratio demonstrates a trend toward decreasing S/N ratio as tool diameter increases from 8 mm to 16 mm. It indicates that an increase in tool diameter is found to raise the amount of forming hardness. This is because a larger tool diameter results in a wider contact zone at the tool-sheet interface, which necessitates the forming of more material at that time compare to smaller tool diameter.

4.2.11 Selection of the Significant Factors for Hardness

An analysis of variance (ANOVA) is carried out after factor levels are established to determine the percentage contribution of each factor's effect on the Forming hardness. The ANOVA for forming hardness values is shown in Table 5.8, where a higher F-value indicates a greater significance for the corresponding factor. The FH can be seen to be most affected by lubricants, which has a contribution of 45.38 % subsequently by the step Depth of 17.89 %, Inclinational angle feed20.66%, speed 1.52%, tool diameter of 0.8 % and Feed of 10.52%

To further reduce process variability, it is essential to separate out non-significant characteristics from the significant ones. Using the P-test as a cut-off criterion, ANOVA is particularly helpful in separating significant variables from non-significant variables. Factors with a p-value less than 0.05 are regarded as significant at a 95% confidence level

Table 4. 10 Analysis of variance (ANOVA) for forming hardness

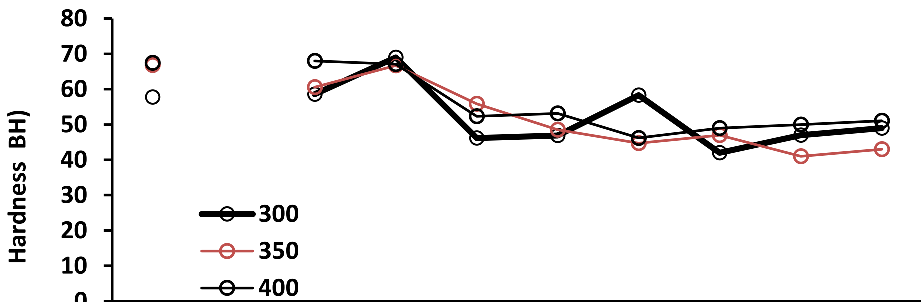
Factor	DF	Sum of square	Mean of square	F - Value	Adj SS	P – Value	% of contribution
A: Tool Diam (mm)	1	9.22	9.216	0.13	9.216	0.73520	0.80%
B: Inclinational angle	2	122.79	61.394	0.84	122.789	0.47817	20.66%
C: Lubrication	2	407.61	203.807	2.78	407.614	0.04007	45.38%
D: Step Depth	2	148.54	74.272	1.01	148.544	0.41814	17.89%
E: speed (rpm)	2	17.55	8.777	0.12	17.554	0.88936	1.52%

F: Feed (mm/min)	2	6.05	3.024	0.04	6.049	0.95990	10.52%
Error	6	440.40	73.400		440.398		3.23%
Total	17	1152.16					100.00%

Model Summary: R-sq 95.78% , R- sq(adj) 86.00%

4.2.12 Effect of Feed Rate On micro hardness

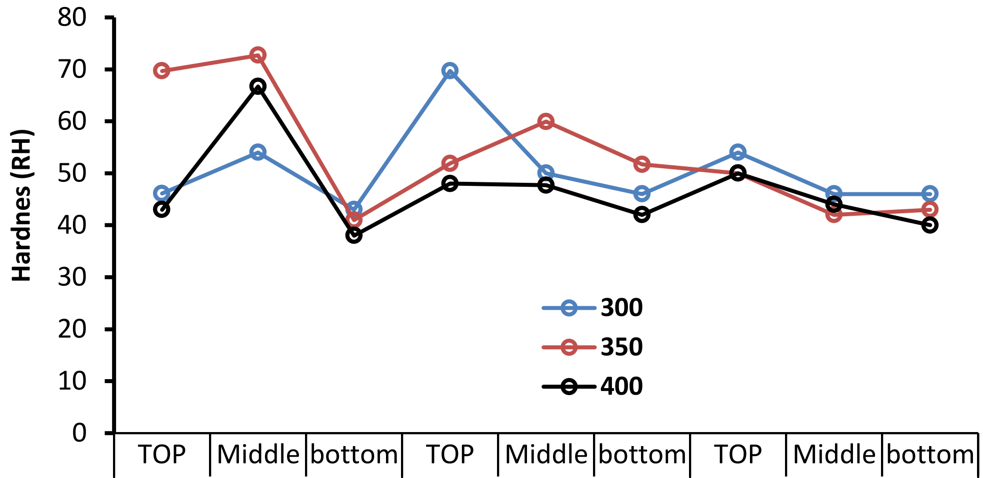
Different lubricants (grease, coolant, and dry) were utilized at three different input rates. In addition, the tool speed, diameter, and other experimental parameters were remained constant at 1000, 2000, and 2500 rpm, respectively. Results of hardness measurements for various feed rates are shown in Table 4.9. The hardness value is inversely correlated with the kind of lubricant used; it rises when the feed rate is raised and grease, coolant and dry is used (see Figure 4.21), and (see Figure 4.22).



	TOP		Middle	bottom	TOP	Middle	bottom	TOP	Middle	bottom
				Grease			Coolant			Dry
300	57.8		58.6	68.99	46.2	46.9	58.3	42	47	49
350	66.8		60.6	66.7	55.9	48.5	44.7	47	41	43
400	67.5		68	67.1	52.3	53.1	46.2	49	50	51.1

Feed rate mi/mm

Figure 4. 21 Effect of Feed Rate on tool 8 diameter micro hardness



	Grease TOP	Grease Middle	Grease bottom	Coolant TOP	Coolant Middle	Coolant bottom	Dry TOP	Dry Middle	Dry bottom
300	46.1	54	43	69.7	50	46	54	46	46
350	69.7	72.7	41	51.9	59.96	51.7	50	42	43
400	43	66.7	38	48	47.7	42	50	44	40

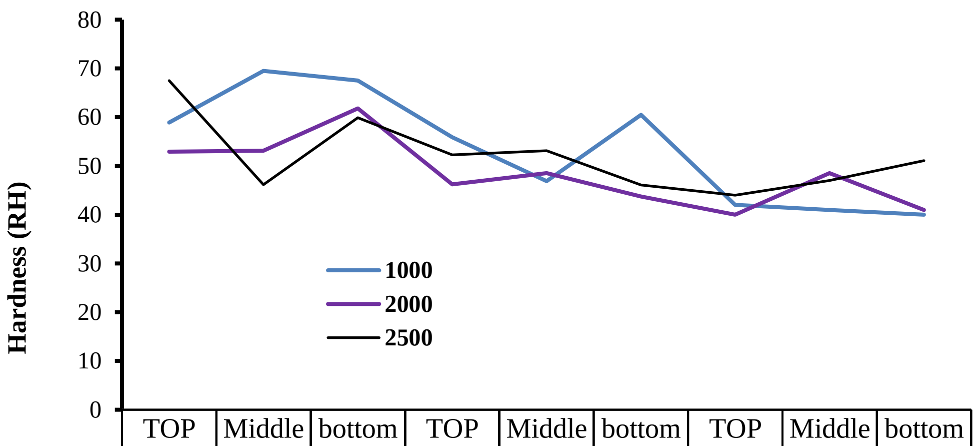
Figure 4. 22 Effect of Feed Rate On tool 16 diameter micro hardness

Hardness increases with feed rate, and hardness is negatively correlated with formability. According to, an increase in feed rate results in a reduction in formability. Because the peaks of the aspirates created by the generated debris shoot and shatter, changes in surface asperities induce a loss in hardness. New grooves may be made by connecting the debris to the tool and cultivating the sheet's surface, and the asperities' sharp peaks can also be smashed. Finally,

Only a significant stress in the underlying bulk material may further affect the sheet surface asperities since they are already in sheet metal state. They assert that this stress produces enhanced metal deformation of asperities and is perpendicular to the normal force. Finally, this thesis results in an expanded contact area, which is recognized as a loss in effective hardness because of the huge pressure on the underlying material.

4.2.13 Effect of spindle speed on micro hardness

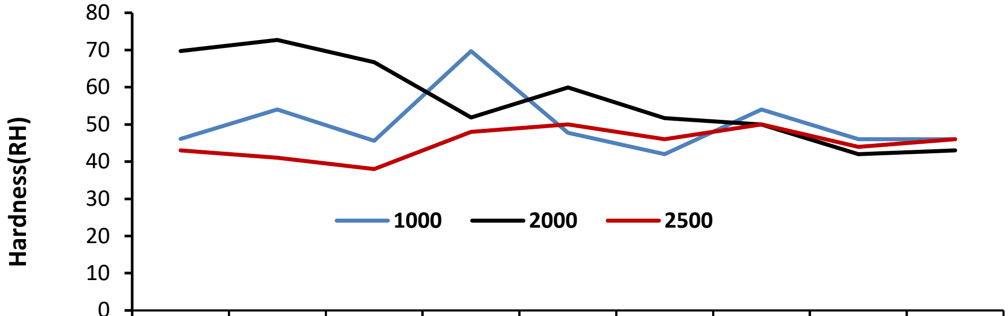
With the experimentally determined hardness values, alternative tool rotation speeds are listed in Table 4.9. Figure4.22and 4.23 demonstrates the relationship between tool speed and hardness. When a sheet is moving at a high speed, the resultant particles hit the sheet's surface more quickly than when it is moving at a moderate speed, which causes the surface to harden. As opposed to that, High tool speeds cause the tool head to make more passes across the sheet in the same contact area as low tool speeds do. The sheet material appears to be operating in cold temperatures due to stretching and longitudinal deformation. Different types of crystal deformation, such as compressing, twisting, and bending, are produced during cold working. and this results in comparatively uniform plain crystalline particles. New imperfections created by these movements result in more resistance and, finally, increase hardness



	Grease TOP	Grease Middle	Grease bottom	Coolant TOP	Coolant Middle	Coolant bottom	Dry TOP	Dry Middle	Dry bottom
1000	58.9	69.5	67.5	55.9	46.9	60.5	42	41	40
2000	52.9	53.1	61.8	46.2	48.5	43.7	40	48.5	41
2500	67.5	46.15	59.9	52.3	53.1	46.1	44	47	51.1

Spindle Speed (rev/mm)

Figure 4. 23 Effect of spindle speed on tool 8 diameter micro hardness



	Grease			Coolant			Dry		
	TOP	Middle	bottom	TOP	Middle	bottom	TOP	Middle	bottom
1000	46.1	54	45.6	69.7	47.7	42	54	46	46
2000	69.7	72.7	66.7	51.9	59.96	51.7	50	42	43
2500	43	41	38	48	50	46	50	44	46

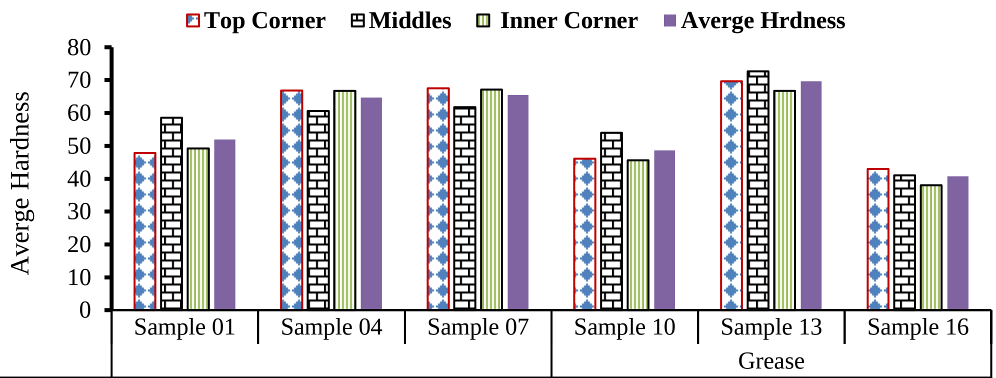
Spindle Speed rpm

Figure 4. 24 Effect of spindle speed on tool 16 diameter micro hardness

4.2.14 Effect of Grease Grade On micro hardness

Results for how different greases affected hardness are shown in Table 4.9 and Figure 4.24,4.25 and 4.26,Lowest hardness was given by the grease with the greatest drop point, and vice versa. It is obvious that the annealed sheet has lesser hardness since ISF involves localized shaping and targeted heating to anneal the sheet progressively. On the other hand, a grease with a low drop point value will become liquid more quickly than grease with a high drop point value owing to viscosity loss. Low-viscosity grease can travel between the grooves and the sheet's surface and moving tool.

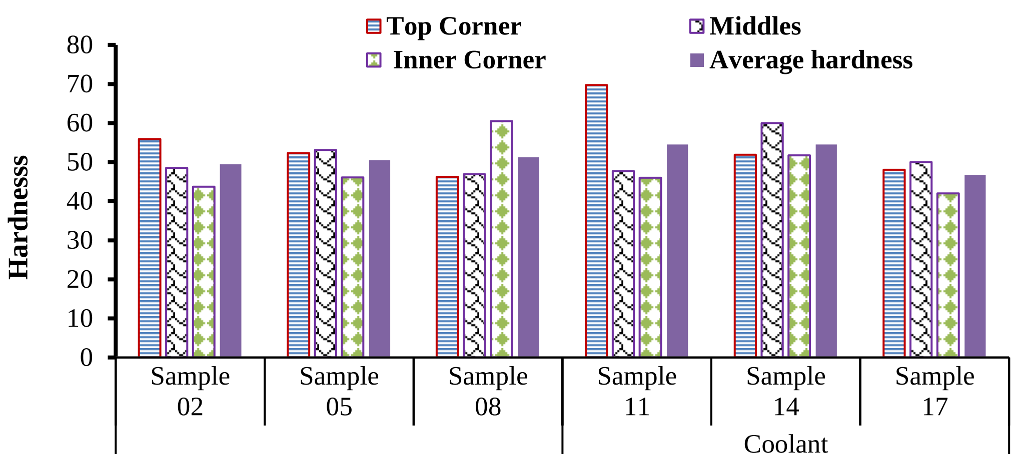
It is demonstrated that using the grease with a higher flash point led to a more stable hardness value when comparing the attributes of various greases. In reality, it can be observed that using grease as opposed to coolant oil results in harder sheets at different spots on the sheet, with coolant oil somewhat differing from Gp Grease Calcium type grease in this regard.



	Sample 01	Sample 04	Sample 07	Sample 10	Sample 13	Sample 16
Top Corner	47.8	66.8	67.5	46.1	69.7	43
Middles	58.6	60.6	61.8	54	72.7	41
Inner Corner	49.2	66.7	67.1	45.6	66.7	38
Averge Hrdness	51.9	64.7	65.5	48.6	69.7	40.7

Grease

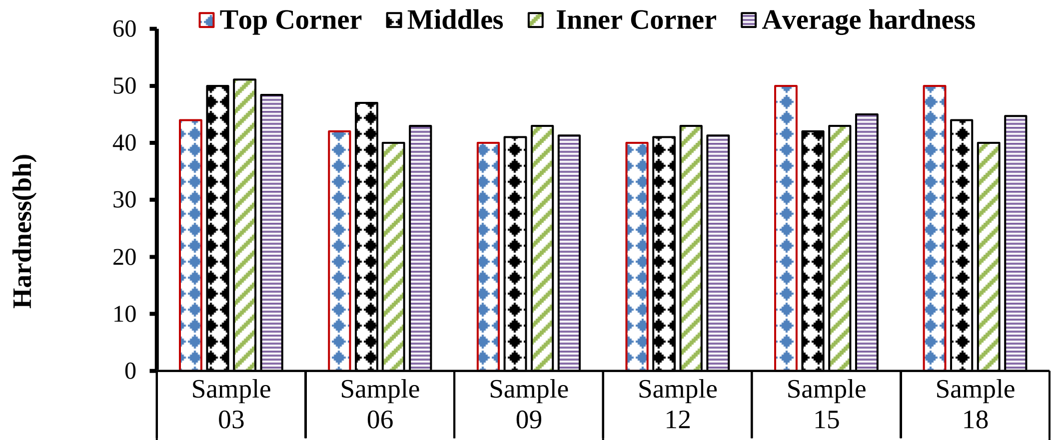
Figure 4. 25 Effect of Grease Grade On grease micro hardness



	Sample 02	Sample 05	Sample 08	Sample 11	Sample 14	Sample 17
Top Corner	55.9	52.3	46.2	69.7	51.9	48
Middles	48.5	53.1	46.9	47.7	59.96	50
Inner Corner	43.7	46.1	60.5	46	51.7	42
Average hardness	49.4	50.5	51.2	54.5	54.5	46.7

Colant

Figure 4. 26 Effect of Grease Grade On coolant micro hardness



	Sample 03	Sample 06	Sample 09	Sample 12	Sample 15	Sample 18
Top Corner	44	42	40	40	50	50
Middles	50	47	41	41	42	44
Inner Corner	51.1	40	43	43	43	40
Average hardness	48.4	43	41.3	41.3	45	44.7

Dry condition

Figure 4. 27 Effect of Grease Grade On coolant micro hardness

CHAPTER FIVE
5. CONCLUSION AND RECOMMENDATION

5.1. Introduction

This chapter discusses the important conclusions drawn during the Parametric Investigation and Optimization of Single Point Incremental Forming for soft to Form Material. In this research work, the effort has been made to investigate surface roughness, forming hardness and simulation improvement of the AA 6063 sheets using SPIF with friction heat. The effect of process parameters, namely lubricant, Inclinational angle, speed, feed, step size, and tool diameter, on the forming hardness and surface roughness indicator response characteristics are observed using Taguchi's based experimental plan.

5.1.1. Conclusions of Work

The important conclusions from the present research work on Parametric Investigation and Optimization of Single Point Incremental Forming for soft to Form Material are:

- The important conclusions from the present research work on Parametric Investigation and Optimization of Single Point Incremental Forming for soft to Form Material are:
- Experimental results showed that lubricant of grease, angle of 55°, speed of 1000 rpm, step size of 1.5 mm, feed rate of 300 mm/min and a tool diameter of 8 mm in optimum parametric condition for minimizing the FH on AA 6063 alloy sheets using TM
- According to ANOVA statistical analysis, the most dominant input parameter is lubricants with the contribution, of (35.38 %) for FH followed by the step Depth of (12.89 %), Inclinational angle feed (10.66%), speed (1.52%), tool diameter of (0.8 %) and Feed of (0.52%).
- The average roughness of formed parts increased with lubricants, feed, step size, and angle whereas decreased with speed and tool diameter. Better surface finish is obtained with lower lubricants, feed, step size, and angle whereas higher tool diameter and speed.
- Experimental results showed that at lubricant of grease, angle of 45°, speed of 2000 rpm, step size of 1 mm, feed rate of 300 mm/min and a tool diameter of 8 mm of hemispherical shape result in optimal parametric condition for average roughness of the components produced during the SPIF process using TM.
- According to ANOVA statistical analysis, lubricants is the most significant factor for average roughness with a contribution, of (58.31 %) for FH followed by the step Depth of

(4.53 %), Inclinational angle feed (4.57%), speed (1.25%), tool diameter of (0.53 %) and Feed of (15.06%).

5.2.RECOMMENDATION

5.2.1. Concluding Remarks for Average Surface Roughness

- Confirmation tests which is conducted at optimum levels of input factors showed that average surface roughness was within the confidence interval at 95% confidence level and close to predicted results. The estimated optimal value for average surface roughness is 1.87 (µm), whereas, in order to form conical frustums, the suggested model successfully predicted the surface quality of formed components. Consequently, using the provided instructions regarding a relationship between input parameters and required surface roughness, SPIF applicability can be improved on an industrial scale.
- In incremental sheet forming (ISF) most of the researchers used step increment from .2 mm to 1 mm. The conclusions from this survey expressed that surface finish improved with decreasing in step increment.
- Analysis of variance (ANOVA) results analyzed that step increment has also significant effect on surface quality and has contribution up to 37%. If less forming process time is required in in sheet forming process then value of step increment should be optimized. This illustrates that material requirements should be considered in order to select this process parameter and it also demonstrates the significance of catering to utilize the interactions of step increment with tool diameter and sheet thickness

5.2.2. Concluding Remarks for Forming hardness

Hardness forming are found to steadily grow up to peak values due to bending mechanics until a limited forming depth. Stretching mechanics, which varied the force trends as a result of strain hardening and sheet thinning, is believed to exist after a particular forming depth. In order to safely use the forming operation, the gradient of the force curve following peaks can be considered. It used as a hidden variable for changing process parameters by continuous comparison of important value and immediate value. Because of the relationship between input parameters and necessary forming forces, SPIF applicability can be improved on an industrial scale using the provided suggestions.

5.3. Scope of Future Work

Although the Single Point Incremental Forming (SPIF) process has been thoroughly investigated for forming of AA6063 work material Pyramid cone with hard steel tool using friction heat, still there is scope for further investigation. The following suggestions may be helpful for future work:

1. Future research can focus on investigating the SPIF process for hard to form alloy sheet material by using FEM software with displacement-thermal couple for cost effectiveness.
2. Future research can focus on developing the fracture forming limit diagrams and stress-based forming limit diagrams for the formability analysis of different hard to-form materials in the ISF process using sophisticated and more precise measuring instruments.
3. There is also a need to understand the effects of process parameters of friction stir SPIF process on the temperature distribution using more precise measuring instruments.
4. Microstructural evolutions during the heat-assisted SPIF process can be investigated under different process parameters to get more insight into the deformation mechanics for hard-to-form material.
5. Future studies can be focused on studying the spring back, orange peel surface phenomena and form accuracy of hard-to-form parts produced in multi stage incremental forming.

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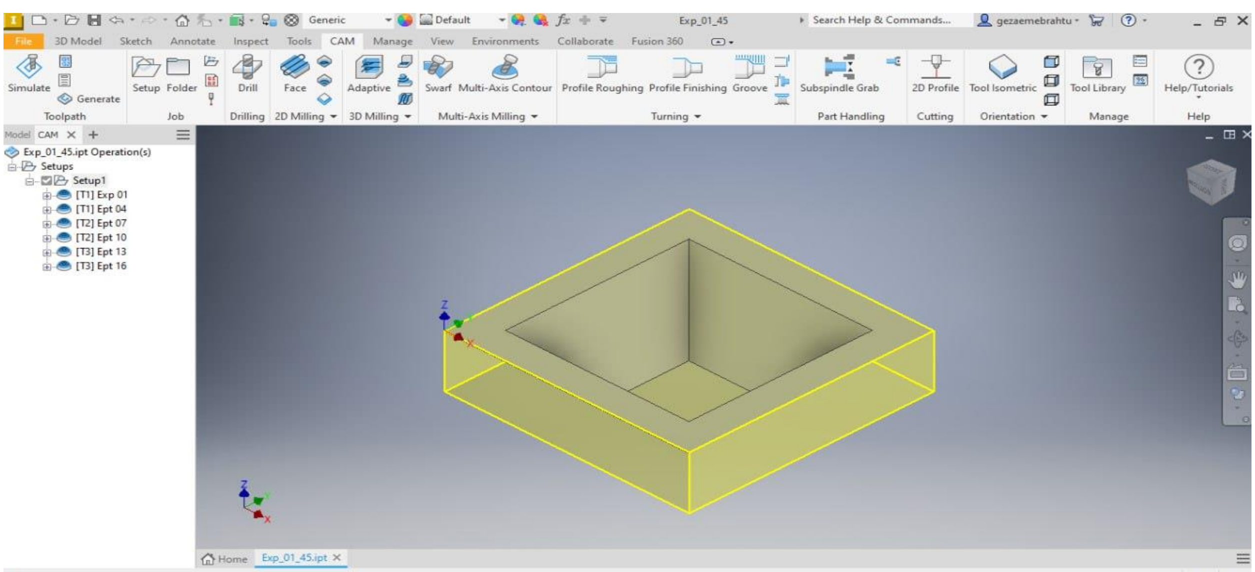
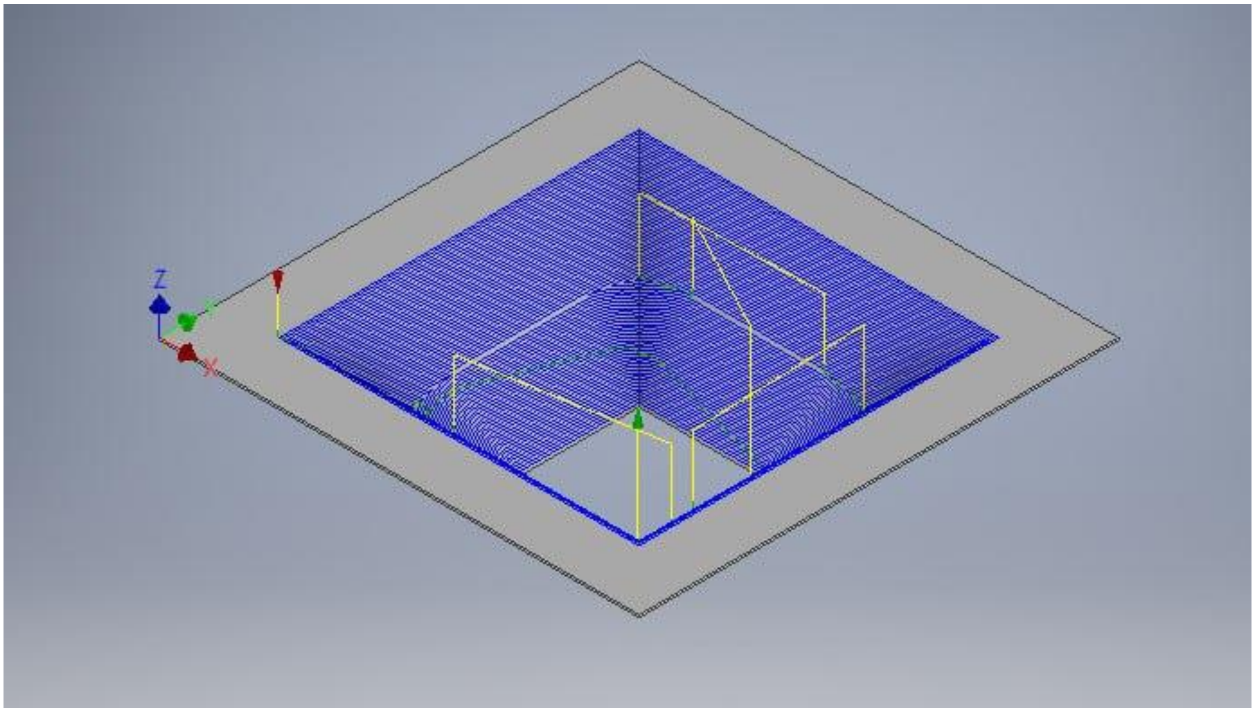
Appendix

Sample preparation for experimental testing





G-CODE generate simulation test

Setup Sheet for Program 1001

Setup

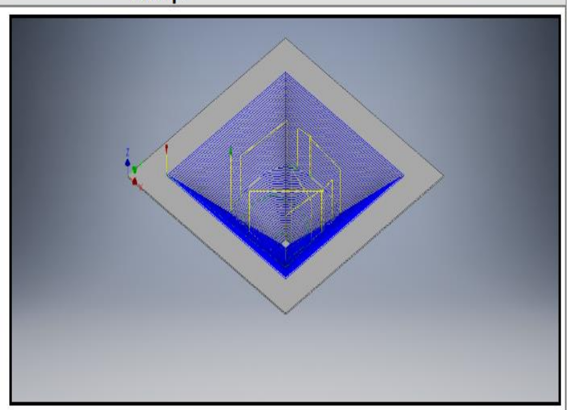
WCS: #0

Stock:
DX: 200mm
DY: 200mm
DZ: 50mm

Part:
DX: 200mm
DY: 200mm
DZ: 50mm

Stock Lower in WCS #0:
X: 0mm
Y: 0mm
Z: -50mm

Stock Upper in WCS #0:
X: 200mm
Y: 200mm
Z: 0mm



Operations

Operation 1/1		**T1** D1 L1	
Description: Exp 03	Maximum Z: 15mm	Type: ball end mill	
Strategy: Scallop	Minimum Z: -49.12mm	Diameter: 8mm	
WCS: #0	Maximum Spindle Speed: 2000rpm	Corner Radius: 4mm	
Tolerance: 0.01mm	Maximum Feedrate: 350mm/min	Length: 90mm	
Stock to Leave: 0mm	Cutting Distance: 18879.87mm	Flutes: 3	
Maximum stepover: 1.5mm	Rapid Distance: 751.8mm		
	Estimated Cycle Time: 54m:6s		
	Coolant: Flood		

Total

Number Of Operations: 1
Number Of Tools: 1
Tools: **T1**
Maximum Z: 15mm
Minimum Z: -49.12mm
Maximum Feedrate: 350mm/min
Maximum Spindle Speed: 2000rpm
Cutting Distance: 18879.87mm
Rapid Distance: 751.8mm
Estimated Cycle Time: 54m:21s

Tools

T1 D1 L1		
Type: ball end mill	Minimum Z: -49.12mm	
Diameter: 8mm	Maximum Feed: 350mm/min	
Corner Radius: 4mm	Maximum Spindle Speed: 2000rpm	
Length: 90mm	Cutting Distance: 18879.87mm	
Flutes: 3	Rapid Distance: 751.8mm	
	Estimated Cycle Time: 54m:6s	

Forming Experiment _01_45.ipt

Setup

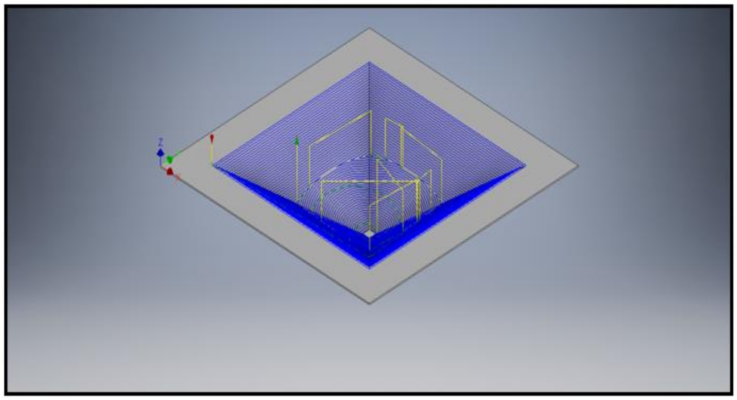
WCS: #0

STOCK:
DX: 200mm
DY: 200mm
DZ: 50mm

PART:
DX: 200mm
DY: 200mm
DZ: 50mm

STOCK LOWER IN WCS #0:
X: 0mm
Y: 0mm
Z: -50mm

STOCK UPPER IN WCS #0:
X: 200mm
Y: 200mm
Z: 0mm



Total

NUMBER OF OPERATIONS: 1
NUMBER OF TOOLS: 1
TOOLS: **T1**
MAXIMUM Z: 15mm
MINIMUM Z: -49.12mm
MAXIMUM FEEDRATE: 350mm/min
MAXIMUM SPINDLE SPEED: 2000rpm
CUTTING DISTANCE: 18879.87mm
RAPID DISTANCE: 751.8mm
ESTIMATED CYCLE TIME: 54m:21s

Tools

T1 D1 L1

TYPE: ball end mill
DIAMETER: 8mm
CORNER RADIUS: 4mm
LENGTH: 90mm
FLUTES: 3

MINIMUM Z: -49.12mm
MAXIMUM FEED: 350mm/min
MAXIMUM SPINDLE SPEED: 2000rpm
CUTTING DISTANCE: 18879.87mm
RAPID DISTANCE: 751.8mm
ESTIMATED CYCLE TIME: 54m:6s

Operations

Operation 1/1
DESCRIPTION: Exp 03
STRATEGY: Scallop
WCS: #0
TOLERANCE: 0.01mm
STOCK TO LEAVE: 0mm
MAXIMUM STEPOVER: 1.5mm

MAXIMUM Z: 15mm
MINIMUM Z: -49.12mm
MAXIMUM SPINDLE SPEED: 2000rpm
MAXIMUM FEEDRATE: 350mm/min
CUTTING DISTANCE: 18879.87mm
RAPID DISTANCE: 751.8mm
ESTIMATED CYCLE TIME: 54m:6s
COOLANT: Flood

T1 D1 L1
TYPE: ball end mill
DIAMETER: 8mm
CORNER RADIUS: 4mm
LENGTH: 90mm
FLUTES: 3

Forming Experiment_01_55.ipt

Total
Number Of Operations: 1 Number Of Tools: 1 Tools: **T1** Maximum Z: 15mm Minimum Z: -17.86mm Maximum Feedrate: 400mm/min Maximum Spindle Speed: 2500rpm Cutting Distance: 12234.05mm Rapid Distance: 468.79mm Estimated Cycle Time: 30m:56s

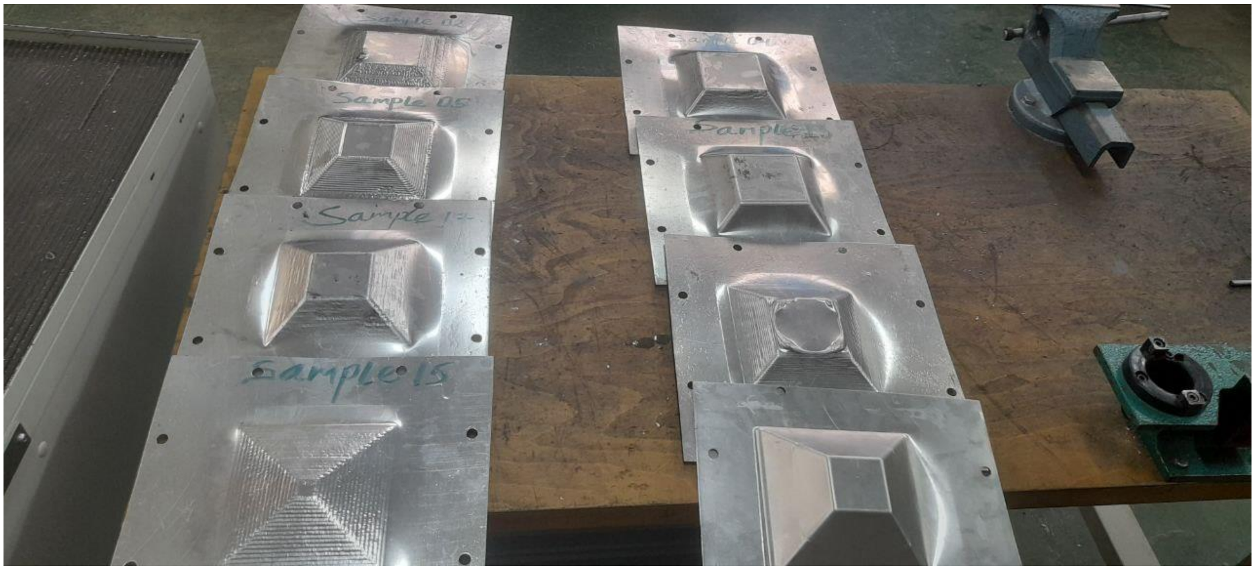
Tools		
T1 D1 L1 Type: ball end mill Diameter: 8mm Corner Radius: 4mm Length: 90mm Flutes: 3	Minimum Z: -17.86mm Maximum Feed: 400mm/min Maximum Spindle Speed: 2500rpm Cutting Distance: 12234.05mm Rapid Distance: 468.79mm Estimated Cycle Time: 30m:41s	

Operations			
Operation 1/1 Description: Exp 03 Strategy: Scallop WCS: #0 Tolerance: 0.01mm Stock to Leave: 0mm Maximum stepover: 2mm	Maximum Z: 15mm Minimum Z: -17.86mm Maximum Spindle Speed: 2500rpm Maximum Feedrate: 400mm/min Cutting Distance: 12234.05mm Rapid Distance: 468.79mm Estimated Cycle Time: 30m:41s Coolant: Flood	**T1** D1 L1 Type: ball end mill Diameter: 8mm Corner Radius: 4mm Length: 90mm Flutes: 3	

Forming Experiment_01_75.ipt

```
%
O1018
(T3 D=16. CR=8. - ZMIN=-17.718 - BALL END MILL)
N10 G90 G94 G17 G49 G40 G80
N15 G21
N20 G28 G91 Z0.
N25 G90
(EPT 18)
N30 T3 M06
N35 S1000 M03
N40 G54
N45 M08
N50 G00 X23.4 Y25.
N55 G43 Z15. H03
N60 G00 Z2.
N65 G01 Z1.6 F350.
N70 G18 G02 X25. Z0. I1.6
N75 G01 X175.
N80 Y174.999
N85 X174.994 Y175.
N90 X25.
N95 Y25.
```

```
%
O1005
(T1 D=8. CR=4. - ZMIN=-49.117 - BALL END MILL)
N10 G90 G94 G17 G49 G40 G80
N15 G21
N20 G28 G91 Z0.
N25 G90
(EPT 05)
N30 T1 M06
N35 S2500 M03
N40 G54
N45 M08
N50 G00 X24.252 Y25.
N55 G43 Z15. H01
N60 G00 Z2.
N65 G01 Z0.8 F400.
N70 G18 G02 X25.052 Z0. I0.8
N75 G01 X175. Y25.001
N80 X174.999 Y175.
N85 X25.001
N90 X25. Y25.001
```



After the G-Code generate simulation test