ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

Parameter optimization of single point incremental forming on Al6063A sheet

A Thesis Submitted to the Graduate School of Addis Ababa University in Partial Fulfillment of the requirements for the Degree of Master of Science in Mechanical Engineering

(Manufacturing Engineering)

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CANDIDATE DECLARATION

I hereby confirm that the work provided on this thesis, "Parameter Optimization of Single Point Incremental Sheet Forming on Al6063A sheet," is an actual record of my own work completed under the guidance of Dr. Mesfin Gizaw, Program of Manufacturing Engineering, Addis Ababa Institute of Technology, Ethiopia, and is submitted in partial fulfillment of the requirements for the award of a diploma of Master of Science in Mechanical Engineering.

I have not applied for any other degree or diploma using the material included in this thesis. All relevant sources of information used in this thesis have been properly acknowledged.

Submitted by

Bayissa Bedada ------------------------------- --------------------------------

Candidate Signature Date

This is to certify that the above recognition made by the candidate is accurate to the quality of my understanding and belief. This has been approved and submitted for review.

Approved by

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Parameter optimization of single point incremental forming on Al6063A sheet

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Abstract

The incremental sheet forming (ISF) method is regarded as a practical solution for forming a variety of sophisticated and small-batch sheet components. Surface finish is an important aspect of incremental sheet forming (ISF), and it is influenced by a number of process variables such as tool diameter, step depth (vertical depth increment), spindle speed, and feed rate. As a result, for incremental sheet forming, process parameter optimization is chosen to produce products with an excellent surface finish and with no defects. Hence, the optimization's goal is to produce a good surface-finish product using a single point incremental forming process without fracture. In order to achieve this, aluminum alloy (Al6063A) is studied using ABAQUS simulation technique and experimental analysis. Due to its moderate strength to weight ratio and easy of formability, the aluminum alloy Al6063A is widely used in automotive and part profiles for architectural applications. The Taguchi technique of DOE with ANOVA and L9 orthogonal array is designed to identify the rank, Percentage contribution and optimum values of process parameters in ISF (incremental sheet forming) to reduce the surface roughness. The results of ANOVA revealed that Tool diameter has greater contributions (88.94%) followed by feed rate (7.44 %), Spindle Speed (3.4%), Step depth 0.22% respectively. The stress value of experiment 7 (1216 MPA) which is a good surface finish product of all. The predicted optimum value for the surface roughness is 0.43µm and the confirmation experiments was conducted thrice and the value of surface roughness found to be 0.37µm which is at 95% confidence level. The confirmation result shows the recommended forming process parameter values to surface roughness based on Taguchi analysis were precise and fitted to the optimum values.

Key words: SPIF, Optimization, surface roughness, Taguchi, ANOVA

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List of abbreviation

ISF ***Incremental Sheet Forming***

SPIF ***Single point incremental forming***

ANOVA ***Analysis of Variance***

CAD ***Computer Added Design***

CAM ***Computer Added Manufacturing***

CNC ***Computer Numerical Controller***

FEA ***Finite Element Analysis***

RPM ***Revolution per minute***

SR ***Surface Roughness***

Ra ***arithmetic surface roughness***

2D ***Two Dimensional***

3D ***Three Dimensional***

Al ***Aluminum***

TD ***Tool Diameter***

SD ***Incremental Step Depth mm***

SS ***Spindle Speed***

FR ***Feed rate***

α ***Wall angle***

CL ***Cutter location***

CC ***Cutter contact***

µM ***Micro Meter***

MPA ***Mega Pascal***

Chapter 1

Introduction

1.1 Background of the study

Among the most important manufacturing sectors in industries is sheet metal forming. Through the years, many technological advances have been made within sheet metal forming process. Some of the conventional sheet metal forming methods includes deep drawing, stamping and so on [1]. Those methods require the design and manufacturing of complex shaped dies which are necessary for carrying out the forming process. The cost of tooling and die making is only justified if those techniques are involved in mass production. In case of small batch production, Incremental Sheet Metal Forming (ISF) is most preferable to minimize the cost of tooling and die-making which is a prevailing sheet forming technique widespread for small batch production. It makes use of a simple form tool which is generally hemispherical in shape in order to deform the sheet [2]. With the help of a CNC machine, the tool is programmed to make progressive deformation on the sheet by making 2D contours in XY plane, further indenting the tool into the 3rd dimension, i.e., the Z direction offers us the desired geometry of the final product [2].The surface quality of incremental sheet forming product is affected by a number of different variables including tool radius, spindle speed, step down, feed rate and lubrication system [3].Several studies have demonstrated that a greater step-down has a detrimental effect on the ISF surface quality. The impact of step size on single point incremental forming is another important factor. According to some researchers, step size has no significant impact on the process [4, 5, 6, 7].

According to Cerro et al 2006 [8] research, the surface quality of the manufactured product is significantly influenced by the forming speed. "Forming speed" in SPIF refers to both the feed rate and the rotational speed (rpm) of the tool. The heat generated by friction is directly related to the relative speed of the tool and the sheet metal [9]. The surface smoothness of the material rises with increased with lubrication media, as was stated in the preceding section, and this influence forming speed. M. Durante, 2009 [10] stated that tool rotation has an impact on the feed and feed rate in ISF models and shows the role that tool rotation plays in the accurate manufacturing of sheet metal components.

1.2 Rationale of the study

In incremental sheet metal forming process most of the studies are focus on the formability of the forming product but this study give attention on the surface finish quality of the product due to its necessity in this advanced technology by reducing surface roughness of the formed product.

After finishing this study, it is possible to obtain high surface quality of formed product based on the proposed significant input parameters and with which input process parameters, surface finished quality can be achieved with constant wall angle and which process parameter has a major impact on the surface finish quality of produced products.

1.3 Statement of the problem

Incremental Sheet metal forming is important fabrication operation in different sheet metal industry especially for prototype and small batches like automobile, aerospace and sheet metal industries throughout the years. The ISF process starts with a type of geometric distortion in the incrementally formed parts. Differences between the desired part geometry and the actual one is brought on by an undesirable bend in the sheet that is clamped along the base's edge. The placement of a stiff support adjacent to the forming zone or the use of a simple backing plate could be the only solutions to this source of geometrical distortion [11].The problem in this thesis arise due to ISF is die-less process and the free surfaces in Incremental Sheet forming forms uneven deformation or surface waviness and this result rough surface which leads to bad surface finish quality [12].

1.4 Objective of the study

1.4.1 General objective of the study

To determine optimum process parameter to improve surface quality of Al6063A sheet Truncated Pyramid shape product on Incremental Sheet Forming Process.

1.4.2 Specific objective of the stud

- Determining correlation of the experimental result with Simulation model analysis.
- To determine process parameters which have high influence on the output surface roughness values.
- To identify optimum levels of the input process parameters of ISF process which can enhance surface finish quality.
- Validating optimum ISF process parameters using experimental approach

1.5 Scope of the Study

The primary goal of this thesis is optimization of process parameters such as tool diameter, Step depth, Spindle speed, and Feed rate in ISF to reduce the surface roughness and to get good surface finish quality of formed products.

The sample specimen which used to conduct the experiment is selected based on the availability of the aluminum alloy sheet metal on local market and based on its good formability for the undergo deformation during the forming process.

The ISF process for this study is done on XHS three axis Vertical CNC milling machine based on the Taguchi L_9 orthogonal array with different tool diameter, step depth, spindle speed and feed rate. The surface roughness is measured by Vogel surface roughness measuring instrument.

Lastly the regression analysis, S/N ratio and ANOVA were performed to identify the optimum ISF process parameter values to reduce surface roughness of the formed product.

1.6 Significance of the study

The significance of this study is to control the effect of Process Parameter of incremental forming process through determining incidence related to deformation and geometry. The proposed system can also be input for better control design world in 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 an input for others that work their study on forming process. This paper is beneficial for the manufacturing sector because of technology is simple and able to adapt on a three-axis milling machine, and it helps Society utilizes a variety of production equipment.

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

- ✓ For the high productive company such as sheet forming industries.
- ✓ To increase surface quality of the formed product
- ✓ To improve service life of the formed product
- ✓ For the researchers to refer the result and conclusion of this paper as a reference for their related future work.

1.7 Research questions

This study addresses research questions such as: -

- ✓ How do the input variables for single point incremental sheet forming affect the finished product's surface roughness?
- ✓ In what extent the experimental result and the simulation analysis coincides each other?
- ✓ Which process variable has a major impact on the surface finish quality of formed product?

1.8 Organization of the Thesis

This thesis deals with parameters optimization of single point incremental forming on Al6063A sheet. The thesis is organized by five chapters shown as follows: -

Chapter One: Background of the study, Rational of the study, statement of the problem, General and Specific objective of the study, scope of the study, Significance of the study, Research question, Research motivation are stated in this chapter.

Chapter Two: contains a literature review which has findings to provide information for the input of this thesis. It presents the background of incremental sheet forming technology, influences of different process parameter on surface finish quality, application of incremental sheet forming process and gaps of the literature reviews.

Chapter Three: in this chapter data about the material and experimental methods used in this thesis are written that includes aluminum alloy chemical and mechanical composition, method of sample preparation, experimental set up and techniques, process of incremental forming and surface roughness measurement technique.

Chapter Four: this chapter contains the result and discussion on the surface roughness and verification of recommended parameters using Taguchi method of regression analysis, signal to noise ratio and analysis of variance.

Chapter Five: includes conclusion based on the conducted experiment of the thesis and recommendation for future works.

Chapter 2

Literature Review

2.1 Introduction

The study's primary focus areas in this chapter are the incremental sheet forming process background, the effect of process factors on surface quality, and the analysis employed for optimization purpose. The following section uses a review of previous researches in order to get the process awareness of ISF.

2.2 ISF Process

Incremental sheet forming and spinning processes are nearly the same. Conventional spinning technique involves the rotation of blank held in a mandrel while the roller progressively twists the sheet to form the mandrel's shape. In case of ISF, the edges of the blank are clamped and have to remain fixed in position. Generally, the tool is given rotational motion and blank is held stationary but it can be vice versa too. ISF will become distinct by means of the nature of motion of the tool which is free to move in xyz direction whereas in spinning process, it has limited movement. ISF involves sheet thinning just like the shear forming technique. Yet, unlike the shear forming process, the thinning cannot be controlled by the tool movement [13]

Table1. Comparison between Spinning and ISF process [13].

Used factors	Spinning	ISF
Blank Edge	Move inwards	Clamped
Wall thickness	More or less constant	Decreases based on the process
Die/mandrel is needed.	Yes	No
determined by shapes	Mandrel or roller movement	punch or roller movement
Asymmetry shape possibility	Limited	Yes

as incremental sheet formation is a relatively new technology, the underlying physical processes have not yet been adequately explained or not yet fully understand [14].

ISF method is widely used in asymmetrical incremental deformation process, but it is also open in the area of sheet forming process. ISF process investigations have been conducted on the effects of different method characteristics. A few authors use finite element experiment design to demonstrate how these parameters affect the results. Many input parameters (design factors) have been generated and their effects on a number of Response variables, or output variables, have been assessed using each design of experiments and FE methods. Design variables for tool modeling have included sheet thickness, coefficient of friction, tool radius, and number of turns [15]. In response to the needs of the sheet metal forming business, customer demand for a variety of stamped sheet metal products, and new production techniques

have been developed. These techniques are unique in that may provide small production batches with fairly affordable tooling. Modern manufacturing techniques the goal of incremental sheet metal forming (ISF) is to increase the formability, surface quality and flexibility of sheet metal. while also lowering setup costs for sheet metal forming and prototype production time. [16].

2.3 Tool path strategy of incremental forming

The uniformity of sheet thickness in ISF is greatly influenced by the forming tool's path. Also, it helps a great deal in figuring out the part's formability, surface finish, and dimensional accuracy. Surface quality is affected by a number of variables, including tool radius, spindle speed, step down, and lubrication system [3].

Dimensional accuracy, surface roughness, processing time, and thickness variation are all significantly impacted by the tool path. Hence, an important phase in incremental sheet building is tool path development (ISF). In this review, 3 distinct techniques have been utilized to generate the tool path for ISF. Commercial computer-aided manufacturing (CAM) software is used for (i) tool path development, (ii) a method based on cutter location (CL), and (iii) cutter contact (CC) based approach [17]. Commercial CAM applications provide a variety of tool paths for the forming application. One of the tool paths among those appropriate for ISF application is the profile tool paths. The tool moves in a single plane along the profile tool path until it reaches its starting position. After then, it declines vertically in the designated step-depth direction. After completing the subsequent plane, the tool keeps moving in the same direction as the previous cycle. When the entire geometry is constructed, this process is repeated. Any complex geometry can be produced with a profile tool path, but the surface of the part will be scarred. In portions that are significant in terms of appearance, this scarring will not be authorized. The numerical modeling of incremental forming processes is shown in Fig.1 below [18].

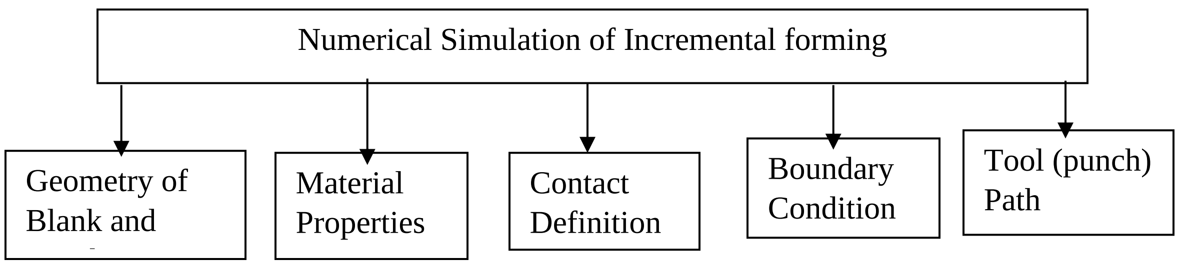

Fig.1 numerical simulation of incremental forming process [18]

The tool path input in numerical simulation software packages cannot be the part program produced by a CAM package. With a bi-directional tool path, the tool finishes one cycle and delivers one-fourth of the cycle before moving on to the second cycle. This prevents scars from showing on the part geometry as the tool position changes from one cycle to another. Also, by doing this, the forming force is distributed evenly throughout the geometry's edge, improving the part's geometric accuracy seen in Fig. 2. This tool path reduces twist and improves the formed component's geometric accuracy. Unfortunately, it might not always be viable to move the scar to an unused place. Bi-directional profile tool paths with dispensed increments which are not included in commercial CAM programs were also proposed [19].

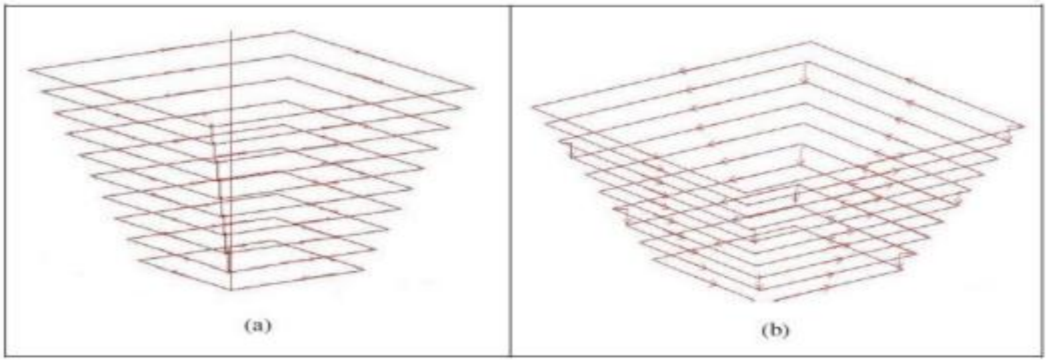

Fig2. (a) Bi-directional tool path (b) Bi-directional tool path with distributed increment [19]..

2.4 Effect of process parameters on incremental sheet forming processes

M. Moayedfar et al [20] analysis enhances the scope of sheet metal products; incremental sheet forming is suggested as a suitable procedure. Unfortunately, this method has some shortcomings, including poor surface quality and a strong probability of sheet failure.

Gatea S. Ouh. et al. (2016) [21] implemented analysis to identify the ideal settings for the ISF method. By increasing the tool diameter and wall angle and decreasing the step-down, uneven plastic strain and thickness distribution can be produced. The minimal thickness was found to be significantly correlated with the tool diameter when the conventional tool path (constant step depth) was used, and its placement was mostly established by use of the incremental depth (Z) [22]. Lowering the step-down can help to reduce strains in the area where the tool and sheet come into contact as well as in the ISF part's wall [23]. Through research that is experimental measure the forming force in ISF. The formability of the ISF process is not significantly affected by the step-down, as demonstrated by Duflou J. Tunçkol Y. et al. in 2007 [24]. According to Kim & Park, 2002 [25], as the feed rate decreases, so does the surface quality. Apply a tool path with a feed rate determined by the geometry of the product to achieve good results in terms of geometric accuracy and enhanced surface quality [26]. To investigate high ISF surface roughness, a smaller tool diameter can be used rather than a larger tool diameter [21, 22, 26]. On the circumference with the biggest tool diameter, the maximum main strain value and sheet thinning were observed along the whole tool path [27].

The principal strain at fracture in ISF was discovered to be over Nakajima's Fracture Forming Line (FFL) while employing a smaller tool diameter [28]. The impact of step down is thought to be insignificant in comparison to the impacts of tool diameter and feed rate on the finished surface quality [29]. Moreover, the quality of the surface finish is more affected by the tool's rotational speed than by the feed rate [30]. However, the resource of converting the feed rate can be used to change the formability of ISF. As an illustration, low feed rates can be used to improve the formability of the ISF portion [16, 4]. Commercially pure titanium (CP Ti) must have a small tool diameter to step-down ratio (T/Z) in order to have a pleasing surface finish in SPF [31]. In addition, by reducing the tool diameter, step-down, and feed rate, CP Ti's formability improved. The surface roughness of an ISF item can be altered by the step-down value, producing a good surface finish S.Gatea et al [32] conduct an experimental examination to determine the impact of the step-down at the surface equality of Al5052 sheet. The findings showed that surface roughness increases after a particular angle and reduces with increasing step-down. Similar to this, surface finish degrades as tool diameter increases. Another study established that the tool's surface roughness, the friction between the sheet and the tool, as well as the tool's radius, all affect the equality of the created component (Ti-6Al-4 V sheet) [33].

Table 2 surface roughness of the tools [33]

Experiment No.	Tool Material	Surface treatment	Average Surface Roughness (μm)	Lubricant
1	Cr12MoV steel	-	3.0	Heavy machine oil
2	Cr12MoV steel	Case hardening (50-55 HRC)[a]	2.75	Heavy machine oil
3	HSS	Surface hardening (62-65 HRC)	2.15	Heavy machine oil

When compared to surfaces acquired at higher feed rates (8400 mm/min), rough surfaces of ISF components may be achieved at low feed rates (1200 mm/min) [34]. In order to characterize the formability of an annealed aluminum alloy, Shim and Park [35] created a new forming tool with a ball that could rotate freely and a simple incremental forming process in which the tool's path changed to a square loop. The most often used technique in sheet metal forming (SMF) to determine forming limits is the enhancement of forming limit diagrams (FLD). Limit diagrams are created using plots of the major and minor principal strains; these plots show an early investigation that found the material's strains during SPIF deformation are substantially higher than those observed in conventional SMF techniques [36]. The capacity to form pieces with the SPIF approach was overestimated by conventional FLDs, which are used to anticipate failure in SMF. Hence, the most efficient component of the solution for det ermining sheet metal formability is provided by traditional FLDs. and (maximum forming angle) [37]. A tangent line from the surface of the unformed sheet to the surface of the deformed sheet is used to measure the forming angle. The two properties of deformation in this forming approach were proposed by Filice et al [38]. The deformation pattern is one. Although the tool moves straight on a horizontal plane, the deformation that occurs at the starting and ending points of the straight line is biaxial stretching [20].

2.5 Effects of input parameters on surface finish

Finding out how forming parameters affect surface roughness and maximizing surface finish at the manufacturing level has a great significance.

M.Skjoedt et al [39] investigated that ISF is thought to have a weakness in surface finish, which is illustrated by the tool path's large-scale waviness. A dummy sheet can be used to solve the issue of poor surface quality of single point incremental manufactured items caused by extensive waviness caused by the tool path

Forming variables, including step-down size and spindle speed, were examined by Hagan and Jeswiet [40] for their effect on the ISF process' surface roughness. Researchers discovered that the surface finish roughness can be explained as the result of both large- and small-scale waviness caused by a tool path and considerable surface stresses. As the step-down size is decreased, Surface morphology changes from waviness to a strict roughness that lacks waviness. Powers et al. [41] used an SPIF case study to examine the surface morphology. The primary impact of the direction of the sheet rolling marks on the surface topology in SPIF

topic of the initial investigation. The data must demonstrate that when the rolling markings are parallel to the direction of formation, the surface roughness Rz increases.

Von Uma Lasunon et al. [42] examined a factorial design to study the influence of three process parameters at the surface roughness in SPIF. It was shown that feed rate had little effect on surface roughness, while wall angle and step-down size had a significant impact.

Durante et al. [43] presented a model that takes into account three variables—the tool radius, the step-down size, and the slope angle—to assess roughness in terms of amplitude and spacing. The models' output has been evaluated using the roughness parameters Ra, Rz, and the average distance between profile peaks. The projection indicates that a satisfactory agreement with an error rate of less than 10% when compared to experimental results should be achievable. Hamilton et al [44] finding out how high-speed spindle rotation and tool feed rates affect the non-contact side roughness during forming might help determine the best process parameters to use in order to improve the external surface quality.

2.6 ABAQUS Simulation and optimization techniques

M. H. and S. A. M. R. [45] Using ABAQUS software program, FE simulation for the incremental sheet forming approach was carried out. The impact of process parameters on the forming force have been investigated using both bimetallic and single metallic sheets. The process has been simulated using the S4R shell components. The behavior of the material was assumed to be isotropic. The results of the FE simulation demonstrated adequate agreement with the experimental findings and, as a result, can be used to industry. Even so, a safety factor can be used to make up for the fact that the force predicted by the FEM was 15% higher than the experimental results. In order to enter the damage criterion into the ABAQUS software and obtain suitable result regarding to the forming height at fracture for the incremental sheet forming method. T. L. D. T. N. T. Kien Hoang [46] validated that the forming limit curve at fracture can be employed. The results from the FE models and the measured forming height were in excellent agreement. Plotting the maximum forming height achieved and the forming angle showed precise accuracy. According to Xiao X, Jae Kim, et al. (2020) [47] 2nd-order polynomial regression models provide a very good match for both the forming angle and the thickness reduction. RSM is used to evaluate each parameter's impact on the formation outcome. Among these, the diameter and step depth of the tool have a substantial impact on the forming angle and thickness reduction. Growing tool diameter and step depth result in decreased formability and claimed thickness. The range of feed rates considered in this experiment was, however, too restricted to significantly change the forming process' outcomes. Ham and Jeswiet [48] applied the box-Behnken design of experiments and the response surfaces strategy to produce developing limit diagrams. Through the use of numerical simulation based on the finite element approach for the SPIF process, engineers were able to significantly improve the process. It enables a more affordable investigation of arbitrary combinations of input factors, such as design parameters and method conditions [49].

Dejardin et al [50] based on this experience, experimental studies and numerical modeling were established to better understand the incremental sheet forming system for sheet metal components. According to Boufioux et al. [51], a combination of many approaches has been employed to construct the material and numerical models and conduct out on this. Since the objectives of this have been met, it is possible to recreate the process precisely and quickly. Numerical simulations are quite beneficial for expanding manufacturing processes (feasibility, optimization). Numerical modeling based on the finite element method has been carried out to develop the ISF process [52]. One of the key areas of interest for automotive study groups nowadays is the optimization of forming processes for the creation of net-shape components and excessively resistant products. The optimization of forming processes by the ISF method has been the subject of numerous articles [[53], [54]]. Design of experiments and response surface approximation [55] are often employed as reliable approaches for the investigation and optimization of sheet metal forming. Azaouzi and Lebaal's paper from 2012 [56] gives an optimization strategy tested for tool path optimization in single point incremental sheet forming using response surface method in order to save production time and homogenize the thickness distribution of an uneven component. Several articles have made an effort to establish a novel strategy for manufacturing-related numerical optimization problems.

2.7 Applications of Single point incremental forming

Forming technology makes considerable use of the necessity for incremental sheet metal forming using a single factor. It applies to numerous homes, medical equipment, automotive spare parts, and various components. The aerospace industries use aluminum and its many alloys because of its very high strength-to-weight ratios. SPIF is carried out to make parts of the aircraft. Not only metals, SPIF can also be performed on composite materials. in the medical area, SPIF is used to make patient-particular outhouses, implants, skull hole filling, manufacturing of denture base, and also implemented in electronics, cell phones and hard disk drives [57].

The application of this formed product in this thesis is for household appliance such as sinks and dish like shaped products with good surface finish qualities.

2.8 Summery of Literature Review

According to the literature study, numerous researches have been done on the effects of various parameters in the incremental sheet formation process. Several authors use Taguchi experiment design and other optimization techniques to describe the effects of certain parameters. The following table provides a summary of the literature review based on their investigation.

Table3. Summary of literature review

Author	Title	Material used and process parameters	Findings	Comparison the previous research with this research
Hagen and Jeswit (2004) [40]	Analysis of surface roughness for parts formed by computer numerical controlled incremental forming	Annealed Al 3003 sheet with process parameter tool depth increment and spindle speed	The researchers discovered that a tool path's large-scale waviness and a large surface strain's small-scale roughness are both responsible for the surface finish's roughness.	The author focuses on the influence of input parameters excluding tool diameter which has high influence on the surface finish whereas this research use tool diameter as one of input process parameter.
Power et al (2010) [41]	Small data set analysis in surface metrology: an	Rolled Al 3003 - 0	A SPIF case analysis was used to investigate the surface	The author investigates surface morphology using process

	investigation using a single point incremental forming: case study scanning		morphology, and the results suggest that rolling markings perpendicular to the forming orientation increase surface roughness (Rz)	parameters excluding tool diameter but this paper work use tool diameter as one of input process parameter.
Von Uma Lasunon et al. (2013) [42]	Surface roughness in incremental sheet metal forming of AA5052	AA5052 sheet with process parameter Feed rate, depth increment and wall angle	It was determined that feed rate has little impact, whereas wall angle and step-down size have a significant impact on the surface roughness	The author investigates the impact of input parameters excluding tool diameter for analyzing the surface roughness contrarily on this research use tool diameter as one of input process parameter with constant wall-angel.
Durante et al. (2010) [43]	Comparison between analytical and experimental roughness values of components	AA7075T0 sheet with process parameter vertical step, tool diameter and slope angle	Describe a model for evaluating the roughness in terms of both amplitude and spacing associated with	The author evaluating the roughness of the output product for comparing experimental and

	created by incremental forming		three parameters slope angles, the step-down size and the tool radius.	analytical roughness value but in this paper work concern on surface finish quality
Hamilton et al. (2010) [44]	Friction and external surface roughness in single point incremental forming: A study of surface friction, contact area and the 'orange peel' effect	Al3003-H14 steel with process parameter Step size, wall angle, spindle speed and feed rate.	examines the effects of tool feed rates and fast spindle rotation during forming on the roughness of the non-contact side	The author examines the effects of two input parameters on the roughness of non-contact side but in this paper work the surface finished quality is investigated on the contact side of the product by testing the roughness as output response.

2.9 Literature **Gaps**

As incremental sheet formation is a relatively new technology, the underlying physical processes have not been adequately explained or not yet fully understand [14].

M. Moayedfar et al [20] analysis enhances the scope of sheet metal products; incremental sheet forming is suggested as a suitable procedure. Unfortunately, this method has some shortcomings, including poor surface quality and a strong probability of sheet failure.

M.Skjoedt et al [39] investigated that ISF is thought to have a weakness in surface finish quality, which is illustrated by the tool path's large-scale waviness.

In this work, Experimental analysis was conducted to develop and apply to assess the critical efficient parameters in this sheet-forming process and determining the optimum values of the parameters which have higher surface quality than previous studies.

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Chapter 3

3. Material and method

3.1 Choice of material, composition and size

The material chosen for this thesis is Al6063A aluminum alloy due to limited works done previously on this material. Al6063A 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. So, this commercially available aluminum alloys Al6063A is chosen for the current work because it is known to have good formability.

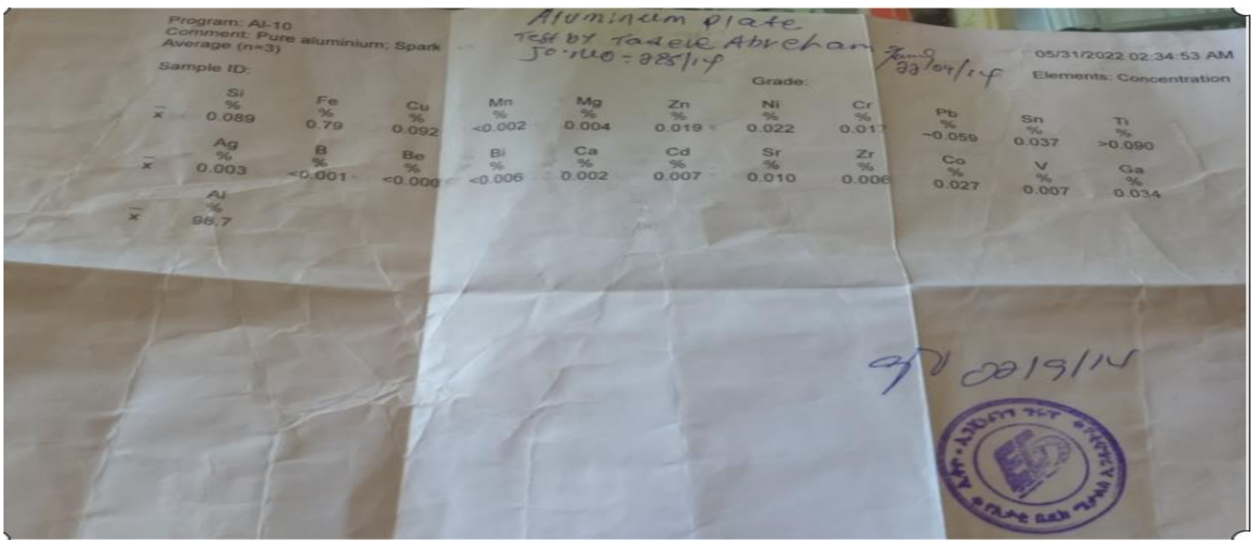


Fig3. Spectrometer test result for chemical composition of Aluminum alloy Al6063A specimen for experimental work.

Table4. The composition of Al6063A alloy from examining data by spectrometer

Component	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Wt%	98.7	0.02	0.1	0.79	0.004	0.002	0.1	0.1	0.02	0.164

Table5. Mechanical Properties of Al 6063A alloy

Properties	**Metric Units**
Density	2.70 g/cc
Hardness no. Brinell	50
Ultimate tensile Strength	200MPa
Tensile yield strength	160MPa
Modulus of Elasticity	68.9GPa
Poisson’s ratio	0.33
Fatigue strength	68.9 MPa

Source: ASM material data sheet for standard specification of Al6063Aalloy

1 mm thick sheet of Al6063A was used in this paper. Al6063A's chemical composition and mechanical properties are displayed above. This composition of the aluminum grade is tested by spectrometer in Akaki Basic Metal Industry.

3.1.1 Blank size and tool type

The size of the blanking sheet has been selected for this research is 200mm x 200mm out of this the working area is 100mm x 100mm in which the ISF is performed, this dimension is selected only to perform the experiment.

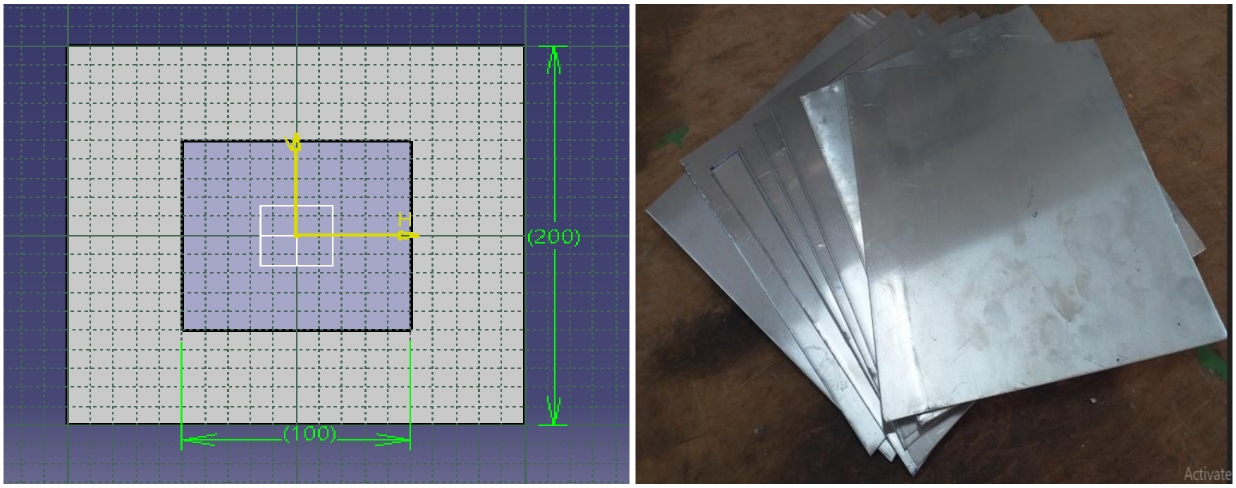


Fig.4 Size of the backing plate

In incremental sheet forming (ISF), simple tools with rounded or hemispherical ends can be used generically with the appropriate diameter depending on the work piece.

The type of tool used for this paper is HSS with a hemispherical end. As figure below shows their tools of different diameter such as 5mm, 8mm and 11mm are used to conduct experiment sample.

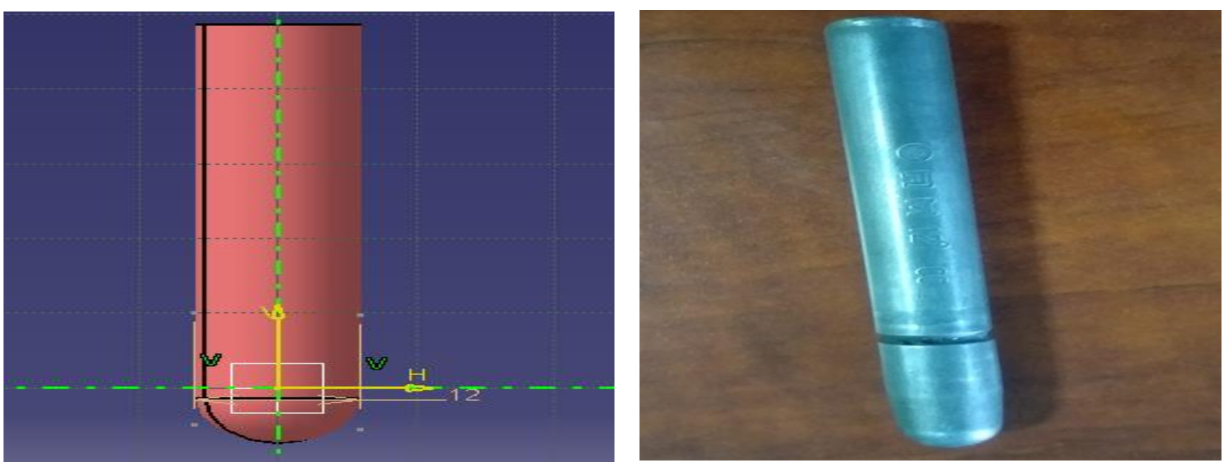


Fig.5 Size and shape of the tool

3.1.2 Geometry of the finished product

The model of the square sided truncated pyramid is prepared to its mentioned dimension which the blank size is 200mm x 200mm out of this the working area is 100mm x 100mm in which the ISF is performed, its maximum depth is 40 mm and with different wall angle by Catia software.

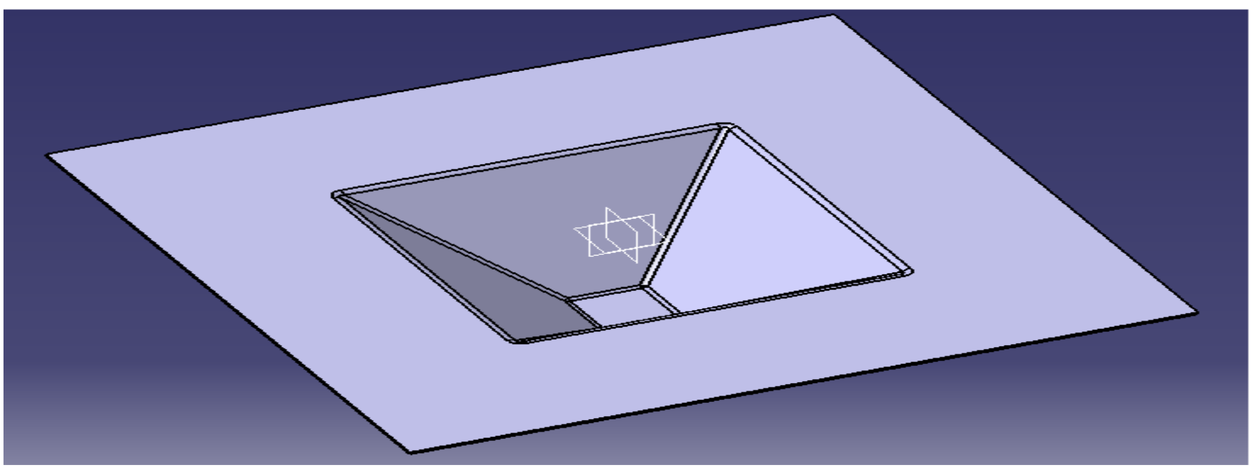


Fig. 6 Final geometry to be obtained truncated pyramid with wall angle of 45^0

3.1.3 Methodology

The flow chart in the fig. 7 shows the process that was used for experimental and simulation modeling analysis.

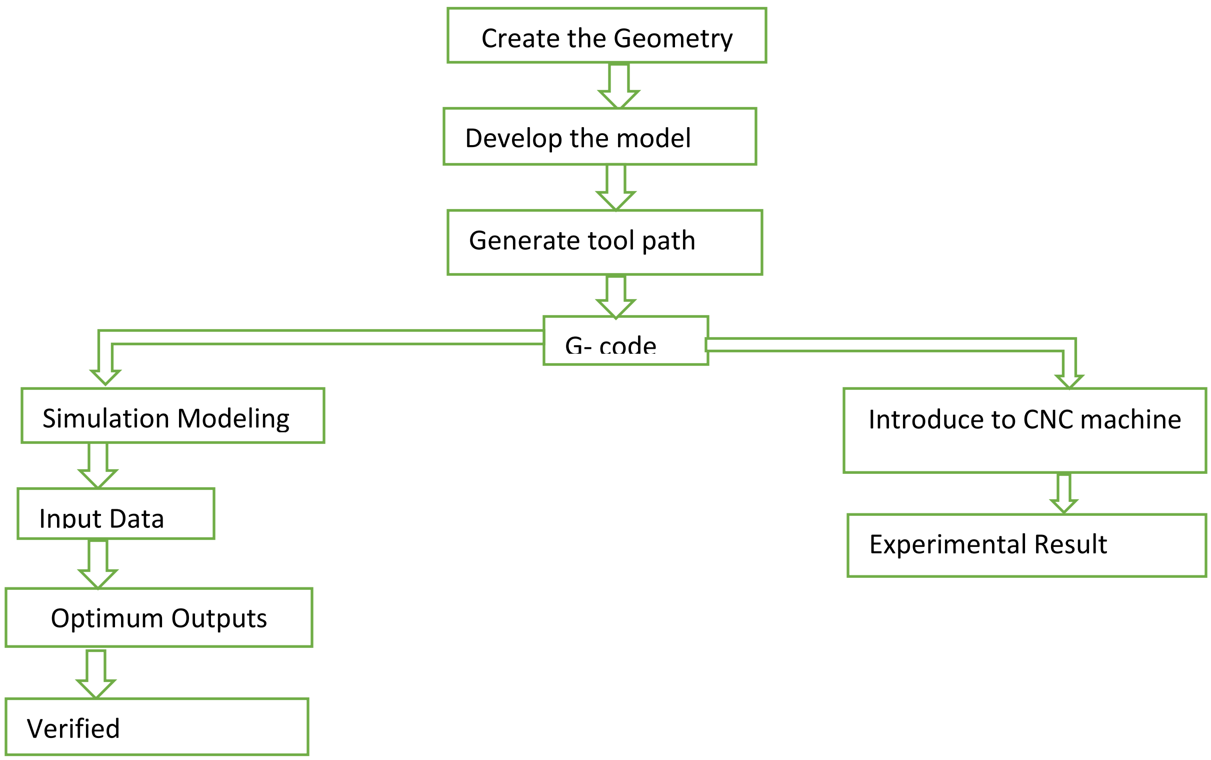


Fig. 7 process flow diagram

3.1.4 Tool path Generation by Autodesk Inverter 2023

The analysis to determine tool path has been generated by using Autodesk Inverter 2023 to perform the forming of the sheet with constant step size.

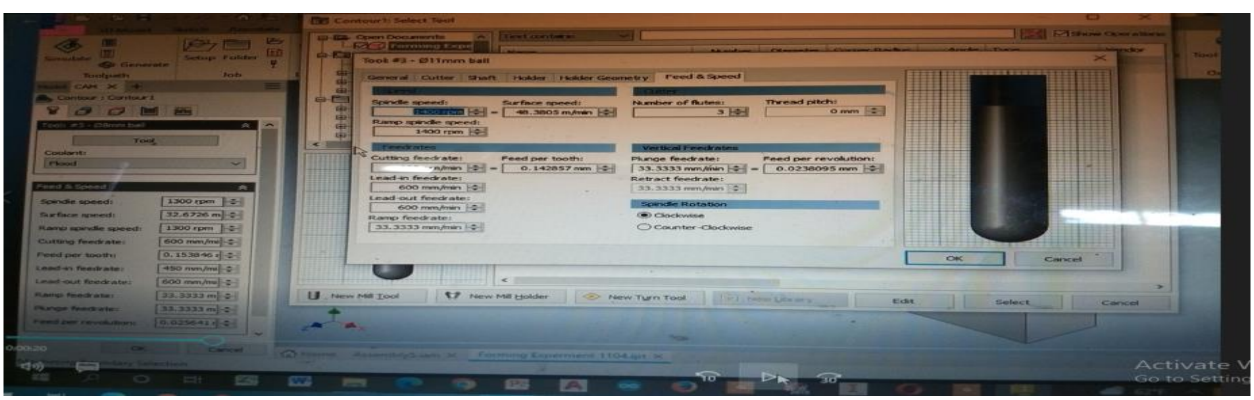
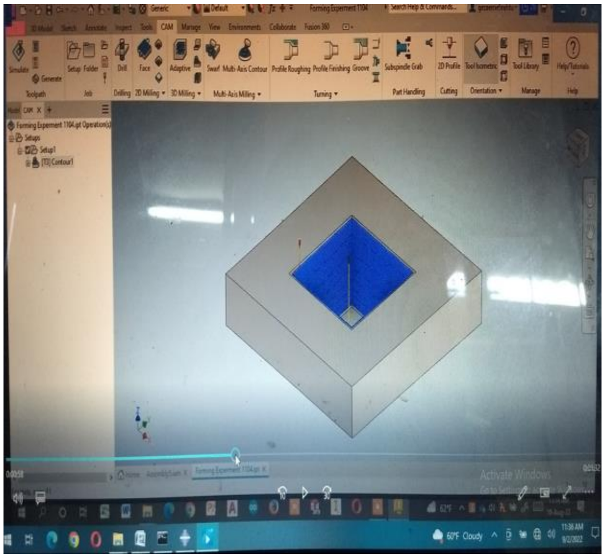


Fig.8Tool setting setup



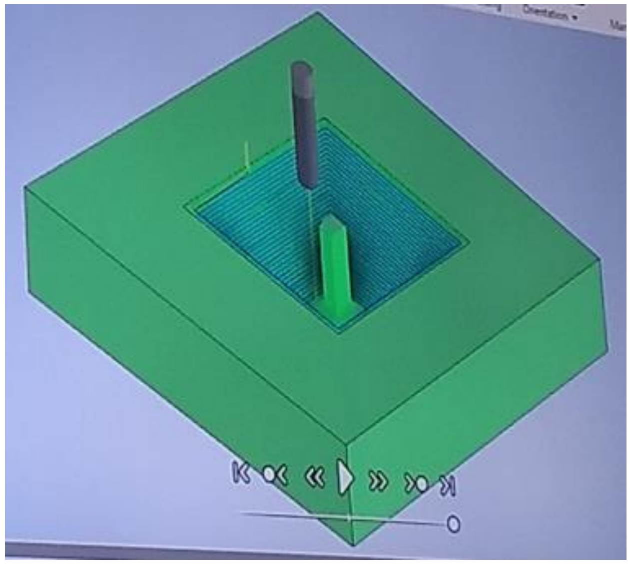


Fig.9 Tool path generation by Autodesk inventor 2023

3.2 ABAQUS Modeling Simulation Modules

The full ABAQUS program, ABAQUS/CAE, provides an easy, common interface for creating, submitting, tracking, and assessing results from ABAQUS/standard and ABAQUS/explicit simulations. Each of the several modules that make up ABAQUS/CAE describes a logical aspect of the modeling process, such as the modules that specify the geometry part, material properties, step modules for sequential loading, interaction modules, load modules, assembly modules, and mesh generation. Creating the model that ABAQUS/CAE uses to produce the input report that will be submitted to the ABAQUS/standard or ABAQUS explicit analysis product varies from module to module. The analysis tool performs the analysis, generates an output database, and provides data to ABAQUS/CAE so may track the job's progress. Using the ABAQUS explicit solver, the simulation analysis of the sheet metal was investigated in order to create a final product with the shape of a trunked pyramid with a range of wall angles [58].

3.2.1 Geometry Part module and material properties

The geometry parts are drawn based on their actual size and dimensions both tool and the sheet metal were drawn by parts and then assembled by using the ABACUS software and the material properties of the forms sheet metal is incorporated with this software. In the elastic module, density value of 2.7gm/cc, Poisson's ratio is 0.33, young's modules value of 69.8GPa.

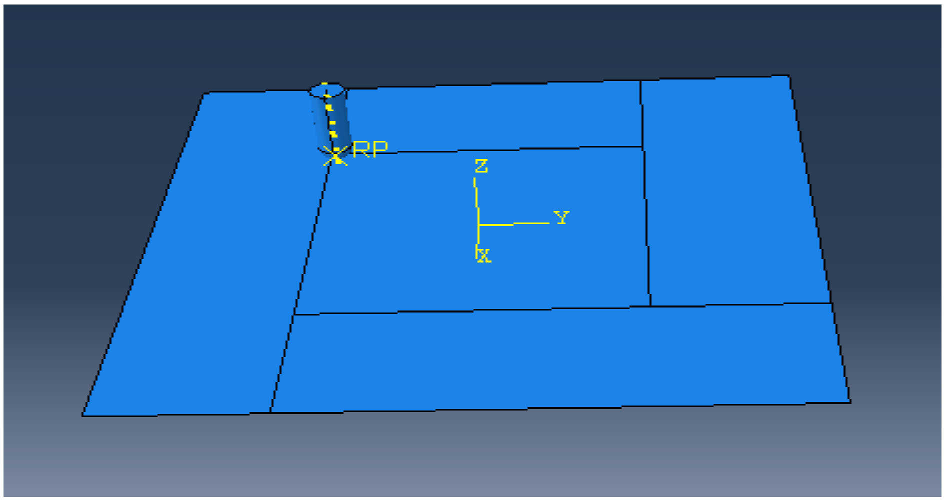


Fig. 10 Assembling Module of tool and sheet metal

3.2.2 Interaction and Boundary Conditions

Under the interaction module, the interaction property was defined as tangential behavior and frictional with assumed coefficient of friction of 0.6. The resulting mean value of the COF between the tool and the workpiece equals 0.4 for Eq. (1) initial contact, stabilized forming: Eq. (1) 0.656 and Eq. (2) 0.469 and this shows the preferable coefficient of friction for the contact ranges from 0.4 to 0.656 [59] The contact between the tool and sheet as well as the sheet and backing plate was defined as surface-to-surface type. A total of five boundary conditions were used for this simulation. At first, the outer region of the sheet was fixed from all the sides selecting the Displacement/Rotation boundary condition, keeping Displacement/Rotation in the given region as zero.

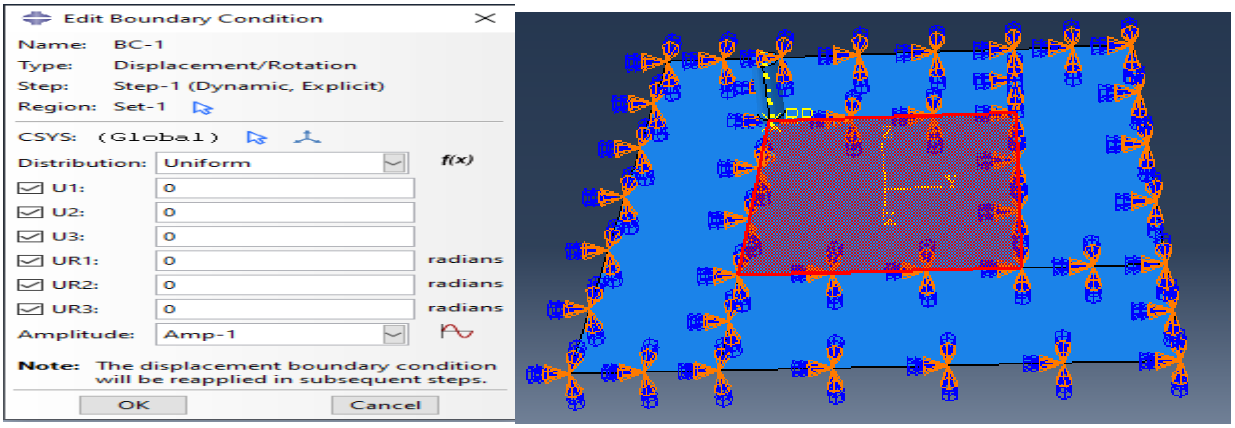
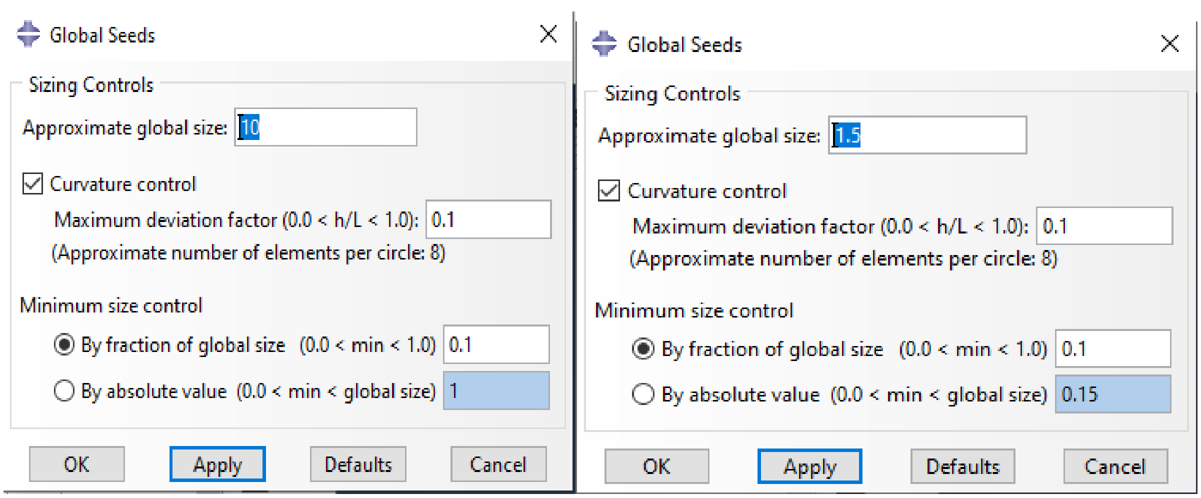


Fig.11 sheet fixed from each side as boundary condition

3.2.3 Meshing Module

One of the major significancy of the ABAQUS software is the simplicity of its meshing. Meshing is provided to the sheet and backing plate alone. The tool being analytical rigid type requires, mesh elements are used to mesh the sheet. Three – node shell elements with reduced integration and four integration point, S4R elements along the thickness of the sheet are used.



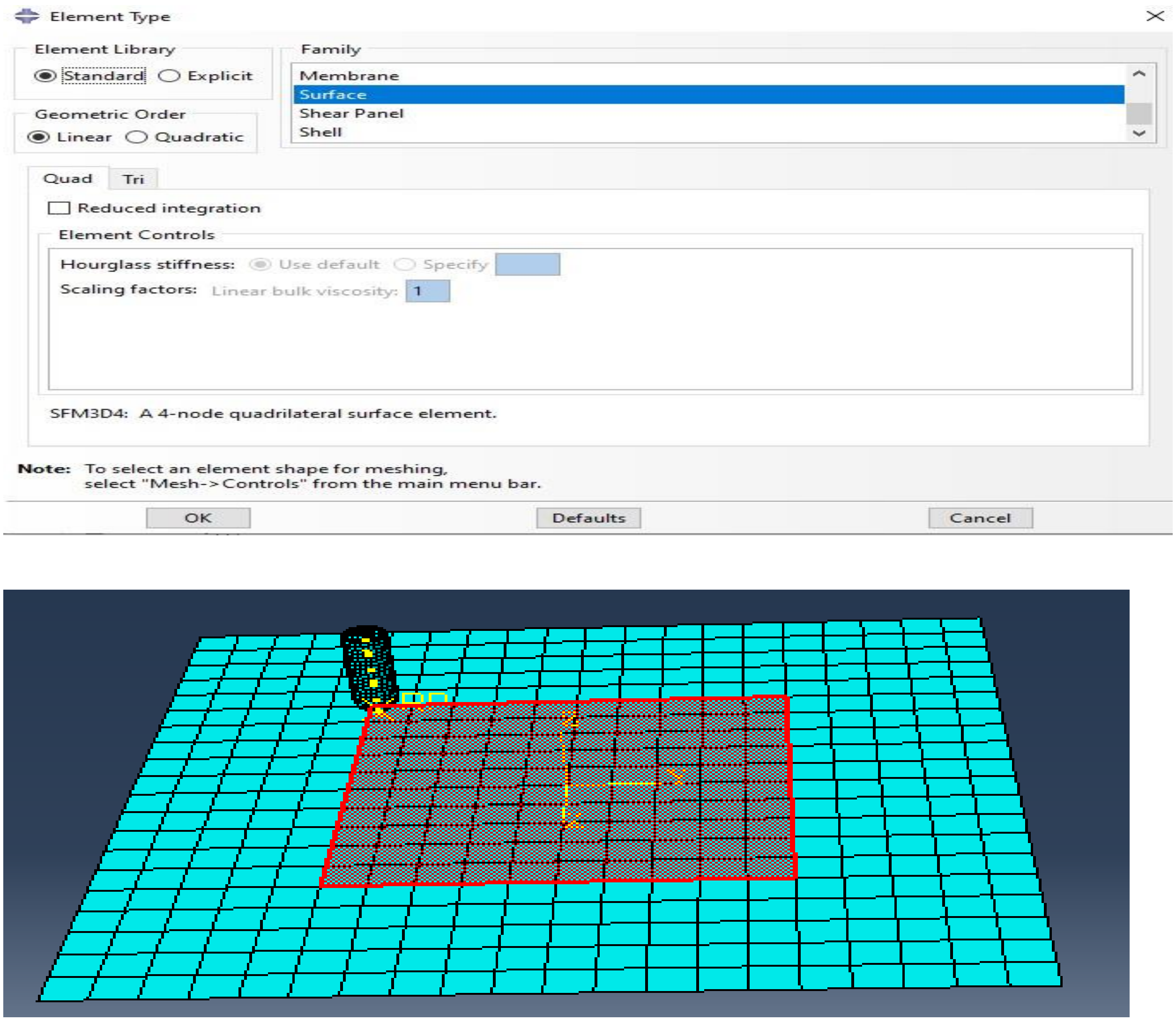


Fig.12 Meshing Diagram

3.3 Experimental Procedure

3.3.1 Process, method and material

In this work, trials are conducted on a three-axis CNC vertical milling machine. A truncated pyramid with a face length of 100mm and a base length of 20mm and a slant angle of 45^0 is created from a blank sheet of aluminum alloy 6063A that is 200mm x 200mm x 1mm in size because of its availability and average sheet thickness to conduct the experiment. Ball stops and hemispherical form tools are typically used in incremental sheet forming to achieve superior surface finish [60].

In this work, trials are conducted using a three-hemispherical form tool with diameters of 5mm, 8mm, and 11mm. On this study, a special Jig arrangement is designed and manufactured to hold 200 mm × 200 mm sheets. A backing plate with an outside component profile is utilized to guide the sheet when the shape is tightened.

Tool path affects the output response's surface quality [60]. So, choosing the right tool path is essential for achieving the intended result. Spiral and profile tool paths continue to yield the most notable outcomes, despite the fact that many alternative Tool path generation techniques have been used in the past. To decrease the uneven scare on the profile tool path, the helical tool path is now advised [61]. Spiral tool path was therefore employed as a technique for evaluating surface roughness. Using the auto desk Inverter 2023 software, a spiral tool path has been generated in the form of G-codes and N-codes, which were then immediately uploaded into a CNC machine for testing. Following the single point ISF, the roughness of the surface was evaluated by using Vogel Germany digital surface roughness tester.

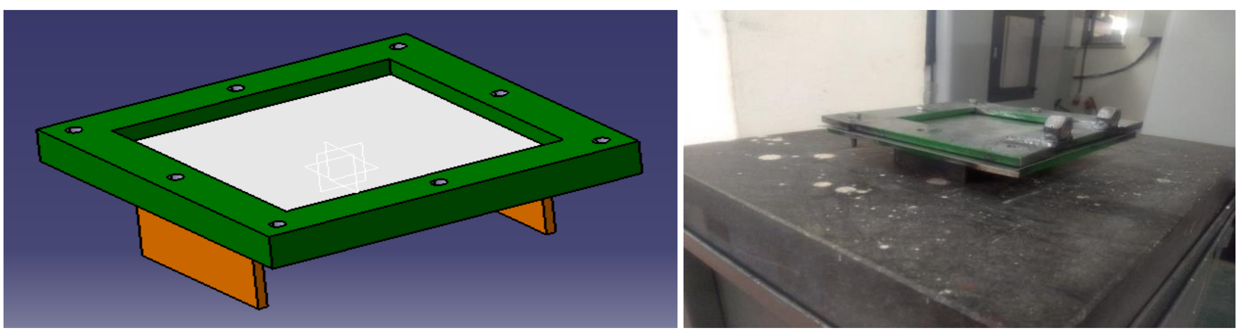


Fig.13 Jig fixture for aluminum holder with 8 clamping

3.3.2 Design of experiment by Taguchi Method

Table 6 below lists the four important parameters that were used for this thesis: - tool diameter, step depth, spindle speed, and feed rate.

And each of these parameters has three levels that can be changed to alter the value of the outcome. Here it is performed nine experimental tests by combining these different parameters based on some related works.

Table6. Four process parameter and three levels

Parameter	Symbol	Unit	Levels		
			Level 1	Level 2	Level 3
Tool diameter	**D**	Mm	5	8	11
Step depth	**(Δz)**	Mm	0.4	0.8	1.2
Spindle speed	**(V_R)**	Rpm	1300	1400	1500
Feed rate	**(F_r)**	mm/min	300	450	600

3.3.3 Selection of Orthogonal Array

With the Taguchi method, choosing an appropriate Orthogonal Array (OA) is a crucial task. Using a number of runs in the experiment, Taguchi's tabular design system (arrays) enables the estimation of a maximum number of main effects in an orthogonal manner. For this investigation, three levels and four process parameters are chosen using orthogonal L9 (3^4) and this Taguchi method is selected because of its effectiveness to analysis a single objective response study.

Table7. L9 Orthogonal Array

Number of Experiments	Control factors (Process parameter)			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.3.4. Conducting Experiment

The experiments were carried out on a CNC vertical milling machine using different sizes of HSS hemispherical end tools based on the designed orthogonal arrays.

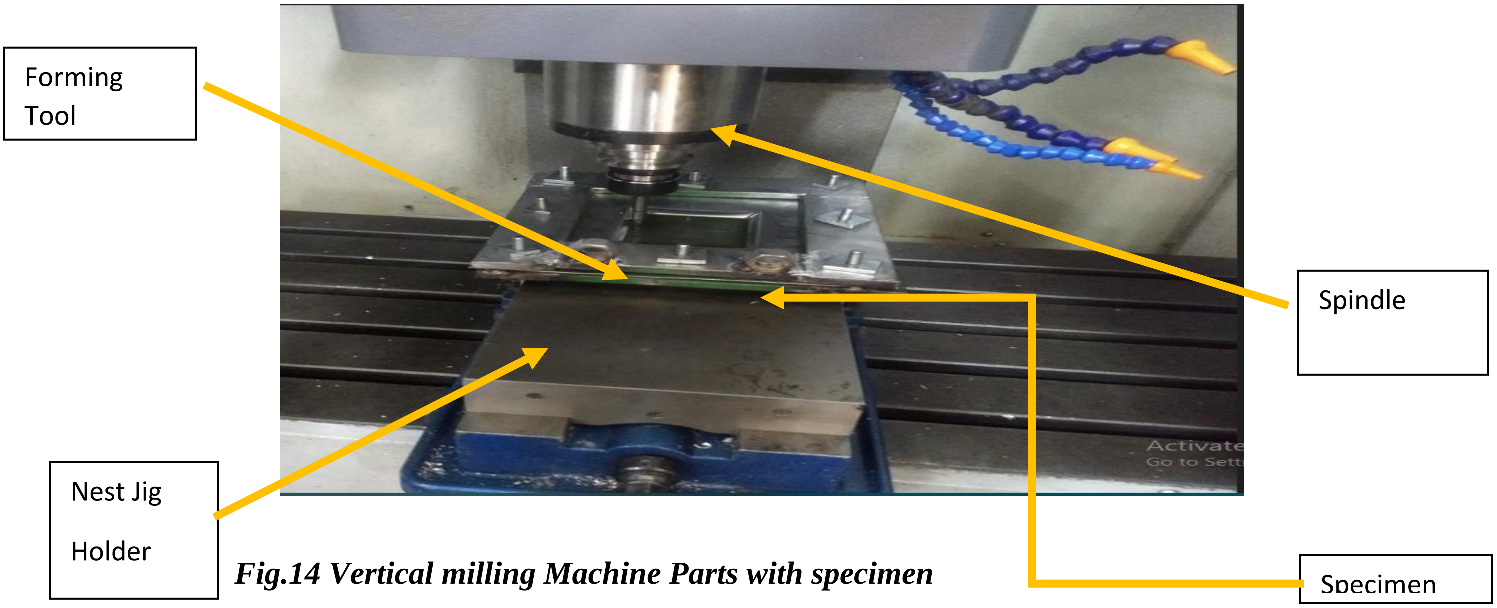


Fig.14 Vertical milling Machine Parts with specimen

Fig15. Working principle of Incremental Sheet forming Diagram

The basic steps for conducting forming operation

Step1: preparing the square specimens 200mm * 200mm *1mm for performing forming operation on CNC milling machine.

Step2: adjusting the reference point and checking the CNC machine is ready for forming operation.

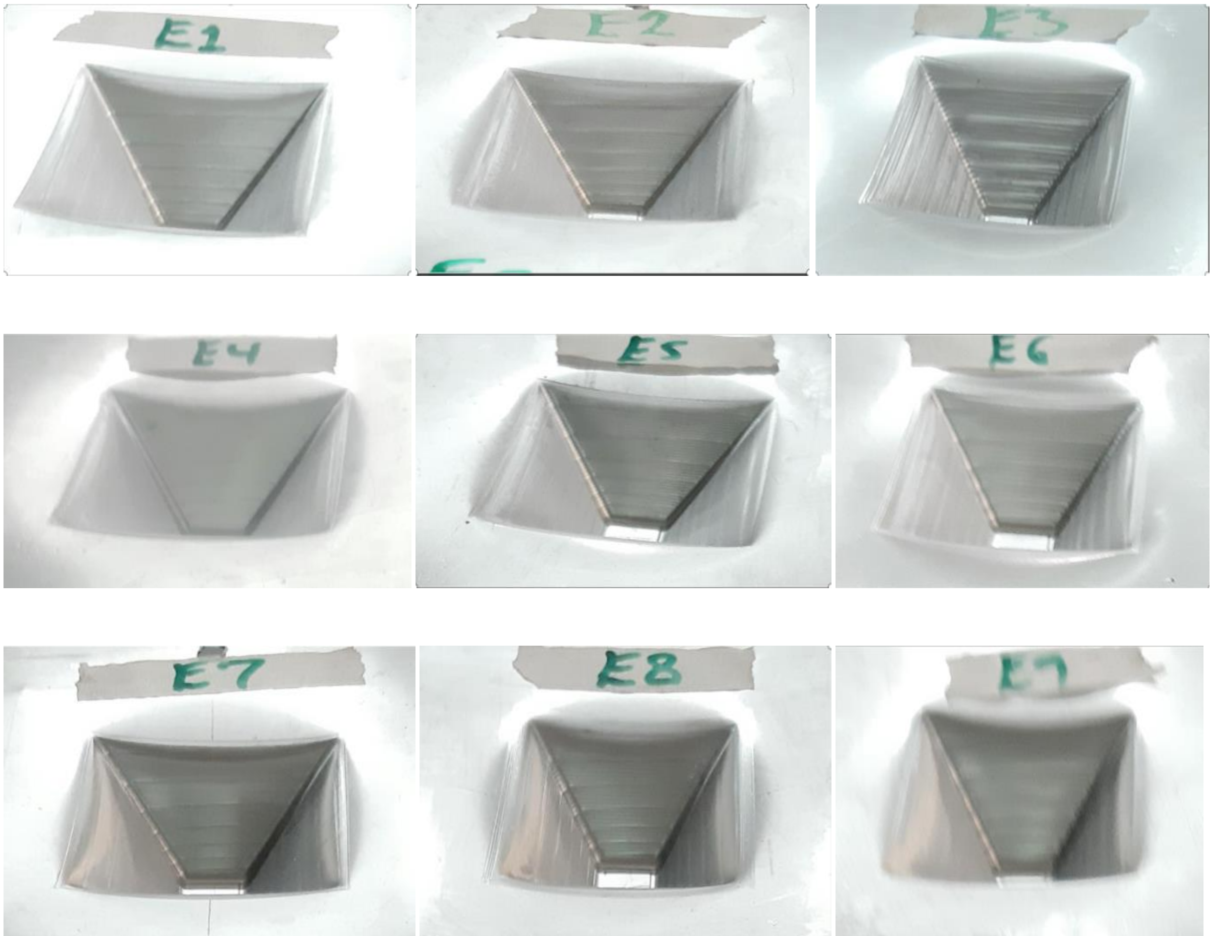
Step3: making the CNC part program for tool pathways utilizing different degrees of tool diameter, step depth, spindle speed, and feed rate for specified commands.

Table 8 Experimental layout of L9 (3^4) orthogonal array (data from table 6)

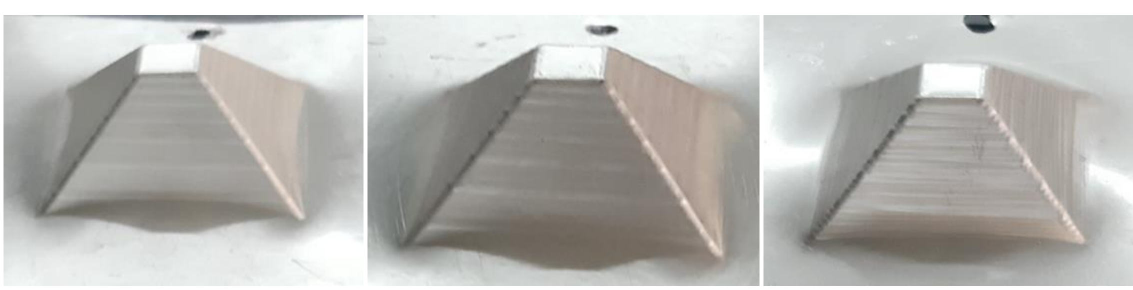
Number of Experiments	Input parameters			
	Tool Diameter (mm)	Step Depth (mm)	Spindle Speed (rpm)	Feed Rate(mm/min)
1	5	0.4	1300	300
2	5	0.8	1400	450
3	5	1.2	1500	600
4	8	0.4	1400	600
5	8	0.8	1500	300
6	8	1.2	1300	450
7	11	0.4	1500	450
8	11	0.8	1300	600
9	11	1.2	1400	300

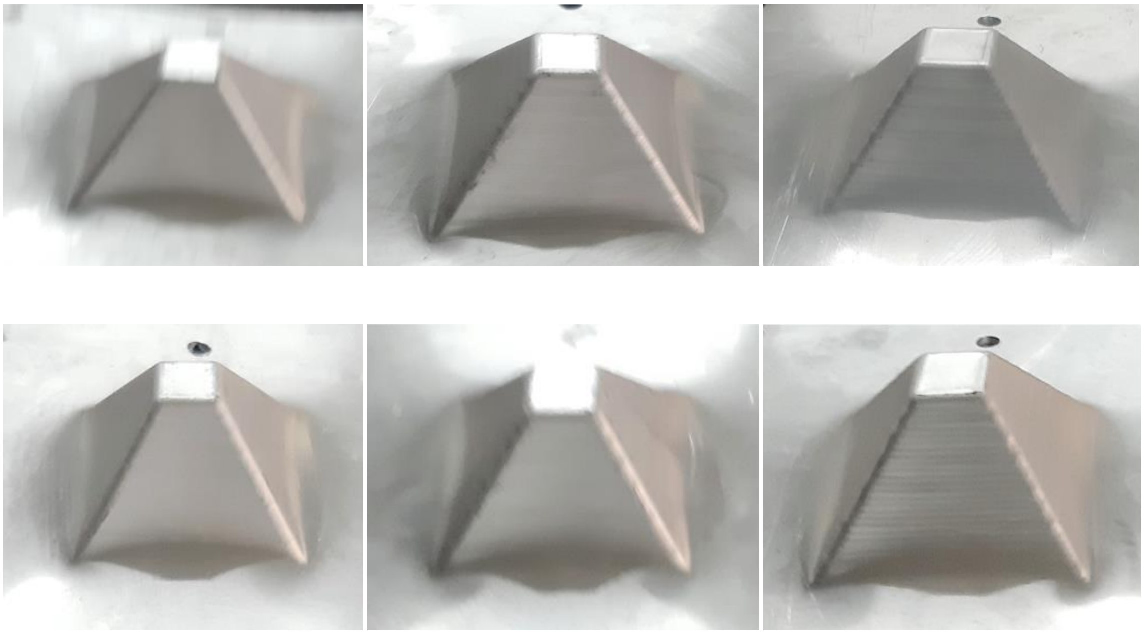
3.3.5 Fabricated Forming Product

The fabricated product that are shown below were obtained using various input parameters, including Tool Diameter, Step Depth, Spindle Speed, and Feed Rate at various levels based on an orthogonal array L9.



a) front view





b) back view

Fig. 16 Formed Product using ISF processes (a) front view, (b) back view

Fig. 16 shows different surface finish products were obtained in each experimental test for every different input process parameter without any fracture of the formed product and it is observed from the figure which process parameter have a significance influence for producing good surface finish product.

3.3.6 Measurement of Surface Roughness

After performed forming operation, roughness of the surface is measured with the aid of surface roughness measuring instrument called Vogel surface roughness tester.

The surface roughness of the input sheet metal before forming process ranges from 0.32µm to 0.50µm.

The four each experimental run at particular samples, the measuring technique is repeated three times, and the average values of the three measurements are chosen as the measured results. Out of all the surface roughness measurement criteria, average surface roughness (Ra) is frequently used to show the roughness of produced surfaces and is also utilized in comparison processes for each sample specimen.

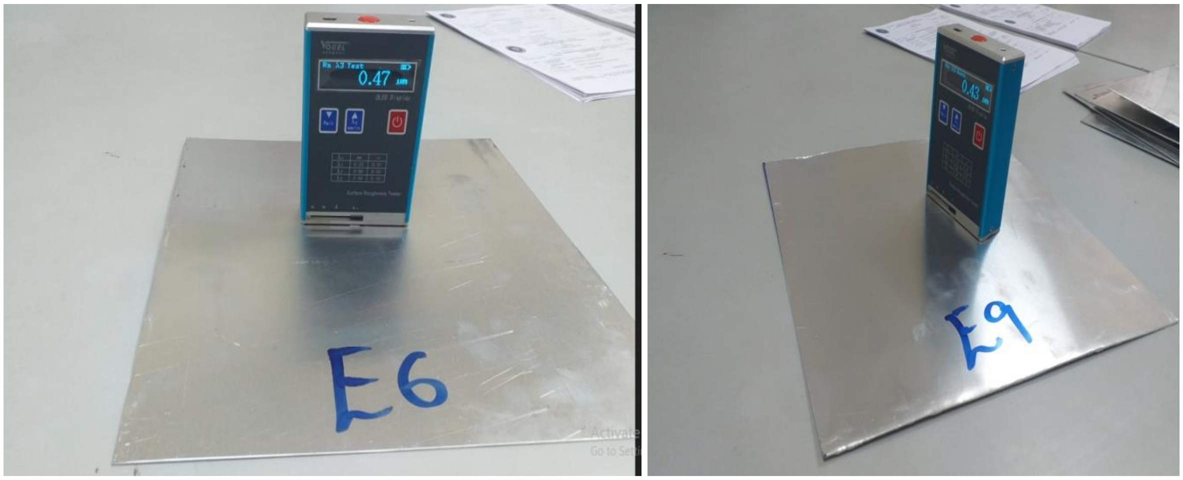


Fig.17 Initial plane sheet Surface Roughness test measurement

Fig. 18 Formed product Surface Roughness test measurement

The surface roughness is tested by using Vogel Germany Digital surface roughness test by putting the device on the surface of produced formed product the reading is in micrometer (µm) and the measurement is in different parameter such as Ra, Rz, Rp and Rt among these parameters, the selected parameter unit for this study is arithmetic mean roughness (Ra) value for analysis of surface roughness.

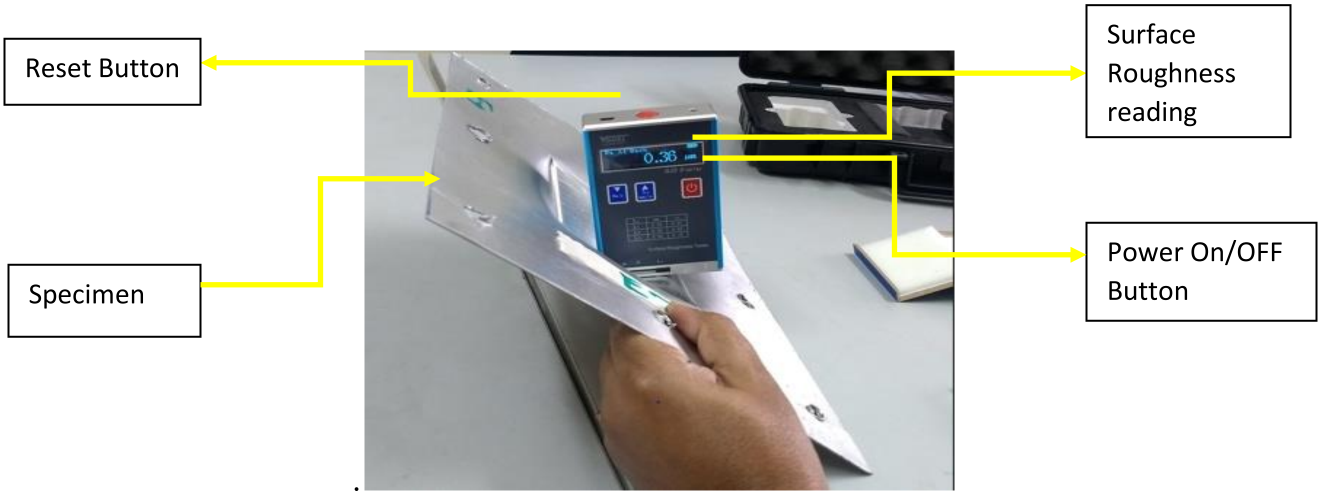


Fig. 19 Surface roughness experimental set-up

Table9. Forming Product Measured Surface roughness value

Number of Experiments	Ra(μm)	Rz(μm)	Rp (μm)	Rt(μm)	Mean Ra(μm) value
1	1.84	16.43	3.18	19.63	1.91
	1.92	16.05	3.24	21.72	
	1.96	17.63	3.29	24.17	
2	1.71	14.59	3.29	28.31	1.56
	1.52	11.34	2.63	19.24	
	1.44	14.67	2.98	19.73	
3	1.40	9.85	2.38	22.86	1.35
	1.31	11.55	2.81	20.67	
	1.34	10.68	2.30	19.74	
4	0.88	5.56	1.11	7.47	0.87
	0.86	5.51	1.09	6.83	
	0.87	5.49	1.10	6.64	
5	0.89	4.81	1.11	6.36	

	0.92	5.49	1.13	6.84	0.93
	0.98	6.63	1.25	9.10	
6	0.81	4.93	1.03	7.14	0.77
	0.76	4.79	0.95	5.57	
	0.75	4.67	0.97	5.83	
7	0.36	2.83	0.52	4.31	0.39
	0.37	2.70	0.52	4.56	
	0.43	3.39	0.61	5.20	
8	0.60	4.84	0.99	9.62	0.53
	0.5	4.61	0.80	6.66	
	0.5	3.88	0.72	5.91	
9	0.75	4.72	1.25	10.38	0.68
	0.74	4.92	1.12	10.04	
	0.56	4.43	0.94	11.31	

Table10. surface roughness Ra means values of final forming product

Experimental No.	Final product Ra (μm) Mean value
1	1.91
2	1.56
3	1.35
4	0.87
5	0.93
6	0.77
7	0.39
8	0.53
9	0.68

Chapter four

Result and Discussion

4.1 Introduction

In this chapter, the ISF-produced forming product is the main focus of the results and discussion on surface roughness. After performing the process and the surface roughness test, the process parameters such as tool diameter, step depth, spindle speed, and feed rate are integrated with the response of surface roughness using the Taguchi technique. The outcome recorded from the explicit modeling and simulation software of ABAQUS 2021 student edition. Poor surface finish qualities or high surface roughness can be obtained from maximum principal stress which is concentrated on the contacted surface [62]. the effect of different parameters on the result are shown below.

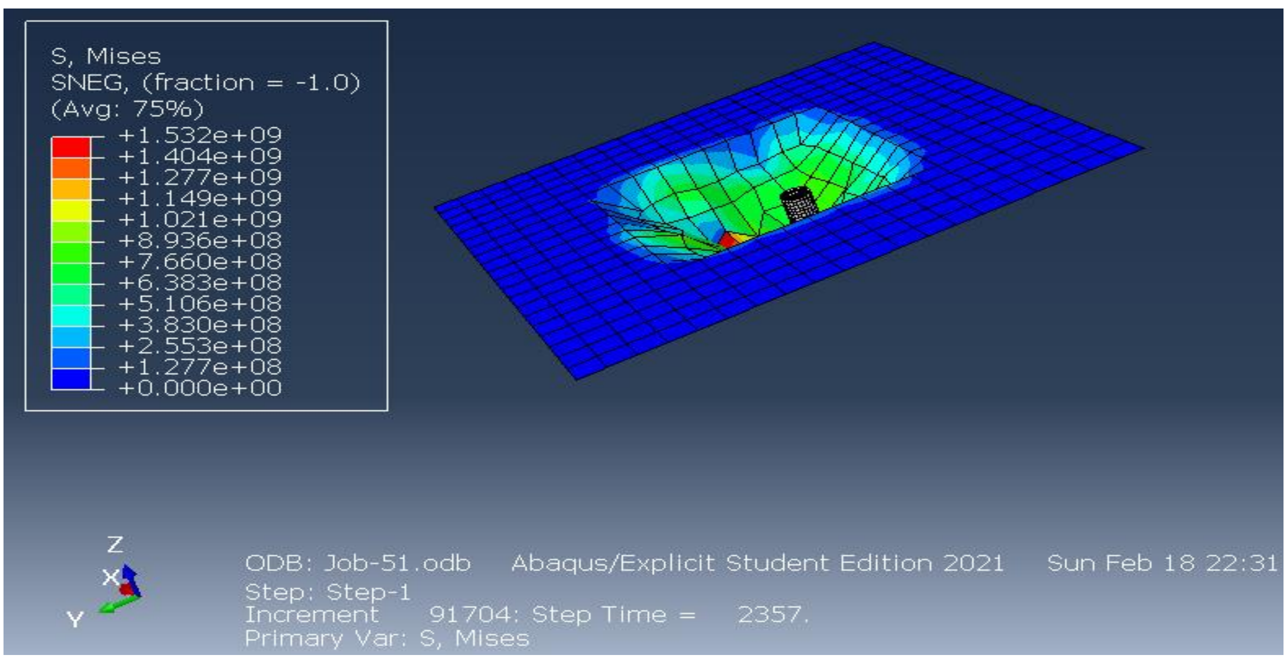


Fig. 20 E1 (TD= 5mm, Step D = 0.4mm, SS = 1300 rpm and FR = 300mm/min).

Max Von Mises stress is 1532Mpa which is more than 160Mpa yield stress.

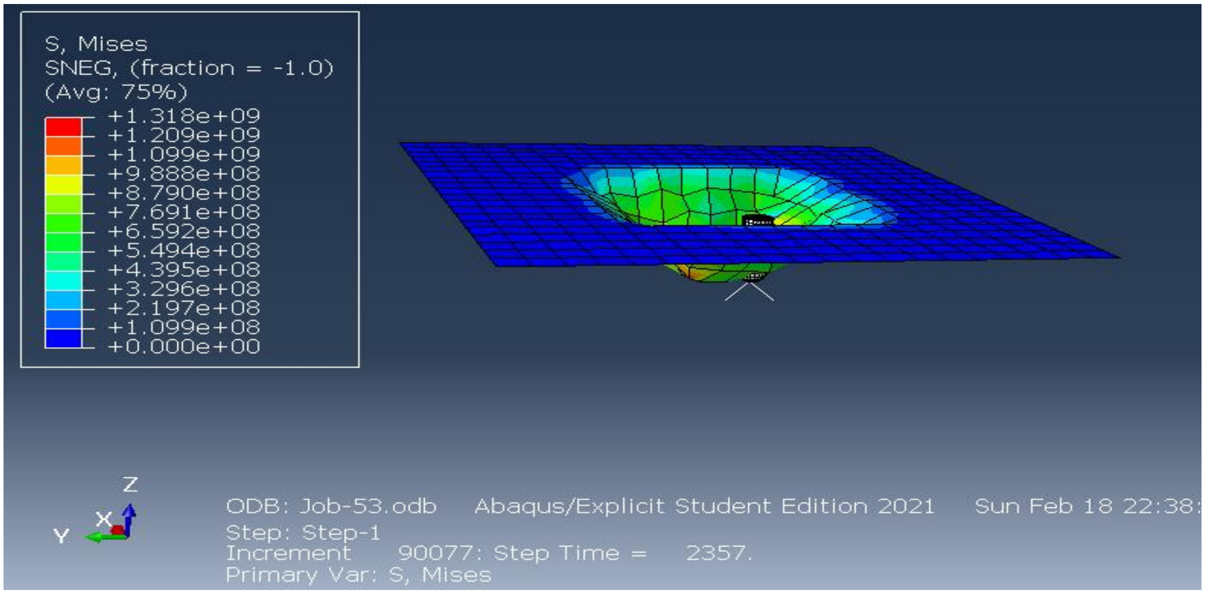


Fig. 21 E2 (TD = 5mm, Step D = 0.8mm, SS = 1400rpm and FR = 450mm/min).

Max Von Mises stress is 1318Mpa which is more than 160Mpa yield stress.

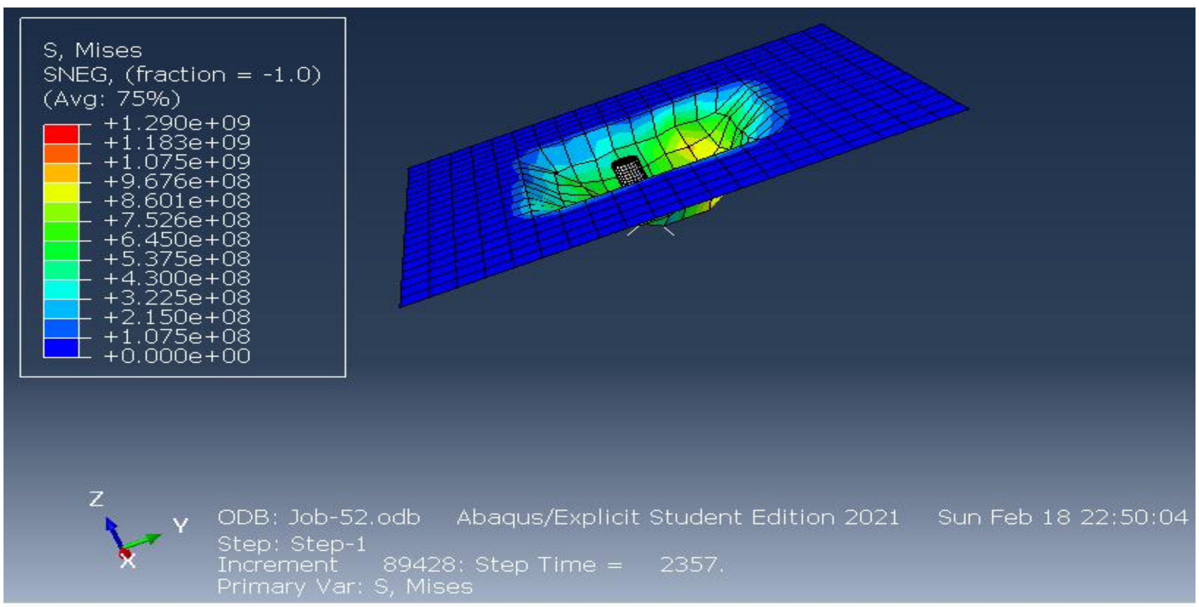


Fig. 22 E3 (TD = 5mm, Step D = 1.2mm, SS = 1500rpm and FR = 600mm/min).

Max Von Mises stress is 1290Mpa which is more than 160Mpa yield stress.

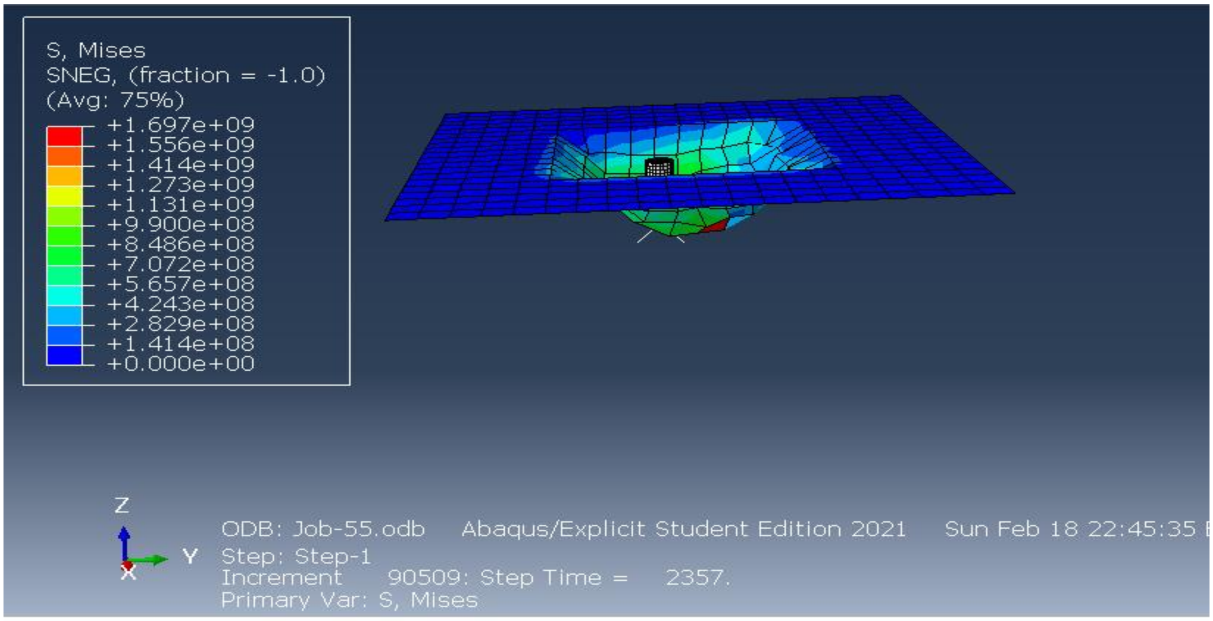


Fig. 23 E4 (TD = 8mm Step D. = 0.4mm, SS = 1400rpm and FR = 600mm/min).

Max Von Mises stress is 1697Mpa which is more than 160Mpa yield stress.

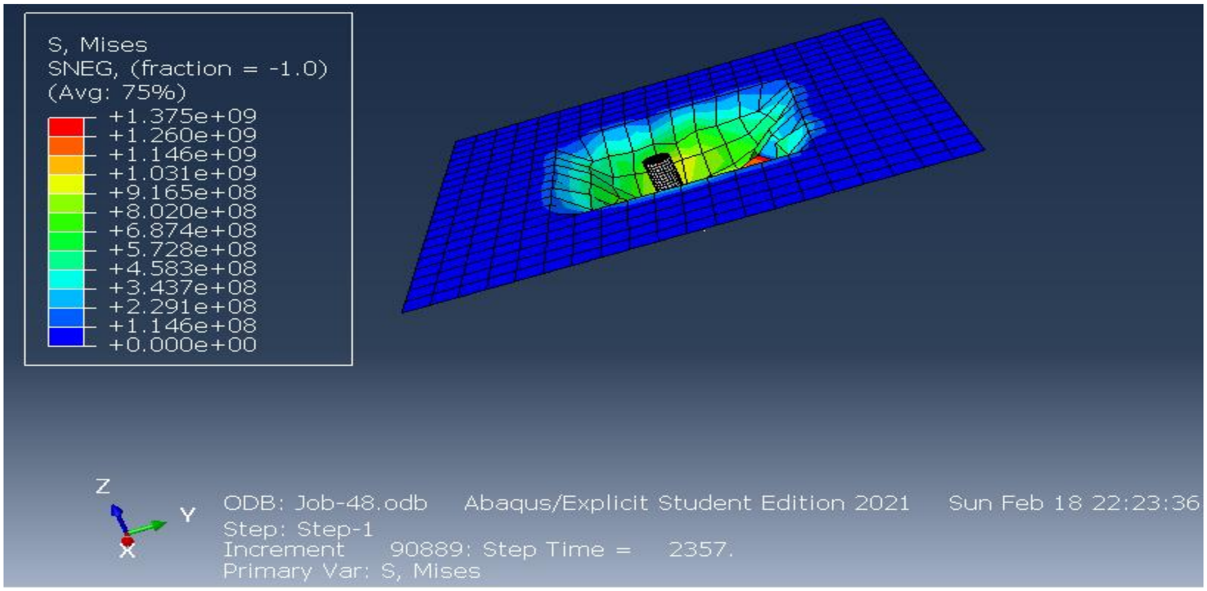


Fig. 24 E5 (TD= 8mm, Step D. = 0.8mm, SS = 1500rpm and 300mm/min).

Max Von Mises stress is 1375Mpa which is more than 160Mpa yield stress.

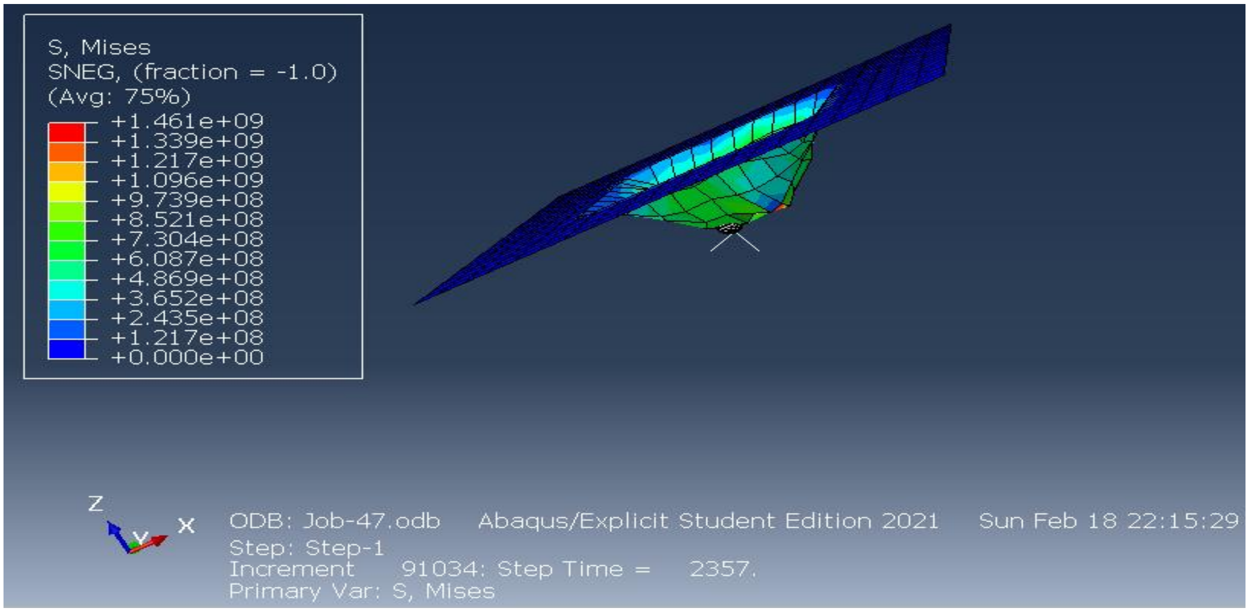


Fig. 25 E6 (TD= 8mm, Step D. = 1.2mm, SS = 1300rpm and 450mm/min).

Max Von Mises stress is 1461Mpa which is more than 160Mpa yield stress.

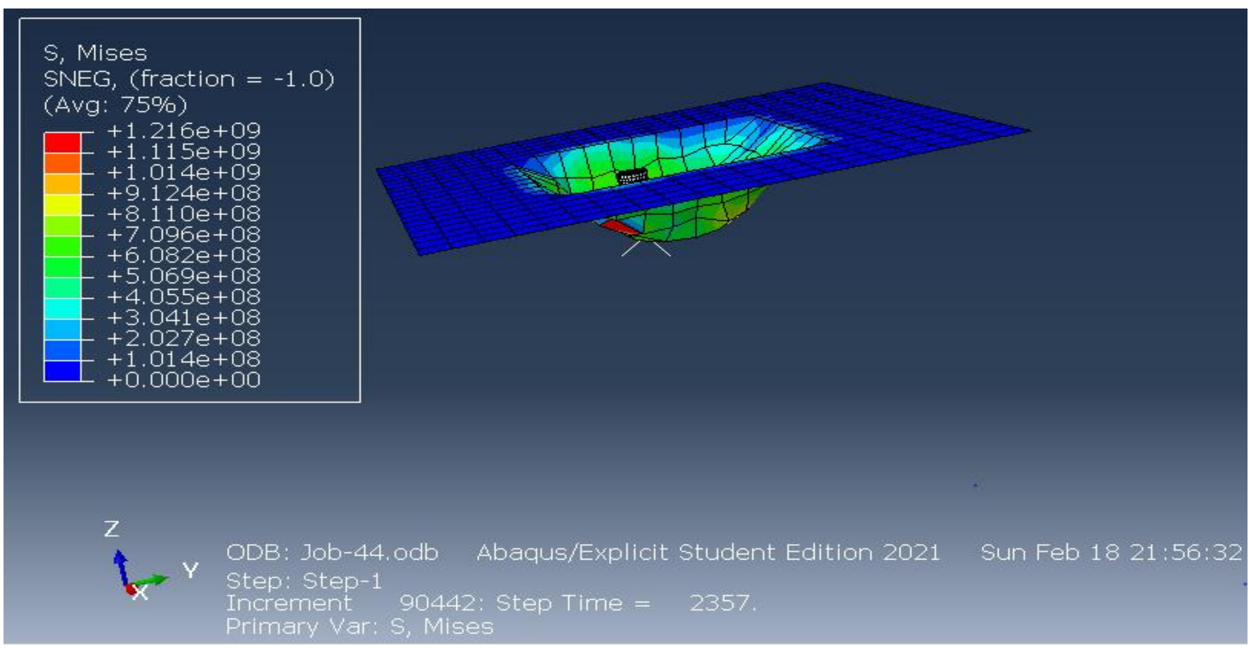


Fig. 26 E7 (TD = 11mm, Step D. = 0.4mm, SS = 1500rpm and FR = 450mm/min).

Max Von Mises stress is 1216Mpa which is more than 160Mpa yield stress.

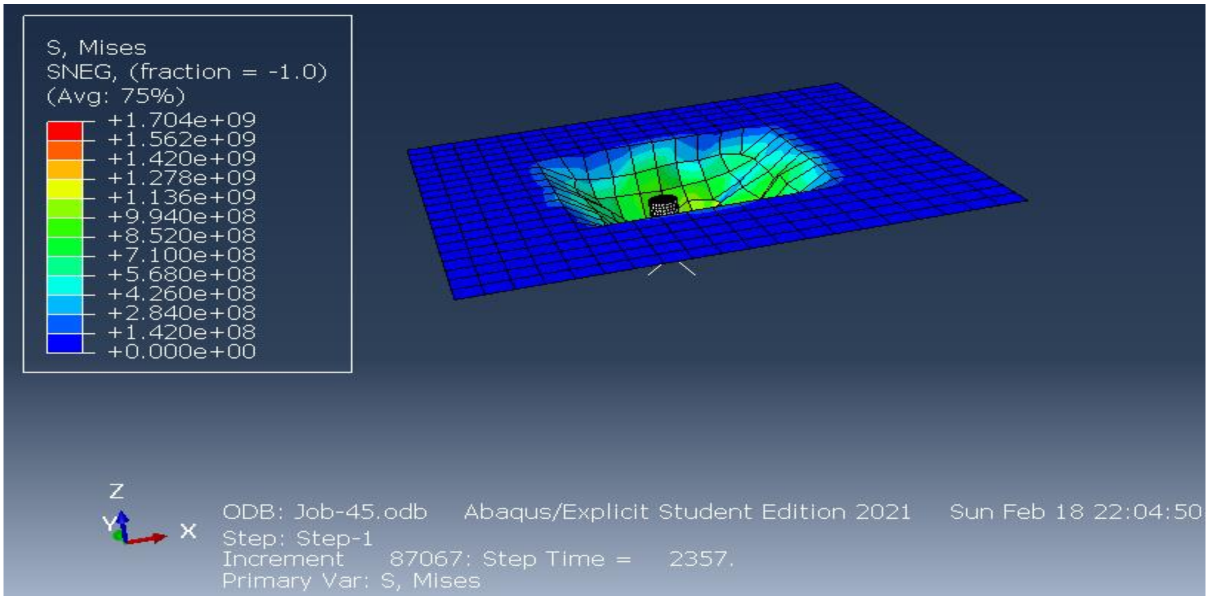


Fig.27 E8 (TD = 11mm, Step D. = 0.8mm, SS = 1300rpm and FR = 600mm/min).

Max Von Mises stress is 1704Mpa which is more than 160Mpa yield stress.

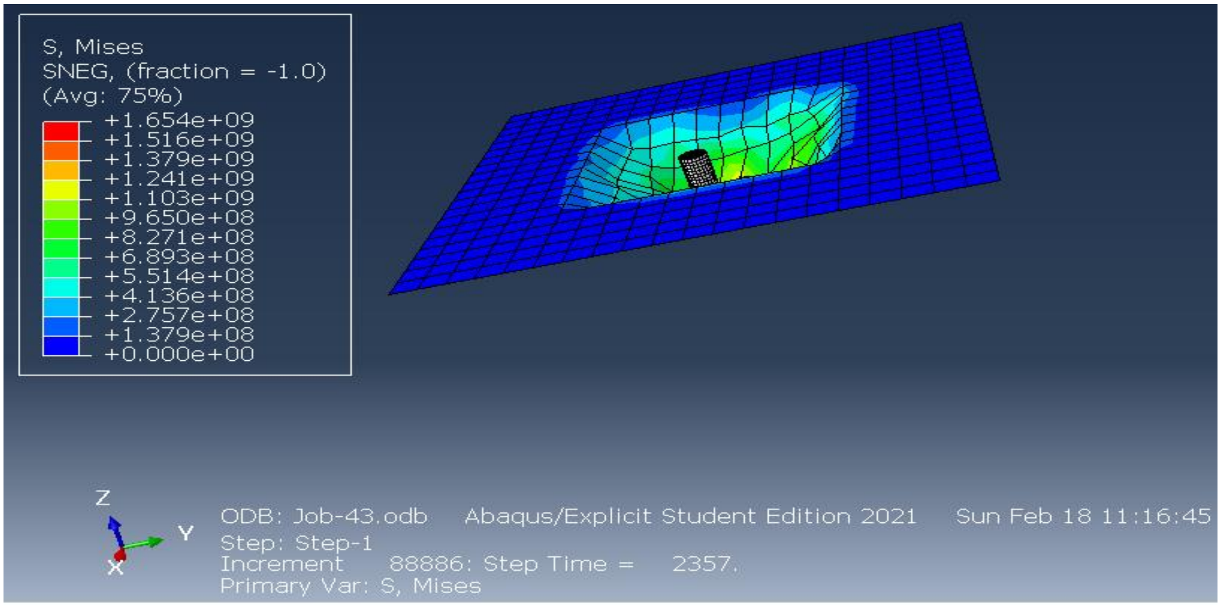


Fig. 28 E9 (TD = 11mm, Step D. = 1.2mm, SS = 1400rpm and FR = 300mm).

Max Von Mises stress is 1654Mpa which is more than 160Mpa yield stress.

Table11. Summary of experimental and simulation result

Experiment. No.	Experimental result surface roughness Ra (µm) Mean value	Simulation Model Von misses stress Result (MPA)	Remark and conclusion on both Experimental and Simulation model results
1	1.91	1532	From the simulation model of Von - misses stress result the lowest average stress is 1216 MPA which is the stress value of Experment7 that shows good surface finish quality. So, both the experimental and simulation results are coinciding.
2	1.56	1318	
3	1.35	1290	
4	0.87	1697	
5	0.93	1375	
6	0.77	1461	
7	0.39	1216	
8	0.53	1704	
9	0.68	1654	

As a conclusion, from the simulation modeling observed above on experiment 7 which have the lowest principal stress and which leads for good surface finish quality are on parameters values of large tool diameter with lower step depth, medium Feed rate and higher spindle speed as similar as the value of surface roughness which is obtained from the experiment7. So, good surface finish product has been produced by these parameter values.

4.2. Results and Recommendation of surface roughness

A number of Experimental outcomes based on the L9 orthogonal array have been obtained and evaluated using the commercial statics MINITAB 18 program. Taguchi L9 Orthogonal array, signal to noise (S/N) ratio, and analysis of variance were utilized to determine the impact of process parameters on the surface quality of the manufactured product (ANOVA).

4.2.1 Signal to Noise Ratio Analysis

In the Taguchi technique, the terms "signal" and "noise" refer to the desired (controlled) value and the undesirable (uncontrolled) value, respectively.

S/N ratio calculations are analyzed to show both the conventional and alternative versions of experimental results. Our objective for this article is a superior surface finish. Thus, the S/N value should be as little as possible. The calculation below yields the S/N ratio: -

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{1}^{n} y_i^2\right] \text{ ....eqn.1}$$

Where n is the number of observations per row, which in this case is 3 (three)for surface roughness.

Yi = the calculated roughness.

Using an orthogonal array L9, the value of surface roughness is associated for various levels of process factors, such as tool diameter, step depth, spindle speed, and feed rate, and the results are tabulated below.

Table12. Surface Roughness result

Experiment number	Tool Diameter (mm)	Step Depth (mm)	Spindle Speed (rpm)	Feed Rate (mm/min)	Mean Surface Roughness(µm)	S/N Ratio
1	5	0.4	1300	300	1.91	-5.6207
2	5	0.8	1400	450	1.56	-3.8625
3	5	1.2	1500	600	1.35	-2.6068
4	8	0.4	1400	600	0.87	1.2096
5	8	0.8	1500	300	0.93	0.6303
6	8	1.2	1300	450	0.77	2.2702
7	11	0.4	1500	450	0.39	8.1787
8	11	0.8	1300	600	0.53	5.5145
9	11	1.2	1400	300	0.68	3.3498

Table13. Response Table for Signal to Noise Ratios

Smaller is better

Level	**Tool Diameter**	**Step Depth**	**Spindle Speed**	**Feed Rate**
1	-4.0299	1.2559	0.7213	-0.5468
2	1.37	0.7608	0.2323	2.1955
3	5.681	1.0044	2.0675	1.3725
Delta	9.7109	0.4951	1.8351	2.7423
Rank	1	4	3	2

Response value for Signal to Noise ratio for Tool Diameter at the three levels is calculated by finding the average of S/N ratios at the corresponding level.

N.B Delta is the absolute value difference between maximum and minimum average value of each parameter,

Table14. Response value for Signal Noise ratio for Tool Diameter (TD)

TD level 1	S/N	TD level 2	S/N	TD level 3	S/N
1	-5.6207	2	1.2096	3	8.1787
1	-3.8625	2	0.6303	3	5.5145
1	-2.6068	2	2.2702	3	3.3498
Average	-4.0300	Average	1.3700	Average	5.6810
Delta	5.6810 -(-4.0300) = 9.711				

Table15. Response value for Signal Noise ratio for Step Depth (SD)

SD level 1	S/N	SD level 2	S/N	SD level 3	S/N
1	-5.6207	2	-3.8625	3	- 2.6068
1	1.2096	2	0.6303	3	2.2702
1	8.1787	2	5.5145	3	3.3498
Average	1.2559	Average	0.7608	Average	1.0044
Delta	1.2559-0.7608 = 0.4951				

Table16. Response value for Signal Noise ratio for Spindle Speed (SS)

SS level 1	S/N	SS level 2	S/N	SS level 3	S/N
1	-5.6207	2	-3.8625	3	-2.6068
1	2.2702	2	1.2096	3	0.6303
1	5.5145	2	3.3498	3	8.1787
Average	0.7213	Average	0.2323	Average	2.0674
Delta	2.0674 -0.2323 = 1.8351				

Table 17. Response value for Signal Noise ratio for Feed Rate (FR)

	S/N	FR level 2	S/N	FR level 3	S/N
1	-5.6207	2	-3.8625	3	-2.6068
1	0.6303	2	2.2702	3	1.2096
1	3.3498	2	8.1787	3	5.5145
Average	-0.5469	Average	2.1955	Average	1.3724
Delta	2.1955 -(-0.5469) = 2.7424				

4.2.2 Effect of process parameters on surface Roughness (Ra)

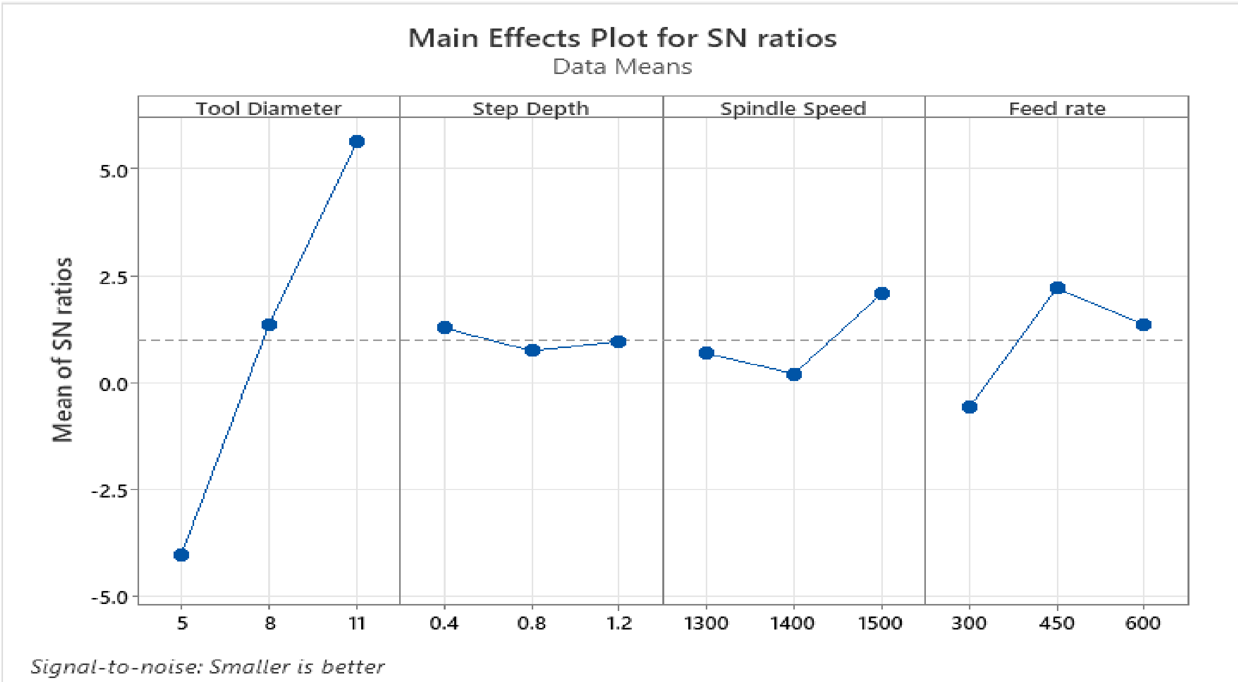


Fig.29 Response graph for surface roughness

The influence of process factors on surface roughness is illustrated in the figure 29. It was discovered that Ra falls off as tool diameter increases. This is because a large tool's diameter increases the surface area that will come into contact with the work piece, which reduces the force needed to force the work piece to be formed. Additionally, the heat generated by the contact causes the work piece to soften thermally, which improves surface smoothness and results in good surface finished forming. As it is observed from **Fig.29**, an increase of all process parameter values decreases surface roughness Ra. However relative to the other, the step depth is the less significant parameter due to its lowest influence on the surface roughness Ra. therefore, the maximum influenced parameters from the first to the last on the surface roughness Ra are tool Diameter, Feed rate, Spindle speed and Step depth respectively.

4.2.3 Selection of optimum forming parameter for surface Roughness (Ra)

Table18. displays the S/N ratio response table that was acquired for surface roughness (Ra), and **fig.29** shows the mean S/N ratio graph that was produced using the Minitab statistical program. Better S/N ratio, according to the data, signifies the least amount of fluctuation between desired and measured output. The highest mean S/N ratio for Ra has been obtained for the following parameters: tool diameter at 11 mm, step depth at 0.4 mm, spindle speed at 1500 rpm, and feed rate at 450 mm/min. consequently, the predicted optimum process parameters for acquiring the low surface roughness using Taguchi method are observed as tool diameter = 11mm, step depth = 0.4mm, spindle speed = 1500rpm and feed rate = 450 mm/min and corresponding level values are Bolded in the below **table18**. This predicted optimum combination is represented as tool diameter level 3 – step depth level 1 – spindle speed level 3 – feed rate level 2 for surface roughness response.

Table18. Mean S/N ratio Response table for response surface roughness

S.N.	Process parameters	Mean S/N ratio				
		Level 1	Level 2	Level 3	Max – Min	Rank
1	Tool Diameter (mm)	-4.03	1.37	**5.68**	9.71	1
2	Step Depth (mm)	**1.26**	0.76	1.00	0.50	4
3	Spindle Speed(rpm)	0.72	0.23	**2.07**	1.83	3
4	Feed Rate(mm/min)	-0.55	**2.20**	1.37	2.74	2

4.2.4 Conformation test

Validating the Taguchi predicted optimal conditions requires the execution of conformation tests. The projected S/N ratio (ε) is used to evaluate and verify the response at expected optimal forming circumstances., which was computed as follows:

$$\varepsilon_{predicted} = \varepsilon_t + \sum_{i=1}^{n}(\varepsilon_o - \varepsilon_t) \text{ ....eqn2.}$$

Where: - ε_t = Total Mean S/N ratio

ε_o = Means S/N ratio at optimal level

n = No. of input process parameters

The conformation analysis has been conducted at the Taguchi predicted optimum forming condition, and outcomes are reported in **table19.** for the surface roughness. The overall performance characteristic outcome is improved by the expected optimum forming circumstances for Ra. The S/N ratios for the predicted and optimal forming conditions for the surface roughness Ra are very similar. When comparing the optimal Ra forming situation to the initial parameter values the S/N ratio of improvement is 8.214dB. According to the outcomes of the confirmation analysis, Taguchi correctly predicted the optimum conditions for forming Ra reduction was determined to be 61% under the Taguchi projected optimal formation conditions compared to the original parameter conditions. In order to get low surface roughness when forming Al6063A under the given conditions, the Taguchi predicted optimum forming condition are adopted as the optimum forming condition.

Table19. Confirmation test results for surface roughness

	Initial process parameter	Optimal process parameters	
		Prediction	Experiment
Level	TD_2-SD_2-SS_2-FR_2	$TD_3 – SD_1 – SS_3 – FR_2$	$TD_3 – SD_1 – SS_3 – FR_2$
Surface roughness (µm)	1.0004	0.43	0.39
S/N ratio (dB)	-0.035	-1.2048	8.179
Improvement in S/N ratio (dB)	8.214		
Percentage reduction of surface roughness	61		

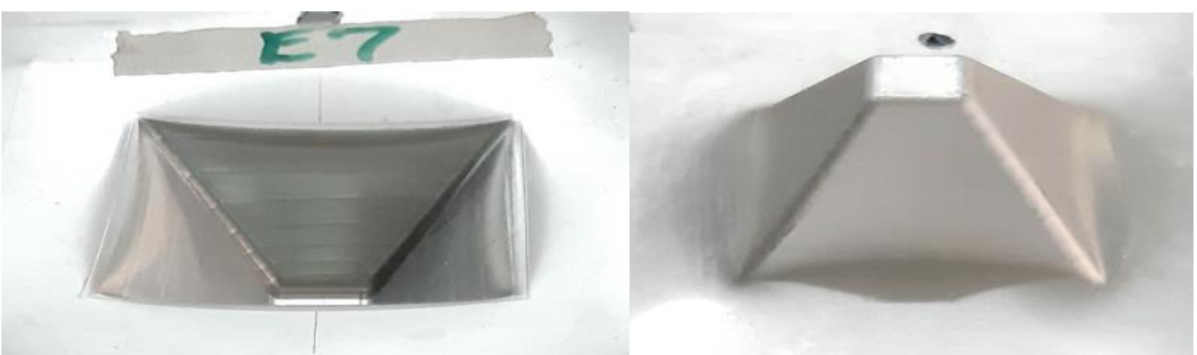


Fig. 30 Minimum obtained surface roughness (0.39µm, Experiment 7)

4.3 Analysis of Variance

Analysis of variance (ANOVA) is performed to evaluate the significant process parameters which considered as affecting the product quality. This single objective optimization determining which parameter significantly affects the quality characteristics (surface roughness).

ANOVA is performed by dividing the total mean S/N ratio from the tool variability of the S/N ratios which is determined by sum of square deviations. The total sum of square deviation is calculated as: -

$$\mathbf{SST} = \sum_{i=1}^{N} \boldsymbol{yi}^2 - \frac{\sum(\boldsymbol{yi})^2}{\boldsymbol{N}} \text{ …………...eqn3}$$

Table20. Analysis of Variance for S/N ratio.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1.8983	0.47458	13.96	0.013
Tool Diameter	1	1.72807	1.72807	50.83	0.002
Step Depth	1	0.02282	0.02282	0.67	0.459
Spindle Speed	1	0.0486	0.0486	1.43	0.298
Feed Rate	1	0.09882	0.09882	2.91	0.163
Error	4	0.13599	0.034		
Total	8	2.03429			

Where the degree of freedom (DF), Sum of Squares (SS), Contribution: Contribution as a percentage, adjusted mean square (Adj MS), adjusted sum square (Adj SS), Calculated probability (P-value), variance (F-value), Sequential sum of squares (Seq SS) with a 95%. confidence level.

% Of contribution calculated for all parameter as follows

$$\% \text{ Tool Diameter} = \frac{142.047}{159.715} * 100 = 88.94\%$$

$$\% \text{ Step Depth} = \frac{0.368}{159.715} * 100 = 0.22\%$$

$$\% \text{ Spindle Speed} = \frac{5.419}{159.715} * 100 = 3.40\%$$

$$\% \text{ Feed Rate} = \frac{11.881}{159.715} * 100 = 7.44\%$$

***Table21. ANOVA of Surface roughness*.**

Source	Degree of freedom	Sum of squares	Mean squares	% Contribution
Tool Diameter	2	142.047	71.0234	88.94
Step Depth	2	0.368	0.1839	0.22
Spindle Speed	2	5.419	2.7095	3.4
Feed Rate	2	11.881	5.9406	7.44
Total	8	159.715		100

Therefore, Tool Diameter is most influential then Feed Rate, Spindle Speed and Step Depth.

Table22. Conformation Result from the developed model

↓	C1	C2	C3	C4	C5	C6	C7	C8	c9
	Tool Diameter	Step Depth	Spindle Speed	Feed Rate	Surface Roughness	SNRA 1	SNRA 2	FITS	RESI
1	5	0.4	1300	300	1.91	-5.62	-5.62	1.82	0.09
2	5	0.8	1400	450	1.56	-3.86	-3.86	1.54	0.02
3	5	1.2	1500	600	1.35	-2.61	-2.61	1.26	0.09
4	8	0.4	1400	600	0.87	1.21	1.21	0.93	-0.06
5	8	0.8	1500	300	0.93	0.63	0.63	1.04	-0.11
6	8	1.2	1300	450	0.77	2.27	2.27	1.03	-0.26
7	11	0.4	1500	450	0.39	8.18	8.18	0.43	-0.04
8	11	0.8	1300	600	0.53	5.51	5.51	0.42	0.11
9	11	1.2	1400	300	0.68	3.35	3.35	0.53	0.15

4.4 Regression Analysis

With the aid of an equation based on the experiment of single point incremental sheet forming process, regression analysis is used to correlate the control parameter, such as tool diameter, step depth, spindle speed, and feed rate, and response parameter, which is surface roughness.

For creating the predictive mathematical models for dependent variable Ra as a function of tool diameter, Step depth, Spindle speed, and Feed rate, respectively, the linear regression analysis model is developed using MINITAB 18 statistical software. The response has not undergone any. modifications. The regression analysis's prediction equation is as follows:

Ra = 4.20 - 0.1789TD - 0.154 SD- 0.0009 SS - 0.000856FR (R2 = 93.32 %) …...………eqn.4

Where Ra – surface Roughness, TD – tool Diameter in mm, SD = Step depth in mm, SD – Spindle speed in rpm, FR – Feed rate in mm/min.

The capability of developed model is checked with the aid of the usage of a coefficient of determination R2. The range for the coefficient of determination is 0 to 1. It is a good match between the dependent and independent variables if it is near to one. For instance, if R2 = 95%, newer observations were expected to have a 95% variability. In this work, a regression model for Ra was created, and its R2 value was 93.32%. The significancy of the coefficients in the projected model is assessed using the residual plot. If the residual plot is straight, the residual error is regularly distributed and the model's coefficients are important. Residual plots obtained for Ra which is shown within the figure below showed that the residual fall near the strait line implies that the developed coefficient model is significant.

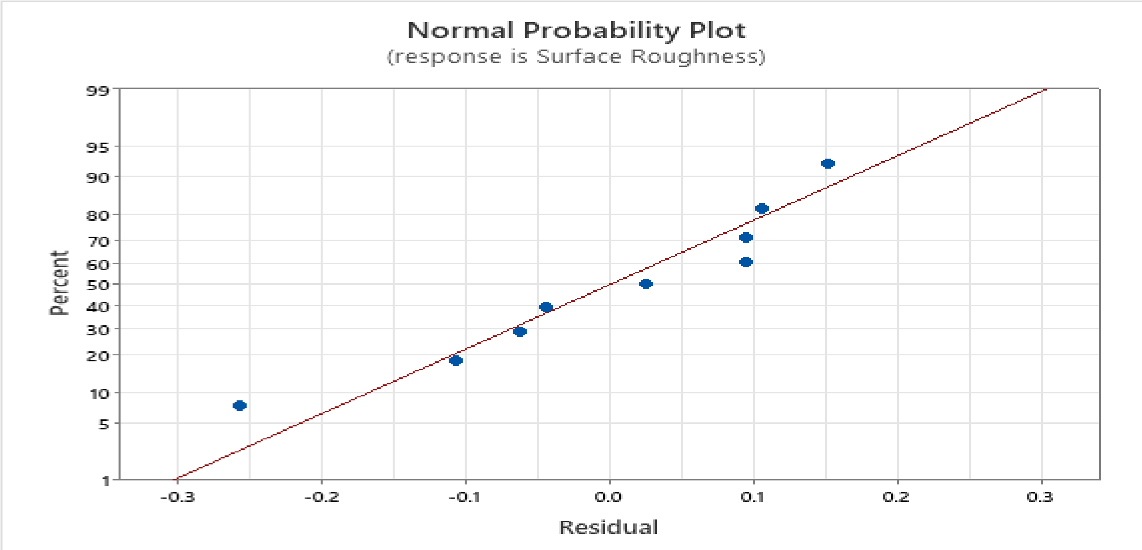


Fig. 31 Normal Probability plot of the residuals for surface roughness

The constructed model is validated by a confirmation test, the results of which are displayed in table below. A random sample of the L9 orthogonal experimental design's test results is used. It was discovered from the conformation result that the models anticipated result and the experimental result are in good agreement within the specified parameter range.

4.5 Validation of the experimental result

The proposed experimental set up for fabricating good surface quality forming product is validated by comparing the predicted surface roughness with experimental result as shown in **table23. and fig.31**. In this work, the forming surface roughness test is performed by using Vogel Germany Digital surface roughness test device, by measuring surface roughness reading three times for each experiment and the predicted surface roughness by the proposed commercial statics MINITAB 18 Software. It can be seen that the predicted surface roughness is in good agreement with measured values as shown in the following table and figure.

Table23. Experimental and Expected value of Surface Roughness

Run	Experimental Result	Predicted Result	Residuals
1	1.91	1.82	0.09
2	1.56	1.54	0.02
3	1.35	1.26	0.09
4	0.87	0.93	-0.06
5	0.93	1.04	-0.11
6	0.77	1.03	-0.26
7	0.39	0.44	-0.05
8	0.53	0.43	0.1
9	0.68	0.53	0.15

The experimental and predicted values of surface roughness are shown on the above table and the graph which shows the comparison between these surface roughness's shown below.

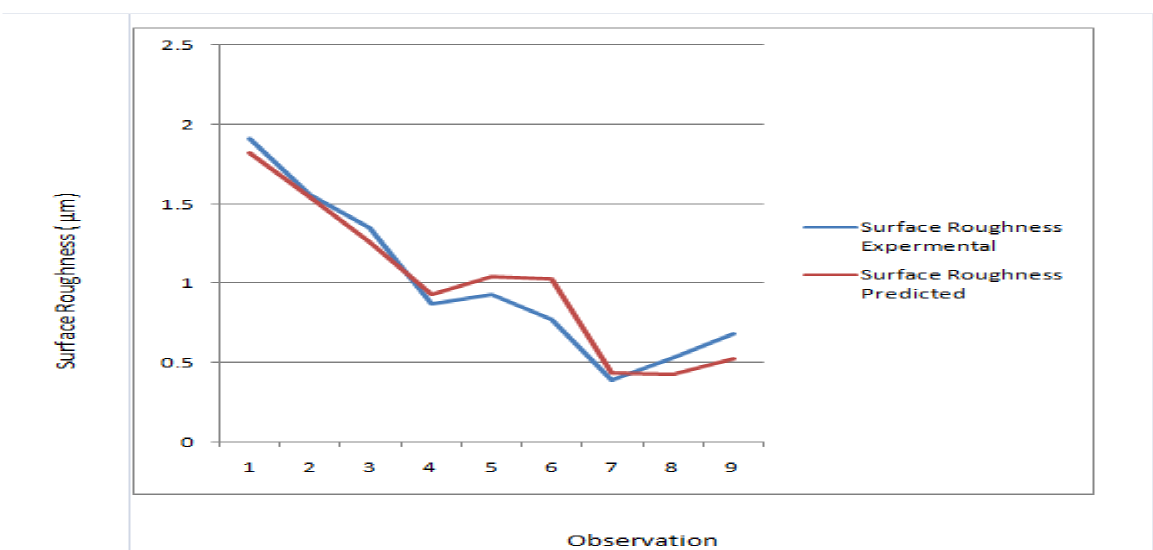


Fig.32 Comparison of Experimental and predicted Values of surface roughness

Chapter five

Conclusion and Recommendation

5.1 Conclusion

In this study, single point incremental forming (SPIF) experimental analysis is carried out, and Taguchi regression analysis, signal-to-noise ratio analysis, and ANOVA analysis are used to examine process parameter optimization on SPIF. Based on the experimental findings in this paper work, it is possible to draw the following conclusion.

- From the experimental result which is done on Minitab statistical software. The surface roughness decreases or good surface finish obtained with the higher value of all process parameters (Tool Diameter, Step Depth, Spindle Speed and Feed rate).
- The influential process parameters of surface roughness have been identified with the help of response table and ANOVA. The process parameters that have the most influence on surface roughness is Tool Diameter followed by Feed Rate, Spindle Speed and Step Depth in descending order.
- Tool diameter has more influence on the surface roughness. The surface roughness found to be minimum, based on the size of tool diameter which is in contact to the working blank when it is large in size.
- According to the analysis and the main effect plot graph of Signal to Noise ratio the optimum value of reduced surface roughness is Tool Diameter 11mm, Step Depth 4mm, Spindle Speed 1500 rpm and Feed Rate 450 mm/min.
- From the ANOVA analysis Tool Diameter (88.94%) and Feed Rate (7.44%) have a significant influence (96.38%) on the surface roughness compared to Spindle Speed (3.4%) and Step Depth (0.22%) which is (3.62%).

- The predicted optimal value for the surface roughness is 1.07667µm.
- The conformation tests are carried out to confirm the optimal forming parameters and the value of the optimal surface roughness is to be 0.39µm.
- From the result, The Taguchi method's parameter design offers an easy-to-use, systematic, and effective approach for optimizing the forming parameters of SPIF process.

5.2 Recommendation on future work

- Further analysis and optimization of SPIF process recommended on different thickness blank sheet, various angle and other process parameters in addition to aluminum sheet.
- Analyze the effect of different forming tool type such as Spherical, Hemispherical, and parabolic shape tools on surface quality of forming process and optimize their level for output response of minimum surface roughness.
- The effect of tool rotation on ISF formability and its effect on sheet metal type should be studied.
- Focus on finding the relationship between tool rotation and feed rate and develop table of suitable tool rotation as a guide for some important materials used in ISF processes.

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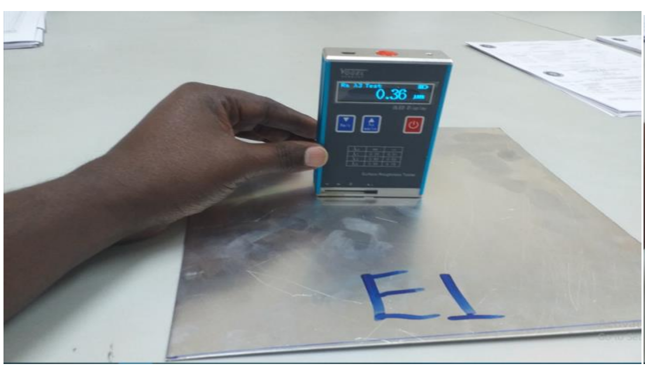
APPENDIX A

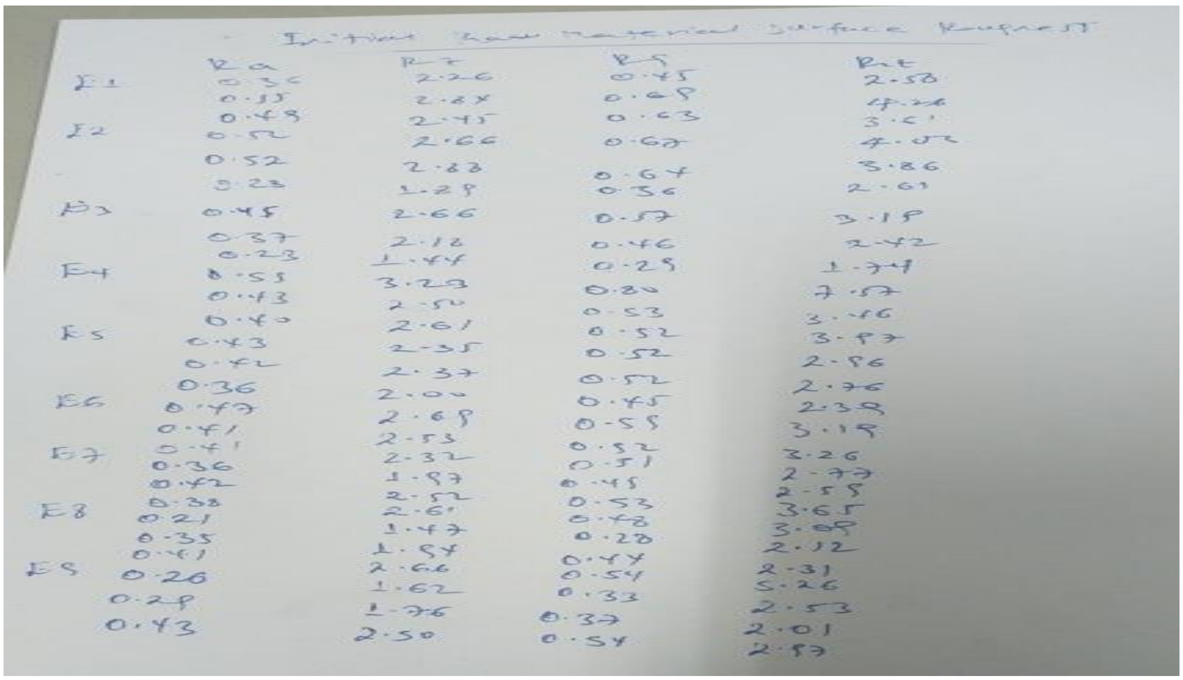
Fabrication forming time of each experiment

Fabrication forming time of each experiment		
S. No.	**Experimental Sample No.**	**Forming time (min)**
1	E1	87
2	E2	47
3	E3	25
4	E4	72
5	E5	34
6	E6	22
7	E7	64
8	E8	29
9	E9	14

APPENDIX B

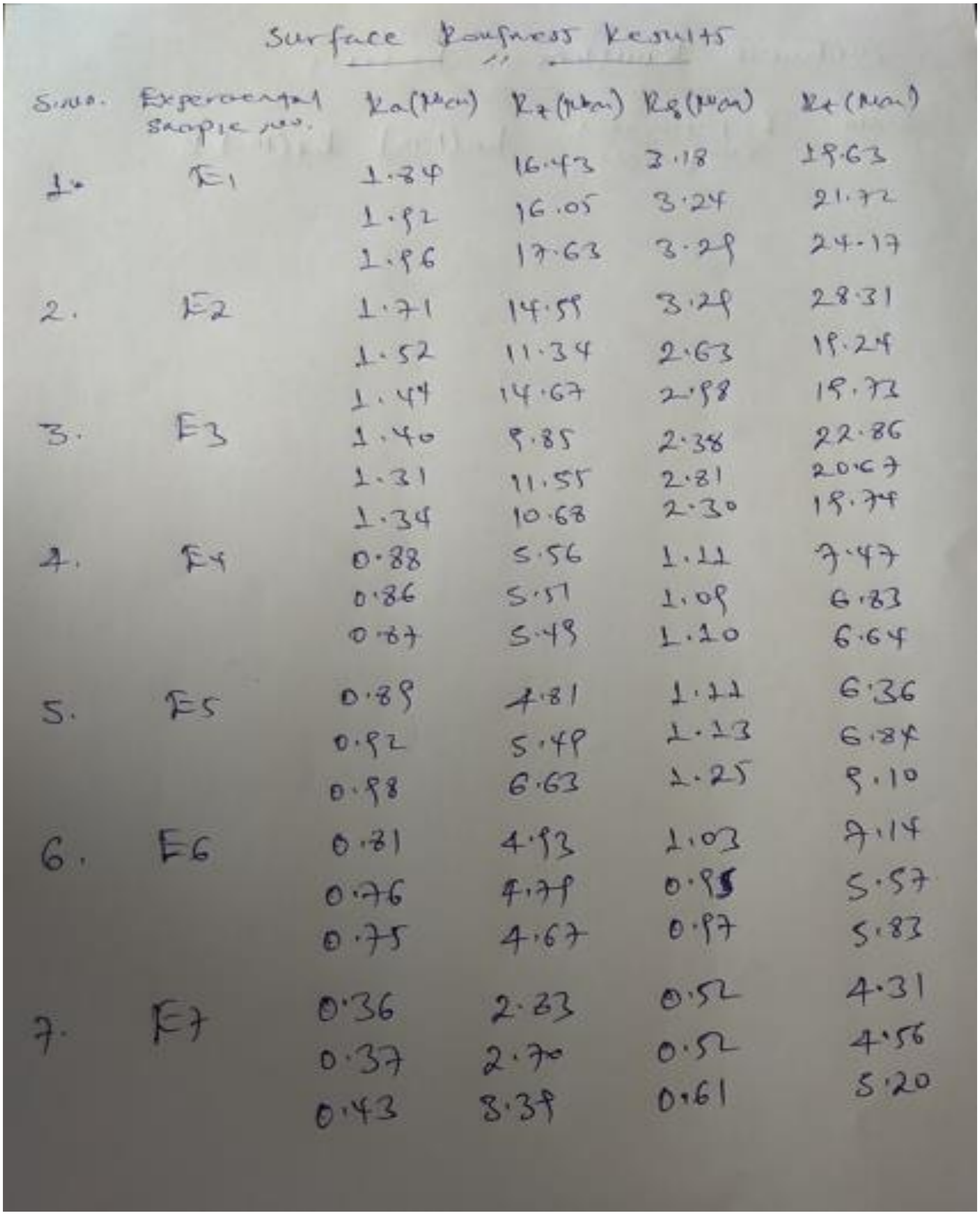
Surface roughness reading of both initial and final product





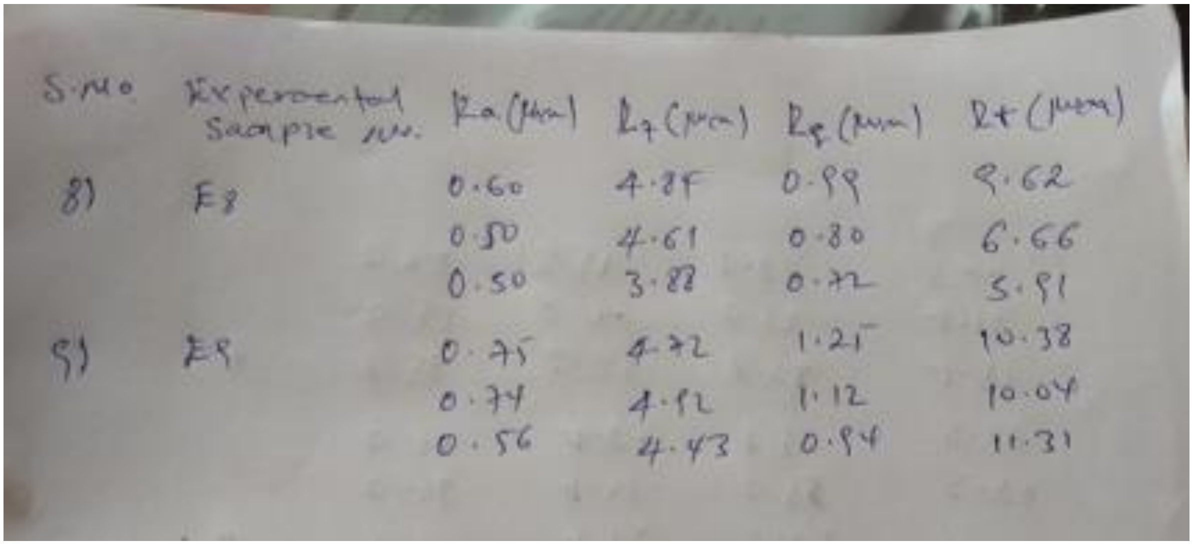
Initial Raw Material Surface Roughness

	Ra	Rz	Rq	Rt
E1	0.36	2.26	0.45	2.58
	0.35	2.84	0.68	4.26
	0.48	2.45	0.63	3.61
E2	0.52	2.66	0.67	4.02
	0.52	2.83	0.64	3.86
	0.23	1.28	0.36	2.61
E3	0.45	2.66	0.57	3.18
	0.37	2.12	0.46	2.42
	0.23	1.44	0.29	1.74
E4	0.53	3.23	0.80	7.57
	0.43	2.50	0.53	3.46
	0.40	2.61	0.52	3.87
E5	0.43	2.35	0.52	2.86
	0.42	2.37	0.52	2.76
	0.36	2.00	0.45	2.38
E6	0.47	2.68	0.55	3.19
	0.41	2.53	0.52	3.26
	0.41	2.32	0.51	2.77
E7	0.36	1.87	0.45	2.58
	0.42	2.52	0.53	3.65
	0.38	2.60	0.48	3.08
E8	0.21	1.47	0.28	2.12
	0.35	1.54	0.44	2.31
	0.41	2.66	0.54	5.26
E9	0.26	1.62	0.33	2.53
	0.28	1.76	0.37	2.01
	0.43	2.50	0.54	2.87



Surface Roughness Results

S.No.	Experimental sample no.	Ra (μm)	Rz (μm)	Rq (μm)	Rt (μm)
1.	E1	1.34	16.43	3.18	19.63
		1.92	16.05	3.24	21.72
		1.96	17.63	3.29	24.17
2.	E2	1.71	14.59	3.29	28.31
		1.52	11.34	2.63	19.24
		1.44	14.67	2.98	19.72
3.	E3	1.40	9.85	2.38	22.86
		1.31	11.55	2.81	20.67
		1.34	10.68	2.30	19.74
4.	E4	0.88	5.56	1.11	7.47
		0.86	5.51	1.09	6.83
		0.87	5.49	1.10	6.64
5.	E5	0.89	4.81	1.11	6.36
		0.92	5.49	1.13	6.84
		0.98	6.63	1.25	9.10
6.	E6	0.81	4.93	1.03	7.14
		0.76	4.79	0.98	5.57
		0.75	4.67	0.97	5.83
7.	E7	0.36	2.83	0.52	4.31
		0.37	2.70	0.52	4.56
		0.43	8.39	0.61	5.20



S.No	Experimental Sample No.	Ra (μm)	Rz (μm)	Rq (μm)	Rt (μm)
8)	E8	0.60	4.85	0.99	9.62
		0.50	4.61	0.80	6.66
		0.50	3.88	0.72	5.91
9)	E9	0.75	4.72	1.25	10.38
		0.74	4.92	1.12	10.04
		0.56	4.43	0.94	11.31

APPENDIX C

Appendix C-1

In this study G-Code and M-Code is generated using Auto Desk Inverter 2023 which is the latest version for generating program for the CNC milling for forming operation.

Part program for the verification of the recommended optimum forming parameters

TD = 5mm, SD = 0.40mm, SS = 1300rpm and FR = 300 mm/min

```
%

O0504(Experiment1)

(T3 D=5. CR=2.5 - ZMIN=-38.8 - BALL END MILL)

N10 G90 G94 G17 G49 G40 G80

N15 G21

N20 G28 G91 Z0.

N25 G90
```

```
N30 T3 M06

N35 S1300 M03

N40 G54

N45 M08

N50 G00 X-48.644 Y-27.78

N55 G43 Z15. H03

N60 G00 Z1.157

N65 G01 Z0.52 F300.

N70 G19 G02 Y-28.269 Z0.02 J-0.5 F33.

N75 G01 Y-48.641 Z-0.399

N80 X-48.641 Y-48.644

N85 X-48.581 Z-0.4

N90 X-48.571

N95 X48.641 F300.

N100 X48.644 Y-48.641

N105 Y48.641

N110 X48.641 Y48.644

N115 X-48.641
```

N120 X-48.644 Y48.641

N125 Y-48.641

N130 X-48.641 Y-48.644

N135 X-48.571

N140 X-48.39 Y-48.643

N145 X-48.209 Y-48.642 Z-0.401

N150 X-48.029 Y-48.641 Z-0.402

N155 X-47.848 Y-48.639 Z-0.403

N160 X-47.533 Y-48.634 Z-0.406

N165 X-47.218 Y-48.627 Z-0.411

N170 X-46.903 Y-48.619 Z-0.416

N175 X-46.588 Y-48.61 Z-0.422

N180 X-46.273 Y-48.599 Z-0.429

N185 X-45.958 Y-48.587 Z-0.437

N190 X-45.643 Y-48.575 Z-0.446

N195 X-45.328 Y-48.561 Z-0.455

N200 X-45.013 Y-48.547 Z-0.466

N205 X-44.698 Y-48.532 Z-0.476

N210 X-44.383 Y-48.517 Z-0.487

N215 X-44.068 Y-48.502 Z-0.498

N220 X-43.753 Y-48.488 Z-0.509

N225 X-43.438 Y-48.473 Z-0.52

N230 X-43.123 Y-48.459 Z-0.531

N235 X-42.808 Y-48.445 Z-0.542

N240 X-42.493 Y-48.431 Z-0.553

N245 X-42.178 Y-48.418 Z-0.564

N250 X-41.863 Y-48.404 Z-0.575

N255 X-41.548 Y-48.391 Z-0.586

N260 X-41.233 Y-48.378 Z-0.597

N265 X-40.918 Y-48.365 Z-0.608

N270 X-40.603 Y-48.353 Z-0.619

N275 X-40.288 Y-48.34 Z-0.63

N280 X-39.973 Y-48.328 Z-0.641

N285 X-39.658 Y-48.316 Z-0.652

N290 X-39.343 Y-48.304 Z-0.663

N295 X-39.028 Y-48.292 Z-0.674

```
N300 X-38.713 Y-48.28 Z-0.685

N305 X-38.398 Y-48.269 Z-0.696

N310 X-38.083 Y-48.257 Z-0.707

N315 X-37.768 Y-48.246 Z-0.718

N320 X-37.453 Y-48.235 Z-0.729

N325 X-37.138 Y-48.225 Z-0.74

N330 X-36.823 Y-48.215 Z-0.75

N335 X-36.508 Y-48.206 Z-0.759

N340 X-36.193 Y-48.197 Z-0.767

N345 X-35.878 Y-48.19 Z-0.775

N350 X-35.563 Y-48.183 Z-0.781

N355 X-35.248 Y-48.178 Z-0.787

.

N17655 X1.794 Y14.537 Z-34.427

N17660 X1.479 Y14.53 Z-34.435

N20020 G28 G91 X0. Y0.

N20025 G90

N20030 M30
```

%

APPENDIX D

The part program used to form sample using SPIF on Taguchi's L9 orthogonal array matrix for different tool diameter is listed below from all 9 experimental some of G - code and N-code

Tool path generation are: -

Appendix D-1

TD = 5mm, SD = 0.8mm, SS = 1300 and FR = 300)

```
%

O0508

(T3 D=5. CR=2.5 - ZMIN=-38.4 - BALL END MILL)

N10 G90 G94 G17 G49 G40 G80

N15 G21

N20 G28 G91 Z0.

N25 G90

N30 T3 M06

N35 S1300 M03

N40 G54

N45 M08

N50 G00 X-48.164 Y-23.676
```

```
N55 G43 Z15. H03

N60 G00 Z1.389

N65 G01 Z0.54 F300.

N70 G19 G02 Y-24.158 Z0.041 J-0.5 F33.

N75 G01 Y-48.162 Z-0.798

N16270 G17 G03 X-5.287 Y-9.711 J0.5

N16275 G00 Z15.

N16280 M09

N16285 G28 G91 Z0.

N16290 G90

N16295 G49

N16300 G28 G91 X0. Y0.

N16305 G90

N16310 M30

%
```

Appendix D-2
TD = 8mm, SD = 0.8mm, SS = 1500rpm and FR = 300mm/min

```
%

O0808

(T3 D=8. CR=4. - ZMIN=-37.6 - BALL END MILL)

N10 G90 G94 G17 G49 G40 G80

N15 G21

N20 G28 G91 Z0.

N25 G90

N30 T3 M06

N35 S1500 M03

N40 G54

N45 M08

N50 G00 X-47.6 Y-22.766

N55 G43 Z15. H03

N60 G00 Z1.28

N65 G01 Z0.84 F300.

N70 G19 G02 Y-23.538 Z0.041 J-0.8 F33.

N75 G01 Y-47.598 Z-0.799
```

```
N13935 G17 G03 X-9.377 Y-3.914 I0.8

N13940 G00 Z15.

N13945 M09

N13950 G28 G91 Z0.

N13955 G90

N13960 G49

N13965 G28 G91 X0. Y0.

N13970 G90

N13975 M30

%
```

Appendix D-3
TD = 11mm, SD = 0.8mm, SS = 1300rpm and FR = 600mm/min

```
%

O1108

(T3 D=11. CR=5.5 - ZMIN=-37.6 - BALL END MILL)

N10 G90 G94 G17 G49 G40 G80

N15 G21

N20 G28 G91 Z0.

N25 G90
```

```
N30 T3 M06

N35 S1300 M03

N40 G54

N45 M08

N50 G00 X-47.143 Y-21.988

N55 G43 Z15. H03

N60 G00 Z1.218

N65 G01 Z1.141 F600.

N70 G19 G02 Y-23.049 Z0.041 J-1.1 F33.

N75 G01 Y-47.123 Z-0.799

N12830 G17 G03 X2.379 Y-8.244 J1.1 F600.

N12835 G00 Z15.

N12840 M09

N12845 G28 G91 Z0.

N12850 G90

N12855 G49

N12860 G28 G91 X0. Y0.

N12865 G90
```

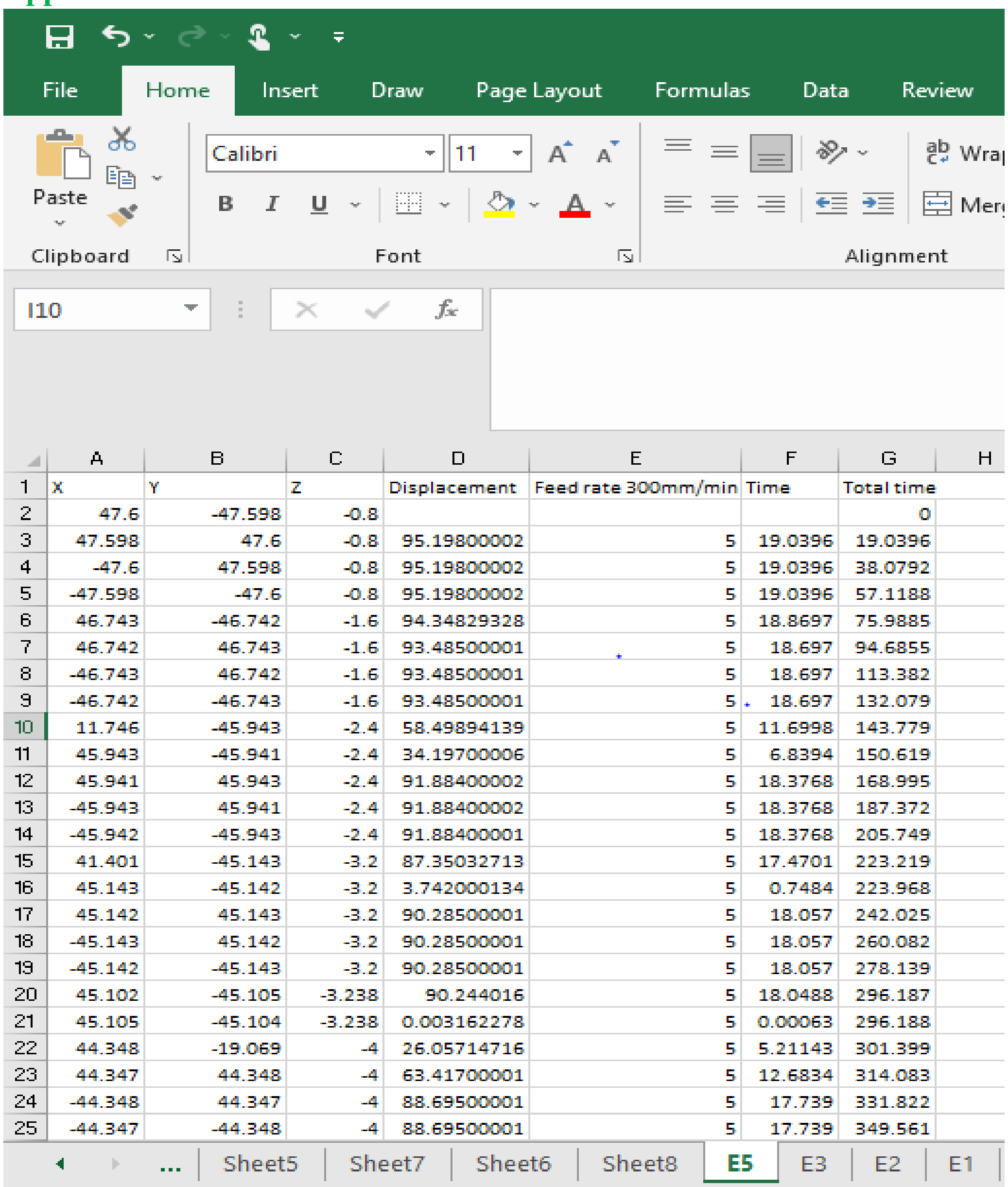
N12870 M30

%

Appendix E

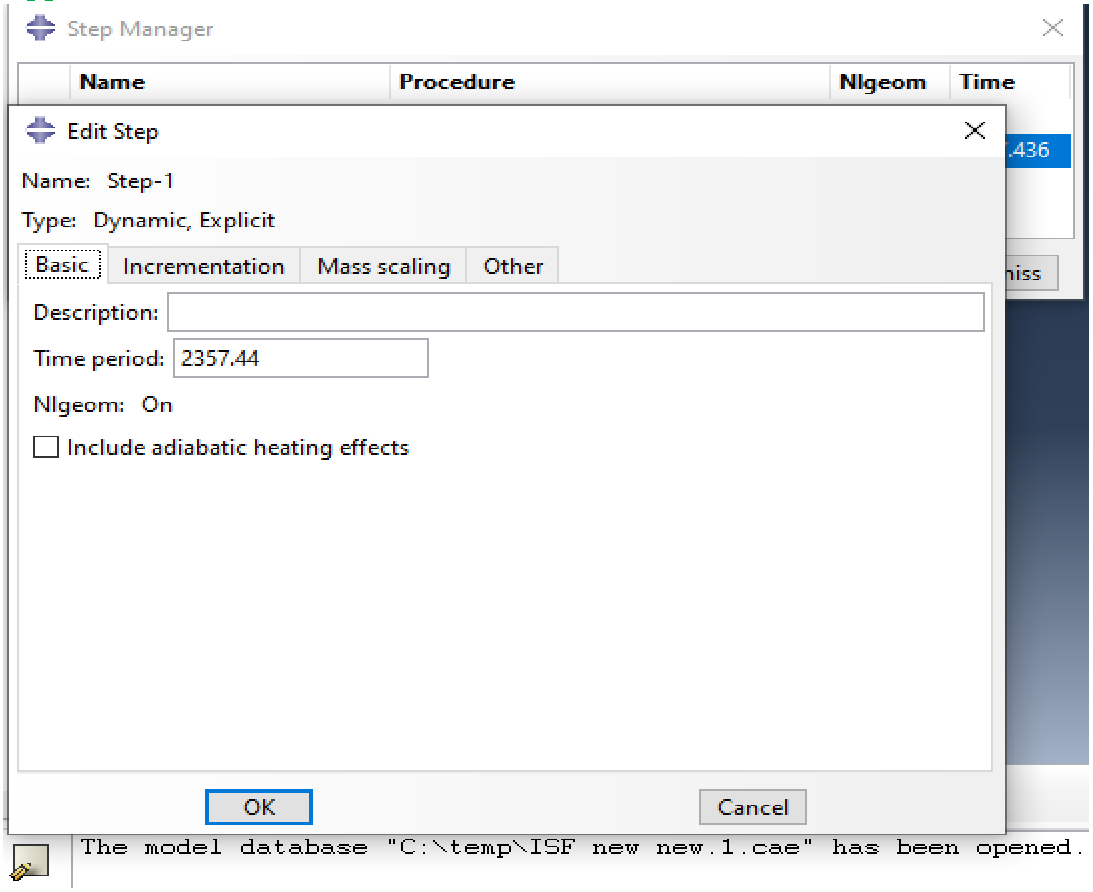
Input data for Simulation analysis and modeling results

Appendix E - 1

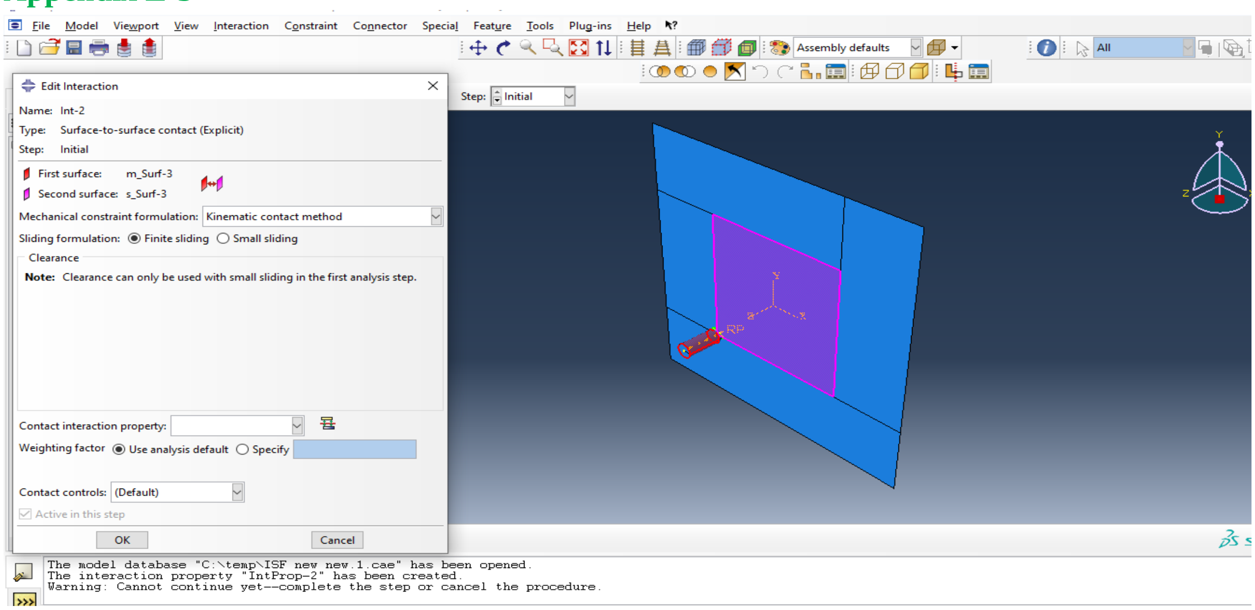


	A	B	C	D	E	F	G
1	X	Y	Z	Displacement	Feed rate 300mm/min	Time	Total time
2	47.6	-47.598	-0.8				0
3	47.598	47.6	-0.8	95.19800002	5	19.0396	19.0396
4	-47.6	47.598	-0.8	95.19800002	5	19.0396	38.0792
5	-47.598	-47.6	-0.8	95.19800002	5	19.0396	57.1188
6	46.743	-46.742	-1.6	94.34829328	5	18.8697	75.9885
7	46.742	46.743	-1.6	93.48500001	5	18.697	94.6855
8	-46.743	46.742	-1.6	93.48500001	5	18.697	113.382
9	-46.742	-46.743	-1.6	93.48500001	5	18.697	132.079
10	11.746	-45.943	-2.4	58.49894139	5	11.6998	143.779
11	45.943	-45.941	-2.4	34.19700006	5	6.8394	150.619
12	45.941	45.943	-2.4	91.88400002	5	18.3768	168.995
13	-45.943	45.941	-2.4	91.88400002	5	18.3768	187.372
14	-45.942	-45.943	-2.4	91.88400001	5	18.3768	205.749
15	41.401	-45.143	-3.2	87.35032713	5	17.4701	223.219
16	45.143	-45.142	-3.2	3.742000134	5	0.7484	223.968
17	45.142	45.143	-3.2	90.28500001	5	18.057	242.025
18	-45.143	45.142	-3.2	90.28500001	5	18.057	260.082
19	-45.142	-45.143	-3.2	90.28500001	5	18.057	278.139
20	45.102	-45.105	-3.238	90.244016	5	18.0488	296.187
21	45.105	-45.104	-3.238	0.003162278	5	0.00063	296.188
22	44.348	-19.069	-4	26.05714716	5	5.21143	301.399
23	44.347	44.348	-4	63.41700001	5	12.6834	314.083
24	-44.348	44.347	-4	88.69500001	5	17.739	331.822
25	-44.347	-44.348	-4	88.69500001	5	17.739	349.561

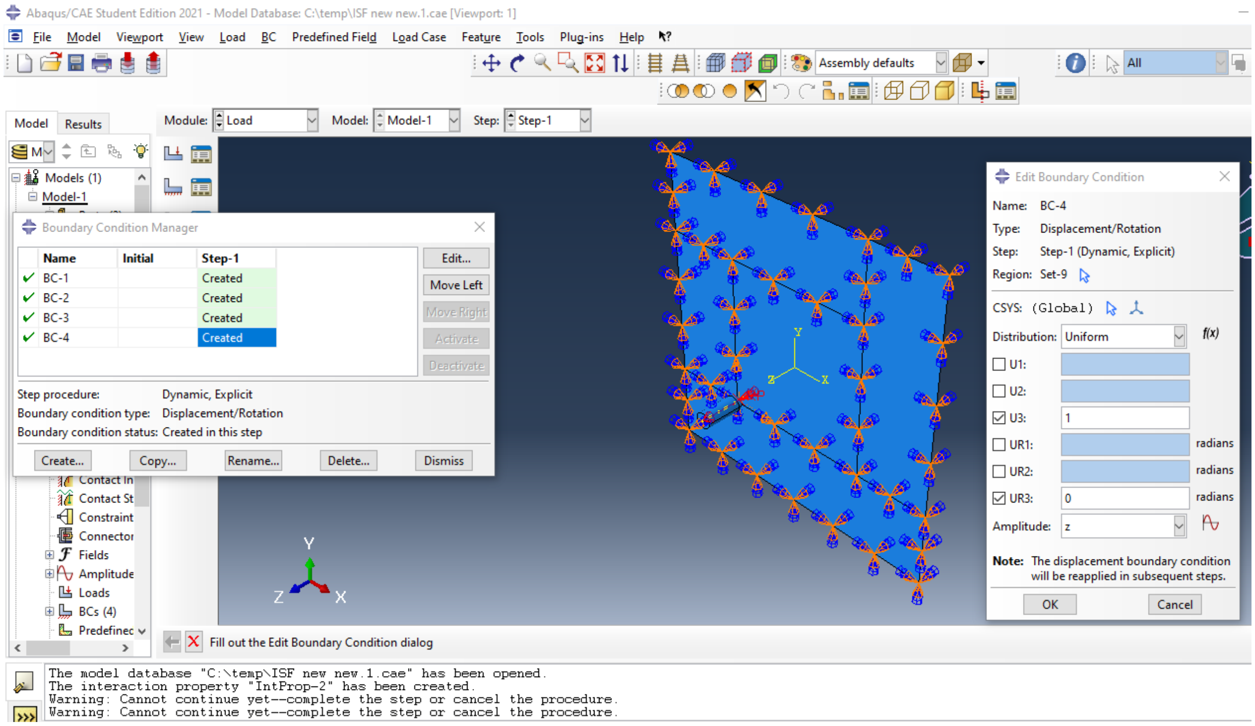
Appendix E-2



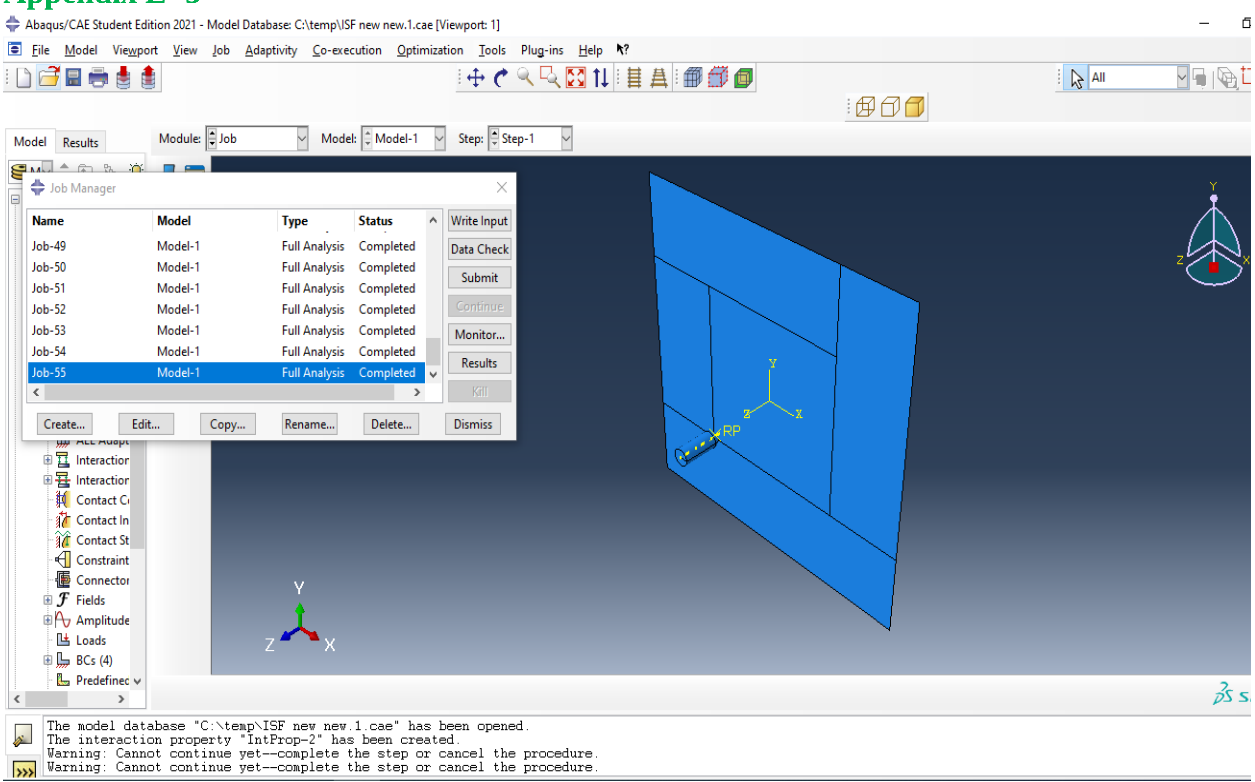
Appendix E-3



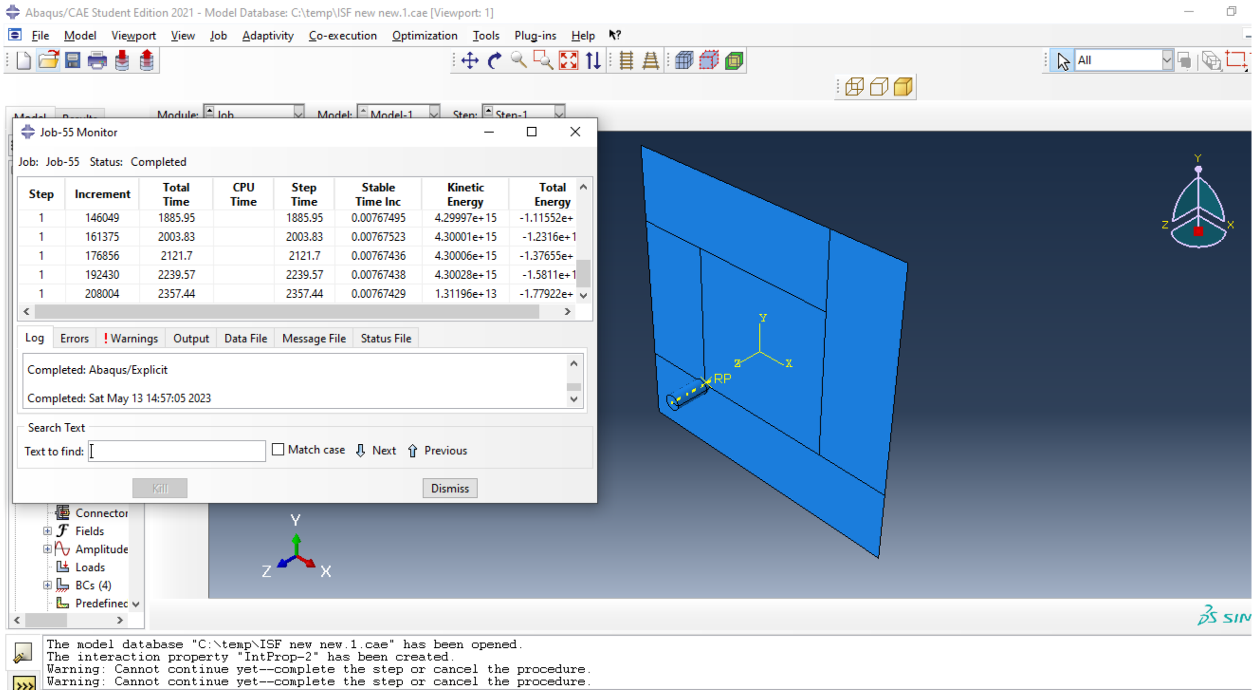
Appendix E - 4



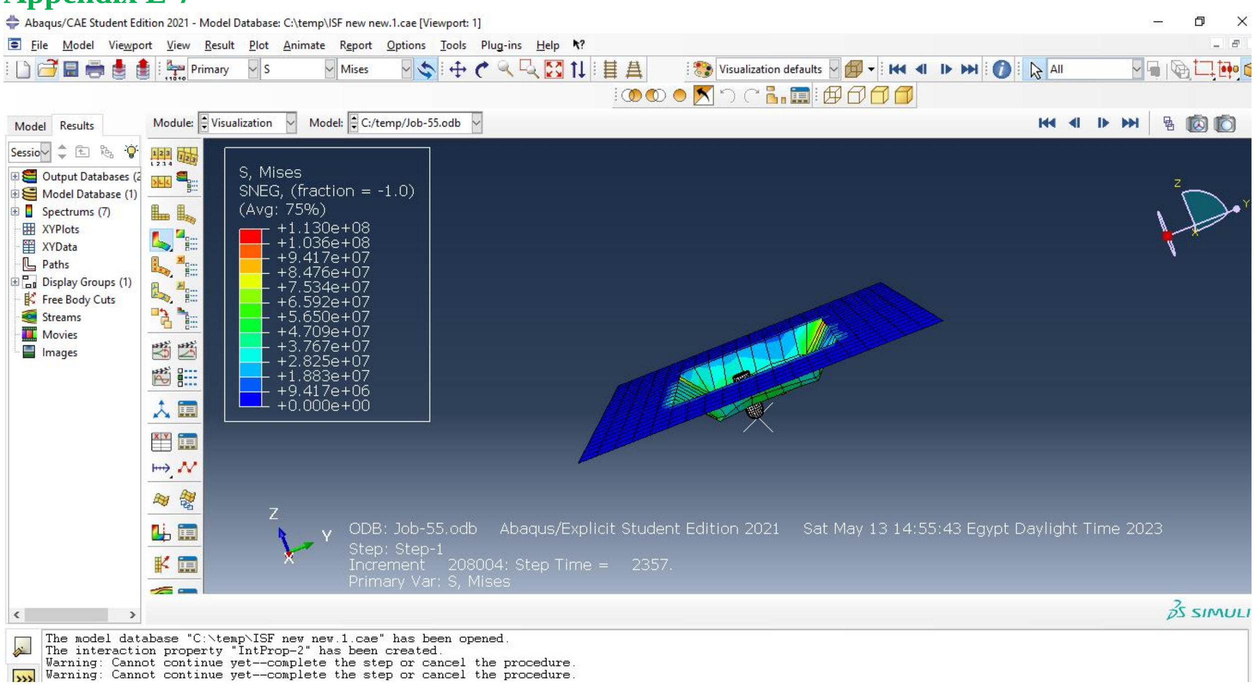
Appendix E- 5



Appendix E- 6



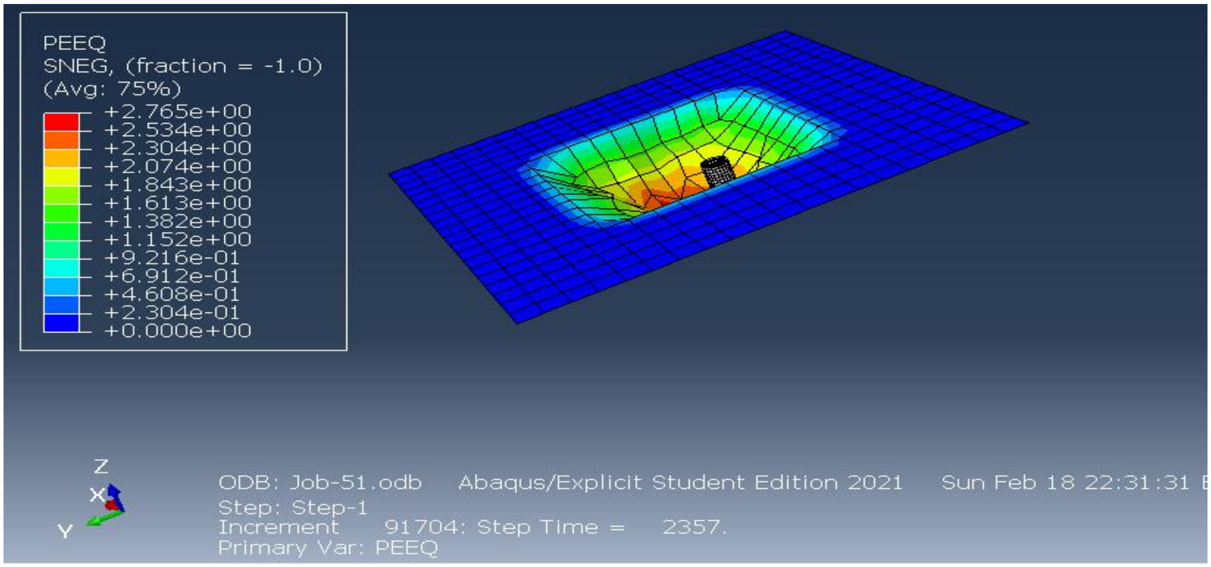
Appendix E-7



Appendix F

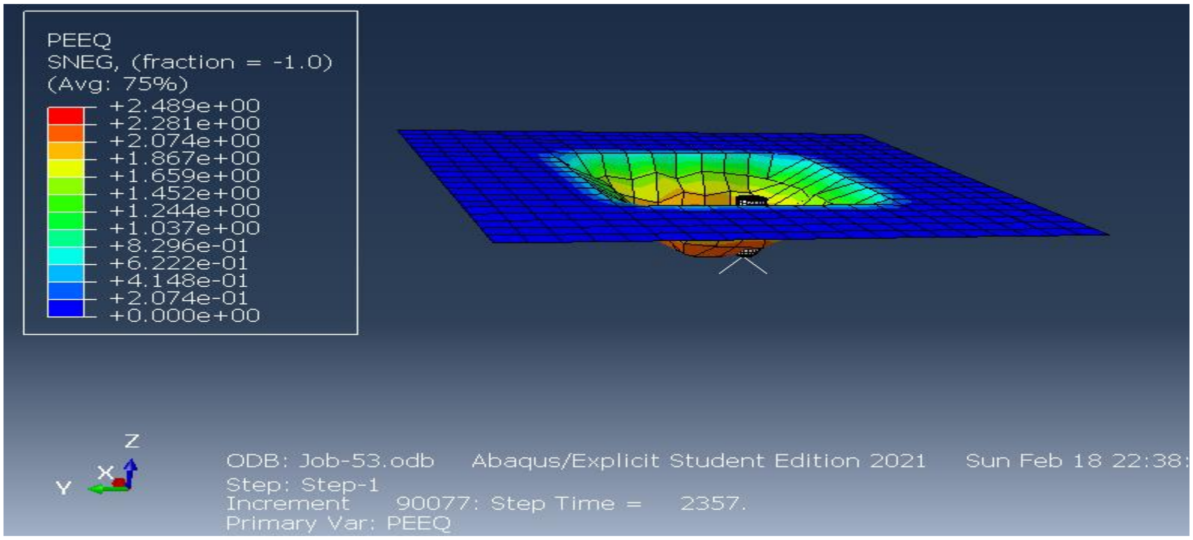
Simulation which shows strain values of each experimental sample analysis.

Appendix F-1



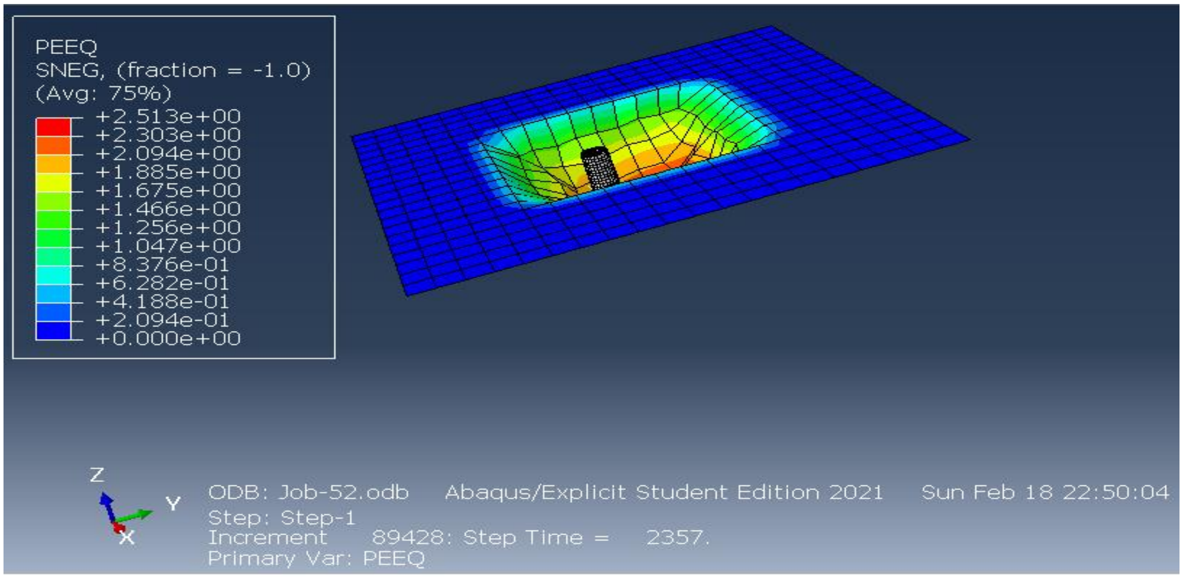
E1 (TD= 5mm, Step D = 0.4mm, SS = 1300 rpm and FR = 300mm/min).

Appendix F-2



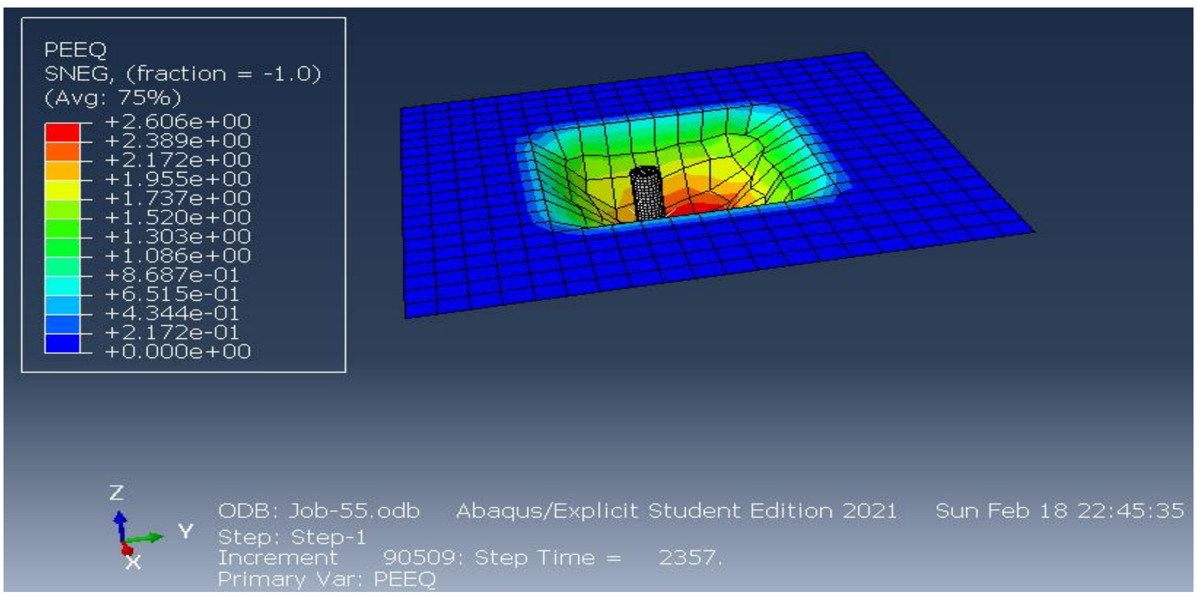
E2 (TD = 5mm, Step D = 0.8mm, SS = 1400rpm and FR = 450mm/min).

Appendix F-3



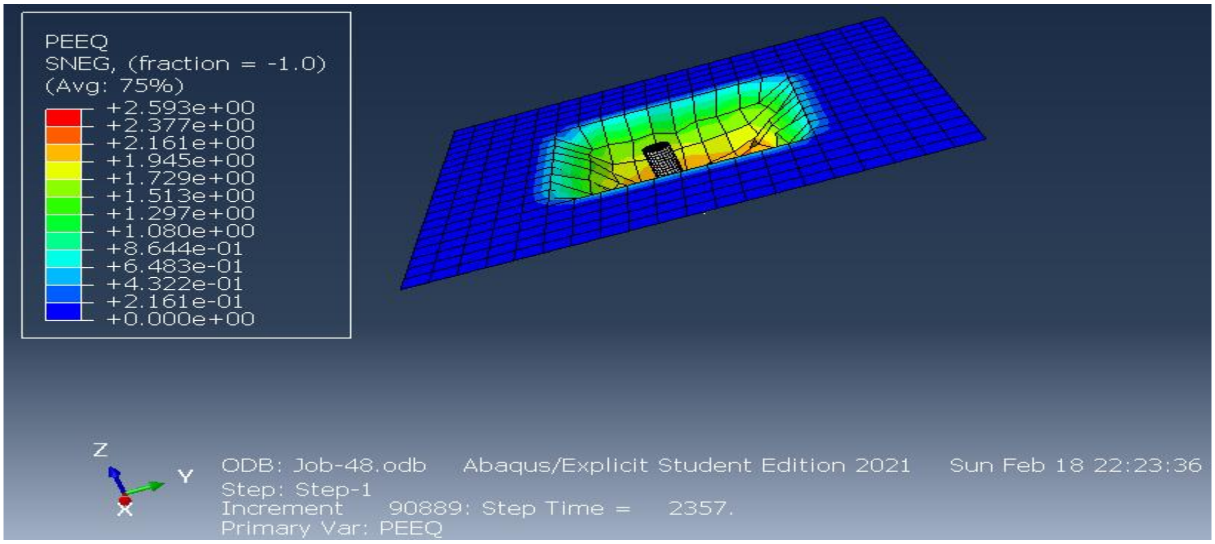
E3 (TD = 5mm, Step D = 1.2mm, SS = 1500rpm and FR = 600mm/min

Appendix F-4



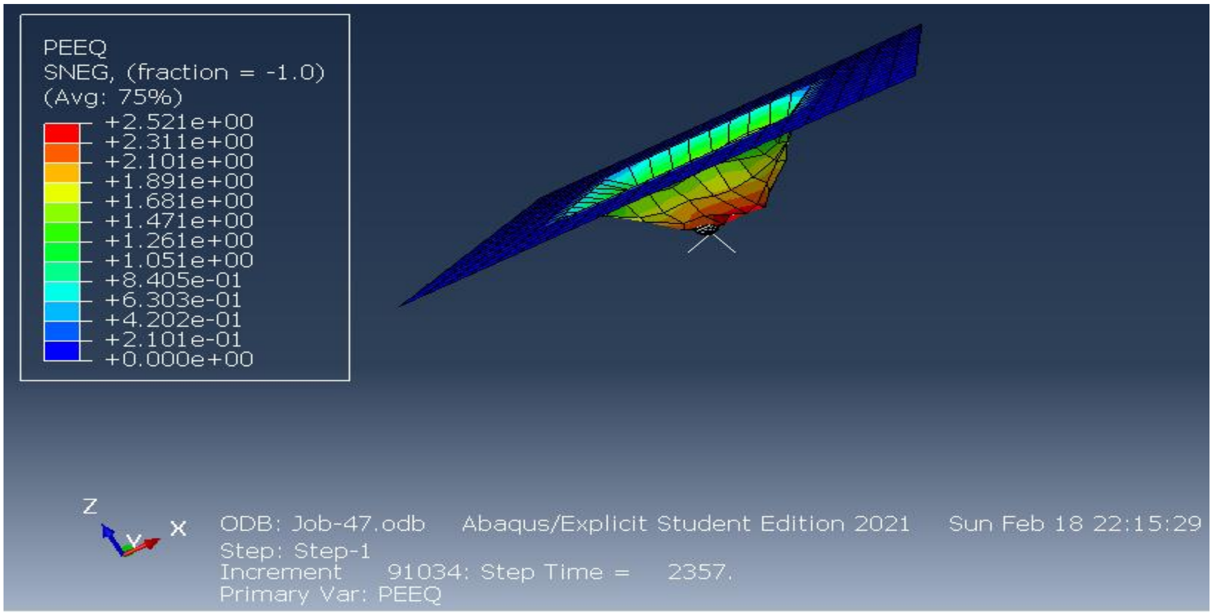
E4 (TD = 8mm Step D. = 0.4mm, SS = 1400rpm and FR = 600mm/min).

Appendix F-5



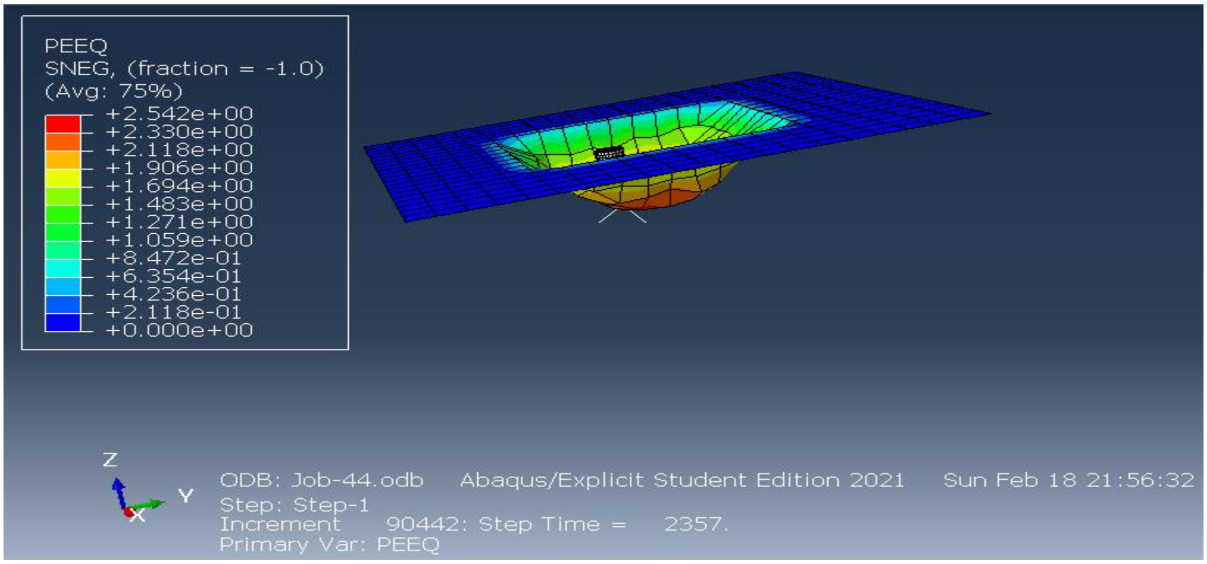
E5 (TD= 8mm, Step D. = 0.8mm, SS = 1500rpm and 300mm/min).

Appendix F-6



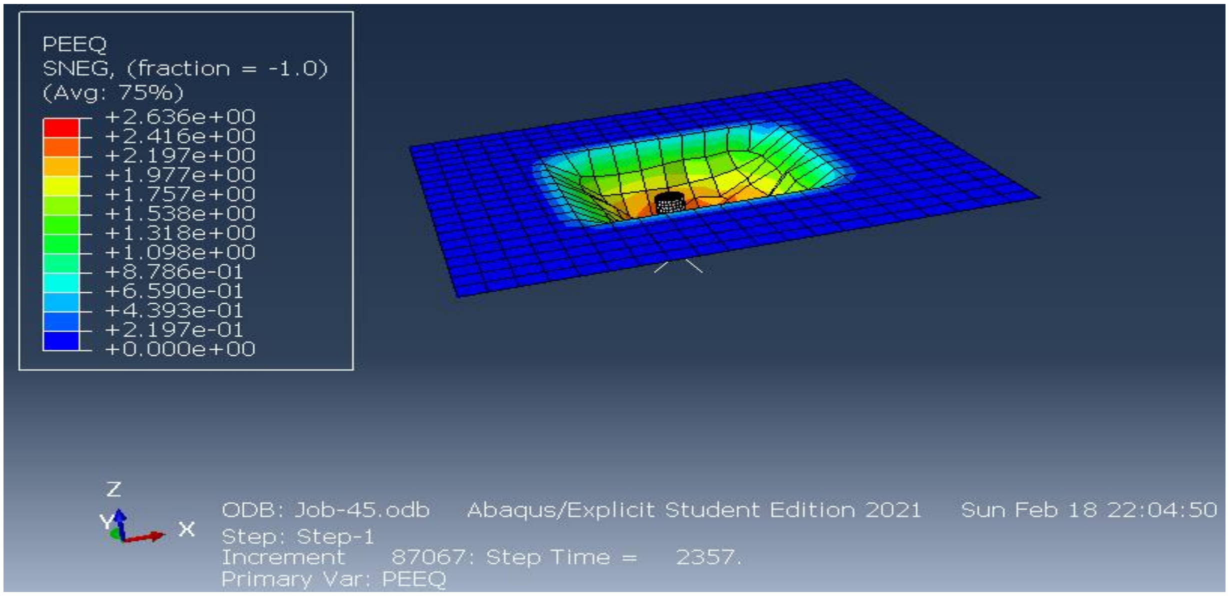
E6 (TD= 8mm, Step D. = 1.2mm, SS = 1300rpm and 450mm/min).

Appendix F-7



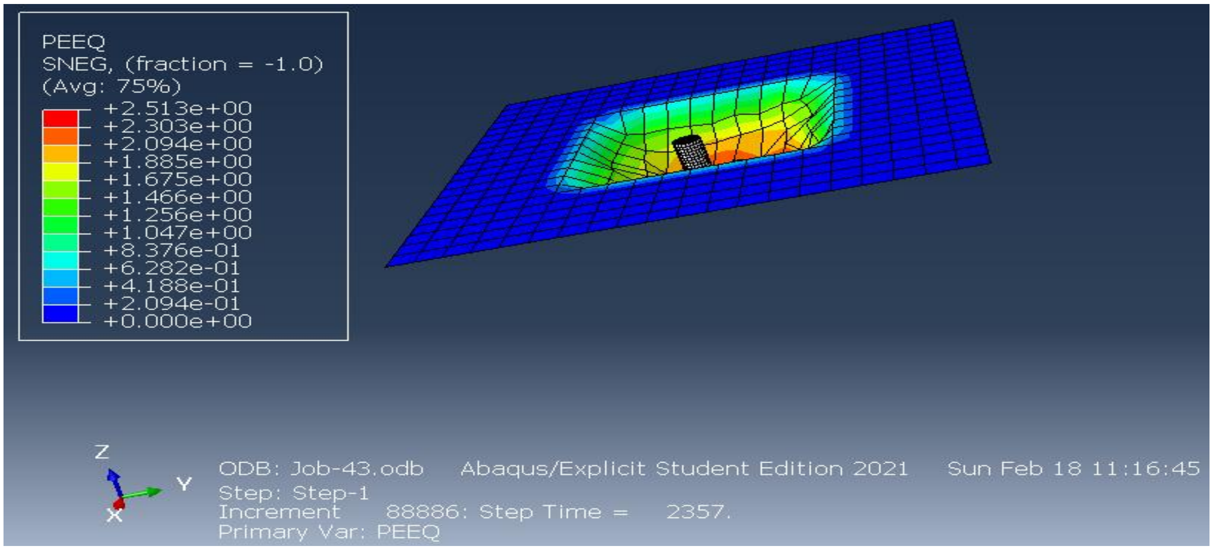
E7 (TD = 11mm, Step D. = 0.4mm, SS = 1500rpm and FR = 450mm/min).

Appendix F-8



E8 (TD = 11mm, Step D. = 0.8mm, SS = 1300rpm and FR = 600mm/min).

Appendix F-9



E9 (TD = 11mm, Step D. = 1.2mm, SS = 1400rpm and FR = 300mm).