Experimentation and Validation of Analytical Modeling and Finite Element Simulation of Different Metal Sheets Using Incremental Sheet Forming (ISF)

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ISLAMABAD

SEPTEMBER, 2022

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

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Declaration

I certify that this research work titled "*Experimentation and Validation of Analytical Modeling and Finite Element Simulation of Different Metal Sheets Using Incremental Sheet Forming (ISF)*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Acknowledgements

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought, for the sincere leadership of my supervisor, and for selfless friends. Indeed nothing happens but happens with Allah's "kun" and He, with no doubt is the creator of all.

I am profusely thankful to my beloved parents who raised me with love, care and sheer support. All I am today and whatever good I bring to this world would be the fruit of their guidance and teachings.

I would also like to express special thanks to my supervisor Dr. Shahid Ikramullah Butt for his help throughout my thesis and also for the courses like CIM and QRM which he has taught me. His confidence in me and his constant support, appreciation and guidance to manage my research in parallel with my job is extraordinarily commendable. Special gratitude to my GEC Members, Dr. Najam Ul Qadir, Dr. Hussain Imran and Dr. Aamir Mubashar for their cooperation and kindness. Mentors like them are a great source of motivation and knowledge for all of us at our department.

I would also like to pay special thanks to my friends Abdullah Pal, Hamza Majeed, Usama Tahir and Zubair Hassan for their tremendous support and cooperation. Each time I got stuck in something, they have rushed to my support. Without their help I wouldn't have been able to complete my thesis. Special token of gratitude to Hamza Majeed for his unconditional support in the development of the python based application for tool path. I owe you all a great deal. May Allah bless you all.

I would also like to thank Mr. Akseer, Mr. Waseem, Mr. Umar and Mr. Ghulam Abbas for their help in operating machinery, procuring materials, and helping me out with the paperwork and related formalities. They are true gentlemen at heart and hold a key role in the completion of my thesis.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my heroes, my parents, who have always supported me in my lows and cherished my achievements, and my beloved sisters, for the numerous coffees, snacks and bundles of motivation throughout those long study nights.

Abstract

An ever increasing demand of manufactured products calls for new manufacturing techniques that are cost effective and efficient. The global population is at an unprecedented rise and anticipating an increased demand for efficient, cheap and durable vehicles as well as automobile parts is nothing but obvious. With a population of over 216 million people, Pakistan stands 5^{th}in the global ranking population wise. The population boom in Pakistan is growing at the rate of about 1.8pc a year, which, when extrapolated to the year 2030, brings out a staggering figure of 240 million people. With little growth in the industrial sector of Pakistan, the local market is forced to import goods for the Pakistani consumer. This presents the businesses and manufacturers all over the world a great opportunity to attract a huge mass of potential buyers in the Pakistani market. However, being a struggling economy, the import culture immensely upsets the balance of imports and exports of Pakistan. The purpose of this research is to promote a cost effective means of manufacturing for the local firms in order to counter the huge influx of imports. Novel techniques will not only promote the culture of research and development in the country, but will also enable the local manufacturers to explore options to fulfil the demand in the local market and provide opportunities for indigenous talent to play their part in the economic development of the nation.

Single Point Incremental Forming (SPIF) is a relatively new technique of sheet metal forming. It is a die-less process that shapes the metal sheet in incremental steps for precision and accuracy. The process is relatively simple; a tool path is generated in accordance with the CAD model, the metal sheet is subjected to forming force via computer numeric controlled tool in presence of a lubricant. Once the tool completes its path, the sheet is formed in the desired shape. The materials used in this research are procured from the local market of Pakistan, hence suggesting the automakers over here to try new lines of manufacturing that uses indigenous materials to minimize imports.

This study is based on the incremental formability of two materials; Al 5083 and Low Carbon Steel (0.04% Carbon). Both materials are readily available in the local market. The research targets the results of ABAQUS simulations run on the aforementioned materials to experimentally verify them and see their applicability on the practical side.

Key Words: *Incremental sheet forming, single point incremental sheet forming, surface finish*

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

Incremental sheet forming is an emerging technique in the field of metal forming that has the potential to revolutionize rapid prototyping and die-less forming. This research has been done on single point incremental sheet forming. In this thesis, we will see how the simulated results and experimental work can be compared and how valid the simulated results are.

1.1 Background, Objectives and Motivation

The booming demand for efficient and cost effective manufacturing calls for research in versatile and agile techniques to develop and test newer designs that may prove helpful in better designs and increased efficiency. The design of experiments should be such that it can rapidly adapt to varying CAD models and provide immediate results. In the world of sheet metal forming, SPIF comes in handy. It is a fast, versatile, and precise process that eliminates the need to develop dies for complex and intricate parts. The process is performed at room temperature, with a spherical headed tool controlled by a CNC Machine. The flat sheet is clamped at a certain height, lubricant is applied and the tool travels a predefined path. The elimination of the need of a dedicated die substantially reduces lead times and cost of tooling and die preparation. The remarkable versatility of the process enables us to produce symmetric as well as asymmetric parts, with a wide range of sheet thicknesses.

1.1.1 Validation of ABAQUS Simulated Results

This research was aimed to validate and refine the results achieved via ABAQUS simulation on the parameters like step size and lubrication in the simulation. The simulation was done to find out the best parameters for ISF of locally available steel and aluminum that are also used for production of local automotive body panels. The scope of this research was limited to surface finish of the final product and the specimens were observed for their formability as well

1.1.2 Usage of Locally Available Material in Incremental Sheet Forming

When choosing the sources for this research, three factors were taken into account:

1) Application:

   Steel and aluminium are frequently used as materials in automotive body panels.

2) Formability

Aluminum is light in weight, has a good strength to density ratio, and is easily formed.

3) Market Availability

Materials used in this research are subject to their availability in the local Pakistani markets.

1.1.3 Organization of Report

This postulation is organised into five separate sections, including this presentation and a conclusion that highlights the key commitments and findings of the research as well as the suggested additional work in relation to this exposition.

The second section focuses on writing reports and includes a survey of the common gradual shaping techniques currently used in modern practise as well as an overview of continuous shaping cycles. It then introduces SPIF and provides recognisable evidence of practical applications as well as the boundaries that affect formability in single point incremental shaping.

Last but not least, we'll talk about the hypothetical basis of the SPIF cycle, with a focus on break limits, shaping cutoff points charts similar to the SPIF interaction, mathematical error connected with the profiles created through SPIF, and some rectification procedures for these in correctness.

CHAPTER 2: LITERATURE REVIEW

2.1 Metal Forming Processes

Forming is a shaping technique that neither requires addition or subtraction of material. Usually it is done on a prepared blank, which then undergoes a force via a tool and die. There are a number of metal forming methods in practice.

2.1.1 Hammering

One of the old forming methods that has been used for centuries is hammering. Modern day hammering is done using Computer Numeric Controlled Machines. A computer controlled actuator moves the tool according to user’s input on the work piece that is clamped in a frame, in a round path, going step by step down the Z axis. [1]

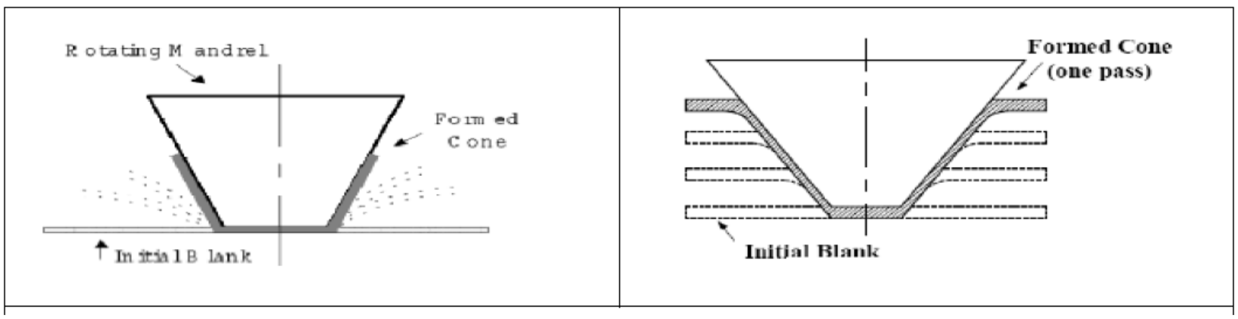


Figure 1 Hammering

2.1.2 Deep Drawing

Deep drawing is a metal framing process in which a device applies descending force to a sheet metal and pushes the sheet, constraining it into a die depression looking like the ideal part. The sheet is plastically distorted into a cup molded part by the tensile force applied by the instrument. The profundity of a deep drawn part is typically the greater part of the breadth of the part. Albeit barrel shaped or rectangular parts are the most widely recognized deep drawn parts, these parts can likewise have different cross segments with straight, tightened or even bended walls. Flexible metals like aluminum, metal, copper and gentle steel are best for deep drawing. Deep drawn parts are most utilized in car bodies and gas tanks, making cups, jars, kitchen sinks, pots, dish and some more.

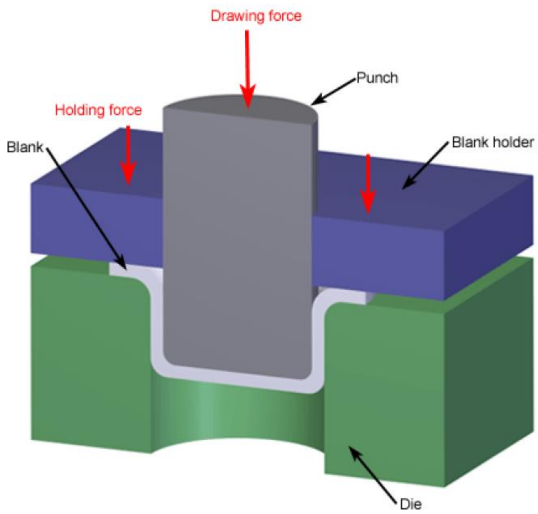


Figure 2 Deep Drawing

The deep drawing technique incorporates a clear, clear holder, punch and a die. The clear is a piece of sheet metal which is by and large circle or rectangular shape, that bears the tensile force and plastically disfigures into the ideal part. A device called punch utilizes the pressure driven force to apply sufficient force to the clear, extending it into the die pit. As the die and punch both experience wear during this cycle, so they are produced using carbon steel or device steel. This course of drawing parts should be possible through a progression of tasks, called draw decreases. In each step, the punch presses the part into various die, extending the part to more noteworthy profundity each time. After a section is totally drawn, the punch and clear holder can be raised, the part can be eliminated at long last and the flanged part around the drawn part could be managed off.

2.1.3 Spinning

The most common way of forming sheet metal into a tube shaped part by pivoting the sheet metal piece and applying forces aside, is known as spinning or spin forming. There is a

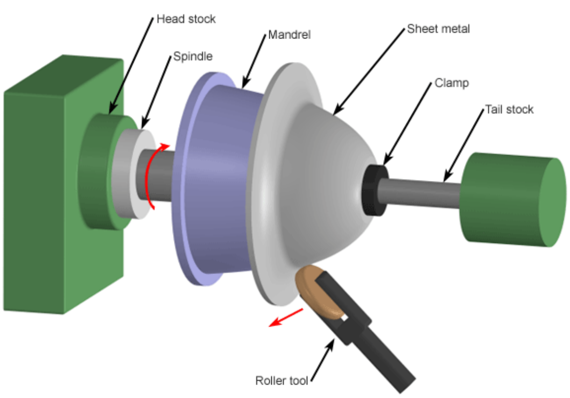


Figure 3 Spinning

roller tool that presses the quick spinning metal plate against a tool called mandrel, to frame the ideal shape as displayed in Figure. One extraordinary benefit of this strategy is that the turned metal parts have a rotationally even empty shape, that are utilized in mechanical fields like satellite dishes, hubcaps, rocket nose cones and utilized in cookware and instruments as well.

Commonly, this strategy is performed on a manual or CNC machine and the essential prerequisites is a clear, mandrel and roller tool. Here, clear means the sheet metal which is cut into plate molded entirely appropriate shape for this forming technique. Mandrel is a strong aspect which looks like the ideal part, against which the clear will be squeezed. At times, multi-piece mandrels are utilized for the perplexing parts. Since the mandrel doesn't encounter a lot of wear during spinning, wood or plastic mandrel could likewise be utilized. However, for the high-volume creation, metal mandrel is utilized overall. The head stock and tail stock braces mandrel and board together. Then, at that point, the spindle begins the revolution and makes mandrel and clear to turn along. During this revolution, tool applies force to the clear sheet, making it twist and structure around the mandrel. By and large, this tool is a roller wheel joined to a switch. These rollers which are economical and experience little wear, can be accessible in various breadths and thickness, and are typically produced using steel or metal.

2.1.4 Stretch Forming

Stretch forming is a metal forming process in which sheet metal is stretched and twisted all the while supporting over a die to shape an enormous molded part. As displayed the Figure, stretch forming is performed on a stretch press, which contains grasping jaws that holds the sheet metal safely along its edges. Holding jaws, which are appended to the carriage, are arranged fully backed by pneumatic or hydraulic force, so the sheet could be stretched. A strong molded piece

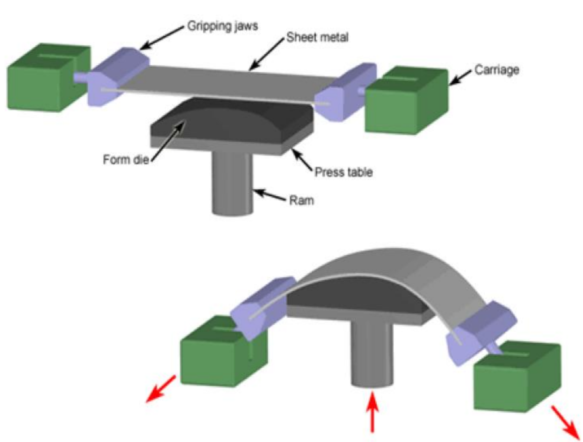


Figure 4 Stretch Forming

known as structure die, is utilized to help the sheet metal while stretching. Typically, the vast majority of the stretch forming presses is situated upward, in which the structure die is put on a press table that can be effortlessly raised into the sheet by a hydraulic ram.

As the structure die applies vertical force onto the firmly braced sheet, the tensile force increments, and the calculation of the sheet is altered. Stretched shaped parts are ordinarily huge and have enormous sweep twists. Assortment of shapes can be created from this technique from a straightforward bended surface to a non-uniform cross segment. Stretch forming is fit for molding leaves behind high precision and smooth surfaces. Malleable materials like aluminum, prepares, and titanium are ideal for this strategy. The stretched part, framed from this strategy, are normally enormous which are utilized for huge primary part, for example, entryway boards in vehicles or wing boards on airplane.

2.1.5 Stamping

Hard tools are typically used to complete specialised tooling in stamping processes. These cycles, which are either carried out in a single die station or a different die station, are typically associated with the production of parts in high volumes. Mechanical presses and

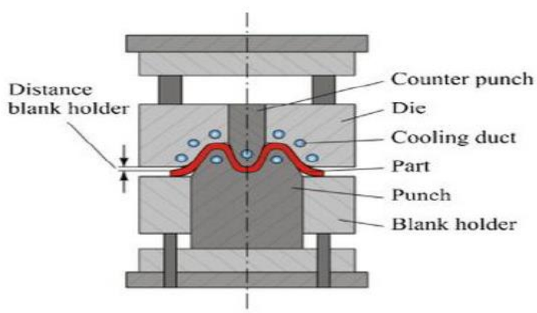


Figure 5 Stamping

hydraulic presses are two ways that the stepping gear can be arranged.

Mechanical presses have a mechanical flywheel which stores the energy and afterward move it to punch to shape the part. They range in size from 20 tons as much as 6000 tons. Strokes range from 5 to 500 mm (0.2 to 20 in) and speeds from 20 to 1500 strokes each minute. Mechanical presses are appropriate for fast blanking, shallow drawing and for making accuracy parts where as Hydraulic presses use hydraulics to convey a controlled force. Weight can change from 20 tons to 10,000 tons. Strokes can differ from 10 mm to 800 mm (0.4 to 32 in). Hydraulic presses are appropriate for profound drawing, compound die activity as in blanking with forming or begetting. One of the detriments of this cycle is the high tooling cost as to expand the tool or punch life it must be continually honed alongside the expense connected with the die which builds the general tooling cost.

2.2 Single Point Incremental Sheet Forming

With the rising speed of improvement and acquaintance of new items with the market reasonable for the client's cravings, it is important to get into the worldwide tension of contest. Through a rising number of advancements, subsequently decreasing time and expenses of assembling prototypes, one can deal with the modern contest. Today, sheet metal forming requires conclusive techniques since it's about monetarily valuable as well as assembling excellent useful and adaptable parts which are challengeable however vital. These days, when we take a gander at the pattern in auto creation, more complicated and complex part calculations are made and requires a quicker presentation of new items utilizing sheet metal prototypes. Also, the interest of new imaginative items that is producible just in little part estimates, is expanding.

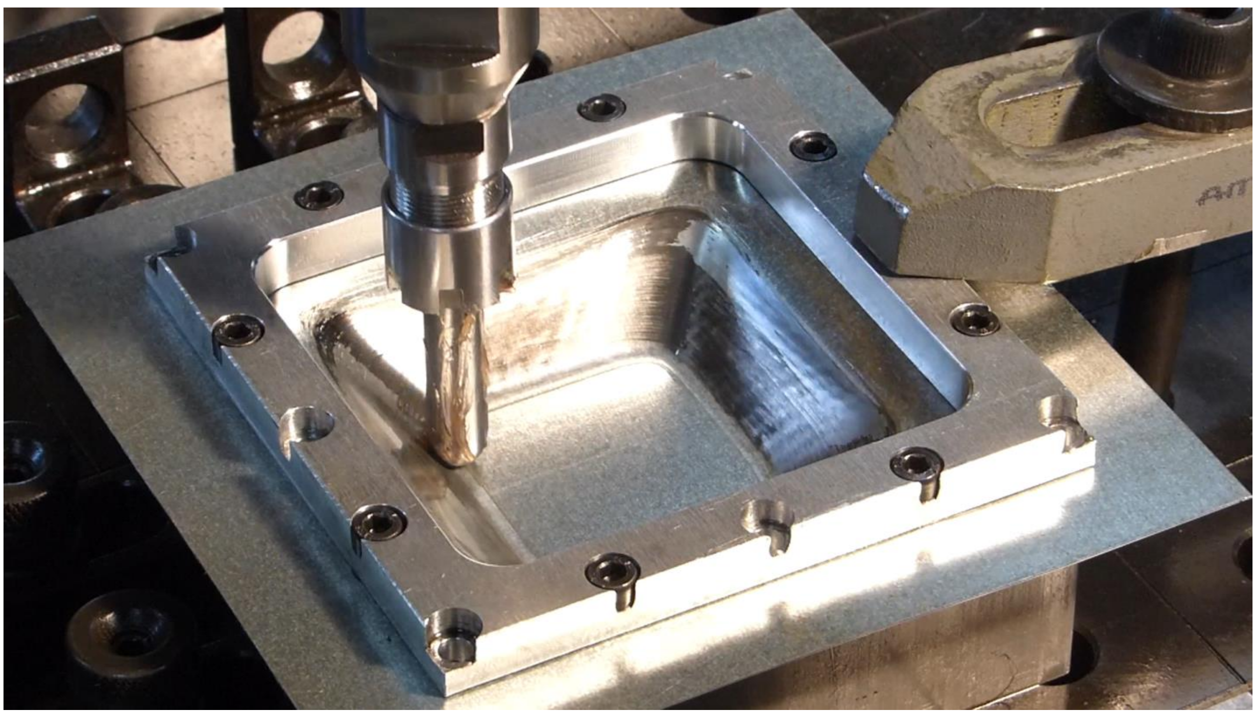


Figure 6 Incremental Sheet Forming

Utilizing a multi-axis CNC milling machine and a tool with a hemispherical tip is part of the SPIF forming process. Due to computer-aided forming, SPIF can frame both axis symmetric and asymmetric structures, unlike its close relatives, shear forming and spinning. With this method, a few advantages are acknowledged successfully. This interaction is very adjustable because to its die-less nature, simple forming rig, and use of non-exclusive hemispherical forming tools. The size of the forming tool, the item being framed, the desired level of surface smoothness, and other factors might affect efficiency and cycling time, making this a low volume manufacturing approach.

2.2.1Key Forming Parameters:

Literature tells us that impacts of process parameters like tool shape, tool size, step size and lubrication are huge on surface roughness of the parts. Besides, this die-less cycle is as yet restricted in manufacturing industry because of absence of data about the factors that affect the process. Information about the cycle factors is expected to get which would assist the process with designing to carry out SPIF in modern area.

Moreover, parameters like sheet material, and tool path have a substantial effect on the process of Single Point Incremental Sheet Forming

2.2.2 Sheet Material:

Formability varies among materials and a study by Fratini et al attempted to lay out the impact of common material properties on formability. From their review, they found that the strain hardening coefficient (n) as well as the cooperation between the strength and strain hardening coefficients (K.n), had the most elevated impact on formability. This study showed that strain hardening coefficient, which contrasts significantly between materials, affected formability. By and large, higher hardening coefficient will have higher formability. [2]

2.2.3 Tool Selection

Hemispherical, The tip of the tool is tungsten carbide [3]

2.2.4 Tool Shape

In his research, Kumar P et al concluded that when the tool shape was changed from FlatEnd-R1 to Hemispherical, average roughness (Ra) decreased approximately to 28.34% for 7.52mm, 40.38% for 11.60mm and 47.05% for 15.66mm.

2.2.5 Tool Size:

Cavalar et al showed in their study that tool diameter has a significant effect on surface roughness; it decreases with increase in tool diameter. [4]

2.2.6 Lubrication:

Lubricants are another affecting variable for the ISF interaction. Grease is exceptionally fundamental part in ISF strategy for giving tools a more extended life by minimizing, if not eliminating grating and wear, further developing intensity dispersion and eliminating waste materials. There are assortment of lubricants in high endlessly number of unmistakable items with various attributes, some of which are likewise displayed in the table given. R. Alves de Sousa with his colleagues researched the effect of different lubricants in ISF explicitly for steel (hard metal) and aluminum (soft metal). [5]

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

Table 1 List of Lubricants

2.2.7 Step Size:

Some of the papers researched in this thesis conclude that surface quality of the work piece increased with a decrease in step size, yet it does not affect the formability of the blank. On the other hand, other researches claim that the step size significantly affects the formability of the sheet used and formability decreases with an increase in step size. Hagan tried different step increase for aluminum (AA 3003) with one replication of each analysis. They found that a smaller step size increases surface finish. Bhattacharya et al. tried different step increase on aluminum (Al 5052). They analyzed that increasing the step size resulted in rougher surfaces up to specific levels. [6]

2.2.8 Feed Rate:

Feed rate is an important forming parameter which includes the rotational speed of the tool as well as the lateral feed rate. Higher feed rates may increase formability, but they can lead to lower quality surface finishes, increased tool wear and lubricant film break down. Moreover, higher spindle speeds can result into waviness in the surface and lead to chatter marks. [7]

2.2.9 Applications of SPIF

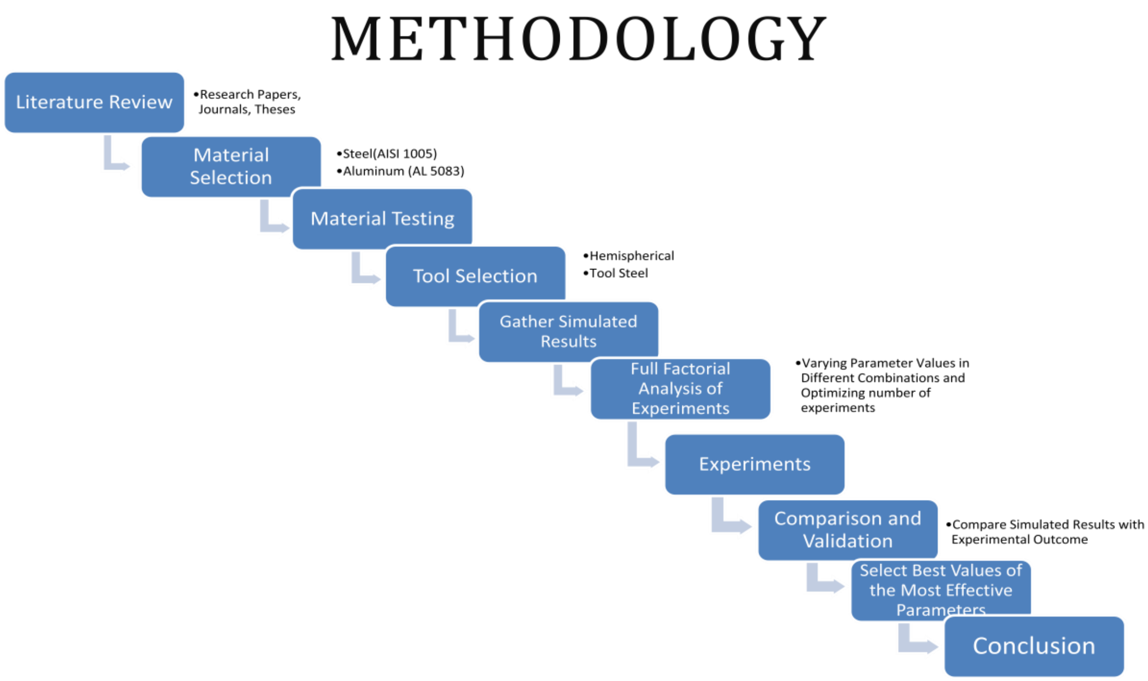
Incremental sheet forming offers a great advantage for small batch productions as it requires no dies. Moreover, it can be used to produce parts with intricate designs which are harder to achieve with other methods like deep drawing etc. The basic idea of using this technique is to develop a tool path straight from the CAD model or an application based tool path and implement it on the blank without any other steps involved in production.

Therefore, incremental sheet forming has a wide range of applications in rapid prototyping, die formation in the automobile and aerospace industries and for fields where parts are needed within low tolerances which would be difficult to achieve otherwise like medical and surgery. [8]

CHAPTER 3: METHODOLOGY

The methodology designed to carry out this research was initiated with a literature review, comprising of research papers, articles and theses in the field of metal work. Different forming techniques related to single sheet forming and tailor welded blanks was studied. Moreover, requisites of effective forming which include CNC programming, tool path generation, tool material, tool shape, tool size, blank thickness, blank material, fixture and lubrication were studied and formulated throughout the process of research.

A general overview of the methodology has been exhibited in the following flowchart:



3.1 Selection of Experimental Parameters

3.1.1 Step Size

In the scope of ISF, step size counts for the distance the tool is supposed to move in the negative z direction after completing one full cycle of tool path according to the design. In our case, the design was of a truncated cone, therefore the tool was supposed to move a step downwards after moving in a rectangular path once.

3.1.2 Feed Rate

Feed rate determines the speed of tool movement along the x and y axes to complete the forming cycle and create a truncated cone in our case. As found in the literature, the ideal feed rates for the selected tool shape and size were chosen for experimentation. [9]

3.1.3 Lubrication

Lubricaction plays a key role in the surface finish of the formed part. Moreover, it reduces tool wear, allows the part to dissipate heat and improves the overall quality of the work piece. SAE-30 is an easily available lubricant that has provided good results in ISF.

3.2 Optimization of Iterations

The experiments carried out in this research used 9 iterations of possible combinations of 3 different step sizes and feed rates for Aluminum and Steel each while keeping the lubricant constant. The lubricant was chosen based on the best results in ISF and ease of availability in the market in light of the literature review carried out. [10]

The following tables show the L9 factorial analysis for AA 5083 Aluminum and AISI 1005 Steel blanks using the step sizes from the simulations carried out in Abaqus in *Analytical Modeling and Finite Element Simulation of Aluminum and Steel sheet using Incremental Sheet Forming(ISF)* by Abdullah Pal.

Orthogonal L9 factorial analysis (for AA-5083)			
Experiment No.	Step Size	Feed Rate	Lubrication
1.	0.20	1000	SAE-30
2.	0.20	1100	SAE-30
3.	0.20	1200	SAE-30
4.	0.25	1000	SAE-30
5.	0.25	1100	SAE-30
6.	0.25	1200	SAE-30
7.	0.3	1000	SAE-30
8.	0.3	1100	SAE-30
9.	0.3	1200	SAE-30

Table 2 DOE for AA-5083

Orthogonal L9 factorial analysis (for AISI 1005)			
Experiment No.	Step Size	Feed Rate	Lubrication
1.	0.3	1000	SAE-30
2.	0.3	1100	SAE-30
3.	0.3	1200	SAE-30
4.	0.4	1000	SAE-30
5.	0.4	1100	SAE-30
6.	0.4	1200	SAE-30
7.	0.5	1000	SAE-30
8.	0.5	1100	SAE-30
9.	0.5	1200	SAE-30

Table 3 DOE for AISI 1005

3.3 Prerequisite Testing

3.3.1 Spectrography

After a thorough literature review and market survey, the material procured from the market was tested [11] and the results declared the chemical composition of steel and aluminum. The results are shown in the tables below:

Chemical Composition of AA 5083 Aluminum	
Element	Percentage
Aluminum (Al)	94.01
Silicon (Si)	0.4
Iron (Fe)	0.4
Copper (Cu)	0.5
Manganese (Mn)	4.2
Magnesium (Mg)	0.25
Titanium (Ti)	0.15
Chromium (Cr)	0.09

Table 4 Spectroscopy Resuts for AA 5083

Chemical Composition of AISI 1005 Steel	
Element	Percentage
Iron (Fe)	99.5
Manganese (Mn)	0.35
Carbon (C)	0.60
Sulphur (S)	0.50
Phosphorus (P)	0.40

Table 5 Spectroscopy Results for AISI

3.3.2 ASTM E290 3 POINT BEND TEST

3 Point bend tests help find out the bending forces at a single point while the blank is leveled between two point supports. This helps us find out the force and displacement at which the specimen goes from elastic to plastic deformation. Unguided bend tests were carried out for both materials. [12]

The 3 point bend test report for Aluminum is given in the table below:

LengthMode	Position
Test Type	Bending
Operator	Taqveem
Shape	bend3p_flat

Mat.Name	Aluminum
Test Date	20210914
Mat.Type	AA 5083
Time Used	396.28
Test Standard	ASTM 290
Speed mm/min	3
Fmax N	104.3395
Area mm²	0.2509843
Eb MPa	56137.72
Elastic Rate	12.28447
F@elas N	1.044459
Fbreak N	103.616
Fpb0.01 N	71.46568
Fpb0.02 N	75.27321
Fpb0.05 N	82.99461
Fpb0.1 N	89.2025
Fpb0.2 N	95.87184
Fpb0.5 N	102.9647
I	4.78125
Len At Fmax mm	18.31702
Lbreak mm	19.87436
Le mm	100
Lmax mm	19.87436
Lo mm	1146.951
Load Cell Rate N	100000
Ls mm	101.6
PreLoad N	0
Rbb MPa	415.7215
Rpb0.01 MPa	284.7417
Rpb0.02 MPa	299.9121
Rpb0.05 MPa	330.6766
Rpb0.1 MPa	355.4107
Rpb0.2 MPa	381.9835
Rpb0.5 MPa	410.2436
Thick mm	1.5
W	6.375

Width mm	17

Table 6 Report of 3 Pt. Bend Test of AA 5083

The following figure exhibits the force-displacement curve of the 3 point bend test carried out for AA 5083:

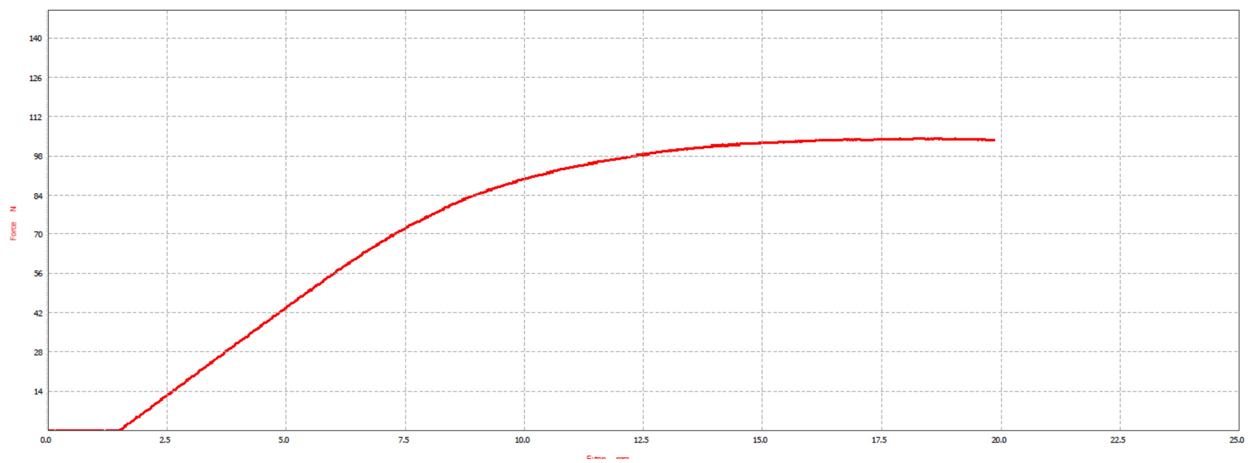


Figure 7 Force DIsplacement Graph of 3 Pt. Bend Test of AA 5083

Similarly, the test report for 3 point bend test of AISI 1005 is as follows:

LengthMode	Position
Test Type	Bending
Operator	Taqveem
Shape	bend3p_flat
Mat.Name	STEEL
Test Date	20210914
Mat.Type	AISI 1005
Make Date	2021-09-14
Time Used	398.64
Temp ℃	0
Humi %	0
Speed mm/min	3
Fmax N	143.9113
Area mm^2	0.2559055
Eb MPa	237917.7
Elastic Rate	35.38915
F@elas N	1.477435
Fbreak N	140.8538
Fpb0.01 N	73.02098

Fpb0.02 N	95.00969
Fpb0.05 N	120.8268
Fpb0.1 N	132.1696
Fpb0.2 N	136.8963
Fpb0.5 N	140.8994
I	3.25
Len At Fmax mm	18.19099
Lbreak mm	19.99315
Le mm	100
Lmax mm	19.99315
Lo mm	1720.427
Load Cell Rate N	100000
Ls mm	101.6
PreLoad N	0
Rbb MPa	562.3609
Rpb0.01 MPa	285.3435
Rpb0.02 MPa	371.2686
Rpb0.05 MPa	472.154
Rpb0.1 MPa	516.4783
Rpb0.2 MPa	534.9486
Rpb0.5 MPa	550.5916
Thick mm	1
W	6.5
Width mm	39

Table 7 Report of 3 Pt. Bend Test of AISI 1005

And the forced-displacement graph of the aforementioned test is as follows:

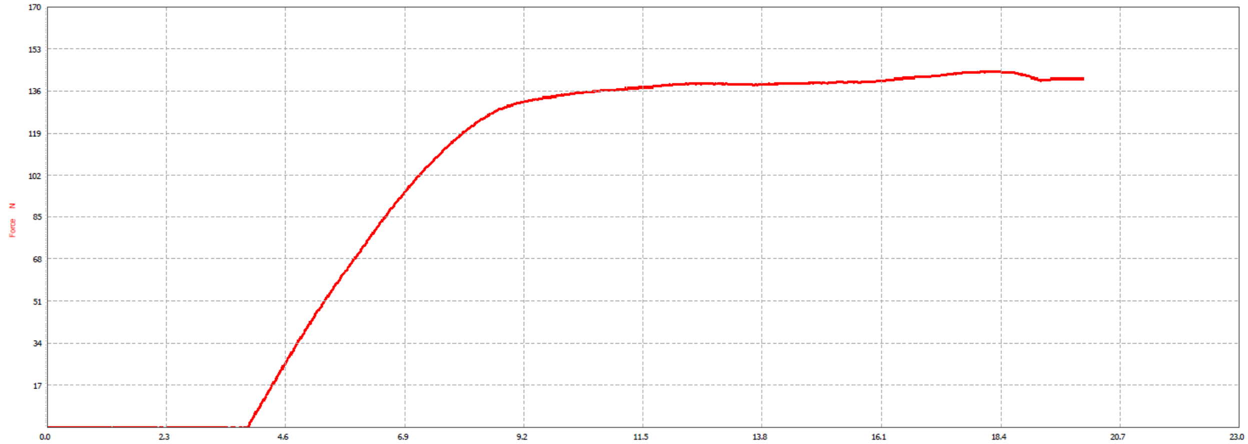


Figure 8 Force Displacement Graph of 3 pt. Bend Test of AISI 1005

3.4 GENERATION OF TOOL PATH

Generation of tool path was a key aspect to look into for the process of experimentation. In different controllers in various CNC machines, selection of controller is extremely important for the generation of accurate tool path. In order to assure that the tool follows the exact path designed to form a truncated cone, a dedicated python based application was developed.

The source code of the file is as follows:

```
print('Program to Write G and M codes for incremental sheet forming of frustum on CNC machine \n\nEnsure all units in mm\n\nPlease ensure the presence of taees.txt file in the code directory')
x = input('enter max required value in X-AXIS: ')
y = input('enter max required value in Y-AXIS: ')
z = input('enter max required Depth in Z-AXIS: ')
s = input('enter X,Y-step value: ')
d = input('enter Z-Step value: ')
try:
    x=float(x)
    y=float(y)
    z=float(z)
    s=float(s)
    d=float(d)
except:
    print('invalid input, Kindly restart')

handle = open('taees.txt','w')

a = "0"      #X0
b = "0"      #Y0
```

```
c = d
x=str(x)
y=str(y)
z=str(z)
s=str(s)
d=str(d)

#Round 1 (Complete box)__________________________________________________________________

handle.write("M03 S1000 F400\nG71 G90\nG00 X0 Y0 Z20\nG01 Z-"+d)
handle.write("\nG01 X"+a+" Y"+y)
handle.write("\nG01 X"+x+" Y"+y)
handle.write("\nG01 X"+x+" Y"+b)
handle.write("\nG01 X"+a+" Y"+b)      #Box Complete

handle.write("\nG01 X"+s+" Y"+b)      #back to X0 plus S

#Round 2 (Internal Loop)__________________________________________________________________

x=float(x)
y=float(y)
z=float(z)
s=float(s)
d=float(d)
a=float(a)
b=float(b)
c=float(c)
a=a+s

while abs(c) <= abs(z):

   y=y-s
   a=round(a,3)
   a=str(a)
   y=round(y,3)
   y=str(y)
   handle.write("\nG01 X"+a+" Y"+y)
   x=x-s
   x=round(x,3)
   x=str(x)
   handle.write("\nG01 X"+x+" Y"+y)
   b=b+s
   b=round(b,3)
   b=str(b)
```

```
    handle.write("\nG01 X"+x+" Y"+b)
    a=float(a)
    a=a+s
    a=round(a,3)
    a=str(a)
    handle.write("\nG01 X"+a+" Y"+b)         #Back to Origin plus step

    a=float(a)
    y=float(y)
    x=float(x)
    b=float(b)



    c=c+d
    c=round(c,3)
    c=str(c)
    handle.write("\nG01 Z-"+c)              #Depth increased, ready for next loop
    c=float(c)

handle.write("\nM05 M30")
```

Upon running this application, the program asks the user for maximum dimensions in x and y axes and the maximum depth to be achieved in the negative z direction. Moreover, the variables like decrement in x and y axes and feed rate are also taken from the user.
The user interface of the developed application is as follows:

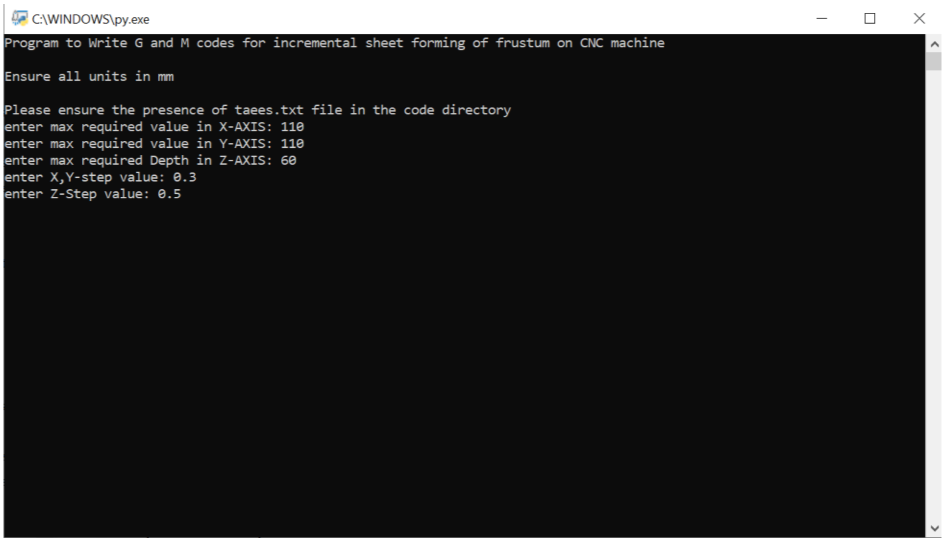


Figure 9 User Interface of App for Tool Path Generation

In order to observe if the tool was following the correct path as per design, a simple tool path simulator named Camotics was used. It gave a visual representation of how the tool formed its trajectory over the blank and what to expect of the final outcome. This helped in fine tuning the research and make required modifications to avoid accidents.

Tool Path at different step sizes in negative z and decrements along x and y axes can be seen in the figures below:

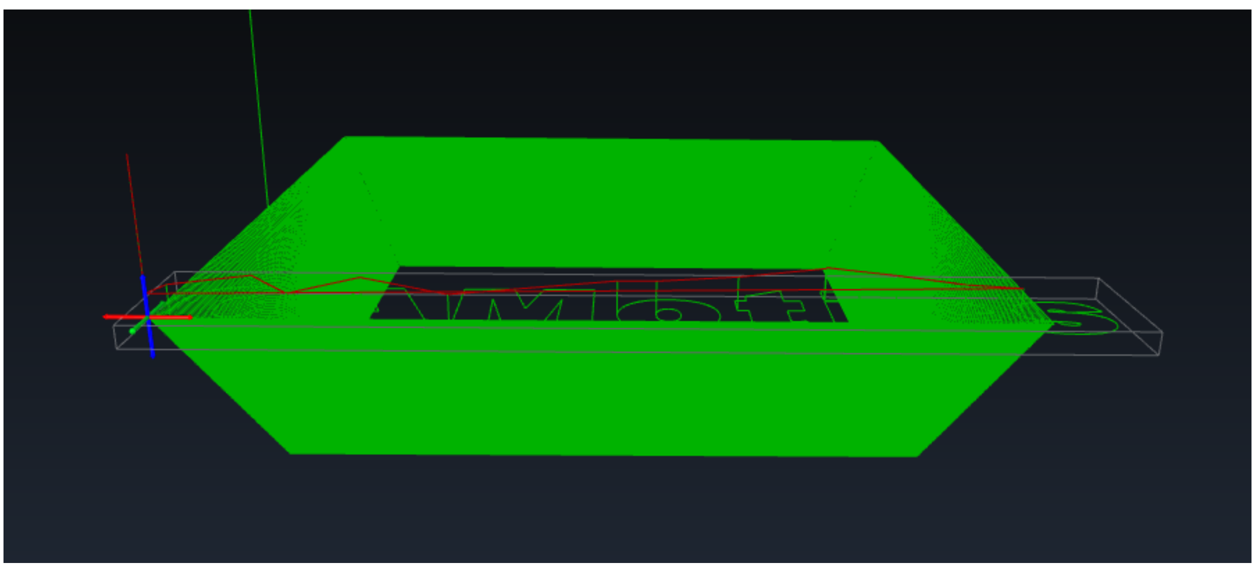


Figure 10 Tool Path with -0.1 in x.y and -0.2 step size in z

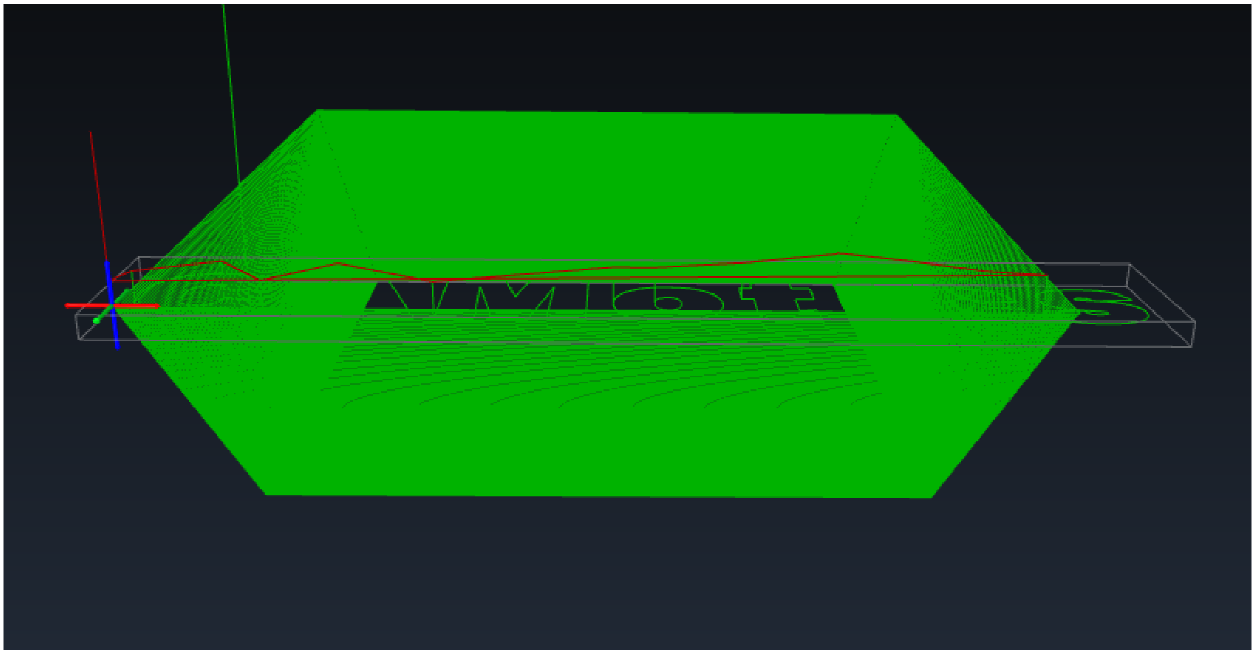


Figure 11 Tool Path with -0.1 in x.y and -0.25 in z

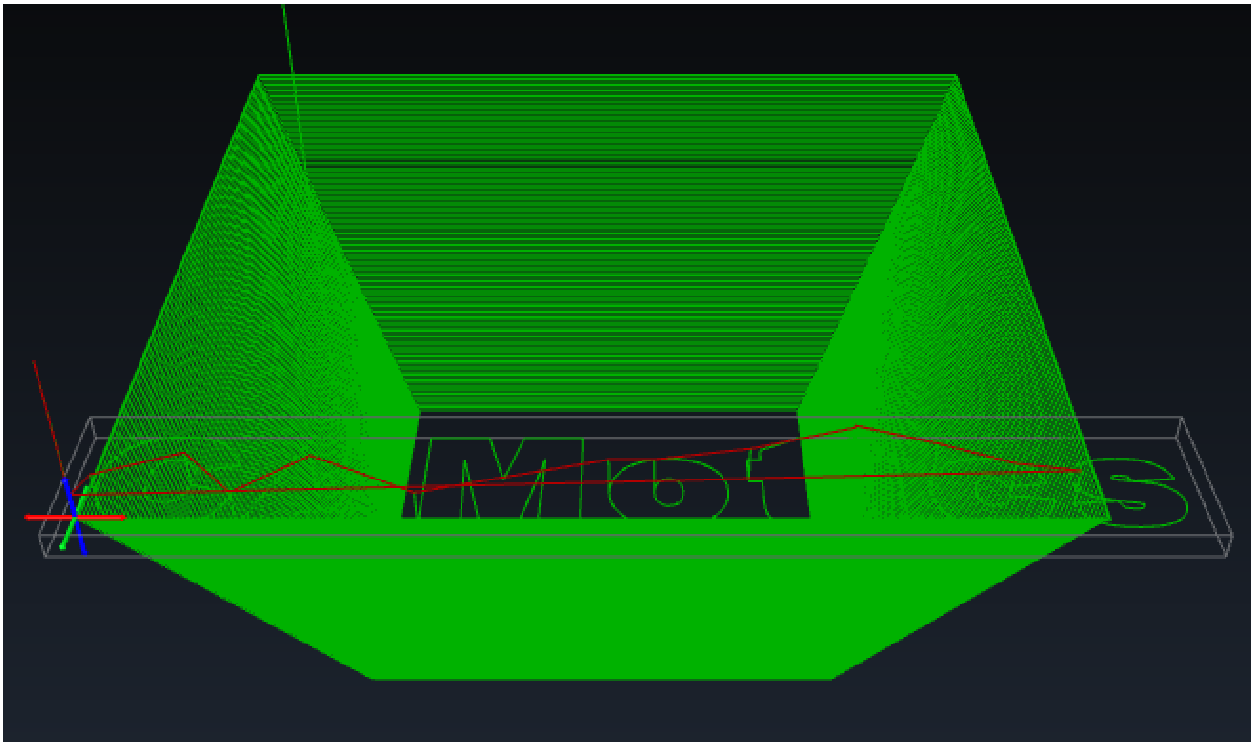


Figure 12 Tool Path with -0.2 in x,y and -0.4 in z

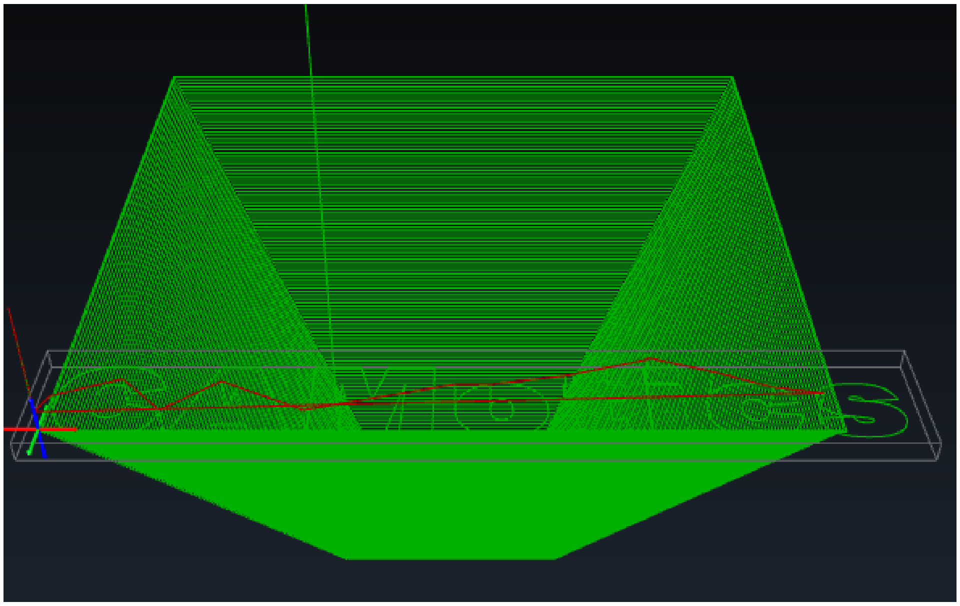


Figure 13 Tool Path with -0.3 in x.y and -0.5 in z

3.5 Experimental Setup:

3.5.1 Computer Numeric Controlled Machine

The experiments were carried out on MV-1060 3 axis CNC Milling Machine. The said machine was available in the School of Mechanical and Manufacturing Engineering, National University of Science and Technology, Islamabad. The machine takes coordinates value upto three decimal points and therefore, the program for the ISF needed to have coordinates rounded off to the lowest number decimal points.

Figure 14 MV-1060 CNC Milling Machine

3.5.2 Forming Tool

3.5.2.1 Tool Shape:

The shape of the tool used in this research was hemispherical. According to the literature review, rounded tipped tools performed best for better surface finish, minimum tool wear and reduced friction.

3.5.2.2 Tool Material:

Available and cost effective material for the AISI 1005 and AA-5083 was tool steel. Therefore, tool steel was used to carry out the experimentation.

3.5.2.3 Tool Size:

To ensure the desired step sizes were easily achieved, 10 mm diameter tools were used. [13]

Figure 15 Hemispherical 10mm dia Tool

3.5.3 Lubrication

In the experiments performed for this research, SAE-30 was used as a lubricant since it has a friction coefficient of 0.37 and its performance and cost effectiveness has been demonstrated in the articles and papers studied.

3.5.4 Fixture

Fixture is a key component in single point incremental sheet forming to clamp, support and allow the tool to move according to the design on the blank sheet during forming.[14] The fixture comprised of two 10 mm thick steel plates. The upper plate had a pocket of 140x140mm, while the lower plate had a 130x130mm pocket for tool movement.

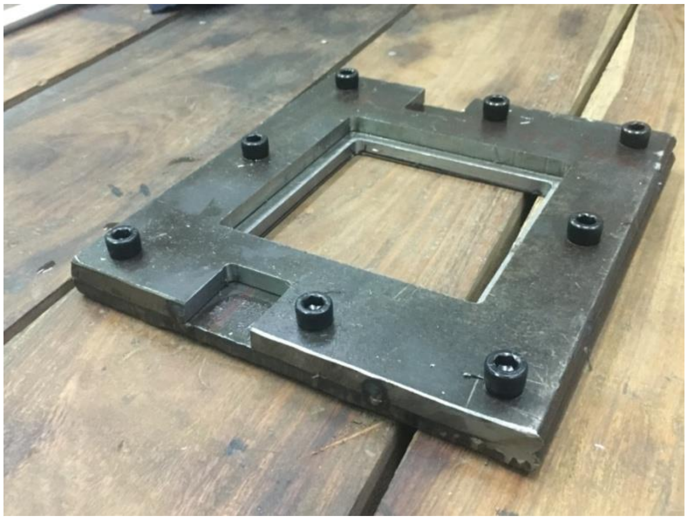


Figure 16 Fixture for Incremental Sheet Forming

The upper plate was drilled with eight 10.5mm holes while the lower plate was tapped with 8.5 mm holes with a pitch of 1.5 mm.
Both plates of the fixture were fastened with 10mm allen key bolts and the upper plate had two more pockets of 35mm each on opposing sides for clamping.

3.5.5 Metal Sheets

The sheet materials for ISF were AA 5083 and AISI 1005. The blank dimensions were 120x120mm. AISI 1005 sheets were 1mm thick while AA 5083 sheets were 1.5mm thick.

3.5.6 Olympus Digital Microscope Model DSX 1000

Olympus Digital Microscope was used for the study of surface roughness of the formed specimen.

- Roughness is just the average height above and below the reference line, therefore, bigger the R_a number, the more rough the surface is.

- Roughness is a good indicator of the potential performance of a mechanical component, since irregularities on the surface may form nucleation sites for cracks or corrosion

Figure 17 Olympus Digital Microscope Model DSX 1000

3.5.7 G Codes for Experiments

There were 18 codes in total that were generated for different sets of parameter values for AA-5083 and AISI-1005 blanks; consisting of 9 experiments each as per the aforementioned DOE.

3.4.7.1 G Code for Incremental Sheet Forming in Truncated Cone Shape

G codes for incremental sheet forming in truncated cone shape for both AA 50983 and AISI 1005 were generated through the python based application developed for this research. A typical G Code for this process can be seen in the annexure.

CHAPTER 4: RESULTS AND DISCUSSION

The sheet metal blanks were formed using the aforementioned experimental setup using the parametric combinations from the L9 Orthogonal Array. During the experiments, the Aluminum sheets did not bear the load of tool and failed at all the suggested step sizes from the simulation. However, the AISI-1005 blanks were formed successfully and the results are shown in the exhibit.

Figure 18 Formed AISI 1005 Specimen

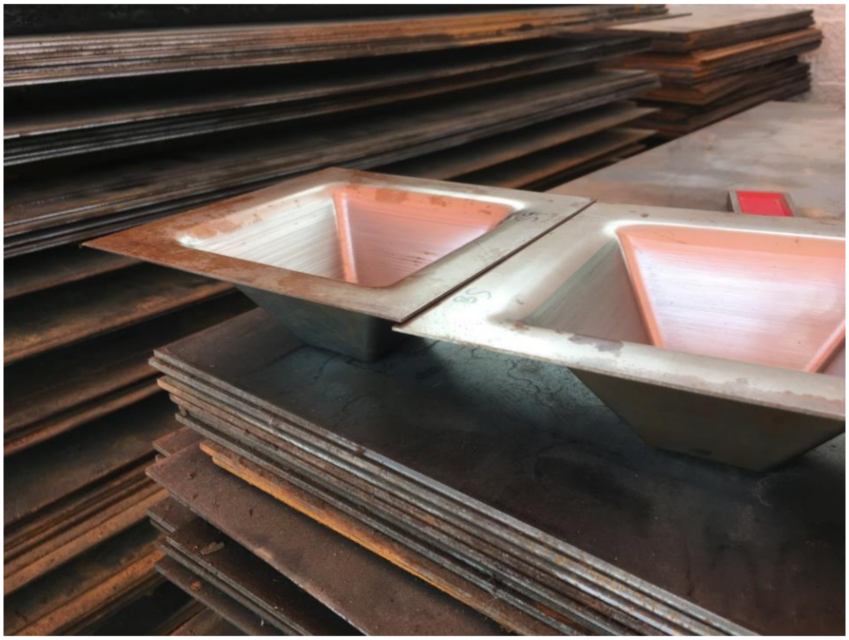


Figure 19 Formed AISI 1005 Specimen

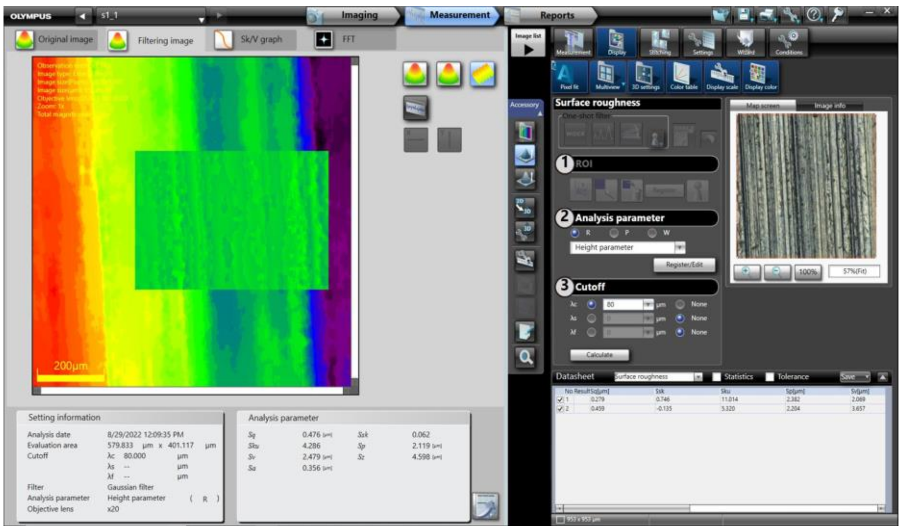
The fracture of the AA 5083 sheets can be explained based on two factors; feed rate and clamping. The feed rate from the simulation was too low for practical work as it took nearly 12 to 15 hours to form one work piece. Secondly, the deflection in 3 point bend test discussed earlier was an unguided and unclamped test according to ASTM E290 standard.

In case of AISI 1005, however, the experiments turned out successful and the parts were formed achieving depths of 36mm, 48mm and 60 mm for step sizes of 0.3mm, 0.4mm and 0.5mm respectively.

After the steel parts were formed, their surface roughness was measured.

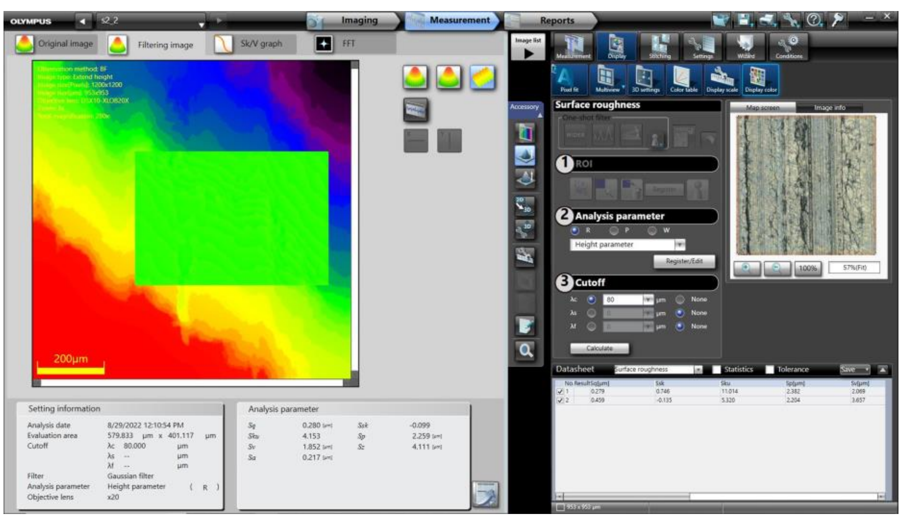
In perspective of surface roughness in ISF, feed rate did not show a significant effect on the process. It is hard to identify a specific trend or behavior based on the step size and feed rate, since the roughness fluctuated randomly in this research.

However, it may be noted that surface roughness was the lowest at lowest feed rate combined with smallest step size, (and at highest feed rate combined with the highest feed rate.



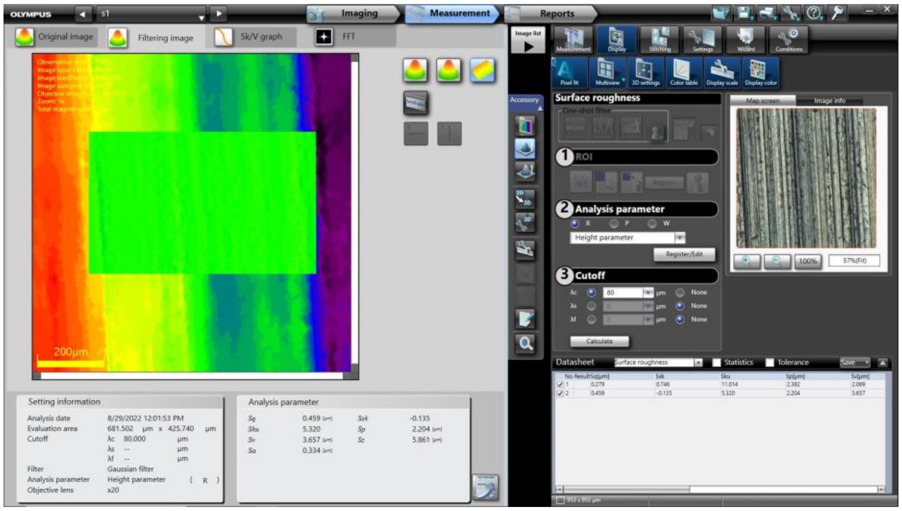
1st Iteration
x,y offset: 0.2
Step size: 0.3
Feed Rate: 1000
Roughness: 0.356 μm

Figure 20 AISI 1005 Sample 1



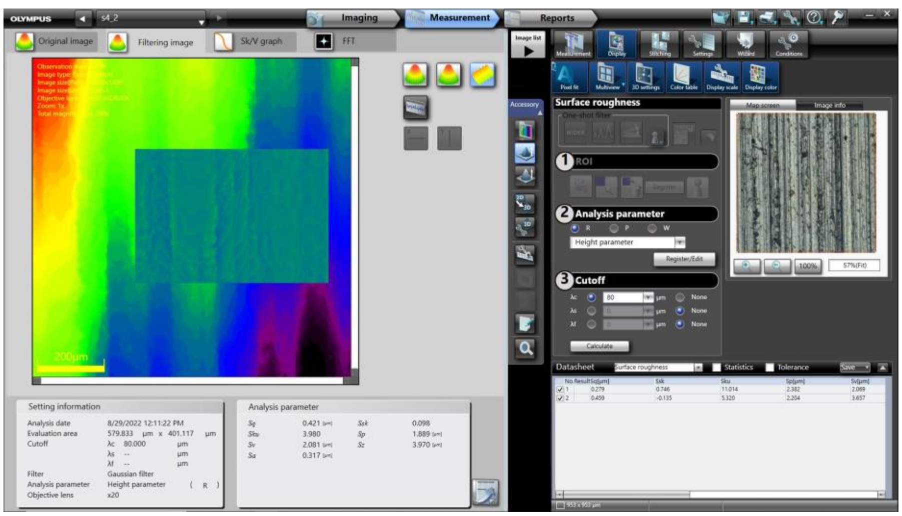
2nd Iteration
x,y offset: 0.2
Step size: 0.3
Feed Rate: 1100
Roughness: 0.217 μm

Figure 21 AISI 1005 Sample 2



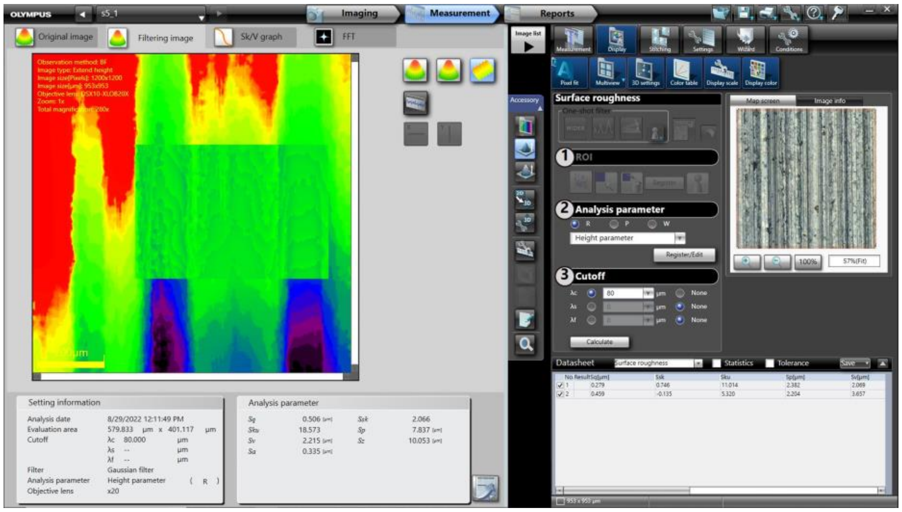
3rd Iteration
x,y offset: 0.2
Step size: 0.3
Feed Rate: 1200
Roughness: 0.334 µm

Figure 22 AISI 1005 Sample 3



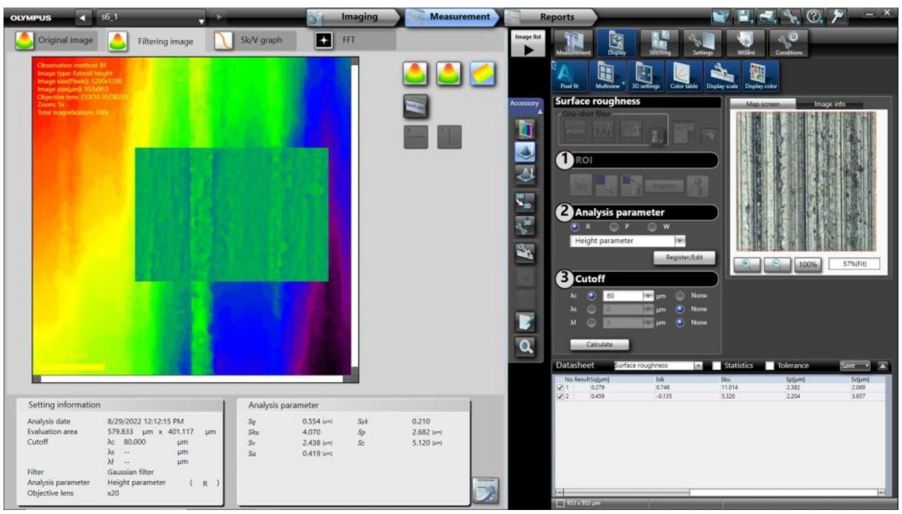
4th Iteration
x,y offset: 0.2
Step size: 0.4
Feed Rate: 1000
Roughness: 0.317 µm

Figure 23 AISI 1005 Sample 4



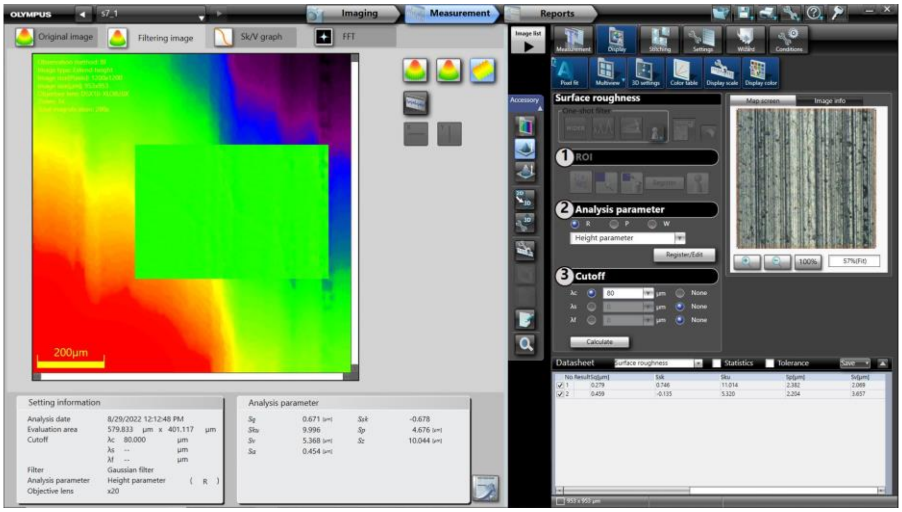
5th Iteration
x,y offset: 0.2
Step size: 0.4
Feed Rate: 1100
Roughness: 0.335 μm

Figure 24 AISI 1005 Sample 5



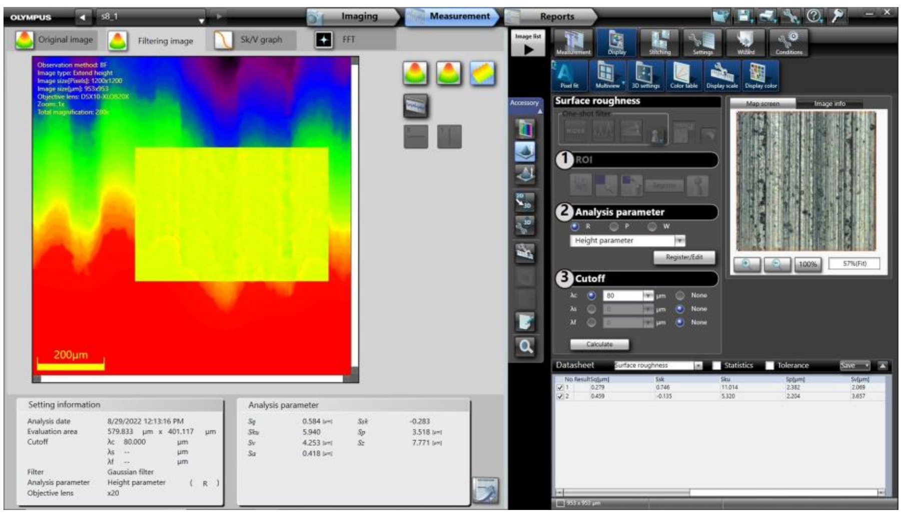
6th Iteration
x,y offset: 0.2
Step size: 0.4
Feed Rate: 1200
Roughness: 0.419 μm

Figure 25 AISI 1005 Sample 6



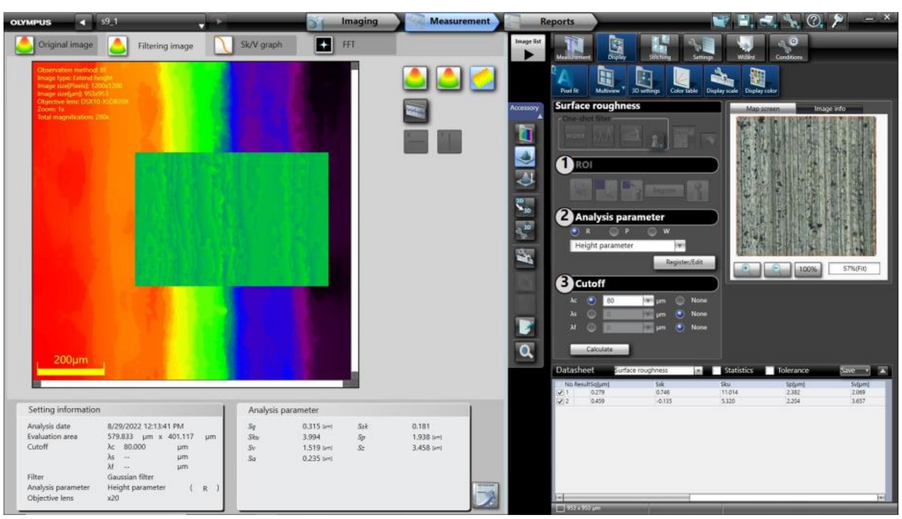
7th Iteration
x,y offset: 0.3
Step size: 0.5
Feed Rate: 1000
Roughness: 0.454 µm

Figure 26 AISI 1005 Sample 7



8th Iteration
x,y offset: 0.3
Step size: 0.5
Feed Rate: 1100
Roughness: 0.418 µm

Figure 27 AISI 1005 Sample 8



9th Iteration
x,y offset: 0.3
Step size: 0.5
Feed Rate: 1200
Roughness: 0.235 µm

Figure 28 AISI 1005 Sample 9

The data compiled against the experiments carried out can be seen in the following table.

Roughness for Different Parameters AISI 1005				
Experiment No.	Step Size (mm)	Feed Rate (mm/min)	Roughness (μm)	Average Roughness (μm)
1	0.3	1000	0.356	0.302
2		1100	0.217	
3		1200	0.334	
4	0.4	1000	0.317	0.357
5		1100	0.335	
6		1200	0.419	
7	0.5	1000	0.454	0.369
8		1100	0.418	
9		1200	0.235	

Table 8 Compiled Results for AISI 1005

Upon studying the effect of the said parameters in the experiments carried out, it was observed that there is not a particular trend in surface roughness against different feed rates for a specific step size.

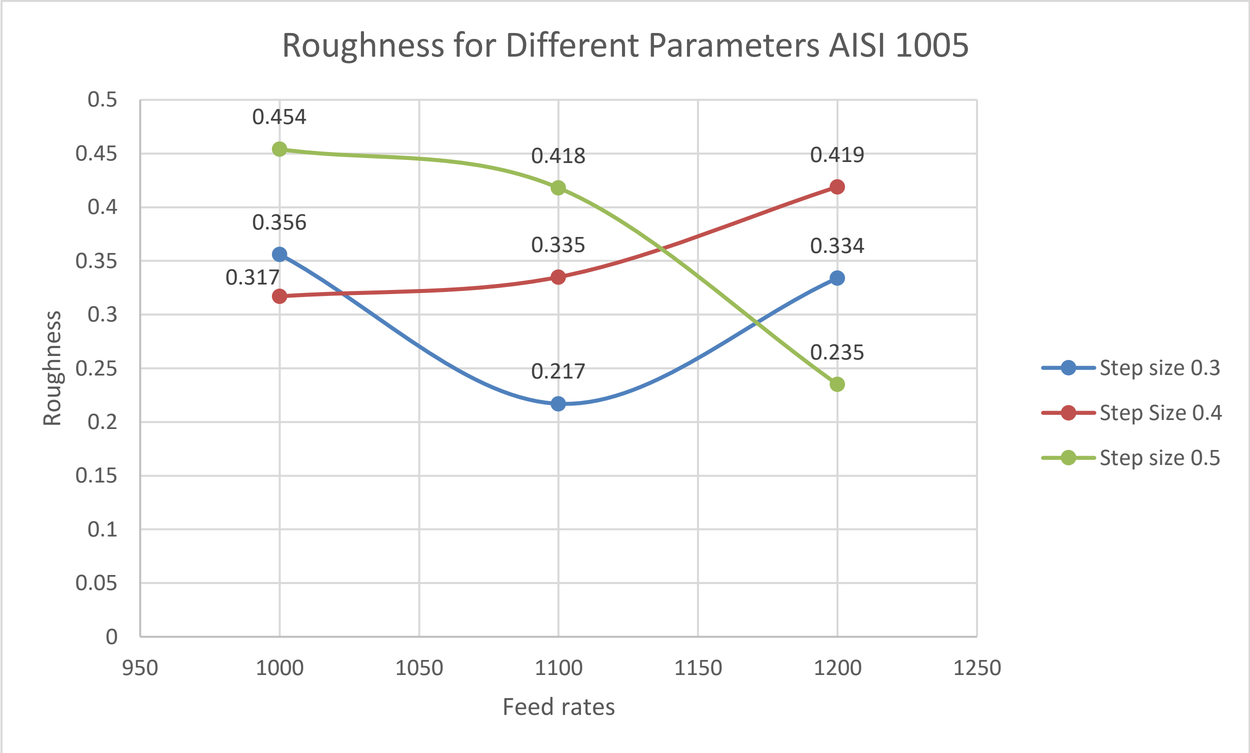


Figure 29 Roughness of AISI 1005 against Feed Rates

As seen in the figure, the roughness decreased with increase in feed rate for step size of 0.3mm, increased with step size of 0.4mm and changed anomalously for step size of 0.5mm.

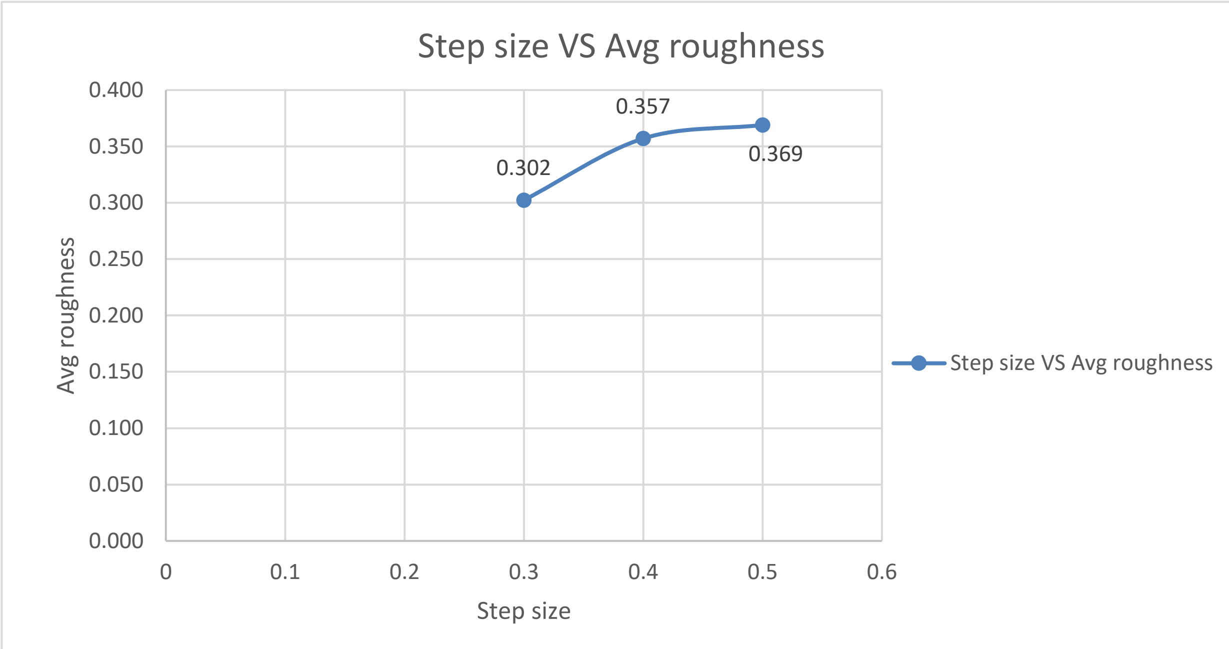


Figure 30 Roughness against Step Sizes

CHAPTER 5: CONCLUSION

From the study it seems that the AA-5083 Aluminum is not as suited for ISF as AISI-1005 Steel at the given feed rates and step sizes. Surface roughness has not shown a significant trend based on Feed Rate. Simulation of AA-5083 was probably successful because of extremely low feed rates, i.e. 75,100,125 mm/minute.

Therefore, on the practical side of ISF of AA-5083, some additional steps need to be taken in order to form the material without fracture and failure.

Incremental Sheet Forming can be a breakthrough in the field of manufacturing and rapid prototyping. Here are some recommendations for future work.

- Development of an application that could help general G Codes for any controller by taking basic parameters as input can save a lot of time and resources.
- Further research on optimizing the process of ISF in terms of time is needed.
- Application of Incremental Sheet Forming for the forming of Titanium might be a scientific breakthrough if done by minimizing time and using heat to avoid fracture.
- There is scope for work in SPIF of Tailor Welded Blanks
- Developing scope of ISF in prototyping in automobile and aerospace industry

Different avenues for work in the field of Tailor Welded blanks for automobile and aerospace industries can be explored with the help of the following mind map as well.

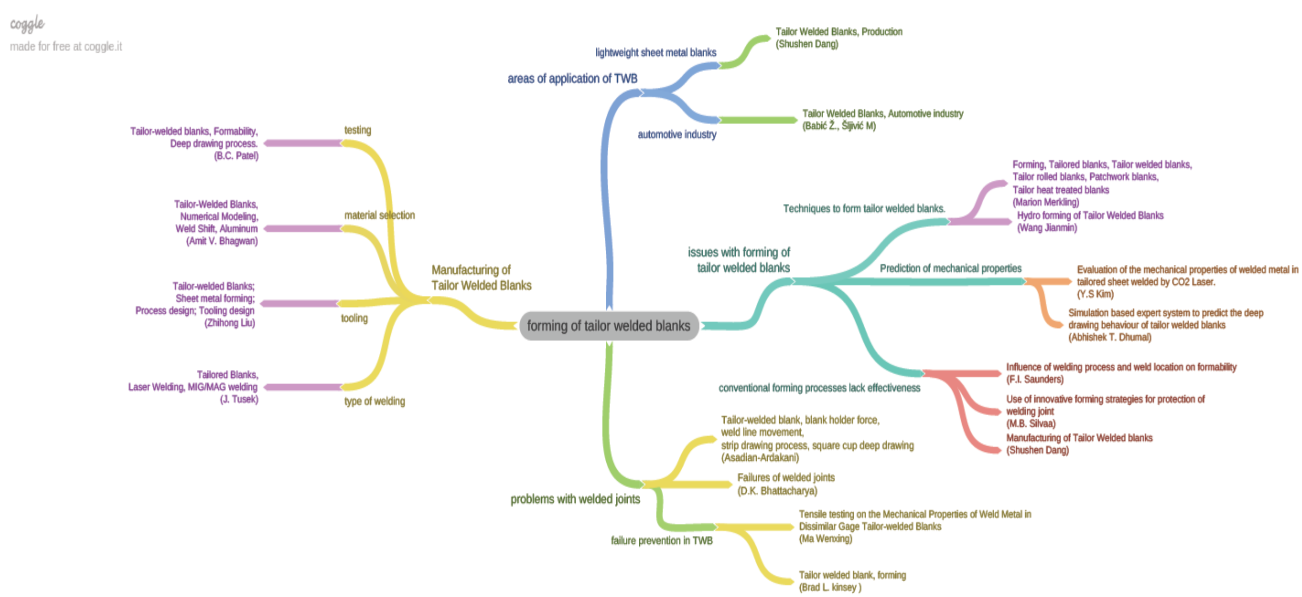


Figure 31 Mind Map for ISF in Tailor Welded Blanks

ANNEXURE 1

```
M03 S000 F1000
G71 G90
G00 X0 Y0 Z20
G01 Z-0.2
G01 X0 Y110.0
G01 X110.0 Y110.0
G01 X110.0 Y0
G01 X0 Y0
G01 X0.1 Y0
G01 X0.1 Y109.9
G01 X109.9 Y109.9
G01 X109.9 Y0.1
G01 X0.2 Y0.1
G01 Z-0.4
G01 X0.2 Y109.8
G01 X109.8 Y109.8
G01 X109.8 Y0.2
G01 X0.3 Y0.2
G01 Z-0.6
G01 X0.3 Y109.7
G01 X109.7 Y109.7
G01 X109.7 Y0.3
G01 X0.4 Y0.3
G01 Z-0.8
G01 X0.4 Y109.6
G01 X109.6 Y109.6
G01 X109.6 Y0.4
G01 X0.5 Y0.4
G01 Z-1.0
G01 X0.5 Y109.5
G01 X109.5 Y109.5
G01 X109.5 Y0.5
G01 X0.6 Y0.5
G01 Z-1.2
G01 X0.6 Y109.4
G01 X109.4 Y109.4
G01 X109.4 Y0.6
G01 X0.7 Y0.6
G01 Z-1.4
G01 X0.7 Y109.3
G01 X109.3 Y109.3
G01 X109.3 Y0.7
G01 X0.8 Y0.7
G01 Z-1.6
G01 X0.8 Y109.2
G01 X109.2 Y109.2
G01 X109.2 Y0.8
G01 X0.9 Y0.8
G01 Z-1.8
G01 X0.9 Y109.1
G01 X109.1 Y109.1
G01 X109.1 Y0.9
G01 X1.0 Y0.9
G01 Z-2.0
G01 X1.0 Y109.0
G01 X109.0 Y109.0
G01 X109.0 Y1.0
G01 X1.1 Y1.0
G01 Z-2.2
G01 X1.1 Y108.9
G01 X108.9 Y108.9
G01 X108.9 Y1.1
G01 X1.2 Y1.1
G01 Z-2.4
G01 X1.2 Y108.8
G01 X108.8 Y108.8
G01 X108.8 Y1.2
G01 X1.3 Y1.2
G01 Z-2.6
G01 X1.3 Y108.7
G01 X108.7 Y108.7
G01 X108.7 Y1.3
G01 X1.4 Y1.3
G01 Z-2.8
G01 X1.4 Y108.6
G01 X108.6 Y108.6
G01 X108.6 Y1.4
G01 X1.5 Y1.4
G01 Z-3.0
G01 X1.5 Y108.5
G01 X108.5 Y108.5
G01 X108.5 Y1.5
G01 X1.6 Y1.5
G01 Z-3.2
G01 X1.6 Y108.4
G01 X108.4 Y108.4
G01 X108.4 Y1.6
G01 X1.7 Y1.6
G01 Z-3.4
G01 X1.7 Y108.3
G01 X108.3 Y108.3
G01 X108.3 Y1.7
G01 X1.8 Y1.7
G01 Z-3.6
G01 X1.8 Y108.2
G01 X108.2 Y108.2
G01 X108.2 Y1.8
G01 X1.9 Y1.8
G01 Z-3.8
G01 X1.9 Y108.1
G01 X108.1 Y108.1
G01 X108.1 Y1.9
G01 X2.0 Y1.9
G01 Z-4.0
G01 X2.0 Y108.0
G01 X108.0 Y108.0
G01 X108.0 Y2.0
G01 X2.1 Y2.0
G01 Z-4.2
G01 X2.1 Y107.9
G01 X107.9 Y107.9
G01 X107.9 Y2.1
G01 X2.2 Y2.1
G01 Z-4.4
G01 X2.2 Y107.8
G01 X107.8 Y107.8
G01 X107.8 Y2.2
G01 X2.3 Y2.2
G01 Z-4.6
G01 X2.3 Y107.7
G01 X107.7 Y107.7
G01 X107.7 Y2.3
G01 X2.4 Y2.3
G01 Z-4.8
G01 X2.4 Y107.6
G01 X107.6 Y107.6
G01 X107.6 Y2.4
G01 X2.5 Y2.4
G01 Z-5.0
G01 X2.5 Y107.5
G01 X107.5 Y107.5
G01 X107.5 Y2.5
G01 X2.6 Y2.5
G01 Z-5.2
G01 X2.6 Y107.4
G01 X107.4 Y107.4
G01 X107.4 Y2.6
G01 X2.7 Y2.6
G01 Z-5.4
G01 X2.7 Y107.3
G01 X107.3 Y107.3
G01 X107.3 Y2.7
G01 X2.8 Y2.7
G01 Z-5.6
G01 X2.8 Y107.2
G01 X107.2 Y107.2
G01 X107.2 Y2.8
G01 X2.9 Y2.8
G01 Z-5.8
G01 X2.9 Y107.1
G01 X107.1 Y107.1
G01 X107.1 Y2.9
G01 X3.0 Y2.9
G01 Z-6.0
G01 X3.0 Y107.0
G01 X107.0 Y107.0
G01 X107.0 Y3.0
G01 X3.1 Y3.0
G01 Z-6.2
```

```
G01 X3.1 Y106.9
G01 X106.9 Y106.9
G01 X106.9 Y3.1
G01 X3.2 Y3.1
G01 Z-6.4
G01 X3.2 Y106.8
G01 X106.8 Y106.8
G01 X106.8 Y3.2
G01 X3.3 Y3.2
G01 Z-6.6
G01 X3.3 Y106.7
G01 X106.7 Y106.7
G01 X106.7 Y3.3
G01 X3.4 Y3.3
G01 Z-6.8
G01 X3.4 Y106.6
G01 X106.6 Y106.6
G01 X106.6 Y3.4
G01 X3.5 Y3.4
G01 Z-7.0
G01 X3.5 Y106.5
G01 X106.5 Y106.5
G01 X106.5 Y3.5
G01 X3.6 Y3.5
G01 Z-7.2
G01 X3.6 Y106.4
G01 X106.4 Y106.4
G01 X106.4 Y3.6
G01 X3.7 Y3.6
G01 Z-7.4
G01 X3.7 Y106.3
G01 X106.3 Y106.3
G01 X106.3 Y3.7
G01 X3.8 Y3.7
G01 Z-7.6
G01 X3.8 Y106.2
G01 X106.2 Y106.2
G01 X106.2 Y3.8
G01 X3.9 Y3.8
G01 Z-7.8
G01 X3.9 Y106.1
G01 X106.1 Y106.1
G01 X106.1 Y3.9
G01 X4.0 Y3.9
G01 Z-8.0
G01 X4.0 Y106.0
G01 X106.0 Y106.0
G01 X106.0 Y4.0
G01 X4.1 Y4.0
G01 Z-8.2
G01 X4.1 Y105.9
G01 X105.9 Y105.9
G01 X105.9 Y4.1
G01 X4.2 Y4.1
G01 Z-8.4
G01 X4.2 Y105.8
G01 X105.8 Y105.8
G01 X105.8 Y4.2
G01 X4.3 Y4.2
G01 Z-8.6
G01 X4.3 Y105.7
G01 X105.7 Y105.7
G01 X105.7 Y4.3
G01 X4.4 Y4.3
G01 Z-8.8
G01 X4.4 Y105.6
G01 X105.6 Y105.6
G01 X105.6 Y4.4
G01 X4.5 Y4.4
G01 Z-9.0
G01 X4.5 Y105.5
G01 X105.5 Y105.5
G01 X105.5 Y4.5
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M05 M30
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