

**ANALYSIS OF RESIDUAL STRESS AND
MICROSTRUCTURE OF PURE TITANIUM DURING
SINGLE POINT INCREMENTAL FORMING FOR
BIOMEDICAL APPLICATIONS**

A dissertation submitted in partial-fulfillment of the requirements for the award of degree of

**MASTER OF ENGINEERING
IN
PRODUCTION ENGINEERING**

Submitted by

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AUGUST, 2019

DECLARATION

I, Rohit Kumar hereby declare that the work presented in this thesis entitled, "Analysis of residual stress and microstructure of pure titanium during single point incremental forming for biomedical applications", in partial fulfillment of the requirement for the award of degree of **Master of Engineering in Production engineering** submitted at Department of Civil Engineering, Thapar Institute of Engineering and Technology (Deemed to be University), Patiala is an authentic record of my own work carried under the supervision of **Dr. Arshpreet Singh, Assistant Professor**, Department of Mechanical Engineering, Thapar Institute of Engineering and Technology (Deemed to be University), Patiala and **Dr. Gulshan Kumar, Professor**, Department of Mechanical Engineering, Birla Institute of Technology and Science Pilani Dubai Campus, from July, 2018 to July, 2019. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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Dedicated
to
my grandmother
Mrs. Piar Kaur
(Fountain of inspiration)

ACKNOWLEDGEMENTS

I would like to express my special thanks and a sense of gratefulness to my supervisor, **Dr. Arshpreet Singh (Assistant Professor)** and **Dr. Gulshan Kumar (Assistant Professor)** for the guidance. I have been extremely lucky to have a supervisor who helped me in my work and I came to know about so many new things. They provided me the technical support, facilities, and skills that really helped me during the work and cared so much about my work over the year. His patience, the adjustments he made, and trust and confidence he had in me really helped me to finish my work at the right time.

I am also thankful to **Dr. Inderdev Samajdar**, Professor, Department of Metallurgical Engineering and Material Science, and **Mr. Aditiya Prakesh**, Research Scholar at IIT Bombay for their help in measurement of residual stress and microstructure for carrying out my thesis work.

The author is highly indebted to all the staff (Mr. Surinder Tathgir, Mr. Rajinder Kumar, Mr. Gagandeep, Mr. Rishab Mehta, and Ms. Gurpreet Kaur Maan) of central workshop, T.I.E.T Patiala and wishes to express my Sincere for extending extensive help and support in the experimentation.

Furthermore, I would like to express my sincere gratitude to the Mechanical Engineering Department, **Thapar Institute of Engineering and Technology** for technical support. Further, I would like to thank my friends **Vijay Hans, Gaganjot Singh Sidhu, Kritika Sharma, Anisha, Gurpreet maan, Sapana kumari , Virender Solanki and Rohit Kumar** for their technical and moral support. Finally, I would like to express my sincerest sense of gratitude to my family for their support and love for me, without which this work could not have been possible.

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Nomenclature

Abbreviations

AA	Aluminum Alloy
SPIF	Single Point Incremental Forming
ISF	Incremental Sheet Forming
ISMF	Incremental Sheet Metal Forming
CNC	Computer Numerical Control
CAM	Computer Aided Manufacturing
CAD	Computer Aided Drawing
RPM	Revolution per Minute
FLC	Forming Limit Curve
NC	Numerical Control
HRC	Hardness Rockwell Scale
HB	Hardness Brinell Scale
HV	Hardness Vickers Scale

Greek Symbols

\emptyset	Forming Angle
$\emptyset \max$	Maximum Forming Angle
μ	Coefficient of friction
α	Drawing Angle (Sine Law)
σ	Stress
ϵ	Strain

Latin Symbols

Δz	Incremental step depth
T_f	Final Thickness
T_i	Original Thickness
G	Shear Modulus
E	Modulus of Elasticity
N	Newton (Force)
Nm	Newton Meter (Torque)

ABSTRACT

Single point incremental forming (SPIF) is a branch of incremental sheet forming where a very small portion of the sheet is deformed plastically at any moment. This incremental highly localized point deformation is done by a simple hemispherical tool, whose path is numerically monitored by a CNC device, performs this progressive extremely localized deformation. Since no die is required during forming, highly customized and user-oriented sheet metal products can be manufactured employing the process. SPIF can be readily employed in manufacturing of customized orthopedic implants and braces, e.g, cranial implants, ankle implants, elbow and knee support braces. The forming of these sheets through SPIF would result in generation of residual stress in the sheet metal. With time and other physical factors, these residual stresses would be relieved resulting in dimensional inaccuracy. This inaccuracy is highly detrimental in the case of implants and highly undesirable for supporting braces. The objective of this work is to investigate, experimentally, the state and magnitude of residual stresses on commercially pure titanium grade 2 by SPIF for biomedical applications with respect to important process parameters (forming angle and incremental step depth). The X-ray diffraction technique was used for the experimental measurements of the residual stresses. Microstructural behavior of the final product at incremental step depth and forming angles are also observed by EBSD and correlated with residual stresses. The experimental findings showed the formation of increased tensile residual stresses with increase in incremental step depth and steepness of forming angles.

Keywords: Residual stresses, SPIF, Titanium grade-2, Microstructure, X-ray diffraction.

Chapter 1

Introduction:

1.1. General

This thesis is part of an Production engineering research area applied to the single point incremental forming (SPIF) of titanium sheets is used in biomedical sector, focusing specifically on the growth and manufacturing of patient specific implants and orthopaedic braces through the SPIF process. This section will introduce a background of this field followed the specific problem statement that initiated this project.

1.2. Metal Forming.

Metal has been a flexible substance from the earliest starting point of its reality. It is utilized all around generally in practically every field all over the world. The fundamental explanation for its adaptability is the metal forming process that stretches the metal parts and changes their geometry to meet the desired shape without changing its volume. Metal forming is the foundation of the present-day manufacturing industry [1].

Sheet metal forming is a broadly used as manufacturing process in automobile, aviation and manufacturing industries. Researchers developed many new methods over the years to deform sheet into desired shape for different applications. In 20th century production sector mainly focuses on mass production or large scale production methods towards aim of decreasing the manufacturing costs. A number of conventional sheet metal processes such as die and punch moulding, deep drawing, roll forming, roll bending, stamping etc. have been very popular for large scale production of sheet metal parts. To perform an operation these conventional processes needs heavy equipment, complex dies, punches to produce sheet metal parts. But in today's due to advancement in technology and consumer's individual choice there is a highly demand of customized products as well as small batch production in industry. By using these conventional processes for making customized products there is a need to design a die, punch and to adjust machine configuration. Dimensional accuracy, high lead time and high cost of tooling are some of challenges faced while making a customized products on conventional machines. To compensate it a new metal forming technique is invented i.e.a incremental sheet metal forming to deform a sheet into desired shape by plastically [2].

1.3. Incremental sheet forming

Incremental sheet forming is a technique where a sheet is formed into the final workpiece by a series of small incremental localized deformation. By using this incremental sheet forming process (ISF) it is possible to make customized products or small-batch products easily. The incremental forming process is developed from stretch forming and metal spinning process. Thus, the ISF process has combined advantages of stretch forming processes and metal spinning process [3]. It is a method of forming intricate, complex, and asymmetrical parts by highly localized deformation. This process can be performed by utilizing any 3-axis robotic arm or CNC machine, which make it a cost-effective and easily available source in the manufacturing industry. A specialized prototype or dedicated equipment for the process are also available in the market and some of them are under research.

The incremental sheet forming process is focused on for the particular project is known as single point incremental forming (types of incremental forming is later discussed in section 1.2.2). In this particular type of IF process i.e. single point incremental forming there is no supporting reinforcement die used on the back surface of the metal sheet. As per the name, Single Point Incremental Forming indicates there is only one point contact between sheet and tool which leads to localized deformation. The important parts required for SPIF process as shown in Figure.1.1, the essential elements are [4]:

- The clamped workpiece (metal sheet)
- Blank holding support
- Deforming tool
- Tool path
- CNC machine

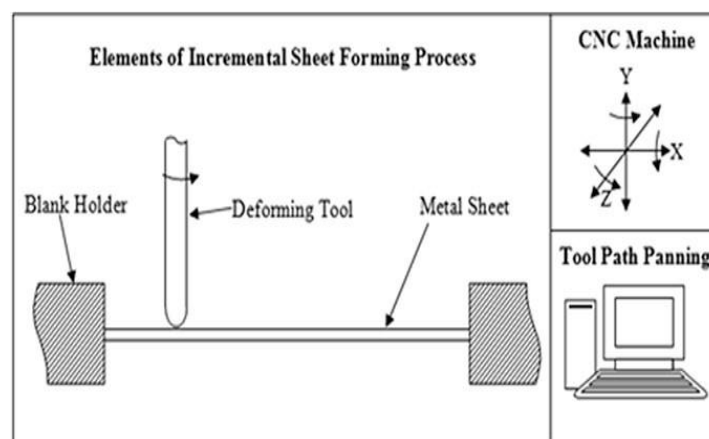


Figure 1.1: Schematic representation of elements of SPIF [5].

1.3.1. History of Incremental Sheet Forming

Advancement in the ISF process is mainly concern from traditional forming techniques such as shear forming and conventional spinning process.[3]. Spinning and shear forming processes which consist of rotating workpiece are deformed into final shape by mandrel or rotating mandrel using a solid rod, forming tool or roller .where metal gradually works over a chuck surface(basically mold is determined the final shape). A broad investigation of Asymmetric or symmetric Incremental Sheet Forming (AISF) is well explained by Jeswiet et al. 4].

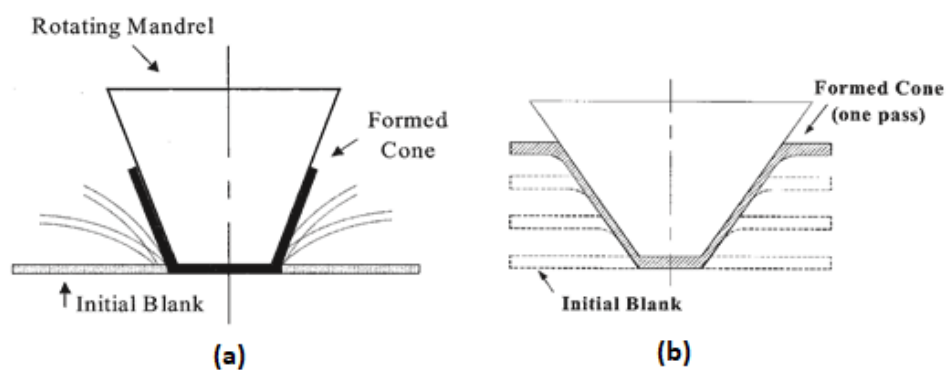


Figure 1.2: Conventional ISF (a) Traditional spinning process (b) shear forming of a inverted cone with a single pass of mandrel [3].

Incremental sheet metal forming procedure utilizing a single point apparatus was patent by Leszak in 1967[6]. Which is later on well known as Die less forming. Later in 1994 Matsubara [7] had invented incremental backward bulge process where the sheet is clamped in downward movement rig with the stationary post is supported the blank at the center. This process eliminates the disadvantage of forming asymmetric parts by spinning and shear forming.

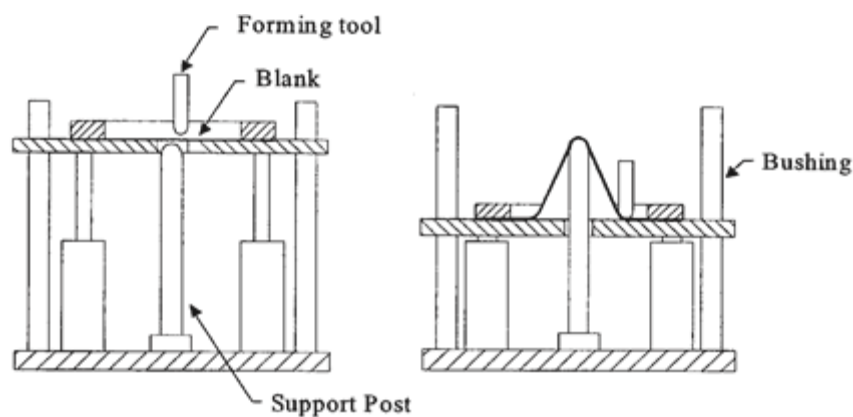


Figure 1.3: Backward bulge forming apparatus 1994 Matsubara [7]

In the early 1990s, technological development and availability of CNC machines were low which leads to the main reason of utilized CNC machines in ISF processes. Now in the present era where the customer required customized products a full use of CNC machine utilizes these days.

Table 1.1: Comparison between Spinning, shear spinning and ISF [3].

Parameters	Spinning	Shear spinning	Incremental Sheet Forming
Blank	Moves inwards	Remains constant	Fixed
Thickness of sheet	Not constant throughout	Thickness reduction follows the sine law	Reduces but totally depends upon a set of parameters
Desired shape obtained by	Movement of a mandrel or by roller	The shape is determined by a mandrel	Movement of deforming tool
Non-symmetric shape possible	Limited	No	Yes
Requirement of die			No
Lead time	Yes	Yes	Very short
Tooling & equipment	Long	Medium	Very low
Cost	Medium	Medium	

1.3.2. Types of Incremental Sheet Forming

In traditional or conventional incremental forming where a sheet is deformed by single point hemispherical tool using localized deformation mechanism. Movement of the tool is running on a pre-defined path which is controlled by CNC machine. A hemispherical point tool is running over the surface with incremental depth (Δz) deform the sheet into the user-oriented shape. Traditional incremental forming process classified as follows:

- a) Single Point Incremental forming (Figure.1.4a) where only single point contact tool run over the sheet to deform into the desired shape. Since there is no need of die so, This process is also called Negative die less forming.
- b) Two-point Incremental Forming (TPIF), where two tools, one of them is called deforming tool and another is called supporting tool which run over the surface with point contact to deform the sheet plastically as shown in Figure. 1.4b.

c) Multi-Point Incremental Forming, where a sheet is pressed in a set of upper and lower die consists of multi punches to get a desired shape of a sheet. To get a variation in shape, the height of punches are adjustable so could specific shape achieved.[8]

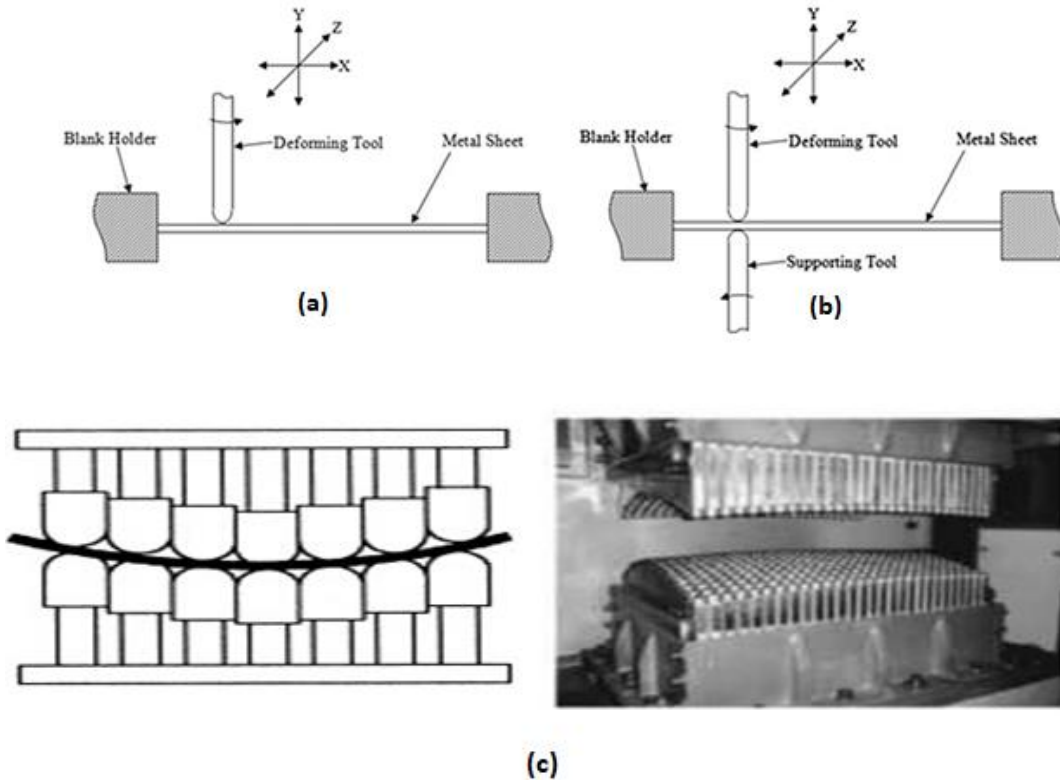


Figure 1.4: (a) shows the schematic of SPIF (b) shows the TPIF and (c) shows the multi-point incremental forming [5,8].

1.3.3. Theory of Process Parameters in SPIF

As mentioned above there are many types of process under incremental sheet forming. But our mainly focused and concern on Single Point Incremental Forming because this process is easily operation able and availability on CNC machine. The main theory behind the incremental forming process is focused on the impacts of process parameters on the enhancement of the formability. A large area of focus on the enhancement on incremental forming is due to customer requirement of customized as well as small-batch products. A number of experiments conducted to conclude the parameters of incremental forming affect the formability of sheet metal parts. Kim et al. conducted the study on impacts of process parameters such as the shape of the tool, size of the tool, feed rate, friction between sheet and tool and plane anisotropy changes with a motion of tool are highly affect the formability of SPIF [9]. The fundamental theory behind the incremental sheet forming consist of different

modes of deformation mechanism, stress and strain behavior, friction induces between forming tool and sheet, surface roughness and the sheet thickness reduction. Jeswiet et al. explained the four major influencing parameters of Incremental forming [4]:

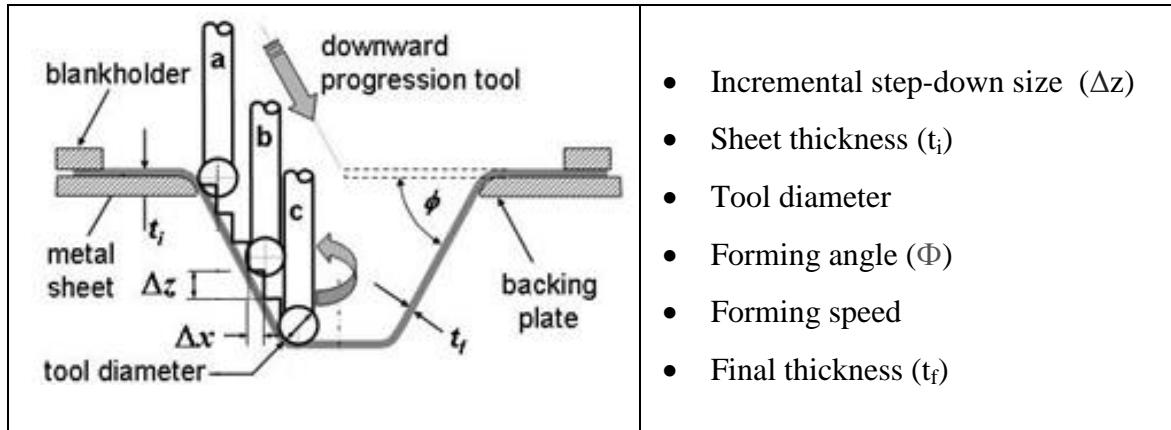


Figure 1.5: Process Parameters of SPIF process with contour tool path [4].

The impact of an incremental step-down and sheet thickness is generally explained by sine law. A sine law predicts the final thickness (t_f) by the relationship between the forming angle (ϕ) and original wall thickness (t_i) states in equation 1. Matsubara first found the sine law prediction is accurate to find out the final thickness of sheet after deforming [7].

$$t_f = t_i \cdot \sin(\alpha) \dots \dots \dots \text{Equation (i)}$$

1.3.4. Advantages and Disadvantages of SPIF

We use incremental sheet forming techniques over stamping, spinning, deep drawing and other conventional processes because of its large amount of advantages that is also written in literature. These advantages are as follows:

- The need of custom die is eliminating because in this process no die is required to perform an operation.
- Due to localized deformation, it enhances the formability of the material and minimizes the forces
- The desired shape of a part or any complex geometry can be produced directly from the CAD model.
- In this process there is no need for specialized equipment and tooling is completely eliminates due to it require the only a single tip of the tool.

- Operation of single point incremental forming is quiet and noise-free as compared to others.
- Design of part is greatly flexible because the geometry of the part is easily modified by utilizing design softwares.
- Surface finish is good of SPIF parts.
- Overhead costs are less because it can be done on a conventional CNC machine.

Some of the disadvantages of the process as written below:

- Because it is progressive deformation so it takes a longer time to perform a operation than deep drawing.
- It has a geometry inaccuracies at bending areas and curves.
- The dimensions of right angle is not achieved by single step. To do this it requires multi step process

1.3.5. Application range of SPIF

On the basis of advantages of SPIF it is observable that there are numerous applications of single point incremental sheet forming in various fields:

- Automobile industry – It has a wide range application in automobile industry. Numbers of parts are made by this technology like Car panels, Reflective surface of headlights, bus panel.[9]
- Biomedical Industry – This technology is very helpful for biomedical application due to its flexibility in part design which fulfill the requirement of customization of manufacturing of human anatomy of patient. This technology is used in medical industry for making a artificial implant or oththopedic products like ankle support for patient, Denture plate and cranial plate for cranioplasty surgery.
- SPIF is also used in ship building industry where large panel is making out. It is also used in construction industry, mold making industry and public art industry where irregular and complex shape are drawn by this method.

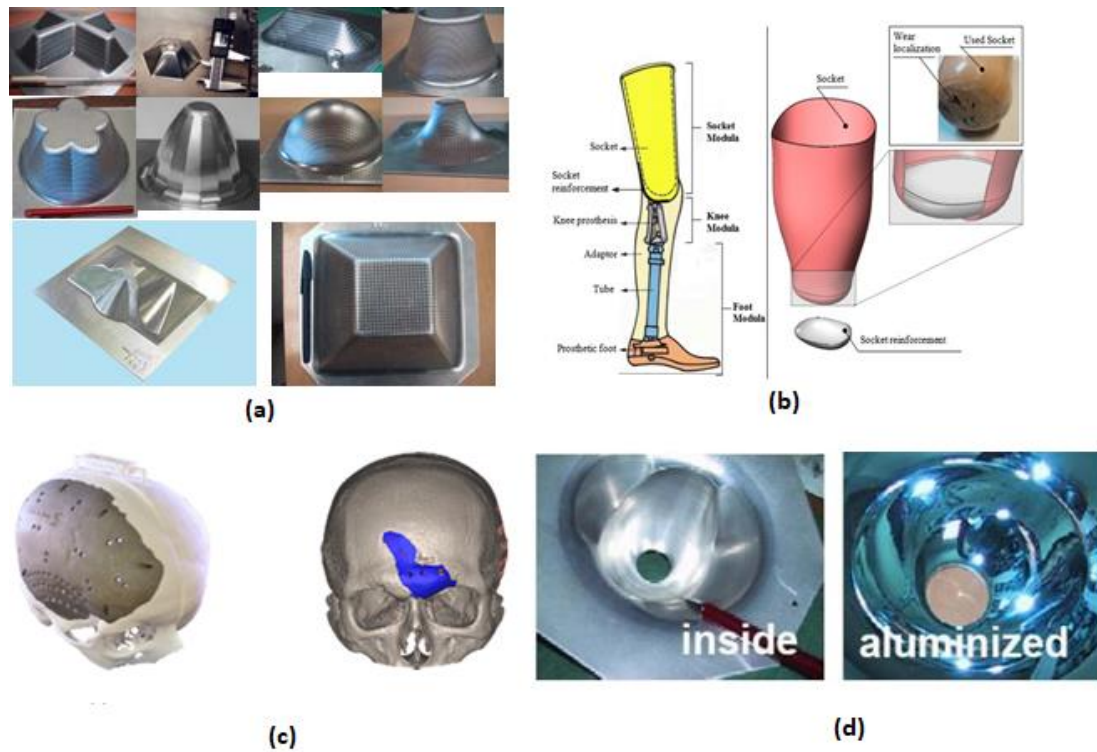


Figure 1.6: (a) Multiple shaped formed by SPIF[4] (b) Socket reinforcement made by SPIF[11] (c) cranial plate and facial implant made by SPIF (d) Automotive reflected surface[12].

1.4. SPIF Employed in Medical Implants

Single point incremental forming is used as fabricating of many implants where a biocompatible material is used to form a user oriented impant.

1.4.1. Cranioplasticity

Cranioplasty is a clinical procedure for repairing human skull deformity due to brain tumour, stroke, or traumatic injury. Cranioplasty operation offers not only the cosmetic and sometimes life-saving advantages, but also psychological draw backs and improves patient's quality of living life [13]. Cranioplasty operation may be done using either autografting, where transplant taken from the patient's own body, allografting, where transplant taken from the donor body or patient's own body and alloplasty (used non-biological materials such as metallic and polymeric).By following the Bio-CAD technique it was possible to have the shape or geometry of the human skull bone [14].

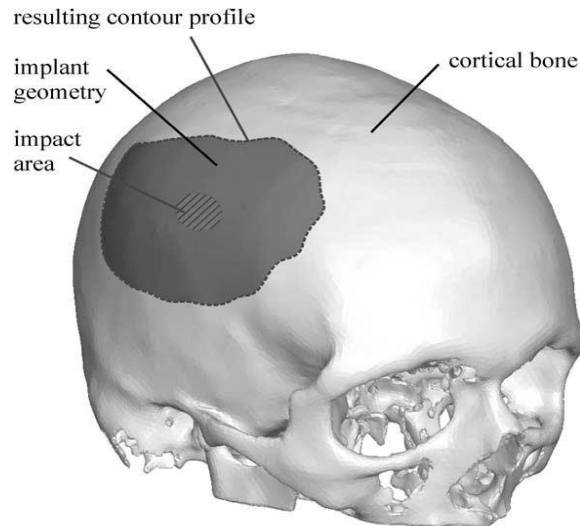


Figure 1.7: CAD/CAM assist skull design [15].

Non-metal materials such as polymethylmethacrylate (PMMA), polyetheretherketone (PEEK) and hydroxyapatite, and metal replacements such as cobalt-chromium, stainless steel, nickel-chromium and titanium, alloplastic materials are frequently used in cranioplasty operation. Medical implant materials are normally selected based on requirements such as biocompatibility, material properties and the experience and preferences of the surgeon. Titanium remains the primary flow material used in cranioplasty surgeries due to its outstanding biocompatibility, infection resistance, outstanding material property, strength and light weight, among all the alloplastic products including PMMA and PEEK [16].

1.4.1.1. SPIF employed in cranioplasticity

Despite widespread use and growing need for biomedical material titanium-based cranial reconstruction, there are a broad range of techniques, including casting[17], manual shaping by hammer and rubber press forming[18], widely used in cranial reconstruction manufacturing. Even with the help of sophisticated CAD / CAM, CT scan and MRI techniques, the procedures required to produce custom casting moulds, templates and die forming in conventional manufacturing of cranial plate are not only expensive but also time consuming. Time consuming process is very severe problem in case of urgency surgery. In latest years, 3D printing, FDM or additive manufacturing based techniques have produced fast progress and it is possible to finish the 3D printing of a cranial or facial prosthetic portion within several hours[19]. But before choosing 3D printing technique over other for medical applications there are still some impediments to be overcome which include insufficient material properties and high cost issues[20].

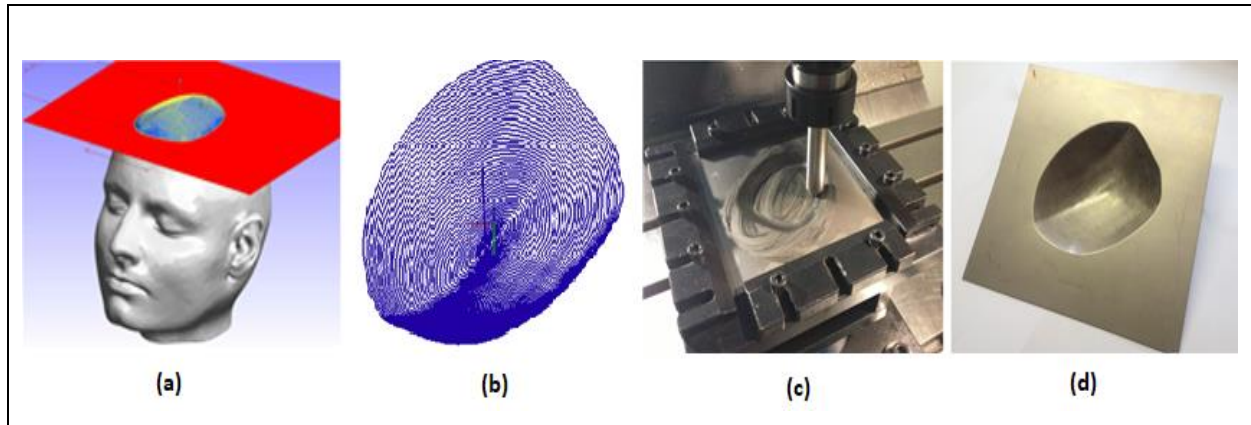


Figure 1.8: (a) Head model (b)Tool path for cranial plate (c)SPIF setup for forming (d) Finished[21].

1.4.2. Knee arthroplasty of incremental forming

The ISF method focuses on plastic deformation of sheet metal that produces asymmetric and symmetric shapes by drawing a rotational tool along a series of contour lines produced directly from the CAD model. [4]. Excellent flexibility to CNC machine through direct control of CAD information, with minimal usage of complicated tooling sets, dies and forming presses, makes the method economical and simple to automate and adjust accordingly for multiple applications. **Knee arthroplasty by Incremental Forming**

As like cranial prosthesis similar in knee replacement surgery which is also known as knee arthroplasty there is also implant designed by single point incremental forming as shown in Figure 1.9. The cause of this surgery is osteoarthritis which is a degenerative bone disease because of degradation of cartilage, thickening in the subchondral bone, and the generation of new irregularities of bone matter in the bone joints. Almost every cases where the osteoarthritis in the knee joint is classified as severe are most commonly treated or operated by means of surgery[23].



Figure 1.9: Complete procedure of Total Knee Replacement surgery using biomedical plate made SPIF[24].

Although a work by Ambrogio et al.[25] presents a paradigm for producing customized ankle support by using the reverse engineering (RE) process, which uses patient scanning data in an optimal way using a computer-aided design system (CAD) and then transfers the three-dimensional CAD model to the Single Point Incremental Sheet Forming (ISF) technique for producing tangible products as shown in Figure 1.10. Atef et al [11] also contribute by designed complex geometry of socket reinforcement for femoral prosthesis.

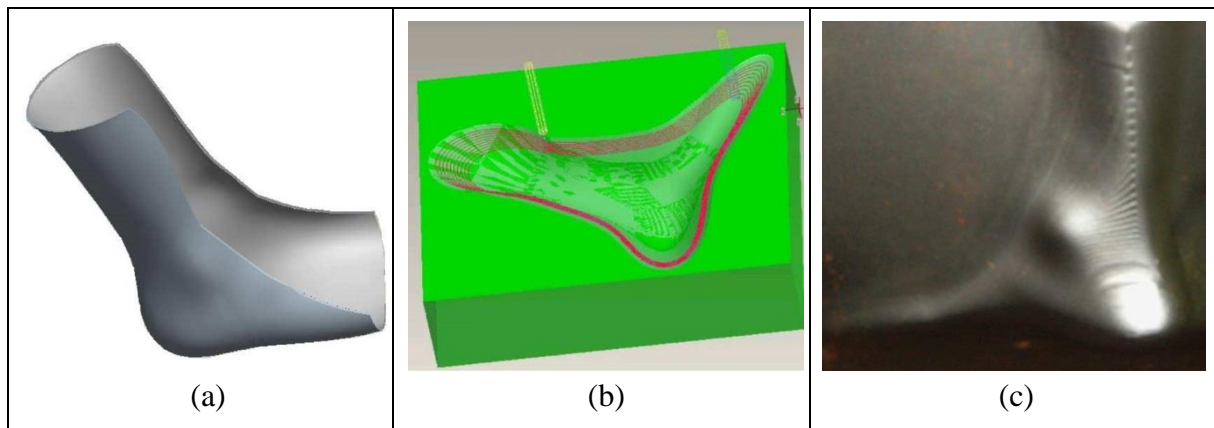


Figure 1.10: Ankle support brace (a) designed CAD model; (b) CNC Tool path (c) Final product[25].

1.5. Titanium and its alloys

Titanium was found in 1791 by geologist and Pastor William Gregor in Cornwall (UK), and later in 1795 named after "Titan" in Greek mythology by German scientist Martin Heinrich Klaproth [22]. Titanium is accessible in numerous mineral stones, for the most part in the type of rutile and ilmenite, which are commonly found in earth's crust and lithosphere. Ti could be separated by dropping titanium tetrachloride ($TiCl_4$) and combining $TiCl_4$ with the reducing magnesium.

As a metal titanium can be alloyed with iron, aluminum, chromium, niobium, zirconium, vanadium, silicon and molybdenum, among different components, to enhance their tensile strength and toughness (even at high temperature). These alloys can be used to fabricate lightweight components for aviation (stream motors, rockets, and shuttle), military, car, horticulture (cultivating), restorative prostheses, orthopedic inserts, dental inserts and medical instruments for different applications.

Titanium and its alloy has a wide range of application because their excellence in physical, mechanical and biological performance in biomedical devices as well as application

in aeronautical and industrial areas. Physical and mechanical characteristics or properties of titanium is shown in Table 1.2.

Table 1.2: Physical and Mechanical properties of Titanium [26].

Property	Values (SI)
• Atomic Number	22
• Atomic Mass	47.90 g.mol ⁻¹
• Density	4.51 g.cm ⁻³
• Boiling Point	3287 °C
• Melting Point	1660 °C
• Ultimate Tensile Strength	900 Mpa
• Poission Ratio	0.3
• Young's Modulus	105-120Gpa

1.5.1. Types of Titanium [27]

Table 1.3: Shows types of grades of titanium

CP grades 1-4	These commercial pure grades of titanium are most corrosion resistant and unalloyed of any material. It contains pure form of titanium upto 99.97% to 99.99%. Commercial pure titanium grade 1 is the best formable, whereas higher grades have a gradually higher oxygen content for higher strength. These grades are used widely in structural, aerospace and biomedical industries.
Ti-6Al-4V ELI	This α - β alloy is used for medical industry to manufacture of aerospace parts and needles, surgical instruments, spinal fixation devices in medical industry. The ELI grade of titanium was created to increase the breaking strength and cryogenic flexibility.
Ti-6Al-7Nb	The α - β alloy have common mechanical and physical properties compare to Ti-6Al4V, but when addition of

	niobium results increases corrosion resistance.
T-13Nb-13Zr	The β alloy has a high strength and low value of modulus of elasticity, which makes it best suitable for implants.
Ti-15Mo-3Nb	The β -class alloy has a greater resistance and lower elasticity modulus than Ti-6Al-4V. This can be long survival implants than Ti-6AL-4V.
Ti-12Mo-6Zr-2Fe	A new metal alloy formed includes iron with poor elasticity modulus, high ductility, resistance to corrosion and excellent formability as well as less wear and excellent fatigue strength.

1.5.2. Biocompatibility of Titanium

From the Table 1.3 commercial pure titanium grades having a good formability (which need a SPIF) properties states as a best material for medical prosthesis and it is also easily available in market. Biomedical implants requires a properties of biocompatibility, corrosion resistant and high strength to weight ratio where titanium as a metal fulfill all these requirements. As titanium is completely integrates with human body, stands with bone development, robust and adaptable, It is considered to be the best biocompatible of metals.[26].

Why is titanium biocompatible?

Titanium has recognized with its good biocompatibility and corrosion resistance because of oxidization of outer layer when it contact with oxygen. Therefore, when it comes to oxygen response, a highly stable oxide is formed on the surface of metal. This stable oxide is called Titania(TiO_2). This TiO_2 can further modifications upon binding various ions from surrounding, which include calcium, phosphate, hydrogen due to its high dielectric constant of 85MHz [28]. This makes a ability of metal to binding with bones and living tissues. The layer of TiO_2 protects the implant from body environments under fatigue, stress and corrosive conditions. This layer of oxide is insoluble, non transportable and take care of any reaction to human tissues.

1.5.3. CP Titanium Grade 2 material characteristics

Commercial pure titanium has been long utilized for biomedical applications like surgical instruments, heart stents, wires, bone fixation devices, cranial plate ,knee arthroplasty parts etc.Commerical pure titanium grade 2 is used for these applications rather than other CP Ti grades and alloys because of its better formability and osseointegrate with bio-tissue in human body.While trying upgrade the mechanical performance of CP Ti-2 Rack et al [26] reported strengthening technique by using equal channel angular pressing.The mechanical charcterstics of CP Ti-2 with different microstructural states as given below in Table 1.4.

Table 1.4: Mechanical properties of CP Ti-2 at different microstructural states [26]

Microstructure Type	Hv (Mpa)	UTS (Mpa)	YS (Mpa)	EL (%)	RA (%)	Fatigue limit
Coarse-grained	1800	460	380	26	60	238
UFG (Equiaxed, submicron-grained)	2700	460	625	14	60	403
UFG (Fibrous w. high dislocation density)	2821	960	725	10	45	434
UFG (subgrained w. internal cells)	2850	1100	915	9	40	500
Ti-6Al-4V ELI (annealed)	-	965	875	10-15	25-47	515

1.6. Residual Stresses

Residual stresses are those stresses which present with in a body after removal of load or without any thermal gradients.These stresses are also called locked-in stresses which exist in a part material without any external load applied [29].

1.6.1. Factors that cause residual stresses

Due to many causes, residual stresess can occur in any mechanical system. The residual stresses occur in system due to various reasons.The manufacturing methods of using during manufacturing of part can be the one of cause of generation of residual stress. The most prevalent causes of residual stress are manufacturing techniques applied on a part. Almost all

fabricating and manufacturing techniques, such as casting, machining, welding, molding, heat treatment, plastic deformation during roll bending, roll forming and forging, may develop the residual stresses on the manufactured part. Residual stress may be induced by localized material yield due to a sharp tool or surface procedures such as shot peening or surface hardening applied on surface of component or part [29].

1.6.2. What residual stresses can cause with a component

- Residual stresses can be enough to cause a metal portion into instantly divide into two or more parts after it rests on a table or ground without applying external load.
- Residual stresses can lead to a element being visibly distorted.
- Relaxation with residual pressures can deform a piece when it comes to machining.

1.6.3. Origin of residual stresses

At the atomistic stage, the generation of residual stress can be well understood through the mechanism of lattice displacement as shown in Figure 1.11. The deformation may change or alter interplanar spacing or may include defects in the lattice spacing[30]. The deformation is caused by the movement of dislocations through the crystallite, the yield stress on the exterior surface is exceeded and the plastic areas expand inwards leading to creation of residual stress [30,31,32,33] as shown in Figure 1.11 below.

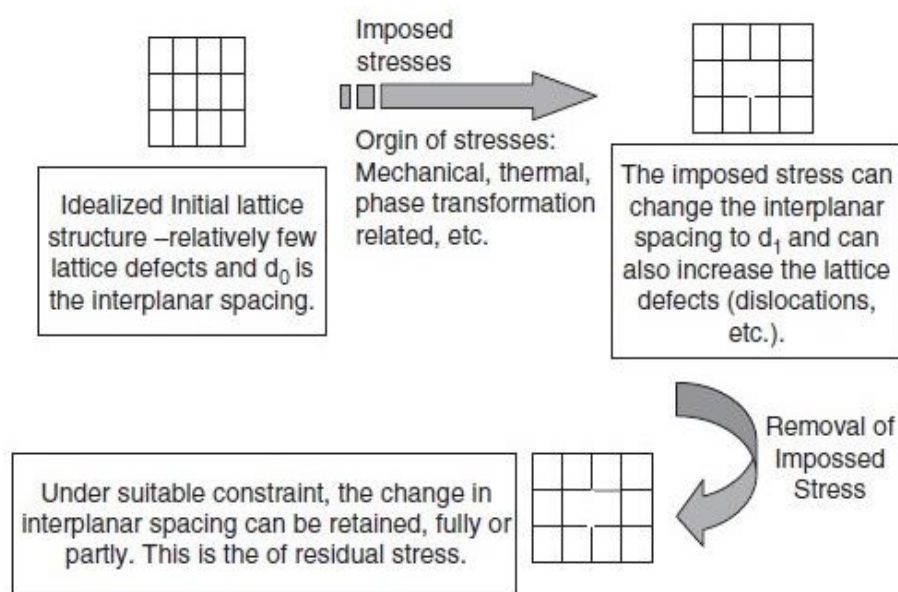


Figure 1.11: Deformation mechanism shows the development of residual stresses through lattice displacement [30].

1.6.4. Role of Residual stresses

Residual stress can sometimes play a major role in explaining or preventing a component from failing. Depending on how residual forces communicate with internal loads, they can have a beneficial or negative impact on the mechanical behaviour and life of parts [35]. For example, compressive residual stresses on the surface will improve fatigue resistance as the residual stress and stress applied are additive. On the other side, the tensile residual stress on the component's surface is usually unwanted owing to reduced fatigue strength and increased crack propagation[32,33,34] as shown Figure 1.12 below.

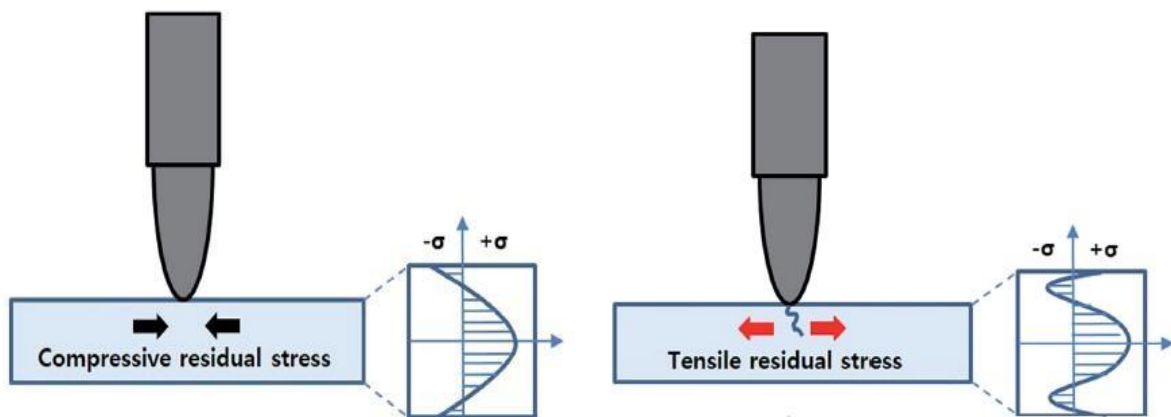


Figure 1.12: Compressive residual stress in the surface and tensile residual stress in the surface [34].

2.1. General

The chapter first clarifies the basics of sheet metal forming, drawbacks of ISF, the need of ISF over other conventional ones, basics single point incremental forming, types and applications areas of SPIF. The major drawback in conventional type sheet forming is less formability of sheet due to large strain and strain hardening and another drawback is a restriction in part design which is desirable in cranioplasty surgery for manufacturing of cranial plate according to patient's geometry uniqueness. Before defining the problem statement for this research work, it is important to overview the literature related to the process. A review of the literature presenting all the work and conclusions is presented below which is arranged in chronological order for simplicity and easy comparison.

2.2. Single Point Incremental Sheet forming

Incremental sheet forming was first introduced by Leszak in 1967[6] which is later developed by Matsubara in 1994[7] using a single point hemispherical tool in backward bulge incremental forming process. The working principle of incremental forming is well explained by Jeswiet et al. in 2005[4]. While producing the custom implants for biomedical applications, single-point incremental forming has benefits over the standard forming process, but at the same time this method is simultaneously limited to used. The reason is few parameters of this process are not well established yet. To achieve optimum parameters in methodology there is a need to recognize process parameters and afterward have to understood the impact of these parameters of SPIF. Following are a few process parameters which are having an extensive impact on the process where some of the significant findings on different aspects of incremental sheet forming are discussed.

2.2.1. Forming materials

A number of researchers have been focused on materials used in single point incremental forming for making light weight, good formable, easily accessible and good strength able parts. Depending on their applications, there is plenty of material used in different industries. Titanium alloys wellknown for their corrosion resistant and high strengthable alloys and magnesium alloys known for their lightweight which are used in many industries [36,37].

Table 2.1: Findings in forming sheet material

Material Category	Author (s) name and year	Findings / remarks
Aluminum alloys	Xiaoqiang Li et al, 2013[38], J Jeswiet et al, 2002[39], Lievers et al, 2004 [40],	Aluminum alloy 3003,AA5182,AA5754 and AA6111,3003,2024-T3 for automotive panels and aircraft parts
Magnesium alloys	G. Ambrogio et al. 2008[41] and Kim et al, 2007 [42],	G. Ambrogio[37] and Kim <i>et al</i> , 2007 examined the performance AZ31 magnesium alloy under hot incremental forming
Titanium and its alloys	Siddiqi et al, 2016[43] Daleffe et al, 2013 [44]	Commercial pure titanium grade 4,Ti grade 2
Thermoplastics	Yonan et al,2013[45], Le et al, 2008 [46],	polyvinylchloride (PVC), Poly propylene (PP)
Polymers	Franzen et al, 2009 [47], Silva et al, 2010 [48]	Poly vinyl chloride (PVC)
High crystalline and amorphous materials	Martins et.al 2009[49]	Martins et.al in 2009 has done their tests on Five different polymers, polyoxymethylene, polyethylene, polyamide, polyvinyl chloride—PVC and polycarbonate
Mild steel	M. Bambach et al 2009[50]	DC04 mild steel sheet material is used to study the affects of sheet material with process parameters of SPIF.

2.2.2. Tool path strategy

Incremental sheet forming is strongly dependent on the path of the forming tool which significantly affects the dimensions of the part and the distribution of sheet thickness. A distribution of homogeneous thickness requires a thorough improvement of the process parameters and optimal tool path strategy. Mohamed Azaouzi [50] demonstrates a technique

of optimization tested for a given forming approach in order to reduce the production time and homogenize the part's thickness distribution.

Table 2.2: Summary of work on tool path strategies.

Process Parameters	Author (s) name and year	Findings / remarks
Tool Path	Jeswiet et al, 2005 [4], Matsubara 1994 [7]	Authors have been worked on one-directional tool path
	Kopac et al, 2005[51]	It has been found out that forming first in center then from interior into exterior will gives a good results by five different tool path strategies on different shapes.
	Kim and Yang, 2000 [52]	A two-stage or double path tool strategy found to be very effective so that the more uniformity in thickness strain distribution will be achieved.
	Lu et al. 2013 [53]	Compared to standard z-height-based slicing algorithms, Lu et al. proved the benefits of using feature-based tool routes in forming of different geometries.
	Attanasio et al.2008[54]	The study aims to evaluate and optimize the tool path experimentally in order to reproduce an automotive component with the best dimensional accuracy, the best surface quality and the lowest sheet thinning.
	M. Bambach et al 2009[55]	It has been concluded that pyramidal part manufacture by multistage forming can yield an increased accuracy compared to the single-step forming method.
	Malhotra et al, 2010 [56]	Malhotra et al investigated the 3D spiral tool path strategies in order to know the influence on process parameters.
	Essa et al,2011 [57]	Bottom forming, Kinematic tool, and backing plate effect

2.2.3. Forming tool size

Kim and Park [58] studied tool size is a critical parameter while manufacturing a part of a good surface finish. Ambrogio et al [59] also find tool size is very influencing formability of sheet metal part. There are a number of researchers who conducted the experiments shows that larger tool has a larger contact zone between tool and sheet. Furthermore, the larger contact area increases the forming forces. On the other hand, the smaller tool gives concentrated deformation zone and higher strain is produced which gives higher formability [60]. By using smaller diameter tool forces are decreased and induced stresses while forming material is also reduced due to the smaller contact area between tool and sheet. The surface area at a smaller tool-tip is less , so the area of contact is diminished and concentration of force and strain is high. At this point of contact deformation and friction is localized and heating between tool and sheet interface is increased which leads to an increase in the formability [61].

Hussain et al, 2008 made an attempt to examine the best tool and lubricant which can be utilized to form a commercially pure titanium sheet by a single point increment forming method. By estimating surface roughness and examine through the SEM the impact of each combination of lubricant and tool was accounted for. To shape a sheet of commercially pure titanium by SPIF, the hardened high-speed steel (HSS) instrument was observed as suitable.

2.2.4. Feed rate and Tool rotation

According to the past investigation of the impact of forming tool size and material which is having a notable effect on SPIF. Forming speed is also play a crucial role in this forming process. Forming speed is expressed as both rotational speed (rpm) of tool and feed rate (mm/min) in SPIF [63]. Durante et al, 2009 conducted an experiment on different tool rotation speed as well as both clockwise and anticlockwise directions of tool rotation to investigate the impact of tool rotation on SPIF process. They observed that there is an increase in temperature (about 20%) when tool rotation is against the direction of feed [64]. Similarly Uheda et al, 2018 also suggested the experiment to get to know the effect of tool rotation direction on commercially pure titanium grade 2 sheets during the SPIF process [65].

While Kim and park in 2002 initiated preliminary research on tool sheet interface which explains friction in between tool and sheet improve formability and heat generation during the friction is directly proportional to the relative motion between tool and sheet material. As discussed informing tool section due to friction between tool and sheet interface results

higher heating is generated. Thus the formability of material is increasing, and this heat increases if the speed of forming is increased. But there is a negative effect also when we raise the forming speed because higher the forming speed leads to higher surface roughness, which increases the tribological conditions and breakdown of lubrication film between the tool and sheet metal interface [58].

2.2.5. Incremental step size

Impact of incremental or progression step size is also a parameter in SPIF. Some of the researchers said that progression size does not influence the process. But Saad Arshad has seen that progression size affect the formability [66]. Kim in 2002 noted that by increasing step size formability decreases. It has been likewise noticed that the progression size not just influences the external and internal surface roughness's but also has an affects the time of the operation. Small step sizes require more time to complete the job by the more z-plane travel [58]. Significant research has been conducted by Uheda et al on CP-Ti grade 2 sheet with SPIF process is forming temperature is proportional to incremental step size(Δz) because of large deformation rate while increasing the Δz . It is also noticed that forming forces is also directly related to step size [65].

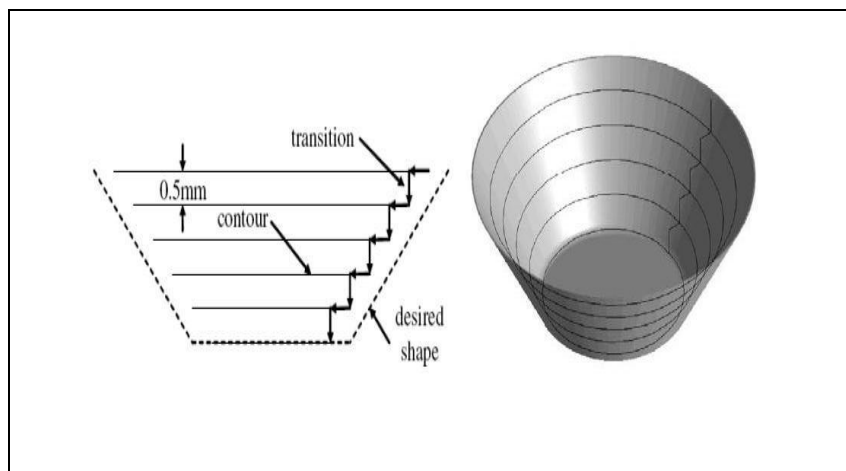


Figure 2.1: Tool path contours of 0.5mm inverted cone [67].

2.2.6. Forces in Incremental forming

Forming stresses and strain led in the study of ISF procedures due to their influences and limitations of the process. In incremental sheet forming process the tool applies a forces on a metal sheet (see in Figure.) have a forces in three directions the components of forces are F_x or F_r (radial force) and F_y or F_t (tangential force) lies in horizontal plane and F_z or F_a (axial

downward force) lies in a vertical plane [4] Both F_x and F_y are repetitive on each contour traveled by tool. It was recorded [68], that the F_z has a significant value of force which valid for both TPIF and SPIF.

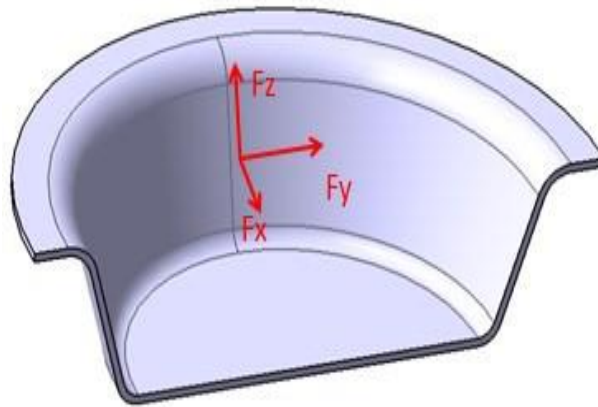


Figure 2.2: Force component in a different direction [68]

Duflou et al. [69] conducted a sequence of tests on a conical reference portion made from five different components by SPIF. They measured the forces and concluded that with the impacts of the thickness of the sheet, forming angle, tool size and step depth (Δz) on total forces:

- While the sheet thickness is increased there is a needed of large forces to deform
- Increase in forming angle thus increase in forces
- While an increase in step depth forces are slightly increased.

A number of authors [70] who also find the forces in similar ways and find out the sheet orientation impact upon the downward forming forces.

2.3. Applications of SPIF in Biomedical implants.

Table 2.3: shows the applications of SPIF in biomedical implant

Application area	Author (s) name and year	Application	Material
Medical Industry	Ambrogio et al, 2005 [71]	Ankle support implant	DDQ steel
	Duflou et al, 2005[72]	Cranial plate	AA 3003-O
	Oleksik et al, 2010 [73]	Knee implant	Pure titanium
	Fiorentino et al, 2012 [74]	Palate implant	PCL, Cp-Ti grade 2

	Eksteen et al, 2012 [75]	Knee prosthesis	Cp-Ti grade 2
	Fiorentino et al, 2012 [76]	Cranial plate	Cp-Ti grade 2
	Duflou et al, 2013 [77]	Cranial plate	Cp-Ti grade 2
	Lu et al,2014 [21]	Cranial plate reconstruct	Cp-Ti grade 1
	Behera et al, 2016 [78]	Cranial plate	Cp-Ti grade 1
	Aracejo et al, 2014 [79]	Facial implants	Cp-Ti grade 2
	Bagudanch et al, 2015 [80]	Cranial plate prosthesis	PCL
	Han et al, 2010 [81]	Skull prosthesis	Titanium alloy
	Göttmann et al, 2013 [82]	Customized cranial	Titanium gr-2
Automotive & Aerospace	Governale et al,2007 [83]	Car body panel	Al alloy
	Bambach et al, 2009 [84]	Car fender	DC04
	Verbert et al, 2010 [85]	Car fender	AA 3103
	Junchao et al,2013 [86]	Car tail light	DC04
	Behera et al,2013 [87]	Airfoils of areophane	AA 5754
Industry equipment	Allwood et al, 2006 [88]	Dies and molds	Aluminum alloy
	Appermont et al, 2013 [89]	Dies and molds	AA 3103, DC01
	Jackson et al,2008[90]	Sandwich panel	Multiple
	Afonso et al, 2016 [91]	Mold	Thermoforming

2.4. Titanium as a Medical implants

Due to the need to customize to the shape of the human body, medical implants were one of SPIF's most researched applications. Specific applications included ankle assistance, cranial plate, dental prosthesis, knee prosthesis, car prosthesis, and facial implant. Titanium was one of the key materials in these studies and was tested in both grade 1[78] and grade 2[76].PCL in biopolymers [73,80] and nano polymer composites are also studied and opted for medical applications. While manufacturing part there are some problem faces like dimensional inaccuracy, surface roughness, locked in stresses at the time manufacturing, etc. which makes researchers are keen to study cranial manufacturing techniques.

2.5. Implants manufactured using SPIF

As has already been mentioned, the biomedical sector has excellent possibilities for incremental sheet forming implementation because it has a technology capable of producing human uniqueness geometry components in a short time and at a very low price than another conventional process. A customized cranial prosthesis is one of the most common applications of ISF. Duflou et al. in 2005 made the first paper that indicated the option of producing a customized cranial prosthesis. While manufactured of the cranial prosthesis by aluminum 3003-O they compared the hydroforming and SPIF w.r.t to step required to build up a cranial plate. It has been disclosed that SPIF has a significant reduction in process time (16.5 days for hydroforming vs. less than four days for SPIF) which makes a SPIF interesting process not only for manufacturing cranial plate but also for other surgical applications like plates using in hip reconstruction [71]. Araujo et al. used the circle grid method to determine the failure limits in SPIF truncated cones and pyramids produced with grade 2 commercially pure titanium. With this data, a facial implant could be obtained effectively without error [92].

Later Lu et al investigate the properties of CP-Ti grade 1 metal sheet and performed FEM and experiment tests to evaluate the feasibility of customized skull implants, studied the forces required to deform the sheet, reduction in thickness, dimensional inaccuracy and surface finish of the material used in implants [77]. Han et al. also optimized the skull prosthesis through computed topographies [81].

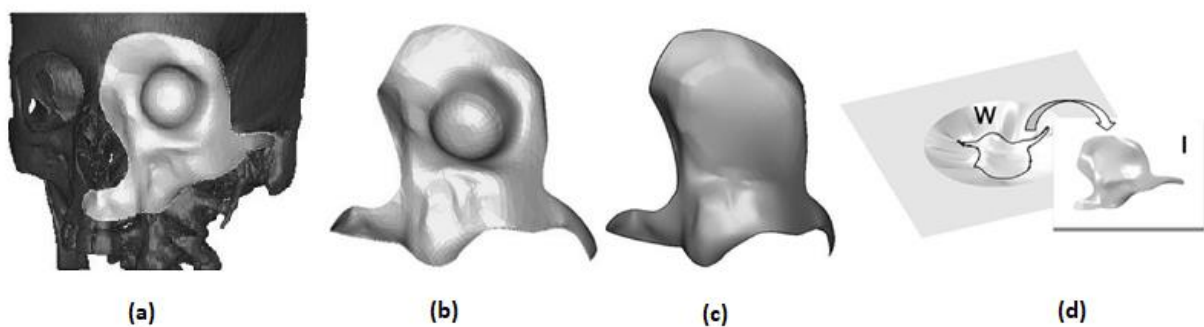


Figure 2.3: A CAD model of facial prosthesis made by SPIF [92]

2.6. Microstructural analysis of Titanium implants made by SPIF

Siddiqi et al. investigated that after performing incremental sheet forming process microstructure of commercially pure titanium was changed from globular hexagonal to uneven elongated shapes (shown in Figure.). Twining and slip are two deformation mode in

incremental sheet forming process performed on Cp-Ti and it has been highly depending on orientation and crystal morphology. They also correlate the mechanical properties with the grain structure of titanium [93]. Linda et al. conducted laser heating tests on Ti6Al4V (Titanium Grade 5) using ISF. Microstructural temperature-dependent evolution was evaluated for micro-hardness [94]. Deformation conduct and physical characteristics such as forming limit are described by an HCP structure [95]. Elias et al. conducted some mechanical experiments (hardness, tensile, compressive and torque) and surface morphology of grain structure was carried out by using SEM analysis. The results show that the required mechanical strength of implant materials. The clinical studies have been also used to assess the biological behavior of Ti G4 and Ti G4 hard dental implants materials [96]

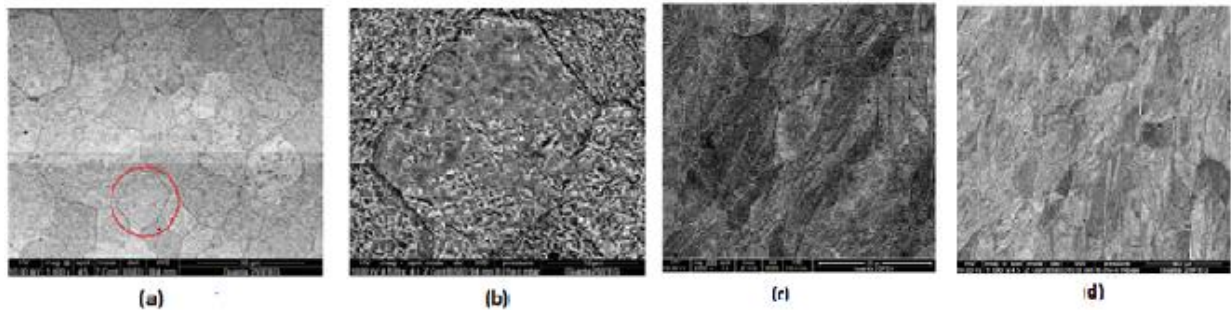


Figure.2.4: Microstructure (a) and (b) is the undeformed area of a sheet having HCP structure, (c) and (d) shows the elongated grains after performing SPIF [93].

2.7. Residual stresses in SPIF

During the part manufacturing by single point incremental forming process, residual stresses are also developed like in other manufacturing methods which effect on the geometrical accuracy and fatigue life of parts made by this process. Residual stresses in produced parts, however, could be useful if they occur in the plane and against the load applied.

In a work, Tanaka et al. examine numerically the factors which severely affect the SPIF made parts. When small rigid ball tool slides on the metal sheet with a certain feed rate, tension residual stress is generated in the upper layer of the sheet and compression stress in the bottom layer. The resultant moment of these stresses causes a negative spring in sheet when the outer portion is removed. Tanaka et al. also found that the hemispherical tool radius has a significant impact on residual stress [97].

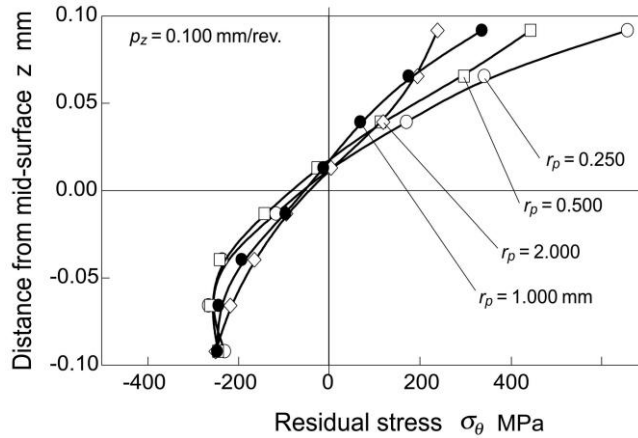


Figure 2.5: Distribution Residual stress across the thickness. (Tip radius $r_p = 0.25$ to 2.0 mm)[97].

Radu et al. discovered the impact of residual stress on the dimensional accuracy of the parts manufactured by SPIF. The remaining stresses in the sample were discovered to be mostly in the compressive type whose distribution change throughout the sheet metal thickness. With respect to process parameters such as increment step depth, feed rate, tool size and spindle speed, Radu et al. shows the magnitude of residual stress on 304 steel parts (given in Figure below) and discovered that they were not spread evenly through the thickness.

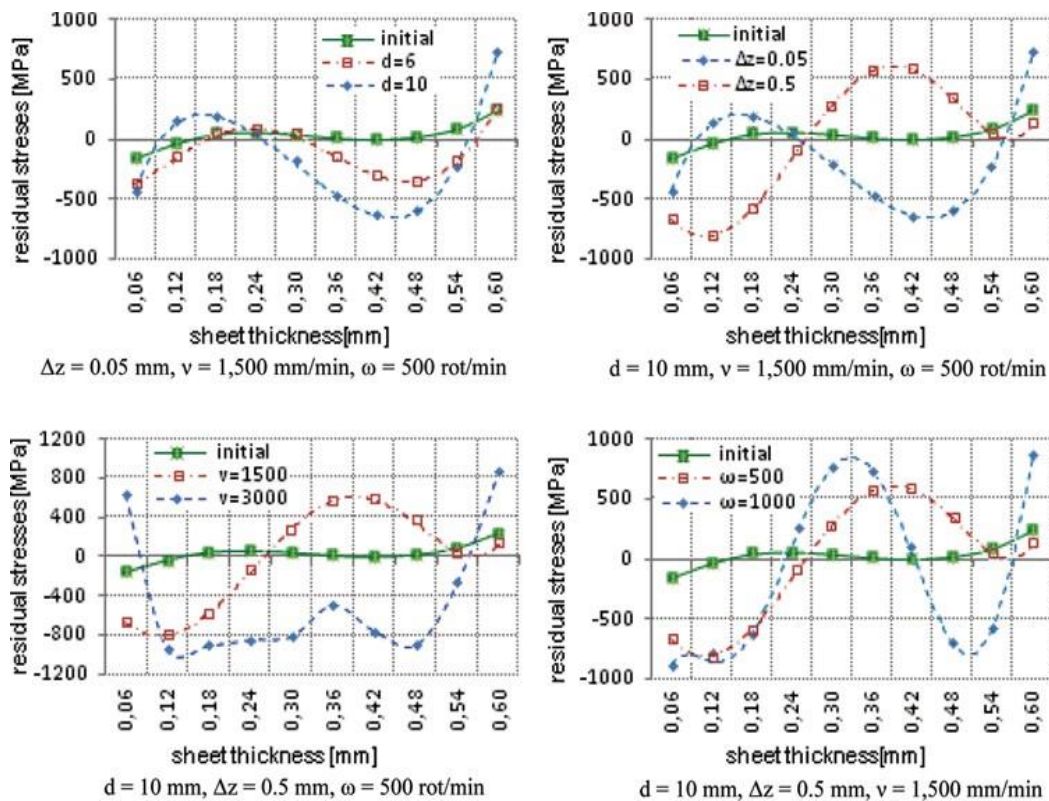


Figure 2.6: Shows the stress distribution of process parameters along the length [98].

It was concluded that favorable residual stress and excellent part accuracy can be achieved when a small diameter of the tool and small increment depth has taken in a process [98].

Further Radu et al. in 2013 in a work on residual stresses generated in the aluminum sheet which was formed by SPIF method. A hole drilling method is used to measure the residual stress in two geometry of aluminum metal sheets. They observed that when tool size and incremental vertical depth is increased tensile stresses are induced which leads to geometrical inaccuracy in a SPIF made parts due to distortion. Also, tensile residual stresses may cause stress corrosion cracking even when the no external load applied on the sheet [99].

Mahnoush Alinaghian et al. investigated on bimetal material by using incremental hole-drilling method to get to know residual stresses influence by tool size, incremental depth and rotational speed of single point incremental forming on parts. They found that smaller the increment step size smaller the residual stress forces induced in Al/Cu bimetal material [100].

Isaac et al. find out the distribution of residual stresses along the aluminum 6061 sheet parts inside and outside surfaces processed by SPIF was investigated. Residual strains have been experimentally recorded using an X-ray diffractometer to find out the residual stresses along the surfaces of the sample. It has been noted that the stress curve has a nonlinear distribution that generates bending impacts in the aluminum sheet, which change the cross-section area thickness of part [101]. Mohammadi et al. using laser-assisted annealing to relieve the stress of SPIF shaped components, the residual stress on the surface of the manufactured components was registered by X-ray diffraction and discovered that the laser annealing reduces the residual stress magnitudes compared to the cold SPIF components [102].

Singh and Agrawal used the method of nano-indentation to achieve the distribution of surface residual stresses in Al 6063-T6 samples produced by deformation machining (DM) method (a mixture of thin structure machining and SPIF). They researched the impact of the forming depth and feed rate on surface residual stress and noted that tensile residual stresses on the surface are growing while the increase in depth and feed rate [103].

2.8. Research Gap

The literature review presented above shows that most of the previous work is concentrated towards Aluminum, steel and PLA and some titanium alloys as biomaterial used by SPIF process. There is no literature available which evaluate the residual stresses in commercially pure titanium grade 2 which used as a biomaterial implant in cranioplasty surgery employed

by SPIF. Residual stresses and their affects on sensitivity of deformation by SPIF has not been considered yet in the literature. Since remaining stresses in the cranial implant may arise deformation in the patient even after a few years of installation which leads to being a very severe problem for the patient. Even minutely deformation in cranial plate due to residual stresses makes it one of the reasons for re-surgery or might be severe pain in the patient`s head.

2.9. Research Objectives

1. Developed of a reliable experimental setup for incremental forming process.
2. Experimental evaluation of the microstructure features of the formed commercial pure titanium grade 2 sheet metal.
3. Experimental evaluation of forces induced during single point incremental forming commercial pure titanium sheet metal.
4. Experimental evaluation of the induced residual stresses at significant process parameters of single point incremental forming process.

3.1. General

This section begins by describing the experimental methods that were utilized for the material characterization, method utilized for evaluate the residual stresses in material, the experimental SPIF setup utilized, the plan of experiments and the design of inverted cone with different process parameters are carried out.

3.2. Plan of Experiment

The experimental work was specifically designed to explore the impact of forming angle on different incremental step depth on residual stresses generated in SPIF parts after manufactured it

Table 3.1: Shows the plan of experiment.

Exp. No.	Incremental Depth(mm)	Forming Angle	Feed (mm/min)	Spindle speed (rpm)
1	0.25	30°	100	300
2	0.25	45°	100	300
3	0.25	60°	100	300
4	0.25	75°	100	300
5	0.5	30°	100	300
6	0.5	45°	100	300
7	0.5	60°	100	300
8	0.5	75°	100	300
9	0.75	30°	100	300
10	0.75	45°	100	300
11	0.75	60°	100	300
12	0.75	75°	100	300
13	1	30°	100	300
14	1	45°	100	300
15	1	60°	100	300
16	1	75°	100	300

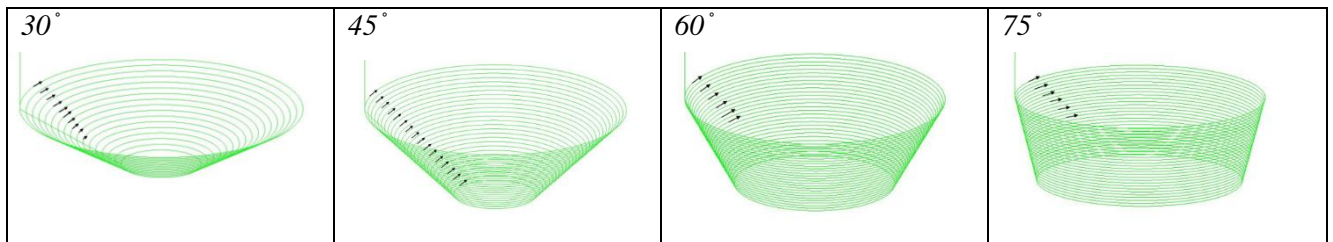


Figure 3.1: Contour tool path for different forming angle [Courtesy: Swan soft CNC simulator].

3.3.Experimental Setup

Experimental configuration overview is defined in the following subsections which include the CNC machine definition, the tool used, the sheet material used, the lubrication used and the fixture used to clamp the sheet during the experiments.


3.3.1. CNC Equipment

All experiments were conducted at the Mechanical Engineering Department at Thapar Institute of Engg. & Tech on a 3 axis BFW's CNC vertical machining center as shown in figure.



Figure 3.2: Three axis BFW's CNC vertical machining center.

Table 3.2: Machine Specification.

CNC Operating System	Fanuc Series Oi Mate MD	
Total Driven Axis	3	
Machining Capacity(mm)	800/350/380 (XYZ resp.)	
Max. Tool Size (mm)	75	

3.3.2. Tool used

The 8 mm diameter tool were manufactured from HSS (High Strength Steel) material with hemispherical shaped tip hardened to 64 HRC as shown in below Figure.

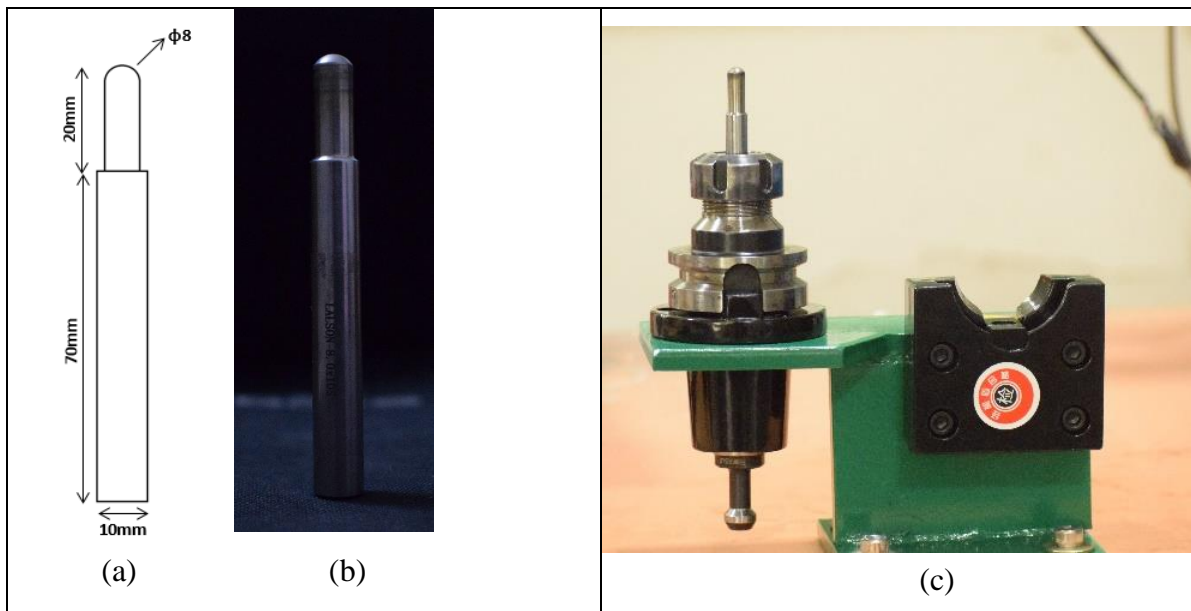


Figure 3.3: Forming tool (a)Drawing of hemispherical tool (b) manufactured tool(c)The forming tool installed in the chuck.

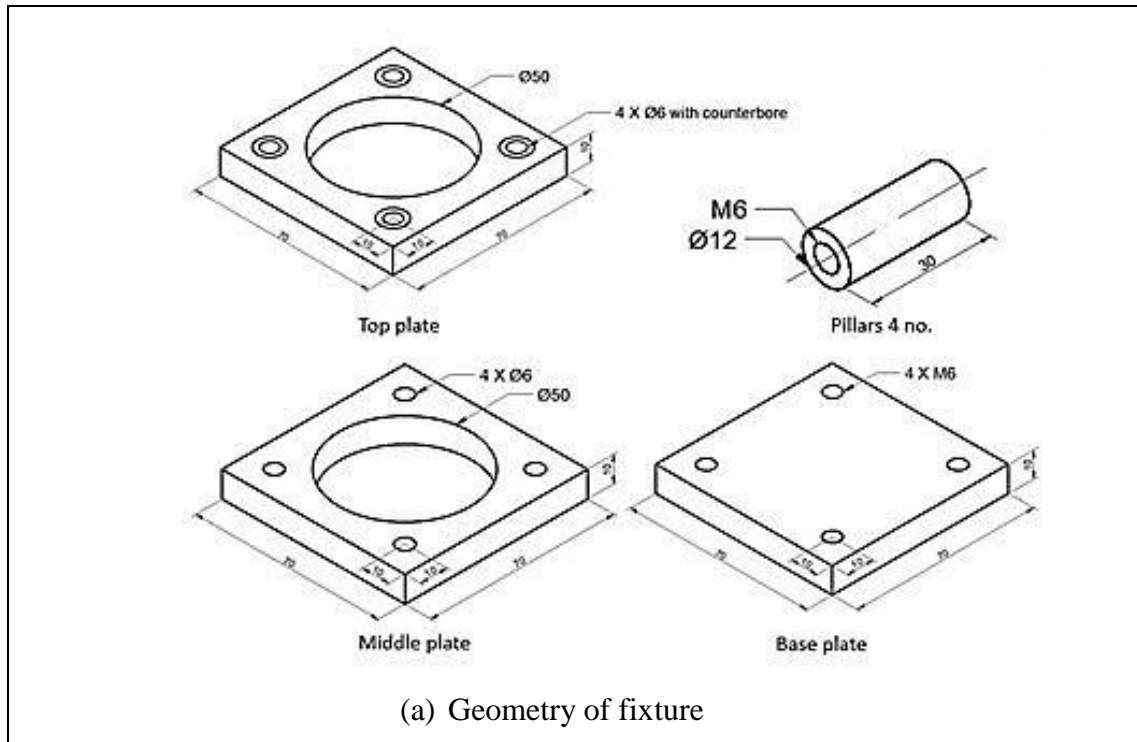
For achieve a good surface quality there is need to polished tool for minimize the friction between tools and sheet metal. A set of operations performed on tool before applying onto a titanium sheet. First with an abrasive paper of 20 μ m applied on tool surface to removed major imperfections and scratches. After this tool was polished with diamond paste with decreasing abrasive grains from 10 μ m to 6 μ m applied to finishing the surface of tool. A 0.7 μ m R_z surface roughness profile is measured by Mitutoyo Surface Roughness tester SJ 400 as shown in Figure.



Figure 3.4: (a) Disc grinder & polisher (b) Surface roughness measured by stylus.

3.3.3. SPIF Fixture

To perform an operation on CNC machine a complete mild steel fixture consist of plates and supporting pillars were fabricated to hold the corresponding sheet metal for incremental forming as shown in Figure. The entire setup is consist of clamped to the bottom corners of the piezoelectric dynamometer by two M8 screws. Further dynamometer is clamped with CNC machine bed. The working area of the forming process was 50 mm diameter where inverted cone deformed at different forming angles. In ISF process there is no need of backing plate which makes it more economically and rapid manufacturing process.



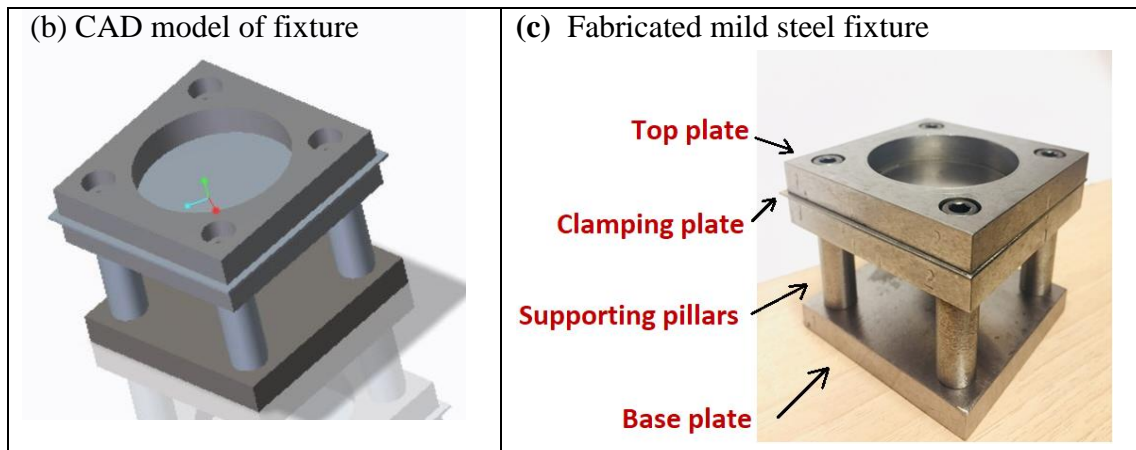


Figure 3.5: Complete model of fixture (a) Geometry of Fixture, (b) CAD model of fixture. (c) Fabricated mild steel fixture.

3.3.4. Initial Material

The Cp-Ti grade 2 sheets was purchased from Sachin Steel Centre Mumbai, India in annealed condition with 450 mm in length, 450mm cm in breadth and 0.98mm (approx. 1mm) thickness which were later cut to 75 x 75 mm sheets for clamping in fixture. The chemical composition of material was obtained using a spectrometer from Metallurgical test laboratory services Mumbai, see in Table 3.3.

Table 3.3: Chemical composition of the studied titanium

Element	%C	%Cr	%Cr	%Fe	%N	%Ni	%Sn	%W	%Ti
Wt.%	0.006	0.004	0.022	0.072	0.014	0.018	0.006	0.007	99.849

3.3.5. Lubrication used

In order to minimize the friction and dissipate the heat between sheet and forming the sheet is lubricated by ISO VG 68 grade servo hydraulic oil. The film of oil is capable of bear load, wear and avoiding the breakdown. To achieve a smooth surface and reduce the wear of forming is also advantage of lubricant in SPIF. A complete setup with lubrication oil as shown in Figure 3.6.

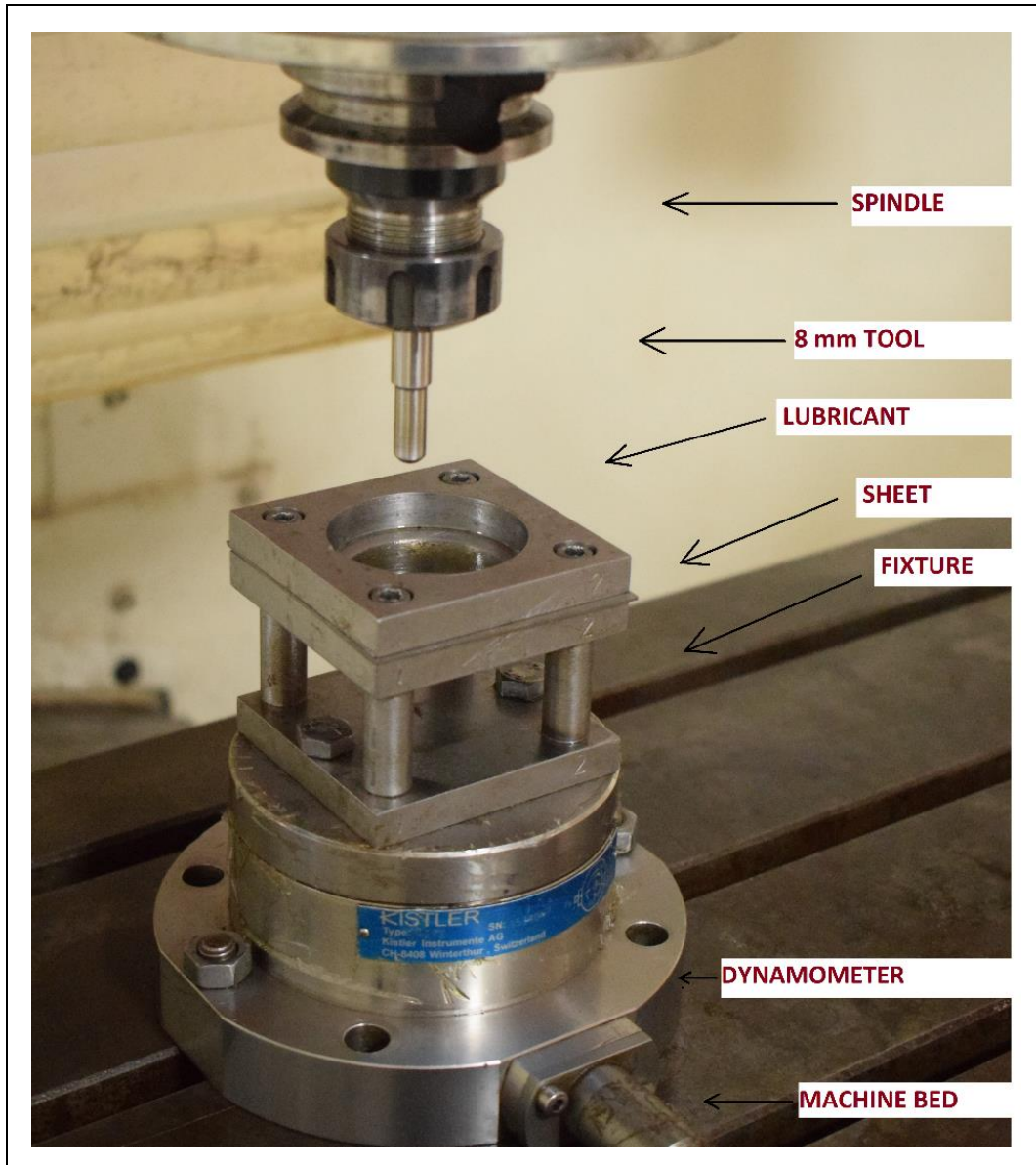



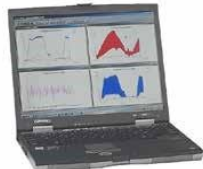


Figure 3.6: Dedicated setup with clamped sheet for SPIF.

3.4. Force measurement

Besides the assessment of deformations, unique emphasis was also provided to the studies of the forming forces, which are particularly crucial in the context of selecting the suitable materials and optimal method parameters to ensure SPIF's accuracy and reliability. The dynamometer running on the piezo effect concept that shifts the mechanical signal with the charge amplifier into the electrical one. This was a Kistler 9272 four-component force dynamometer and connected to it was a complementary Kistler 5070A 8-channel charge amplifier. With these equipments the forces exerted upon the sheet metal by the tool were recorded on a computer based data acquisition system as shown in Table 3.4.

Table 3.4: Measuring instruments of forces measurement.

			
Dynamometer	Connection cable, high impedance	Charge amplifier with integrated DAQ	Notebook (from customer side) with DynoWare
Type 9272	Type 16xx	Type 5070A...	

3.5. Depth Measurement Instrument

The goal of depth estimation is to be understood by SPIF about the geometric or dimensional elements of the parts created. Depth of each sample is measured by Accurate Spectra Coordinate measuring machine which is operated by CNC drive using selected planes at a surfaces. Recorded depth of all 16 samples are shown in Table 4.1 which is achieved by SPIF process.

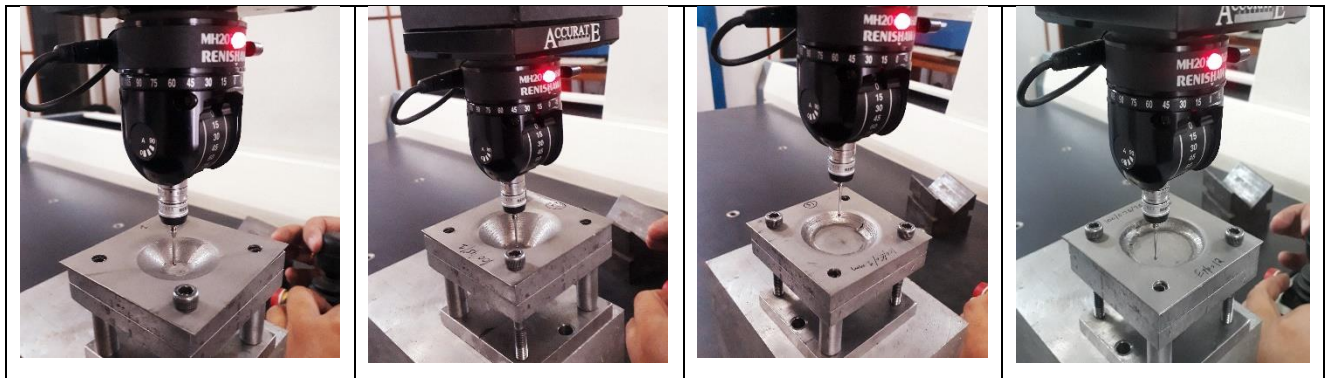


Figure 3.7: Shows the depth measurement of different forming angles 30°, 45°, 60°, 75° resp.

3.6. Sample preparation

3.6.1. Waterjet cutting

Cutting titanium is not an easy task due to its reactive nature, it changes its chemical properties when exposed to heat. Therefore, titanium is cut cold. A Dardi DWJ1525-FC CNC water jet cutting machine is being used to cut the sample for EBSD and XRD of dimensions 10*5mm for 30° and 45° samples and 7*4mm for 60° and 75° according to achieved forming depth. Samples were cut at a speed of 300mm/min with a 4mm stand-off distance between the sheet and waterjet nozzle as shown in Figure 3.8.

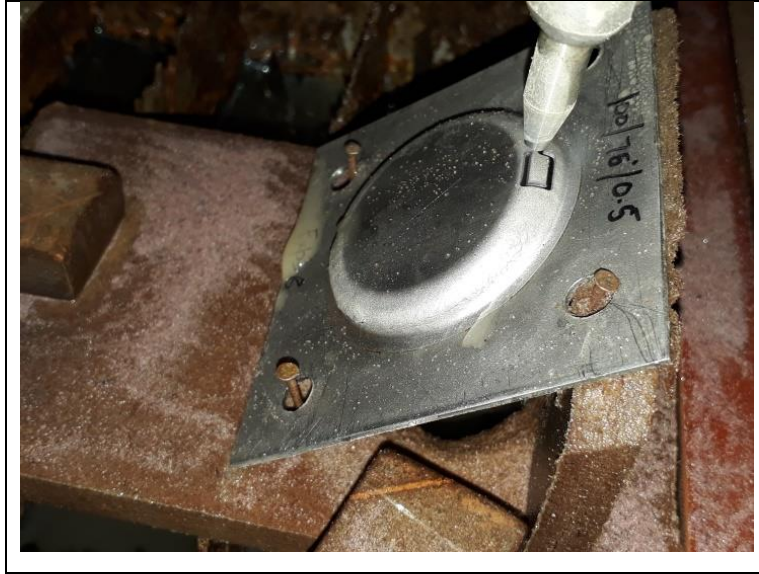


Figure 3.8: Sample cut by Waterjet CNC cutting.

3.6.2. Polishing

The surface to be examined by EBSD has been cleaned with subsequent low grade abrasive paper to high grade paper such as 400, 600, 800, 1000, 1500 and 2000 mesh used to polish the surface until all scratches removed or finer. By apply uniform pressure to avoid deep scratches and avoid overheating of sample results finer surface of sample. To achieve mirror finish and scratch free surface a disc polisher machine is used with diamond paste is applied on a sample. After performing polishing a electro polishing can be performed on ready samples to remove sample dust, scratches and contaminants from the sample. Electro polishing to be done with 20% perchloric acid and 80% methanol at 27V, 4.5A current for the time of 10 sec. The electro-polishing device used in the current job is shown in Figure 3.9(b).

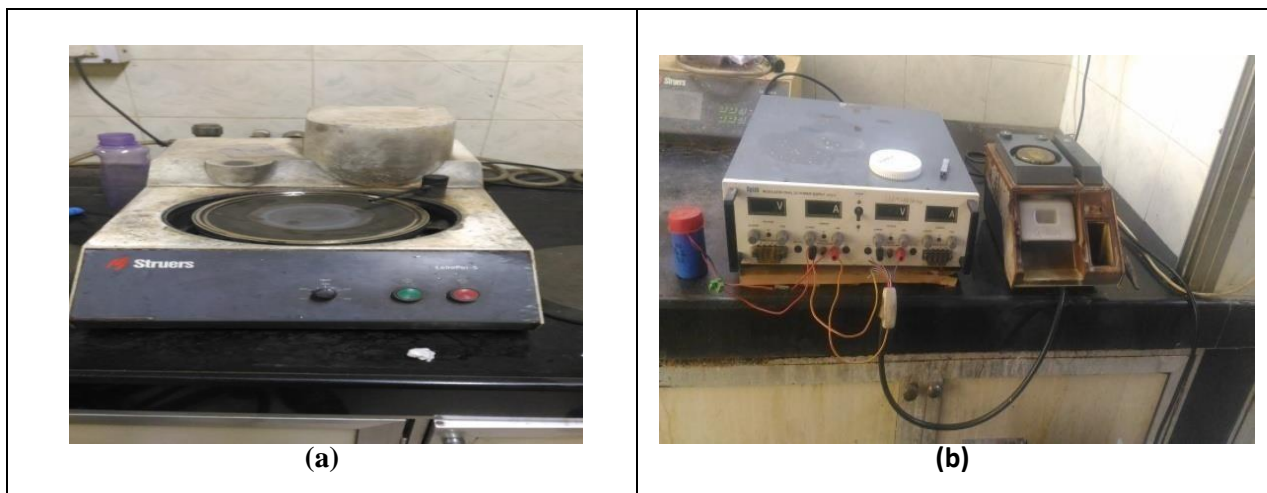


Figure 3.9 : Polishing (a) Polishing Machine (b) Electro-polishing(Courtesy: IIT,Bombay).

3.6.3. X-Ray diffraction (Bruker)

X-ray diffraction (XRD) is a fast analytical, non-destructive device designed to analyze a wide variety of alloys, including metals, polymers and semiconductors. It has become an essential technique for investigating and characterizing the materials. For example, phase assessment, crystallography, determination of composition and relaxation, texture and quantification of residual stress. The Bruker X-ray is fitted with optical encoder stepper motors to assure highly accurate angular readings [104]. Residual stress measurements of 16 samples according to plan of experiment at their exterior surface was measured. The direction of beam of travel follows the circumferential direction of sample. Figure 3.10(a, b) presents the XRD measurement sample setup and Bruker machine respectively.

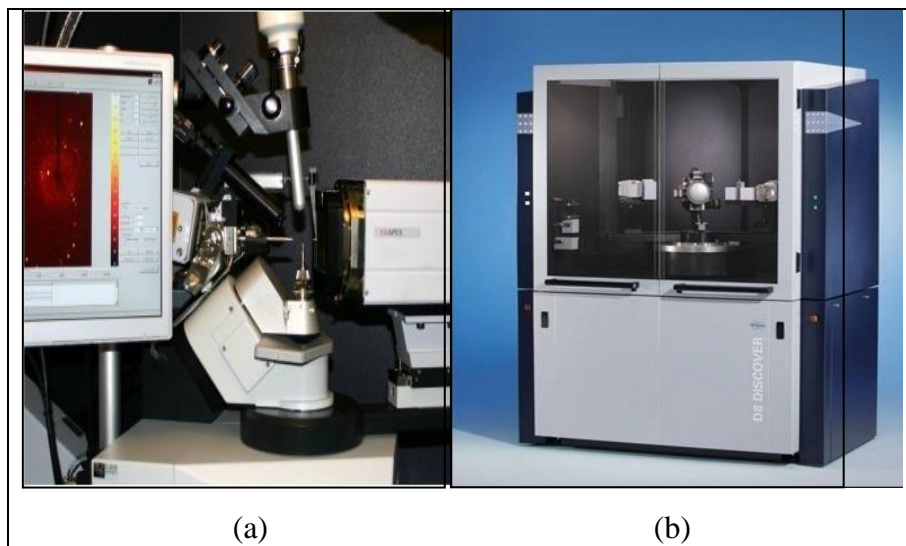


Figure 3.10: (a) Sample set-up (b) Bruker machine [104].

3.6.3.1. *Principle of measurement of residual stress by X-ray diffraction*

When a polycrystalline material is elastically deformed in such a way that the strain is uniform over relatively large distances, the spacing of the lattice plane in the constituent grains changes from their stress-free value to some new value, which is corresponding to a magnitude of the stress applied on the metal sheet. This spacing is measured by the X-ray diffraction technique. It is always strain that is measured; the stress is determined indirectly, by calculation or calibration [105].

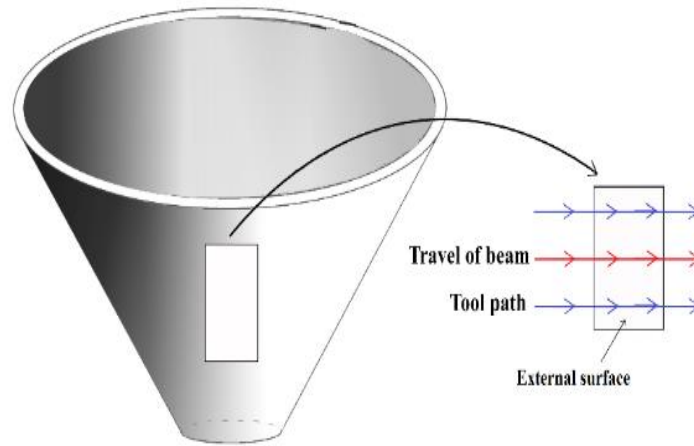


Figure 3.11: Schematic of X-ray beam travel on the surface of prepared sample.

3.6.4. Electron Back Scatter Diffraction (EBSD)

Electron Backscattered Diffraction (EBSD) is a method that enables with the scanning electron microscope (SEM) to obtain crystallographic data from samples. A stationary electron beam hits a inclined crystalline sample in EBSD and the diffracted electrons create a picture on a fluorescent screen. The diffraction model is used to evaluate crystal direction or orientation, misorientation of grain boundaries, recognize various materials, and provide data on local crystalline with excellence. The resulting map shows the constituent grain morphology, orientations and boundaries when the beam is scanned in a grid across a polycrystalline sample and the crystal orientation measured at each point [106]. In this research, EBSD was used to obtain the grain orientation and grain size in the direction of SPIF performed. All the measurements of EBSD were taken on the Quanta 3D FEG machine using the OIM EBSD package to keep the parameters identical between the scans as shown in Figure. 3.12.

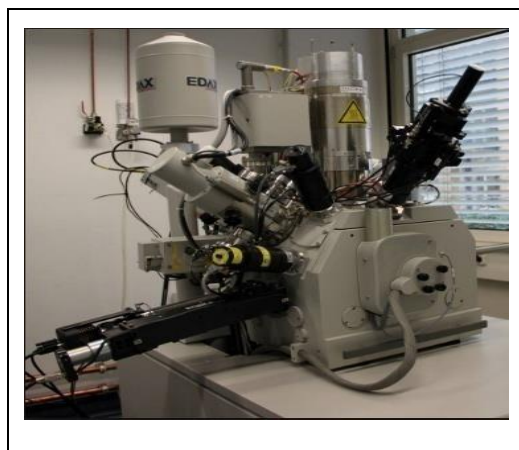
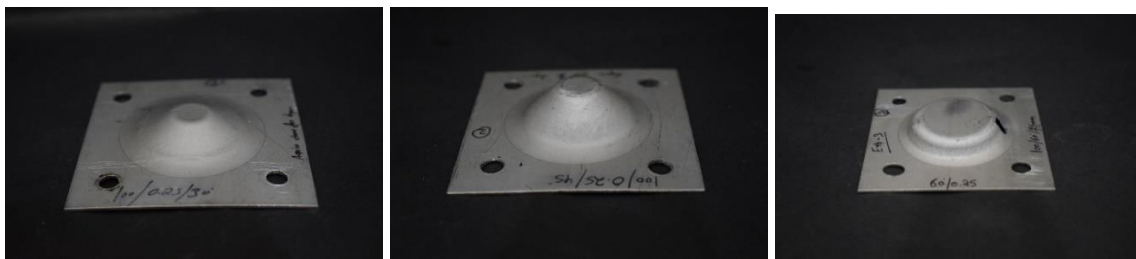


Figure 3.12: EBSD apparatus (courtesy: IIT Bombay)

4.1. General

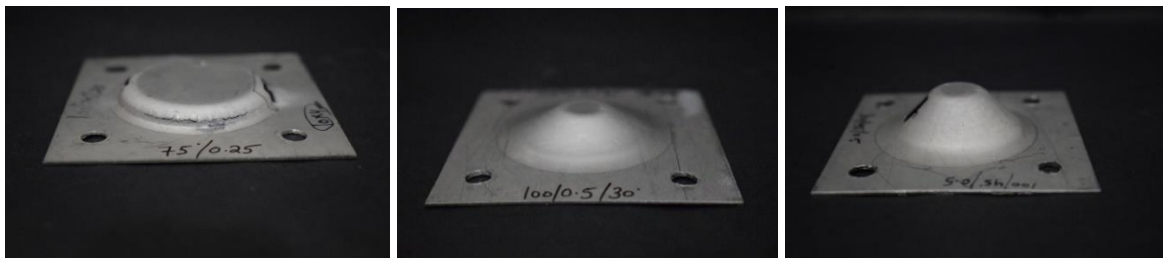
This chapter presents an analysis of the influence of the various forming parameters on the formed parts by SPIF with the objective of understanding if there is a relation between the forming parameters to the residual stresses generated during SPIF for a specific material. . During SPIF, a sequence of experiments were performed to assess the effect of incremental depth and forming angle on the forming forces, residual stresses and co-related with microstructures. The tests ended after the fracture of the each component (Figure 4.1).



(a)

(b)

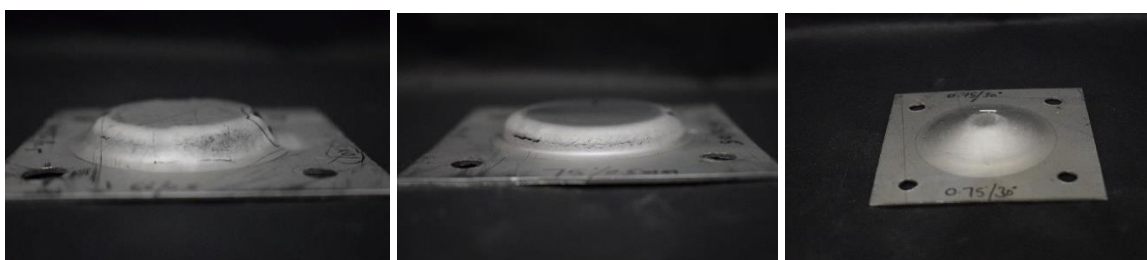
(c)



(d)

(e)

(f)



(g)

(h)

(i)

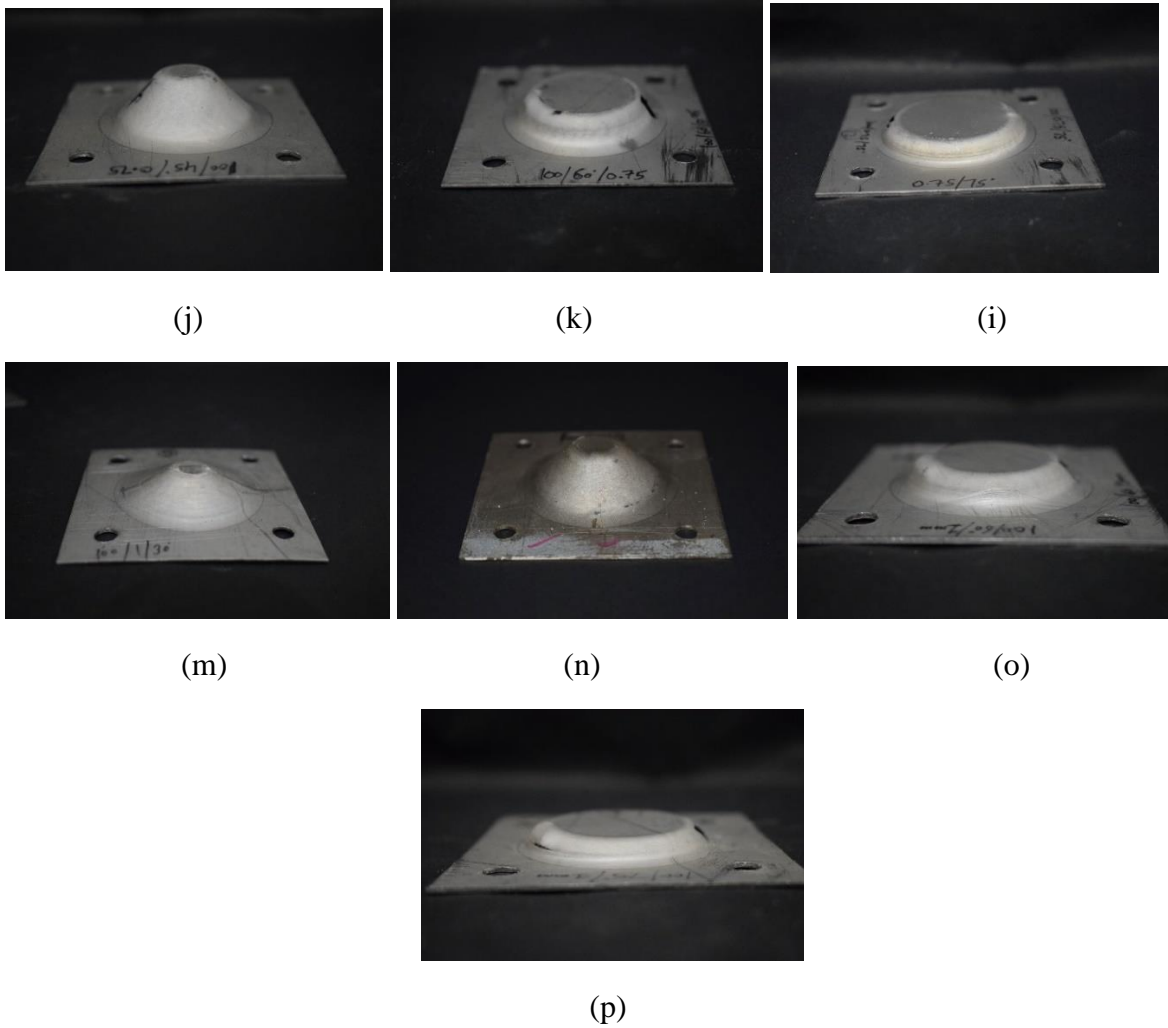


Figure 4.1: Deformed sample with maximum achievable depth at the end of the Sixteen experiments via the SPIF (single-point incremental forming): (a) exp.1; (b) exp.2; (c) exp.3; (d) exp.4; (e) exp.5; (f) exp.6; (g) exp.7; (h) exp.8; (i) exp.9; (j) exp.10; (k) exp.11; (l) exp.12; (m) exp.13; (n) exp.14; (o) exp.15 (p) exp.15.

4.2. Depth measurement

The objective of forming depth measurement is to be known the geometrical or dimensional aspects of formed components by SPIF. Depth of each sample is measured by Accurate Spectra Coordinate measuring machine which is operated by CNC drive. The maximum forming depth was achieved in the experiments of 30° and 45° forming angle at each incremental step depth. A forming depth of 60° and 75° samples at each incremental step depth was to be achieved until the first fracture occurs. A Table 4.1 shows the forming depth achieved at different parameters.

Table.4.1: Shows the maximum achieved forming depth on each experiment.

Experiment No	Incremental depth	Forming Angle	Achieved depth(mm)
1	0.25	30°	8.35
2	0.25	45°	14.02
3	0.25	60°	7.75
4	0.25	75°	5.69
5	0.5	30°	8.47
6	0.5	45°	13.93
7	0.5	60°	7.02
8	0.5	75°	5.84
9	0.75	30°	8.85
10	0.75	45°	14.20
11	0.75	60°	7.47
12	0.75	75°	5.97
13	1	30°	8.96
14	1	45°	13.97
15	1	60°	6.90
16	1	75°	5.20

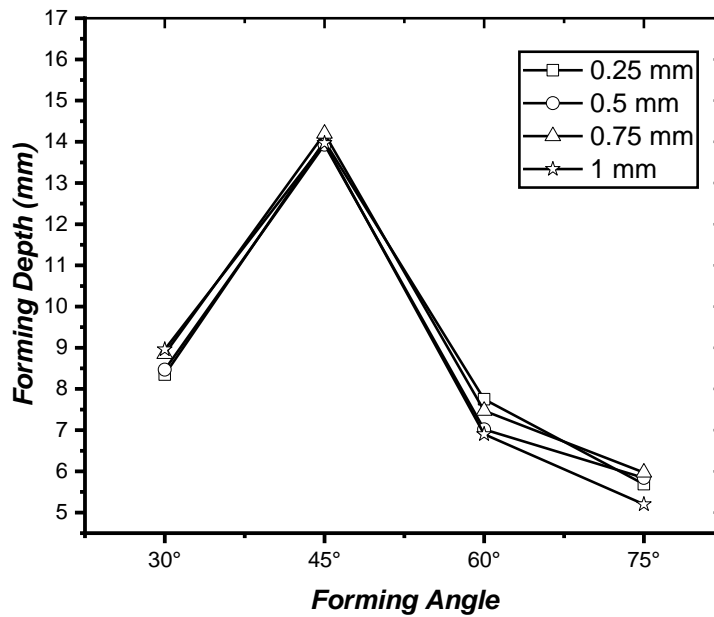


Figure.4.2: Shows the Achieved forming depth with varying forming angles.

As the forming angle increases the depth of forming is decreases because more sheet thinning is occurs when higher angle of formability is coming into the picture as shown in Figure 4.2. Which leads to failure of sheet by excessive sheet thinning of sheet metal and necking at localized deformation zone.

4.3. Investigation of force induced during SPIF

The patterns and magnitude of deforming forces and related stresses caused during stretching activities in a sheet metal during SPIF which affects the springback magnitude and orientation of the portion after unloading. The objective of measuring forces is also to get to know the how much intensity of force required to deform a specific material. Figures 4.3–4.6 show the results of the resultant of forming forces of three direction (F_z , F_y and F_x) measured by the dynamometer.

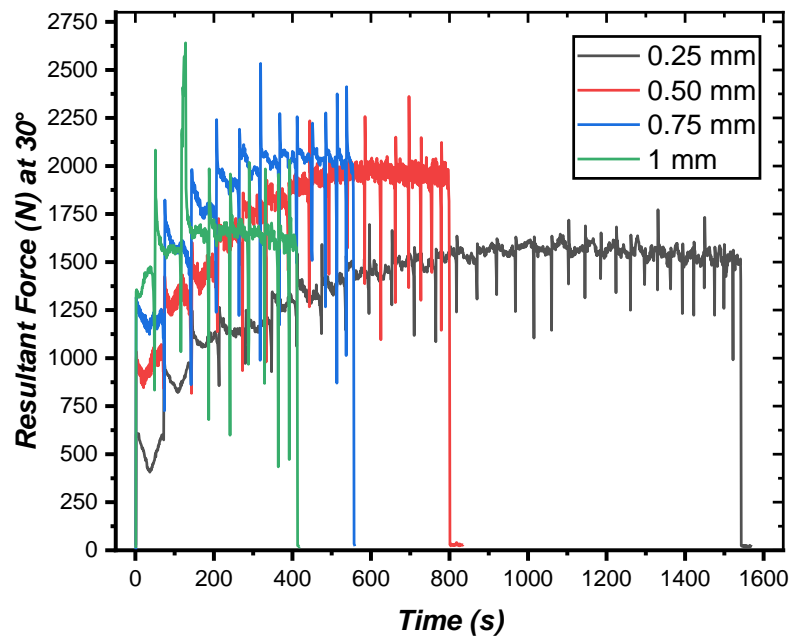


Figure.4.3: Resultant forming forces of 30° forming angle at different incremental step depths.

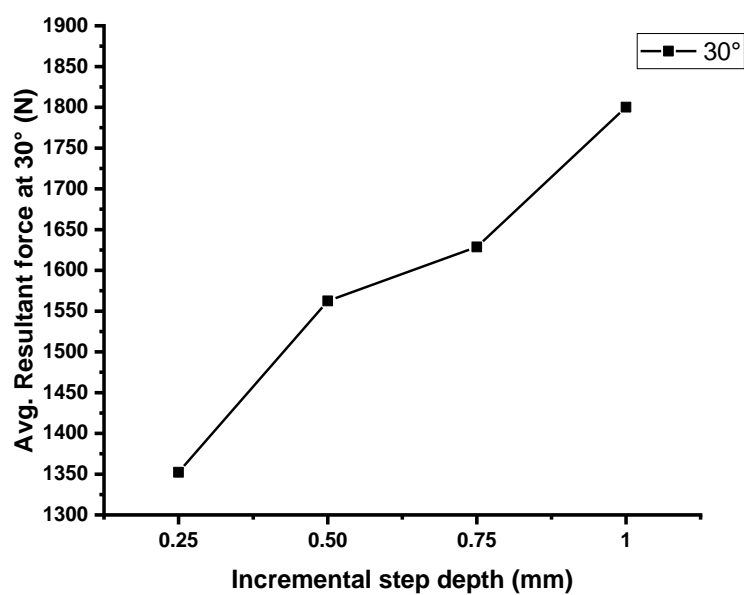


Figure 4.4 Influence of forces on each incremental step sizes at 30° forming angle.

For the geometry of the inverted cone and the trajectory of the tool path, forces were evaluated in three directions corresponding to a scheme of cartesian coordinates. Then these three components of force, F_x , F_y , and F_z , are combined into a form of vector of total force. All outcomes are based on the of resultant of these three variable forces arising at the time of deformation. Upon initiation of the formation, a typical total force (vector sum of three forces) curve begins at zero.

4.3.1. Influence of incremental Step Size

Figure. 4.3 to Figure. 4.10 shows the resultant forces and average resultant forces on all the 16 samples with vertical steps varied from 0.25mm to 1.0mm on each selected parameter of forming angle. All cone experiments were formed to maximum forming depth, which could be reached at the failure of sheet. It is evident that this magnitude of forces also increases as the vertical step size increases i.e clearly shown in graphs of influence of forces on each incremental step size at different forming angles. Like in the Figure of 4.4, 4.6, 4.8, and 4.10 shows the trend of average resultant force which states the as the step size is increases, forces is also increases at each forming angle.

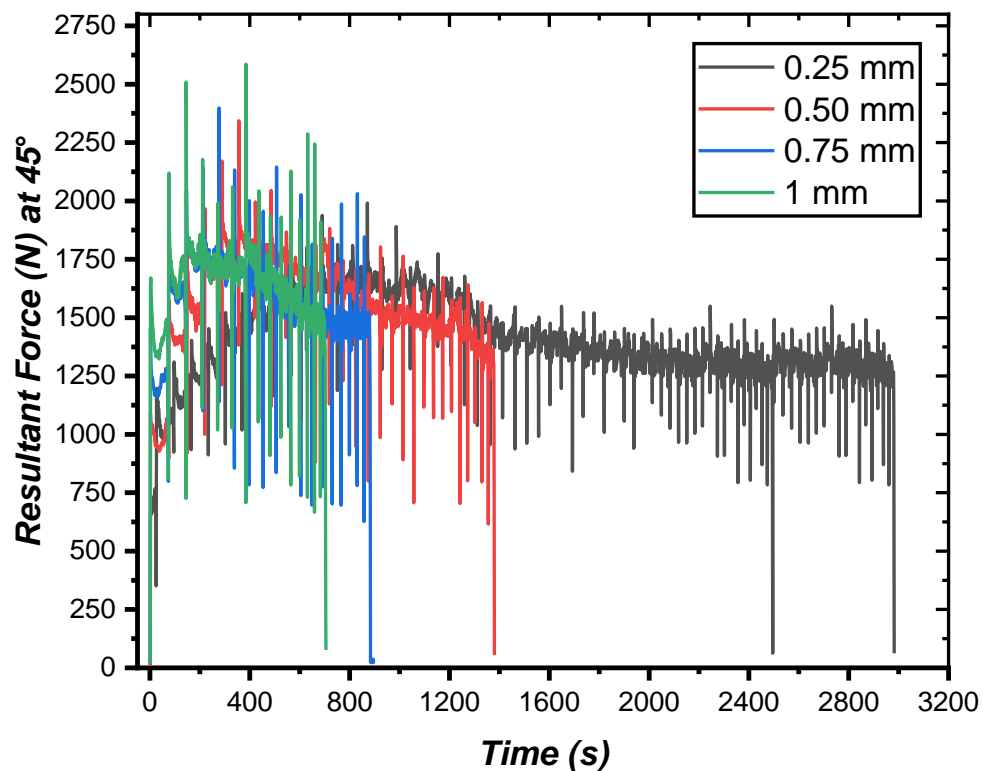


Figure.4.5: Resultant forming forces of 45° forming angle at different incremental step depths.

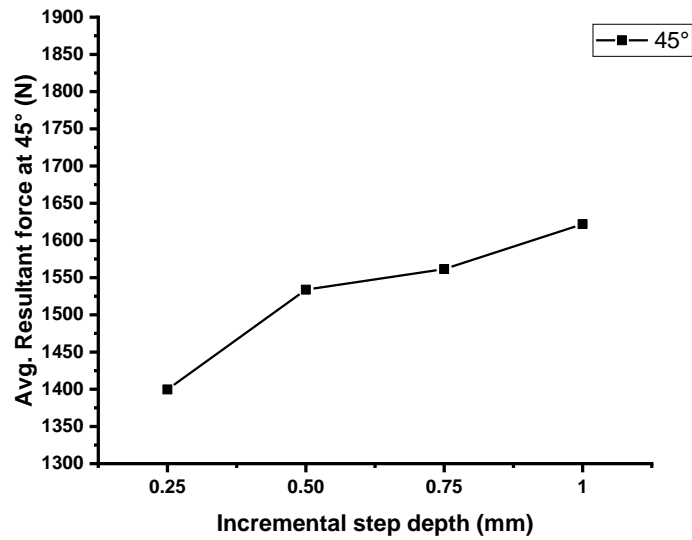


Figure 4.6 Influence of forces on each incremental step sizes at 45° forming angle

As shown in Figure 4.4 on 30° forming angle at progressive incremental step size (i.e. 0.25mm, 0.50mm, 0.75mm and 1mm) the average resultant force is increasing from 1352.36 N to 1800.17 N. Similar in the case of 45°, 60° and 75° forming angles as the step size increases a marginal increase in forces are recorded. The reason for such trend is the amount of deflection and strain increased in each step resulting in greater stress levels and corresponding load values.

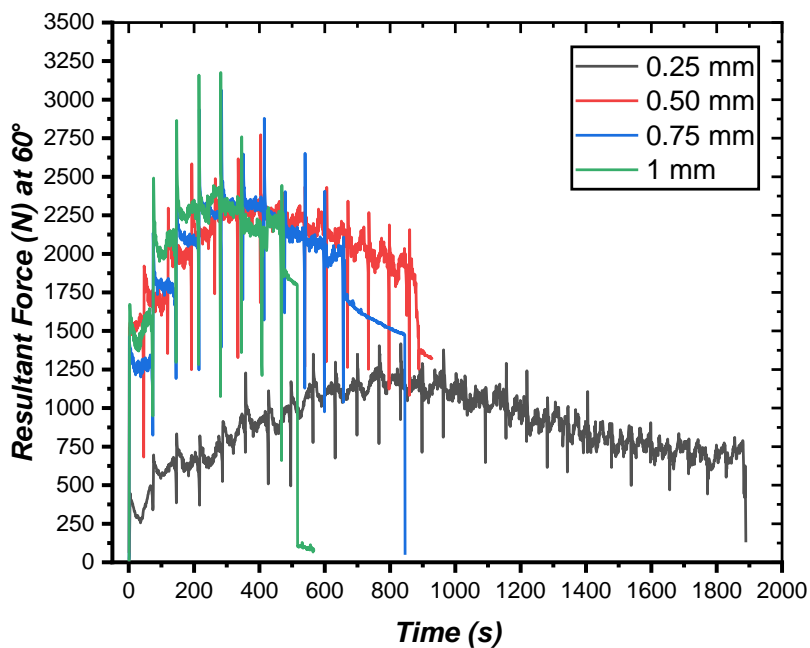


Figure.4.7: Resultant forming forces of 60° forming angle at different incremental step depths

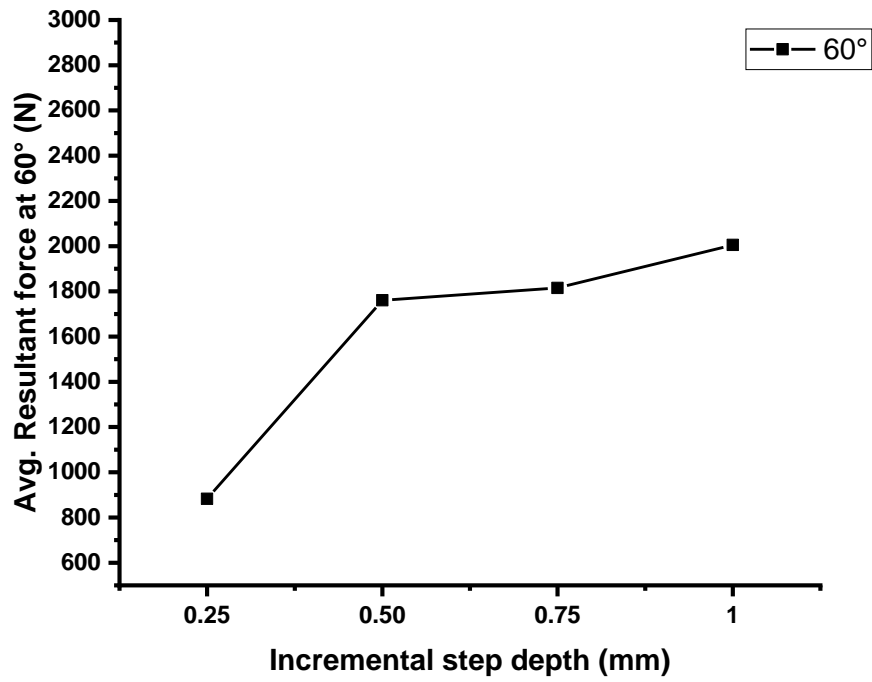


Figure 4.8 Influence of forces on each incremental step sizes at 60° forming angle

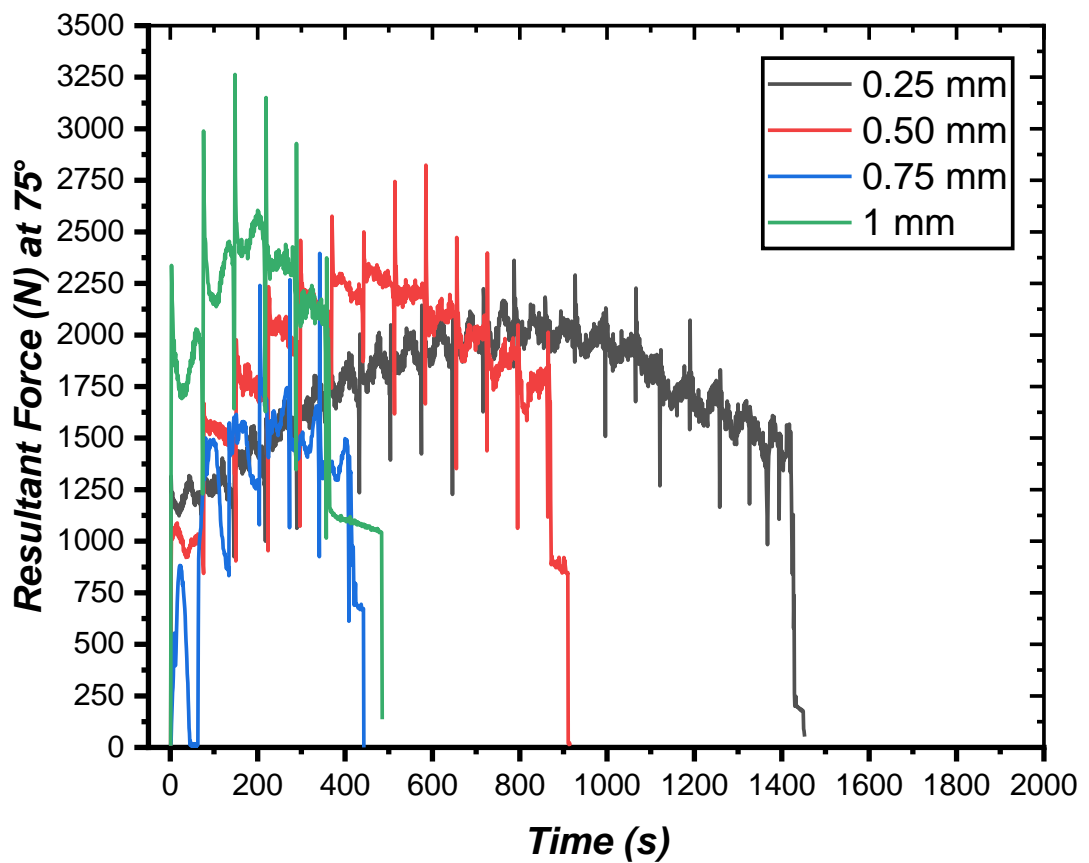


Figure.4.9: Resultant forming forces of 75° forming angle at different incremental step depths

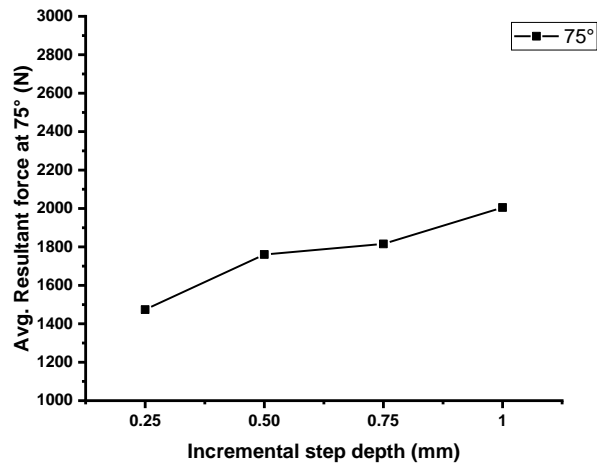


Figure 4.10 Influence of forces on each incremental step sizes at 75° forming angle

4.3.2. Influence of Forming Angle

The magnitude of the force required to deform the sheet metal is gradually increases as the part forming angle becomes steeper. This is evidently because with each move the sheet metal is more stressed and therefore needs more energy input. Test samples with angles of 30°,45°,60° and 75° were manufactured and the resulting force magnitudes shown in Figure 4.11a and Figure 4.12a. In the case of 75° forming angle maximum resultant force 3263.76 N is recorded with a 1 mm incremental depth step. The reason for such increase in the forces at increased forming angles for the same incremental depth is increased level of strain and material displacement at steeper forming angles. Figure 4.11b and Figure 4.12b also shows the influences of all forming angles at 0.25mm and 1mm incremental step depth. Same trend has been also observed in the case of 0.50mm and 0.75mm step depth.

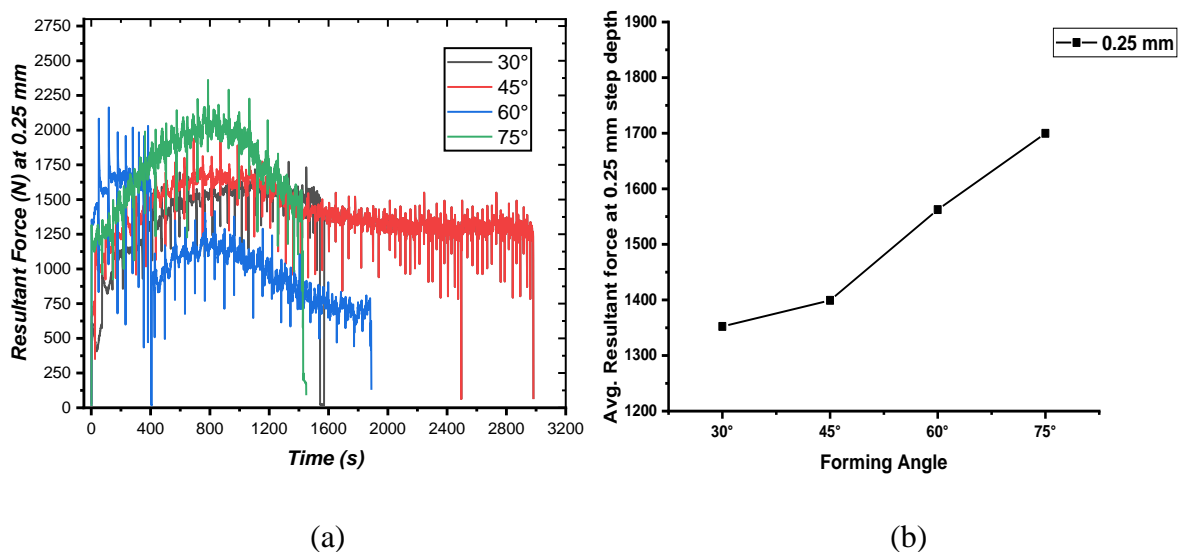


Figure 4.11 (a) Resultant forces at 0.25 mm on different forming angle (b) Influence of forming angles on 0.25 mm step depth.

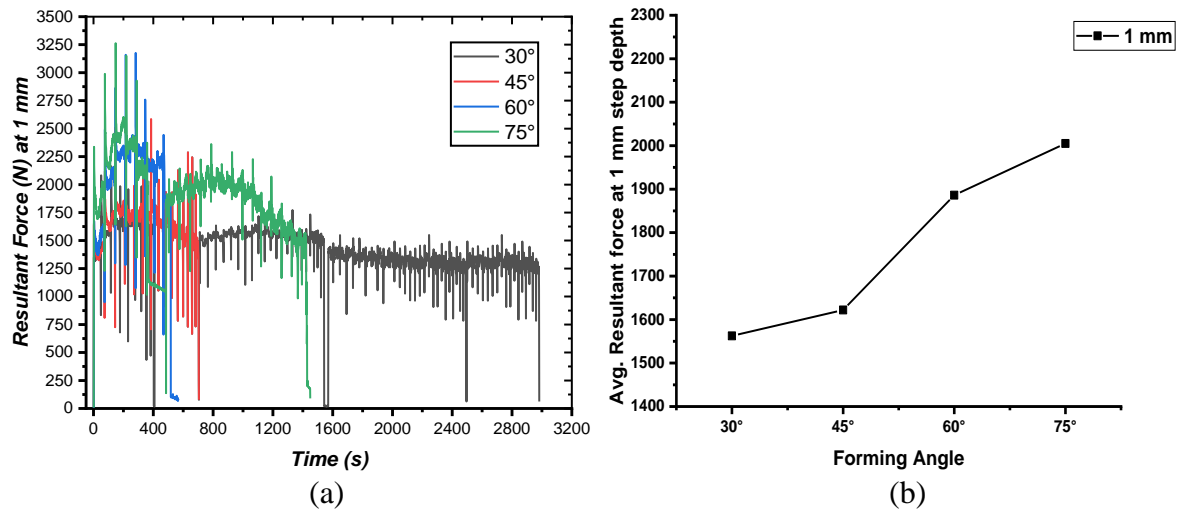


Figure 4.12 (a) Resultant forces at 1 mm on different forming angle (b) Influence of forming angles on 1mm step depth.

4.4. Grain Structure

EBSD technique was used to analyze to changing the microstructure of the material during SPIF process. It has been that the as received material has bimodal microstructure having few small grains and coarser grains as shown in Figure. 4.7. With increase in the incremental depth the plastic flow of material is increasing.

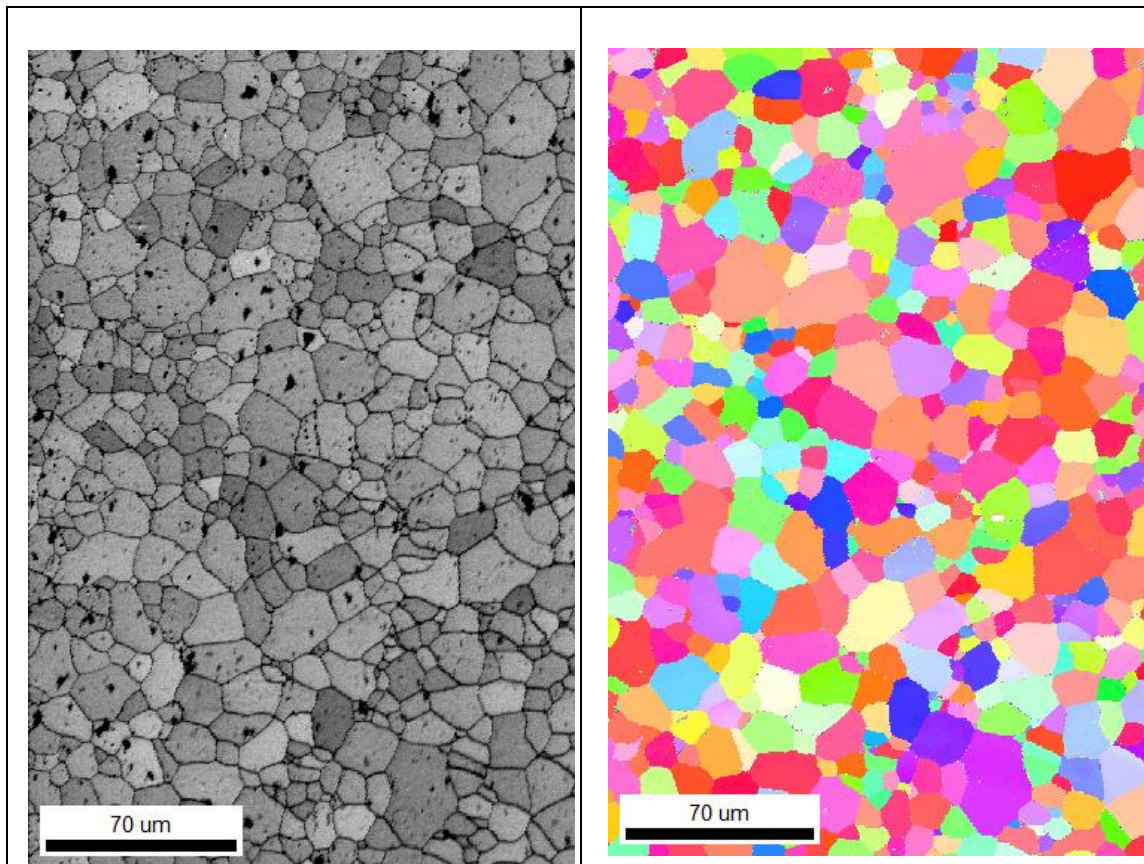


Figure 4.13: Microstructure of as received titanium metal sheet measured using EBSD technique.

The same has been found on the forming angle such as 30°,45°,60°, and 75° respectively. The Microstructure also revealed that there is very less effect of incremental forming at a depth of 0.25mm and forming angle 60°. However a marginal effect on the microstructure can be seen at a forming angle of 75°. The plastic flow of material increased at a depth of 0.5mm to 1mm for forming angle of 45°,60° and 75° respectively.

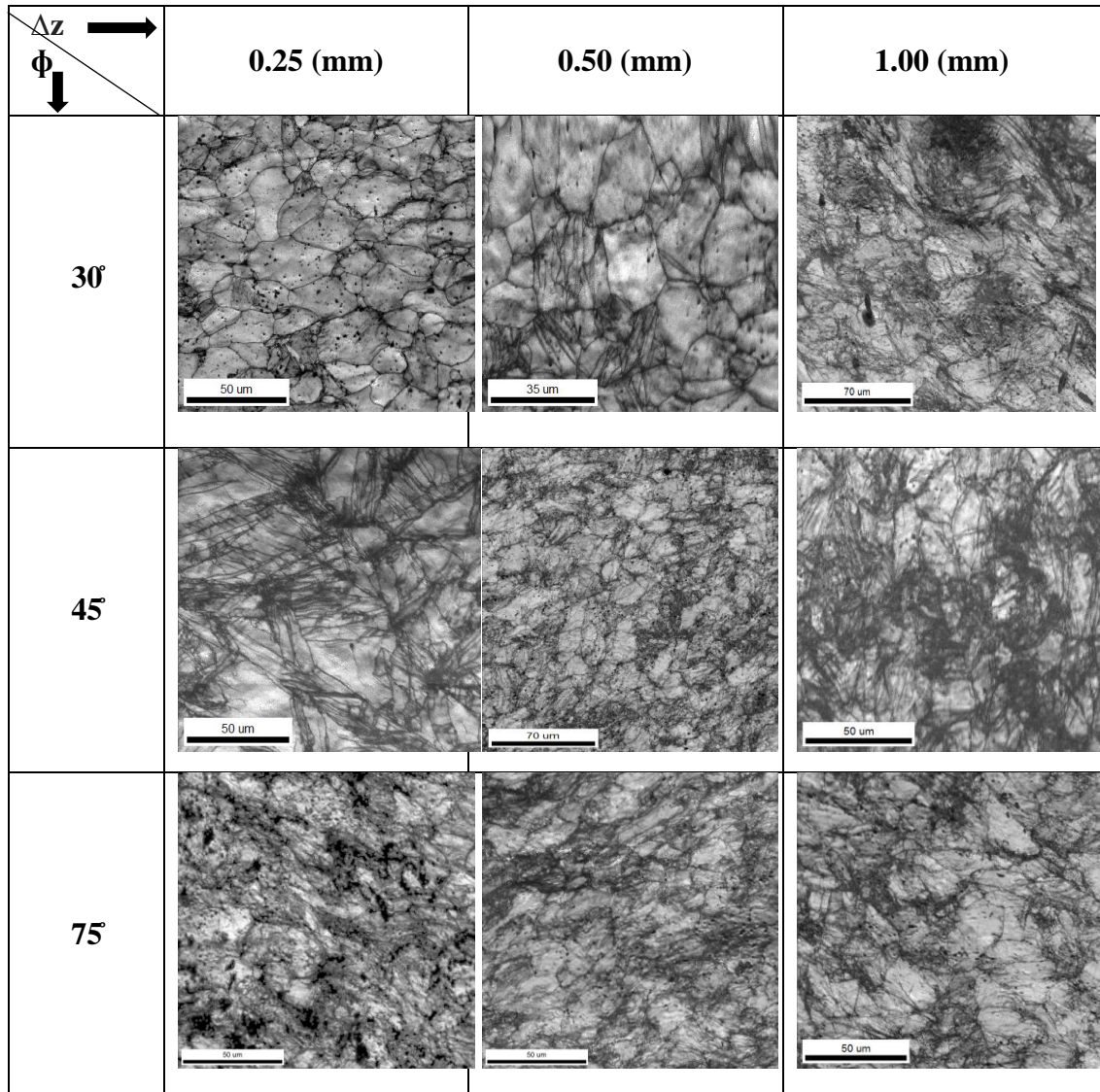


Figure. 4.14: Shows the microstructure evolution at given parameters

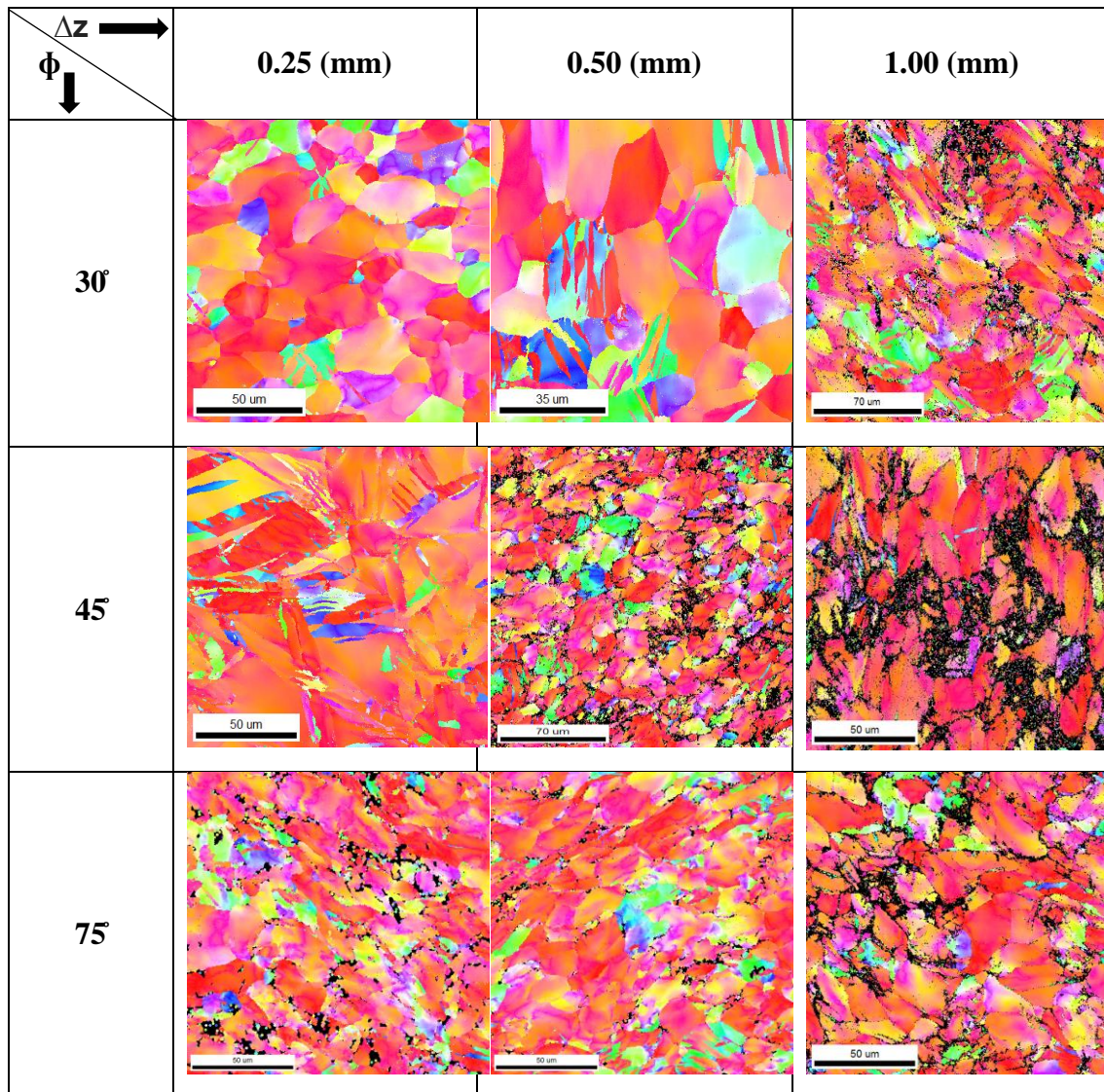


Figure.4.15. Shows the microstructure evolution at given parameters.

The microstructure was further analyze to in terms of average grain size and grain average misorientation. There is a drastic change in grain size when we compare initial grain size to forming sheet metal grain size in single incremental forming process.

Gradient in grain size has been observed through out the process. However this gradient is reduced with increase in forming angle. Unlike grain size the griendent in microstructure was relative to residual stresses induced during the SPIF.

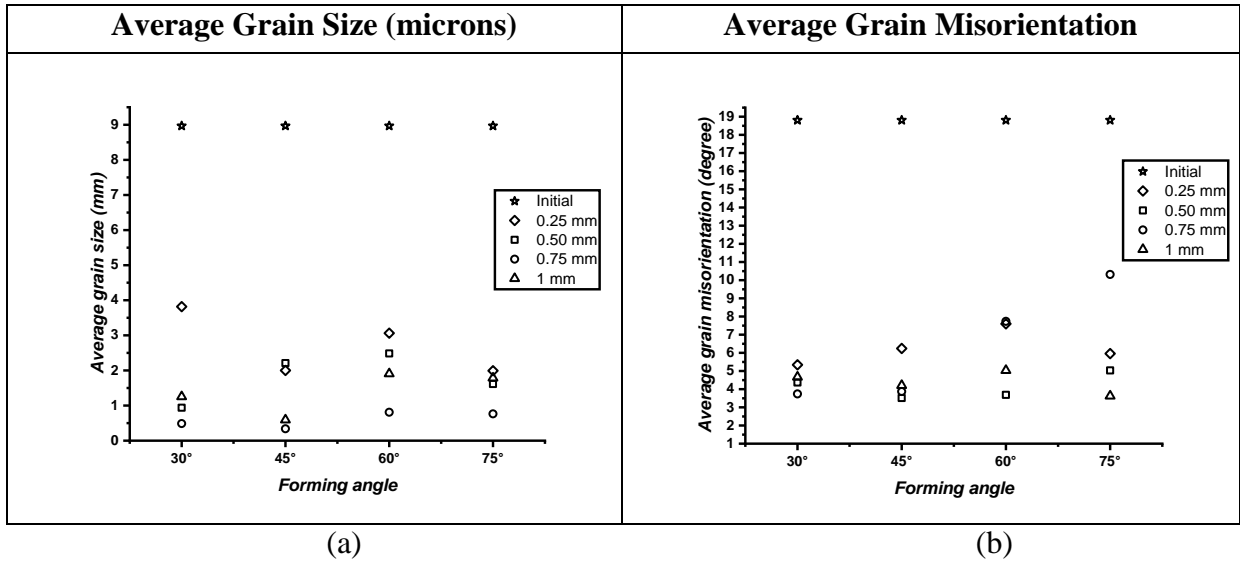


Figure 4.16: EBSD data for different forming angle with varying step size (a) Average grain size and (b) Average misorientation angle.

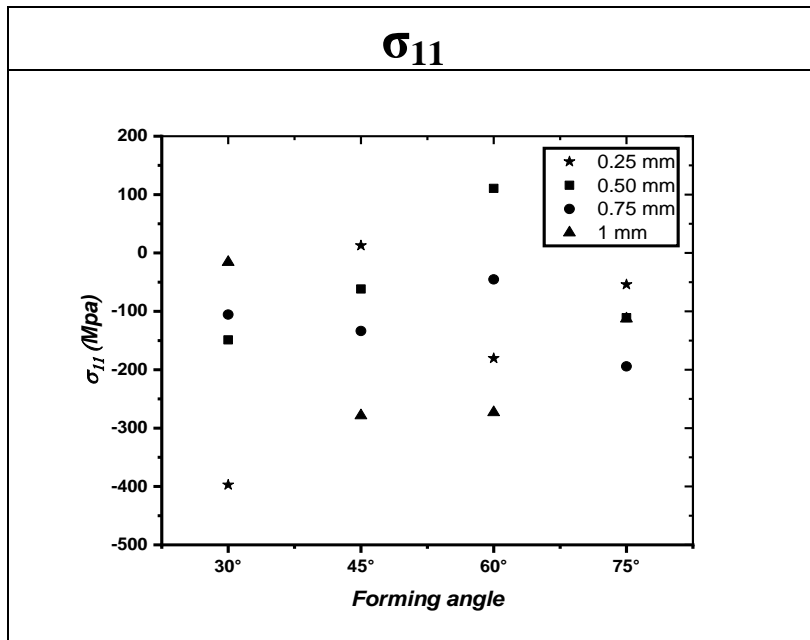


Figure 4.17: Residual stress σ_{11} distribution along with process parameters of SPIF.

The Figure 4.17 shows that the compressive residual stresses are induced during this incremental forming process. However these stresses changed its nature to tensile value with increase in forming angle from 30° to 60° and then again it comes to the compressive nature at 75°. The same trend has been observed for incremental depth 0.25mm, 0.5mm, and 0.75mm respectively. On the other hand the stresses are always compressive in nature for incremental depth of 1mm. Carefulll observation of residual stresses plot shows residual stresses gradient is increased from 30° to 60° and then further decreases at the 75° forming angle.

5.1. Conclusion and observations:

- Force magnitude is directly proportional to the increase in incremental depth and steepness of forming angle.
- Incremental forming has resulted in general reduction of grain size at all the tested parameters and levels. This will result in improved strength in the formed sheets in comparison to parent raw material.
- Generally, formation of low angle grain boundaries are noticed in incremental forming of titanium sheets, conforming stability of crystal structure of the material in comparison to parent raw material.
- The Microstructure also disclosed that the incremental forming impact at a depth of 0.25 mm and a 60 ° angle forming effect is much less. However in the case of 75° forming angle a marginal effect on the microstructure is observed.
- Residual stresses generated during SPIF is mostly compressive in nature but these stresses changed there nature to tensile value with increase in forming angle from 30° to 60° and then again it comes to the compressive nature at 75°. Therefore, residual stresses can be controlled or tailored for a specific application by changing the process parameters accordingly.

5.2. Future Scope of work:

- Detailed evaluation of residual stresses induced in single point incremental forming of titanium sheets at all important process parametrs.
- Based upon the evaluation, Development of robust strategy to minimize those stresses.
- Detailed evaluation of geometrical discrepancies in the process like spring back, tool deflection, radial erro,etc.
- Fabricated a real time component according to human uniqueness anatomy.

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