Numerical and Experimental Analysis on Surface Quality in Single Point Incremental Forming Through Varying Tool Path

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List of abbreviations and symbols

Some symbols appear more than once, their specific meaning follows from their context.

Commonly used notations

w	Width of sheet
h	Height of sheet
t	Thickness of sheet
t_i	Initial thickness of sheet
t_f	Final thickness of sheet
Δz	Size of incremental stepdown
φ	Forming angle
r	Radius of tool
Ra	Surface quality
σ_e	Engineering stress
ε_e	Engineering strain
σ	Displacement
Mm	Millimeter
Mm/s	Millimeter per second
Al	Aluminum
Fe	Iron
Cu	Copper
Mg	Magnesium
Zn	Zinc
Cr	Chromium
Mn	Marganese
Ti	Titanium
Ni	Nickel

Abbreviations

ISF	Incremental Sheet Forming
SPIF	Single Point Incremental Forming
TPIF	Two Point Incremental Forming
HISF	Hybrid Incremental Forming
FEA	Finite Element Analysis
FEM	Finite Element Method
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAE	Computer Aided Engineering
INP file	Input File
CNC	Numerical Control
3D	Three Dimensions
MPa	Megapascal
AA5052	Aluminum ally

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ABSTRACT

Nowadays, worthwhile and customer friendly sheet forming processes are big demand in small batch and prototype production due to changing trends. Therefore, developing flexible and economical sheet forming processes and technologies is very important. However, in sheet metal processing, such an approach is difficult, since the implementation of new technologies requires time for their development and production of die equipment, as well as significant capital investments at the pre-production stages. In order to master new technologies without these complex steps, an approach with the most efficient use of information technology is required. This principle is embedded in CNC systems and can be implemented for processing sheet material by incremental forming. Incremental sheet forming (ISF) is one of the promising sheet forming processes and it can be valid for these purposes. Single point incremental forming (SPIF), especially, becomes popular because of its low expenses and rapidly adaption to customers' needs.[1]

The aim of this study is investigating three types of tool path experimentally and numerically and impact of tool path type on quality of surface of final product. During the study, design of final product and three types of tool path for forming process is generated using student version of Autodesk Fusion 360 CAD/CAM software. All three tool path names as 'Contour', 'Ramp' and 'Spiral' according to generating method of these tool path in CAD/CAM software. Commercial aluminum alloy AA5052 and combination of oil with grease were used as a material and lubrication respectively. In order to carry out practical experiments low-cost 'TinyCNC-S' CNC milling machine with some modifications is utilized. During implementing SPIF process aluminum workpieces were formed using mentioned tool path with change step size between 0.2 – 0.8 mm and same forming tool with hemisphere end is employed for all experiments. Measurement and comparison of final products' surface quality is carried on using 3D Nano Profiling System. Furthermore, Finite Element Analysis (FEA) is also employed to analyze thickness distribution and deforming forces during SPIF process. The features of FEA can help investigate advantages and drawbacks of all three types of tool path.

[1] This author of this thesis is a Global Korea Scholarship scholar sponsored by the Korean Government.

요약본

오늘날에는 트렌드 변화로 인해 소량 배치 및 프로토타입 생산에서 가치 있고 고객 친화적인 시트 형성 공정이 큰 수요가 되고 있다. 따라서 유연하고 경제적인 시트 성형 공정 및 기술 개발은 매우 중요한다. 그러나 판금 가공에서, 그러한 접근법은 어렵다. 왜냐하면 새로운 기술의 구현은 그들의 금형 장비의 개발과 생산에 시간이 필요하고 생산 전 단계에서 상당한 자본 투자가 필요하기 때문이다. 이러한 복잡한 단계 없이 새로운 기술을 마스터하기 위해서는 정보 기술을 가장 효율적으로 사용하는 접근 방식이 필요하다. 이 원리는 CNC 시스템에 내장되어 있으며 시트 재료를 증분 성형하여 가공하기 위해 구현될 수 있다. 증분 시트 형성(Incremental Sheet Forming, ISF)은 유망한 시트 형성 공정 중 하나이며 이러한 목적으로 유효할 수 있다. 특히 단일 포인트 증분 형성(SPIF)은 비용이 저렴하고 고객의 요구에 빠르게 적응하기 때문에 인기를 끌고 있다[2].

본 연구의 목적은 실험적으로 수치적으로 3 가지 유형의 공구 경로와 최종 제품의 표면 품질에 대한 공구 경로 유형의 영향을 조사하는 것이다. 연구 중에 최종 제품 설계 및 성형 프로세스를 위한 세 가지 유형의 도구 경로가 Autodesk Fusion 360 CAD/CAM 소프트웨어의 학생 버전을 사용하여 생성된다. CAD/CAM 소프트웨어에서 이러한 도구 경로를 생성하는 방법에 따라 세 가지 도구 경로 이름이 모두 'Contour', 'Ramp', 'Spiral'로 지정된다. 시판되는 알루미늄 합금 AA5052 와 기름과 그리스와의 조합이 각각 재료와 윤활제로 사용되었다. 실제 실험을 수행하기 위해 일부 변형된 저가형 'Tiny CNC-S' CNC 밀링 머신을 활용한다. SPIF 프로세스를 구현하는 동안 알루미늄 공작물은 변경 단계 크기가 0.2 - 0.8 mm 인 언급된 공구 경로를 사용하여 성형되었으며, 모든 실험에 반구 끝을 가진 동일한 성형 도구가 사용되었습니다. 형성된 모든 부품의 표면 품질을 측정하고 비교하기 위해 3D Nano Profiling System 을 구현하고 표면 거칠기 값을 기록하였다. 또한, 유한 요소 분석(FEA)은 SPIF 과정 중 두께 분포와 변형력을 분석하기 위해 사용된다. FEA 의 기능은 세 가지 유형의 공구 경로 모두에 대한 장단점을 조사하는 데 도움이 될 수 있다.

[2] 본 논문작성자는 한국정부초청장학금(Global Korea Scholarship)을 지원받은 장학생임

I. INTRODUCTION

1.1 Sheet Metal Processing

The development of the national economy of the country is largely determined by the growth in the production of metals, the expansion of the range of products from metals and alloys and the increase in their quality indicators, which largely depends on the conditions of plastic processing. Knowledge of metal processing assists to choose the most optimal method of technological processes, the required main and auxiliary equipment and technically competently operate it. One of the major manufacturing process is sheet metal processing.

Sheet metal processing is a technological operation that allows obtaining a volumetric workpiece of required form. Products of sheet metal processing are used in building body of automobiles, wings and fuselages of aircrafts, parts of ships, roofs of building and many other applications. Thickness of sheet metal can vary from 0.1 to 6 mm according to demand of production. Material diversity in sheet metal processing is wide and depending of use of the parts materials can be steel, tin, cobber, brass, titanium, nickel and alloys of aluminum.

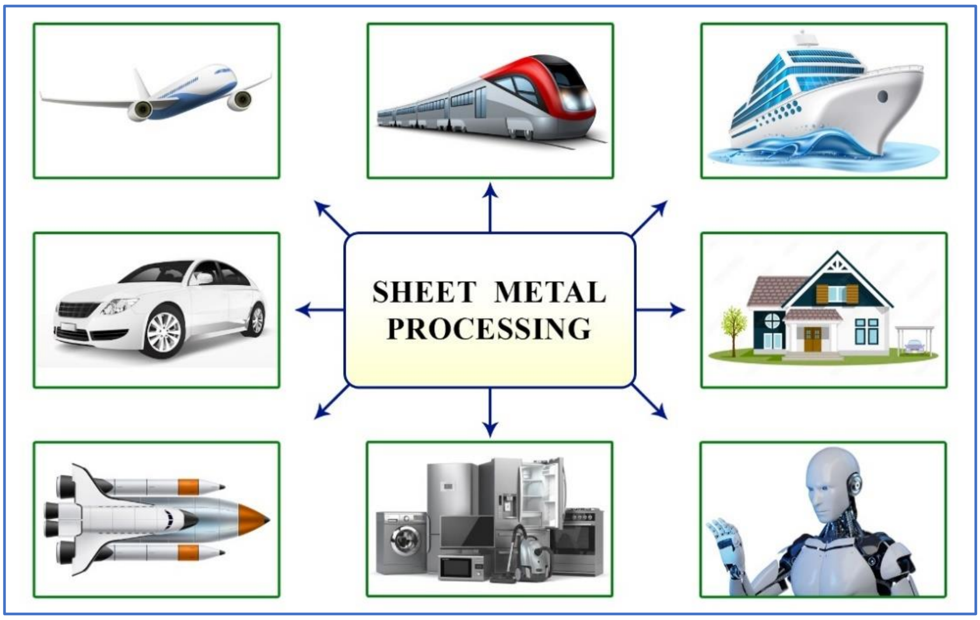


Figure 1. Application area of sheet metal processing

During sheet metal processing particular force is applied to the sheet workpiece and it will be converted to desired form without removing any metal excess. Applied force stresses out and plastically deform the sheet workpiece beyond sheet's yield strength.

As mentioned above sheet metal processing involves reshaping a workpiece so there are several common forming processes of the sheet workpiece, and they are curling, ironing, bending, punching, hydroforming and incremental forming. Each of these carried out through cold forming without melting and heating.

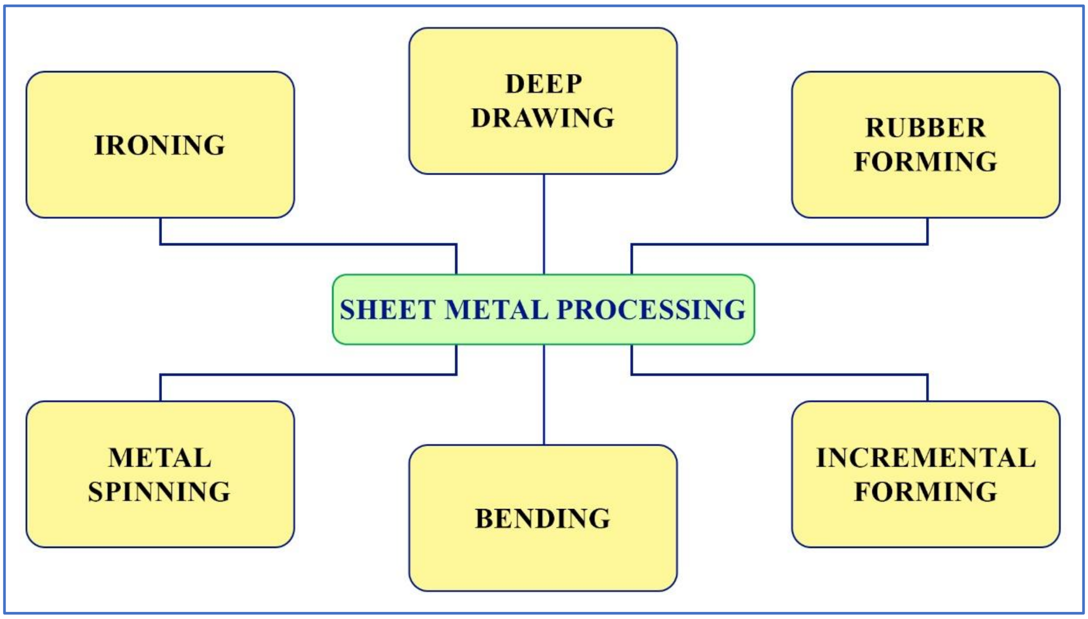


Figure 2. Classification of sheet metal processing

1.2 Ironing

Ironing of sheet metal is a manufacturing process that workpiece is uniformly thinned in a particular area. The combination of this process with deep drawing assists to achieve a uniform wall thickness. Ironing process also can be performed separately. In parts which produced by deep drawing, variation in wall thickness often exists. During this process sheet workpiece is pushed by specific punch and die through a gap. That will cause a certain reduction in entire wall thickness of sheet blank. Also, ironing will cause the workpiece to lengthen while reducing the entire wall thickness. Usually, it is observed that in ironing wall thickness can be reduced 40% to 60%. A lot of products go through more than two ironing operations. Common product of ironing process are beverage cans.

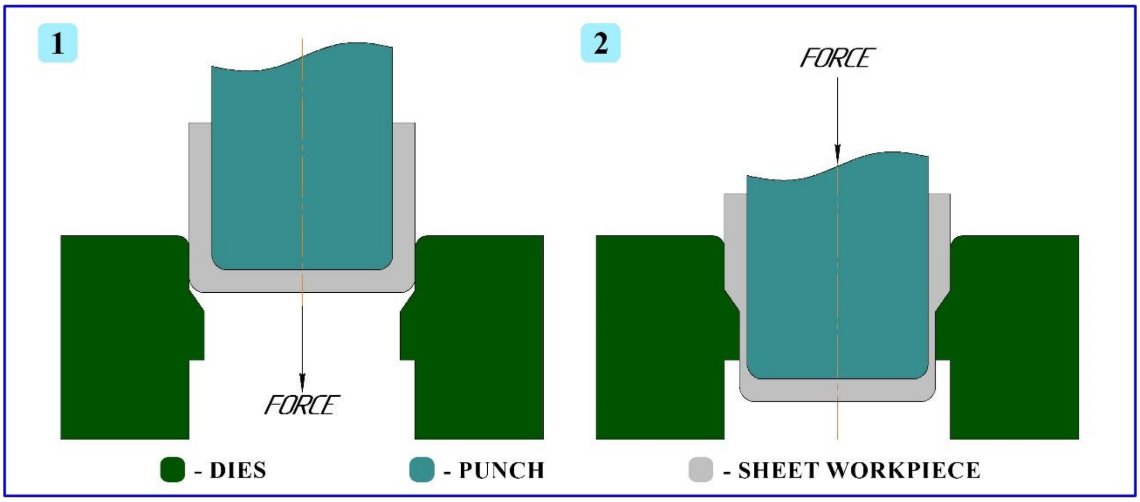


Figure 3. Schematic illustration of ironing process

1.3 Deep Drawing

Deep drawing is a process in which a hollow part of any shape is obtained from a flat workpiece. Forming is the result of plastic deformation, accompanied by a displacement of a significant part of the metal being processed along the height of the product. With a large degree of deformation and a small thickness of the initial material, an unfavorable stress-strain state arises, which leads to the formation of corrugations, cracks, and metal ruptures. Details obtained by deep drawing, depending on their shape, are divided into three groups: a) axisymmetric; b) box-shaped; c) complex asymmetrical. Products tha manufactured by sheet by metal deerp drawing are cooking pans, pots, containers, sinks, automobile parts, such as gas tanks and gas tanks.

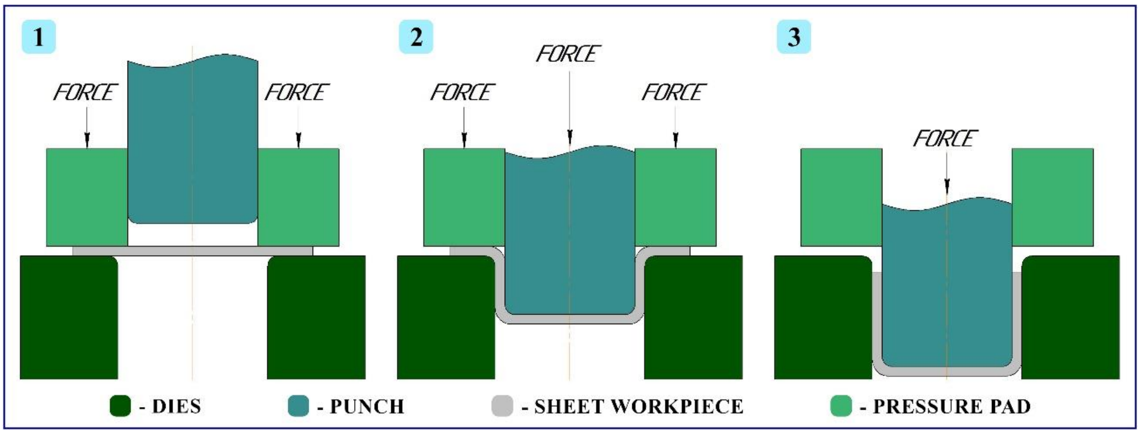


Figure 4. Schematic illustration of deep drawing process

1.4 Rubber Forming

During rubber forming in order to form a sheet metal work piece a flexible material, such as polyurethane or rubber is utilized. Frequently, the rubber is placed in a steel container and be in use as a punch. A sheet blank is placed over a rigid die and the punch deforms the workpiece moving along z-axis into the rubber. Shapes of rubber canbe like membrane or alternatively, it can be produced as a shape of punch or die. Between die and punch rubber can be located in differend positions. In this case, a rigid punch presses a sheet blank stock that is located over a die consisting of rubber incased in a steel container. The process of rubber forming is illustrated in Fig. 5.

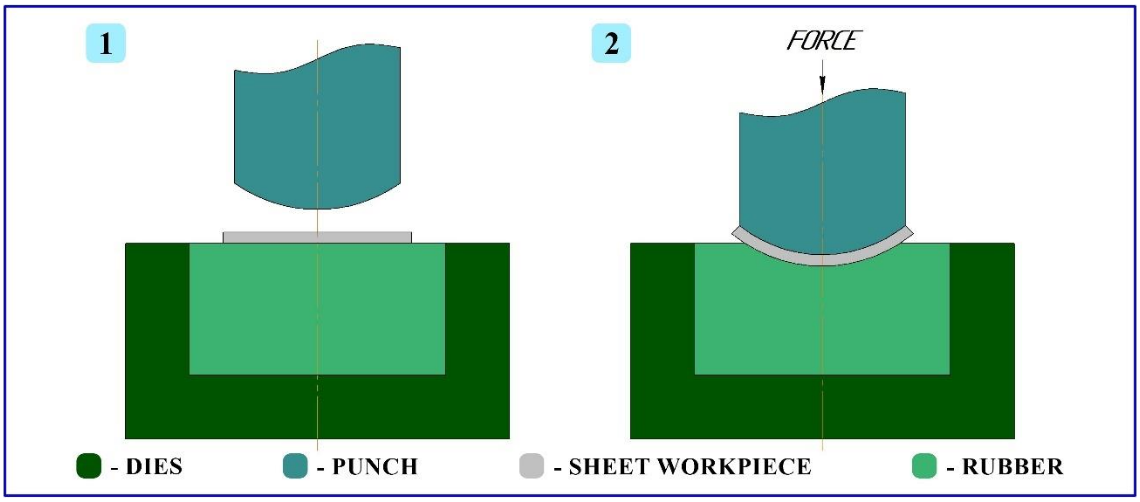


Figure 5. Schematic illustration of rubber forming process

1.5 Bending

Bending sheet metal is carried out by turning one part of the workpiece relative to another around a certain line, called the bend line. This ensures the specified location of parts of the part in two or more planes at certain angles and roundings along the arc of a circle or along the arc of another curve. During bending, elastic and plastic deformations occur in the material. Elastic-plastic deformation occurs differently on different sides of the bent billet. In the bending zone, the material is strengthened, and the farther from the neutral layer the metal layers are located, the more they are strengthened. With free bending, the workpiece contacts the tool only at two or at three points. Fitting of the part to the surfaces of the punch and the matrix does not occur. Such bending is usually accompanied by a large springback.

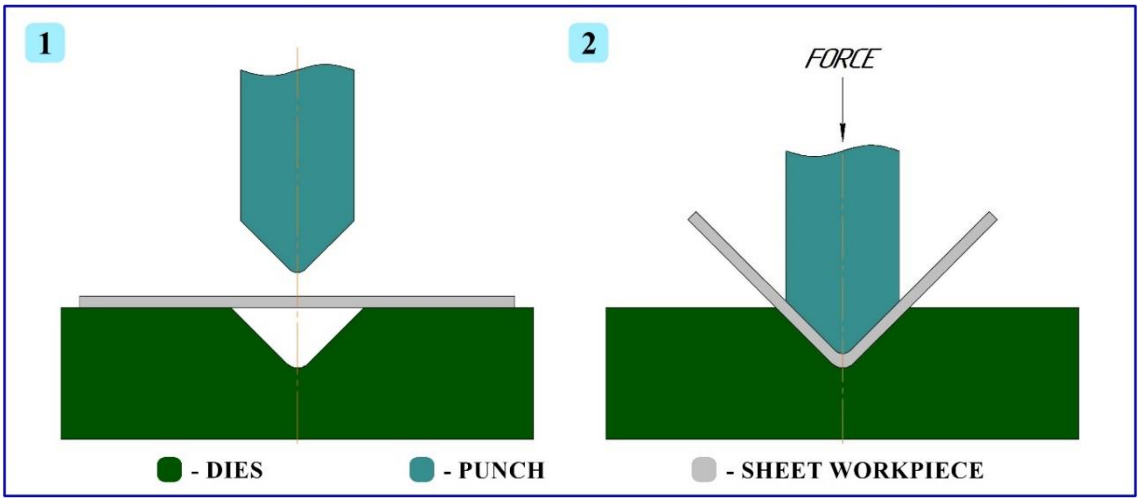


Figure 6. Schematic illustration of Bending process

1.6 Metal Spinning

Metal spinning or spinning is the technological process of manufacturing thin-walled parts in the form of hollow bodies of revolution using the force of the tool on the material being processed. As a result of a localized deforming load on the sheet blank, the starting material takes the form of a mandrel, and a hollow axisymmetric part is obtained. During this process an axis-symmetric part will be formed over a rotating mandrel and force is delivered by a roller. The variety of methods of spinning allows to produce parts of various shapes, lengths and complexity.

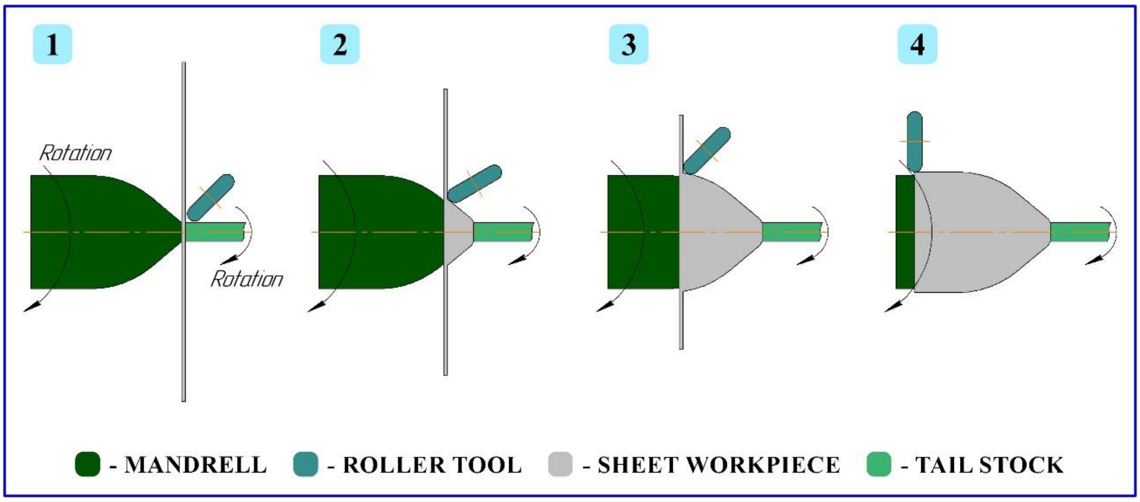


Figure 7. Schematic illustration of metal spinning process

II. INCREMENTAL SHEET FORMING (ISF) PROCESSES

2.1 Introduction

The basis for the successful development of production is the ability to quickly respond to demand. To ensure these conditions, one of the most important factors is the flexibility of production and the ability to meet the needs of the customer in the shortest possible time. With the use of incremental forming technologies, it becomes possible to quickly respond to market needs by quickly and efficiently fulfilling these needs by significantly reducing the labor intensity of pre-production and subsequent manufacturing of parts. Such technologies are widely studied abroad and successfully take their place in the procurement industry. The implementation of this flexible approach to product manufacturing is especially relevant in the field of prototyping and product design, aerospace, medicine, and is an important task in today's competitive metal products market. The phrase of ‘incremental forming’ is used for a different process and all of these characterized by the actuality that only a small part of the workpiece is being deformed at any time. Local deformation area is passing over entire workpiece [1].

Incremental forming (ISF) is a die less sheet metal process in which a sheet workpiece is locally deformed little-by-little in progressive layers using a spherical or hemispherical end punch by moving one or more tools along the tool path. The edges of sheet blank are rigidly clamped between the die plate and the blank holder. In addition to moving along a given path to reduce the influence of contact friction forces, the punch rotates around its axis.

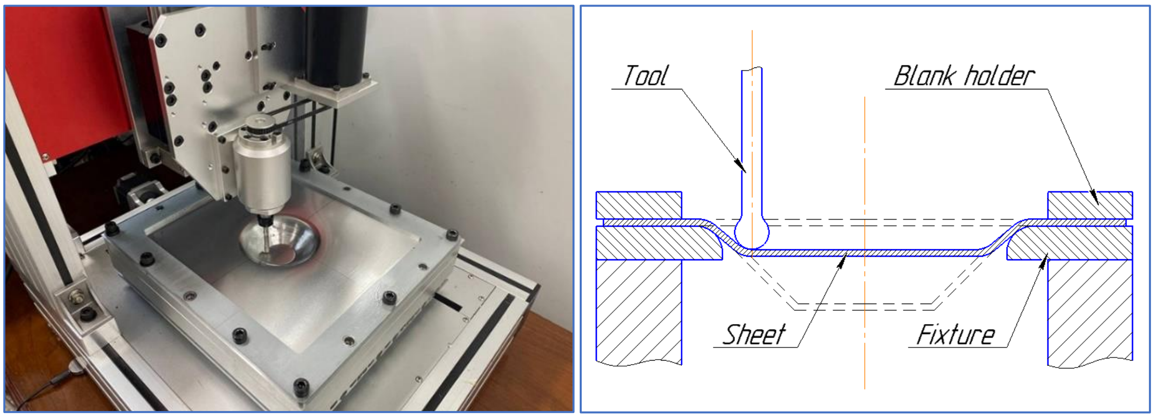


Figure 8. Incremental sheet forming a) Forming process b) Schematic diagram

This technology allows working with several types of steels, non-ferrous metals, titanium, aluminum, and other materials. The main difference from traditional technologies is that it does not require the manufacture of expensive forming tools and the use of powerful pressing equipment. In the other words, sheet forming is performed not by filling the cavity by combining the lower and upper engravings of the stamp, but by implementing tool movements along a given contour along pre-calculated trajectories.

A similar approach to deformation is implemented in the processes of rotational drawing and other processes, which also use the method of localization of the plastic deformation zone. This method allows to effectively intensify the processes, thereby eliminating the formation of stress concentrations and microcracks and increasing the degree of shape change. However, ISF differs in that deformation in incremental forming is carried out only by moving the tool with complete fixation of the workpiece. Thus, it is possible to obtain not only axisymmetric products, but products of almost any shape, including those with internal corners and in a wide range of sizes. Also, due to the control and management of the change in the thickness of the material along the cross section of the workpiece, which is achieved using various tool movement strategies, it is rational to use the technology of incremental forming to obtain spherical workpieces, which are mainly obtained by the method of reverse forming.

2.2 Application area of Incremental Forming

There are several spheres, where requirement for accuracy of the performance with high precision of final product is demanded. Single-Point Incremental forming (SPIF), along with several advantages at this stage of development, have low productivity, which in some degree limits their scope.

Incremental forming technologies, along with a number of advantages, have low productivity at this stage of development, which to some extent limits the scope of its applicability. The presented technology can become an indispensable tool for prototyping parts, and, as foreign experience shows, it is already widely used in industry of automatization. It is promising to use incremental forming technologies in the aerospace and other types of industry, where, along with a small batch size, it is required to manufacture large-sized body parts and, as a result, use expensive overall die equipment along with specialized press equipment of large nominal force. It is promising to implement the technology of incremental forming in medicine, in particular in the field of prosthetics, where an individual approach to each prosthesis is required, for example, cranial, dental or orthopedic plates.

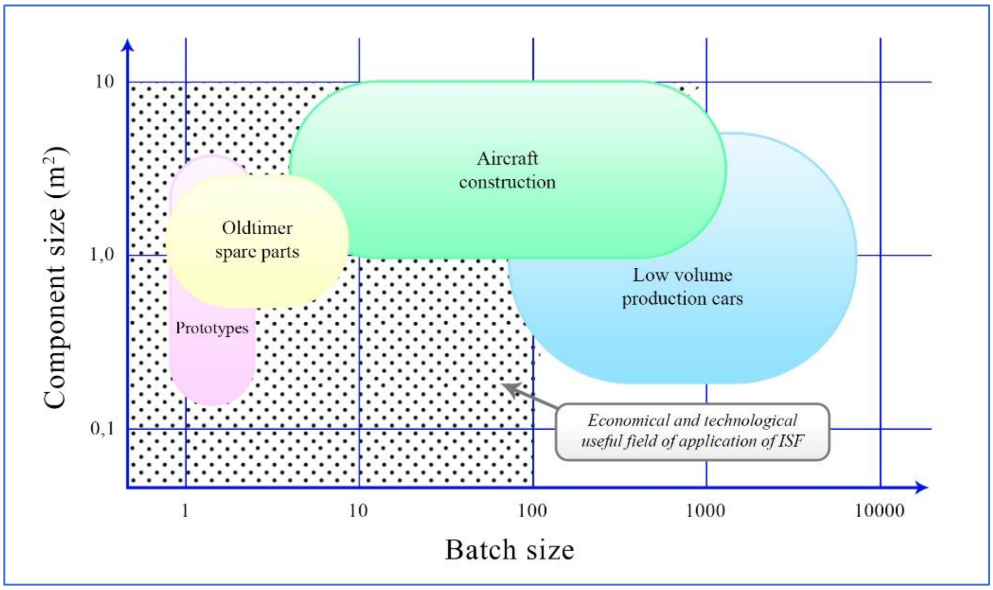


Figure 9. Application area of single point incremental forming

2.3 Classification of Incremental Forming Process

In ISF in order to increase the accuracy of the obtained products and expand the technological capabilities, various forming methods and equipment are used. Moreover, according to these methods and installation ISF divided into several types. Figure 2 shows typical schemes of the incremental forming process.

The most usual classification of incremental forming is according to forming method. According to forming method incremental sheet forming can be distinguished into 3 types:

- Single-Point Incremental forming (SPIF) is one of the widely utilized processes and named as negative incremental forming. This process is carried out using one forming tool without the use of additional supports (Fig. 9a). Due to the action of bending moments, the accuracy of the resulting workpiece is low, and its use is not rational with significant degrees of shape change.
- Two-Point Incremental Forming (TPIF) is frequently named as a positive incremental forming and in TPIF two tools move over the surface of blank sheet. The scheme of TPIF presented in Fig. 2f includes the advantages of all other schemes due to the presence of a counter punch that moves

together with the main punch. Thus, the influence of the bending moment is reduced, and it becomes possible to obtain more complex shapes of the product, including those with internal corners, but this requires specialized equipment.

- Hybrid Incremental Sheet Forming (HISF) is a modified type of conventional incremental sheet forming. The shortcomings SPIF are eliminated by using various types of supports (Fig. 2b, c, d, e) that provide a rigid structure and exclude the action of a bending moment but require additional equipment.

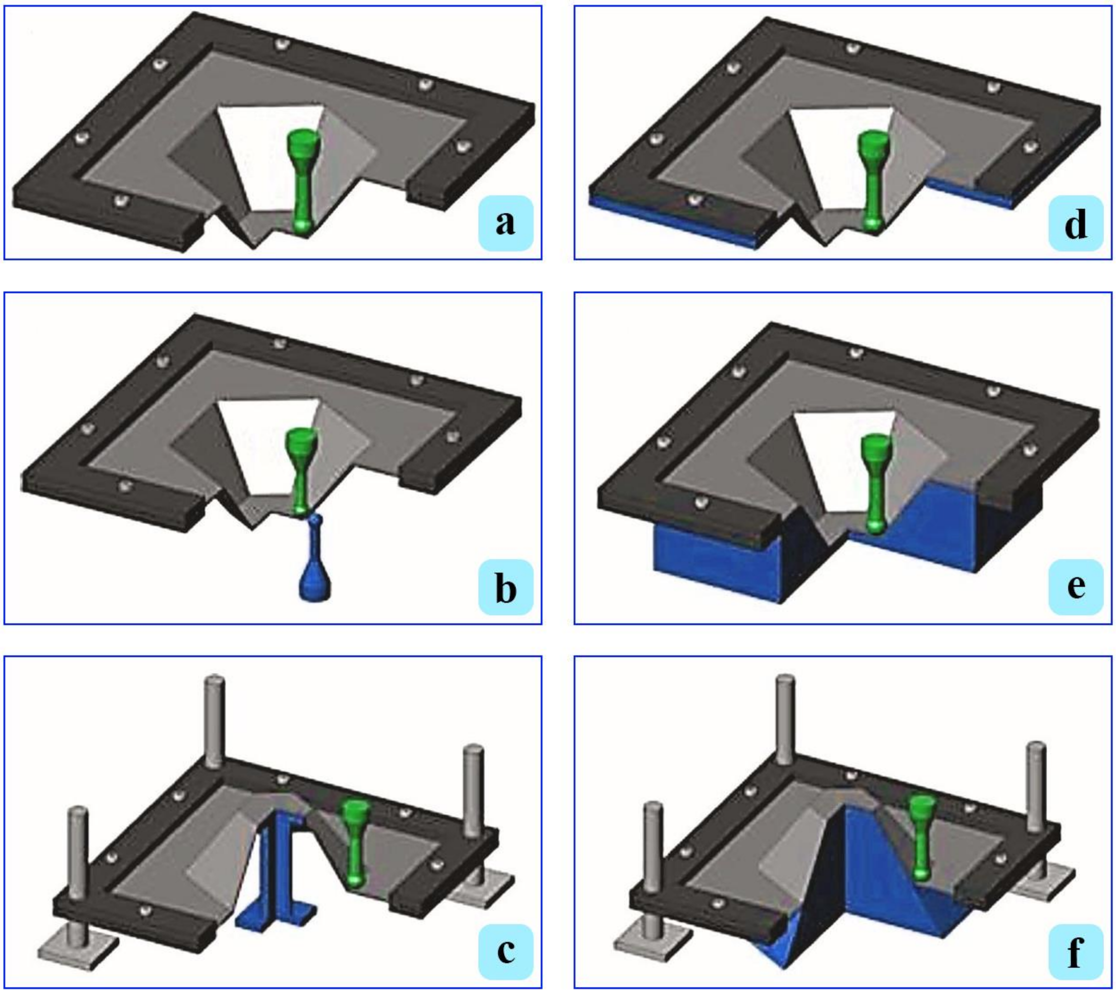


Figure 10. Typical schemes of incremental sheet forming processes.
a – SPIF; b – TPIF; c, d, e, f – HISF.

Although, Two-Point Incremental Forming and Hybrid Incremental Sheet Forming processes have more advantages compared to SPIF, they demand dissimilar supports and tools, which makes forming technique more complicated and increases cost of final product. Therefore, SPIF is a proper choice for research and small-batch production.

2.4 Advantages and drawbaks of SPIF

Advantages of SPIF are as follows:

- using a CAD model of a part to obtain the required dimensions without the use of a stamping equipment
- an increase in the degree of deformation and a decrease in deforming forces due to the localization of the center of plastic deformation
- the possibility of using CNC milling for forming
- the dimensions of the part are limited only by the size of the equipment table
- no complex stamping equipment is required

Disadvantages of SPIF:

- low productivity in contrast to traditional processes
- applies only to small-scale production
- complex algorithms for the movement of the tool, which allow to ensure a high degree of deformation and accuracy of the resulting part, considering elastic deformations
- forming of right angles requires a multi-step process, instead of forming in one step.

III. OVERVIEW OF SINGLE POINT INCREMENTAL FORMING

3.1 General overview

Nowadays composite materials and titanium are widely used for the industrial construction, but aluminum alloys have been the best choice material in aircraft and automobile components manufacture [2]. Due to advances in these industries, advanced and flexible manufacturing technologies have become popular recently [3]. Single point incremental forming is a basic type of incremental forming process which requires only workpiece fixing elements and forming tool. During this operation metal sheet blank is fixed between bottom fixture and blank holder, and rotation forming punch deforms the workpiece step by step in progressive layers until sheet formed as desired profile. SPIF has several advantages such as forming complex geometries with high accuracy. Due to easy implementation for prototyping and small-batch production SPIF has a big potential in industry [4].

SPIF is an innovational and low-priced technology to form metal sheets and, in this process, using a CNC machine enables producing complex geometries without implementing a special die [5]. Compared to other traditional sheet forming processing is more flexible, especially in small-batch production and prototyping [6]. Those traditional methods as stamping allows to produce same products as SPIF, compare to stamping or other techniques SPIF is more cost-effective and does not require expensive equipment. This technology will make it possible to practically reduce the cost of manufacturing die equipment to zero, confine to a universal set of tools and equipment for incremental forming. In several areas, where final products require high precision in order to get accuracy of the performance. Industries where SPIF can be implemented are electronics, healthcare, automobile, aerospace, sensors, miniature fasteners and so on [7].

3.2 Surface quality

One of the drawbacks of SPIF that impedes wide utilization in industrial area is unsatisfied surface quality [8]. In SPIF selecting main process parameters appropriately is significant and this will ensure satisfied surface quality in terms of surface roughness and forming time [9]. A lot of researchers studied methods of improving surface quality in SPIF and Murugesan [10] also investigated surface roughness in SPIF considering major process parameters. During this research it is recognized that step size and tool radius were most significant parameters influencing on surface quality. [11] demonstrated that there is no clear impact of the tool rotational speed on surface roughness. The influence of factors such as forming stage, stress triaxiality and normalized load angle on surface quality can be tested using finite element model (FEM) with high precision [12].

3.3 Tool path

Trajectory of the tool during forming process is called tool path and it is also important parameter in sheet metal processing, especially in SPIF. Tool path plays main role in formability, accuracy and surface quality. In SPIF it is easy to make adjustments in geometry that's why tool path generation becomes key parameter related to SPIF. It determines key points like surface quality, formability, thickness variation and processing time.

Sometimes it possible to get over thinning of material due to utilizing invalid tool path however using multi-step forming strategies helps to overcome this problem [13]. In order to investigate residual stresses, it is possible to implement unidirectional and bidirectional tool path methods [14]. [15] presented new approach for SPIF and during experiments they drove the forming tool tangentially with constant axial feed or step down instead of movement in the radial direction. It is observed that using this method increases the formability for more than 20 percent. Further studies shows that defects like spring back and undesired surface quality can be result of tool path and these defects can be solved by implementing radial travels of forming tool along the center of sheet blank.

In industrial implementation of SPIF part accuracy is major disadvantage. Although industrial products demand ±0.5mm dimensional accuracy, parts that produced utilizing single point incremental forming have lower dimensional accuracy [16]. In [17] forming and dimensional faults is demonstrated and during this study several types of methods used to overcome inaccuracies. [18] showed that, driving the tool from the edge to the middle of workpiece.

In research of [19] two types of tool path, spiral and contour tool path are examined, and results showed that spiral tool path are proper than the second one. Utilizing spiral tool path leads to eliminate scarring outcome from tool path step downs along z-level contouring.

Process parameters aside from the tool path like step size, shape, and radius of forming tool, forming height, forming angle and lubrication can also impact on quality of final product. Behavior of these factors are briefly explained in next parts.

3.4 Shape of the forming tool

Since shape of the forming tool determines contact area of tool and workpiece, tool shape has a significant influence on single point incremental forming. Contact area of blank and tool has main impact on frictional forces appeared between contact surfaces. The effect of tool geometry on formability was studied by researchers in [20]. During their research a roller and hemisphere end tool are implemented to examine the impact on formability. Result of that study showed that roller end tools produced parts with better quality. [21] studied the impact of tool shape on geometrical accuracy of formed part. They implemented several types of tools and investigated that tool with flat end deforms the parts with better accuracy than others.

Radius increase in forming tools decreases formability of SPIF [22]. [21] Proved that during implementation of several types of tools, sheet thickness determines formability not the radius of forming tool.

Previous studies shows that single point incremental forming have several advantages whereas it is obvious to see some shortcoming in this process. Besides, possibility of occurring various defects during this process is not small. Types of defects in SPIF which are spring back effect, twist effect and pillow formation.

3.5 Formability

Ability of undergoing plastic deformation without failure is formability of metal. This ability for SPIF can be identified by several methods. In [23], the technique of membrane analysis is used to determine formability. [24], [25] offered that calculation of formability is possible using the ultimate angle of forming wall just before the failure. Employment of sine law in order to predict minimum wall thickness for curved shell parts by [25] lead to remark that it was limit of safe thinning.

[26] accomplished that the formability of traditional forming processes is lower than SPIF. Main characteristics of SPIF formability are tensile strength, strain hardening and elongation percentage [27].

Studies of many researchers showed that material flow behavior has main effect on high formability. [28] Showed that, during SPIF process failure happens at fracture instead of necking.

Main parameters that affect formability is tool radius, forming speed, friction, and size of stepdown. The interaction between stepdown size and tool radius is major factor in determining formability of SPIF.

3.6 Forming step size

The importance of forming step size in SPIF and its impact on formability is not well researched. However, [29] opined that size of forming stepdown is significant factor in SPIF and it directly influences on time used to form the workpiece to desired shape. Large stepdown size leads the blank to stretch and can be reason for premature fraction.

Opinion of some researchers is that step size impacts only surface roughness whereas others opined that due to the change of step size it is possible to identify change in formability also. [30] demonstrated that there is significant influence of step size on formability. It is proven that step size affects surface roughness and time of forming. Decreasing step size along z-axis leads to high surface quality but it demands more time for forming part.

3.7 Speed of forming

Generally forming speed can affect the formability of SPIF process because high forming speed generates heat along the forming area and softens that part. As a result, process requires fewer deforming forces which leads to improve formability. The summation of tools rotation and feed speed of forming tool is called feed rate during incremental forming. Increasement in tool rotation motion leads to higher roughness in formed surface. Big values of feed speed of the tool decreasing the forming depth and however there is no significant effect on formability. Additional impact of high feed rate on SPIF are growth in sheet waviness and in tool wear.

3.8 Lubrication

The contact between forming tool and sheet workpiece generates friction so there is a demand for proper lubrication in order to reduce the tool wear and increase the quality of formed surface. In SPIF wear of the tool is minimal however it can increase considerably at higher temperatures. High temperatures during SPIF causes softening in workpiece and forming surface can be distorted easily. This effect can be reduced by using lubrication and choosing lubrication is also important because it improves quality of formed surface. [10] showed that using combination of oil and grease gives better surface quality in SPIF. During their study first oil and grease utilized separately and there was an experiment using mix of using these lubrication materials.

IV. STUDY PURPOSE

Main parts of single point incremental forming process are done only with CNC machine and controlling computer so compare to other sheet processes number of labors are small in this method. It is possible to form more complex geometry and increase quality of final product, but it requires extra equipment. SPIF is not hot forming process which leads to saving in energy cost and manufacturing time. Due to modern CAD software, it is not difficult to design complex shapes accurately and numerical control of process allows forming those compound designs. In SPIF it is possible to form ferrous and non-ferrous metals, composite materials and nowadays aluminum and its alloys are more popular in incremental forming area. Another superiority of SPIF is it does not require big-sized manufacturing places due to small sizes of equipment. As another sheet processes it is normal to identify minor shape defects in SPIF which discussed in further sections.

However, main purpose of this thesis is organizing practical and numerical experiments in order to better understand the impact of tool path type on the surface roughness of final product. Analyzing major process parameters of SPIF such as forming angle, step size, spindle speed and feed rate in each type of tool path.

The second objective of this work is to identify the shape accuracy of formed sheets in terms of thickness reduction, forming angles and surface quality compared to designed CAD files. Other aim of the study includes reducing the simulation time in finite element analysis (FEA). It is important to check result accuracy in simulation while time of simulations reduced using several methods.

V. RESEARCH METHODOLOGY

5.1 Material characterization

During experimental analysis commercial Aluminum alloy AA5052 was used as a material of workpiece and thickness of sheets are 0.5mm. The dimensions of sheet workpiece are 280mmx320mm, but actual working area of workpieces was 210mm for length and 250mm for width. The other areas of sheets are used to fix and clamp the workpiece. The sheet's mechanical properties are unknown, and these properties may be influenced by cold/hot working in manufacturing process.

AA5052 was chosen as the workpiece material for this study because of its low cost and availability [31]. High formability and exceptional corrosion resistance of this material makes it application area wider and AA5052 usually used for both hot and cold metal forming. Manufacturing marine, aircraft, fuel tanks and streetlights are most common areas where this material used.

The tensile test was employed in a hydraulic operated UTE 20 Universal Testing Machine. Summary of chemical composition of commercial AA5052 is illustrated in Table 1, and Energy dispersive X-ray test is implemented in order to determine chemical composition.

Table 1. Chemical compositions of AA5052 material (mass fraction, %)

Materials	Si	Fe	Cu	Mg	Mn	Zn	Cr	Al
AA 5052	0.05	0.2	0.03	3.2	0.08	0.12	0.23	balance

Table 2. Mechanical properties of AA5052 alloy

Mechanical Properties	Metric	English
Ultimate Tensile Strength	228 MPa	33000 psi
Tensile Yield Strength	193 MPa	28000 psi
Shear Strength	138 MPa	20000 psi
Modulus of Elasticity	70.3 GPa	10200 ksi
Shear Modulus	25.9 GPa	3760 ksi

In order to numerically calculate the strain and engineering stress of the material load-displacement measurement is used as shown below:

$$\sigma_e = P/Ao \ and \ \varepsilon_e = \sigma/Lo \quad (1)$$

where, P - applied load,

A_0 - initial cross-sectional area,

δ – displacement,

L_0 - gauge length of the specimen.

Materials engineering stress-strain curve from tensile test is illustrated in the Figure 4,

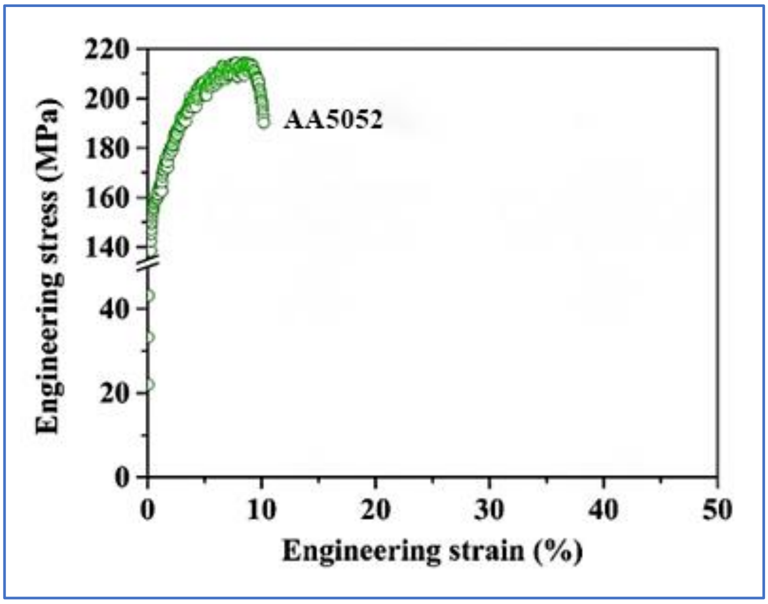


Figure 11. Cure of engineering stress and strain.

In the beginning, AA5052 illustrates linear behavior up to stress of 160 Mpa. Rising the load causes entering of material into elastic and then plastic zone. Following step is reaching ultimate strength. At last, strength of material is lost and at the one-point necking begins, which leads to fracture of the sample. In order to represent the plastic deformations of aluminum alloy, Hollomon power law is used in numerical simulation and the stress-strain curve is specified as below:

$$\sigma = K\varepsilon^n \quad (2)$$

where, K – coefficient of strength and n – coefficient of hardening.

5.2 Geometric analysis

The chosen geometry as final product for SPIF experiment is truncated cone shape with 80° wall angle. All geometrical parameters of final product are demonstrated in Figure 12. where, D is diameter of forming area, h indicated forming depth, represents thickness of sheet blank and α is forming angle. Working area of machine is 240x280 mm^2 on the worktable, so sheet workpiece also prepared using laser cutting according to those dimensions.

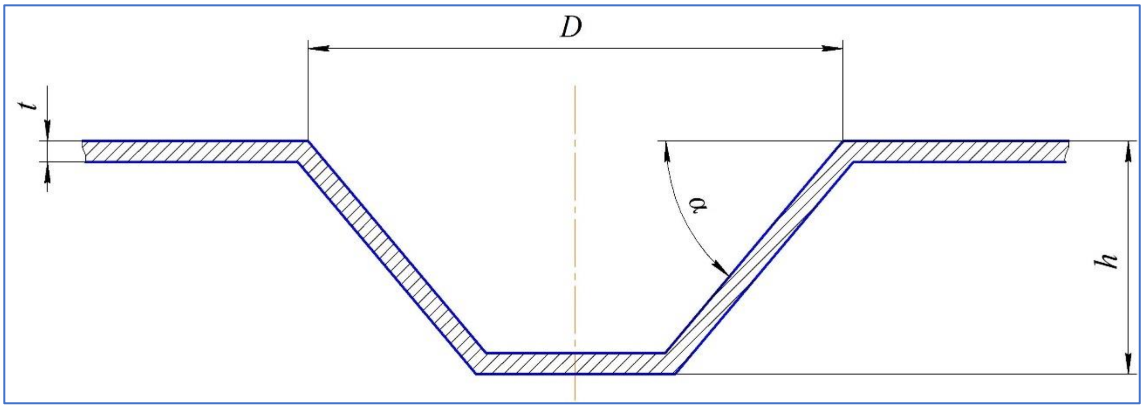


Figure 12. Geometrical characteristics of forming workpiece

The angle between horizontal part and formed wall of the workpiece is forming angle, and it is dependent on thickness of sheet and properties of material. In SPIF formability indicated by highest angle ψ of deformation a sheet blank can hold without occurring failure during one pass. Equation that predicts the maximum forming angle with the use of material characteristics and forming parameters is shown in (3)

$$\psi = \frac{\pi}{2} - \left(\frac{\sigma_Y}{\sigma_Q} - 1\right)\frac{r_{tool}}{kt_0} = \frac{\pi}{2} - \left(\frac{kt}{r_{tool}}\right)\frac{r_{tool}}{kt_0} = \frac{\pi}{2} - exp^{\varepsilon_t} \qquad (3)$$

where: ε_t – fracture limit strain of thickness, t – fracture thickness at forming limit.

This formula can be implemented in order to determine beginning of fracture since fracture ideas at the limit of formability in principal strain direction and the forming angle earlier than failure can be identified. Also, it is possible to express above equation using the sine law (Figure 13).

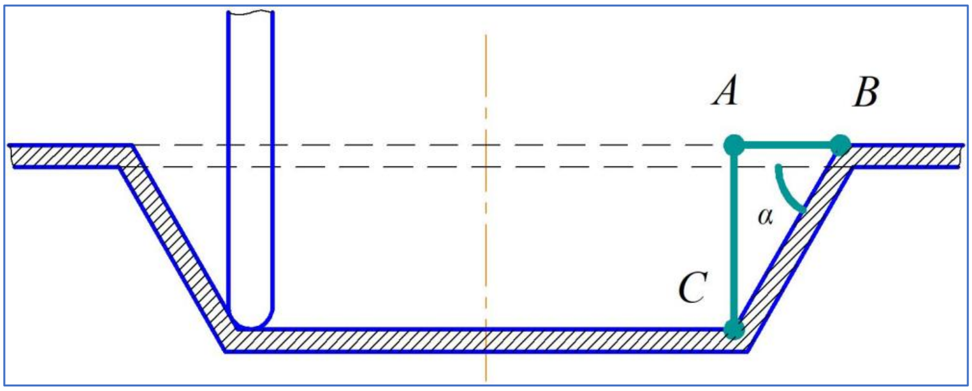


Figure 13. Sine law demonstrates the maximum forming angel

$$T_{BC} = T_{AB} Sin(90 - \alpha) \quad (4)$$

where, T_{BC} is final thickness of deformed sheet and T_{AB} is initial thickness of sheet.

The bigger thinning in BC zone can be occurred because of a sharper angle as shown in formulation. The highest forming angle before the fracture in increased through extending sheet's initial thickness T_{AB} however it can cause requirement of increased force for deform the workpiece which may be out of machine load limit. Moreover, increase in sheet thickness may not satisfy the specifications of design [32]. If design specifications require higher forming angles, it possible to use multiple forming passes in order to deform the sheet steadily, which can lead to obtain higher forming angles [33]. Working area of machine is 240x280 mm^2 on the worktable, so sheet workpiece also prepared using laser cutting according to those dimensions.

5.3 Development of CAD/CAM design

Shape of final product which is 50^o degree truncated cone shape with 20mm forming depth and 50mm diameter modeled in Autodesk FUSION 360 software (Fig. 14). Forming procedure of this shape in sheet workpiece will be carried out using three types of tool path and these types named as 'Contour', 'Ramping' and 'Spiral' respectively. Names are based on methods forming type in FUSION 360 software. Stepdown sizes of all tool path are 0.2 mm. All forming process have been carried out using same tool. Graphical illustrations of all types of tool path are shown in Figure 15a, Figure 15b and Figure 15c, respectively. In order to make contrast between numerical data and results of experiment, forming process was executed numerically and practically. The methods that used to measure these parameters will be interpreted in further sections.

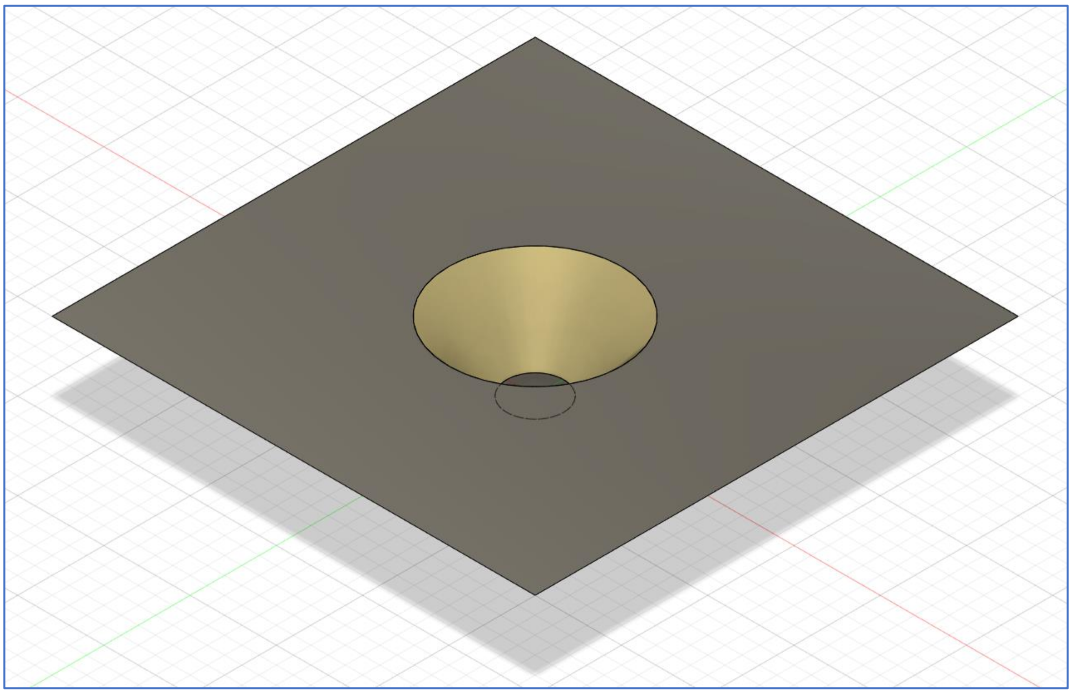
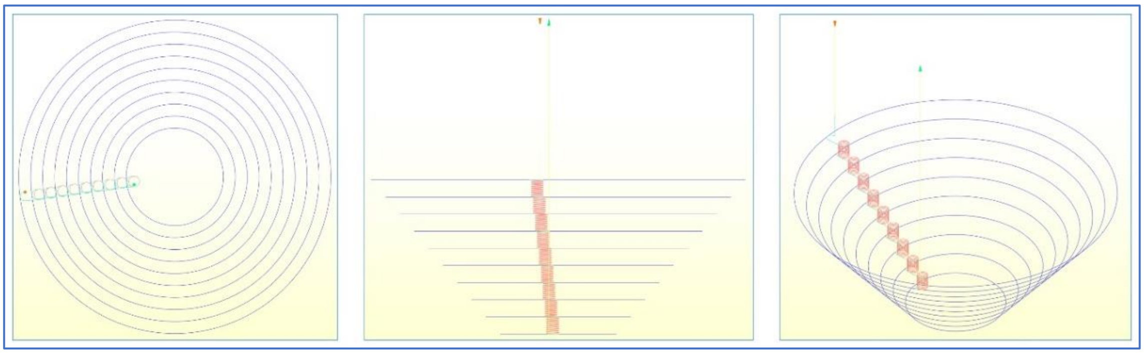
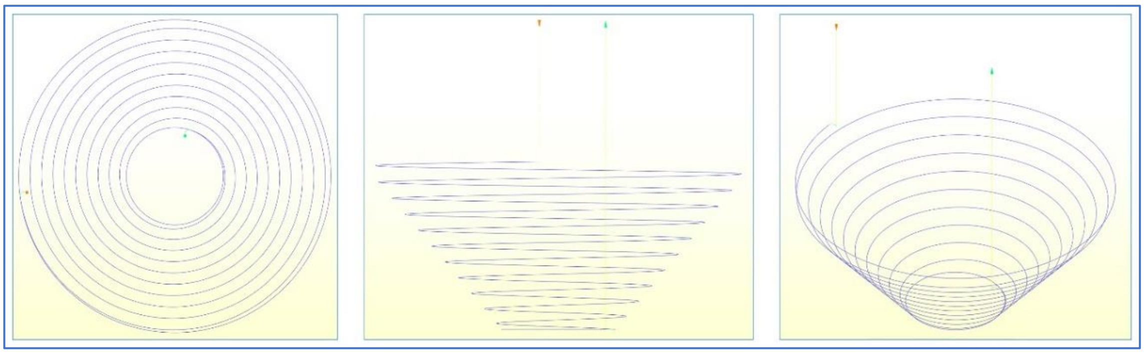


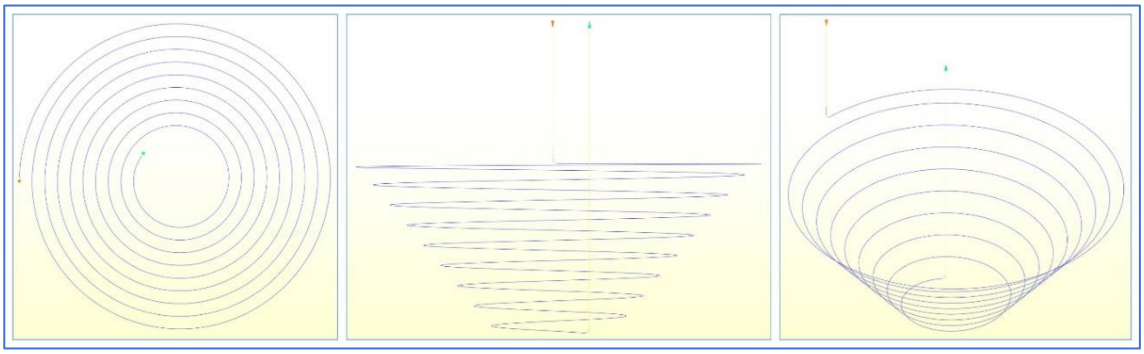
Figure 14. Design of final product



a



b



c

Figure 15. Types of tool path that used in experiments.

a – 'Contour', b – 'Ramp', c – 'Spiral',

5.4 Plan of experiments

During the studies of SPIF, in total 9 experiments in room temperature were performed. Plan and order of experiments are demonstrated in Table 3.

Table 3. Plan of experiments

№	Tool path	Step size	Material	Thickness	Lubrication
1	Contour		AA5052	0.5 mm	Mix of grease and oil
2	Ramp	0.2	AA5052	0.5 mm	Mix of grease and oil
3	Spiral		AA5052	0.5 mm	Mix of grease and oil
4	Contour		AA5052	0.5 mm	Mix of grease and oil
5	Ramp	0.4	AA5052	0.5 mm	Mix of grease and oil
6	Spiral		AA5052	0.5 mm	Mix of grease and oil
7	Contour		AA5052	0.5 mm	Mix of grease and oil
8	Ramp	0.8	AA5052	0.5 mm	Mix of grease and oil
9	Spiral		AA5052	0.5 mm	Mix of grease and oil

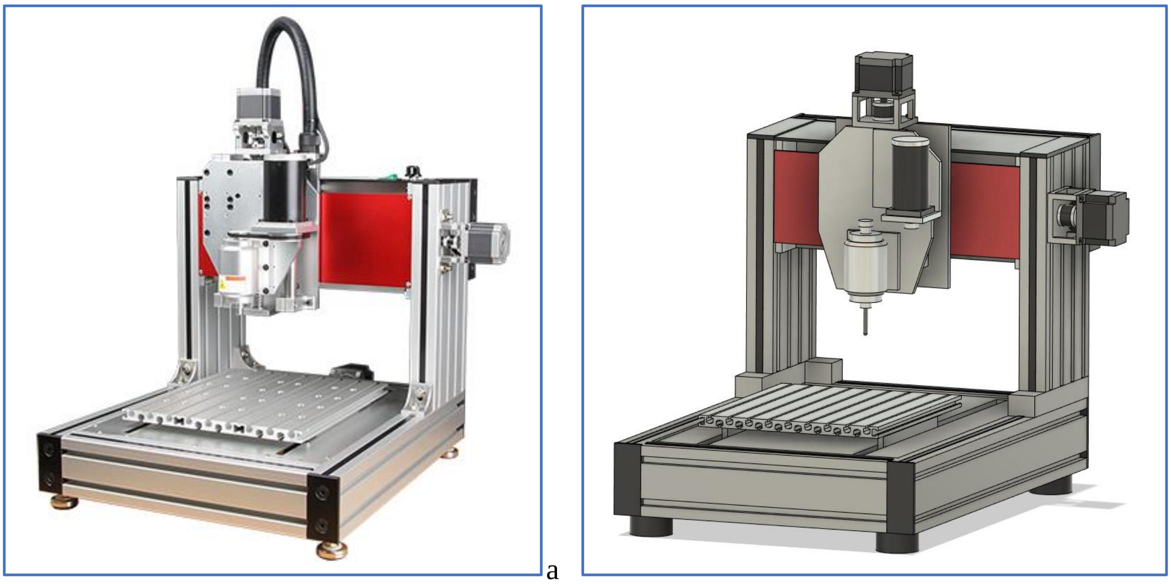
For this thesis process parameters, such as forming depth, spindle speed, feed rate considered 20mm, 6000 rpm and 30000 mm/min, respectively. Before beginning of each experiment, it is important to find the workpiece's origin and height so that a special positioning sensor is utilized to absolute origin of sheet.

VI. EXPERIMENTAL SETUP OF SPIF

The main equipment that used in experiments are in following order: CNC machine tool, clamping equipment, forming tool, lubrication, and software.

6.1 The CNC milling machine

In incremental forming processes, especially in SPIF it is very significant to fix sheet workpiece rigidly in order to achieve the ultimate desired shape of final product. If the fixing mechanism of forming machine is not set up perfectly, then vibration or other factors of incorrect fixing will produce inaccurate result at the finish of forming. During our experiments we used TinyCNC-S milling machine with some modifications. Original image and 3D model of this machine shown in Figure 16.



a b

Figure 16. TinyCNC-S milling machine.

a – original machine; b – Modified version of machine

The milling machine that used in experiments is produced in Republic of Korea and it is very suitable for small-batch metal forming operations. Table 1 gives more information about main characteristics of TinyCNC-S machine which used for experiments.

Table 4. Main specifications of TinyCNC-S milling machine

Installation area (W x L x H)		450 * 600 * 650mm
Table size (X x Y)		280 * 320 mm
Table type		T – SLOT
Workspace (W x Y x Z)		210 * 250 * 90mm
Operating voltage		Single phase 220V 0.3Kw (50Hz, 60Hz)
Spindle motor	Maximum rotation	12,000rpm (Option: 18,000rpm)
	Volume	150W
	Drive type	belt
	Collet	ER11 (Ø0.1 ~ Ø7)
Feed motor		Micro Step Motor
Weight		35Kg
Feed rate		4.2m/min
Precision	Repeatability	0.005mm
	Conveyance	0.01mm
Transfer device		Ball Bush / Ball Screw
Default option		clamp
Selectable options		200w high frequency spindle / oil mist device /
		Index System / Dust Collector / Vacuum Table
Processing material		All series including AL 6061,7076
		ABS, MC nylon, carbon, FRP, POM bed
		All resins including light

The dimensions of CNC machine are demonstrated in Figure 18, where the total height from place of installation is 650 mm. Total width and length of machine are 450mm and 600 mm respectively. The size of table is 280mm for width and 320mm for length. However, because of some modifications, which enables SPIF experiments in this milling machine, actual working area is decreased. So actual dimensions of X, Y and Z axis are 210mm x 250 mm x 90mm respectively.

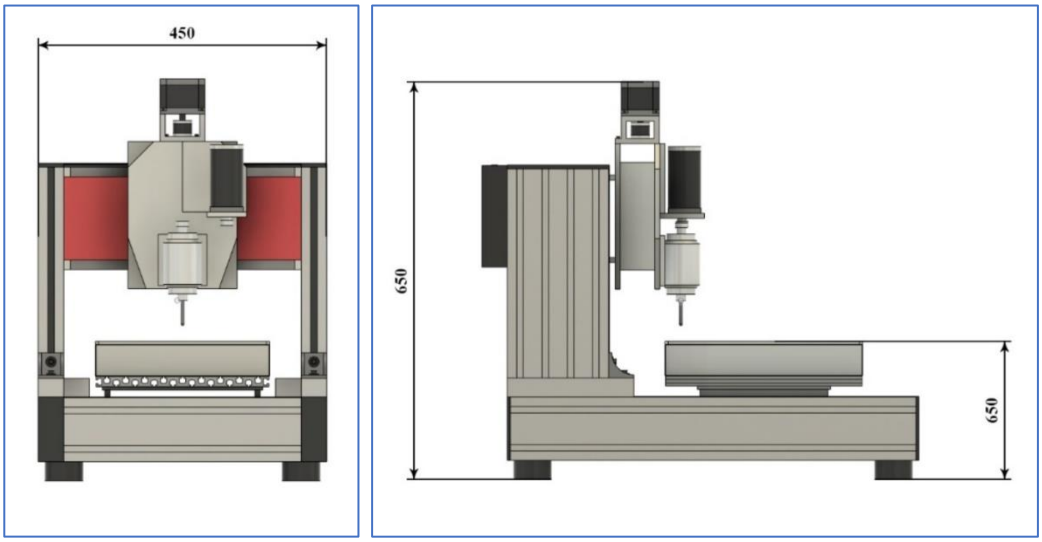


Figure 17. Dimensions of modified TinyCNC-S machine.

6.2 Clamping equipment

The CNC milling that chosen for experiments is originally designed to form materials via vertical milling, so in order to implement SPIF, this machine have to be modified some special clamping equipment that fixes the sheet blank rigidly. The clamping system that used during our experiments shown in Figure 18. It consists of special bottom die, upper blank holder and number of standard 14mm screws. Figure 19 illustrates the graphical order of fixing sheet workpiece with clapping equipment.

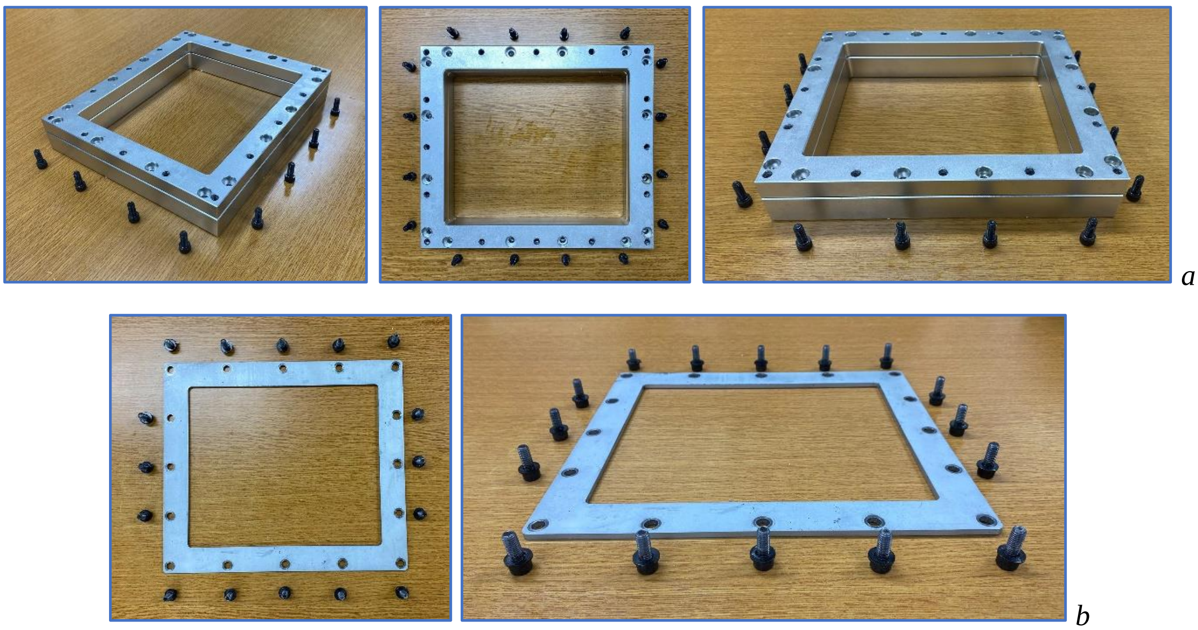


Figure 18. Parts of clamping equipment.

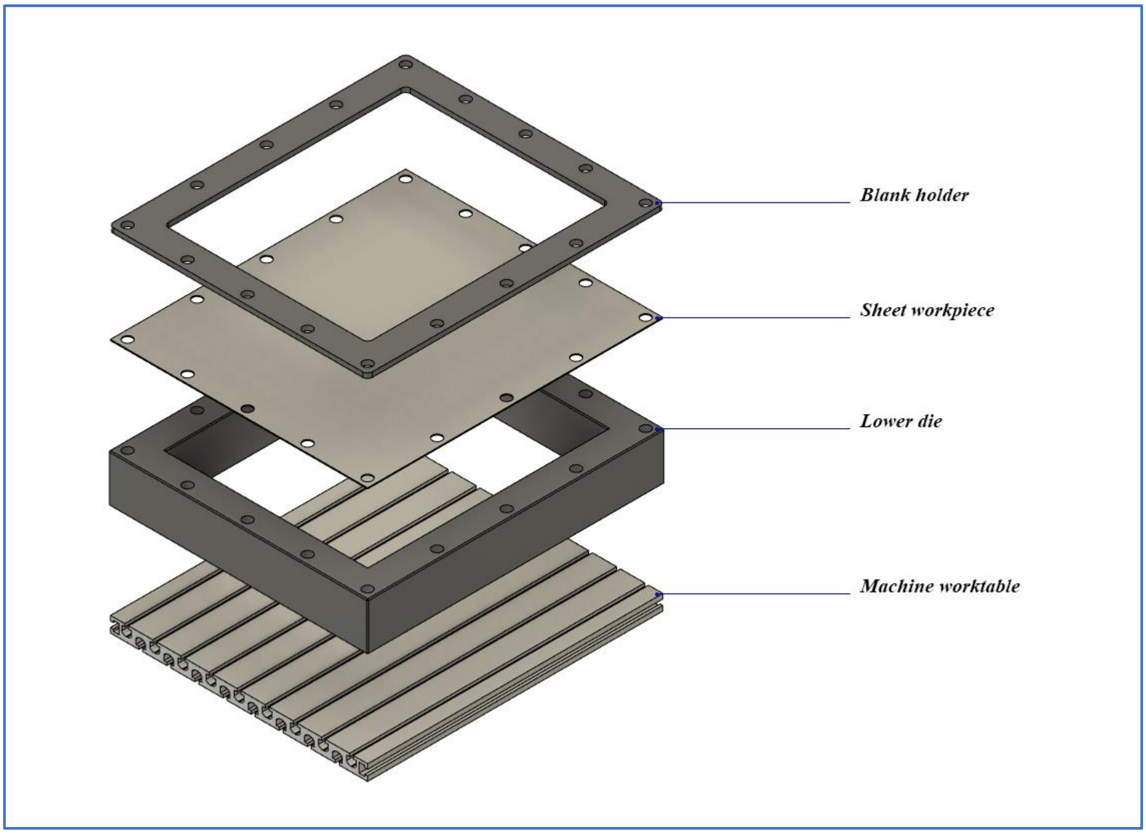


Figure 19. Parts of clamping equipment.

Firstly, this die screwed rigidly on to original worktable of CNC machine using screws. The special die manufactured especially for SPIF operations, and it has 50mm height allows to raise workpiece form machine worktable. Above this bottom die the AA5052 aluminum sheet workpiece should be put. After locating sheet blank correctly, it should be fixed using metal blank holder (Fig.18 b), which has a same width and length dimensions as bottom die. However, thickness of this holder is only 5mm and it made from same material as die. After putting the blank holder on top of the workpiece, it is fastened using blank holder and eighteen screws. Picture of clamping equipment with fixed sheet shown in Figure 20.

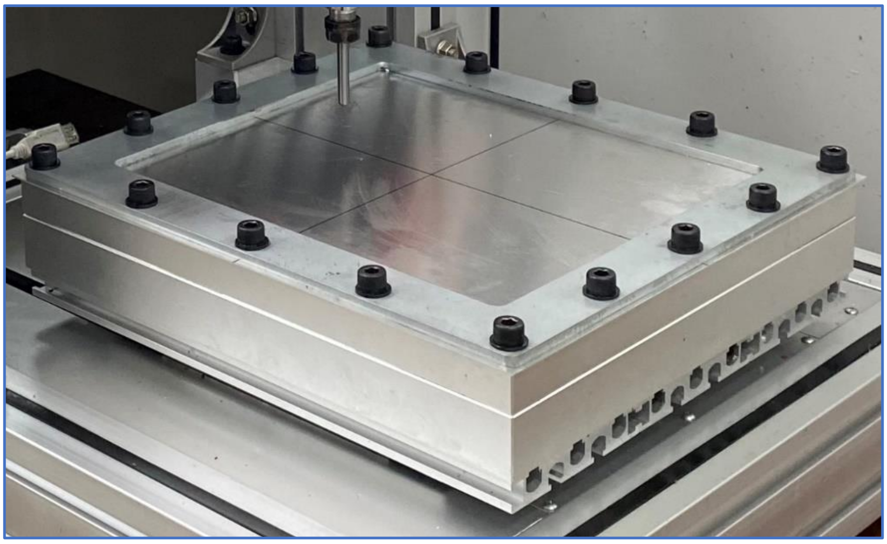


Figure 20. Ready-to-use clamping equipment.

Before beginning of each forming process, it is necessary to check coordinates of tool movement in order to prevent sudden move of tool. It can cause damage to sheet workpiece and forming tool respectively.

6.3 Forming tool

In order to deform the workpieces, it is important to use special tools. The tool movement is controlled by G code which generated by CAM software. For each type of tool path designed unique G code. Material of the forming tool is high speed steel and diameter of the tool is 6mm. Illustrations of forming tools are shown in Figure 20.

Figure 21. Types of forming tools.

6.4 Lubrication

Role of lubrication is important in SPIF because it can reduce wear of forming tool. Furthermore, accurate lubrication improves formability and surface quality of the sheet. During our tests we used combination of oil and grease as a lubrication. Bramley identified that lubricants are not significant factor, however later, Carrino observed that comparison between forming with lubricant and forming without use of lubricant gives obvious friction difference.

a b

Figure 22. Lubrication materials

a – grease, b – oil.

Mohan Raj Murugesan in [10] examined several types of lubrication during the SPIF process and identified that mix of oil and grease gives better results, so during our experiments as lubrication mix of grease and oil illustrated in Figure 22 is used.

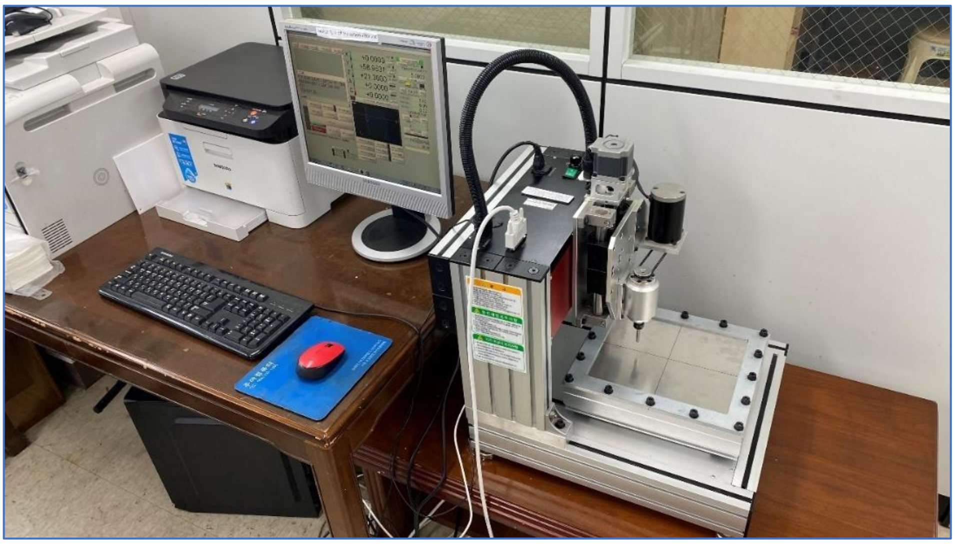


Figure 23. Full complect of SPIF equipment.

The spindle's feed rate was 500 mm/s during the experiments. The tool is rotated over its own axis in 6000 rpm. The rotation creates heat between the tool and sheet which increases the formability of workpiece. Figure shows the forming process and final part of SPIF.

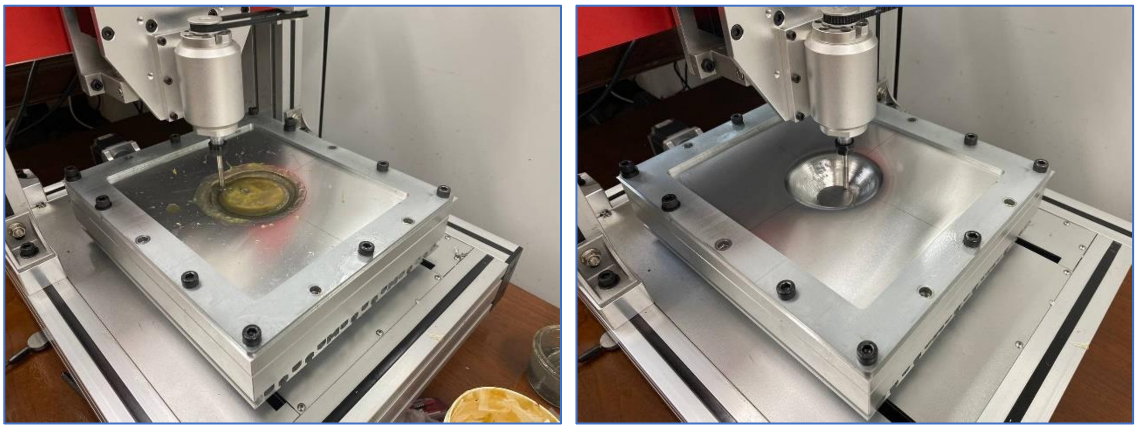


Figure 24. Forming process and last step of SPIF.

VII. FINITE ELEMENT ANALYSIS

The numerical simulations are important in order to understand the forming processes because it possible to model them as integral and partial equations [34]. Nowadays, the finite element method (FEM) is popular in solving engineering and mathematical problems [35]. It can reduce the time and cost of experiments. Firstly, FEM utilized to simulate elastic and plastic applications [36]. Today, sheet processes as bending, stamping, incremental forming, etc. are possible to model and it gives more opportunities to understand these processes. Moreover, utilizing FEM helps to predict defects, failures and analyzing forming parameters. In order to investigate process parameters of SPIF it possible to use finite element analysis (FEA). Two types of models can be used to simulate SPIF, and they are implicit and explicit models. Studies of [37] showed that explicit model of FEA more cost effective and it is close to realistic expectations for simulating SPIF operation.

During these studies ABAQUS 2021 software package is used to implement numerical analysis (FEA) of SPIF. This software package is not expensive according to computing power and simulation time in order to numerically analyze SPIF. ABAQUS includes some options like rigid-plastic deformation and plastic-elastic behavior and these options reduces the time demand to model parts in simulation.

Simulating SPIF is not easy and one of the most complicated parts is tool path definition. The reason is that tool path definitions in finite element analysis programs usually need to be programmed in other software. After programming it is necessary to import this tool path definition to FEA program as an input file [38]. There are two ways of defining tool path in ABAQUS and they are using boundary conditions with position or velocities. In our study we used method of positional boundary conditions. In order to define variation of forces during SPIF process an amplitude is used. Data of amplitudes for each type of tool path generated using one external software. This software converts typical G codes into define tool path for ABAQUS software.

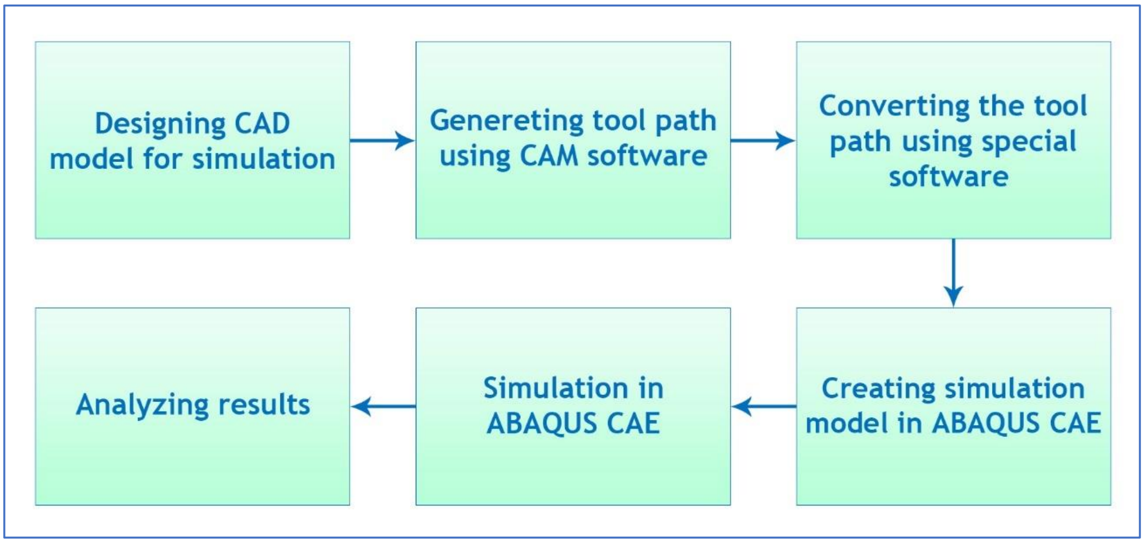


Figure 25. Main steps in finite element analysis of SPIF.

The first step of FEA is creating 3D model of final product using CAD software and, in this study, same software (Autodesk FUSION 360) and same design which utilized for practical experiments is used. As FUSION 360 has integrated CAM functions, generating all types of tool path is done in this program. After generating tool path, assigning G code for tool is established using G-code Ripper free software, which creates amplitude data along the profile of modeled part. These data are used to create boundary conditions in next steps.

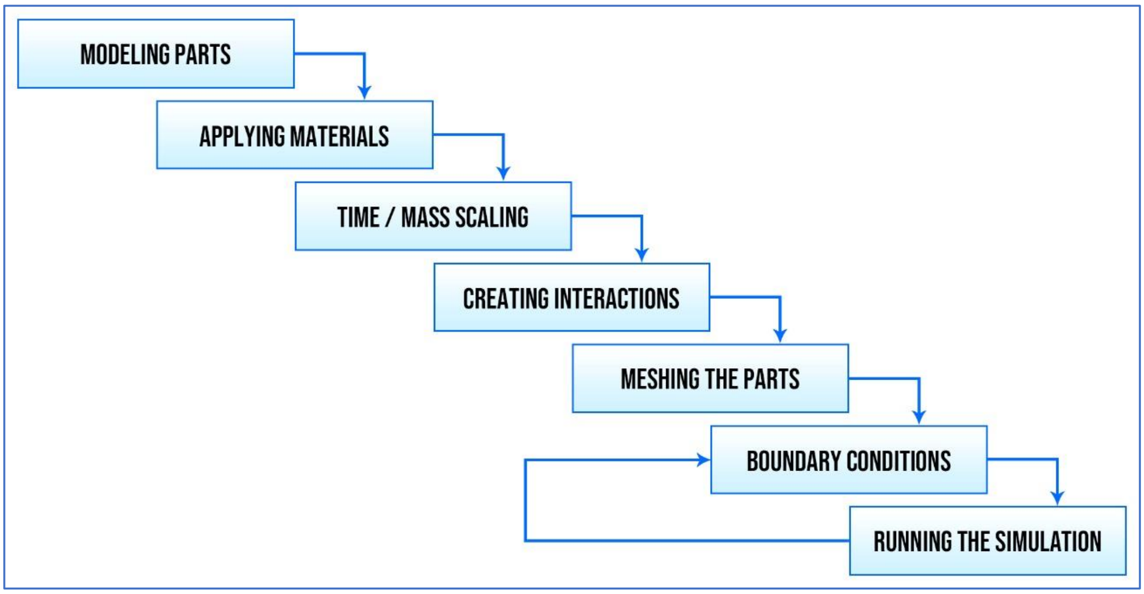


Figure 26. Main steps in finite element analysis of SPIF

Simulation on ABAQUS 2021 starts with creating model of SPIF equipment and they are forming tool, sheet workpiece, die and blank holder [39]. During modeling, these elements their type needs to be defined and among them only sheet workpiece is deformable element. Also, sheet can be shell or solid element. In this simulation type sheet workpiece selected as a shell element. Other parts of SPIF elements are created as analytical or discrete rigid elements. Type of forming tool is analytical rigid and it has revolved 3D shape. Die and blank holder are also created as a shell element, and they are discrete rigid.

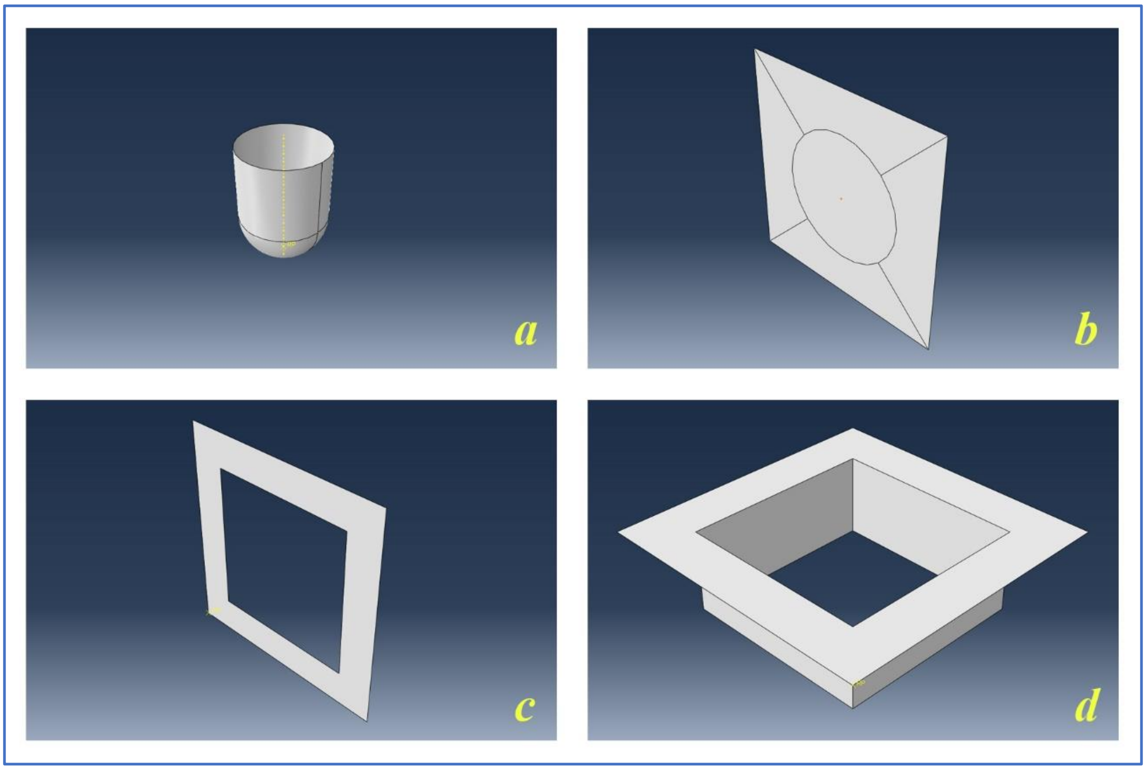


Figure 27. SPIF elements in ABAQUS

a – forming tool; b – sheet workpiece; c – blank holder; d – die.

The next step is assigning properties of every part. However, three parts of this assembly are analytical rigid so it not necessary to mention their properties. The only deformable part is sheet, so we assigned thickness and properties to this part. Material properties are same as AA5052 aluminum alloy which used in experiments and thickness is 0.5mm.

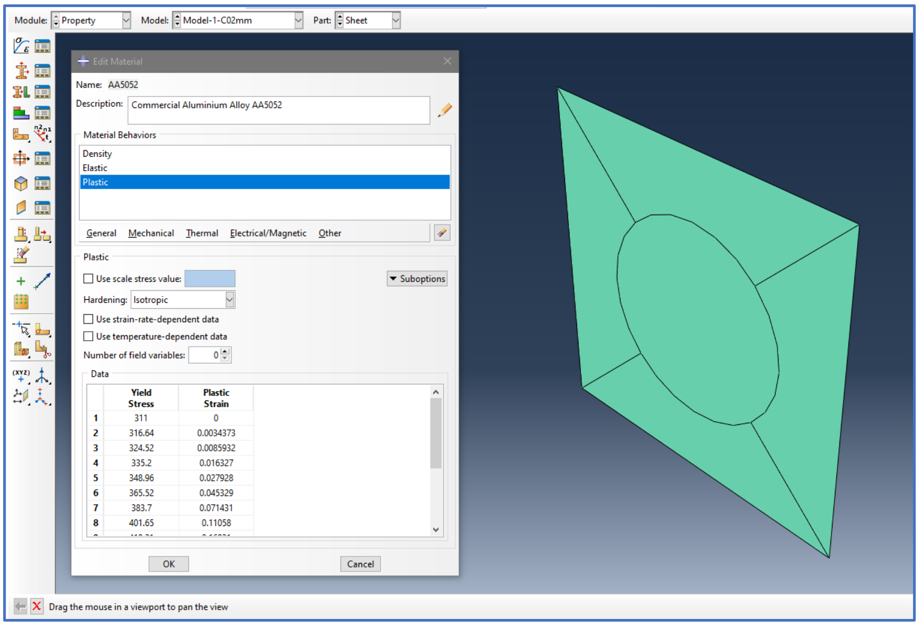


Figure 28. Assigning properties of sheet workpiece.

In order to increase the accuracy of simulation it is significant to create correct mesh in forming sheet. One of the important parameters of meshing is size of mesh, since bigger mesh can reduce the time of simulation, on the other hand it can affect negatively on the accuracy of results. So, in this case, we used mixed mesh size, which is smaller in main working area, and it is getting as bigger as it is far from main forming area. In ABAQUS and other finite element software it is not possible to mesh analytical or discrete rigid bodies so other elements of simulations are not meshed.

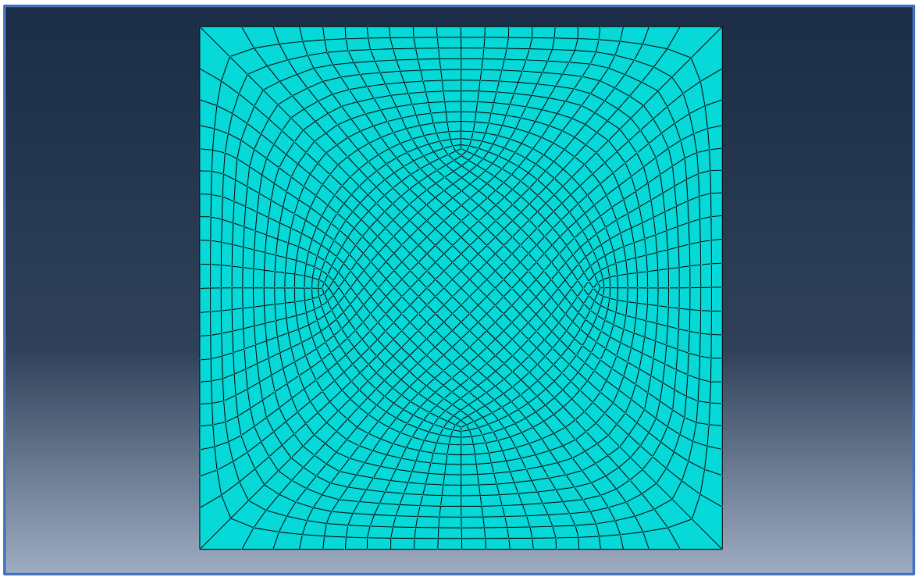


Figure 29. Mixed mesh of sheet workpiece

After creating mesh for deformable part, all components of the SPIF process in ABAQUS are assembled and this assembly shown in Figure 30. During creation of assembly using interaction module of ABAQUS 2021 necessary interaction properties between all parts are implemented. Tangential behavior selected as a 'contact property' between the tool and workpiece. A coefficient of friction selected as 0.1 and contact penalty method used as friction formulation because of using lubrication during forming process.

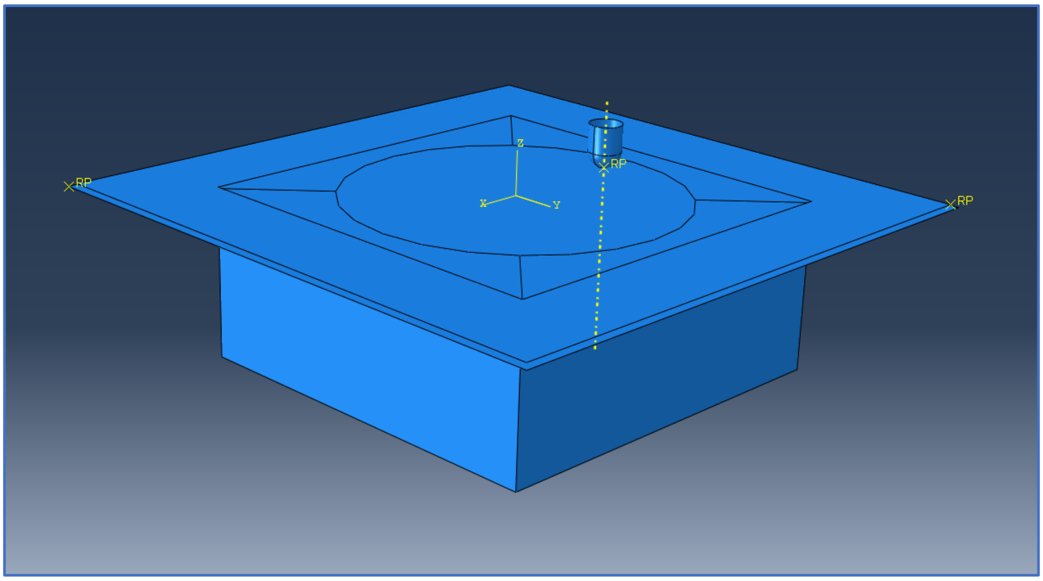


Figure 30. Assembly of all SPIF elements in simulation.

In the 'Step' module of software parameters such as forming time and mass scaling set according to experimental data. Time of forming calculated during experiments and for each type of tool path this parameter allocated differently. Mass scaling is one of the methods of reducing simulation time in software so in this study this parameter selected 2, 4, 8 respectively.

The next is applying boundary conditions to model and primary boundary conditions created to fixing workpiece between die and blank holder. In order to create such mechanical boundary conditions 'Symmetry/Antisymmetry/Encastre' mode selected and all boundary conditions of displacement for selected parts have to closed. Figure 31 shows boundary conditions of non-moving parts such as die, sheet and blank holder. These boundary conditions stop all 6 degrees of freedom.

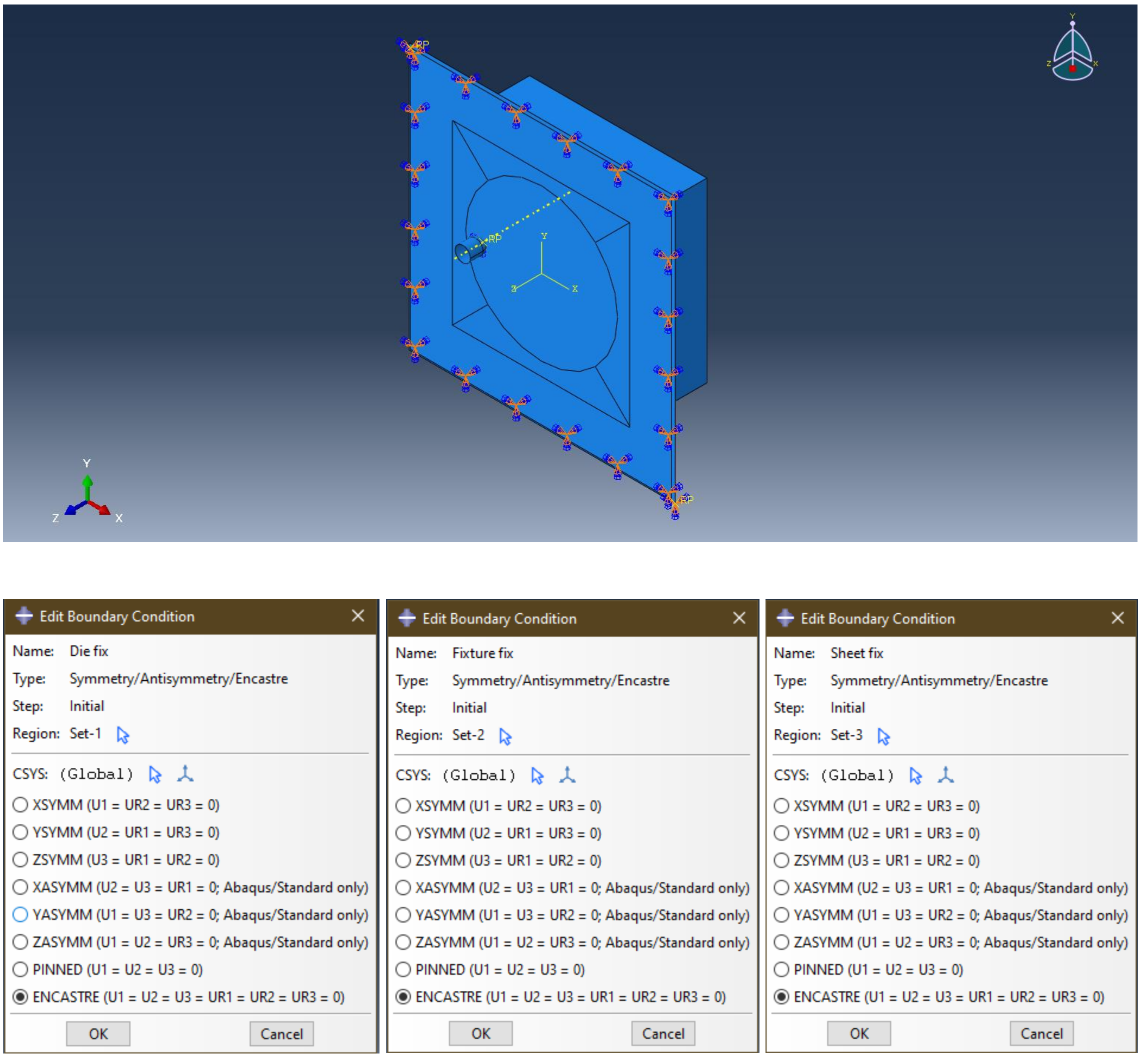


Figure 31. Boundary conditions to fix workpiece.

Since boundary conditions of non-moving parts are created, next step is assigning tool path for forming tool using boundary conditions and creating amplitudes. The force amplitude applied to each step in so this can define movement of forming tool in X, Y and Z directions. Contact point of tool with sheet is selected as a reference point and all displacements followed according to this reference point [40]. Figure 32 demonstrates boundary conditions of tool movement. Another important action is changing starting point of forming tool because according to generated tool path tool starts movement from particular point does not form the center of the coordinate system.

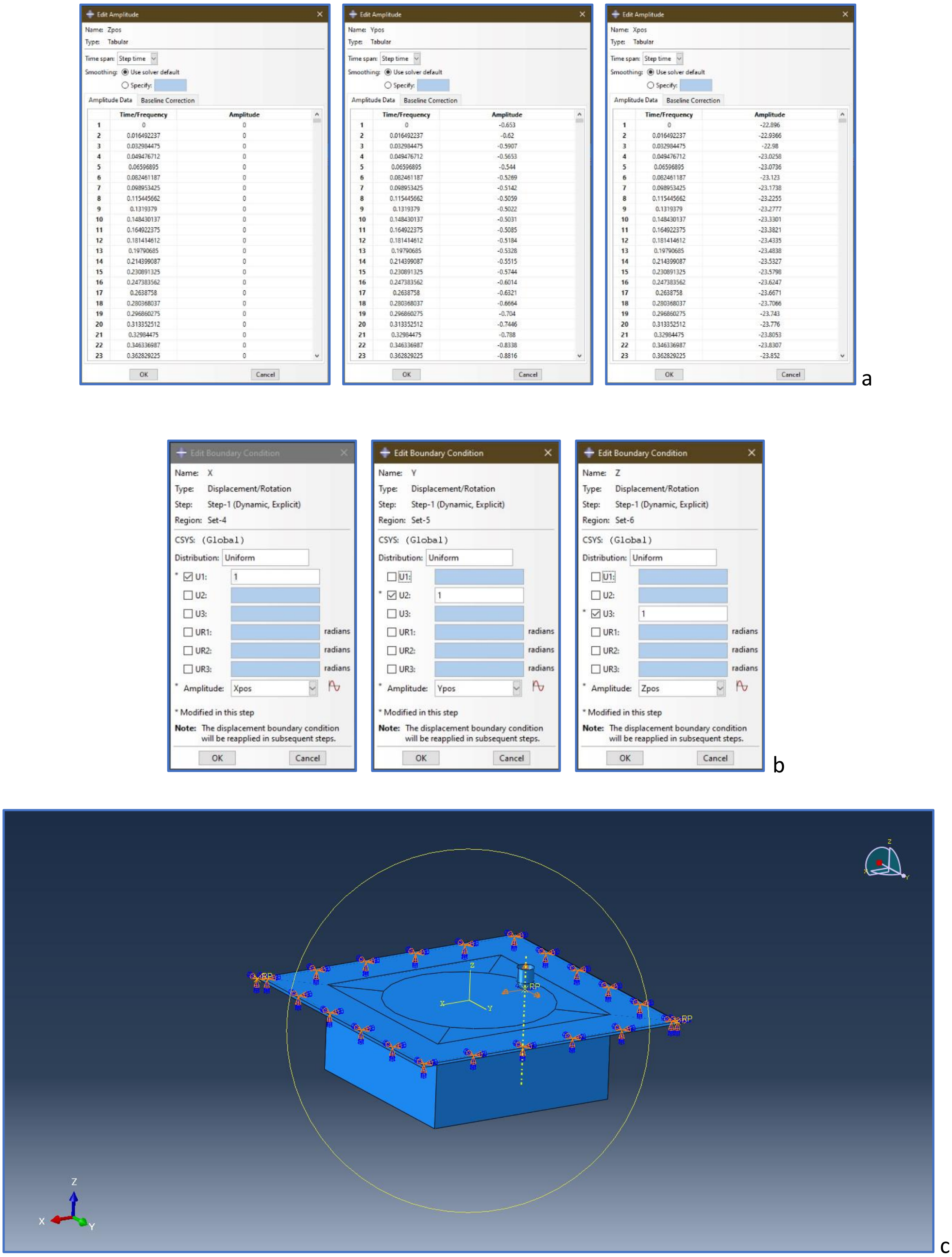


Figure 32. Boundary conditions and amplitudes data for tool movement.

a – amplitudes XYZ; b – boundary conditions; c – starting point of forming tool

The last step of FEA on ABAQUS is creating ‘Job’ and submitting it with accurate parameters. Since reducing the time of simulation is important, it is necessary to use parallelization option which allows to utilize multiple processors of computer. In Precision tab ‘Double-analysis only’ option of Abaqus/precision produces more accurate results than others [41].

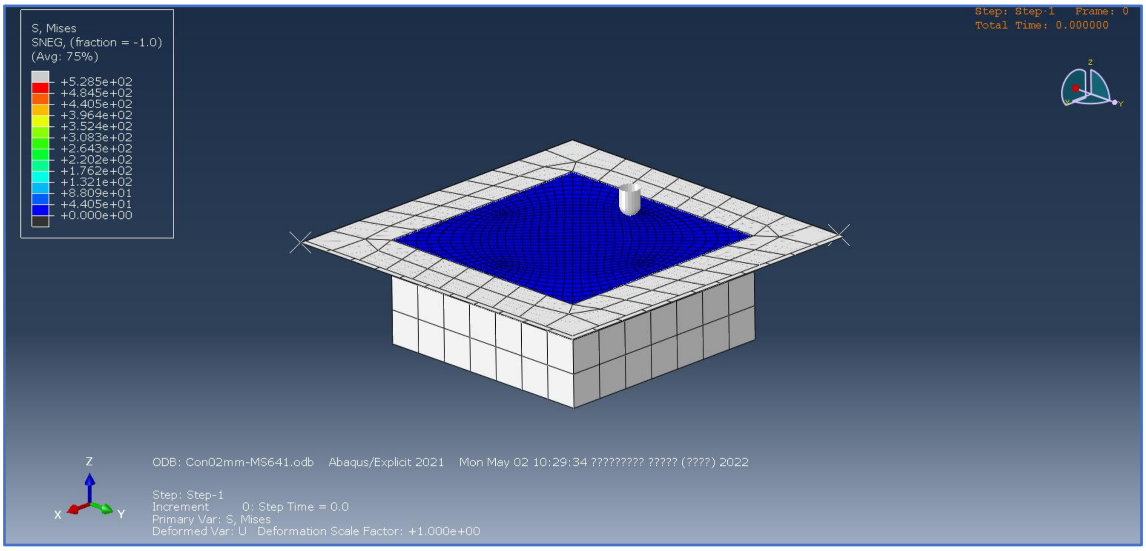


Figure 33. Condition of all parts before starting of simulation

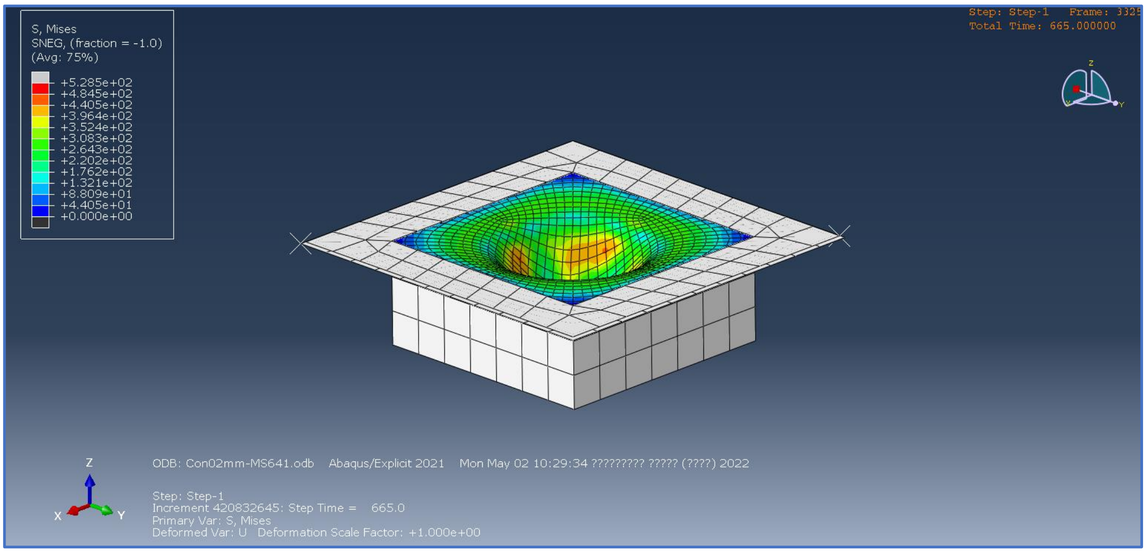


Figure 34. Final status of simulation – workpiece fully deformed.

VIII. RESULTS AND DISCUSSION

The effects of choosing tool path type on surface quality of SPIF final product discussed in this section. During efforts to understand what kind of tool path can produce higher surface quality, formed part of all workpieces are cut as a sample in order to measure their roughness. Each sample labeled according to tool path type and forming step so total of nine samples prepared to examine the surface quality. The obtained surface roughness data of all samples are compared with each other so that we can identify the most proper tool path which can produce higher surface quality.

The second part of this section is analyzing the FEA data and comparing them with the results of experimental analysis. The thickness distribution

8.1 Surface roughness measurement

The surface roughness of all formed parts is measured using 3D Nano Profiling System (NanoSystem NV2200) with an accuracy of 0.1 nm. All technical characteristics of this equipment is illustrated in in Table 5. NV2200 3D Nano Profiling System is shown in Figure 35. The measurements are made to check the values below:

Table 5. Main specifications of 3D Nano profiling machine.

№	Specification	Data
1	Measurement Technology	Non-Contact White Light Scanning Interferometer System
2	Light Source	Stable Hight Power LED
3	Z resolution	< 0.1 nm with piezo-stage and capacity sensor
4	Z axis scan range	250um
5	Z repeatability	< 0.3 % (3sigma)
6	Z accuracy	< 0.75 %
7	Sample Stage	Motor stage 300x300mm/Motor Z 100 mm / auto tilt +/- 3°
8	X Y resolution	0.15 to 3.6 um
9	Measurement speed	50um / sec

Ra - the arithmetic average of the absolute values of the profile heights over the evaluation length.

Rt – total height of the roughness profile: Difference between height Zp of the highest peak and depth Zv of the deepest valley within the evaluation length ln

Rz - the average value of the absolute values of the heights of five highest-profile peaks and the depths of five deepest alleys within the evaluation length.

Figure 35. 3D Nano Profiling System.

8.2 Effects of tool path on surface quality.

The influence of tool moving trajectory or toolpath type on surface roughness of SPIF final product is investigated using three types of tool path 'Contour', 'Ramp' and 'Spiral' respectively. Sheet blanks are formed using these tool path and each tool path type used three times when forming step sizes were 0.2, 0.4 and 0.8 mm. It observed that surface quality of formed parts is higher when 'Ramp' toolpath is utilized. In each step sizes results of experiments showed that surface roughness values (Ra, Rt, Rz) of parts are better where 'Ramp' toolpath is utilized. Table 6 below shows the roughness values of samples' surface. Figure 36 illustrates results of practical experiments.

Table 6. Results of measurement.

№	Tool path	Step size	Ra (μm)	Rt (μm)	Rz (μm)
1	Contour	0.2	0.82	5.15	2.28
2	Ramp		0.93	4.30	2.28
3	Spiral		1.01	4.46	2.62
4	Contour	0.4	1.37	6.48	2.93
5	Ramp		1.02	3.95	1.89
6	Spiral		1.51	7.44	4.37
7	Contour	0.8	2.78	13.95	6.21
8	Ramp		2.42	9.30	6.15
9	Spiral		3.32	15.76	7.89

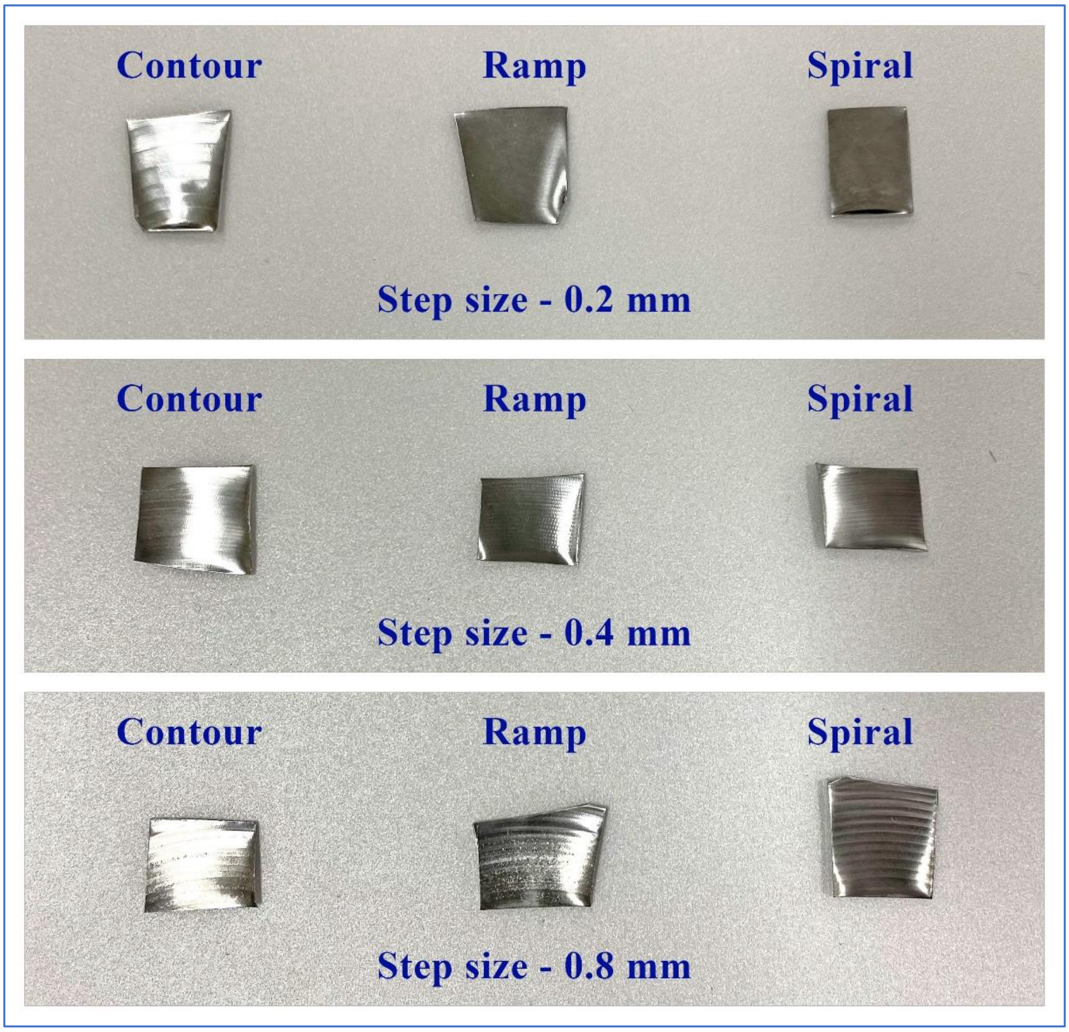


Figure 36. Samples from formed parts for measurement.

Three figures below illustrate result of measurement for samples that formed with 0.2 mm step size.

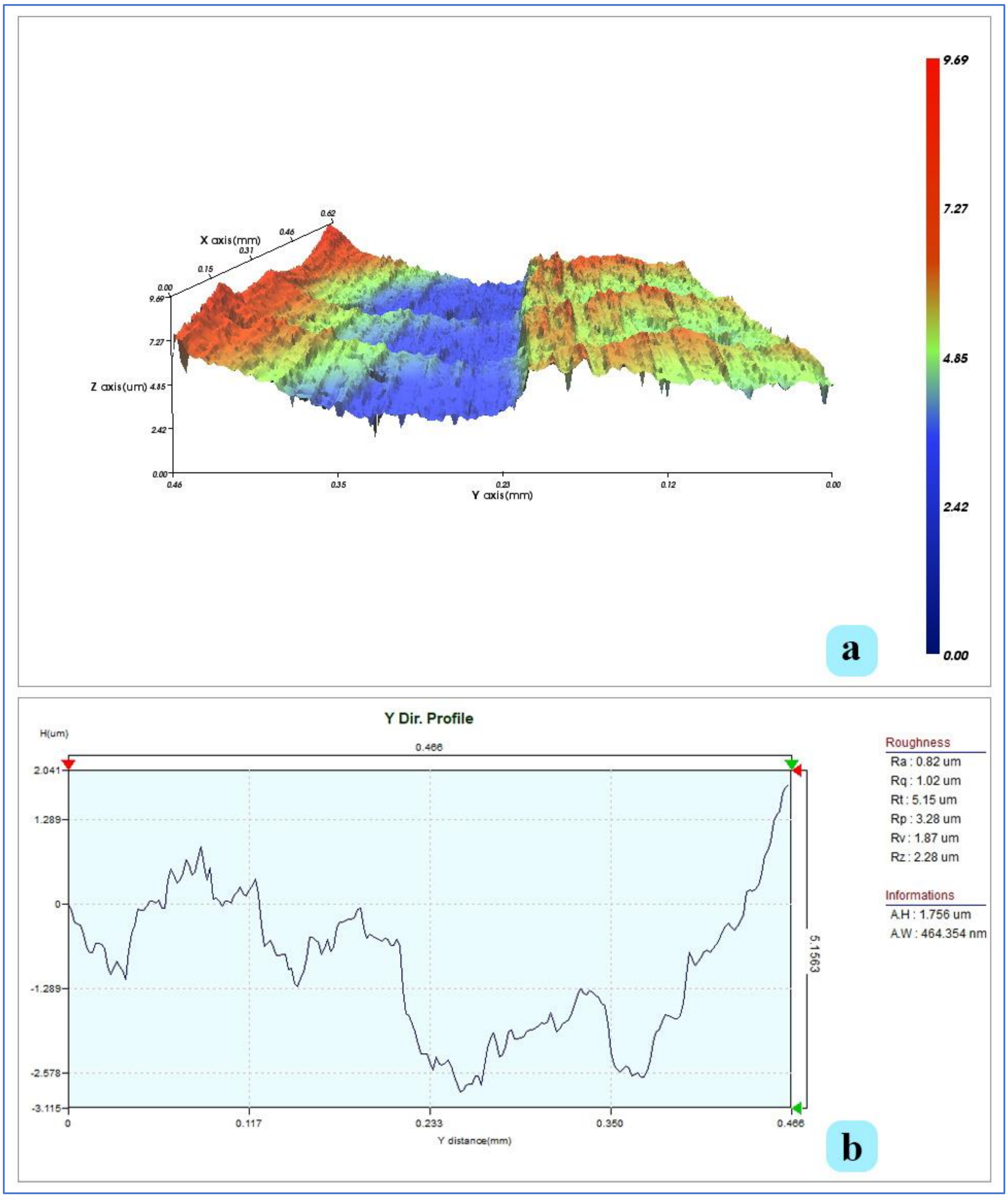


Figure 37. Surface roughness of sample with Contour 0.2 mm

a – along 3D profile, b – along Y direction profile.

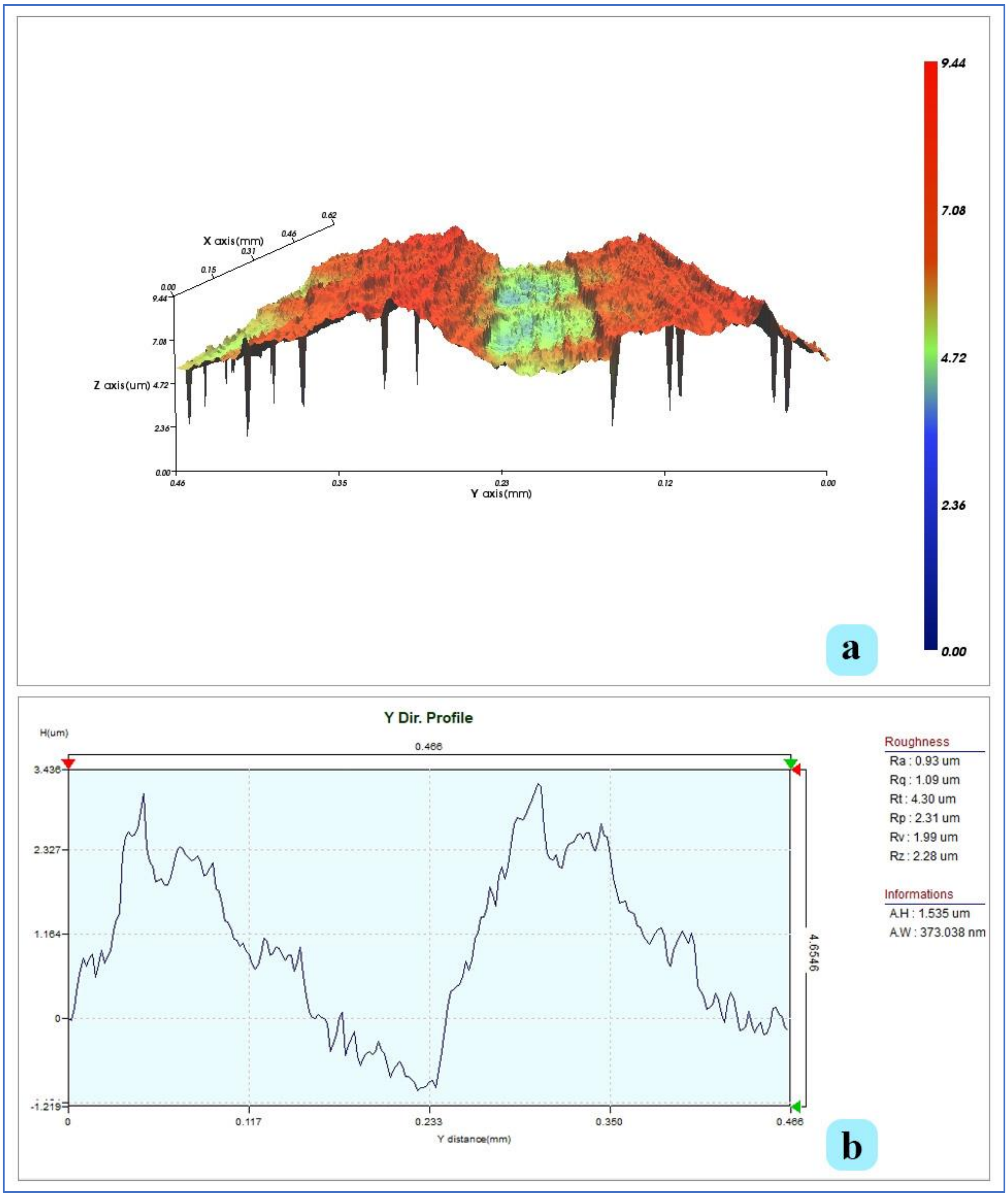


Figure 38. Surface roughness of sample with Ramp 0.2 mm

a – along 3D profile, b – along Y direction profile.

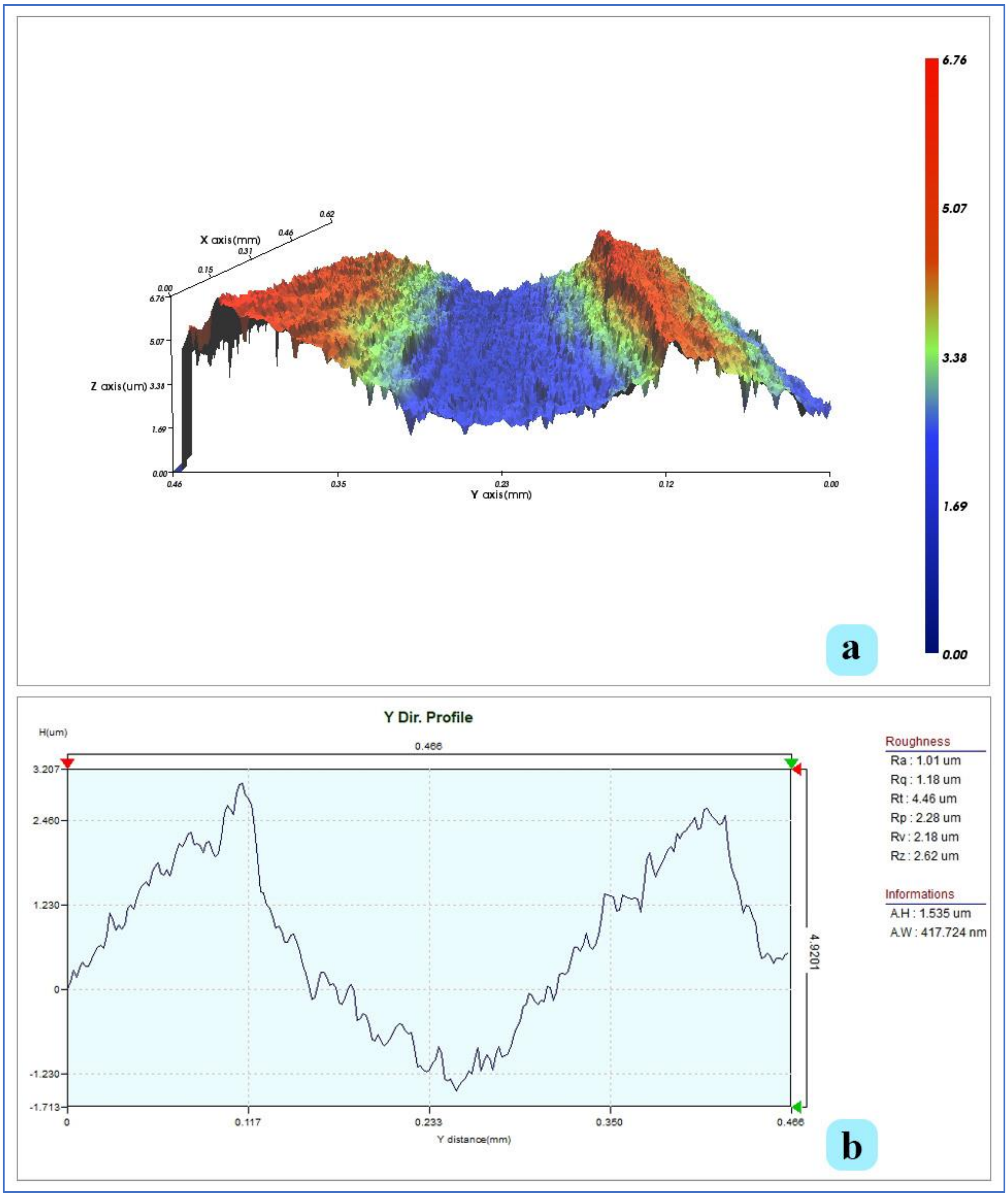


Figure 39. Surface roughness of sample with Spiral 0.2 mm

a – along 3D profile, b – along Y direction profile.

Three figures below illustrate result of measurement for samples that formed with 0.4 mm step size.

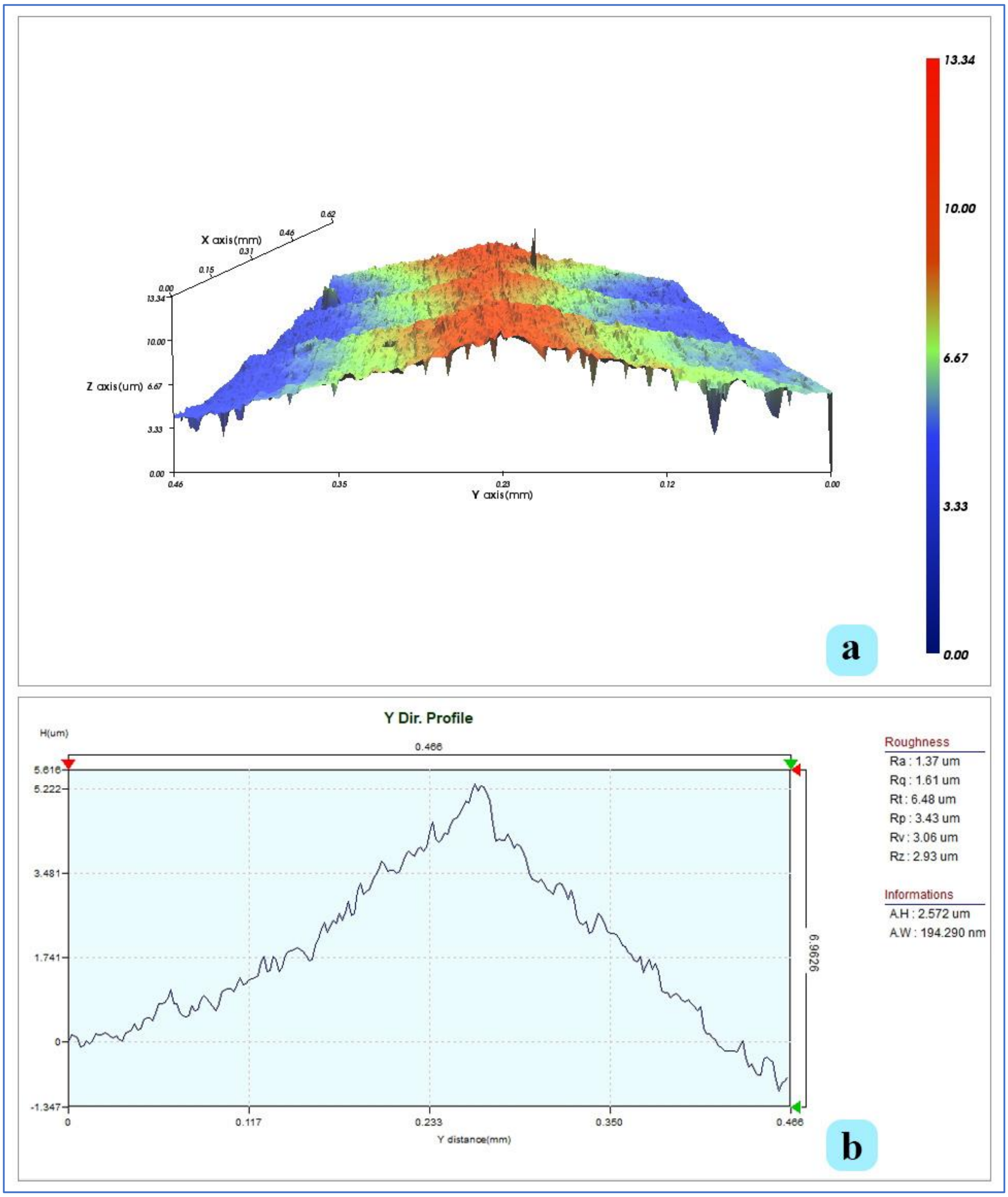


Figure 40. Surface roughness of sample with Contour 0.4 mm

a – along 3D profile, b – along Y direction profile.

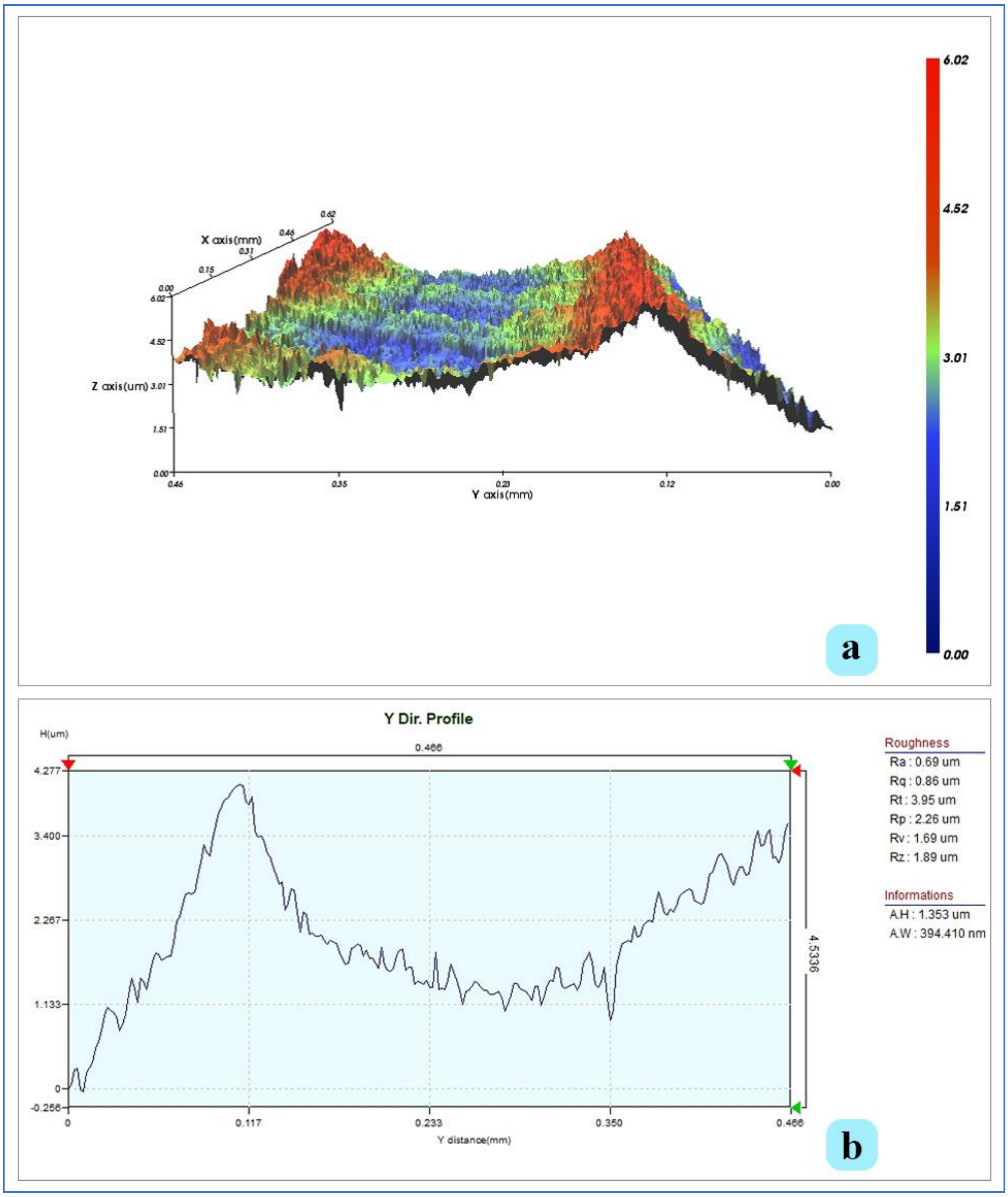


Figure 41. Surface roughness of sample with Ramp 0.4 mm

a – along 3D profile, b – along Y direction profile.

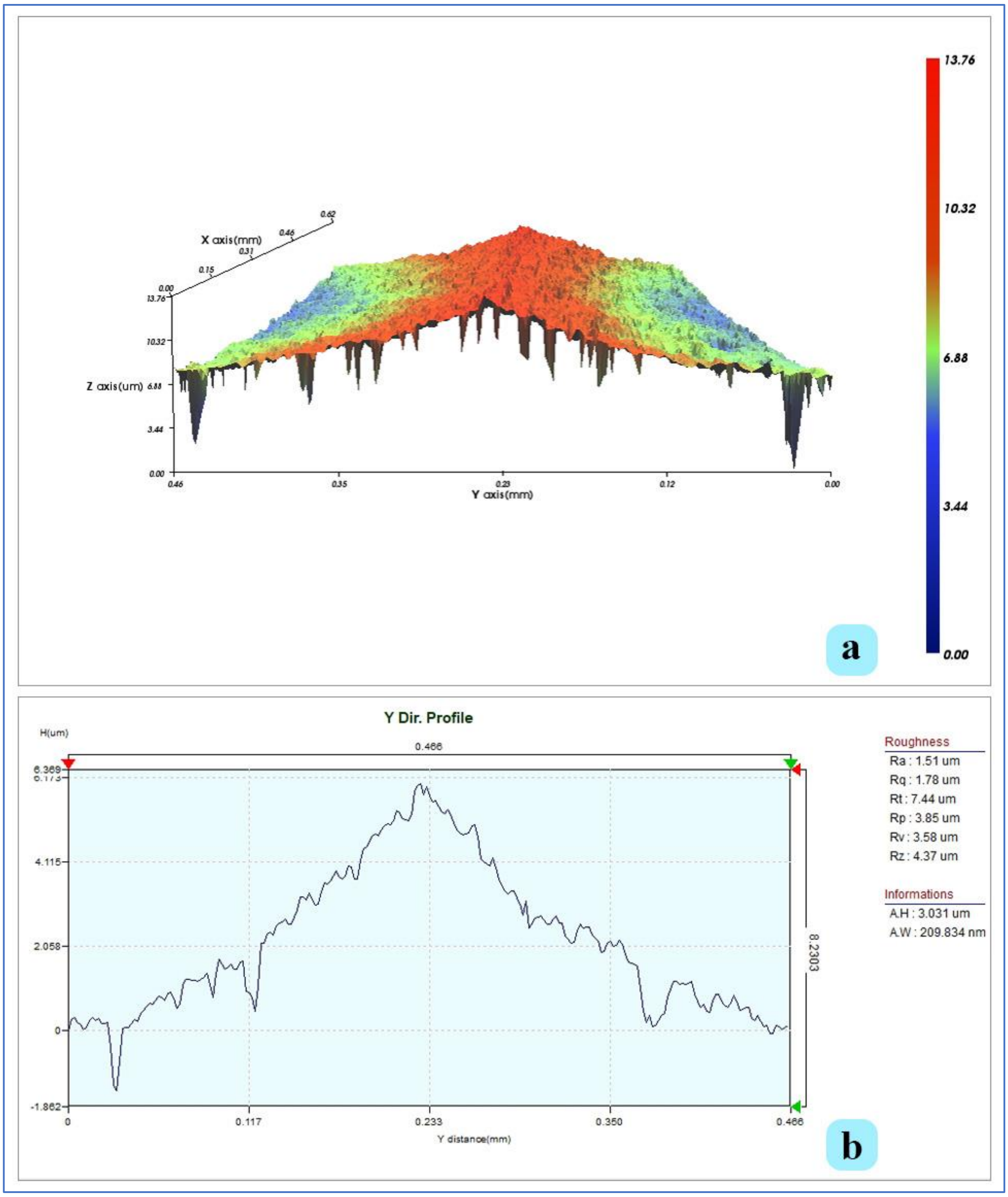


Figure 42. Surface roughness of sample with Spiral 0.4 mm

a – along 3D profile, b – along Y direction profile.

Three figures below illustrate result of measurement for samples that formed with 0.8 mm step size.

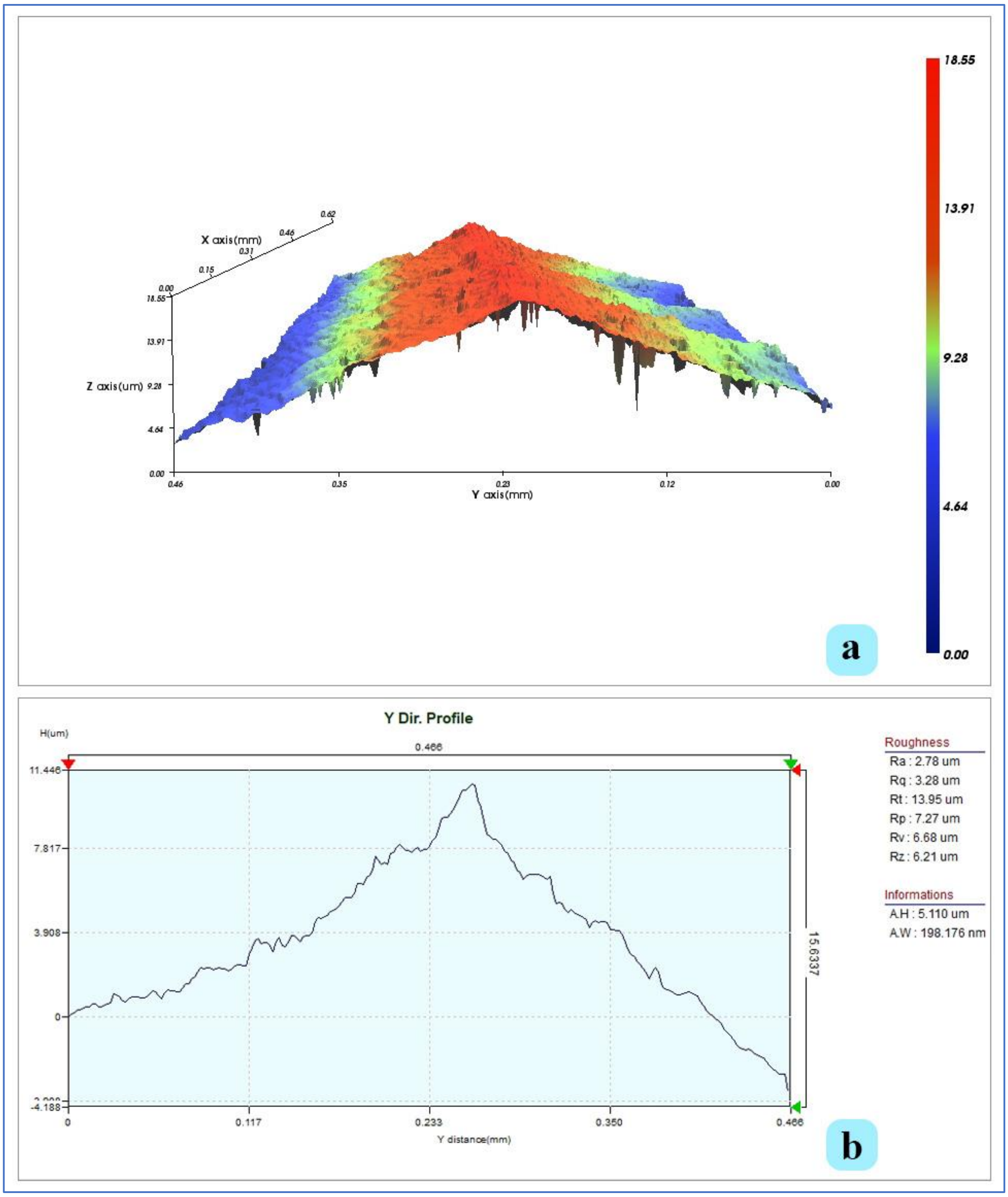


Figure 43. Surface roughness of sample with Contour 0.8 mm

a – along 3D profile, b – along Y direction profile.

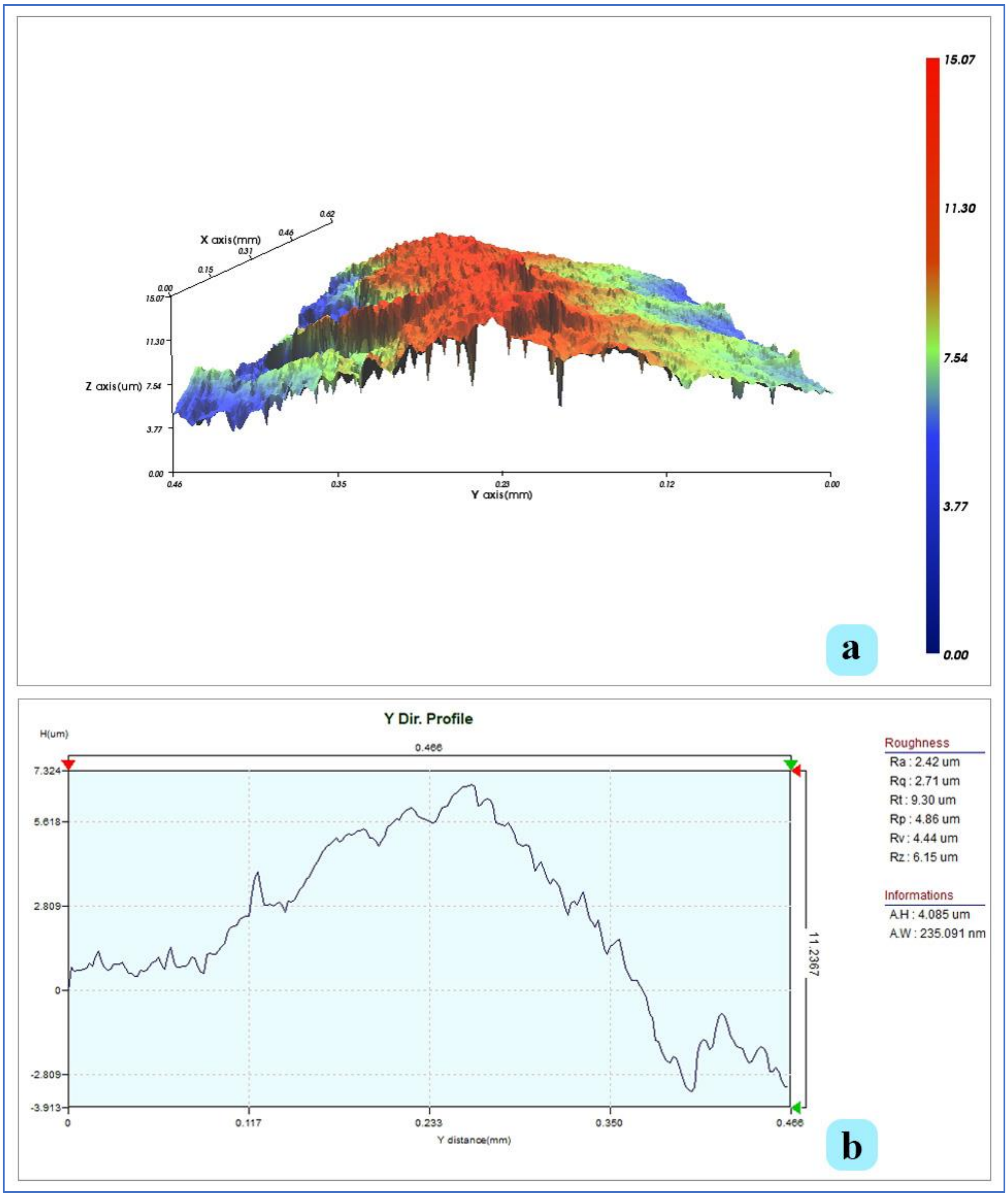


Figure 44. Surface roughness of Ramp with Spiral 0.8 mm

a – along 3D profile, b – along Y direction profile.

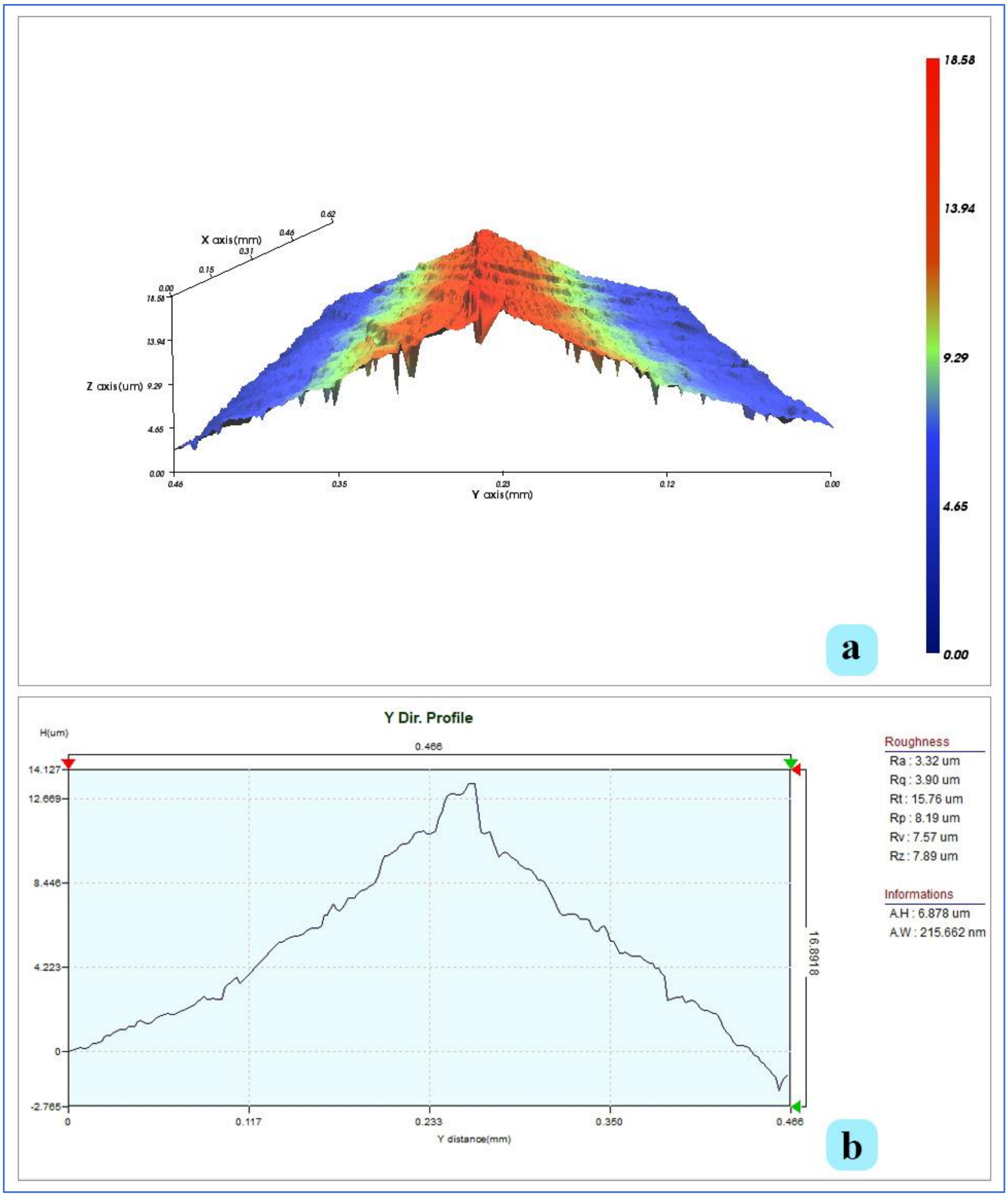


Figure 45. Surface roughness of sample with Spiral 0.8 mm

a – along 3D profile, b – along Y direction profile.

8.3 Effects of tool path on thickness distribution

The impact of tool path type on distribution of thickness also examined using same tool path types. There was total 6 experiments and 3 numerical and 3 practical experiments. In these experiments forming step size was 0.2 mm. Results of numerical experiments were generated using ABAQUS CAE software and in order to determine thickness distribution along cut profile output database of FEA results are utilized. It is possible to get some information to understand and control thickness distribution. During finite element analysis block elements used and it is considered that thickness distribution corresponds to different axis of action.

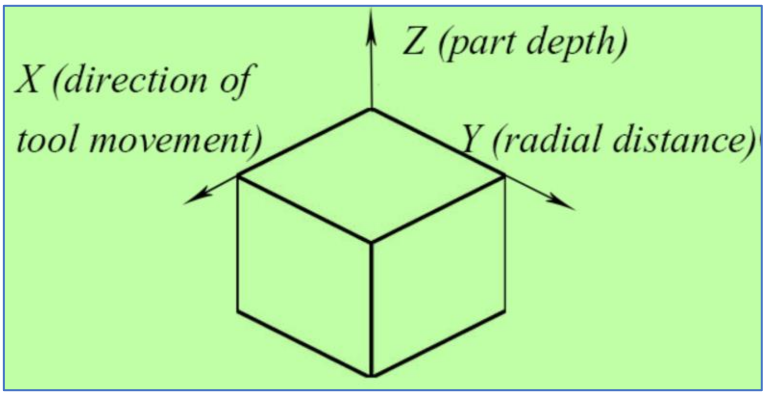


Figure 46. Indication of directions

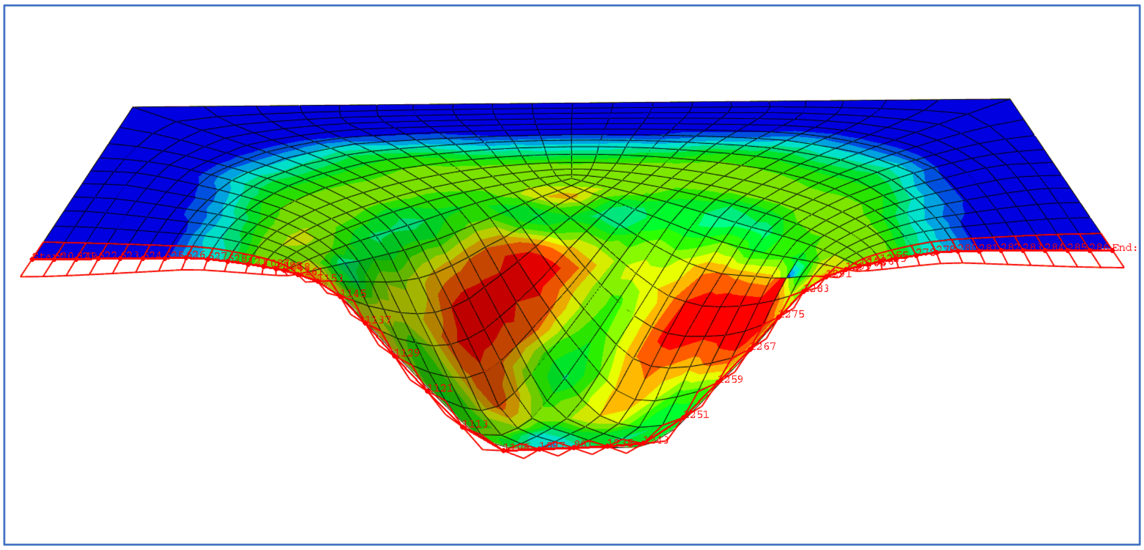


Figure 47. Cut profile for measuring thickness distribution along the surface.

It is possible to determine thickness of any part of workpiece along cut profile during the any step of simulation to receive helpful data on thickness and thickness distribution of the sheet blank. In order to determine thickness of sheet on forming part it is necessary to define a line on top surface of workpiece as shown in Fig 47. Results of FEA showed that thickness distribution of formed sheets using each type of tool path are almost same. Furthermore, size thinnest parts of final products from each tool path were similar and it was close to 0.3mm. Figures 48, 49 and 50 show graphs of thickness distribution along the cut profile for all three kind of tool path.

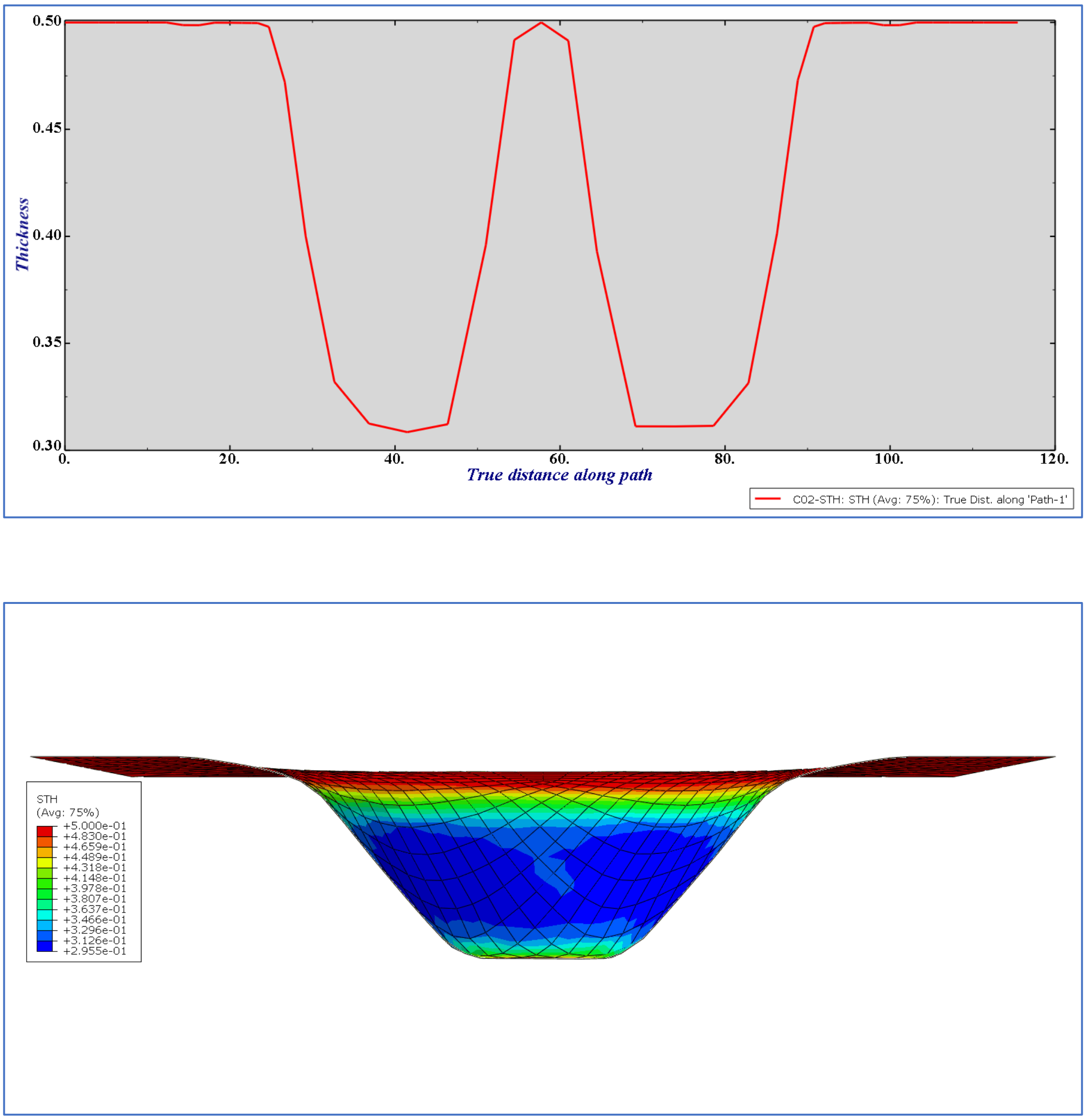
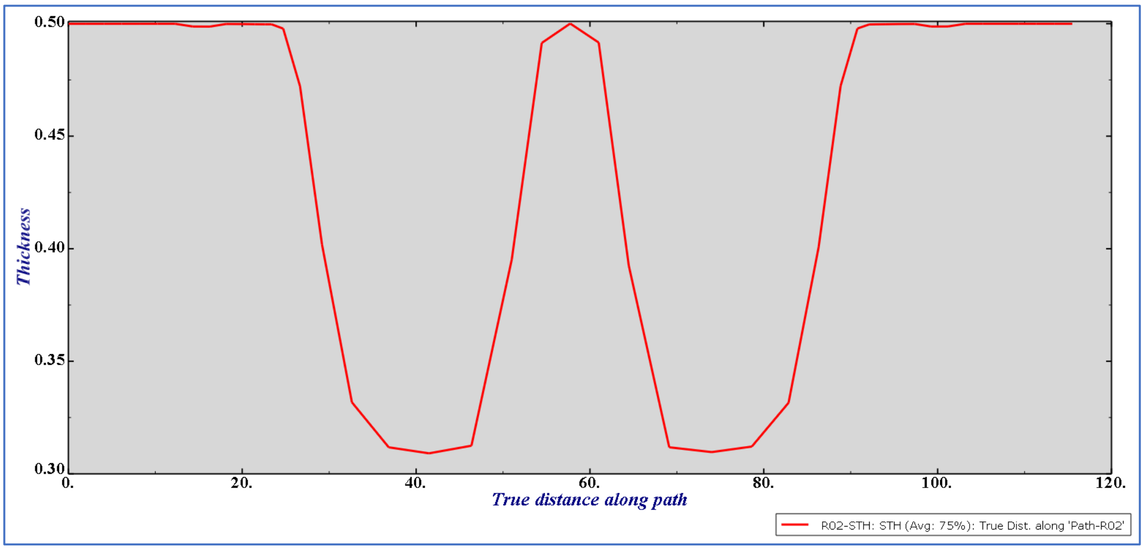


Figure 48. Thickness distribution along the cut profile for 'Contour' tool path.



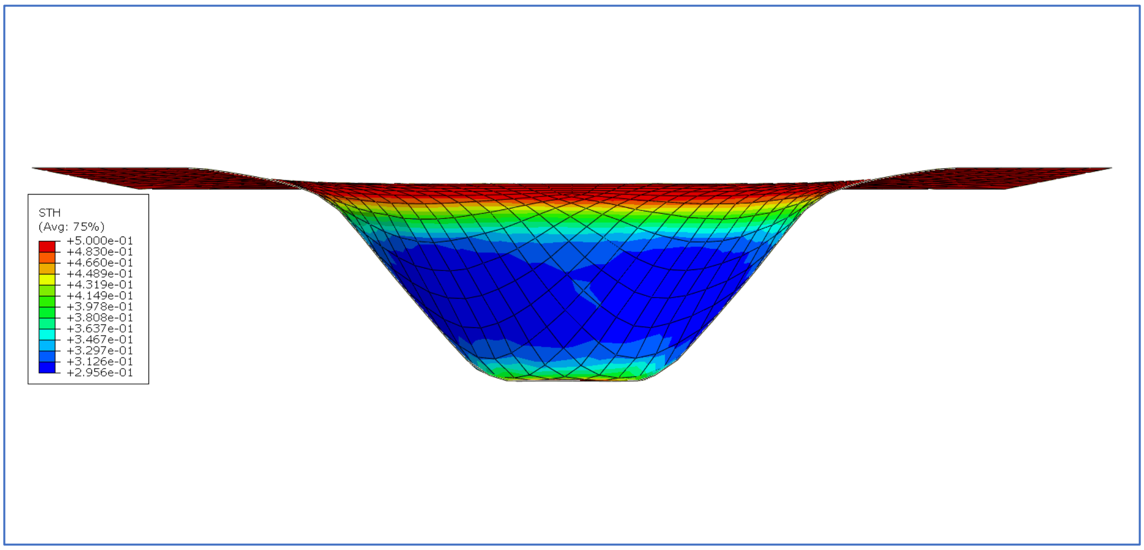


Figure 49. Thickness distribution along the cut profile for 'Ramp' tool path.

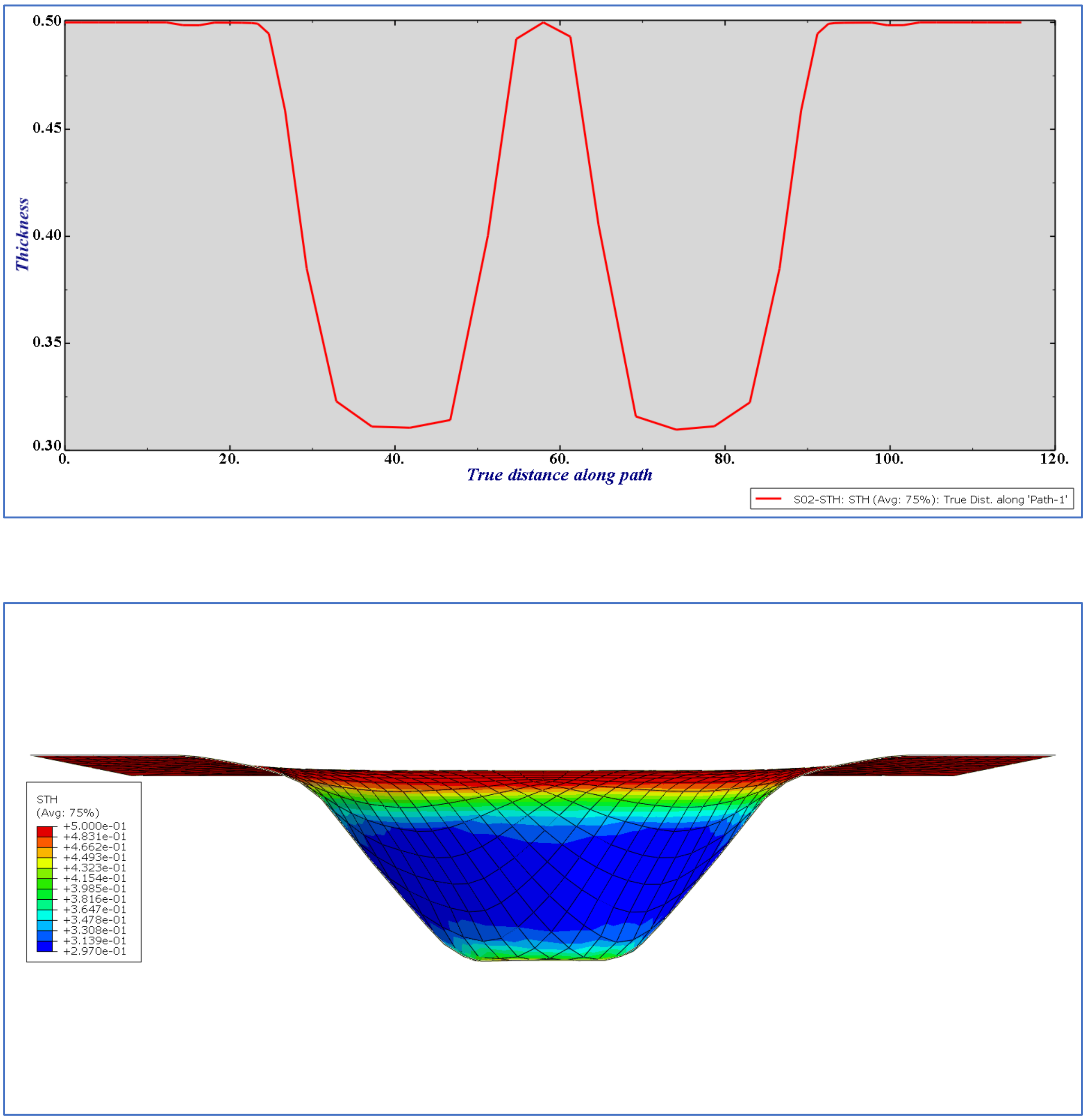


Figure 48. Thickness distribution along the cut profile for 'Spiral' tool path.

However, when using 'Spiral' tool path there was a slight difference in thickness distribution which is possible to observe when thickness distribution graphs all tool path types illustrated together (Fig. 51).

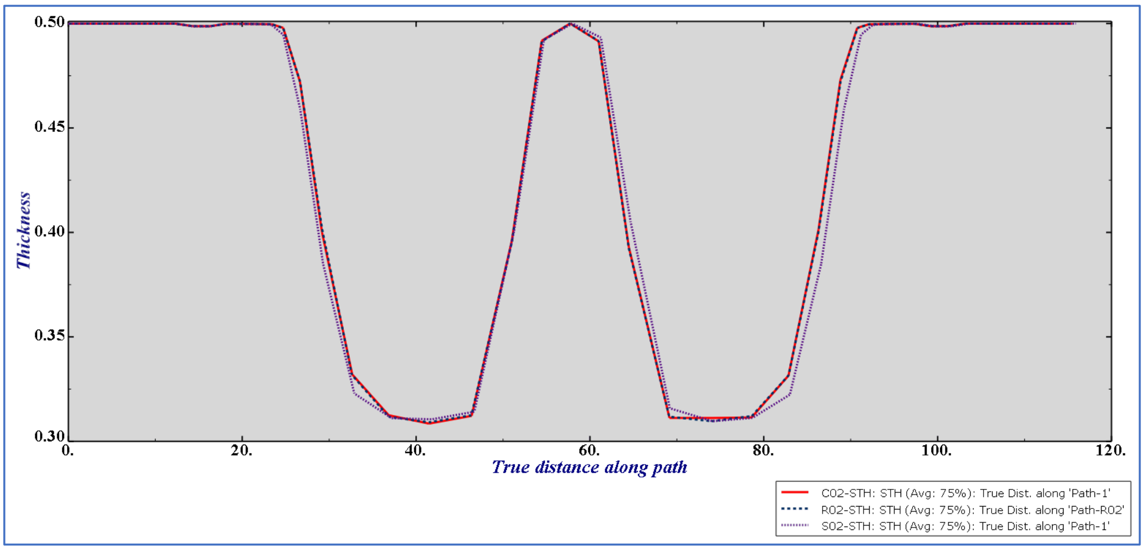


Figure 49. Comparing thickness distribution along the cut profile of all three sheets.

After obtaining necessary data from the simulations, it is possible to compare them with results of practical experiments. Firstly, samples from practical experiments are prepared for measurement through cutting formed pieces of final products (Figure 52). In order to measure the thickness of formed parts two types of equipment were utilized. One of them is Ultrasonic thickness gauge with accuracy 0.2 mm and another one is digital vernier caliper. Measuring instruments are illustrated in Figure 53.

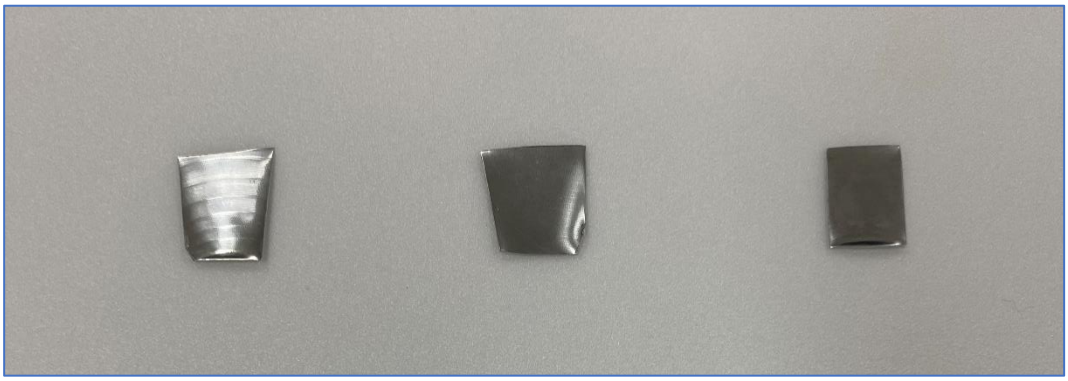


Figure 50. Samples to measure thickness of deformed part of sheet.

Figure 51. Thickness measurement instruments.

Measuring thickness of final products is significant to understand how workpiece can come close to failure during SPIF process. The initial thickness of sheets was 0.5mm and formed parts of the workpiece will be thinner than that. For that reason, it wasn’t possible to utilize Ultrasonic thickness gauge, so all measurements were done using vernier caliper. Results demonstrated that minimum thickness of all formed parts are 0.27mm.

The results of numerical and practical experiments are slightly different, in other words minimum thickness in results of simulations are 0.295mm while thickness of samples from practical experiments is 0.27mm.

IX. CONCLUSION AND SUGGESTIONS

9.1 Conclusion

The research work executed in this MSc thesis was aimed at analyzing surface quality of SPIF products through changing type of tool path. All numerical and practical experiments developed using three types of tool movement path with names 'Contour', 'Ramp' and 'Spiral' respectively. Commercial Aluminum Alloy 5052 sheets of 0.5mm thickness were utilized in order to carry out practical experiments. Those aluminum sheets were deformed in truncated cone shape with 50^{o} forming angle, 50mm diameter and depth forming was 20mm.

As regards the impact of tool path on surface quality of final product which formed using SPIF, the practical analysis revealed that utilizing different types of tool movement will produce various surface roughness. It is noticed that 'Ramp' tool path during forming process can result higher quality of surface while surface quality of other samples which formed using 'Contour' and 'Ramp' tool path is remarkably low.

The finite element analysis which conducted to analyze thickness distribution demonstrated that influence of tool path on the final thickness of formed workpiece is not noticeable. The thickness distribution and minimum thickness of formed parts almost similar with each other, however tool movement method was different in every experiment.

The thickness measurement of practical samples was carried out for comparison between the results of simulation. Comparison illustrated that real thickness distribution and minimum thickness of formed workpiece is measly different. The reasons for variation in results of numerical and real experiments can be some errors in converting the tool path and setting boundary conditions. However, the numerical thickness of distribution results is acceptable in comparison with results of FEA.

9.2 Suggestions

Future works should conduct investigation on impact of tool path to deform sheets high form angles. Furthermore, influence of different methods of tool movement on forming accuracy can be proper topic for next studies. The implementation of FEA in these research and comparison with practical experiments can lead to obtaining valuable investigations.

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