Numerical and Experimental Investigation of Spring-back in Sheet Metal Forming.

By

Bhandari Krishna Singh

Master of Mechanical Engineering (Computational Mechanics/Metal Forming), Jeju National University

Submitted in fulfilment of the requirements for the degree of

Masters in mechanical engineering

June 2022

Numerical and Experimental Investigation of Spring-back in Sheet Metal Forming.

Bhandari Krishna Singh
(Supervised by professor Dong-Won Jung)

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Mechanical Engineering

2022. 06. 17.

This thesis has been examined and approved.

Chang-Nam Kang

Thesis director, Chang-Nam Kang, Prof. of Mechanical Engineering.

Jung D.W.

Thesis director, Dong-Won Jung, Prof. of Mechanical Engineering.

Thesis director, Jin-Hwan Ko, Prof. of Mechanical Engineering.

2022. 06. 17.

Date

Department of Mechanical Engineering
GRADUATE SCHOOL
JEJU NATIONAL UNIVERSITY

Acknowledgment

Appreciation to Jeju National University (JNU) for providing an opportunity of the master's degree course. JNU provide, a place for research and study; - master's degree and explore company opportunities. In addition to that, I am great-full for the support, and expert guidance, throughout the course to the supervisor, Professor Jung Dong Won. Also, I am glad for having supportive parents, Indra Bhandari, and Maya Bhandari who believed on me and gave financial support. Not only that, providing care, love entirely during my education period.

It was impossible without the supports of Nepali community of JNU. So, I would like to express my gratitude to Dr. Suresh Rai, Dr. Pradeep Adakari, Dr. Sunam Kumar Sharma, Dr. Mani Banjada, Mrs. Amrita Khanal, Dr. Shirjana Saud, Mr. Roshan Mangal Bhattarai, Mr. Aneel Poudel and Mr. Mahesh P. Bhatta. For encouragement on me, to continue the study and research works. Along with the positive influence of Mr. Abdul Rahaman and roommate "Yoon Sungmin". Without them, Laboratory work was impossible. Additionally, laboratory collage also helped me to explore extensively on my research work; - as well as reach to my limit for brain-storming the research ideas and writing a scientific article.

Big respect to Dr. Mohan Raj Murugesan, Dr. Shahid Aziz, and Dr. Muhammad Sajjad for the expert knowledge and guidance. Since they did their best to support me, during my master's degree course as a senior and mentor. Along with, big thanks to Mr. Bek, Mr. Chen, Mis. Isagawa, Mr. Han Jaehak, and Mr. Kang Jiyoon working as team, lab mate and classmates. Additionally, as a life mentor Dr. Umer and Professor Pang Dong-Guk for the advising and guiding throughout my master's degree course.

Nomenclature

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

Commonly used notations

L	Length of sheet
h	Flange height
t	Sheet thickness
w	Web width
r	Radius of bend after roll forming
Y	Width of working sheet
Si	Silicon
Fe	Iron
Cu	Copper
Mg	Magnesium
Zn	Zinc
Cr	Chromium
Al	Aluminium
Mn	Manganese
σ_e	Engineering stress
P	Applied load
Ao	Initial cross-sectional area
ε_e	Engineering strain

σ	Displacement
Lo	Gauge length of the specimen
K_S	Strength coefficient
n	Hardening coefficient
mm	Millimeter
mm/s	Millimeter per second
a	Third Roll Stand
b	Last Roll Stand
c	Finished Profile with Bow Defect
d	Distance Between Passes
e	Supporting Stand
$\Delta\theta$	Spring back angle
dB	Distance of bow
Lo	Base length

Abbreviations

FEA	Finite Element Analysis
B.A.I	Bend Angle Increment
AA5052	Aluminum Alloy
CRF	Cold Roll Forming
ICF	Incremental Counter Forming

FEM	Finite Element Method
BLS	Buckling strain limit
MPa	Megapascal
CNC	Computer Numerical Control
G-Code	Computer Coordinates (X, Y, Z,)
SPIF	Single Point Incremental Forming Process.

Contents

List of Figures

List of Tables

Abstract (Hangul)

판금 형성은 금속 시트가 통상의 실온에서 바람직한 형상으로 형성되는 공정이다. 이 방법은 금속 개질로 유명하다. 따라서 금속, 시트 두께 및 금속 조성의 적절한 선택은 골절을 피하기 위해 고려된다. 그렇기 때문에 스프링백의 오류와 함께 금속판의 성형성과 파라미터를 고려한 연구가 중요한 연구이다. 이 연구 전반에 걸쳐 0.5mm, 0.8mm, 1mm, 1.2mm 및 1.5mm, 알루미늄 금속 시트는 전통적이고 현대적인 기술 기계로 형성되었다. 전통적인 방법의 경우 롤 성형 기계가 사용되는 반면, 현대적인 방법에서는 CNC 밀 링 머시니 금속 시트를 변형시키는 데 사용되었다. 롤 성형기에서, 상이한 앵글 시트가 예를 들어 "L" 및 "U" 형상으로 형성된다. 그리고 180°에 대해 10, 20, 30, 40, 50, 60, 70, 80, 90 및 100 rpm 의 다중 압연 속도로 일반 금속 시트를 형성했다. 이는 그림 2 에 나와 있이다. 전반적으로, 변형되는 동안, 스프링 백은 금속 시트의 모서리 측면에서 관찰된다.

마찬가지로, 금속을 변형한 후 현대 CNC 기술을 사용하는 동안 금속 시트 스프링 백의 표면에서 관찰된다. 180° 시트의 평면 금속은 10° 내지 90°로 형성되며, 이는 도 16 에서와 같이 변형되고 있다. 본 실험은 매끄러운 표면과 더 높은 깊이, 개선을 위한 매끄러운 표면 품질 및 스프링백 감소를 위한 금속 시트의 성형성을 평가하기 위해 수행되었다. 스프링백은 감소되었고 매끄러운 금속 시트의 성형성은 실험으로부터 얻어졌다. 나중에 6 장에서는 부드러운 마무리 금속에 대한 산업 아이디어가 논의했다. 매끄러운 완성된 표면을 위해 그리스와 오일과 같은 윤활 사용이 별도로 사용했었다. 그리고, 심지어 복잡한 각도를 변형시키면서 혼합되었다. 그 윤활은 금속 시트에 적용되었이다. 결과적으로, 스프링 백은 혼합 윤활의 도움으로 형성된 금속 시트에서 제어되고 감소되었다. 또한 현대 컴퓨터 수치 제어 CNC 는 전반적인 변형 프로세스를 제어하는 데 사용된다. T 가 형성된 금속시트는 분쇄되어 형성된 시트가 최종 변형된 금속시트에서 매끄러운 마무리와 함께 얇아지는 표면을 나타낸다. 금속 상 시트는 CNC 기술로

형성되었다. 새로운 상장을 수여하는 산업 제품, 금속 시트가 형성이 소개했었다. 10 번 실험을 수행해서 마지막에 질이 좋은 금속 시트를 만들었다. 거칠기, 스프링백 및 최소 최대 깊이와 실험 설정과 방법의 따라 결과를 다를 수도 있다.

ABSTRACT

Sheet metal forming is a process in which a metallic sheet is formed in a desirable shape at a normal room temperature. This method is famous for reforming metal. So proper choice of metal, sheet thickness, and composition of metal are considered to avoid the fracture. That's why research considering the formability of metal sheets and the parameters along with the error of spring back is important research topic. Throughout the research 0.5mm, 0.8mm, 1mm, 1.2mm, and 1.5 mm, aluminum metal sheet is formed with traditional and modern technology machine. For the traditional method roll forming machine is used, whereas in a modern method CNC milling machine is used to deform metallic sheets. In the roll forming machine, different angle sheet is formed for example "L", and "U" shape. With a multiple rolling speed of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 rpm for 180° a plain metallic sheet was deformed. This is shown in figure 2. Overall, while deforming, spring back is observed at the corner side of the metallic sheet.

Likewise, while using modern CNC technology after deforming the metal, at the surface of the metal sheet spring back is observed. Plane metallic of 180° sheet is formed from 10° to 90°, which is being deformed as in figure16. The experiment was performed to evaluate the formability of metallic sheets for a smooth surface and higher depth, smooth surface quality for improvement, and spring back reduction. The spring back has been reduced and the formability of smooth metal sheet has been obtained from the experiments. Later, in the 6th chapter industrial ideas of smooth finishing metal are discussed. For a smooth finished surface, the usage of lubrication, like grease and oil were used separately. And, even mixed, while deforming complex angle. That lubrication has been applied to a metallic sheet. As a result, the spring back is controlled and reduced in a formed metallic sheet with the help of mixed lubrication. Also, modern computer numerical control CNC is used to control the overall deforming process. The formed metallic sheet is milled to deform so the formed sheet shows the thinning surface with the smooth finishing in a final deformed metal sheet. the Metallic prize sheet is formed with the CNC technology. New industrial product for giving an award, metallic sheet is formed. Numerous

experiments were conducted. Problem like roughness, spring-back, and minimum-maximum depth was examined with different experiments setup.

1. Introduction

The metal sheet is used in day-to-day life. Forming and deforming metal sheets for reusing the metal is a common method because of the metallic property. So, due to this quality, metal is used broadly and in daily life. The metallic part can be seen in the automobile industry, aerospace industry, housing, and other small items that are used in everyday life like chairs, plates, spoons, and forks. In manufacturing practices, aluminum alloys are widely used because of their chemical composition and properties. The usage of aluminum is seen commonly in automobile and industrial productions. The significant advantage of this method is that it does not need any predesigned die. These methods can be carried out using a straightforward flat metallic sheet by initiating the local plastic deformations. The technique can be modeled using the computer numerical control (CNC) milling machine. As for the steel analysis of material behavior and shape defect compensation for the flexible forming. Furthermore, steel mechanical properties and residual stresses in cold aluminum channel sections were studied by the researcher [1,2]. More study done about surface quality of forming metal and the results in terms of working parameters such as step size, forming angle, tool diameter, feed rate, and lubricant type for the U-shaped deformation by the researcher [3,4]. Additional recent work by the researcher compared the numerical and experimental deformation on U-profile in the cold forming process, surface roughness estimate models using simulated neural networks [5,6]. Supporting vector regression and genetic programming are the discussion on the improvement for the formality. During forming the metallic sheet, the thinning behavior well discussed in the research article [7]. Therefore, the influence of the tool path on aluminum AA7075, while deforming the metallic sheet is important for smooth finishing and observing the thinning behavior to reduce the crack and fracture in the metallic body. They examined the SPIF process using the FE model in terms of strain, stress, and thickness distribution. The stresses in both circumferential and meridional directions were observed clearly in the inner part of the formed surface. The stresses were developed mainly in the circular direction because of the geometric boundaries. The impact of procedure and geometric parameters on longitudinal edge strain and product defects due to cold forming [8]. The deformation is usually impacted by the method strictures such as spindle speed, feed rate, tool diameter, lubricant, and tool path so robust optimization should be considered during forming a metallic sheet [9]. Examination of the formability problems is in-detail evaluation and required the proper study to achieve better formability. The analysis of forming parts for spring back and a tactic to lower the twist defect in formed uneven-channel sections thinning wall [10]. Investigated the geometrical precision preliminary survey to examine the influence of the supported force and angle on the microstructure, residual stress distribution, and material properties of Friction-Stir AA6061 Aluminum Alloy [11]. Likewise, while deforming a metallic sheet forming limit is considered [12]. Because for formability, forming a material and the characteristics of metal need to be analyzed properly and optimized the surface roughness [13,14,15]. Forming a metallic sheet research has been conducting all over the world because of the widely and commonly usages of the metals. [16,17,18] Different method was used for forming a metal sheet. Either in SPIF, thickness roughness and tool path generation the parameter for conduction experiment show the effect in formability which all bounders cannot be simulated through the computer [19].

In this paper, the study of the metal has been conducted in a detail formed. First the classification of metal forming is discussed. There are two main processes. One forming process is conducted in normal room temperature, whereas other forming method processed with the external heat applied. With the modern technology the computer numerical control CNC method usage was discussed with the forming limit parameters and simulation and experimental data comparison to reduce the Spring-back in the formed metallic sheet with the smooth finishing. Next the formability of an aluminum is studied because aluminum usage in the daily life is common. After forming and formability check the examination of the roughness test were conducted. At last chapter, the usage of those modern technology for forming metal and the industrial uses were being discussed. Concluding the outcome of the results of the experimental and numerical investigation of spring back in sheet metal forming.

2. Sheet Metal Forming

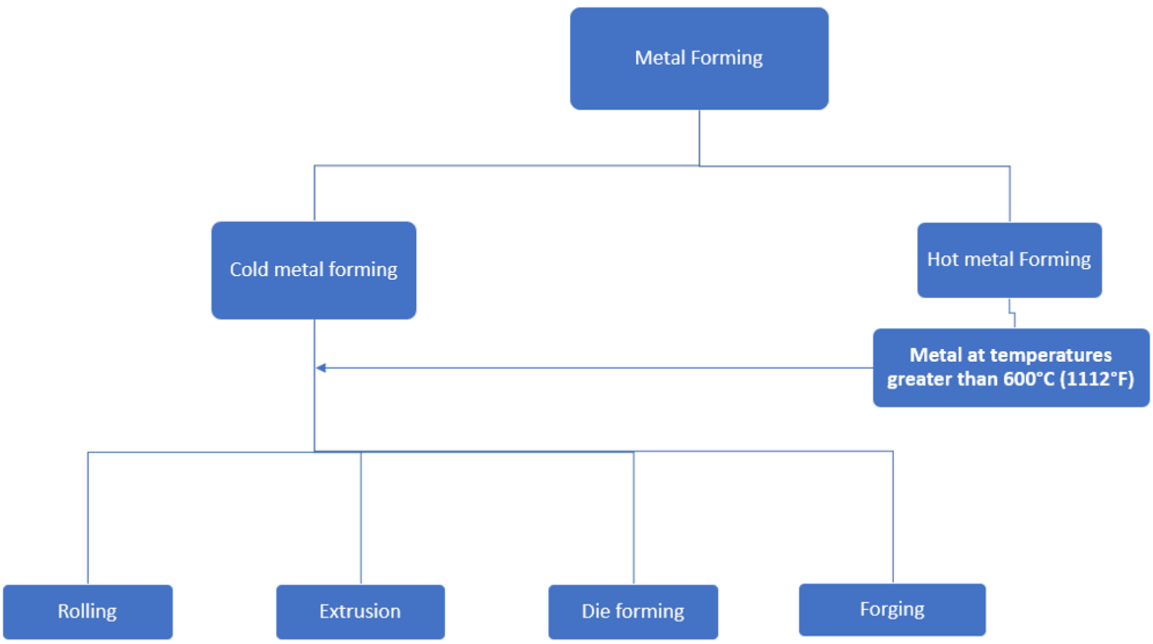


Figure 1. Metal forming main classes

Each of these processes are briefly explain in follow sections.

2.1 Cold Metal Forming

Cold metal is a process of forming a metal in a normal room temperature. Usually, using high pressure to deform the metal shape and size. It is a traditional method which is being in practice for long time. After deformation metal becomes hardness, yield, and tensile strength. As showed in below figure: 2 a cold roll forming machine.

Figure 2. Cold Roll Forming

2.1.1 Rolling

In roll forming, metal is passed through multiple of the roll to acquire a desirable shape. As shown in figure 2. The flat metal sheet is deformed from A to B in a "U" shaped profile. After changing the rolls of the metal, other shapes can also obtain. In the figure, 3 "L" shaped metal is deformed. Likewise, V shape and multiple shapes and be deformed using a roll forming machine. As in the above figure 0.5mm plain sheet is formed to a "U" profile with five different rolling speeds. The rolling speed of the motor was adjusted to 20, 40, 60, 80, and 100 RPM accordingly. After the formation of the sheet the formed shape were compared and found that with the increment of time the deformation sheet has a bow effect at the edge of the metallic sheet. Also, the spring-back was observed in the deformed part at the edge of the metallic sheet. As shown in figure 3 the forming process along with the deformed part before and after were shown in the picture.

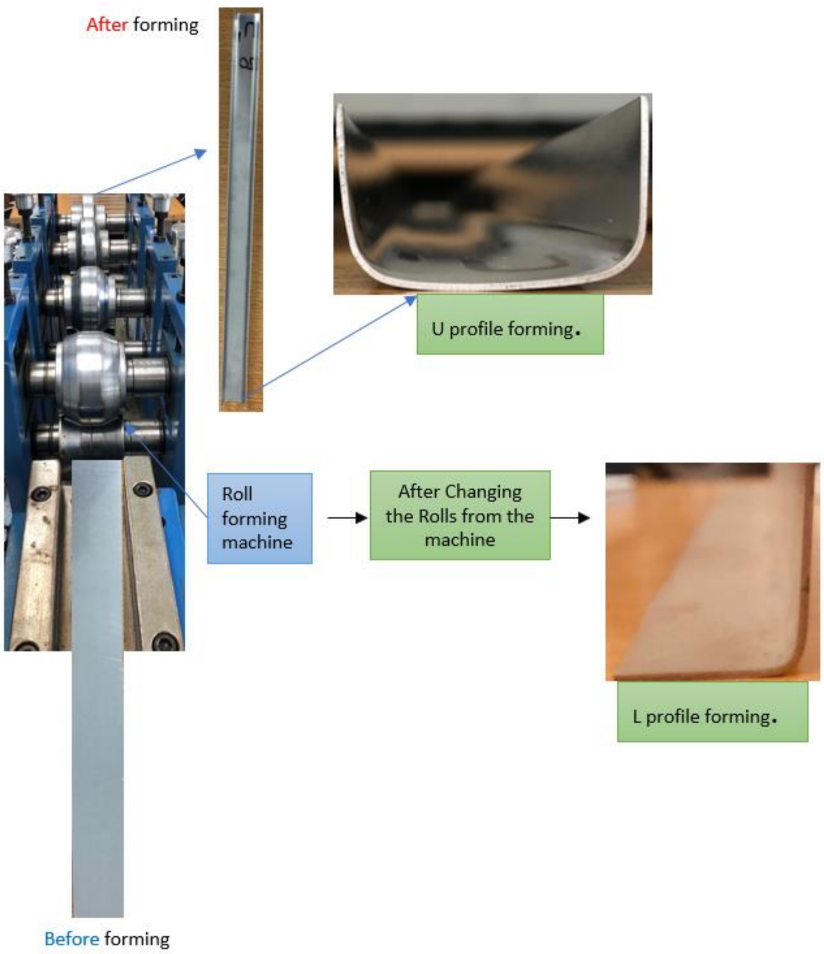


Figure 3. Roll forming process for U profile and L profile

1.1.2 Extrusion and Stretch Forming process

A metal is pushed through an orifice. In other words, a metal is forced to deform through the die. The metal is passed through the cavity. The metal shears the stress and while compression. As in below figure 4 the metal is passed forcefully through the die to deform. The main parts of this process include die, breaker plate feedpipe, barrel, screw, screw drive Motor and Hopper respectively.

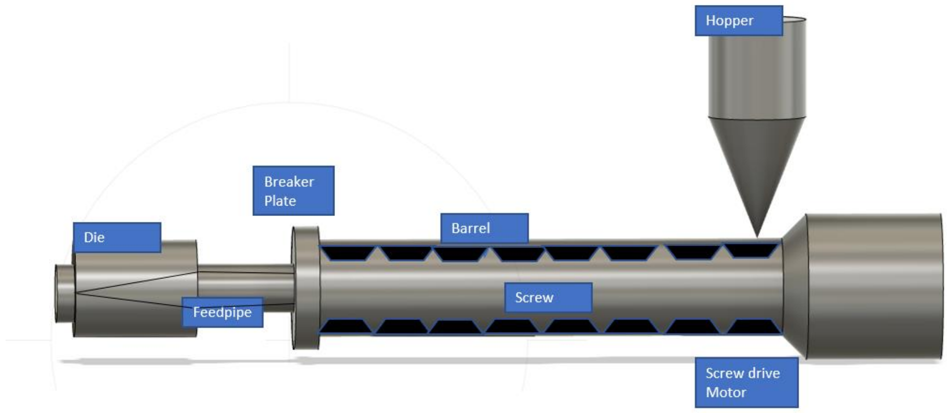


Figure 4 Extrusion of metal

1.1.3 Die Forging

In die forging process a metal is stamped with a pressure. Usually there is two parts in die forging, one is head, and another is bottom. In between of head and a bottom, from the middle the forging part is kept, and the deformed part come from the bottom. Simple figure of Die Forging is showed in the figure 5 below.

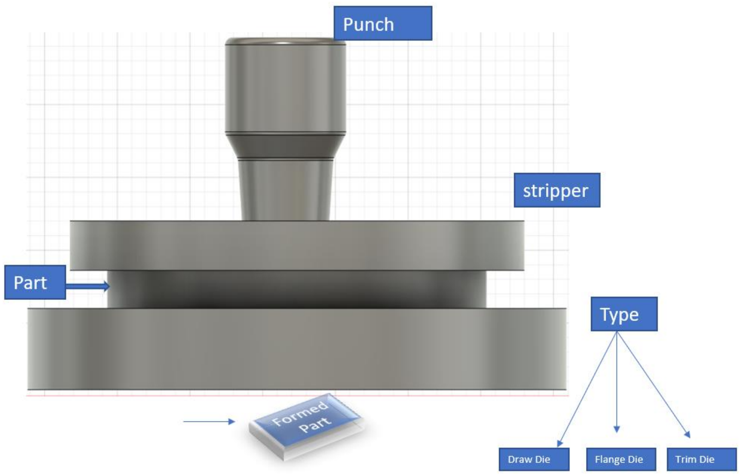


Figure 5. Die Forging

1.1.4 Forging

Forging is a method where a metal is formed with localization compressive force. In this process a metal is deformed by the force. Most of the time the time, metal is used for external heat to give more pressure to obtain accurate shape.

2.2 Hot Metal Forming

Since the cold forming is done in normal temperature. Hot forming is process of additional heat during forming the metal. In this process, metals are recrystallized and deform. All the above cold formed sheet can be deformed and use for hot roll forming too. In other words, for complex shape hot metal forming is widely in use. Today's 21ts century "CNC" computerized Numerical Control is famously used to deform the metal for both cold and hot forming. As showed below, simple external heat is used to the metallic sheet of roll forming machine to deform.

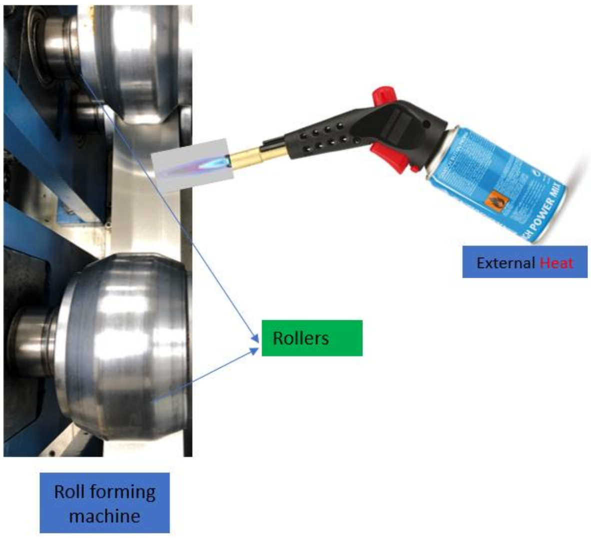


Figure 6. Hot metal forming

3. CNC Forming process and G- code

Computerized numerical control CNC system is a method where the x, y and z coordinates are used to controlled by computer for cutting, milling or 3D printing. It is a computerized manufacturing method in which pre-designed software and code commands the progress of fabrication equipment. CNC code controls the formability of the metallic sheet. A range of complex forming CNC controlled with the G-code, which contains of x, y, z parameters. Those code is used for grinding, twisting, and turning materials. This CNC code is used to cut, re-shape, and create different parts and models. CNC code also called G-code, which is a simple a x, y, and z components can be obtained from Cad software like fusion 360, rhino and many others.

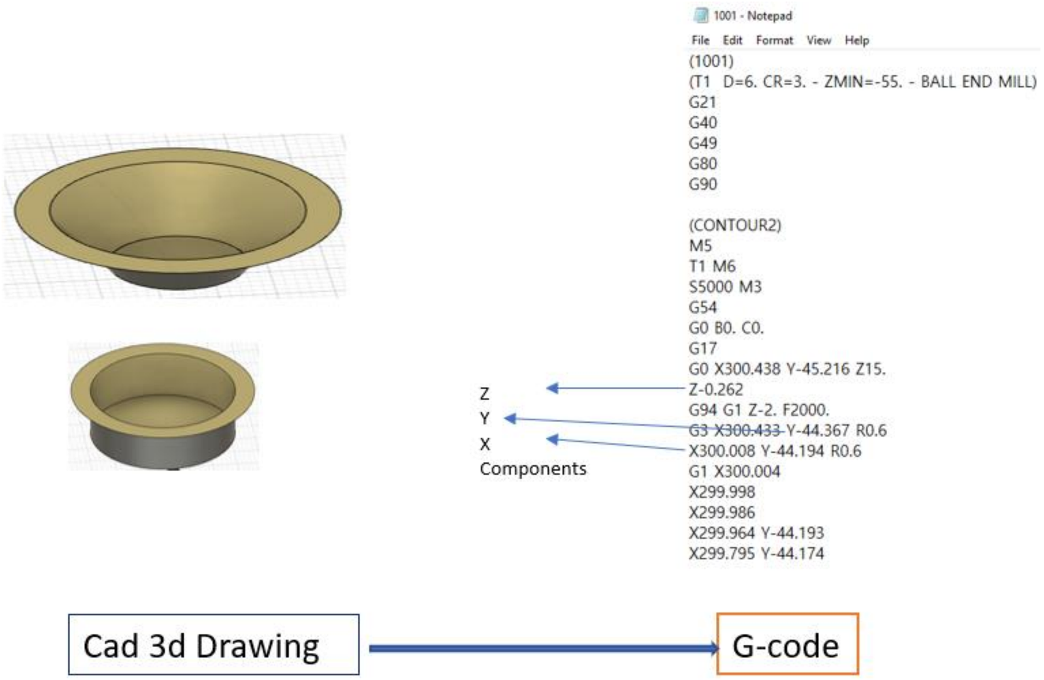


Figure 7. 3D cad modeling and G code

3.1 CNC Introduction

Today's world, CNC technology is famous for manufacturing product. This technology is used to produce the forming parts and even getting popular to produce product by 3D printer parts. With the help of exact coordinates of the G-code, it is accurate for producing part by forming, cutting, and printing. Because of the computer numerical control mechanism, it is easy to manufacture and operate. Sequence controlled coordinate is a command for the tools for performing the performance to the machine for producing product. CNC machines are widely use and the research on it is also had a good scope. Recognize and operate CNC machine language is also called G-code. Which work precisely for manufacture. Whereas there is a factor influence like feed rate, spindle speed, forming location, and controlling coordination has an effect while operating the CNC machine.

Designing mechanical parts form CNC systems are extremely computerized. Contrasting the old manual methods which is dangerous operated by manual factory manufacture process. Computer-aided design (CAD) software is used to define the coordinate for the machine operation. After that CAD coordinate directives by computer aided manufacturing (CAM) software. Thus, it is essential to have a knowledgeable of CNC working mechanism. Likewise for the computer operator to know it for use in the industry to operate CNC. There are two main parts for generating G-code Cad modal designee and Manufacture part. Additional for the safety factors Simulation is also important. Which has been demonstrated in the figure 8. For creating a G-code there are two steps.

1. Cad Design

2. Manufacture

3.1 Cad Design

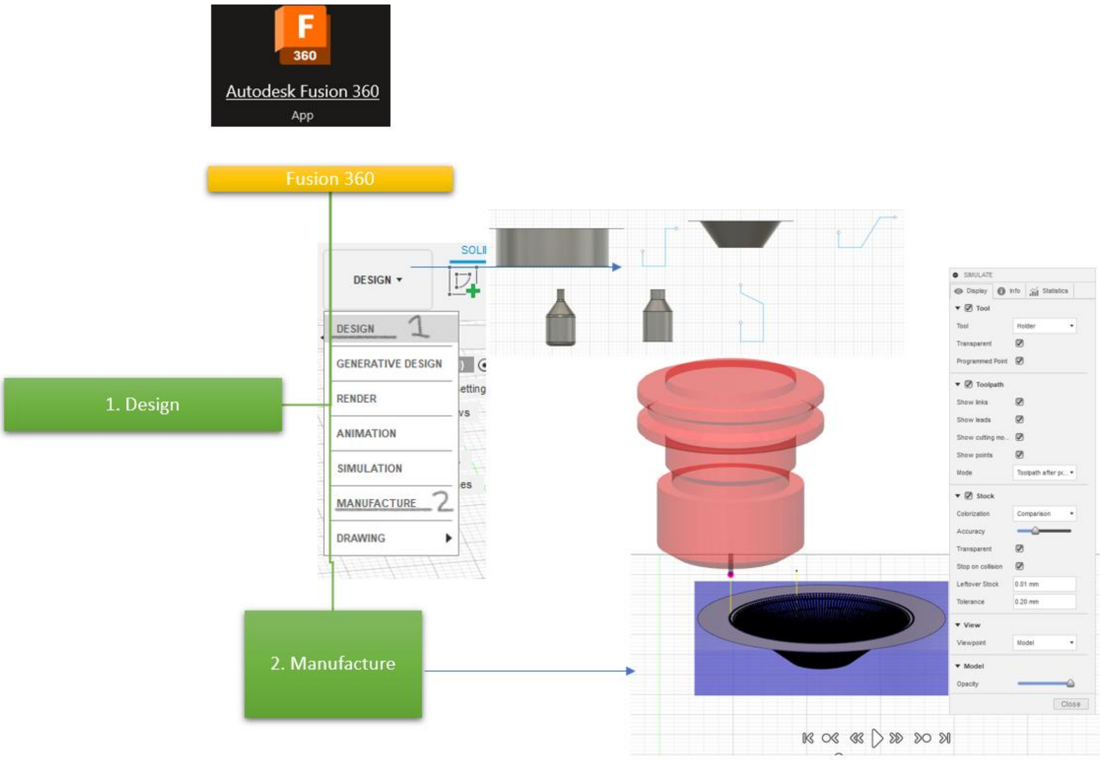


Figure 8: CNC code generating process

For Cad design process, first the sketch and then make a desirable shape, after that the convert the model from 2D to 3D. By using the menu like Patch, extrude, revolve, and sweep. Then the model can be viewed in 3d image with the addition of the material property like aluminum, iron cupper gold or other desirable metal for real world view. As showed in the figure 9, the 3D model and simple drawing.

3.3 Manufacturing Milling machine

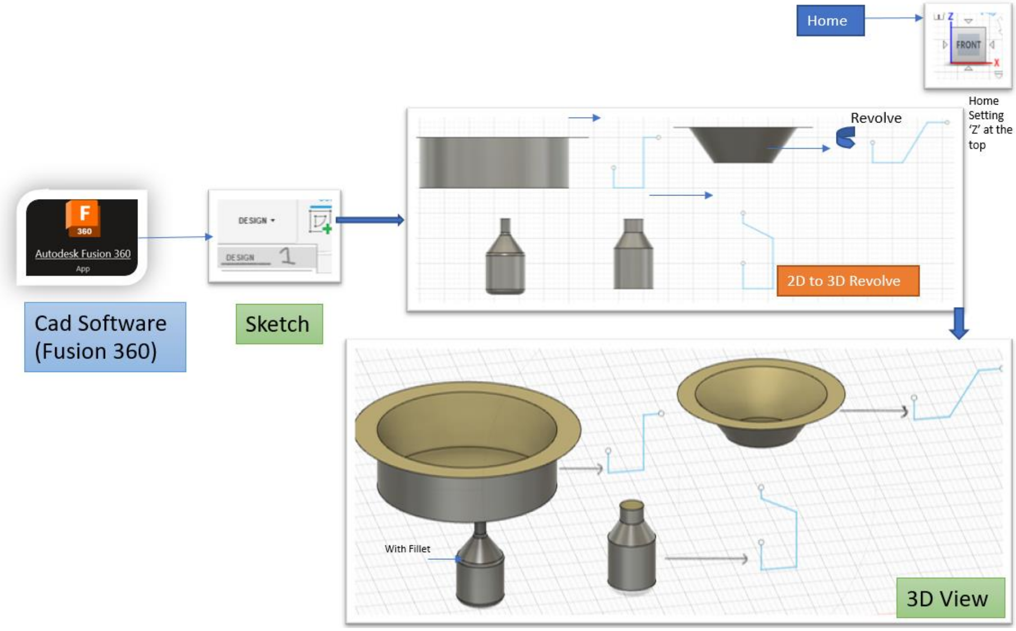


Figure 9. Cad Image in fusion 360

After drawing the 3D model from the design part, manufacture part can be accessed. In this module different type of menu are available like adaptive clearing, pocket clearing, steep and shallow, flat, parallel scallop, contour ramp and many more. For the milling contour from 3D menu can be used. As a tool. As in the figure the option for too appears and select a sample tool because after the tool size and shape can be edited. After selecting the tool again, the editing tool is required in fusion 360. In the figure 10, the process and the tool are showed.

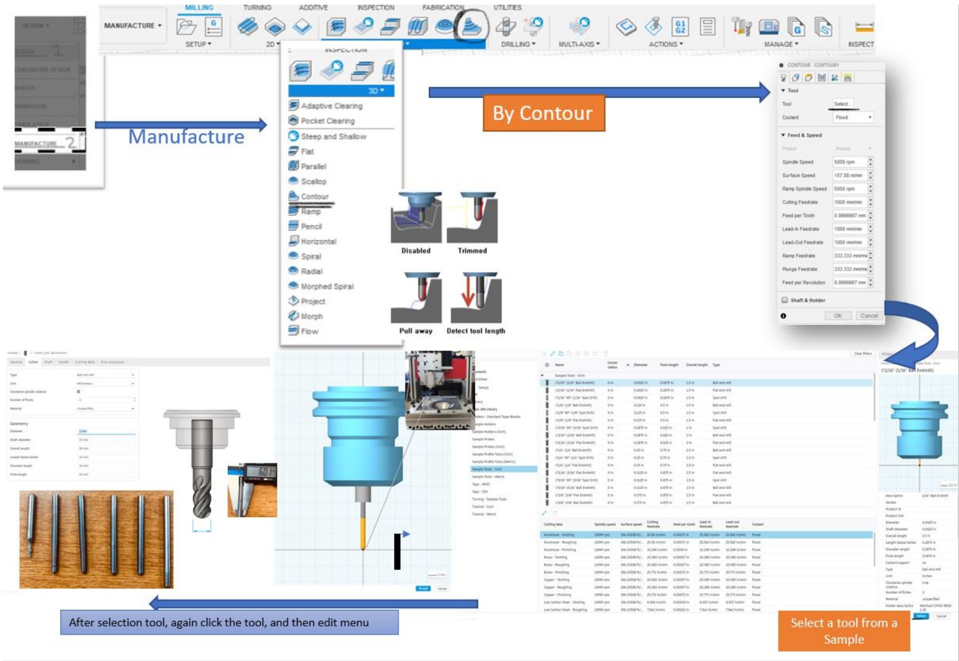


Figure 10. Method of creating the tool for milling machine.

3.4 Simulation

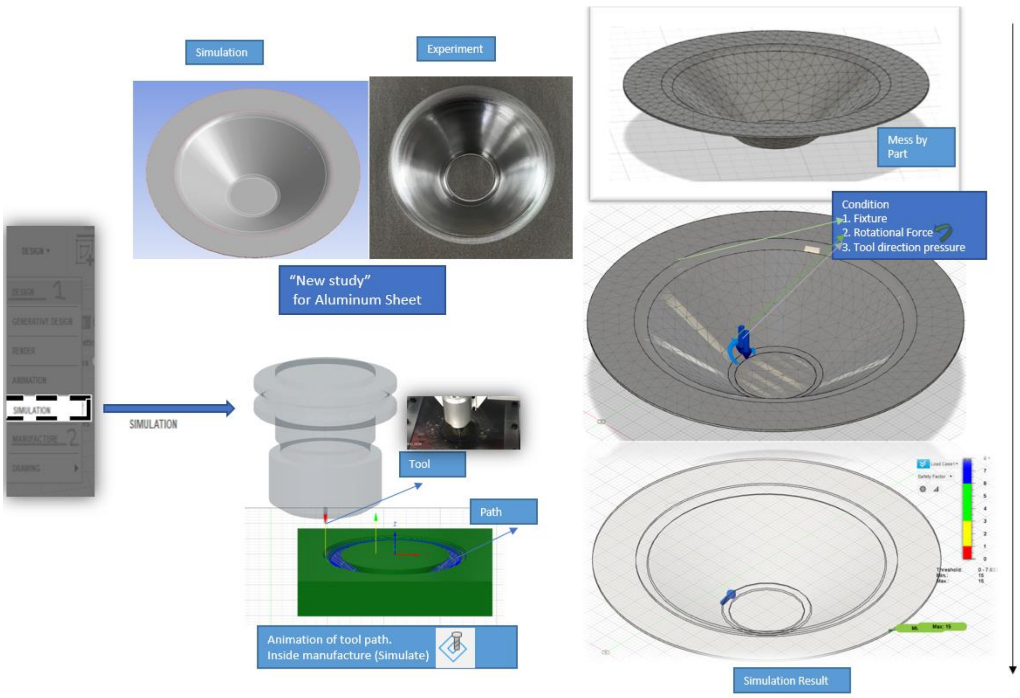


Figure 11. 3D image and real formed image with manufacturing process and result

Simulation is the process for studying the module in the computer. For running the new simulation for the part that has been generated in fusion 360, new study should be created. After that the property of the metal sheet is applied. And then the Static stress or the desired type of study should be selected. Stress and strain can be easily identified from the simulation. With applying the force, momentum and the pressure applied in the metallic sheet as a constraint and the load. Mess part will divide the computerized formed part into tiny pieces and easy the study the strain and stress analysis. As showed in the figure 11 the 3D pard and the computerized study module the experimental sheet after forming sheet metal.

3.5 The Importance of CNC Machining and G-code

CNC technology is important because it uses computer-generated code. Which is obtained after the virtual 3D image from the cad software. The exact forming of a metal sheet can be achieved from CNC. Manufacturers products by CNC is a trend research topic, which is slowly getting famous in the automobiles, aerospace, and submarines manufacturing industry too. So, in the research field for the formability of metal sheets, CNC is popular because the problem of spring back and other defects during forming a metallic sheet can be reduced or manipulated. The spring back image was shown in the figure below:

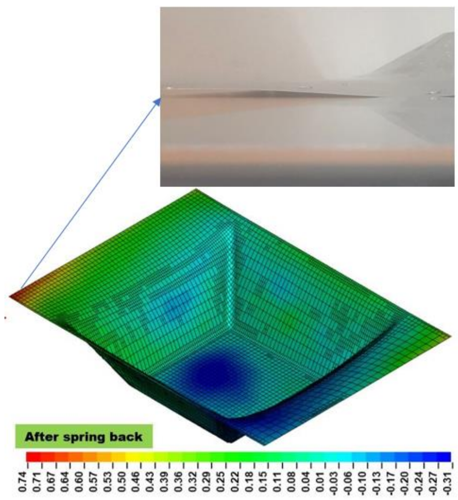


Figure a: Spring Back

4. Formability of Aluminum

Aluminum is soft metal also symbol as Al. The atomic number is 13 and it is a chemical element which has lower density then common metals. Normally its atomic mass is 26.981539 u. melts at 660.3^{0}C and its weight is 2.7 g/cm^3. Nemourus experiment of formability of Aluminum was performed [20,21]. For the experiment Aluminum AA5052 is formed and the formed part were tested, following table is its property.

Table1: AA5052 Chemical Composition

Elements	Al	Mg	Si	Fe	Cu	Mn	Cr	Zn
Material %	96.78	2.5	0.13	0.3	0.01	0.05	0.2	0.03

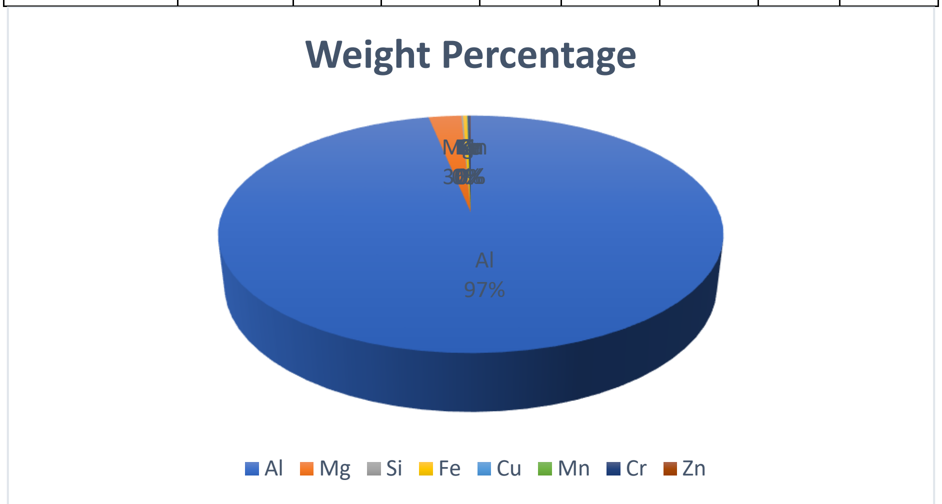


Figure 12. Chemical composition pie chart

Since aluminum sheets are soft and shiny the mechanical property of the formed sheet in this experiment is showmen in the table 1. Aluminum has low density, so it is easy to form. Whereas it has a high thermal conductivity so broadly used in the machine. Along with the material property for easy cast. While forming an aluminum sheet, the care of handling the metal is required. Because aluminum is easy to be scratched and needed to be consider material handling carefully. While deforming aluminum the material composition change. The material become thinner after forming and the thinner part has less density which is likely to be crack or facture. As showed in the figure: 2 below the plain metallic sheet of aluminum is deformed into conical shape by the CNC machine.

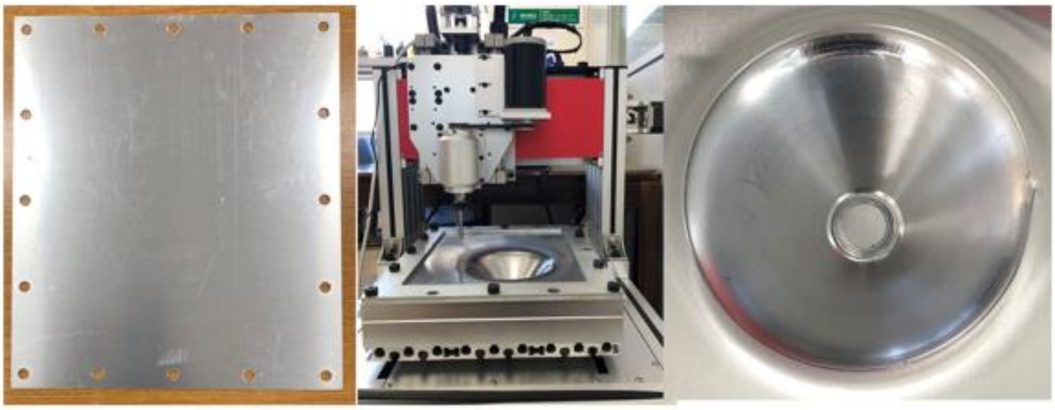


Figure 13. process of formation of aluminum AA5052

As shown in the above figures 2, an aluminum AA5052 sheet, CNC milling machine and formed sheet correspondingly. A pyramid geometry with 45^{o} and 60^{o} wall angles were modeled using the fusion 360 CAD software considering square area and forming depth as 100×100 mm^2 and 35 mm, respectively. The fillets were applied at the corners based on the punch tool radius dimension for obtaining a useful part in terms of the model accuracy. Subsequently, the punch tool path to obtain the desired shape was modeled using predefined forming parameters and considering the path strategy as a contour 3D in the fusion 360 CAM software environment. Following is the image of 3D cad design of conical shape.

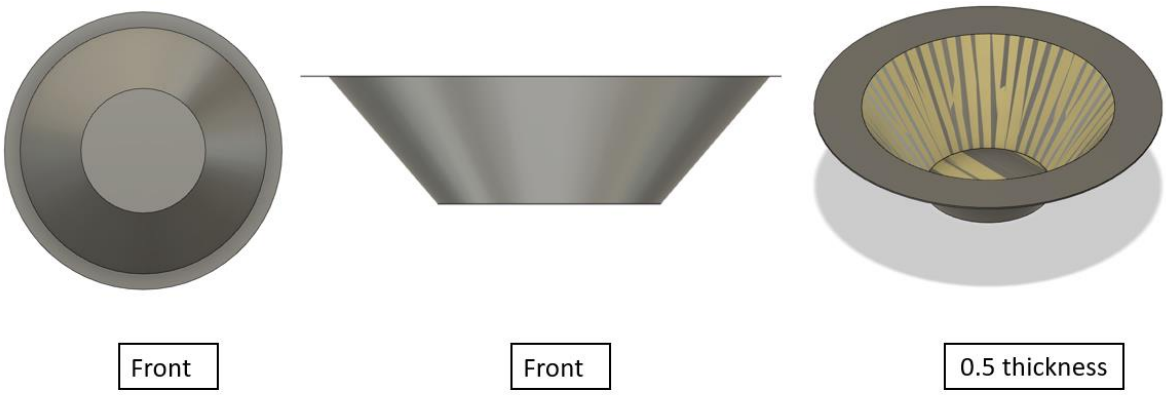


Figure 14: 3D cad design of conical shape

4.1 Numerical design and semi-finished products

Researcher in the field of metal forming has done numerous experiments. The methods for the numerical design and experimental performed for manufacturing a product. Which, depending on the forming process and choice of materials. That should lead to a significant improvement in the formability. Based on an analysis of the forming process, the stress and strain distributions are analyzed, critical forming zones are identified, and an optimal strength distribution. The modeling of the elastic-plastic behavior is based on a comprehensive material characterization depending on the heat treatment parameters. The heat treatment layout required for setting the strength distribution is determined inversely and mapped in a thermal simulation. The resulting mechanical properties are then derived from the calculated temperature distribution, including the transition areas in the heat-affected zones. By coupling the heat treatment simulation with the forming simulation, the sheet can then be transferred directly to the deep-drawing process. Finally, the formed component is assessed about the expansion of the shaping limits as well as the formation of wrinkles and the retraction of the blank. These findings are used to adapt both the blank geometry and the heat treatment layout to achieve an optimal result. Since it has an effect while deforming metallic sheet. Tool path design for manufacture first observed in the computer as figure 15 and deformed in CNC milling machine like in figure 13.

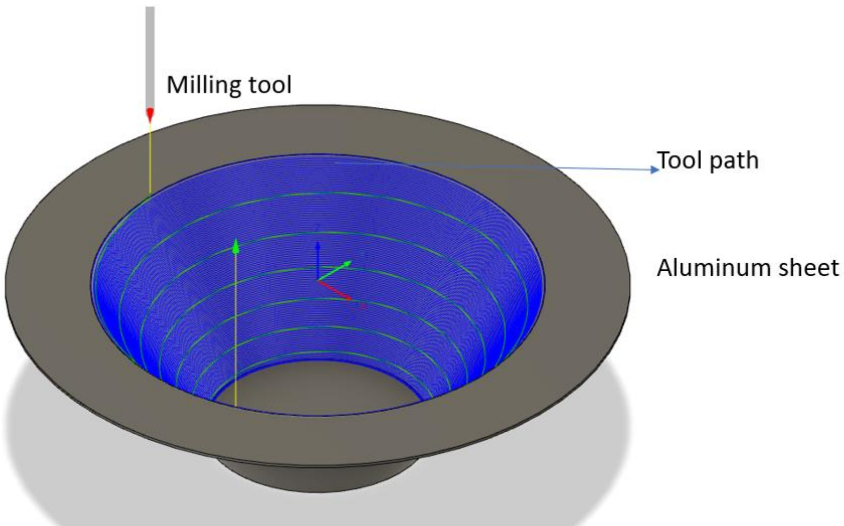
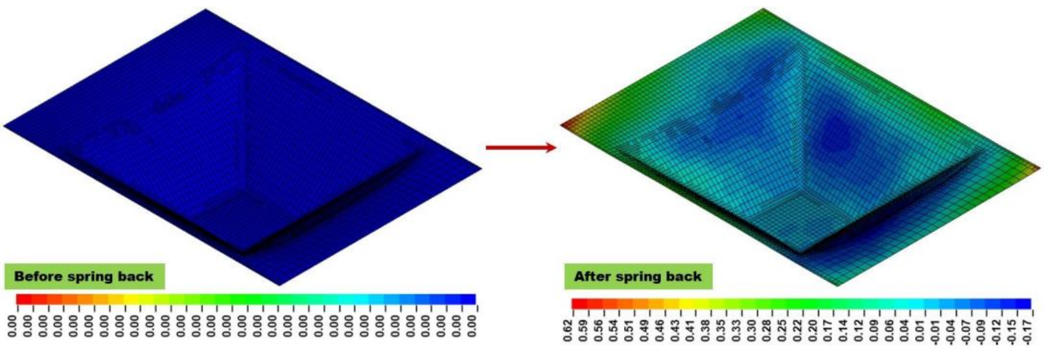


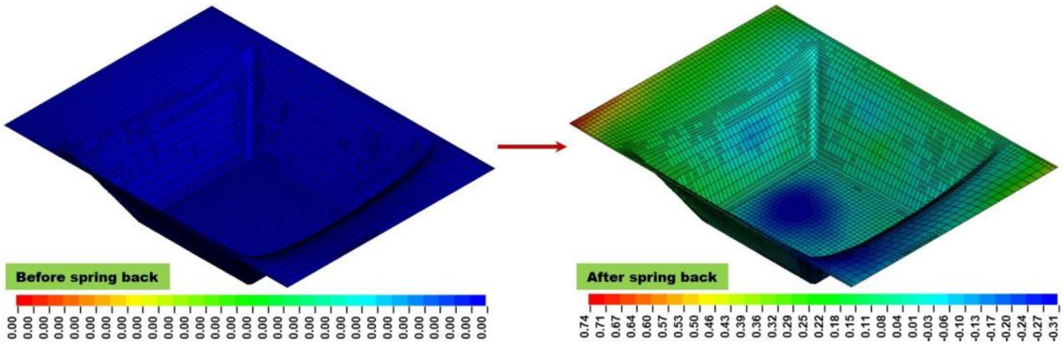
Figure 15. Maximum formality check in manufacturing process

4.2 Laser short-term heat treatment

Various heating methods can be used to implement local heat treatment. These include conduction, induction, and radiation-based methods. Diode lasers are particularly suitable for aluminum alloys because their short wavelength ensures good absorption by the material. For this purpose, a diode laser with 3 kW power and zoom optics from Laser line is used at the chair for manufacturing technology. The zoom optics enable a size-related adjustment of the laser focus from 5 x 5 mm to 45 x 45 mm with a homogeneous intensity distribution while maintaining the same working distance. The guarantees a high degree of flexibility and precision. The size of the laser focus is defined in the x and y directions as a function of the travel path, which enables targeted setting and application of the heat treatment layout. The beam power required for the heat treatment is regulated by comparing measured actual temperatures and specified process parameters. With a connected single-color pyrometer is used for this. In addition, the elevated processing platform enables the temperature distribution on the top and bottom of the board to be analyzed using a thermographic camera. This is used as a further control option for the process management, but on the other hand, it also serves to validate the results determined in the numerical heat treatment simulation. The cold aging process begins immediately after the heat treatment, during which the dissolved alloy components form clusters again and the strength of the material increases again. Therefore, the sheets are usually cold formed within a time interval of 1 to 4 hours after the heat treatment to use the greatest possible improvement in the forming behavior.



(a) Part formed considering 45º Wall Angle



(b) Part formed Considering 60º Wall Angle

Figure 16: Comparison of SPIF Numerical Results Before and After Spring-back

After completing the forming process, the last step stored data such as stress, strain, and thickness was used to model the implicit spring-back simulation for evaluating the presence of a geometric change in the formed part. Before performing the spring-back simulation, the fine-meshed part was converted into the coarsen mesh using the adaptivity and coarsen keyword options to fasten the implicit solution. Further analysis result is shown in the figure 17.

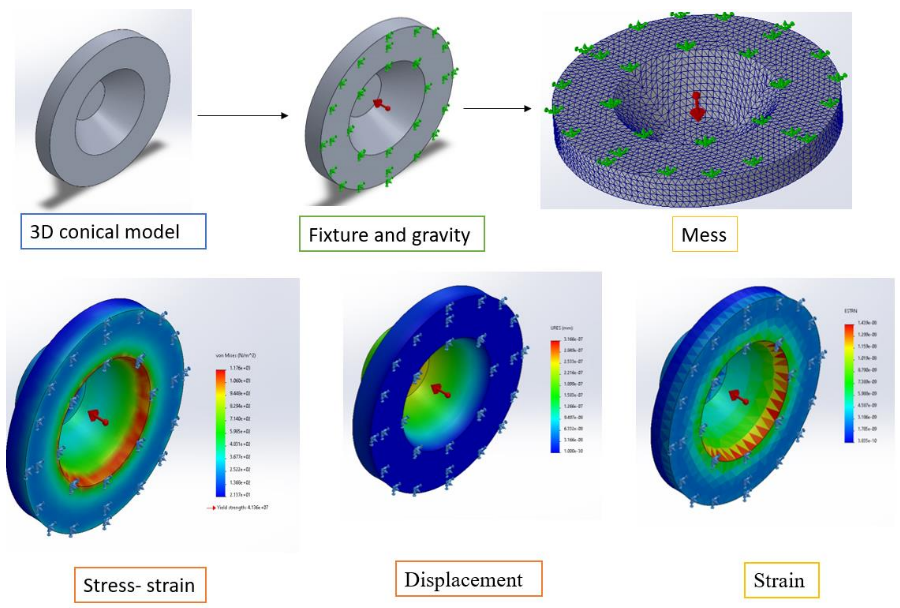


Figure 17. process of 3d modeling to computer analysis

4.3 Conclusion

As a result, the SPIF process has been accomplished for examining the formability of aluminum alloy material. The newly developed CNC vertical milling machine and the pyramid geometry with two wall angles were employed for performing the real-time experiments. The interplay of numerical design and defined methods, to open the use of aluminum semi-finished products for a wider range of applications by locally adapting the mechanical properties. This helps to meet the steadily increasing requirements in the automotive industry and to ensure the competitiveness of aluminum alloys compared to competing lightweight materials such as fiber-reinforced plastics through continuous further development in the future.

5. Roughness Test

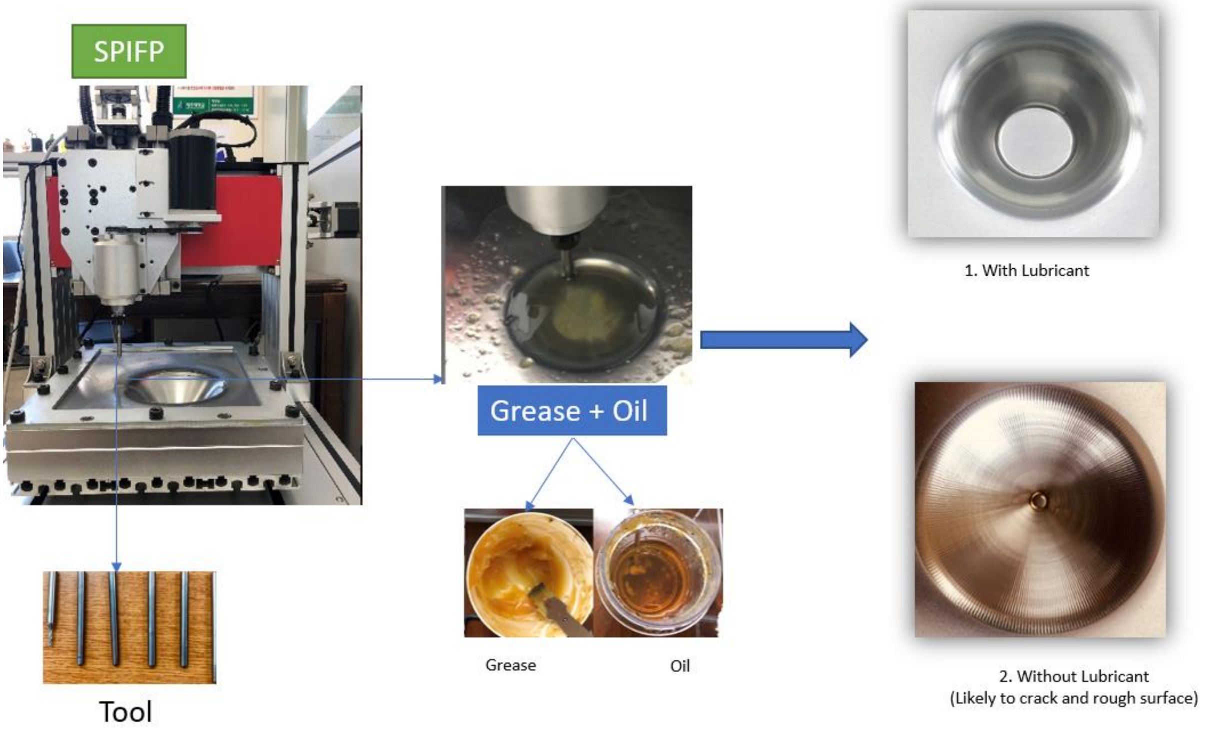


Figure 18. Formed metal AA5052-H34

For the roughness test, 15 set of experiment was performed. The spindle motor speed was adjusted 3000, 4000,5000, and 6000 Rpm. As shown in the table 2.

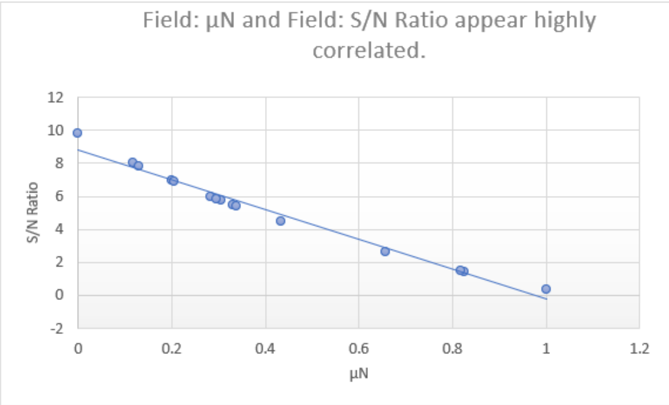
Table 2. Experimental designed for roughness and spindle speed.

Turns	TR (mm)	Speed(rpm)	FR (mm/min)	Roughness (µm)	VS (mm)	µN	S/N Ratio
1	R2.5	3000	500	0.449	0.10	0.2	6.93
2	R2.5	4000	1000	0.531	0.15	0.3	5.46
3	R2.5	5000	1500	0.501	0.20	0.2	5.96
4	R2.5	6000	2000	0.536	0.25	0.3	5.38
5	R3.0	3000	1500	0.395	0.15	0.1	8.02
6	R3.0	4000	2000	0.321	0.10	0.0	9.81

7	R3.0	5000	500	0.845	0.25	0.8	1.44
8	R3.0	6000	1000	0.739	0.20	0.6	2.61
9	T3.0	3000	2000	0.4052	0.20	0.1	7.85
10	T3.0	4000	1500	0.596	0.25	0.4	4.46
11	T3.0	5000	1000	0.451	0.10	0.2	6.87
12	T3.0	6000	500	0.515	0.15	0.3	5.73
13	T2.5	3000	1000	0.955	0.25	1.0	0.38
14	T2.5	4000	500	0.840	0.20	0.8	1.49
15	T2.5	5000	2000	0.511	0.15	0.2	5.84

5.1 Material test

As a material, metal sheet called an aluminum alloy (AA5052–H32), which is cold forming. The material sheet thickness was 0.5mm. The chemical compositions of formed metical sheet are 0.25% Si, 0.10% Mn, 2.2–2.8% Mg, 0.10% Cu, 0.15–0.35% Cr, 0.40% Fe, 0.10% Zn, and remaining % Al. Scanning electron microscope (SEM), MIRA3 TESCAN (Secondary electron detector, Jeju National University. X–ray spectroscopy (EDS), for surface investigation. The FESEM examination data of AA5052-H32 Al alloy. Before forming the test, sample was observed through microstructure, as well as after formation also, microstructure was examined and studied. Moreover, the fracture region magnified of 50 μm, revealing a ductile fracture portion. The tensile test study evaluates the molecular tighten of molecules in the formed metallic sheet for 30^0, 60°, and 90°· The forming directions is as shown in the fig 1. FESEM–EDS method is used for test materials, along with element mapping, image is exhibiting for the spatial dispersion of the elements.



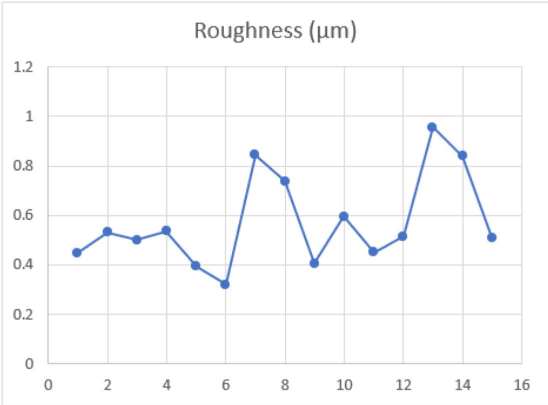


Figure 19. Rough point

5.2 Tensile test and roughness test.

For conforming the strength of the formed metal. First formed metal sheet is cut in a rectangular shape and designed in 3d cad software for tensile test. In room temperature condition tensile tests were performed in a simulation. By using the test samples for AA5052–H34. Next Considering three angles, such as 30◦, 60°, and °, and 90°, to the forming direction, respectively one by one. However tensile test was performed before forming a sheet. The plain sheet was designed in head half rectilinear shaped as in the picture below result with 10,000newton force. Later the experiment was performed by using TSM–100 machine. A maximum load capacity of 99.64 kN, and the test samples were tested at room temperature with a strain rate of 0.001 s^{-1}, as above. The average GOM–ARAMIS technique was adopted for investigating the local deformations in the samples. Using the recorded digital images. During the tensile test till the break. The major strain in terms of technical strain (%). Using the digital image correlation (DIC) system, the test sample was measured.

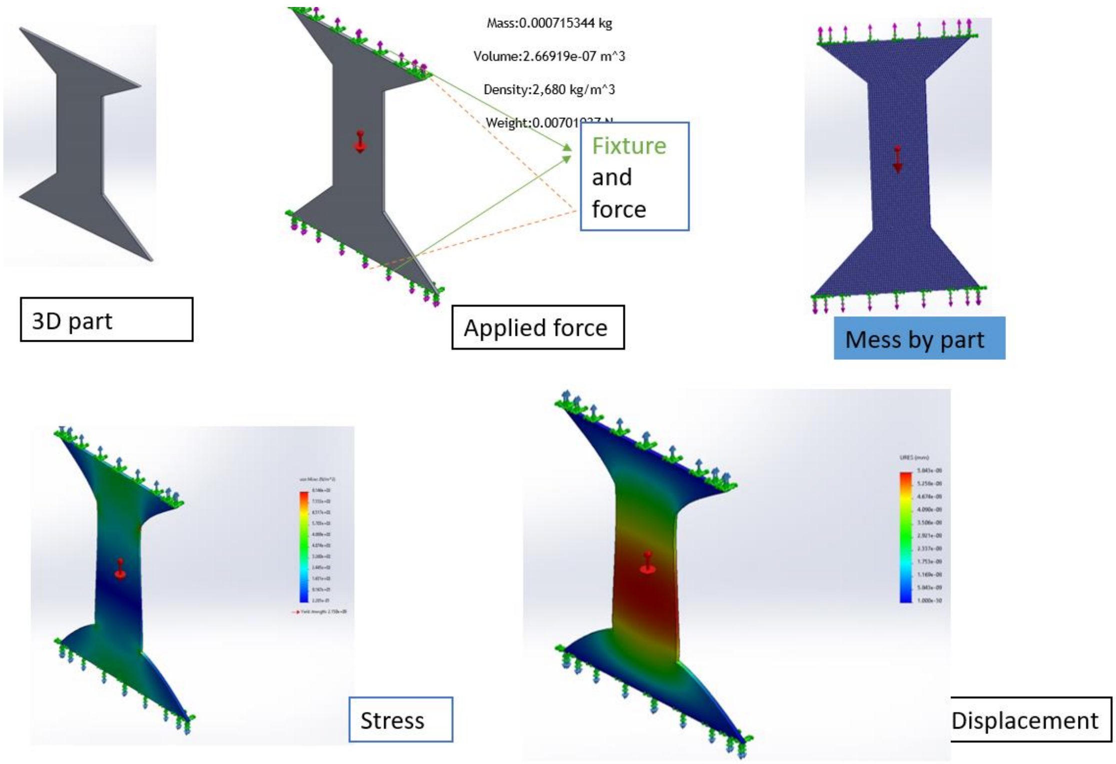


Figure a. Tensile test of Al AA5052–H34

After the strength examination of stress-strain. Conical formed metallic sheet further roughness analysis was accomplished. The metallic sheet was milled in the tiny milling machine. Bending check was performed. Minimum- maximum distance formability studied of Al and Ti metallic sheet completed. The minimum depth was simple touch the metallic sheet and the formability was seen immediately in the aluminum sheet. Whereas in titanium sheet deformed seen less then aluminum. Even though the identical g-code was used. Greater deformation in al with compared with titanium. Because titanium was tougher than an aluminum sheet. Next, an Aluminum sheet of thickness 0.5mm was deformed in a conical and pyramid shape. For the conical shape, the maximum depth was 46.67mm with the use of a mixture of lubricant oil and grease. After a maximum depth of 46.67 mm, the cracking effects were observed. Similarly in the pyramid shape after 42.67 mm deformation, the sheet fracturing effect was observed (although the factors of tool path, steep down, and lubricant will affect the depth of for ability and experimental setup). As a result, with the complexities of deforming shape from rotary to wall angle forming, the formability depth decreases. Following is the roughness check performed by SJ- 400 machine.

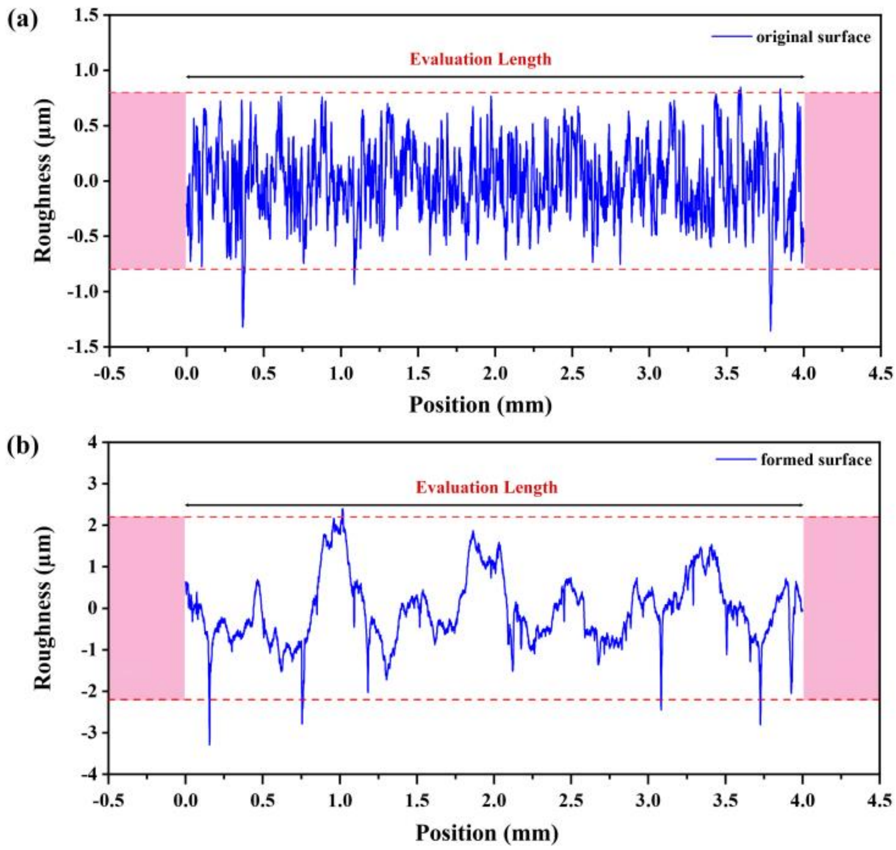


Figure 20. Surface profile from Mitutoyo surf test SJ-400

Furthermore, forming tools of hemispherical ball-end is used to form conical shape. Three step-downs of 0.3mm, 0.2mm and 0.1mm is formed. And surface roughness is checked as shown in the figure below. Lubricant mixture of oil and grease is used equal amount for three step-downs. As a result, With the reduce of the steep-down, the forming surface become smoother accordingly.

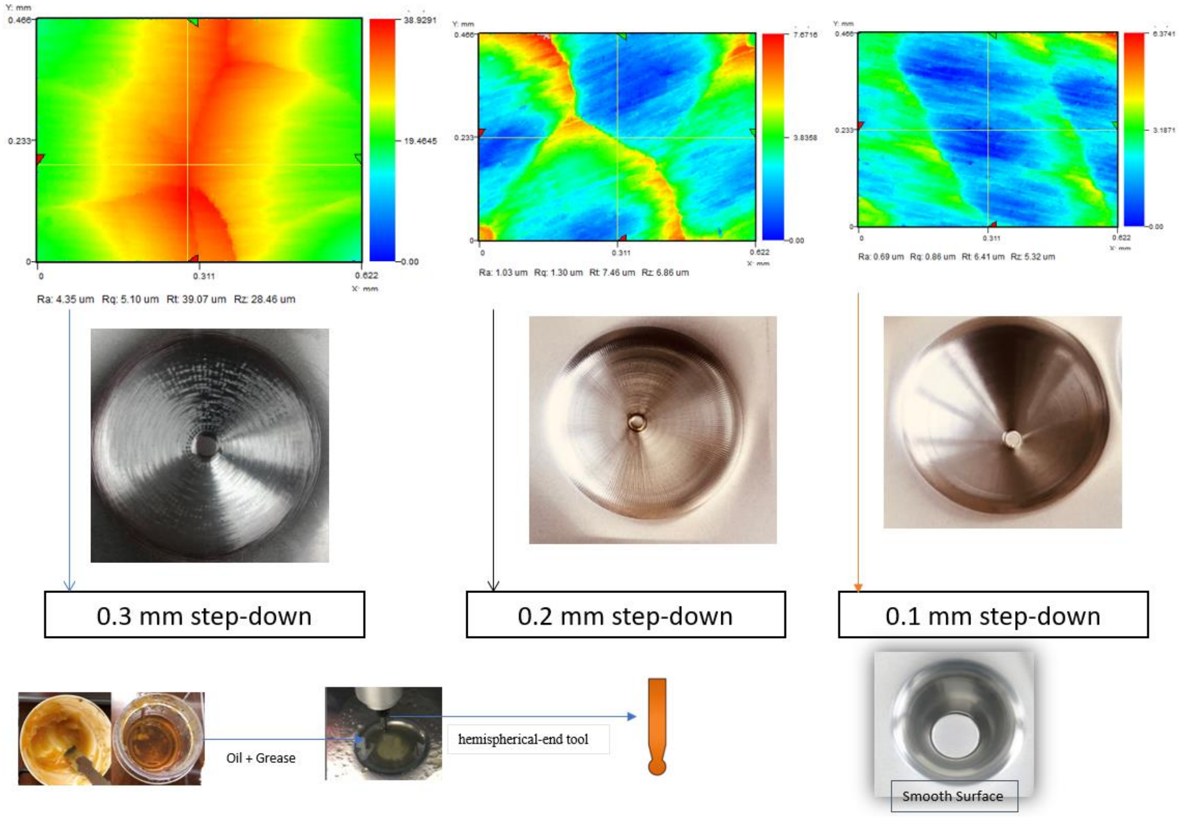


Figure 21. lubricant mixed and forming three metallic sheets for Step-Down 0.3mm, 0.2mm and 0.1mm.

5.3 Result and discussion.

The produced metal was observed formability, along with increase-meant of angle formability increased however step-down decrease-meant results smoother surface; smoother surface was in $30^{0.}$ Though rougher at 90^{0}. Likewise, the formability height at 30^{0} was smooth, whereas at 90^{0}, after certain depth the crack was observed. Similarly, 0.1mm step-down was smoother for hemispherical ball-end tool. The deformed aluminum has shiny surface, and the tool speed was used for 500rpm. Therefore, in cold forming in SPIF the height of the forming sheet can be increased with the combination of lubrication i.e., oil and grease. Besides, magnified views clarify that there are no flawlessly manufactured parts.

5.4 Conclusion.

In this research, the cold forming process has been used to form conical shape of 30^0,60^0 and 90^0 of 0.5mm sheet, AA5052-H32 Al alloys. The forming experiments were performed in the cold forming milling machine called mini milling machine. Throughout all angles, same forming speed and sheet thickness was used i.e., 0.5mm. The forming parameters was studied on the twist, flange height deviation, and spring-back defects was observed. In this research work, the optical image correlation technique essentially used for uniaxial tensile measured. The strain, material properties, and the plastic strain ratios, inveterate that the digital image correlation (DIC) procedure. That can affect the tested samples. The theoretical equation, such as Holloman power-law, was used for depth study for the tested materials. The simulation part was created on computer and extracted the g-code, after that it was compared with experimental part. For the strain and stress allocations, the numerical modeling was modeled in UBECO-Profile software.

The mesh and designed part for simulation were exactly same as experiment part. However, with the addition of proper mixture of lubrication the formality quality improved. As a result, the comparison of experimental results contrary to the numerical simulations was arguable as promised. Conversely, the stress and strain variations were alike for measured forming speed, nonetheless the strain increases for higher sheet thickness. The stress was increased when the angle become more perpendicular as like it goes closer to angle 90^0, as compared for three forming angles, along with the higher sheet thickness. Eventually, the most thinning behavior was appeared at higher speed for thicker metallic sheet. Overall, the tensile tests for cold sheet forming process through SPIF presented in this paper. Material properties approximation and accurately modeling can be improved furthermore in future.

In the formed 0.5mm Aluminum sheet, the spring-back was subjective. As well as the forming parameters such as sheet thickness and the forming speed should be considered, respectively.

6. Industry Level Production

The Single point incremental sheet forming process known as a SPIF process. Which got a great attraction among other existed sheet metal forming processes because of their flexibility to manufacture complex products. The aluminum alloy material mechanical properties are adopted and integrated into the finite element (FE) code. The tool paths for the truncated cone shape are modeled in Fusion 360 software, and the coordinates are converted into 3D punch tool coordinates by the tool path generation framework tool for modeling the numerical simulation. In numerical modeling, three kinds of mesh settings are used to construct the mesh for producing consistent results. Afterward, the obtained results are tested against the experimental observations and the desired parts dimensions to verify the accuracy of the established FE model. Thickness variations in the formed parts are discussed in detail in terms of the thinning part, thinning location, and its size in percentage. A comparison of tested geometries displays that reduction in thickness tends to be uniform in the wall region and small fluctuation noticed near the tool retraction location. Overall, the statistical results of the SPIF process are well in contract with the experimental measurements. In terms of geometry dimensions and thickness reduction. In addition, the surface roughness was noticed to be increased when the step size is more extensive, and on the other hand, the machining time tends to be more if the contour step size is small in the SPIF process.

6.1 Importance

In industrial practices, aluminum alloys are extensively used due to their mechanical properties, and the applications can be noticed widely in automobile and aircraft manufacturing industries. The notable benefit of this process is it does not require any predesigned die, and the procedures can be carried out using a simple flat sheet by causing the local plastic deformations.

6.2 Evaluation

The material properties of an aluminum alloy in the numerical tool, the stress-strain line curves are estimated by the Holloman power law, Eq. (1)

$$\sigma = K\varepsilon^n \quad (1)$$

Table 3. Mechanical Properties of AA3003

	E (GPa)	σ_Y (MPa)	ν	K (MPa)	n
2700	70.1	152.2	0.33	192.7	0.039

In Eq. (1), σ, K, ε, and n are true stress, strength coefficient, true strain, and strain solidifying coefficient, respectively as to table 1. A cone geometry with 30º and 60º wall angles with a depth of 30 mm were modeled in AutoCAD Fusion 360. In addition, the material properties and the tool path are considered as essential inputs for modeling the SPIF process. Consequently, the deigned tool paths were converted into 3D tool coordinates of moving rigid tool considering different step increments to examine the formability of selected material. A contour path was modeled from 0.2 to 0.8 mm, considering a tool radius of 3 mm, a feed-rate of 1,000 mm per minute, and a spindle speed of 5,000 rpm. Besides, the material properties are included in a material card having details of material elastic-plastic behavior (MAT18).

Figure 21. Finite element model for SPIF process

For achieving reasonable numerical results, the material blank has meshed with finer elements using three kinds of mesh settings by dividing the blank into deforming section (radial mesh) and non-deforming section (non-radial mesh) as depicted in Fig. 1. On the other hand, the rigid punch tool has meshed with a significant number of coarse elements for controlling tool penetration against the blank during the forming process. A forming one-way surface to surface contact method with soft option 4 was defined to demonstrate the contact between the blank and the punch tool. Because of the use of excessive lubricant during the SPIF experiments, the friction coefficient was 0.1, and due to material thickness. For optimizing the computational time, the mass scaling option was used, and it was identified to be more useful.

6.3 Results

The experimental results are investigated in detail about the forming depth and its dimensional accuracy, surface quality, and machining time. From produced parts, the part cross-section coordinates are measured manually by drawing the cut section in a white paper. The comparison graph is evident that the free bending is noticed to occur at the initial phase of the forming process. It is due, no extra support in that region. On the other hand, there are a little deviation identified.

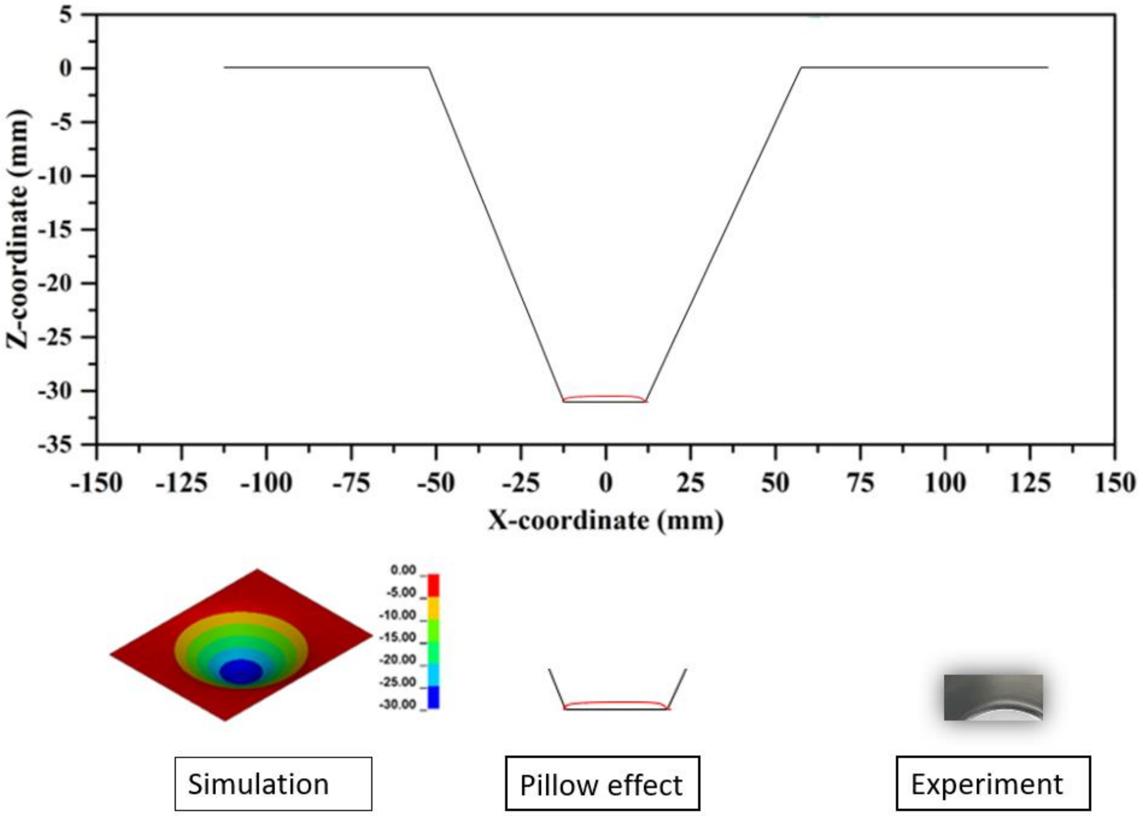


Figure 22. Shape comparison against the experiments (30° angle).

After SPIF process, the material thinning behavior can be estimated from a sine rule in terms of final wall thickness (t_1) using a relationship between the wall angle and initial wall thickness denoting (α), (t_0) respectively.

$$t_1 = t_0\left(sin\left(\frac{\pi}{2} - \alpha\right)\right) \quad (2)$$

The thickness distribution is plotted using the measurement line coordinates, as shown in Figure below:

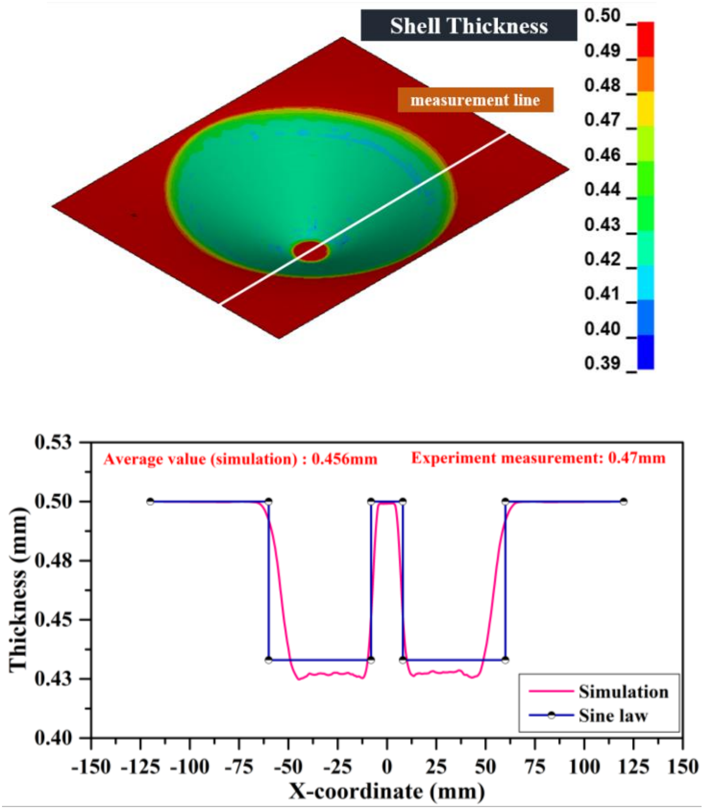


Figure 23. Thinning behavior against experiments and theoretical.

Likewise, a truncated cone shape with 60° wall angle was modeled using the same experimental conditions. For this model, the blank has meshed with quad finer elements. Same as before, the shape coordinates are drawn out from the cross-section, as depicted in Fig.3

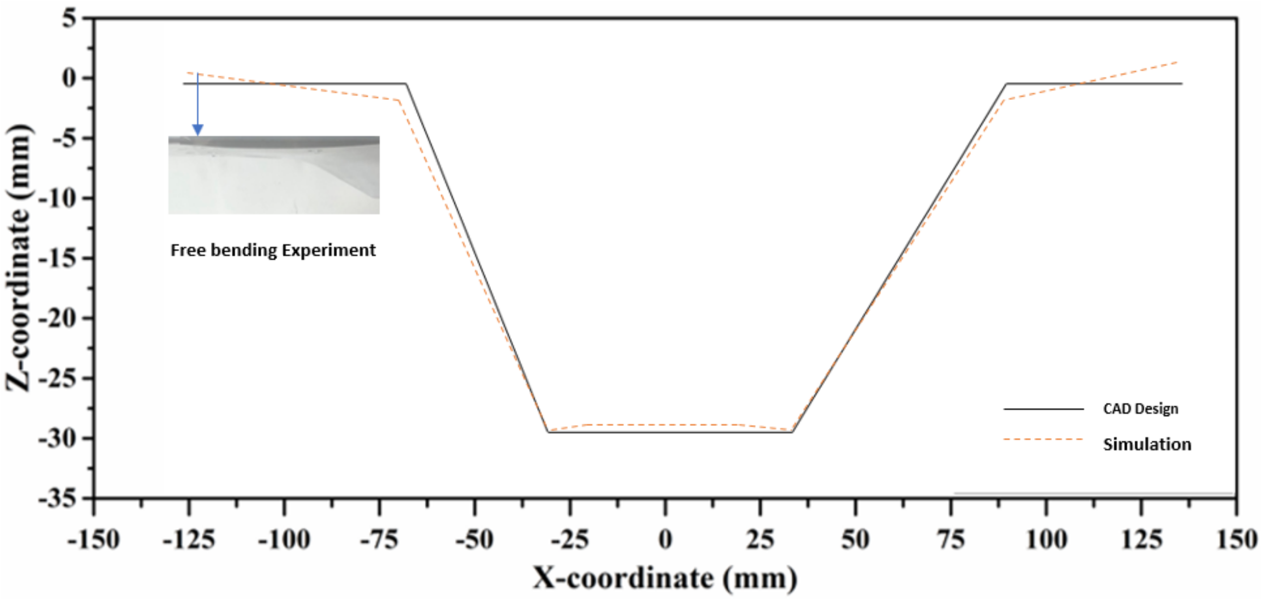


Figure 24. Shape comparison against the experiments (60° angle)

The thickness reduction in rolling and transverse directions are happened to fall along with the theoretical prediction and showed a small, fluctuated variations at the tool extraction location. Further, the real thickness measurement noticed to be significant in the selected locations and the determined number is close to the theoretical estimation.

7. Further discussion

Investigation on the SPIF process was modeled for a cone which have truncated shaped with a wall of 30° and 60° angles utilizing commercial aluminum alloy with computer simulation. The tool paths were designed from Fusion 360 for conducting a real experiment, and the developed tool path generation framework was used for 3D coordinates conversion for running a numerical simulation. The obtained results were found to be significant, and the conclusions are written from the outcomes. Loss in the shape accuracy was observed, notably when a base plate configuration is not adopted in the free bending locations and improper punch tool located at the start of the experiments. Whereas for small deformation for writing in a metallic sheet was further studied like in figure 25. Industrialization product for CNC deformed metallic sheet.

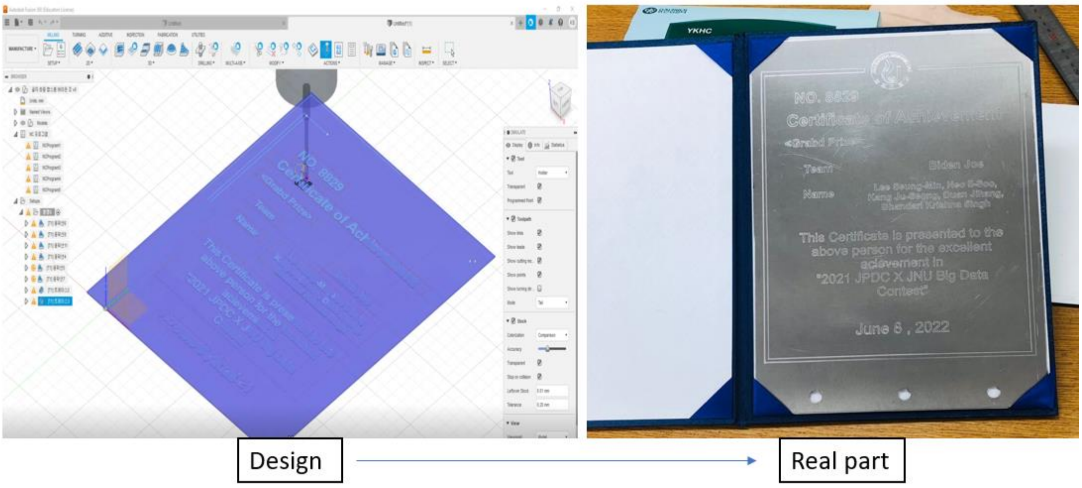


Figure 25. Prize certificate

Additionally with the CNC milling machine certificate of achievement, medal or even die can also be formed for mass production. With the optimization technic further deployment can be achieved for commercializing the product as showed in the figure below

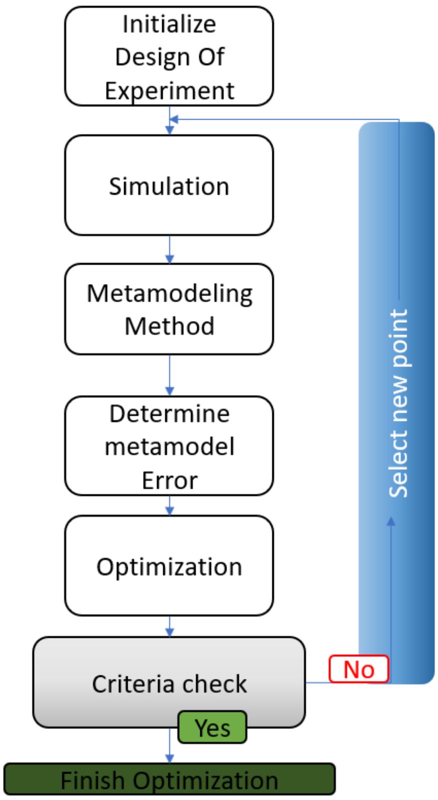


Figure b. Machine learning approach in single Point Incremental Forming

7. Conclusion

In conclusion, the Metallic prize sheet is formed with the CNC technology as shown in the figure. This is a new industrial product for giving an award because the metallic sheet has a greater value than that of paper. For forming a metal sheet numerous experiments were performed. With all the test performed while forming the metal sheet (al, ti) the problem like roughness, spring back, and minimum-maximum depth was observed and investigated as discussed in above experiments. For solving the above issues following things are concluded

1. Roughness: Without the lubricant, the metal formidable was rough while forming through the tiny milling machine (TinyCNC-6060C). So external use of lubricant was applied to the aluminum sheet for forming the metal sheet. Firstly, oil was applied in the surface of the metallic sheet for deforming the al (AA3003) sheet. It results in smoother surface after deformation. However, it was not satisfactory so next time only grease was used for forming a al metallic sheet. Comparatively, grease was smoother than oil. So finally mixing each lubricant test was performed numerous time (more the 30 metallic sheets was deformed). To reduce the roughness, oil-grease mixtures (Figure 18) were laminated on the surface and the results found were smoother. As in the simulated the surface was smooth in computer which is shown in the figure 11. The amount of the oil and grease was half by half.

2. Spring back: Spring back effects were observed while forming the metallic sheet as shown in the figure a. To reduce that effect maximum amount of lubricant was used in the metallic sheet however the spring back effect occurred. Although comparatively the spring back effect reduced due to friction reduction. With the maximum lubricant usage in little amount of spring back was reduced. Next, the deforming time is reduced by decreasing the step down (toolpath) in G-code which reduces the spring back in half than without lubricant. Although the machining time for deforming increased while decreasing the step down. As a result, lubricant, and step-down reduction help to control the spring back on the aluminum sheet.

3. Lastly, Minimum- maximum deforming study was performed. Since the minimum and maximum depth of formability examined of al and ti of metallic sheet. The minimum depth formability was light touch to the metallic sheet, and it was observed that the formability was seen instantly in the aluminum sheet. Whereas in titanium sheet deformation seen lesser then aluminum. Even though the same G-code was used. Higher deformation in al with compared with titanium. Because titanium was stronger than an aluminum sheet which was obtain from roughness test from the experiment above. Next, an Aluminum sheet of thickness 0.5mm was deformed in a conical and pyramid shape. For the conical shape, the maximum depth was 64.67mm with the use of a mixture of lubricant oil and grease in 1000rpm. After a maximum depth of 64.67 mm, the cracking effects were observed. Similarly in the pyramid shape after 61.67 mm deformation, the sheet fracturing effect was observed (although the factors of tool path, steep down, and lubricant will affect the depth of for ability and experimental setup). As a result, with the complexities of deforming shape from rotary to wall angle forming, the formability depth decreased.

With all the experiments, the idea of creating a valuable deforming aluminum metal sheet as a “prize certificate” as in figure25. This product was introduced. And can be industrialized because the CNC milling machine deforms exactly. The aluminum sheet was selected due to its shiny metallic property. As a new industrial product for adding value to the “certificate prize”, it can be commercialized. Since the value of the metal is greater than paper and with the CNC technology adds more value to the product.

References

[1] Ghanei, S.; Abeyrathna, B.; Rolfe, B.; Weiss, M. Analysis of material behaviour and shape defect compensation in the flexible forming of advanced high strength steel. IOP Conf. Ser. Mater. Sci. Eng. 2019, 651, 012064.

[2] Pham, C.H.; Rasmussen, K.J. Mechanical properties, and residual stresses in cold-ed aluminium channel sections. Eng. Struct. 2019, 199, 109562.

[3] Sajjad, M.; Murugesan, M.; Jung, D.W. Longitudinal bow estimation of U-shape profile in cold formed for commercial aluminum alloys. Int. J. Mech. Eng. Robot. Res. 2020, 9, 1097–1103.

[4] Jung, D.-W. Investigation on Variation of Bow Defect in Forming Process. Key Eng. Mater. 2016, 729, 80–85.

[5] Cha, W.G.; Kim, N. Study on Twisting and Bowing of Formed Products Made of High Strength Steel. Int. J. Precis. Eng. Manuf. 2013, 14, 1527–1533.

[6] Bidabadi, B.S.; Naeini, H.M.; Tehrani, M.S.; Barghikar, H. Experimental and numerical study of bowing defects in cold -formed, U-channel sections. J. Constr. Steel Res. 2016, 118, 243–253.

[7] Safdarian, R.; MoslemiNaeini, H. The effects of forming parameters on the cold forming of channel section. Thin-Walled Struct. 2015, 92, 130–136.

[8] Abeyrathna, B.; Rolfe, B.; Weiss, M. The effect of process and geometric parameters on longitudinal edge strain and product defects in cold forming. Int. J. Adv. Manuf. Technol. 2017, 92, 743–754.

[9] Wiebenga, J.H.; Weiss, M.; Rolfe, B.; van den Boogaard, A.H. Product defect compensation by robust optimization of a cold forming process. J. Mater. Process. Technol. 2014, 213, 978–986.

[10] Tajik, Y.; Naeini, H.M.; Tafti, R.A.; Bidabadi, B.S. A strategy to reduce the twist defect in -formed asymmetrical-channel sections. Thin-Walled Struct. 2018, 130, 395–404.

[11] G. M. Reddy, P. Mastanaiah, C.V.S. Murthy, T.Mohandas and N. Viswanathan. Microstructure, Residual Stress Distribution and Mechanical Properties of Friction-Stir AA6061 Aluminium Alloy Weldments. Indian Society for Non-Destructive Testing Hyderabad Chapter.

[12] M.L. Gipiela, V. Amauri, C. Nikhare and P.V.P. Marcondes. A numerical analysis on forming limits during spiral and concentric single point incremental forming. IOP Conf. Series. Materials Science and Engineering, 2017, 164.

[13] D.S. Malwad and V.M. Nandedkar. Deformation Mechanism Analysis of Single Point Incremental Sheet Metal Forming. 3rd International Conference on Materials Processing and Characterization, Procedia Materials Science, 2014, 6, 1505-1510.

[14] Suresh Kurra, N.H. Rahman, S.P. Regalla and A.K. Gupta. Modeling and optimization of surface roughness in single point incremental forming process. J. Mater. Res. Tech. 2015, 4(3), 304-313.

[15] H. Markanday and D. Nagarajan. Formability behaviour studies on CP-Al sheets processed through the helical tool path of incremental forming process. IOP Conf. Series. Materials Science and Engineering, 2018, 314.

[16] Erika Salem, Jaekwang Shin, Maya Nath, Mihaela Banu and Alan I. Taub. Investigation of thickness variation in single point incremental forming. Procedia Manufacturing, 2016, 5, 828-837.

[17] A. Blaga, O. Bologa, V. Oleksik and R. Breaz. Influence of tool path on main strains, thickness reduction an forces in single point incremental forming process. Proceedings in Manufacturing Systems, 2011, 6(4).

[18] H. Markanday and D. Nagarajan. Formability behaviour studies on CP-Al sheets processed through the helical tool path of incremental forming process. IOP Conf. Series. Materials Science and Engineering, 2018, 314.

[19] J. Naranjo, V. Miguel, A. Martinez-Martinez, L.M. Gomez-Lopez, M.C. Manjabacas and J. Coello. Analysis and simulation of Single Point Incremental Forming by ANSYS. The Manufacturing Engineering Society International Conference, Procedia Engineering, 2015, 132, 1104-1111.

[20] Bhandari, Krishna Singh. “Experimental and Numerical Examination on Formability and Microstructure of AA3003-H18 Alloy in Single Point Incremental Forming Process.” Scintific.net.

[21] Bhandari, Krishna Singh. “Incremental Sheet Forming Simulation of Aluminum Alloys for Industry Level Production.” Scintific.net.