EXPERIMENTAL AND ANALYTICAL EVALUATION OF BENDING FOR ALUMINUM

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Report submitted in partial fulfillment of the requirementsfor the award of Bachelor of Mechanical Engineering

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I certify that the project entitled "Experimental and Analytical Evaluation of Bending for Aluminum" is written by Nazrith Bin Zulkafli. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

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STUDENT'S DECLARATION

I hereby declare that this report entitled "Experimental and Analytical Evaluation of Spring-back For Aluminum" is the result of my own research except as cited in the references. This report is not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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DEDICATION

I specially dedicate to my beloved parents

and those who have motivated

and guided me for completing this project

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In order to complete my research, I have met some person in helping my progress. First, I wish to thank my supervisor who is also my advisor, Mr Jasri Bin Mohamad, for giving me the opportunity to work with him in order to complete my Final Year Project. I am particularly thankful for the great confidence he had in me, for his support, enthusiasm and his guidance. Special thanks to my beloved family that always support my decision and works. My thanks also go to the person in charge for mechanical faculty CNC and tensile test laboratory also to Mr. Khairul Adzhar who help and give an idea a bit to complete my project. To Manufacturing Faculty person in charge of press brake machine and finally, my thanks is towards to peoples who are directly or indirectly get involved during my progress while completing this project and writing this thesis.

ABSTRACT

Spring-back is a common phenomenon that occurs in sheet metal bending after unloading the tooling or punch due to material elastic recovery. Three different thicknesses, 1, 2 and 3 mm are selected and 0^o, 45^o and 90^o of orientation are chosen as the considered parameters while the 30^o is selected as reference bending angle. In this research, it studies about determining the spring-back angle by using experimental and analytical method. Different equations are use where the Daw-Kwei Leu equation as the first equation is considers the thickness poisson ratio and strain hardening exponent while the Dongye Fei and Peter Hodgson equation is only consider the thickness effect, poisson ratio and die width for spring-back. Experiment for bending is limited in bottoming v-die bending. Data from the tensile test are used in determining the spring-back value for analytical method while press brake machine is a tool to complete the test. As the finding of the research, increasing the sheet thickness is decrease the spring-back value for analytical and experiment. In experiment, 1 mm and 2 mm gain a decreasing spring-back value related with analytical and previous study, but 3 mm of thickness has a spring-go appearance where the outer layer of outer diameter is happened a crack and this is proved the result where the material already exceed the elastic region for the aluminum.

ABSTRAK

Spring-back merupakan fenomena yang biasa terjadi semasa proses pembengkokan dimana bahan tersebut akan cuba kembali ke bentuk asal seperti sebelumnya. Berdasarkan kajian ini, ianya melibatkan pengkajian mengenai *spring-back* dengan menggunakan dua cara, eksperimen dan analisis. Tiga ketebalan yang berbeza, 1, 2, dan 3 mm telah dipilih manakala tiga arah orientasi 0^{o}, 45^{o} dan 90^{o} dipilih sebagai parameter utama. 30^{o} merupakan darjah pembengkokan yang menjadi rujukan kepada analisis dan juga eksperimen. Di dalam analisis, ianya melibatkan dua penggunaan rumus berbeza. Pertama, rumus Daw-Kwei Lue mengambil kira pengaruh ketebalan bahan dan juga exponen pengerasan terikan manakala rumus Dongye Fei dan Peter Hodgson hanya mengambil kira pengaruh ketebalan bahan dan kelebaran acuan. Acuan-v telah dipilih untuk digunakan bagi melengkapkan eksperimen. Data-data yang diperoleh daripada ujian tegangan akan digunakan untuk melengkapkan proses analisis manakala mesin tekan merupakan peralatan utama untuk melengkapkan eksperimen ini. Penemuan di dalam analisis mendapati bahawa meningkatkan ketebalan bahan akan mengurangkan nilai *spring-back* tetapi, melalui eksperimen, hanya keputusan daripada 1 dan 2 mm sahaja yang menyamai keputusan analisis dan kajian-kajian sebelum ini. Ketebalan 3 mm menghasilkan keputusan yang berlainan dimana *spring-go* terjadi dan ianya disokong melalui keadaan bahan dimana rekahan telah berlaku di lapisan luar pembengkokan. Hal ini disebabkan kerana bahan telah melebihi tahap lenturan aluminium dan tidak mampu untuk kembali ke bentuk asal.

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LIST OF SYMBOLS

L_b	=	Bend Allowance
a	=	Bend Angle
R	=	Bend Radius
k	=	Constant
P_v	=	Bending Force
C	=	Coefficient
B	=	Sheet Metal Width
T/t	=	Sheet Metal Thickness
σ_b	=	Material tensile Strength
w	=	Die Gap
R	=	Anisotropy Value
R_0	=	Anisotropy Value for 0^o
R_{45}	=	Anisotropy Value for 45^o
R_{90}	=	Anisotropy Value for 90^o
r_o	=	Outer Radius
r_i	=	Inner Radius
ρ	=	Neutral Axis
$\Delta\theta$	=	Spring-back Angle
θ	=	Bending Angle

UTS	=	Ultimate Tensile Strength
n	=	Strain Hardening Exponent
E	=	Young Modulus
v	=	Poisson Ratio
e	=	Exponent

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter explains clearly about project background, problem statement, project objective and scope of the project.

1.2 Project Background

Sheet metal is popular in industries. There have many applications using sheet metal such as ductwork, airplane wings, car bodies, medical tables and storage units, building facades, steel sheets, tubing and signs. Sheet metals come in flat pieces or coils and are measured by their thickness or gauge. Very thin pieces of metal are called foil or leaf and thick metals are called plate. Some of the industries using bending machine as their process to produce their product.

This project is about experimental and analytical evaluation of bending for aluminum sheet metal. In this project, 1, 2, and 3 mm thickness of aluminum are selected. Aluminum is selected since it has the light-weight characteristic. Also, aluminum is common usage in industries. For the purpose, tensile test is performed to acquire material data as input to the analytical evaluation. The tensile test is conducted by using a tensile test machine to gain the stress strain data of aluminum. Before that, tensile test specimens are creating by using a CNC milling machine.

Bending test is done by using press brake machine. In this test, bottoming v-die bending is selected since there has many types of die in bending process. 30 degree of die angle is functioning as a reference angle and this project only considers the different thicknesses and rolling directions.

In analyzing the results of an experiment, computer scanner and SOLIDWORK software are used in determining the specimen angle. The angle for each specimen will be deducted by the reference angle in determining the spring-back value. Finally, the results for every thicknesses and orientations are compared.

1.3 Problem Statement

While the sheet metal induct into the bending process, spring back appears where the materials are not in the exact position or it tries to return back to its original position. Usually this phenomenon happens when the die is removed from the material after the bending process. This spring back happens because of the material characteristic that should be considered. Because of this spring back, most of companies in the industry have a problem to control their output product quality. Also, this will cause problems in die making or designing process and this will increase their cost just to reduce the spring back and control their product quality.

1.4 Project Objectives

The objectives for this project are:

i. To determine the reliability of analytical method in sheet metal bending of aluminum.
ii. To determine the influence of thickness and anisotropy in spring-back.

1.5 Scopes of Project

Scopes of project are limited to:

i. To conduct tensile test to collect the data of material properties.
ii. To conduct the V - bending experiment by using press brake machine.
iii. To evaluate the analytical result.
iv. To compare the result between analytical and experiment.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In conducting a research, review is an important section to be familiar with the area of study. In this chapter, it will explain about sheet metal forming, sheet metal bending, type of bending, spring-back, and analytical method. Also, some of previous study is revealed in this chapter.

2.2 Sheet Metal Forming

Sheet metal parts are light weight and can have versatile shape due to its low cost and generally good strength and formability characteristics. Thus, low-carbon steel is the most common used sheet metal (Bruce et al., 2004).

Many sheet metal forming processes are used to produce parts and shapes. Usually, there is more than one method of manufacturing to form the sheet metal. The broad categories of processing methods for materials are as follows:

i. Roll forming: Long parts with constant complex cross-section.
ii. Stretch forming: Large parts with shallow contours that is suitable for low quantity production.
iii. Drawing: Shallow or deep parts with relatively simple shapes for high production rates.

iv. Stamping: Includes punching, blanking, embossing, bending, flanging, and coining.

v. Spinning: Small or large axisymmetric parts with good surface finish and low cost tooling (Kalpakjian and Schmid. 2001).

2.3 Sheet Metal Bending

Sheet metal bending imparts stiffness to the part by increasing its moment of inertia. For example, the flanges, beads, and seams increase the stiffness of structure without adding any weight. Figure 2.1 below show the terminology of bending. (Guidice et al., 2006)

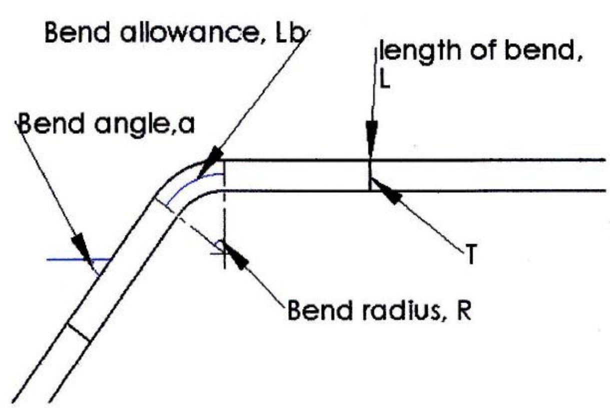


Figure 2.1: Bending terminology

Source: Guidice et.al., 2006

The bend allowance, $\boldsymbol{L_b}$ is length of the neutral axis in bend. The position of L_b will be depends on the radius since the formula of bending angle is:

$$L_b = a(R + k) \quad (1)$$

Where a is bend angle, ^{o}. T is sheet thickness, mm. R is bend radius, mm and k is constant.

In addition, bending is a process by which metal can be deformed by plastically deforming the material and changing its shape. The material is stressed beyond the yield strength but below the ultimate tensile strength. The surface area of the material does not change much. Bending usually refers to deformation about one axis. Bending is a flexible process by which many different shapes can be produced (Olaf D., July 2002).

Bending process is about shaping material without removing any chips around a definite axis through or without heat. Bending is a process of placing a sheet metal over the matrix on the press bed where the sheet metal will follow the die shape and punch tips since entering the die after the punch press it into the die (Ozgur T. et al., 2007).

2.4 Type of Bending

There has many type of bending in sheet metal forming. This project only considers v-die and bottoming bending.

2.4.1 V-Die Bending

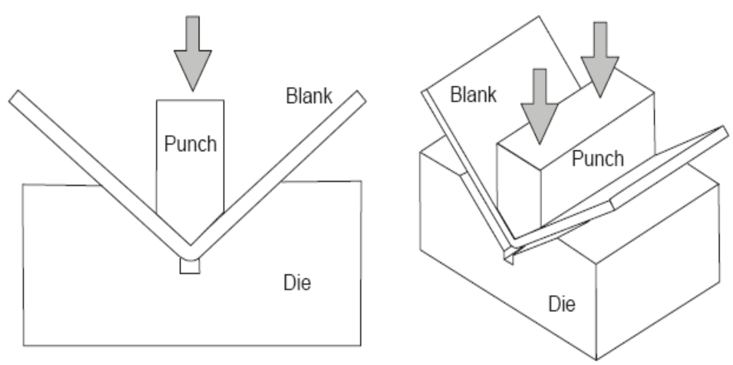


Figure 2.2: V-die bending

Source: Olaf D., July 2002

Figure 2.2 shows the V-die bending. Sheet metal will bend between the punch and die shaping in v shape. There has 3 types of die, bottoming, air or coining. Compare with the U-die bending where the only appear is spring-back, the spring-go and spring-back can be determined using the V-die bending.

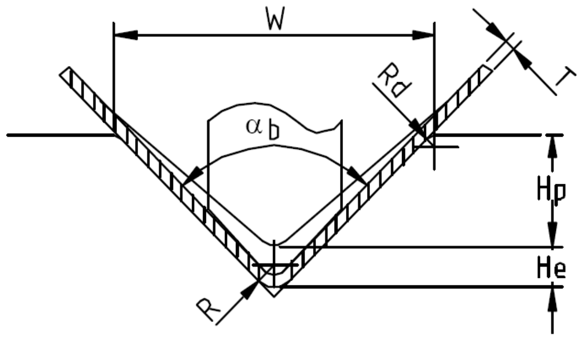


Figure 2.3: Die setup and bending parameter

Source: Ozgur T. et al., 2007

Figure 2.3 shows the setup of die and punch for v-bending process. Before the V-bending test, force for the V-bending machine should can be calculate to avoid the over force while bending test. This calculation method can be use as a guide and also can avoid the die or the specimen of bending process broken if the over press on the specimen or die. The calculation of bending force can be determined by:

Bending Force:

$$P_v = C \times \frac{B \times T^2 \times \sigma_b}{w} \times 10 \tag{2}$$

Coefficient:

$$C = 1 \times \frac{4 \times T}{w} \tag{3}$$

2.4.2 Bottoming

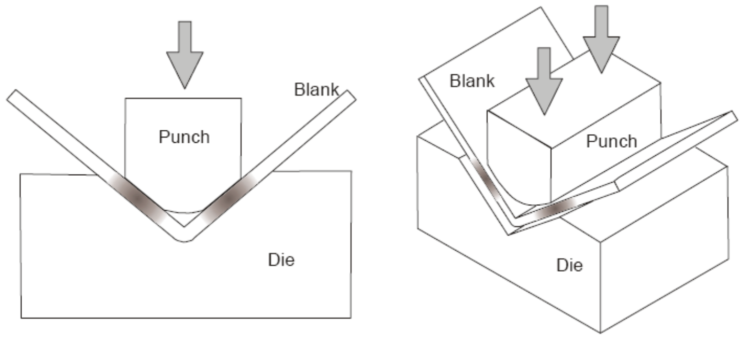


Figure 2.4: Bottoming bending

Source: Olaf D., 2002

Figure 2.4 is a bottoming bending. It has a similarity to both air bending and coining. In this process, the die angle should match the intended angle of the work piece, adjusting a few degrees for spring back, hence the existence of 88 degree tooling to achieve 90 degree angles. The workpiece is first bottomed against the die, then the radius of the punch is forced into the work piece which achieves the angle of the punch, it is then released and the workpiece springs back to meet the die again (Olaf D., 2002).

Unlike coining, however the material is not under so much tonnage that the metal flows. Because of this there is still spring back which must be compensated for. In order to do compensate the angle of the punch can be smaller than the angle of the die by a few degrees allowing an over-bend when the punch tip is forced into the workpiece, it should not be larger or else it will damage the tooling (Olaf D., 2002).

2.5 Spring-back

Sheet metal bending also depends on the spring back effect. All material has their modulus of elasticity and spring back is caused by the redistribution of stress in sheet material after the tooling is removed. (Zhang et al., 2006)

When releasing the load, the material will try to recover back into its initial form and the material bend expands backward with some amount of stretching. This behavior already called as ‘spring-back’ (Ozgur T. et al., 2007).

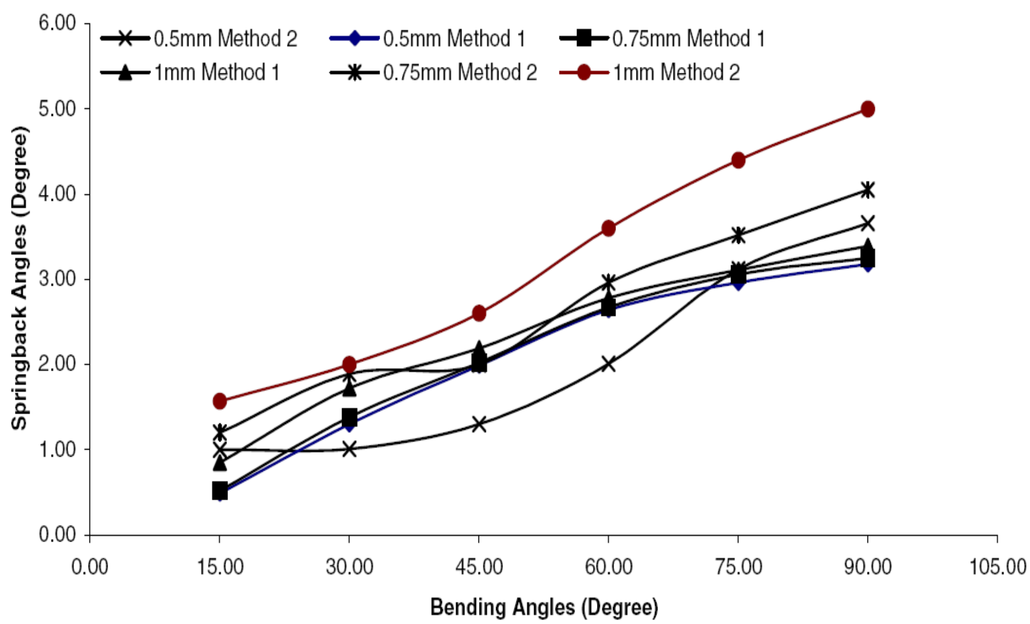


Figure 2.5: A combined presentation of the spring-back graph from first and second method.

Source: Ozgur T. et al., 2007

Figure 2.5 above is a result from (Ozgur Tekaslan et.al., 2007) where there are studying about spring-back of stainless steel sheet metal in V-die bending. Two different methods are used in their research where the first method, the punch is held about 20 second and the second method, the punch is not held but will return after the bending process is complete. From the graph above, it has determined that increasing the thickness of sheet metal will increase the spring-back.

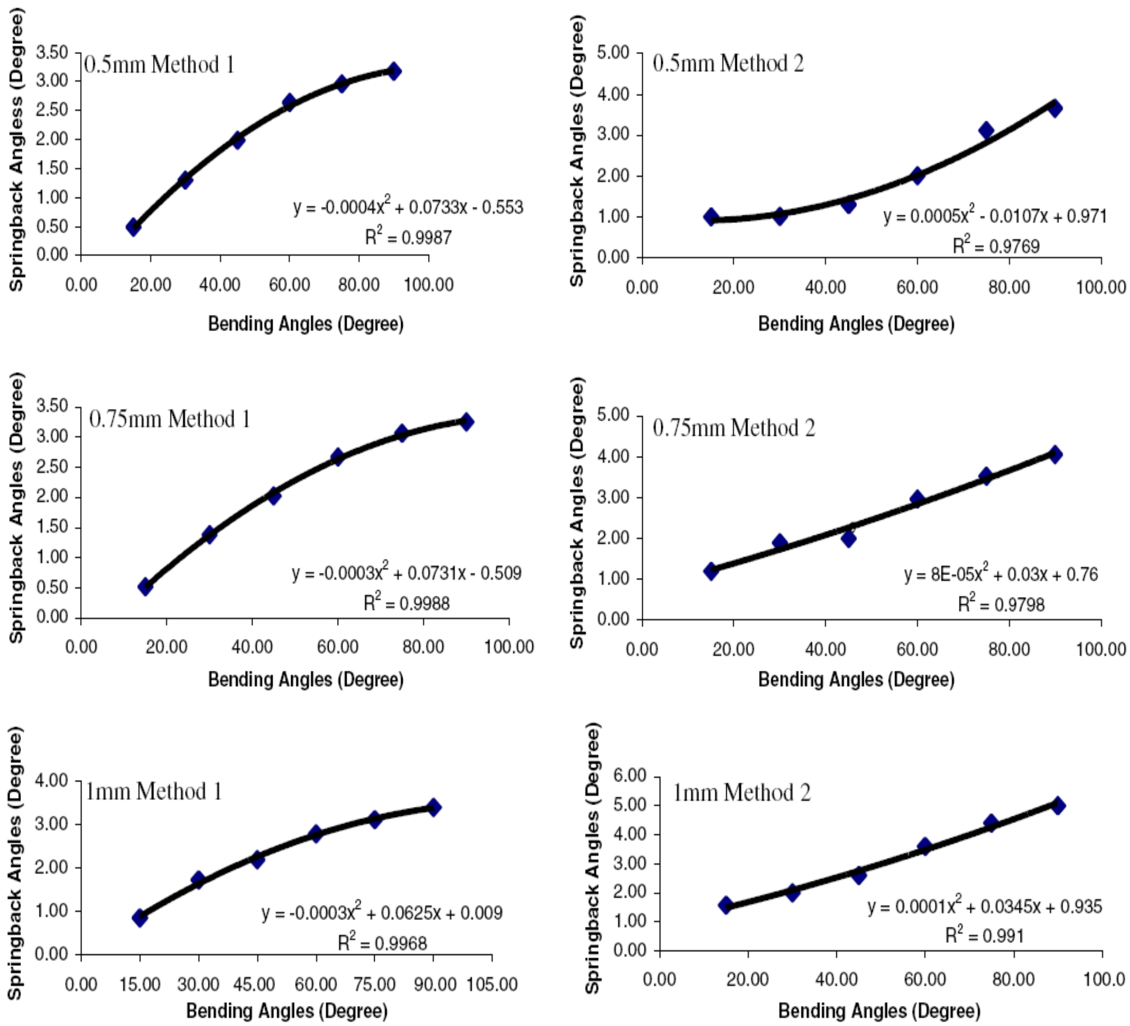
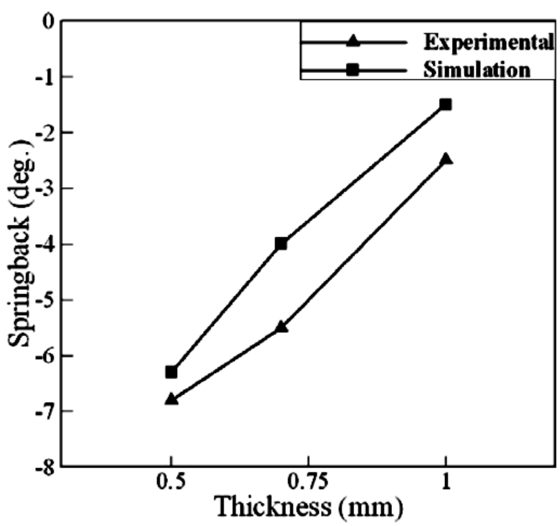


Figure 2.6: Spring-back graphs and polynomial curve.

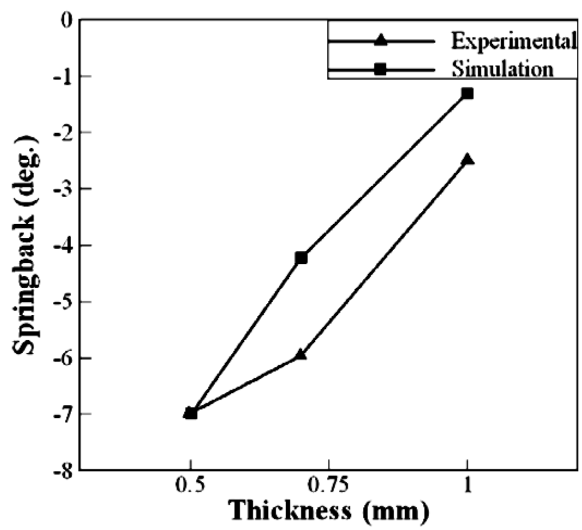
Source: Ozgur T. et al., 2007

The different bending angles also give an effect to spring-back. Compare with the Figure 2.6, changing the bending angle is more effective to increasing the spring-back compare with increasing the sheet metal thickness.

Bakshi M.J. et al., (2009) has studied about spring-back of CK67 steel sheet in V-die and U-die bending process where they are compare the experimental and finite element method. In their study, there are included the orientation of rolling for the sheet metal where 0^o, 45^o, and 90^o are consider. The sheet thicknesses about 0.5, 0.7 and 1 mm were examined. Also, 2, 4, and 6 mm of punch radius are use to determine either the different punch radius effecting the spring-back.



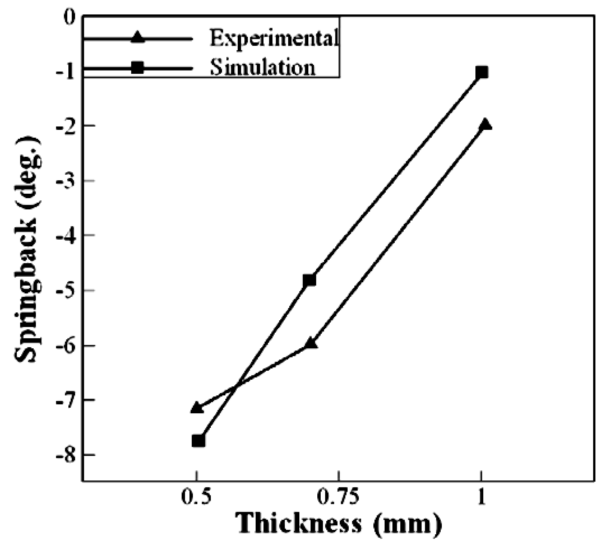
a) Orientation 0^o



b) Orientation 45^o

Figure 2.7: Effect of the sheet thickness between different orientations

Source: Bakhshi M.J. et al., 2009



c) Orientation 90^{o}

Figure 2.7: Continue

Source: Bakhshi M.J. et al., 2009

Figure 2.7 is the finding result of (Bakshi M.J.et al., 2009). Different thicknesses are effected the spring-back and spring-go where spring-go is appear in v-die bending only. Also, the experimental and finite element analysis results are compared and the result prove that finite element can be use to analyze the spring-back since it is has a small amount of differences among the analysis and experimental.

Dilip K.K. (2010), report on spring-back of aluminum sheet metal where the finite element analysis is selected as the method. Results of 1, 2 and 2.5 mm thickness of aluminum are selected in review his study. It concludes an increasing thickness material is decreasing spring-back value. Since this project is using aluminum, result from Dilip K.K will be use in comparing the experiment and analytical result with this study. Figure 2.8, 2.9 and 2.10 is the result from Dilip K.K. study.

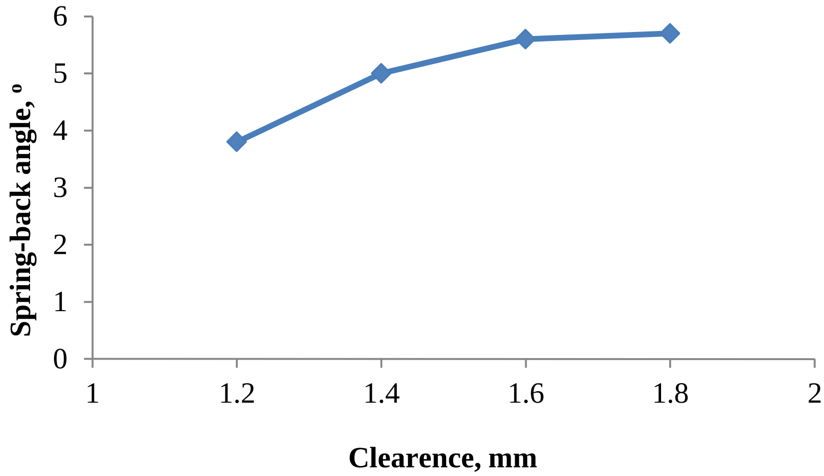


Figure 2.8: Spring-back of 1 mm

Source: Dilip K.K., 2010

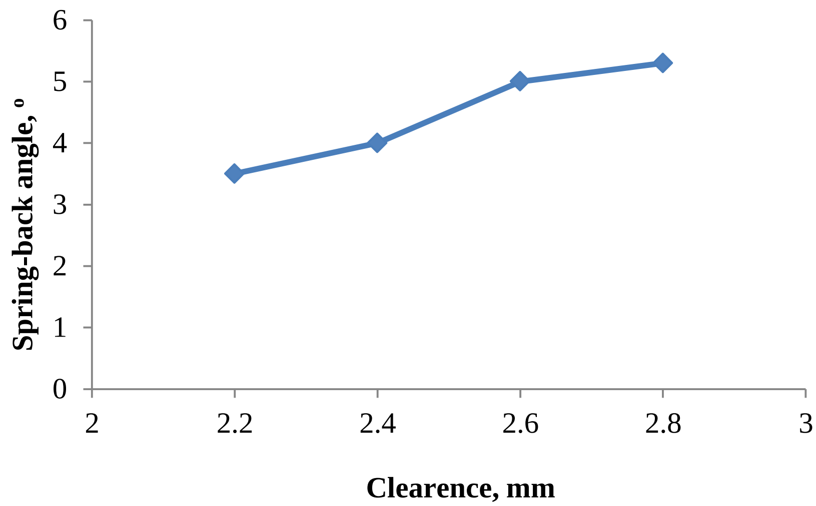


Figure 2.9: Spring-back of 2 mm

Source: Dilip K.K., 2010

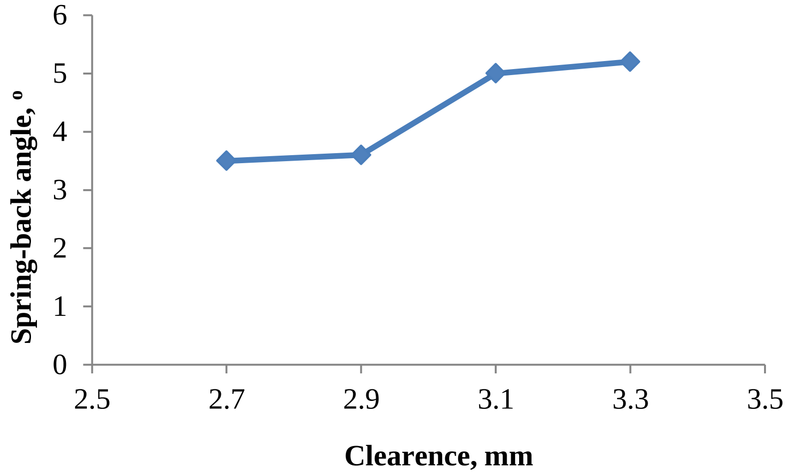


Figure 2.10: Spring-back of 2.5 mm

Source: Dilip K.K., 2010

The clearance is a gap of the die due to the thickness of materials. The clearance value should be minus by the thickness to determine the gap of die from the thickness and the gap value of 0.4 is use in determining the spring-back value in different thickness.

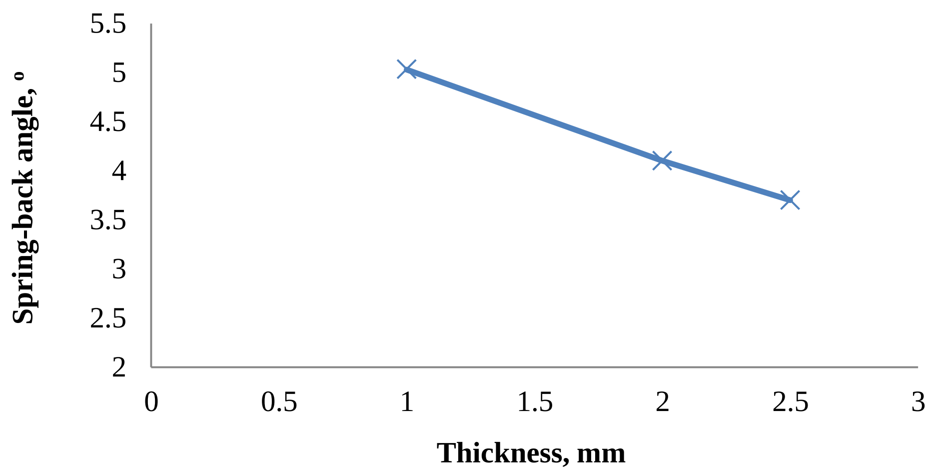


Figure 2.11: Dilip K.K.'s Result

Source: Dilip K.K. 2010

2.6 Analytical Method

Analytical method is a time-saving method and has been widely used for predicting spring-back of bending parts. But most of these researches ignored the effects of contact pressure, transverse stress, neutral surface shifting and thickness thinning on sheet spring-back of bending parts (Zhang et al., 2007).

In this analytical method, two of the equations are selected to compare each other where the Leu D.K. equation is the first equation is consider the effect of rolling direction, *R*, strain hardening exponent, *n* and thickness in spring-back. The other, Fei and Hodgson equation is consider the thickness and die gap, *w*. The comparisons between these two equations are expose through the result chapter.

Rolling direction in this project is selected referring with Leu D.K study where the angle of 90^o is perpendicular with rolling direction. Figure 2.8 shows the rolling direction of sheet metal.

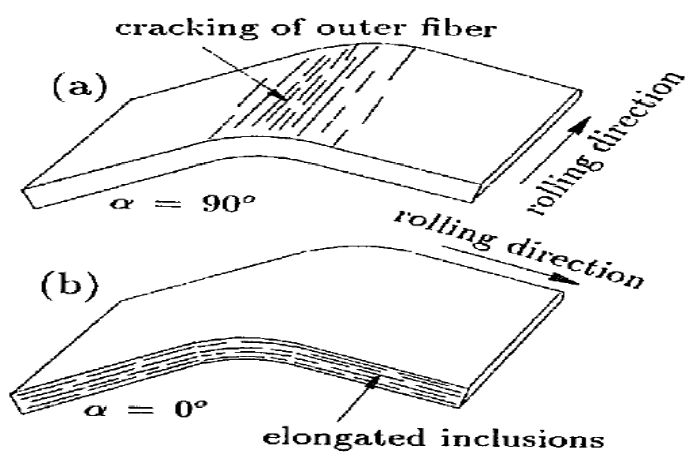


Figure 2.12: Rolling direction

Source: Leu D.K., 1995

Radially symmetrical, *R*:

$$R = \frac{R_0 + 2R_{45} + R_{90}}{4} \tag{4}$$

Since Zhang et al., (2006) is considering the reducing of thickness while bending process for the outer radius, in this study, it did not consider any reduction for the outer radius. So, the outer radius can be calculate by

$$r_o = r_i + t \tag{5}$$

Equation of neutral axis:

$$\rho\sqrt{r_o r_i} \tag{6}$$

Daw-Kwei Leu spring-back equation:

$$\frac{\Delta\theta}{\theta} = \frac{UTS}{e^{-n}n^n} \times \left(\frac{1+R}{\sqrt{1+2R}}\right)^{1+n} \frac{3(1-v^2)}{2E(1+n)} \left(\frac{t}{2\rho}\right)^{n-1} \tag{7}$$

Fei & Hodgson spring-back equation:

$$\frac{\Delta\theta}{\theta} = \frac{3UTS\rho(1-v^2)(1+4t/\omega)}{Et} \tag{8}$$

Young modulus for aluminum is 69 GPa and this is prove by (Yu Z.Q. and Lin Z.Q., 2007) that studying in ‘Numerical analysis of dimension precision of U-shape aluminium profile rotary stretch bending’. Also, (Kalpakjian and Schmid, 2003) mention the same value in their slide presentation with the title of ‘Fundamental of mechanical behavior of materials’ in chapter two. Gilbert Kaufman already wrote a book of ‘Aluminum alloy and tempers’ and state that all of aluminum AA1100 type has the 69 GPa as the

Young modulus. So, the value from the tensile test should be the same or just about with the standard value.

John E. H. (2005) edited a book of ‘Properties and physical metallurgy’ and wrote that 0.242 is a value of strain hardening exponent for aluminum AA1100. (Dharmavira and Srivinasan, 1996) used 0.23 as the value of strain hardening exponent in their study. This value is nearly the same with the John E. H. But, (Kalpakjian and Schmid, 2003) stated that 0.20 is the value of strain hardening exponent for aluminum AA1100 in their slide presentation. This can conclude that strain hardening exponent of aluminum AA1100 is range from 0.20 to 0.242 and the result from tensile test should be in this range.

YU Z.Q. and Lin Z.Q., (2007) already use the 0.33 as the poisson ratio but, (Kalpakjian and Schmid, 2003) has state the range vaue of poisson ratio in their slide presentation with the range 0.31 to 0.34. These two values will be use as the reference to the tensile test result where the poisson ratio of the result will be range from 0.31 to 0.34.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology is an important element in this project where it specifically describes the method will be use in this project. It also functioning as a guideline to ensure the project flow is smoothly and arranged. In this chapter, it will explain through all the method will be use for this project from the start.

Flow chart is created to arrange the step of the project, and then continue by conducting shearing machine that needed to cut the large width of plate into the small dimension. CNC milling machine used to provide the tensile test specimen where the dimension is taken from the ASTM book as reference. Done the preparation of tensile specimens, it is continue with tensile test. This test is conduct by using tensile test machine. Collected data are use in analysis to determine the spring-back angle. After gain the tensile test data, bending process will be follow through and the usage of computer scanner and SOLIDWORK software are needed to determine the spring-back angle.

3.2 Methodology Flow Chart

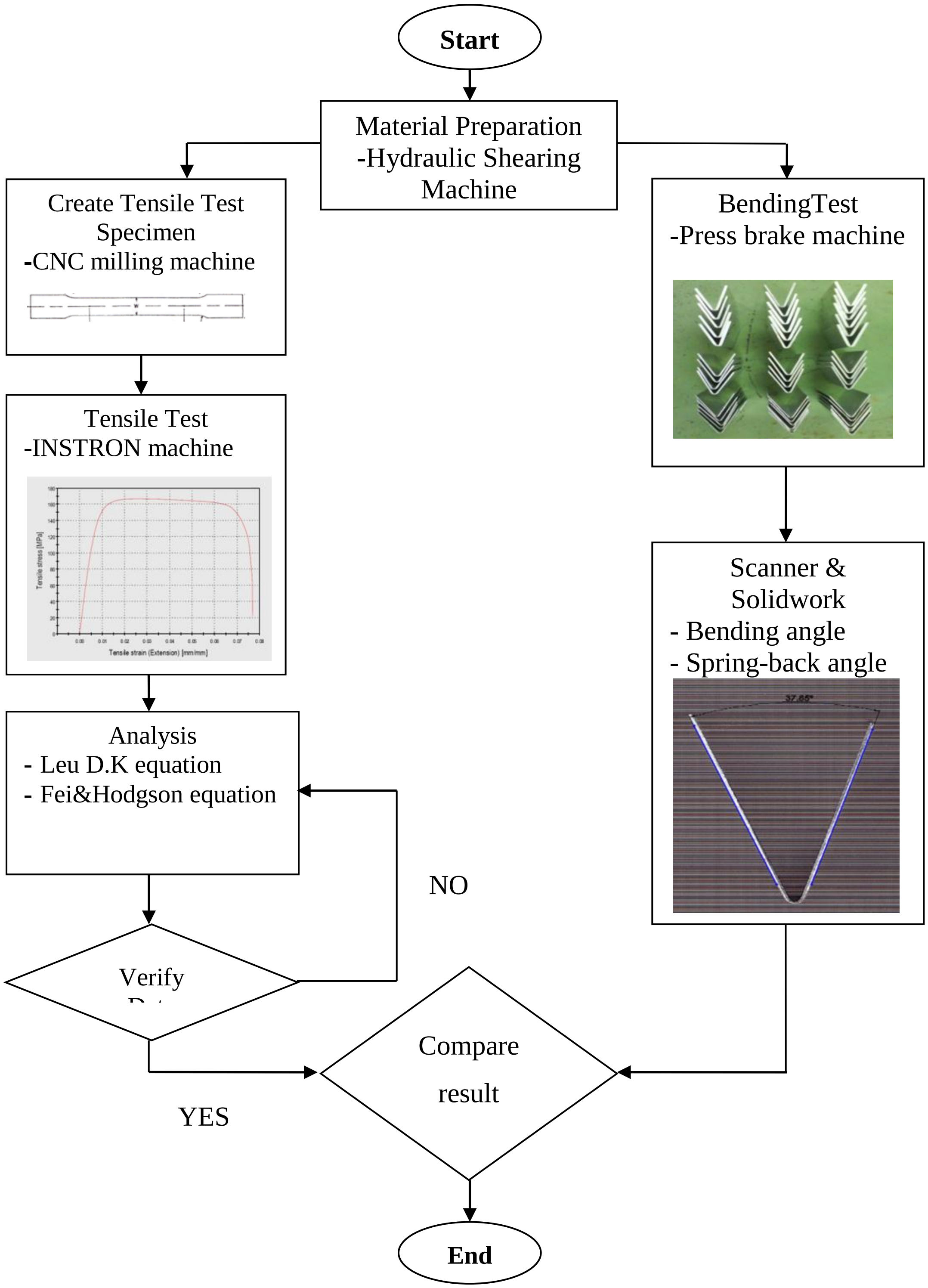


Figure 3.1: Flow chart of methodology

Figure 3.1 shows the flow chart for the methodology. The progress for this chapter starts with material preparation. The actual size is 8 x 4 feet will be minimizing by using the hydraulic shearing machine to the smaller size.

Then, CNC machine is use to create the tensile test specimen and the standard for the specimen is base on the ASTM E8M book. Then, tensile test will be done using the tensile test machine. The data from the tensile test will be use to calculate the spring-back by analytical method. The validation data from calculation will be verified. Since the data did not satisfy, the calculation will repeat.

V-die bending is use into the press brake machine to complete the bending test. After done the bending test, the specimen is scan through the computer scanner and transfer to SOLIDWORK software to determine the bending angle from the specimen. The angle is deducted with die angle and the spring-back angle will be compare with the analytical method. Also, the comparison of bending angle between different thicknesses will be determine.

3.3 Tensile Test

Tensile test is attest that determines the overall strength of a given object. In a tensile test, the object is fitted between two grips at either end and slowly pulled apart until it breaks. A tensile test is provides important information related to the product durability. It is including yield point, tensile strength and stress. The tensile test is conduct to gain the data of characteristic for aluminum. Before the tensile test, the specimens are created by using CNC milling machine. The specification of specimen is determined from ASTM E8M book.

There are various ways of gripping the tensile specimen, some of which are illustrated in Figure 3.2. The end may be screwed into a threaded grip, or it may be pinned or the butt ends may be used, or the grip section may be held between wedges. The most important concern in the selection of a gripping method is to ensure that the specimen can be held at the maximum load without slippage or failure in the grip section. Bending should be minimized (W.F. Hosford, 1992).

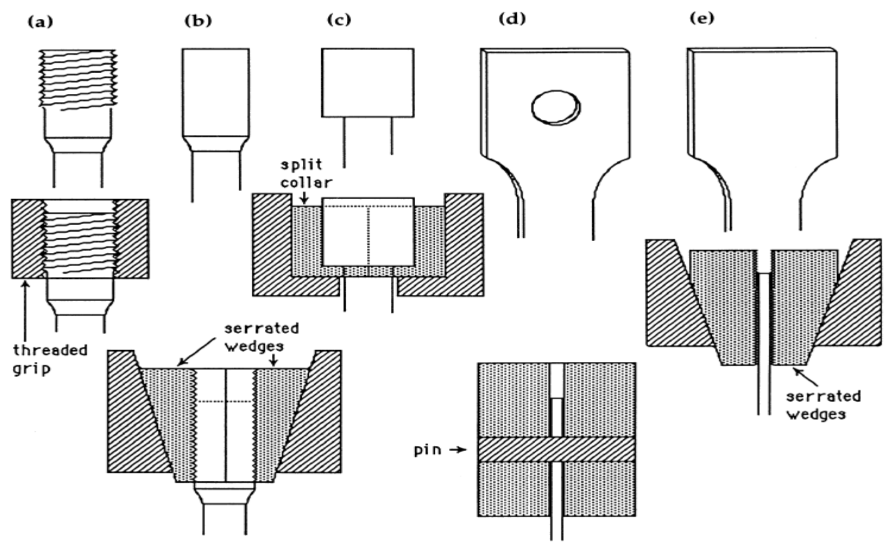


Figure 3.2: Gripping system of tensile specimens

Source: Hosford W.F., 1992

For the round specimens, these include threaded grips (a), serrated wedges (b) and for butt end specimens, split collars constrained by a solid collar (c). For the sheet specimens, it may be gripped with pins (d) or serrated wedges (e). The specification of tensile test specimen is determined referring with ASTM E8M book.

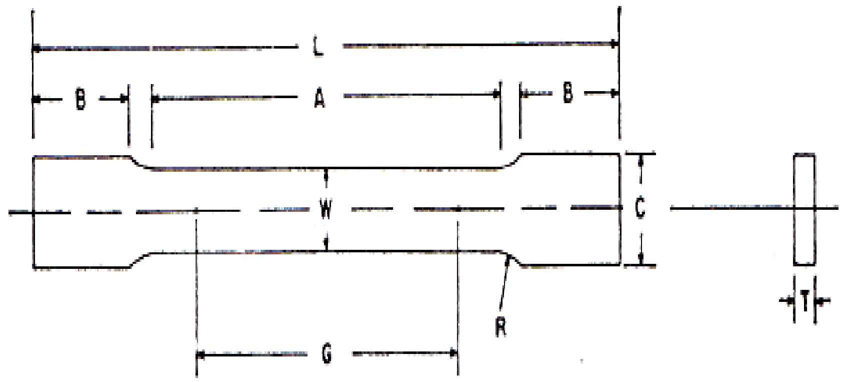


Figure 3.3: Specification of tensile test specimen

Source: Standard Test Methods for Tension Testing of Metallic Materials [Metric]

Table 3.1: Standard tensile test specimen

Standard Specimen, Sheet-Type	
Symbols	**Unit, mm**
G – Gage length	50 + 0.10
W – Width	12.5 + 0.25
T – Thickness	Thickness of material
R – Radius	13
L – Over-all length	200
A – Length of reduced section	60
B – Length of grip section	50
C – Width of grip section	20

Source: Standard Test Methods for Tension Testing of Metallic Materials [Metric]

Figure 3.3 and Table 3.1 is the specification of tensile test specimen. The important part of the specimen is the gage length, G. The cross-sectional area of the gage section is reduced relative to that of the remainder of the specimen so that deformation and failure will be localized in this region. The gage length is the region over which measurements are made and is centered within the reduced section. The distances between the ends of the gage section and the shoulders should be great enough so that the larger ends do not constrain deformation within the gage section, and the gage length should be great relative to its diameter (Mumford P.M, 1992).

3.3.1 Material Preparation

Figure 3.4: Raw material

Figure 3.4 shows the raw material of this project, aluminum sheet metals with 1, 2, and 3 mm of thickness. As the preparation for the tensile test specimen, the material is cut from 8 feet x 4 feet to the smaller size, 300 mm x 100 mm to ease the next process. These dimensions are selected to ease the next process (CNC milling) after considering the clamping and space between specimens. Hydraulic shearing machine in Figure 3.5 is use to cut the raw material into the smaller part. Before the cutting process, the rolling direction is determined. Then, the material will be cut referring with the rolling direction which are 0^o, 45^o, and 90^o.

Figure 3.5: HAAS automotion hydraulic shearing machine

3.3.2 Tensile Test Specimen

Done with material preparation, CNC milling machine is use to produce the tensile test specimen. By using the Master CAM X3 software, the tensile test specimen is drawn and converts into the g-code phase before through the milling process by CNC milling machine.

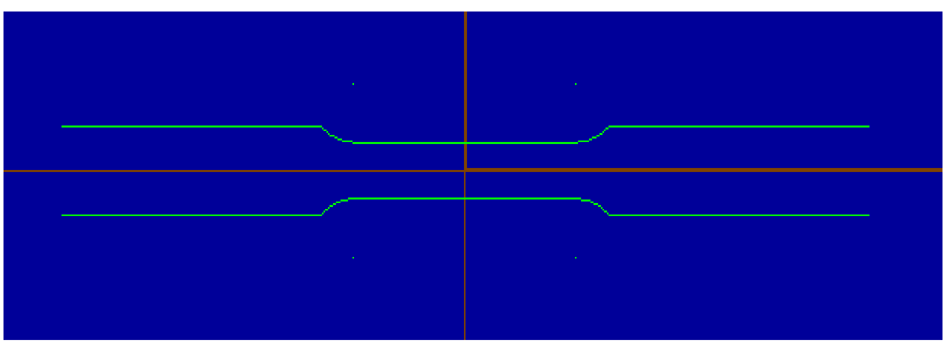


Figure 3.6: Drawing of tensile test specimen

Figure 3.6 is a drawing for tensile test specimen by using Master CAM X3 software, the tensile test is draw referring with tensile test standard. The design is drawn non-continuous after consider the clamping progress where it is ease the milling process.

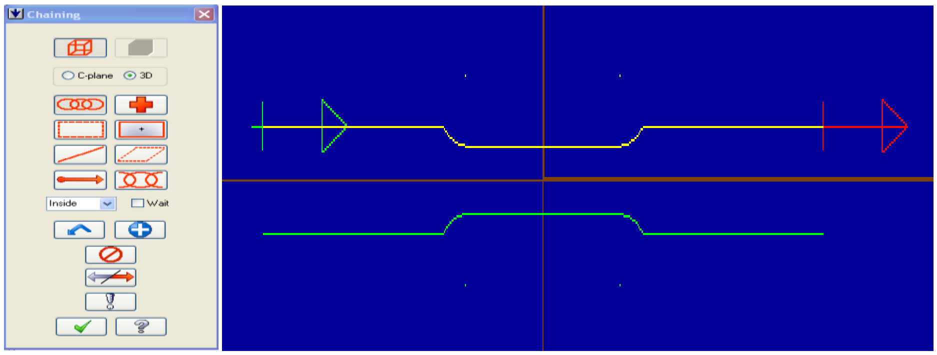


Figure 3.7: Cutting direction

Selecting the cutting style is the next process where chaining is selected and the cutting process will do the upper side until finish before continue on the below part. From the Figure 3.7, since the lines are non-continuous, the process should be set for two times, upper and below line.

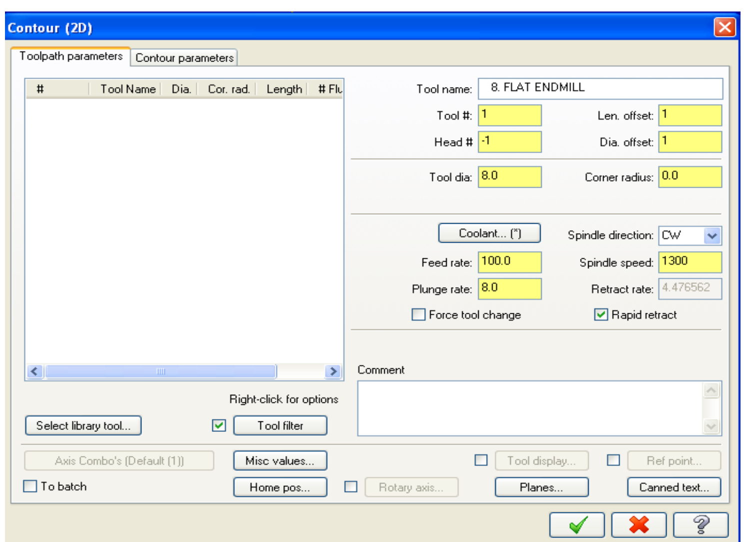


Figure 3.8: Toolpath parameter

After done set the cutting style, Figure 3.8 shows the toolpath parameter that should be set referring with the type of tool will be use. For this machining, 8 mm diameter flat endmill is chosen. Then, set ON for the coolant will cause the coolant is flow during the machining process. Tool is set with 1. So, while the machining, the 8 mm flat endmill should be place on number 1. The direction of spindle is set clockwise and the speed is 1300 rpm. For the feed rate, 100 is decide and plunge rate should be below than 10 and 8 is chosen.

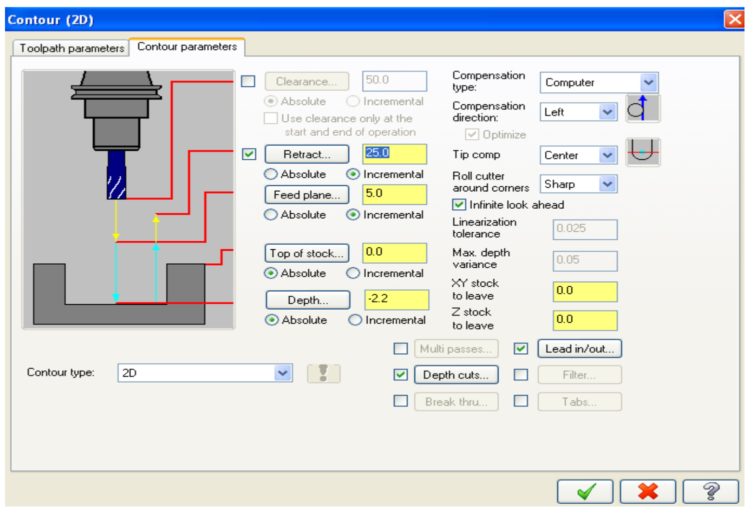


Figure 3.9: Contour parameter

After set the toolpath parameter, contour parameter shown in Figure 3.9 should be set. The depth of cut is set with 1.0 mm and the depth is set -2.2 mm since the material thickness is 2 mm and (-)ve symbol is to mention the downward movement in z-axis. 0.2 mm is added to make sure the material is fully cut and to minimize the burr effect. For the compensation direction, the upper side is set with left direction, but, for the below side, it will be set with right since the tool is cut in different way to maintain the specimen at the middle between the tooling cutting movement.

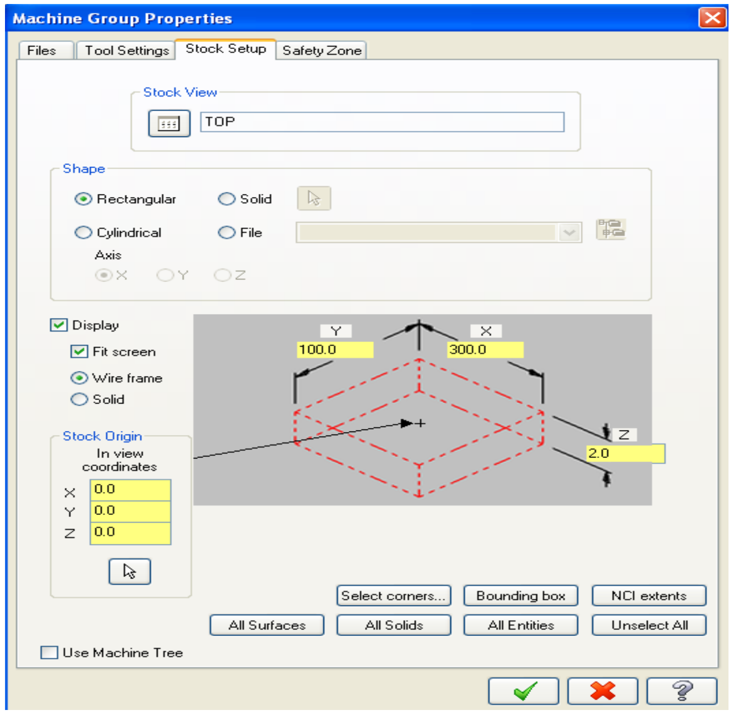


Figure 3.10: Stock setup

Then, the stock setup in Figure 3.10 is mentioning the original size of prepared material. Referring with the sheet metal size, 300 mm x 100 mm x 2 mm is decided for the length, wide and height. This setup is functioning to ease the next step where the movement of milling process can be figure out using the Master CAM X3 software.

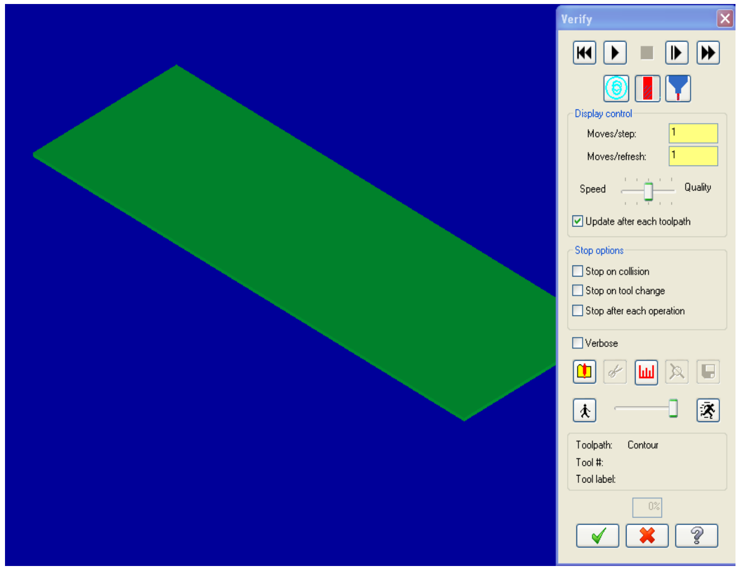


Figure 3.11: Isometric view

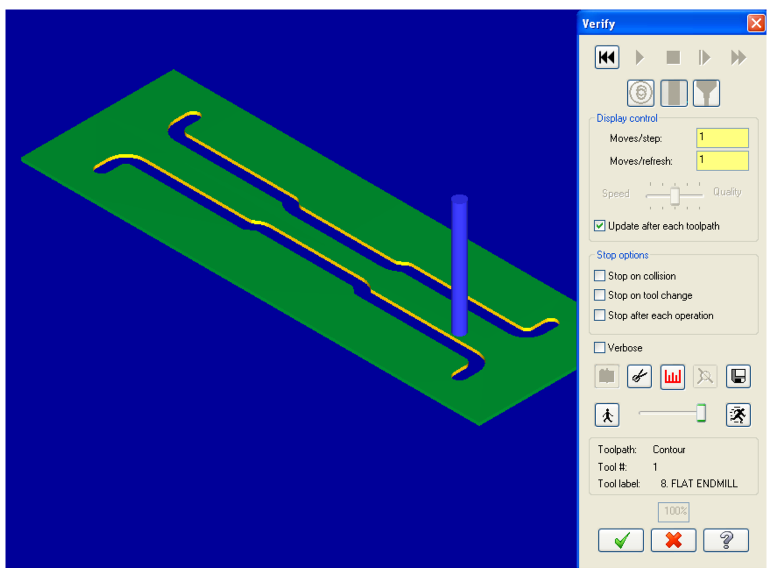


Figure 3.12: Complete process

Figure 3.11 and 3.12 show the movement of milling process for the tensile specimen that will happen during the machining. This process is important to identify either the tool is move in safe way to avoid the out range and over cut during the machining.

Figure 3.13 is a HAAS CNC milling machine that used in creating tensile test specimens. Figure 3.14 shows the milling process during the machining and the complete tensile test specimen is shows in Figure 3.15.

Figure 3.13: HAAS CNC milling machine

Figure 3.14: CNC milling process

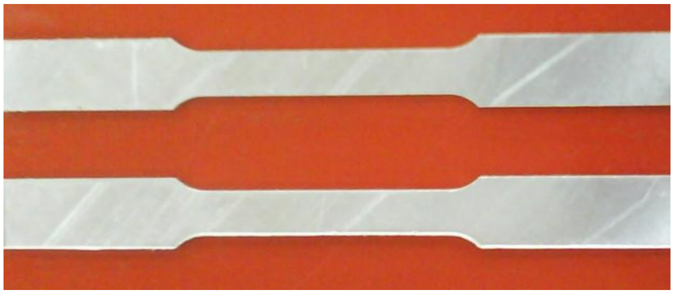


Figure 3.15: Tensile test specimen

3.3.3 Tensile Test

After CNC milling machining process, the incomplete tensile specimen will cut using the hydraulic shearing machine. Before the cutting process, the length for the grip section is marked to avoid the overcutting on the specimen. Then, filing is next process if necessary to remove the occur burr on the tensile specimen's edges.

Figure 3.16: INSTRON tensile test machine

Figure 3.16 is a INSTRON tensile test machine that used to determine the data of aluminum characteristic. The results are come out with the stress-strain data where it can be determine using the software for this tensile test. All the specimens which are consisting 3 pieces for each orientation, 0^o, 45^o and 90^o and different thicknesses are test through the tensile test machine.

Figure 3.17: Griping specimen

The gripping type is in many types in this laboratory. So, the gripping type should be setup firstly before clamping the specimen on them. By referring the standard specification that already decided before, the flat gripping without pins are chosen and Figure 3.17 shows the type that use After setup the gripping part, the specimen will be tighten between the two gripping part. The length of the gripping part already determine by the ASTM E8M book which is 50 mm from the upper and below section. All the data that determine by the tensile test are transfer to the computer and the result will be print out through the printer.

3.4 V-Bending Test

3.4.1 Material Preparation

For bending experiment, the raw material is prepare using hydraulic shearing machine but in different measurement. The dimension of bending specimen is 150 mm x 50 mm. it also consist in three different thicknesses and three different orientations same as tensile test specimen.

3.4.2 V-Bending Experiment

Figure 3.18 is a press brake machine that used in conducting the bending test where it is cover the v-bending process. This press brake machine is provided by Manufacturing Engineering Faculty .The die will be change for each different thicknesses of sheet metal. Radius for the punch is 1 mm, 30^o of the bending angle and 400 kN as force is the parameter for this process. The prepared material which is 100 mm x 100 mm will be place on the die and the punch will be press the sheet metal until the bottom of die. Figure 3.19 is shows the material position during the bending process.

Holding the punch load on the sheet metal is decrease the spring-back (Ozgur T., 2007), this means the punching times is effecting the results. Then, the punch will remove after the punch is done the bending process. In this part, the bending time should be consistence to avoid the too much different result. In this experimental method, the bending process is using bottoming v-bending process where the punch will be press deep in the v-bending die.

Figure 3.18: Press brake machine

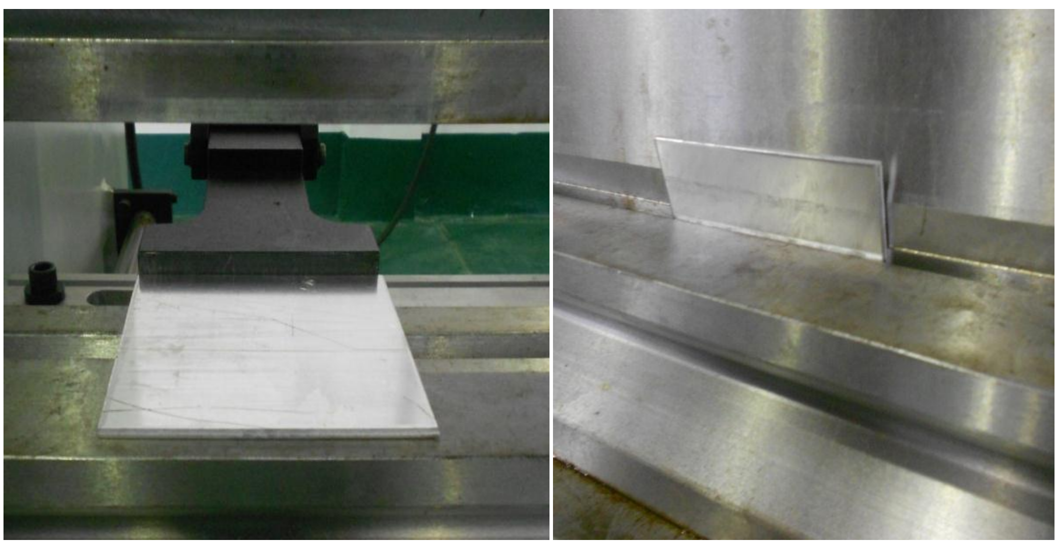


Figure 3.19: V-bending process

3.4.3 Measuring Spring-back Angle

Figure 3.20: Canon Pixma MP258 computer scanner

All the bending specimens should be scan through the computer scanner in Figure 3.20 to determine the spring-back angle. By using the scanner, the scanned specimens saved in jpeg type. Using the SOLIDWORK software, the picture will be transfer into the drawing and lines are construct on it. Smart dimension is use to determine the spring-back angle. The measuring specimens are saved in PNG type and name with referring the thickness and orientation of rolling direction. All the data will be express in table to ease the collecting data process.

3.5 V-Bending Analytical

Analytical results are determined by using the data from tensile test. Since the analytical has 2 methods, the data will be separate into two parts analytical for Leu D.K equation and Fei and Hodgson equation. MICROSOFT EXCEL software is used in calculates the data and produces the graph to ease the comparison part. All the data are summarize in table form. Also, the comparisons between the different equations are generated using this software.

CHAPTER 4

RESULT & DISCUSSION

4.1 Introduction

In this chapter, discussion trough the result from the analytical method and experimental method are shown. Then, results between these two methods are compared to determine the spring-back value. Also, the tensile test results are represented to determine the mechanical properties for aluminum and complete the analytical method. For the analytical, it only considering the influence of thickness only and the anisotropy influence is determine by the experiment.

4.2 Tensile Data

After the test done, the result will appear on the monitor screen where it can be found the maximum load, modulus of elasticity, and strain hardening exponent. All this data are used to determine the other data to complete the v-bending analytical method for Aluminum sheet metal. All the data of aluminum 1, 2, and 3 mm will be explain through this result subchapter. There has an equation to determine the mechanical properties where already decided in chapter 2.

From the gain data and using the equation, the mechanical properties are determined and there are arrange with their thickness and anisotropy condition. It is start with the aluminum 1 mm of thickness and 0^o of rolling direction to 3 mm of thickness and 90^o of rolling direction. Data can be found in Appendix D.

Table 4.1: Tensile data

Orientation Angle (°)	Young's Modulus (GPa)	UTS (MPa)	Strain Hardening Exponent, n	Poisson's Ratio, v	Anisotropy Value, R	Neutral Axis, ρ (mm)
Thickness 1 mm						
0	20.9437	167.9456	0.09173	0.3384	0.5434	1.414213
45	20.5303	166.1893	0.09904	0.3019	0.4515	1.414213
90	23.1597	175.8715	0.09180	0.3484	0.5727	1.414213
average	21.5446	170.0021	0.09419	0.3296	0.5225	1.414213
Thickness 2 mm						
0	14.7767	126.2659	0.05908	0.3429	0.5808	1.73205
45	15.2591	127.4117	0.07498	0.4302	0.8999	1.73205
90	15.5142	130.3673	0.08870	0.4243	0.9191	1.73205
average	15.1971	128.0150	0.07328	0.3991	0.7999	1.73205
Thickness 3 mm						
0	13.6050	153.939	0.11647	0.3915	0.7611	2
45	13.9167	145.079	0.11709	0.3702	0.7178	2
90	12.0720	143.935	0.12786	0.4048	0.9145	2
average	13.6447	147.651	0.11502	0.3888	0.7978	2

Table 4.1 above is the result from tensile test that has been conducted. All of the Young modulus is in error where the value of Young modulus, poisson ratio, strain hardening exponent should be 69 GPa, 0.33 and 0.242 respectively, according to the literature review. So, the data of young modulus, anisotropy value, poisson ratio and strain hardening exponent cannot be use since the data is error and it is replace with the standard value through the literature review. But, the anisotropy value cannot be replaced since it did not have the exact value. The modified data is shown in Table 4.2.

Table 4.2: Modified tensile data

Thickness (mm)	Young's Modulus (GPa)	UTS (MPa)	Strain Hardening Exponent, n	Poisson's Ratio, v	Neutral Axis, ρ (mm)
1	69	170.0021	0.242	0.33	1.414213
2	69	128.0150	0.242	0.33	1.73205
3	69	147.651	0.242	0.33	2

4.3 Analytical Method

In this subchapter, the results of the two equations, Leu D.K. equation and Fei and Hodgson equation is arranged properly and the comparison between these two different equations also studied to determine the validity for both equations. Some of mechanical data have already determined by the tensile test results are not mentioned in this subchapter. Noted that the outer radius is not effected where the outer radius is concerned only the punch tip radius and thickness of materials.

4.3.1 Leu D.K. Equation

From the equation of Leu D.K, it already considering the influence of thickness, anisotropy and the strain hardening exponent value but, since the anisotropy value cannot determine from the tensile test, the anisotropy value is not consider in this analytical process. So, the equation is changed to

$$\frac{\Delta\theta}{\theta} = \frac{UTS}{e^{-n}n^{n}} \times \frac{3(1-v^2)}{2E(1+n)} \times \left(\frac{t}{2\rho}\right)^{n-1} \qquad (9)$$

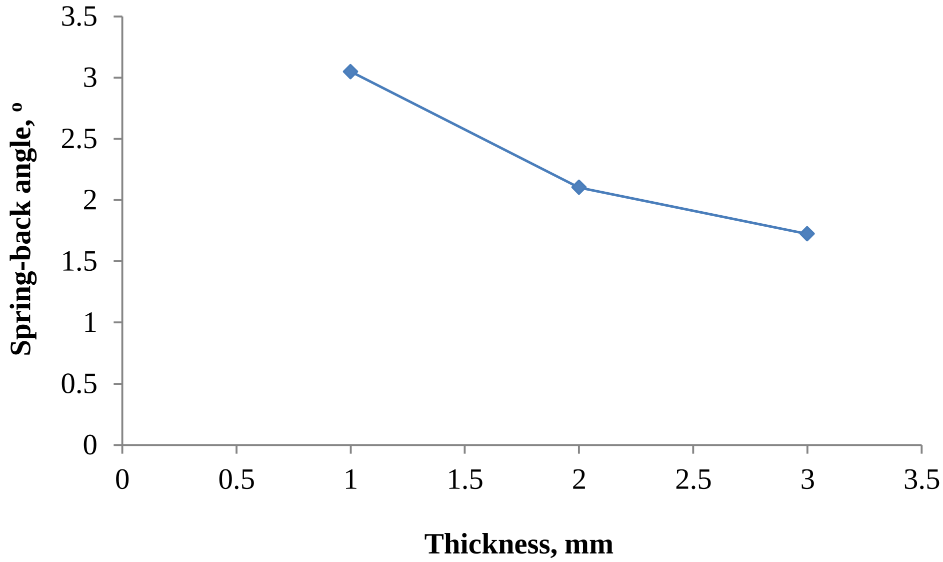


Figure 4.1: Spring-back of Leu D.K equation

From the Figure 4.1, the 1 mm of thickness has the highest value of spring-back compare with the 2 mm and 3mm as the lowest. This means an increasing of thickness is reducing the spring-back since the graph pattern is decline and the range of spring-back value is from 1.72^o to 3.05^o.

4.3.2 Fei and Hodgson Equation

In this equation, the same data with the Leu D.K equation are use but it has a different style where they are not considering the anisotropy value. But, as an additional, the width of die, 16 mm is added to determine the spring-back value. The comparison result between these two equations will be covered in this subchapter.

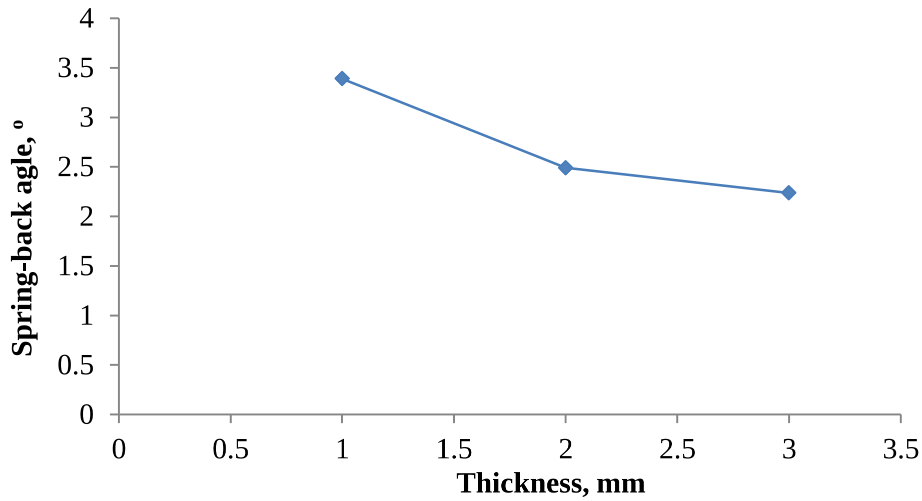


Figure 4.2: Spring-back of Fei& Hodgson equation

From the Figure 4.2, 1 mm has a largest amount of spring-back follow by the 2 mm and the lowest, is 3 mm. This result also producing the same decline graph pattern with Leu D.K equation result where the spring-back value is effected by the increasing value in thickness.

4.3.3 Comparison of Two Equations

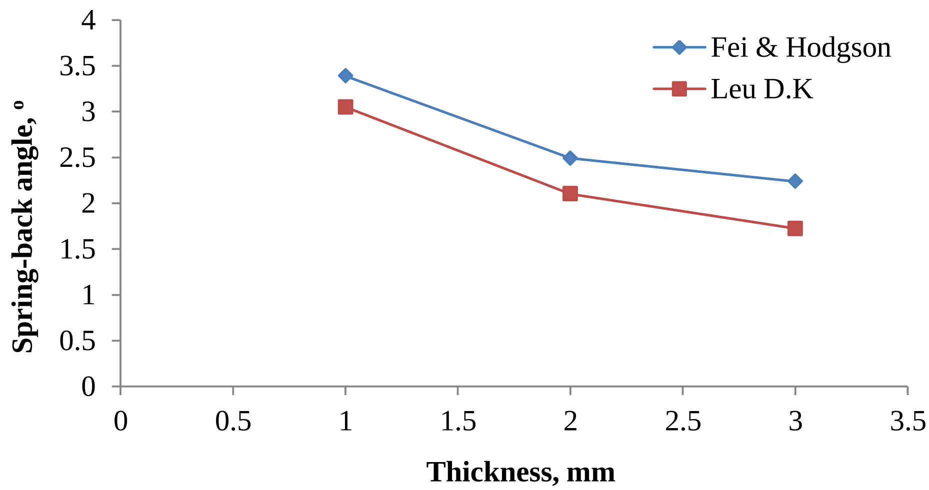


Figure 4.3: Comparison of two equations

Through the Figure 4.3, the Fei and Hodgson equation has higher value than the Leu D.K. equation. Between these two equations, it has a similarity where there are decreasing spring-back while increasing the thickness. But, since Fei and Hodgson equation did not include the strain hardening exponent, the spring-back is larger than Leu equation. This means of considering the strain hardening exponent, the spring-back will be decreased a little bit and by increasing thickness, the spring-back amount is reduced. The difference of both equations is in a range 11% to 29%. Since there did not have much different, both of calculation can be used in calculating spring-back angle.

4.4 Experimental Method

In this subchapter, it will explain through the bending result for 1, 2, and 3 mm of aluminum sheet metal. Completed the v-bending experimental, all of the specimens are scanned through the computer scanner and the analysis are going through by using the SOLIDWORK software. The spring-back value will be revealed for each is shown in this study. Either the orientation iseffecting the spring-back value, it will explain more in this subchapter. Below is shown some specimens of v-bending with different rolling direction that already measured the angle.

4.4.1 Aluminum 1 mm

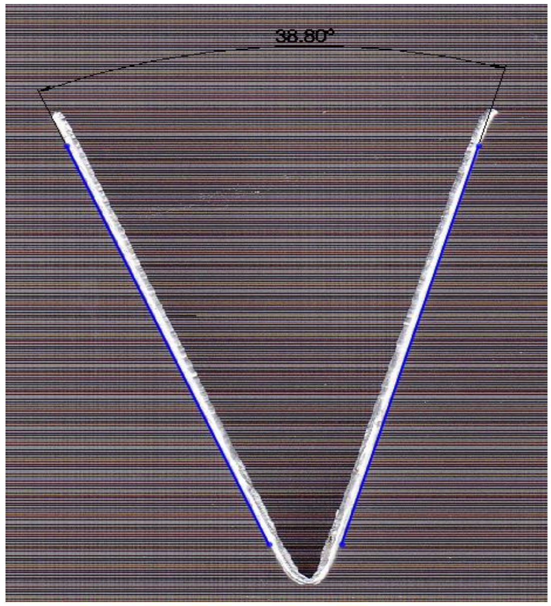


Figure 4.4: Aluminum with angle of 0^o

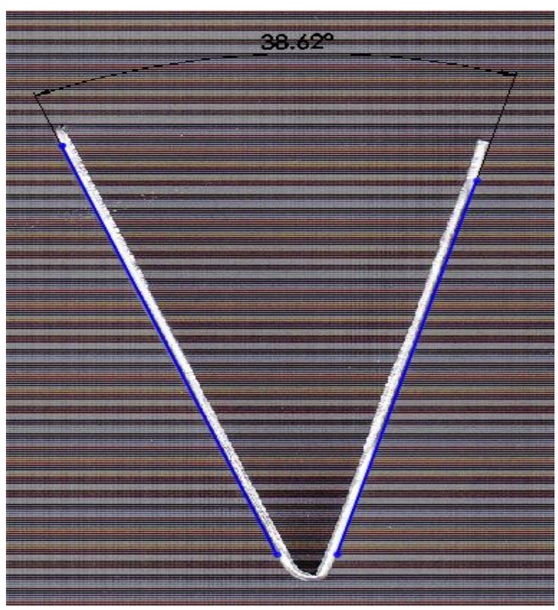


Figure 4.5: Aluminum with angle of 45^o

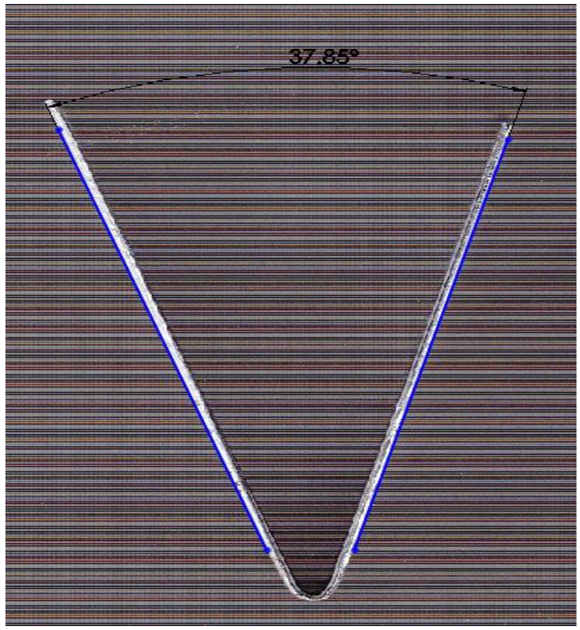


Figure 4.6: Aluminum with angle of 90^o

Figure 4.4 shows the bending angle of some specimen for 1 mm aluminum sheet metal with different orientations. The value for specimen 1 mm 0^o is 38.80^o and the spring-back value for this specimen is 8.80^o. Differ with 1 mm 45^o, the result of spring-back is decreasing where the value of the spring-back is 8.62^o. This means the 45^o of orientation has a large amount of spring-back than the 0^o. Also, the aluminum 1 mm 90^o in Figure 4.6 has a lower value than 0^{o}and 45^{o}where the bending angle value of this specimen is 37.85^o and the spring-back value is 7.85. The differential of the highest and the lowest value of spring-back is 0.95^o. For all this specimen, it proves that a larger orientation of rolling direction decreases the spring-back.

The specimen for 1 mm aluminum is 5 for each different orientation. Then, figure 4.7 is shown the result for total specimen for each different orientation.

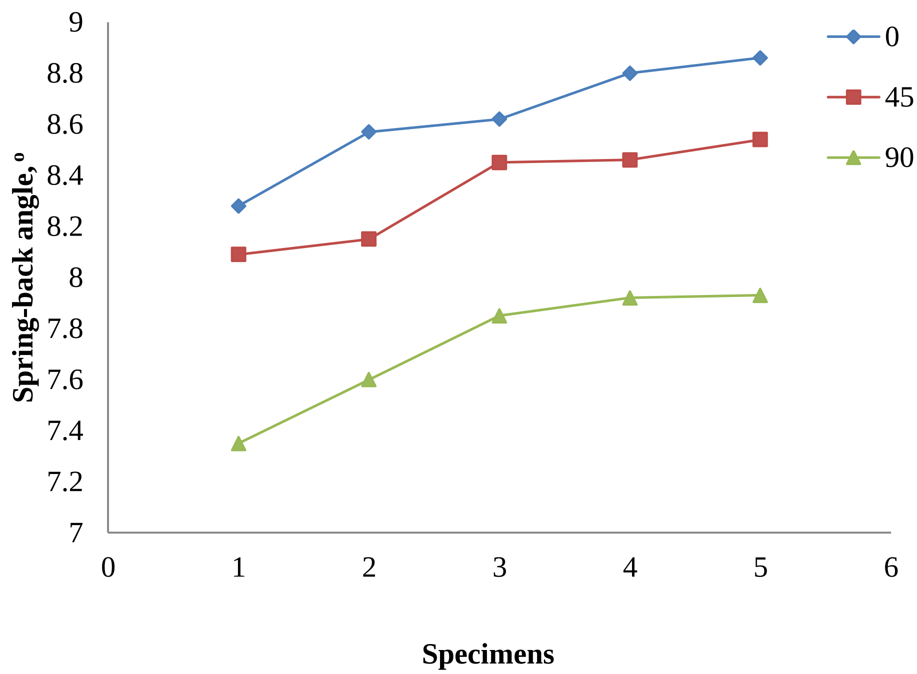


Figure 4.7: Total value of spring-back for 1 mm of aluminum sheet metal

Figure 4.7 above shows the spring-back values of 1mm aluminum sheet metal. The average value for 0^o orientation has the amount of spring-back with 8.626^o compare with the 45^o, 8.338^o and the 90^o, 7.70^o. 0.926^o is the differential value for the highest and the lowest value where it is nearly similar to the single sample as before. This concludes that the 0^o have the highest spring-back value while the 45^o is in the middle and the 90^o has the lowest amount of spring-back where increasing the rolling direction angle will decrease the spring-back. Also, finding from these results, rolling direction is effected the spring-back value for 1 mm aluminum sheet metal.

4.4.2 Aluminum 2 mm

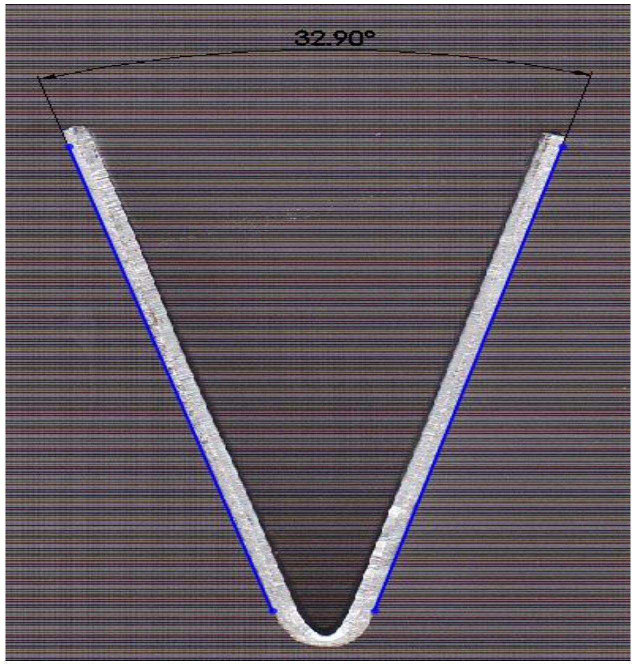


Figure 4.8: Aluminum with angle 0^o

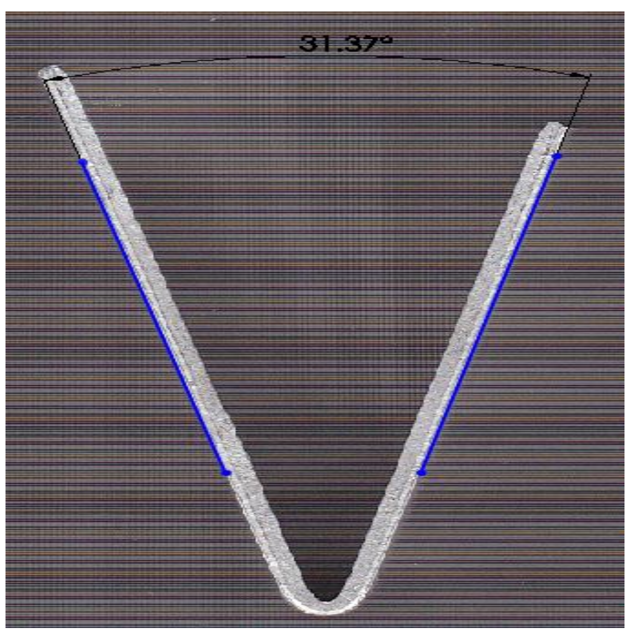


Figure 4.9: Aluminum with angle 45^o

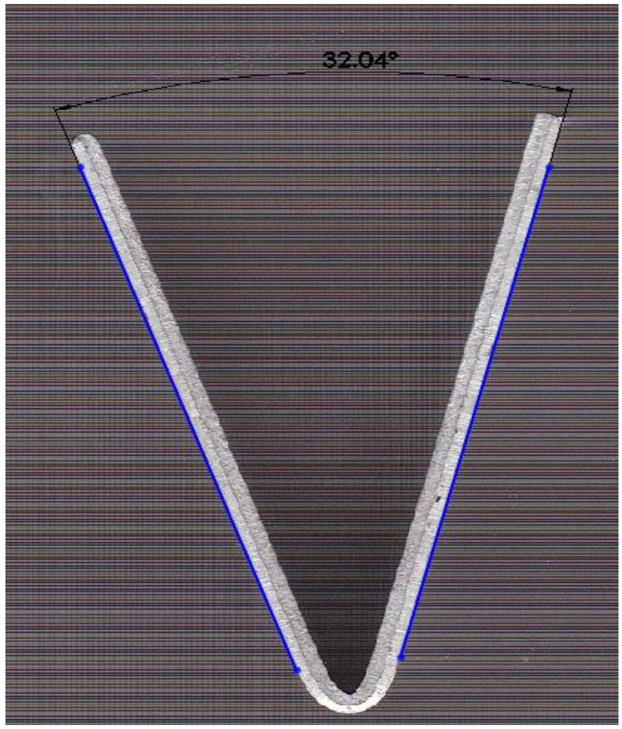


Figure 4.10: Aluminum with angle 90^o

Figure 4.8, 4.9, and 4.10 are shows the single result for aluminum 2 mm for 0^o, 45^o, and 90^o. The 0^o has the 32.90^o for the bending angle. Then, 45^o has 31.37^o and 32.04^o for the 90^o orientation. This means the 0^o orientation still has the highest value for two millimeter of sheet metal thickness. The difference value of the higher and the lowest is 0.86^o, nearly similar with the 1 mm differences value where it is a small amount of the spring-back.

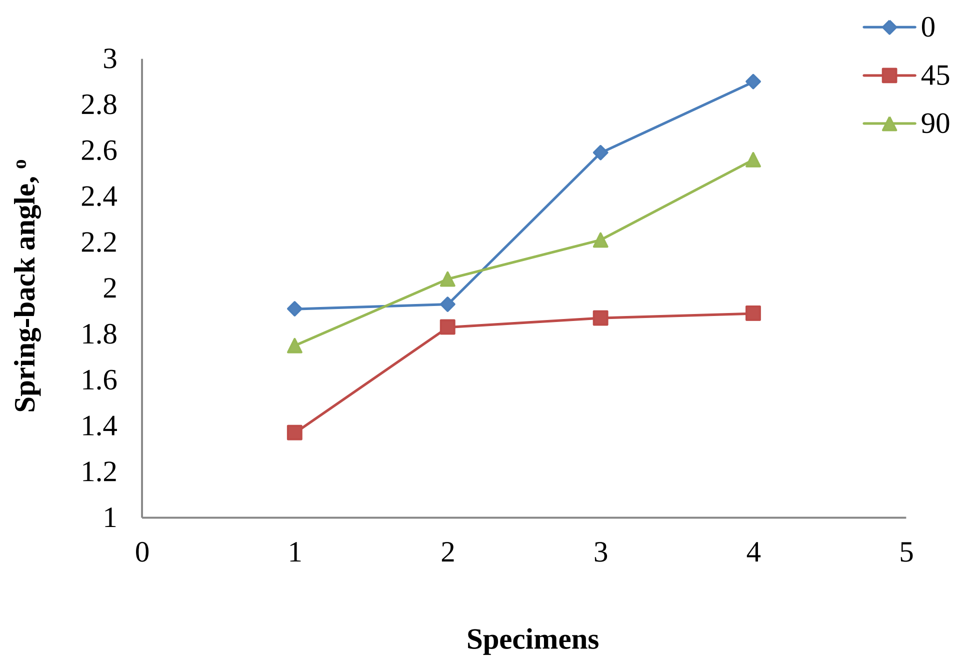


Figure 4.11: Total value of spring-back for 2 mm aluminum sheet metal

Figure 4.11 shows the result of spring-back for the 2 mm aluminum sheet metal where the 0^{o} of orientation has the average value of 2.3325^{o}, 45^{o} with the average value 1.74^{o} and the 90^{o} has the average value 2.14^{o}. These results show the 0^{o} orientation still the highest in amount of spring-back same with the 1 mm result. But, it has a different result from 1 mm where the 45^{o} orientation is the lowest amount of spring-back. For the specimen 2, the 0^{o} specimen is lower than the 90^{o} where it not consistence with the others. This is causing of the time of punching and the force applied on the bending process. Since the punch of press brake machine is controls by using paddle press, the force is not consistence and this will effecting the spring-back appearance in this experiment. The difference value for the highest average value and the lowest value is 0.19^{o} and this amount is very small compare with the 1 mm differences value. It still can conclude that the orientation is effecting the spring-back value where the 0^{o} is has the larger amount of spring-back.

4.4.3 Aluminum 3 mm

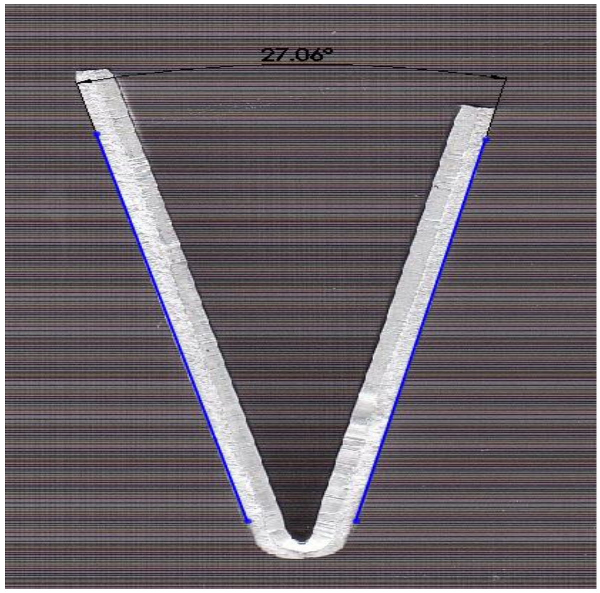


Figure 4.12: Aluminum with angle of 0^o

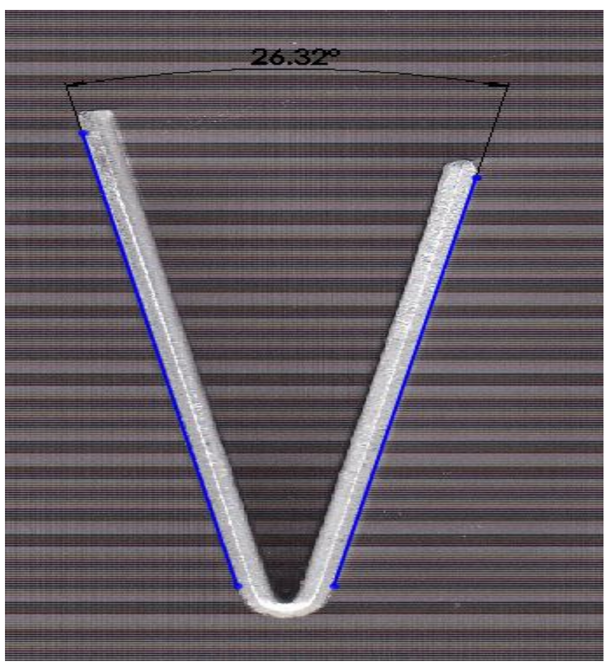


Figure 4.13: Aluminum with angle 45^o

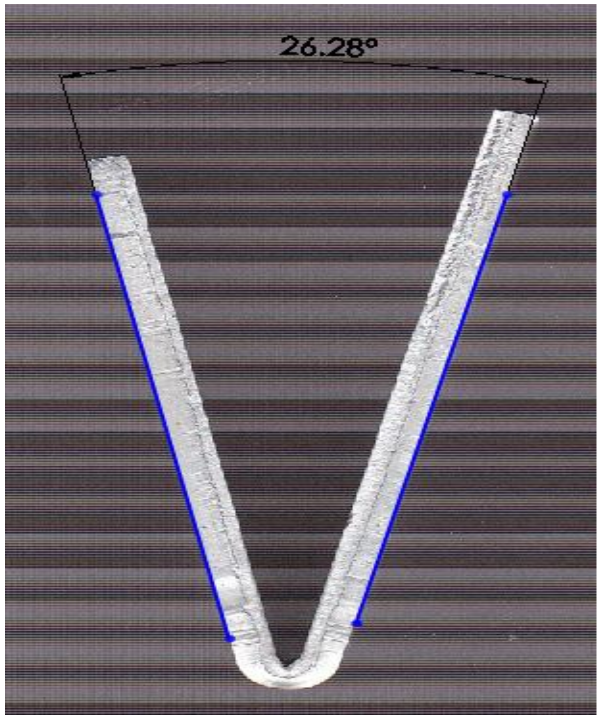


Figure 4.14: Aluminum angle of 90^o

Figure 4.12, 4.13, and 4.14 above shows the single result for 3 mm thickness of aluminum sheet metal. 0^o has the amount of 27.06^o while the 45^o orientation has 26.32^o and 26.28^o for the 90^o orientation. For this result, the spring-back is not appearing in this 3 mm aluminum sheet metal bending. Since the value of spring-back is negative, this phenomenon is called spring-go where the result is lower than bending angle. Related with the single results, the 0^o specimen still has the large value of the bending angle, the 45^o is in the middle and the lowest is the 90^o.

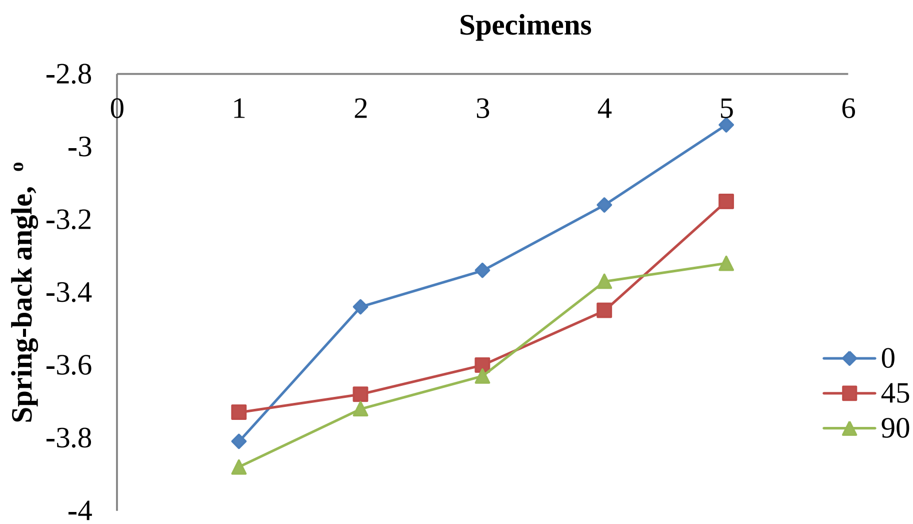


Figure 4.15: Total value of spring-go for 3 mm aluminum sheet metal

Figure 4.15 shows the result for the bending angle and the spring-go for each specimen. The average result shows that the 0^o has the highest value of bending angle, 26.662^o and the lowest value of the spring-go, 3.338^o. Different with the 0^o, the 90^o specimens has the lowest value for bending angle and the highest value for spring-go. The 45^o is still in the middle range with 26.478^o for bending angle and 3.522^o for spring-go value. The difference value of spring-go is 0.246^o and this value is small. There have 2 out of range points, the 0^o for the first specimen and 90^o for the fourth specimen. This is causing of the force and punching time. The first causes of this outrange result is the machine where it is already discuss in 2 mm defect.

Second, it is causing by punching time where while the punching process, the punching time is not constant. The punch is release after the bending process is reaching the bottom of die. But, some specimens did not reach this method since the punch is stuck with the die and it takes a time to release the punch. These results are represent the large rolling direction will decrease the spring-go appearance. The spring-go is appear in this thickness cause by the material characteristic where the crack is appear at outer radius of the specimens. So, the specimens cannot hold the material structure and it already pass the elastic region of the aluminum.

4.4.4 Comparison of Different Thickness

The comparison for each specimen is discuss through this chapter. Below is the comparison between the 1, 2 and 3 mm result.

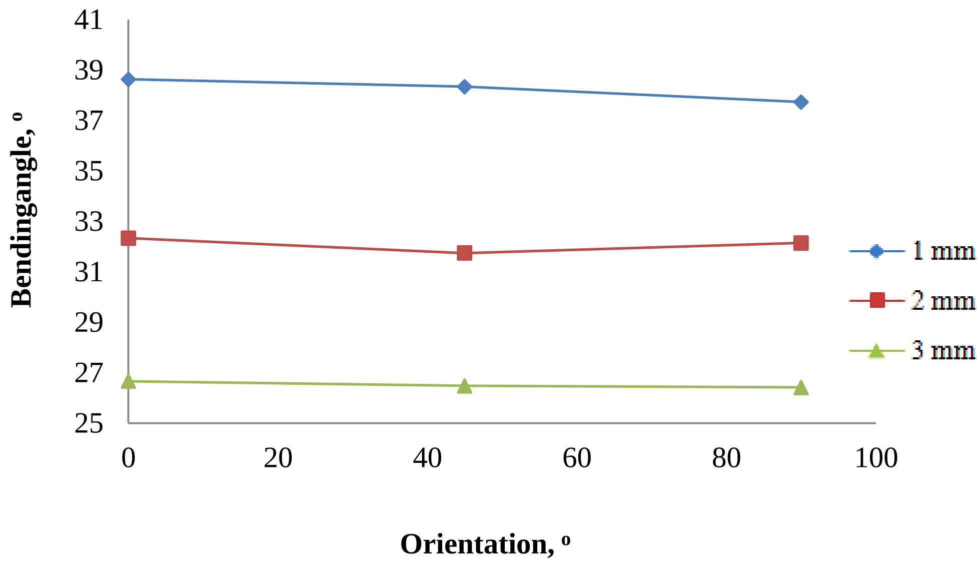


Figure 4.16: Bending angle of 1, 2 and 3 mm for aluminum sheet metal

Figure 4.16 above shows the average value for each thickness with different orientation for 1, 2 and 3 mm for aluminum sheet metal. As 30^{o} is the reference angle, the result is show to find the different between each specimen. The 1 mm thickness has the highest bending angle with the range of average 37.73^{o} to 38.626^{o}. The 2 mm thickness has the best bending angle with 31.74^{o} to 32.33^{o} and the 3 mm of aluminum specimens shows the result below than the reference angle with 26.416^{o} to 26.662^{o}.

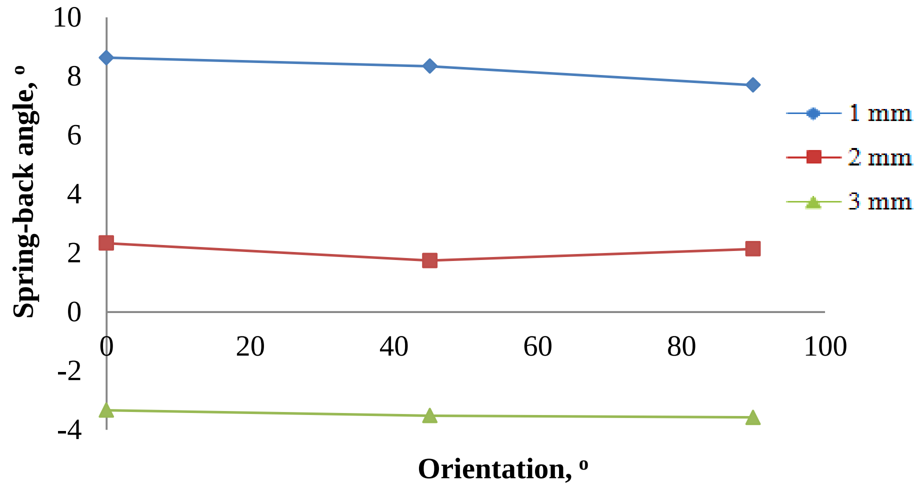


Figure 4.17: Spring-back value for 1, 2 and 3 mm for aluminum sheet metal

Figure 4.17 above shows the 1mm aluminum has the highest spring-back value than 2 mm & 3 mm. The spring-back is higher in the thin sheet metal because of the elastic characteristic of the material. 1 mm has a larger Modulus of Elasticity follows by 2 mm and 3 mm. The negative value for a 3 mm result means the 3 mm thickness is in spring-go condition. Since the thickness is increased, the elastic characteristic will be reduced and the hardness characteristic is increasing. This also will cause the crack on the material if the material thickness is increasing. Through the results of experiments, it can be said that increasing thickness sheet metal of aluminum will decrease the spring-back value.

4.5 Comparison of Different Method

Table 4.3: Average spring-back of three different methods

Thickness, mm	Experiment	D.K Leu	Fei& Hodgson
1	8.2213	3.0489	3.3902
2	2.0708	2.1023	2.4913
3	-3.4813	1.7241	2.2374

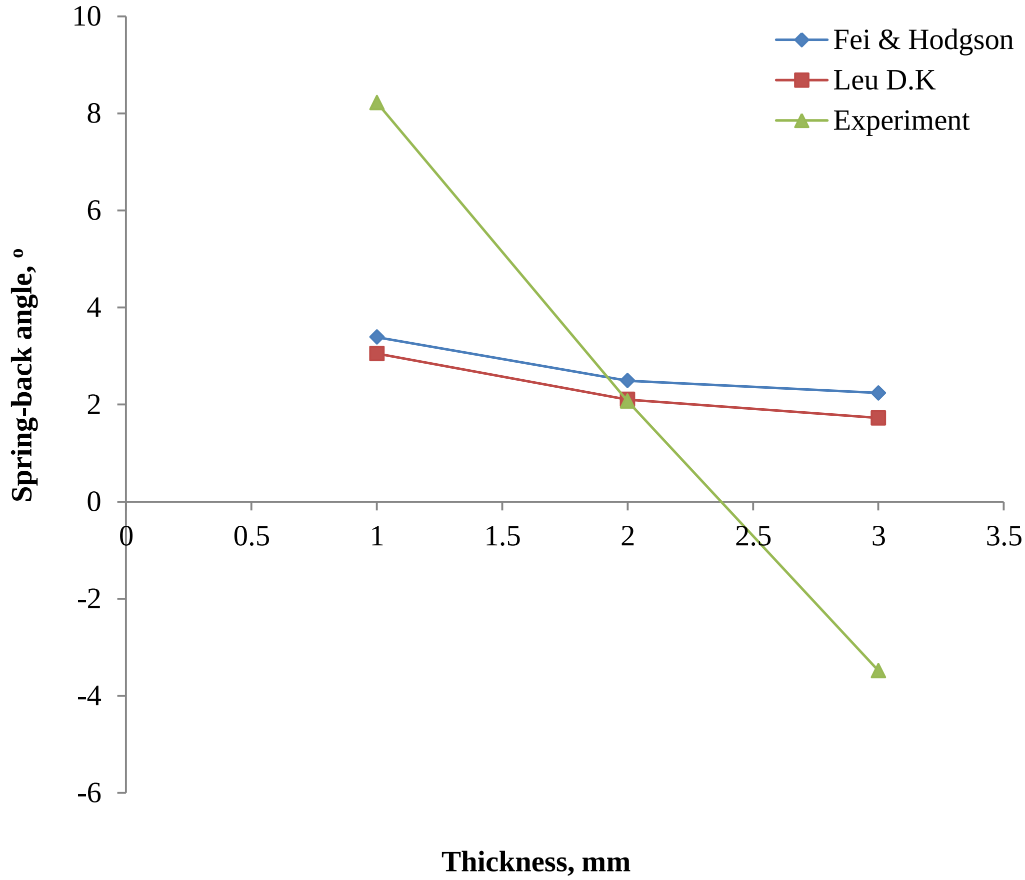


Figure 4.18: Comparison of different methods

Through the Figure 4.18, comparison of three different methods is discussed. The experimental results has a large spring-back value for the 1 mm compare with the two analytical methods, Leu D.K equation and Fei and Hodgson equation. It is also same with the result of 3 mm where it is a large difference between the analytical methods and experiment. The analytical method has a same result with the experimental in 1 mm and 2 mm where increasing the thickness means the spring-back value is decrease. Refer with the experiment results, it is found that larger rolling direction is decreasing spring-back value. Also, the spring-go is appear in 3 mm specimens because the crack is happened on the outer radius and this

4.6 Sheet Metal Condition After Bending

After the bending process, the bottom of the bended material will be changed phase. The effects of the bending process on the materials are shown in this chapter to expose the condition of the material between different thickness and orientation for aluminum sheet metal. The specimens are scan through the computer scanner and it all saved in JPEG type.

4.6.1 Aluminum 1 mm

Refer with the Figure 4.19, 4.20 and 4.21 below, the condition of the sheet metal for 1 mm thickness is fissure for all orientations. But, on the 90^o specimen, the fissure is apparent more than the others. This happened since the 90^o direction is same with the bending direction. Although the 90^o has the highest value of Young Modulus and the 45^o has the lowest modulus for 1 mm thickness, the possibility for the crack to happen is the material grain structure. So, the crack is easier to happen in 90^o orientation.

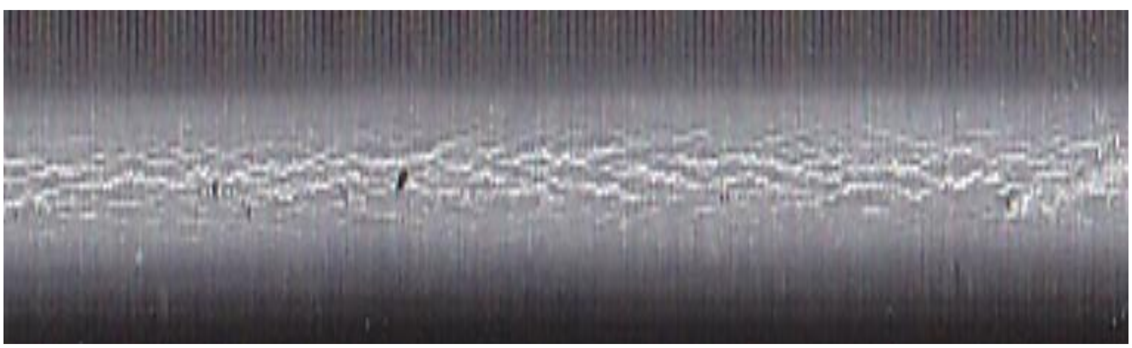


Figure 4.19: Material condition for 1 mm with angle of 0^o

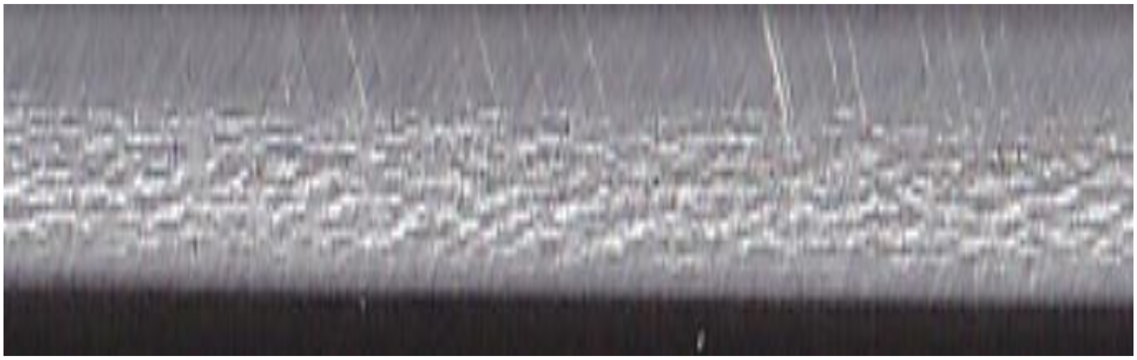


Figure 4.20: Material condition for 1 mm with angle of 45^o

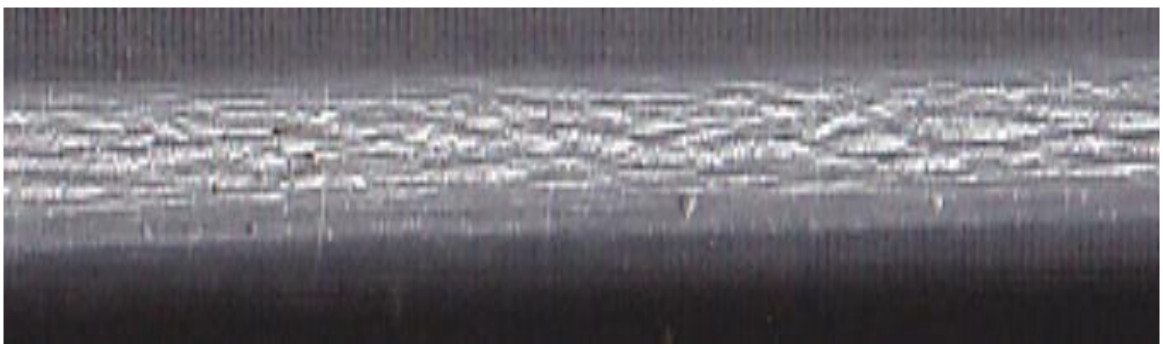


Figure 4.21: Material condition for 1 mm with angle of 90^o

4.6.2 Aluminum 2 mm

Figure 4.22, 4.23 and 4.24 shows the different result for the bottom condition of the specimen. The crack did not happen in this thickness although the modulus of elasticity value is lower than 1 mm thickness. Referring to the spring-back results, this thickness has a lower value in spring-back and this proves why the crack did not happen in this thickness.

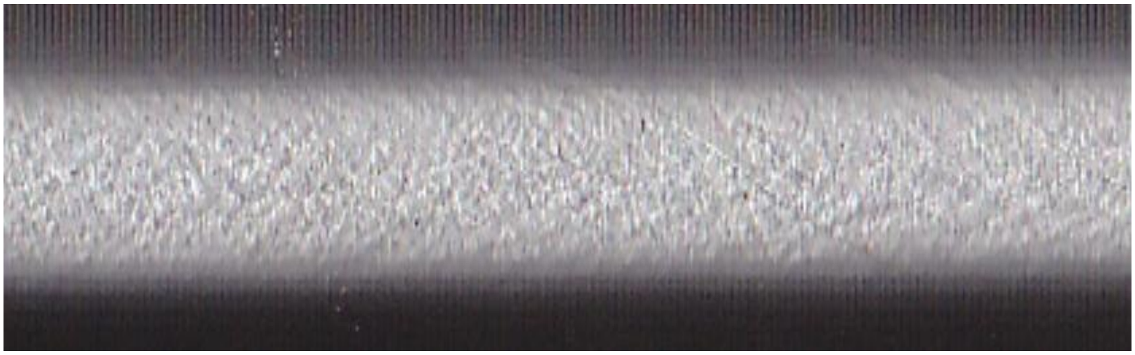


Figure 4.22: Material condition for 2 mm with angle of 0^o

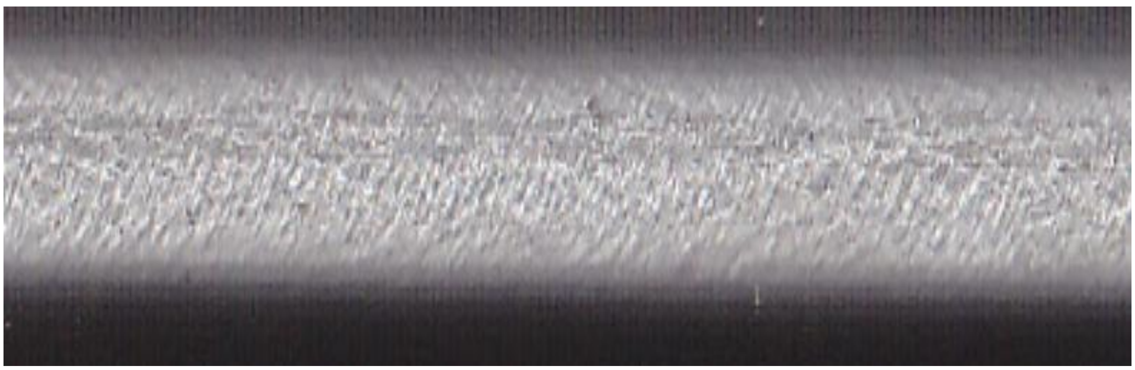


Figure 4.23: Material condition for 2 mm with angle of 45^o

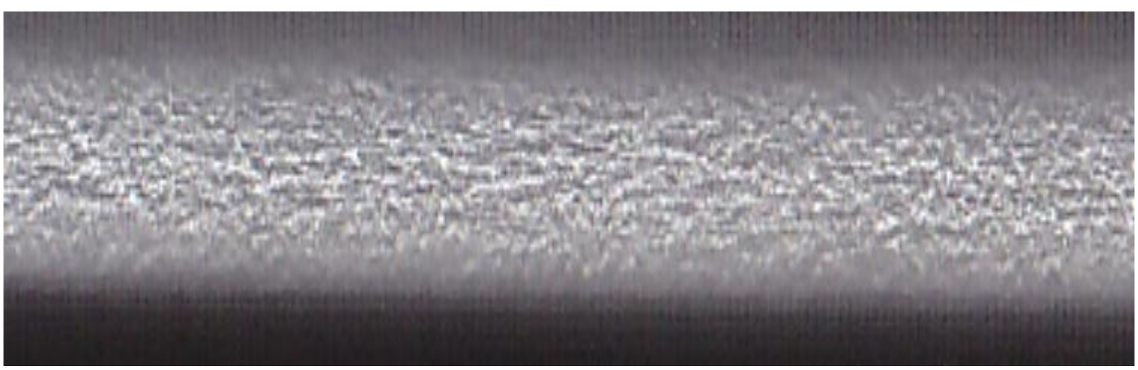


Figure 4.24: Material condition for 2 mm with angle of 90^o

4.6.3 Aluminum 3 mm

From the Figure 4.25, 4.26 and 4.27, the crack is appeared in 3 mm thickness and the worst happened are in the 90^o orientation. Referring with the bending experimental result, the 3 mm has a spring-go appear. This spring-go form is proof by this crack where the material did not have enough ductility characteristic to hold the structure. Also, the tensile results are proving that the lowest modulus elasticity has the worst appearance of crack.

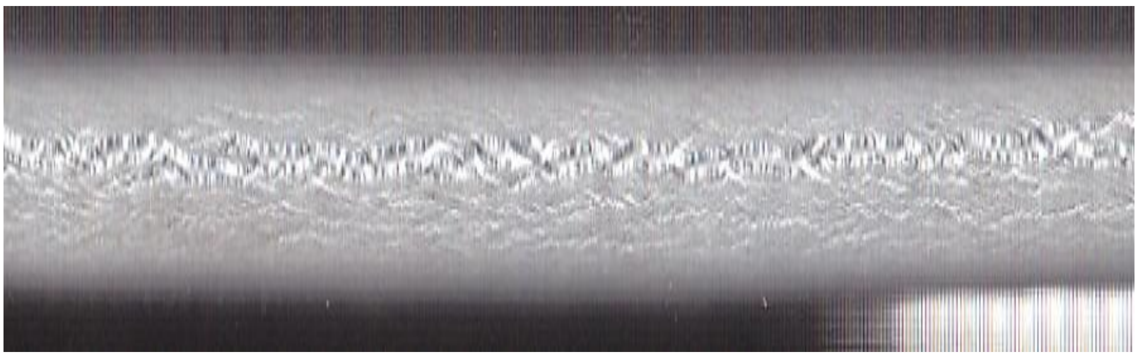


Figure 4.25: Material condition for 3 mm with angle of 0^o

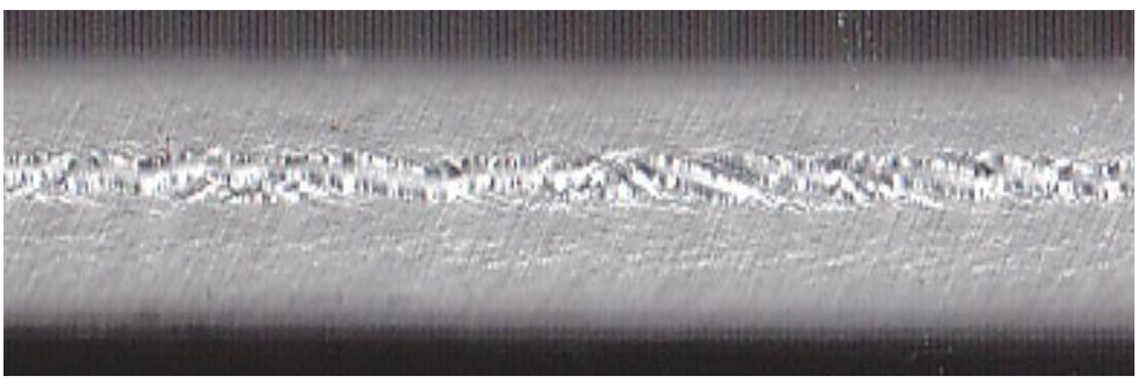


Figure 4.26: Material condition for 3 mm with angle of 45^o

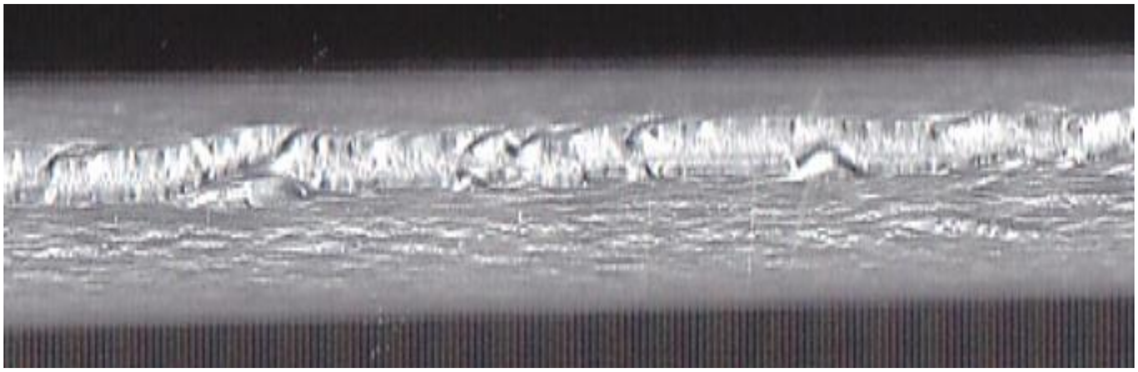


Figure 4.27: Material condition for 3 mm with angle of 90^o

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Introduction

This chapter is about the conclusion of overall study regarding from the gain results and some recommendation for the future works.

5.2 Conclusion

As the conclusion for both experimental and analytical, it can be conclude that both equation can be use in determining the spring-back value since the results for both equation did not has too much different. Also, different thickness is effecting the spring-back and found that increasing thickness is decreasing spring-back angle proves by the pattern of result from the experimental 1 and 2 mm of thickness and all results of the two methods of analytical, Leu D.K. equation and Fei and Hodgson equation. The results are agreed with the (Dilip K.K., 2010) and (Osman et al, 2010). But, for the experiment of 3 mm specimens, spring-back did not occur since the spring-go appeared. From the experiment of rolling direction, it is found that increasing rolling direction is decreasing spring-back and this result is strongly disagree with the Leu D.K., 1995 result where he found that increasing rolling direction is increasing spring-back.

5.3 Recommendation

In the future works, the other students can continue in others parameter such as the consideration of different bending angle, punch tip radius and the punching times. All these parameter can be done by using same thickness of material or in different thickness of material. Bending angle can be done by deciding 30^o, 45^o, 60^o and 90^o since our university has a different die for the different bending angle. Punching time also can be consider since holding the punch longer on the material can reduce the spring-back, Ozgur T. et.al, 2007. Students can sign 0, 10 and 20 as the punching times. Also, punching tip can be effecting the spring-back. So, by using the different punch radius such as 1 and 2 can determine the different results.

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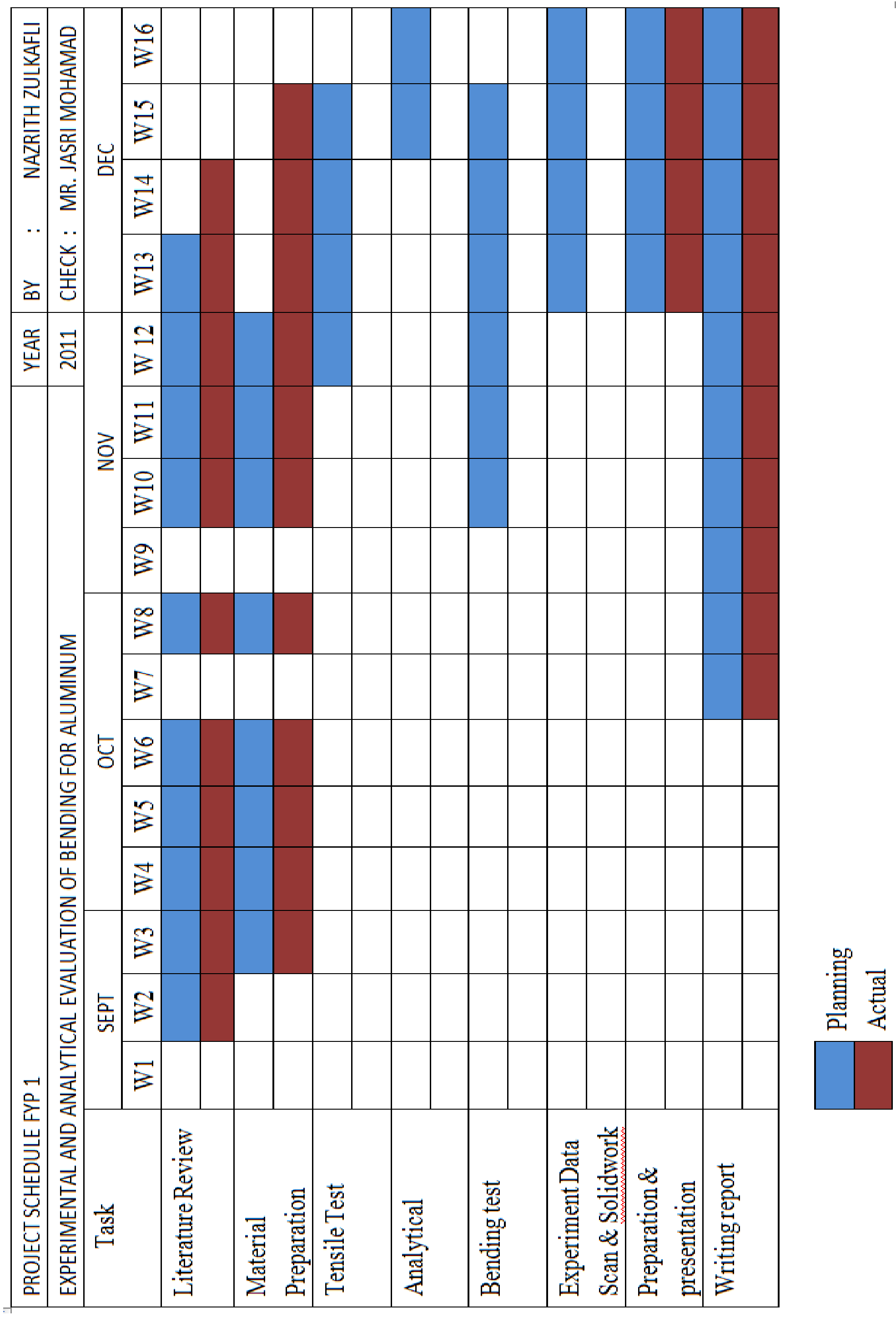
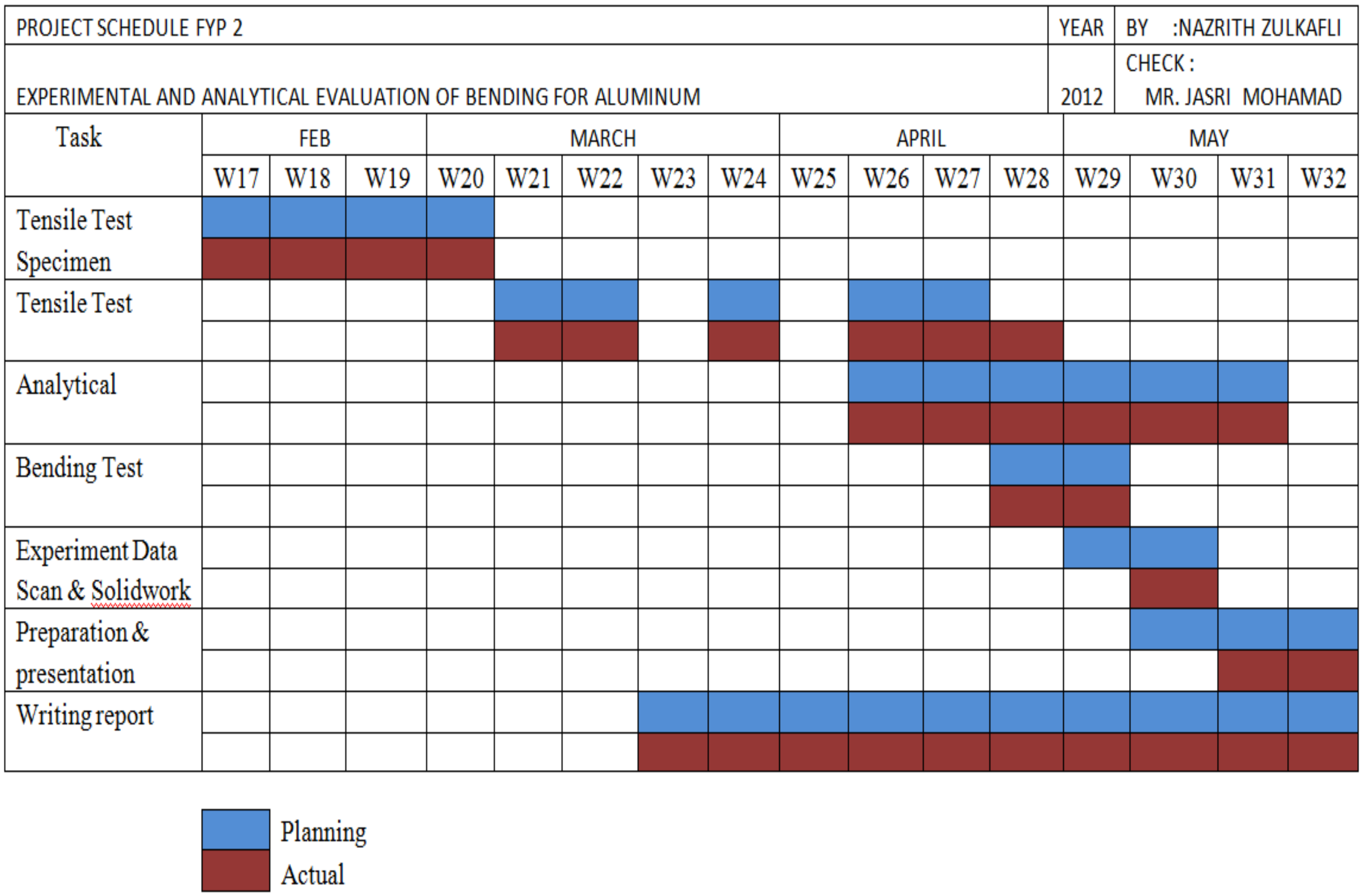
APPENDIX A – GANTT CHART




PROJECT SCHEDULE FYP 2
YEAR
BY :NAZRITH ZULKAFLI
EXPERIMENTAL AND ANALYTICAL EVALUATION OF BENDING FOR ALUMINUM
2012
CHECK :
MR. JASRI MOHAMAD
Task
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W31
W32
Tensile Test Specimen
Tensile Test
Analytical
Bending Test
Experiment Data Scan & Solidwork
Preparation & presentation
Writing report
Planning
Actual

APPENDIX B – G-CODE

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N114 Y22. F100.
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N124 G1 X30.
N126 G3 X36.324 Y12.846 R9.
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N130 X109.134
N132 G3 X117.134 Y22. R8.
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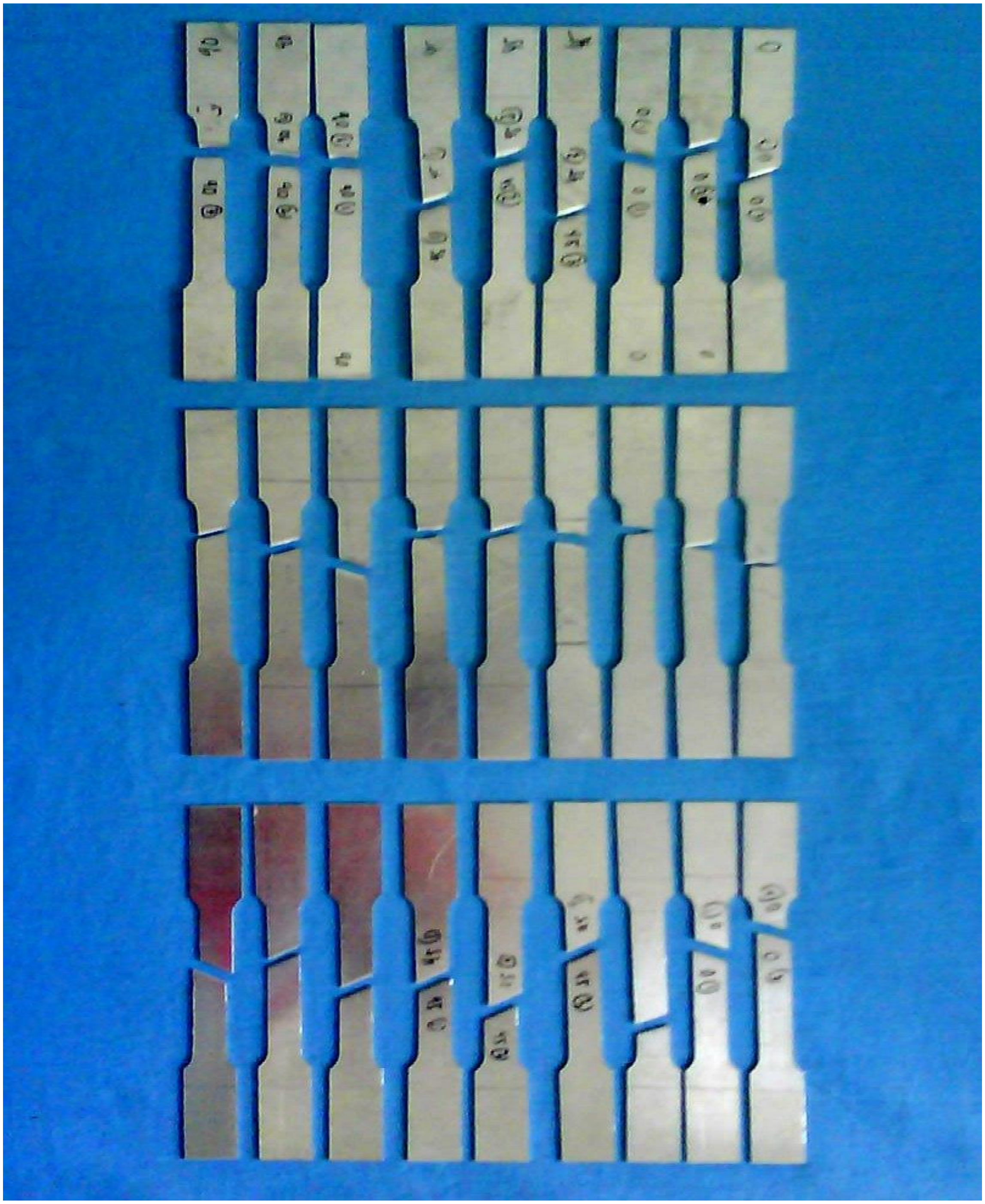
APPENDIX C1 – TENSILE SPECIMEN



APPENDIX C2 – TENSILE RESULT

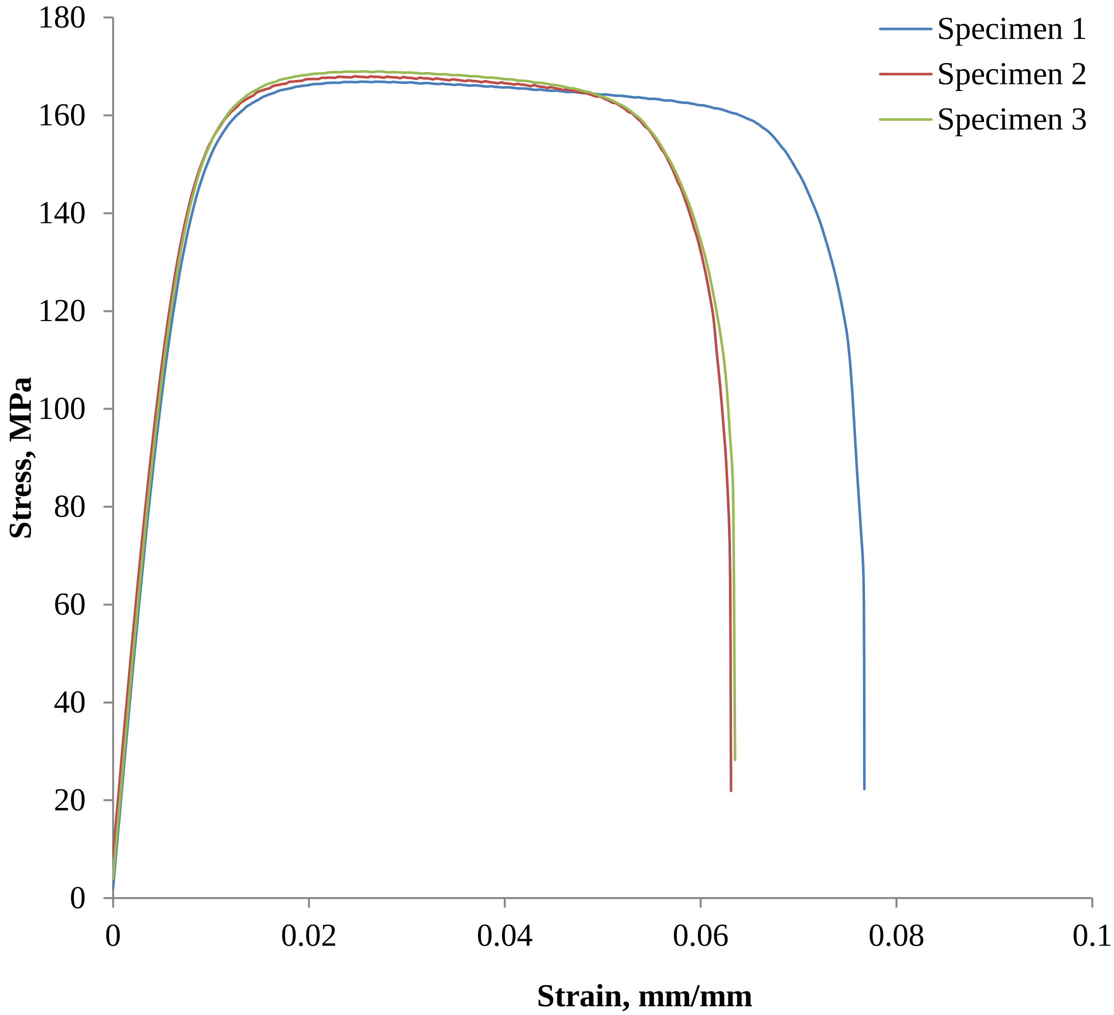


Figure 6.1: Tensile test of 1 mm 0^o

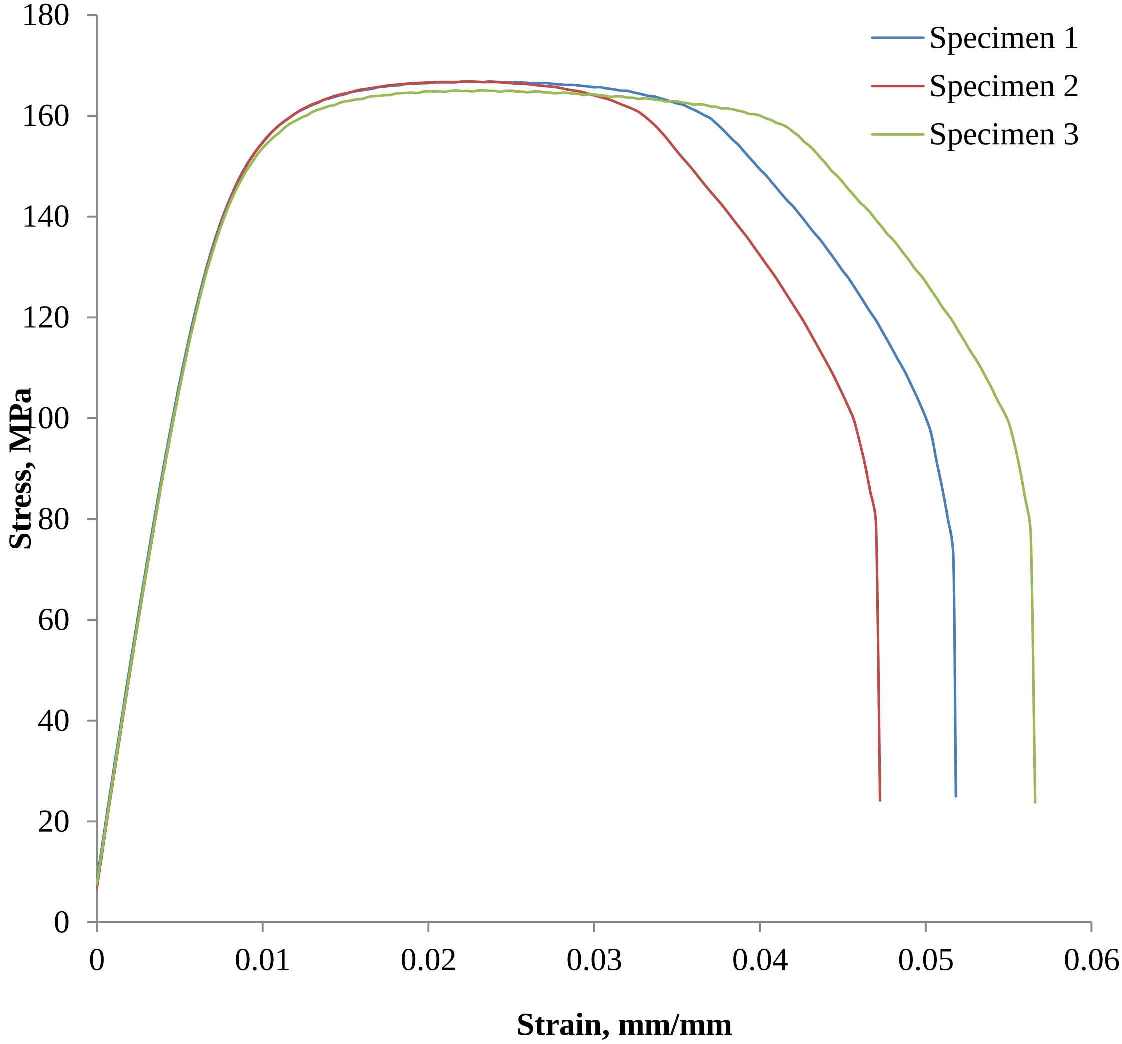


Figure 6.2: Tensile test of 1mm 45°

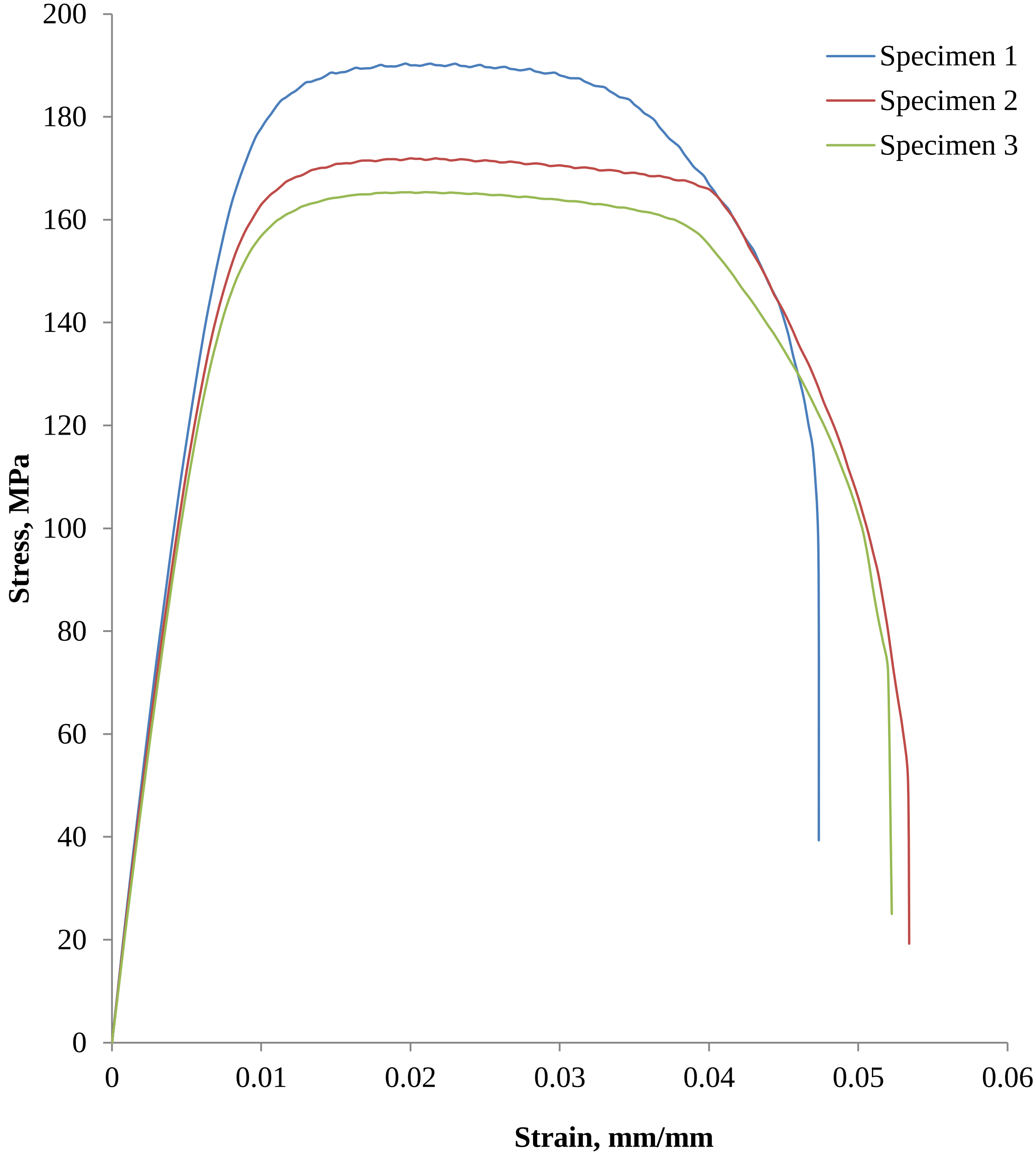


Figure 6.3: Tensile test of 1mm 90°

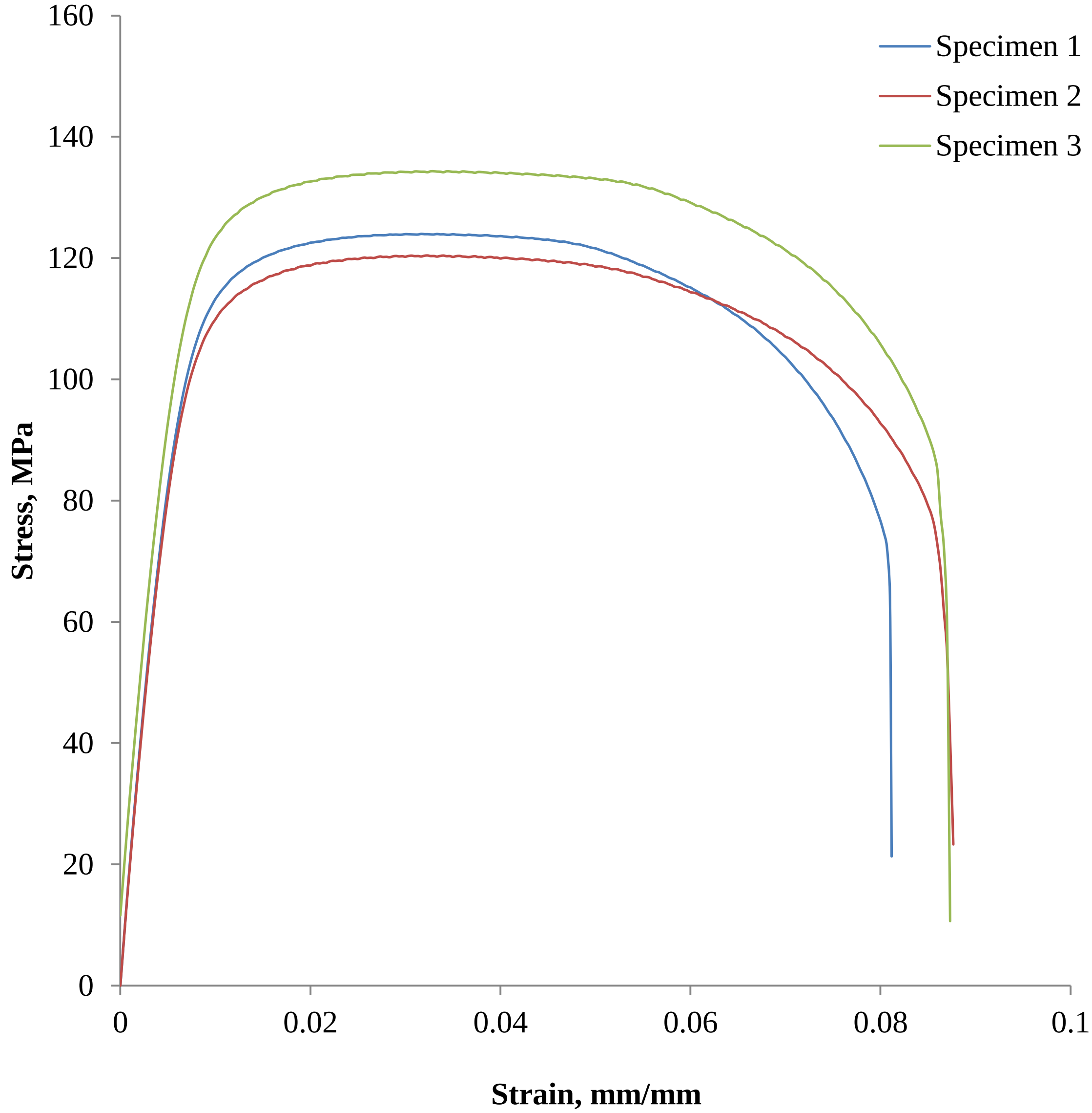


Figure 6.4: Tensile test of 2 mm 0^o

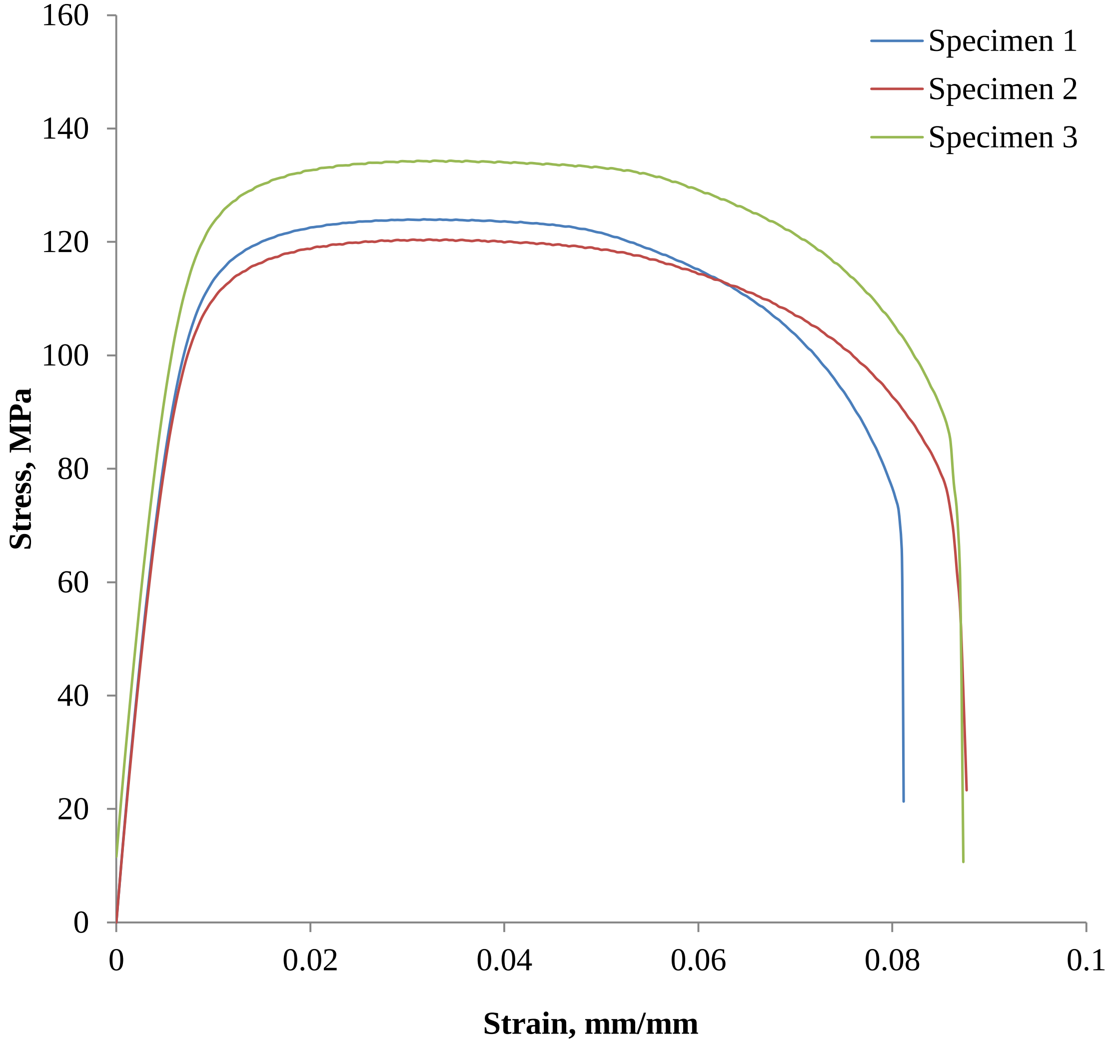


Figure 6.5: Tensile test of 2 mm 45^o

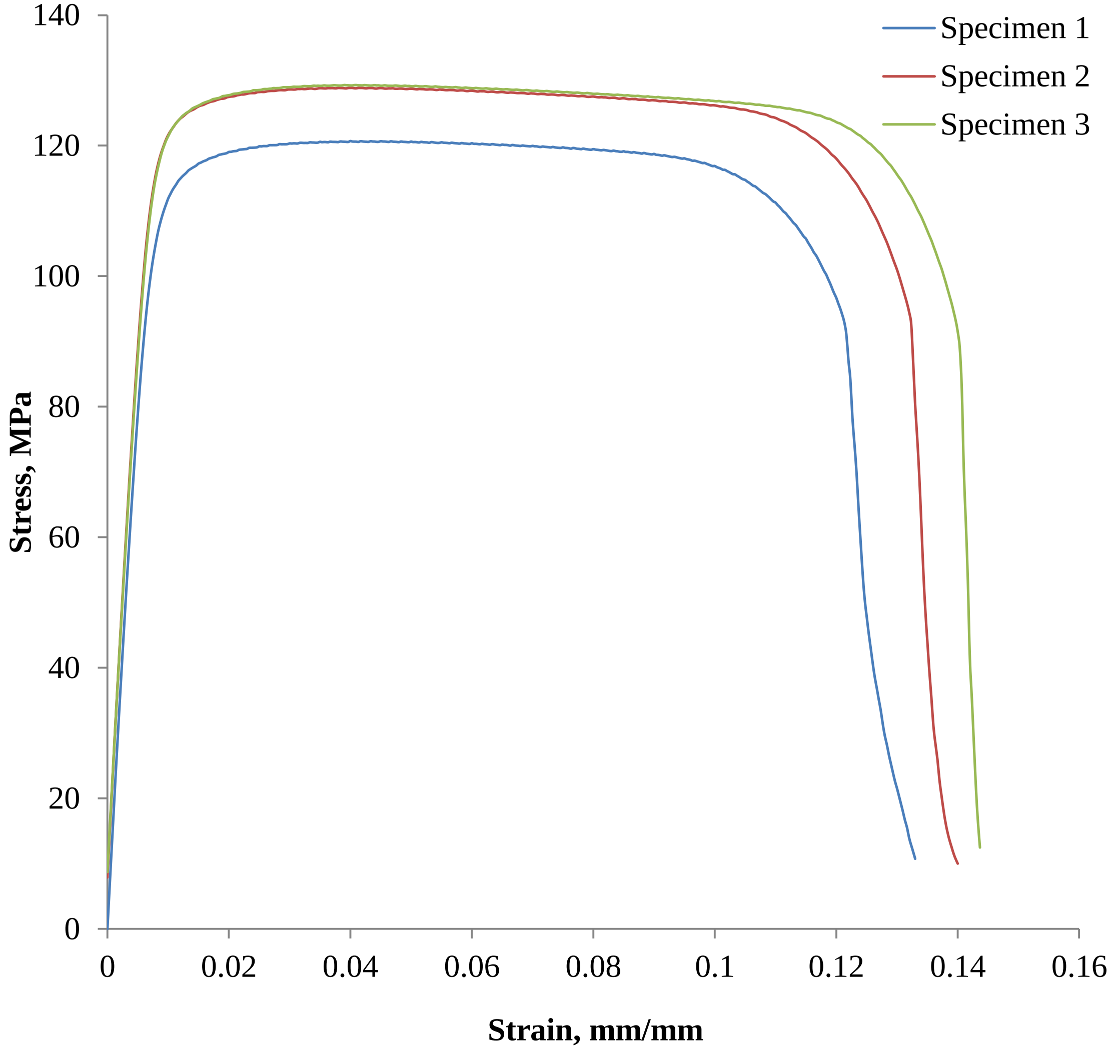


Figure 6.6: Tensile test of 2 mm 90^{o}

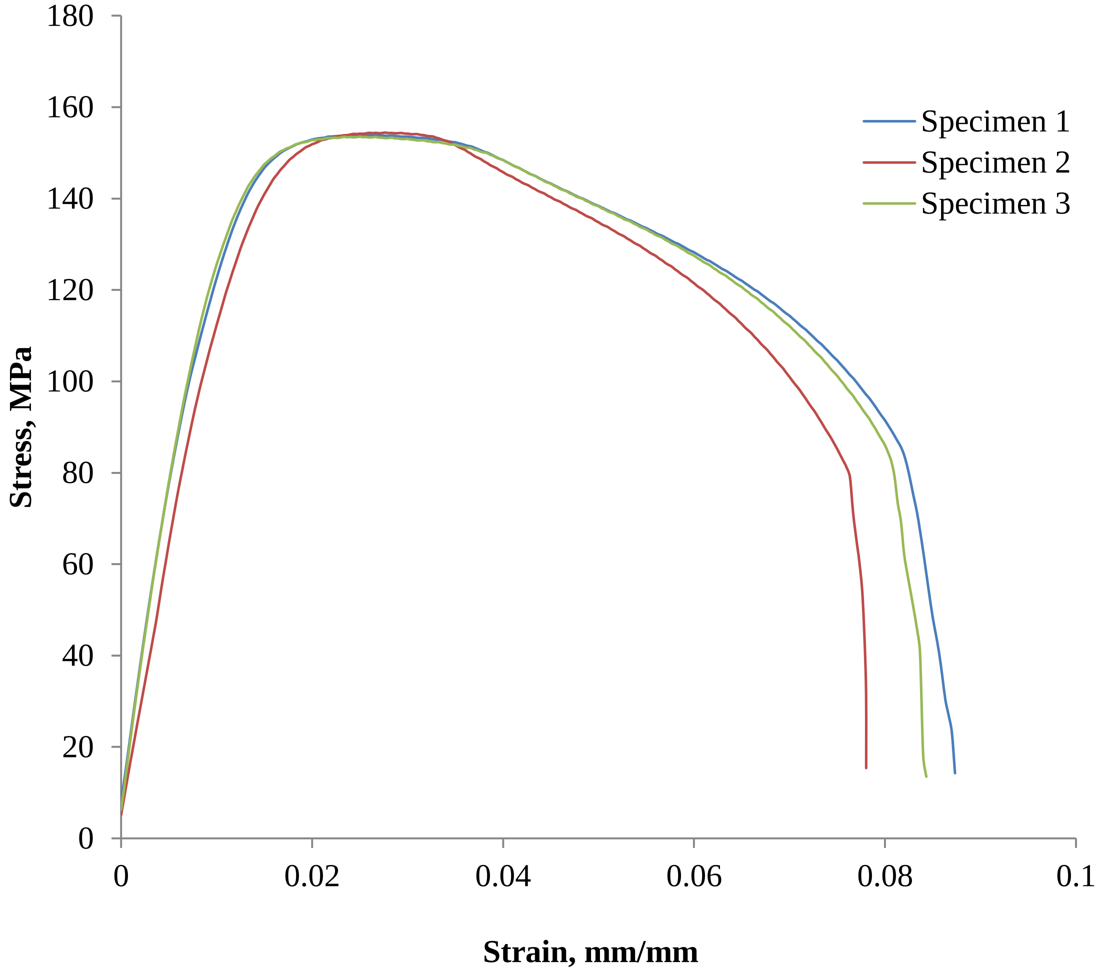


Figure 6.7: Tensile test of 3 mm 0^{o}

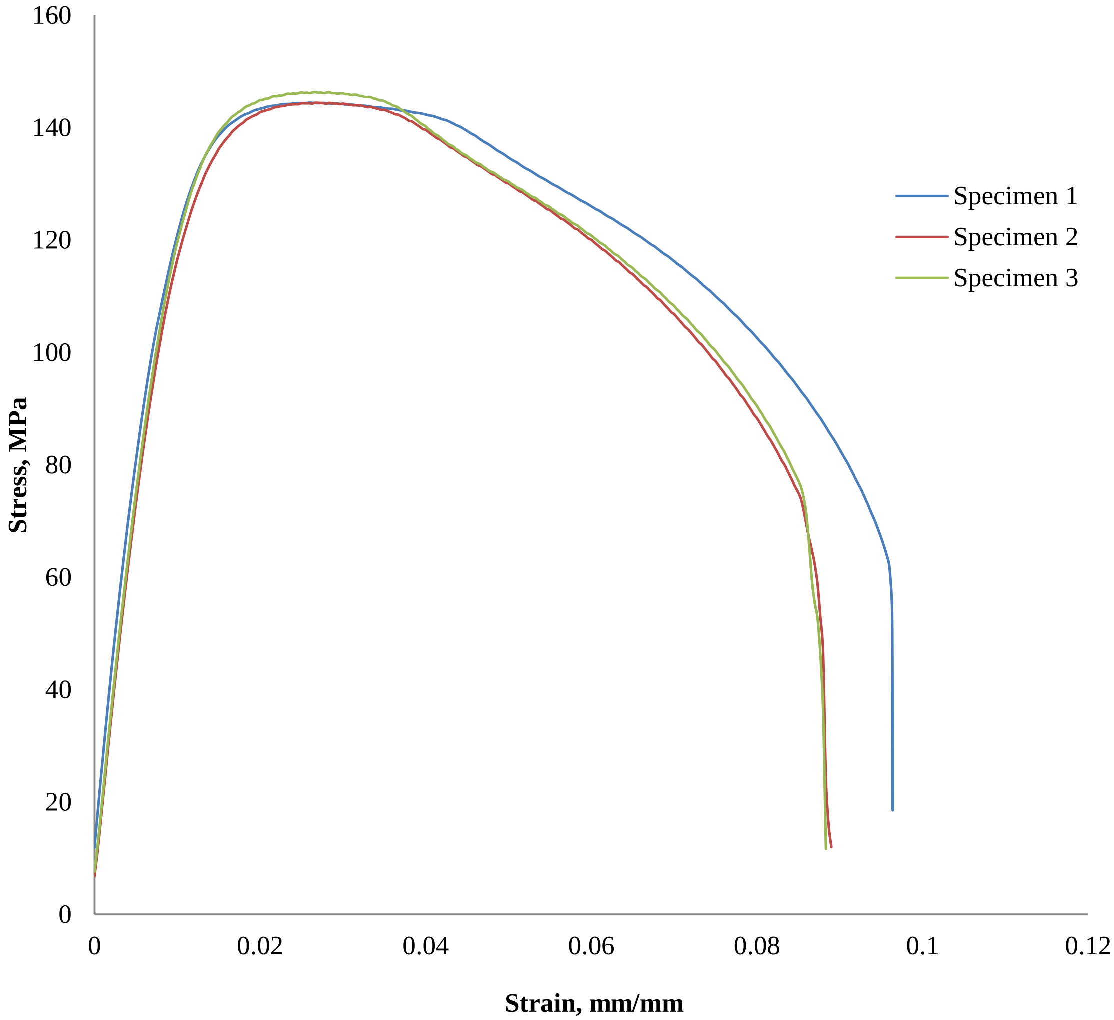


Figure 6.8: Tensile test of 3mm 45^{o}

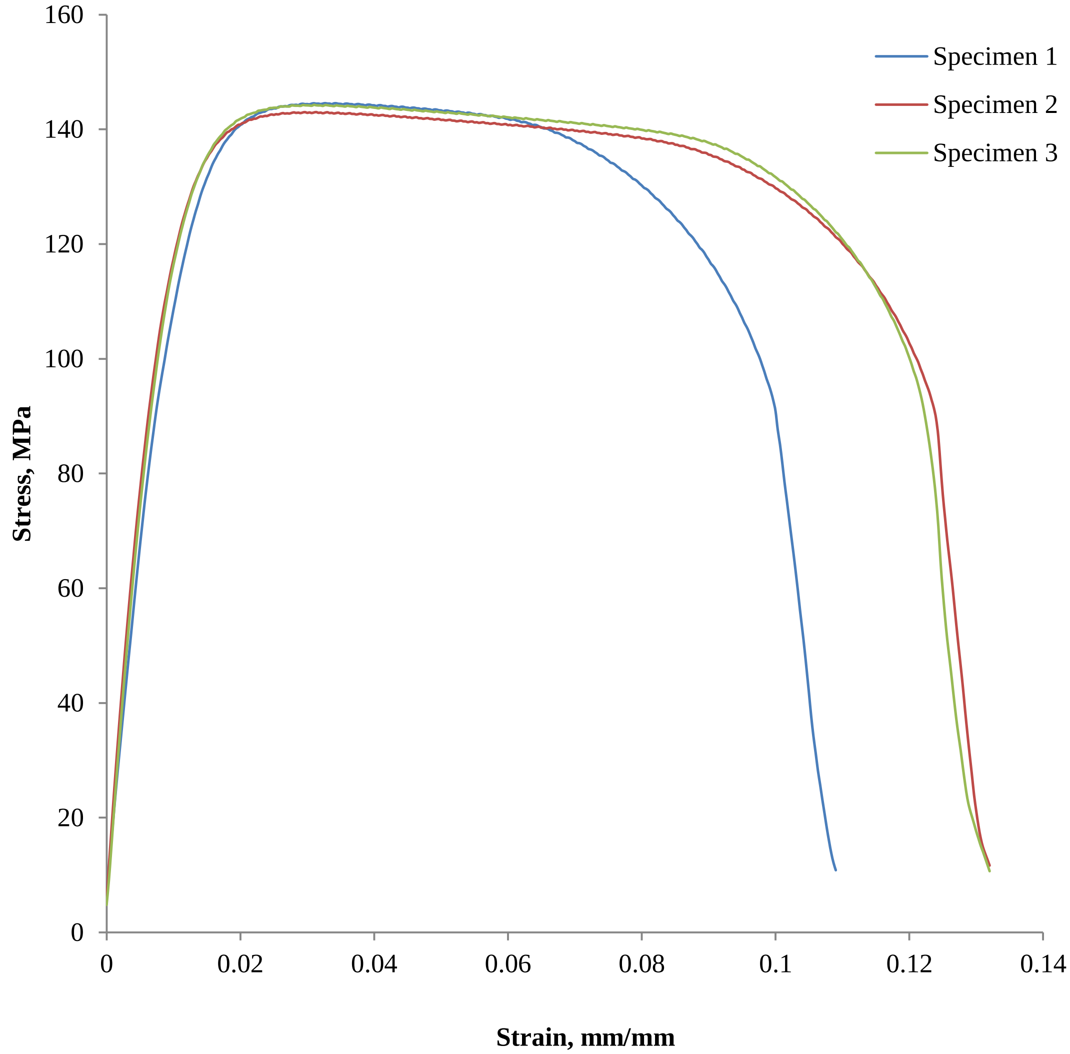


Figure 6.9: Tensile test of 3 mm 90^{o}

APPENDIX D – MECHANICAL PROPERTIES

Table 4.4: Mechanical properties for 1 mm

Test	Modulus (MPa)	Strain Hardening Exponent n	Ultimate Tensile Strength (MPa)	Anisotropy Value R	Poisson Ratio v
			0^o		
1	20511	0.06876	166.8968	0.558909	0.343949
2	21143	0.10451	167.9720	0.599946	0.359133
3	21177	0.10192	168.9680	0.471276	0.308772
Average	20943.6667	0.09173	167.9456	0.543377	0.338395
			45^o		
1	20476	0.10059	166.7512	0.494690	0.321429
2	20702	0.10297	166.7912	0.409891	0.283019
3	20413	0.09355	165.0256	0.449899	0.300395
Average	20530.3333	0.09904	166.1893	0.451493	0.301887
			90^o		
1	24169	0.10116	190.3320	0.610064	0.369565
2	23023	0.08763	171.9192	0.640641	0.382166
3	22287	0.08662	165.3632	0.467258	0.309013
Average	23159.6667	0.09180	175.8715	0.572655	0.348432

Table 4.5: Mechanical properties for 2 mm

Test	Modulus (MPa)	Strain Hardening Exponent n	Ultimate Tensile Strength (MPa)	Anisotropy Value R	Poisson Ratio v
			0^o		
1	14885	0.0582	129.2756	0.671480	0.378378
2	15161	0.05609	128.8448	0.445518	0.290598
3	14275	0.06296	120.6772	0.625476	0.360656
Average	14773.6667	0.05908	126.2659	0.580824	0.342857
			45^o		
1	13614	0.0803	131.4236	1.029900	0.462006
2	15607	0.07315	118.8536	0.762367	0.395210
3	16556	0.07149	131.958	0.907575	0.433735
Average	15259	0.07498	127.4117	0.899948	0.430151
			90^o		
1	15514	0.08870	123.9912	0.882522	0.416667
2	15197	0.08656	120.4288	1.036450	0.450575
3	15965	0.08205	146.682	0.838367	0.405530
Average	15514	0.08870	130.3673	0.919113	0.424289

Table 4.6: Mechanical properties for 3 mm

Test	Modulus (MPa)	Strain Hardening Exponent	Ultimate Tensile Strength (MPa)	Anisotropy Value R	Poisson Ratio v
			0^o		
1	14435	0.10264	153.9021	0.912588	0.438538
2	11707	0.13577	154.4416	0.750535	0.388140
3	14673	0.09653	153.4725	0.620021	0.347826
Average	13605	0.11647	153.9388	0.761049	0.391501
			45^o		
1	14148	0.10808	144.4571	0.621217	0.339703
2	13712	0.12761	144.4491	0.719922	0.371681
3	13890	0.11557	146.3312	0.812120	0.399072

Average	13916.6667	0.11709	145.0791	0.717753	0.370152

Table 4.6: Continue

			90^o		
1	12072	0.12786	144.5421	0.722461	0.358306
2	14079	0.10384	142.9960	0.931377	0.412371
3	14078	0.10282	144.2653	1.089756	0.443686
Average	12072	0.12786	143.9345	0.914531	0.404788

APPENDIX E1 - BENDING SPECIMENS

APPENDIX E2 – SPRING-BACK

Table 4.7 (a): Total value of bending angle for 1 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	38.28	38.09	37.35
2	38.57	38.15	37.60
3	38.62	38.45	37.85
4	38.80	38.46	37.92
5	38.86	38.54	37.93
Average	38.626	38.338	37.73

Table 4.7 (b): Total value of spring-back for 1 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	8.28	8.09	7.35
2	8.57	8.15	7.60
3	8.62	8.45	7.85
4	8.80	8.46	7.92
5	8.86	8.54	7.93
Average	8.626	8.338	7.70

Table 4.8 (a): Total value of bending angle for 2 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	31.91	31.37	31.75
2	31.93	31.83	32.04
3	32.59	31.87	32.21
4	32.90	31.89	32.56
Average	32.3325	31.74	32.14

Table 4.8 (b): Total value of Spring-back for 2 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	1.91	1.37	1.75
2	1.93	1.83	2.04
3	2.59	1.87	2.21
4	2.90	1.89	2.56
Average	2.3325	1.74	2.14

Table 4.9 (a): Total value of bending angle for 3 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	26.19	26.27	26.12
2	26.56	26.32	26.28
3	26.66	26.40	26.37
4	26.84	26.55	26.63
5	27.06	26.85	26.68
Average	26.662	26.478	26.416

Table 4.9 (b): Total value of spring-go for 3 mm aluminum sheet metal

Specimens	0^o	45^o	90^o
1	-3.81	-3.73	-3.88
2	-3.44	-3.68	-3.72
3	-3.34	-3.60	-3.63
4	-3.16	-3.45	-3.37
5	-2.94	-3.15	-3.32
Average	-3.338	-3.522	-3.584