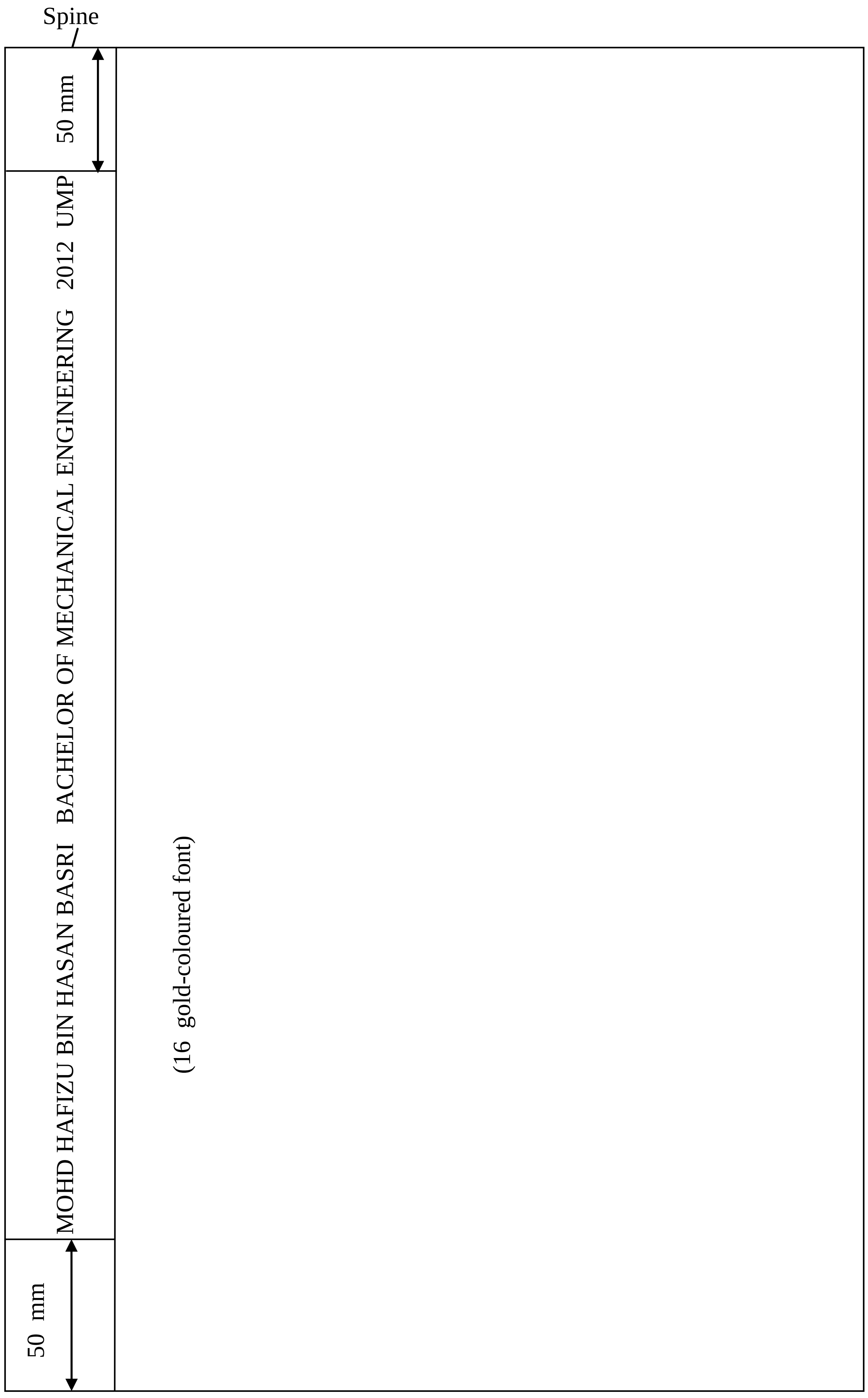
EXPERIMENTAL AND ANALYTICAL EVALUATION OF BENDING FOR STAINLESS STEEL

MOHD HAFIZU BIN HASAN BASRI

UNIVERSITI MALAYSIA PAHANG


Spine
50 mm
MOHD HAFIZU BIN HASAN BASRI
BACHELOR OF MECHANICAL ENGINEERING
2012
UMP
50 mm
(16 gold-coloured font)

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: EXPERIMENTAL AND ANALYTICAL EVALUATION OF BENDING FOR STAINLESS STEEL

SESI PENGAJIAN: 2011/2012

Saya, **MOHD HAFIZU BIN HASAN BASRI (870325-29-5193)**
(HURUF BESAR)

mengaku membenarkan tesis (Sarjana Muda / ~~Sarjana / Doktor Falsafah~~)* ini disimpan di perpustakaan dengan syarat-syarat kegunaan seperti berikut:

1. Tesis ini adalah hakmilik Universiti Malaysia Pahang (UMP).
2. Perpustakaan dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (√)

☐ **SULIT** (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

☐ **TERHAD** (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi / badan di mana penyelidikan dijalankan)

☑ **TIDAK TERHAD**

Disahkan oleh:

(TANDATANGAN PENULIS)

(TANDATANGAN PENYELIA)

Alamat Tetap:
No 3 Lorong 23
PAKR Balok Baru
26100 Kuantan
Pahang
Tarikh: **22 JUNE 2012**

JASRI BIN MOHAMAD
(Nama Penyelia)
Tarikh: **22 JUNE 2012**

CATATAN: * Potong yang tidak berkenaan.

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.

◆

Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara Penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM)

EXPERIMENTAL AND ANALYTICAL EVALUATION OF BENDING FOR STAINLESS STEEL

MOHD HAFIZU BIN HASAN BASRI

Report submitted in partial fulfilment of the requirements
for the award of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2012

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "*Experimental and Analytical Evaluation of Bending for Stainless Steel*" is written by *Mohd Hafizu bin Hasan Basri*. 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 fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

AT-TASNEEM BINTI MOHD AMIN
Examiner Signature

SUPERVISOR’S DECLARATION

I hereby declare that I have checked this project report and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :
Name of Supervisor : JASRI BIN MOHAMAD
Position : FACULTY OF MECHANICAL ENGINEERING LECTURER
Date : 22 JUNE 2012

STUDENT'S DECLARATION

I hereby declare that the work in this report is my own except for quotations and summaries which have been duly acknowledged. The report has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature :
Name : MOHD HAFIZU BIN HASAN BASRI
ID Number : MA09016
Date : 22 JUNE 2012

Dedicated to my father, Mr. Hasan Basri bin Mokhtar, my beloved mother, Mrs. Jamilah binti Deraman, my brothers Muhamad Hafiz bin Hasan Basri and Muhamad Hafizudin bin Hasan Basri, my sister Siti Hajar binti Hasan Basri, my love one and last but not least to all my fellow friends

ACKNOWLEDGEMENTS

I am grateful and would like to express my sincere gratitude to my supervisor Mr Jasri bin Mohamad for his germinal ideas, invaluable guidance, continuous encouragement and constant support in making this research possible. He has always impressed me with his outstanding professional conduct, his strong conviction for science, and his belief that a bachelor program is only a start of a life-long learning experience. I appreciate his consistent support from the first day I applied to graduate program to these concluding moments. I am truly grateful for his progressive vision about my training in science, his tolerance of my mistakes, and his commitment to my future career.

My sincere thanks go to all my labmates, Mohamad Jazmir Hassan bin Mohamed, Azrulhafiq bin Mohd Azizi, Ahmad Aiman bin Ramlan, Nazrith bin Zulkafli, Muhammad Hafiz bin Azam and members of the staff of the Mechanical Engineering Department, UMP, Asmizam bin Mokhtar, Khairul Azha bin Abdul Jalal, Muhamad Rozikin bin Kamaluddin who helped me in many ways and made my stay at UMP pleasant and unforgettable.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I acknowledge the sincerity of my parents, who consistently encouraged me to carry on my higher studies. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. Special thanks should be given to my committee members. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this project.

ABSTRACT

Analytical calculation is one of the methods in predicting the spring-back angle after bending process. Precise predictions of spring-back angle after the bending process are the key to the design of the bending die, bending tool, and to produce the accuracy part geometry. This thesis purpose is to determine the reliability of analytical method in V-bending analysis of stainless steel by comparing the results with experimental results and the experimental measurements of Özgür (2008). The effects of significant parameters including sheet thickness and sheet anisotropy on spring-back in V-bending analysis also have been studies. The mechanical properties that provided from tensile test experiment have been used in the analytical calculation in solving the spring-back equation. Two different equations from previous studies have been used to determine the spring-back angle. In the V-bending experiment, two different test procedures (bottoming and air V-bending process) were used. The experimental results have been used to evaluate the analytical results. The results of this project shown the spring-back values for analytical calculation are generally is not in agreement with the experimental value but the graph trends obtained in this study are generally in agreement with experimental graph patterns. The graph patterns are also in agreement with the past study by other researcher (Özgür, 2008). Increasing the sheet thickness resulted increase in the spring-back angle. The orientation angle and anisotropy value *R* will influence the spring-back. In general, the spring-back angle is increase if the orientation angle is increase. Therefore, the 0 degree orientation angle is a suitable condition in V-bending processes because the spring-back value is smallest compared to other orientation angles. The percentage error is very high because there are some errors occur during the tensile specimen preparation, tensile test experiment and V-bending test experiment. The accuracy and precision of machine in collecting and determined the data is a factors as the higher percentage error. It is conclude that the analytical method is not suitable in sheet metal bending analysis of stainless steel. This is because, combination of various material types and process parameters make the exact prediction of spring-back difficult.

Key words: Stainless steel; V-bending; Spring-back

ABSTRAK

Pengiraan analitikal adalah salah satu kaedah di dalam menentukan bukaan sudut selepas proses membengkok. Ketepatan di dalam menentukan bukaan sudut selepas proses membengkok adalah kunci kepada proses meraka bentuk acuan dan untuk menghasilkan ketepatan bahagian geometri. Tujuan tesis ini adalah untuk menilai ketepatan kaedah pengiraan analitikal dengan membandingkan keputusannya dengan keputusan eksperimen dan juga keputusan eksperimen yang telah dibuat oleh Özgür (2008). Kesan-kesan parameter penting seperti kesan ketebalan kepingan dan kesan anisotropi terhadap bukaan sudut di dalam analisis pembengkokan-V juga dikaji. Sifat-sifat mekanikal keluli tahan karat yang diperolehi dari eksperimen ujian ketegangan telah digunakan untuk menyelesaikan pengiraan bukaan sudut. Dua persamaan berbeza daripada kajian lalu telah digunakan untuk menganggar bukaan sudut. Di dalam eksperimen pembengkokan-V, dua prosedur yang berbeza (bottoming and air V-bending) telah digunakan. Keputusan eksperimen telah digunakan untuk menilai ketepatan keputusan pengiraan analitikal. Keputusan projek telah menunjukan bahawa nilai bukaan sudut bagi pengiraan analitikal secara umumnya adalah tidak sama dengan nilai keputusan eksperimen tetapi tren graf yang diperolehi di dalam kajian ini adalah sama dengan tren graf eksperimen. Tren graf juga sama dengan tren graf yang diperolehi dari kajian terdahulu (Özgür, 2008). Bukaaan sudut akan meningkat sekiranya ketebalan kepingan meningkat. Sudut orentasi dan nilai anisptropi R akan memberi kesan kepada bukaan sudut. Secara umumnya, lebih besar sudut orintasi akan menyebabkan bukaan sudut menjadi lebih besar. Oleh itu, orientasi sudut 0 darjah adalah yang paling sesuai untuk proses pembengkokan-V kerana nilai bukaan sudutnya adalah yang paling minima berbanding orientasi sudut lain. Peratus ralat sangat tinggi kerana terdapat beberapa ralat berlaku semasa proses penyedian specimen ujian ketegangan, eksperimen ujian ketegangan dan eksperimen pembengkokan-V. Ketidak tepatan mesin dalam pengumpulan data adalah factor menyebabkan peratus ralat tinggi. Kesimpulannya, kaedah pengiraan analitikal adalah tidak sesuai digunakan untuk analisis pembengkokan-V bagi keluli tahan karat. Ini kerana, terdapat pelbagai jenis bahan dan parameter proses membuatkan anggaran bukaan sudut menjadi sukar.

Kata kunci: Keluli tahan karat; Pembengkokan-V; Bukaan sudut

TABLE OF CONTENTS

Page

SUPERVISOR'S DECLARATION **iii**

STUDENT'S DECLARATION **iv**

ACKNOWLEDGEMENTS **vi**

ABSTRACT **vii**

ABSTRAK **viii**

TABLE OF CONTENTS **ix**

LIST OF TABLE **xii**

LIST OF FIGURES **xiii**

LIST OF SCHEMES **xv**

LIST OF SYMBOLS **xvi**

LIST OF ABBREVIATIONS **xvii**

CHAPTER 1 INTRODUCTION

1.1 Introduction 1

1.2 Project Background 1

1.3 Problem Statement 2

1.4 Project Objectives 2

1.5 Project Scopes 3

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction 4

2.2 Material 4

  2.2.1 Stainless Steel AISI 304 4
  2.2.2 Stainless Steel Properties 5

2.3 Tensile Test 6

  2.3.1 Specimen 7
  2.3.2 General Procedures of Tensile Test 8

2.4 Bending Test 8

  2.4.1 Principle of V-die Bending Process 11

2.4.2 Spring-back Phenomenon 12
2.4.3 Spring-go Phenomenon 13
2.4.4 Spring Back Prediction using Experimental Method 14
2.4.5 Spring Back Prediction using Analytical Method 16

CHAPTER 3 METHODOLOGY

3.1 Introduction 22
3.2 Flow Chart 23
3.3 Tensile Test 24
3.3.1 Specimen Preparation 24
3.3.2 Cutting Raw Material 24
3.3.3 Cutting Tensile Specimen 25
3.3.4 Design Tensile Specimen using Mastercam's 26
3.3.5 Cutting Tensile Specimen using CNC Milling Machine 27
3.3.6 Tensile Test Experiment 29
3.4 Analytical Method 31
3.4.1 Analytical Equations 31
3.5 V-bending test experiment 34
3.5.1 Specimen Preparation 34
3.5.2 V-Bending Experiment 35
3.5.3 Bending Machine 36
3.5.4 Bending Process 38
3.5.5 Measuring Specimen Angle 40

CHAPTER 4 RESULT AND DISCUSSION

4.1 Introduction 42
4.2 Tensile Test 42
4.2.1 Mechanical Properties of Stainless Steel 43
4.3 Analytical Calculation 50
4.3.1 Daw-Kwei Leu (DKL) Equation 50
4.3.2 Dongye Fei and Peter Hodgson (DFPH) Equation 53
4.4 V-bending test experiment 55
4.4.1 Bottoming Process of V-bending 55
4.4.2 Air V-bending Process 57
4.5 Result Summary 60

CHAPTER 5 CONCLUSIONS

5.1 Introduction 63
5.2 Conclusions 63
5.3 Recommendations 64

REFERENCES 65

APPENDICES

A Final Year Project 1 gantt chart 69
B Final Year Project 2 gantt chart 70
C Tensile test specimen drawing in SolidWorks 71
D CNC milling process simulation using Mastercam's 72
E Mechanical properties of 1.5 mm thickness stainless steel 73
F Mechanical properties of 2 mm thickness stainless steel 74
G CNC milling process G-CODE 75
H Example calculation for Daw-Kwei Leu Bending Equation 76
I Example calculation for Dongye Fei and Peter Hodgson Bending Equation 77
J Die and punch drawing 78
K Die and punch picture 79
L Experimental measurements result of Özgür (Method1) 80
M Experimental measurements result of Özgür (Method2) 81

LIST OF TABLES

Table No.	Title	Page
2.1	Chemical composition of the two studied nuances: AISI 304 and AISI 316	5
2.2	Mechanical characteristic of the two studied nuances: AISI 304 and AISI 316	5
2.3	Chemical composition of the AISI 304 sheets (wt %)	6
2.4	Mechanical properties of the AISI 304 ASSI sheets	6
2.5	Dimension and specification of the tensile test specimen ASTM E8	8
3.1	Total tensile specimen	24
3.2	Total bending specimen	35
3.3	Lower die specification	37
3.4	Upper punch specification	37
4.1	Mechanical properties from tensile test result	43
4.2	Tensile test result for stainless steel 1.5 mm thickness	44
4.3	Final width and length of tensile specimen	48
4.4	Mechanical properties of stainless steel	49
4.5	Daw-Kwei Leu equation data	50
4.6	Effect of sheet anisotropy on spring-back value for Daw-Kwei Leu equation	51
4.7	Effect of sheet anisotropy on spring-back value for Dongye Fei and Peter Hodgson equation	53
4.8	Bending angles result according to the bottoming process	55
4.9	Bending angles result according to the air V-bending process	58
4.10	Comparison between analytical calculation and experimental result with past result conducted by Özgür (2008)	60
4.11	Percentage error of analytical calculation according to the first and second experiment setup (bottoming and air V-bending process)	62

LIST OF FIGURES

Figure No.	Title	Page
2.1	Examples of rectangular (flat) tensile test specimen	7
2.2	Bending in deep drawing process	9
2.3	Classification of bending process	10
2.4	Stress distribution in the V-bending process	11
2.5	Principle of V-bending process	12
2.6	Illustration of the elastic band in the bent part	13
2.7	Illustration of spring-back feature	13
2.8	Illustration of spring-go feature	14
2.9	Illustration of V-free bending	16
2.10	Model of analysis of pure bending	17
2.11	The schematic diagram of sheet bending	18
2.12	Cross sections before and after deformation	20
3.1	LVD shearing machine	25
3.2	ASTM standard tensile specimen solidworks drawing	25
3.3	CNC milling process simulation using mastercam’s	27
3.4	Haas CNC milling machine	27
3.5a	CNC milling process	29
3.5b	Finish tensile specimen	29
3.6	Griping specimen at Instron universal testing machine	29
3.7	Breaking tensile specimen	31
3.8	Model of analysis of pure bending	32
3.9	Illustration of V-free bending	33
3.10	LVD shearing machine	35

3.11 LVD-HD bending machine 36

3.12a Die specification 37

3.12b Punch specification 37

3.13 Specimen on the die 38

3.14a Bending specimen after bending process 40

3.14b Bending process 40

3.15 Specimen scanning picture 41

4.1 Different orientation angle of stress-strain graph for stainless steel 1.5 mm thickness 45

4.2 Different orientation angle of stress-strain graph for stainless steel2 mm thickness 46

4.3 Linear stress-strain graph for 1.5 mm thickness 47

4.4 Effect of sheet anisotropy on spring-back value for Daw-Kwei Leu equation 51

4.5 Effect of sheet thickness on spring-back value for Daw-Kwei Leu equation 52

4.6 Effect of sheet anisotropy on spring-back value for Dongye Fei and Peter Hodgson equation 53

4.7 Effect of sheet thickness on spring-back value for Dongye Fei and Peter Hodgson equation 54

4.8 Effect of sheet thickness on spring-back value according to the bottoming process 56

4.9 Effect of sheet anisotropy on spring-back value according to the bottoming process 57

4.10 Effect of sheet thickness on spring-back value according to the air V-bending process 58

4.11 Effect of sheet anisotropy on spring-back value according to the air V-bending process 59

4.12 Effect of sheet thickness on spring-back value at various methods 61

LIST OF SCHEMES

Scheme No.	Title	Page
3.1	Design tensile specimen using Mastercam's process	26
3.2	Basic processes to running the milling machine	28
3.3	Tensile test experiment procedures	30
3.4	V-Bending processes using the LVD-HD bending machine	39
3.5	Measuring specimen angle using SolidWorks software	40

LIST OF SYMBOLS

$\Delta\theta/\theta$	Spring back ratio
n	Strain hardening exponent
R	Normal anisotropic value
v	Poisson’s ratio
E	Young’s modulus
t	Sheet thickness
ρ	Neutral axis
$\Delta\theta$	Spring back angle
I	Inertia moment of cross-section per unit width
$M(\alpha)$	Bending moment along the bending surface
R_n	Neutral layer radius of the sheet
K	Ultimate tensile strength
w	Die gap
t	Sheet thickness
ΔK	Spring back curvature
M	Bending moment
L	Inertia moment of cross-section

LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Material
TRIP	Transformation Induced Plasticity
CNC	Computer Numerical Control
UTS	Ultimate Tensile Strength
DKL	Daw-Kwei Leu
DFPH	Dongye Fei and Peter Hodgson

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

This chapter provides a brief overview of the entire project. It consists project background, problem statement, objectives, scopes and flow chart of the project.

1.2 PROJECT BACKGROUND

Materials testing are often the first step in the manufacturing process to measure the quality of the material. If the material that uses into the product is defective, then the product will be defective. Quality cannot be put in after the fact. In forming materials, understanding the materials properties can help to better predict the manufacturing outcome and result. Study the effect of spring-back in bending process can reduce cost in the die design and die making.

Some measured properties that must be considered when designing a new product include tensile strength, yield strength and Young’s Modulus of Elasticity. Another important property is ductility, which is the ability for plastic deformation in tension or shear. Ductility controls the amount a material can be cold formed, which is the process used when forming automobile bodies or wire products. Two commonly used indices of ductility are total elongation and reduction of area. For suppliers, the mechanical properties are an important measure of product quality, and buyers often require certification of the values.

In this project, tensile test have been conducted to determine the mechanical properties. The mechanical properties that provided from tensile test have been used in the analytical method in solving the spring-back equation. Then, experimental of the effects of significant parameters including sheet thickness and sheet anisotropy on spring-back or spring-go in V-bending processes of stainless steel have been conducted. The results of the experiments have been used to evaluate the reliability of analytical method in sheet metal bending analysis of stainless steel.

1.3 PROBLEM STATEMENT

Spring-back is a very significant problem in sheet metal forming industry, especially in sheet bending process. The dimension precision is a major concern in bending process, due to the considerable elastic recovery during unloading which leads to spring-back. In a certain conditions, it is also possible for the final bend angle to be smaller than the original angle that normally called as a spring-go. The amount of spring-back or spring-go is depended by various process parameters, such as tool shape and dimension, contact friction condition, material properties, sheet anisotropy and sheet thickness. The accuracy of the methods such as analytical calculation and finite element analysis in predicting the spring-back value are also a major concern in V-bending analysis.

1.4 PROJECT OBJECTIVES

The objectives of this project are:

i. To determine the spring-back angle in sheet metal bending of stainless steel.
ii. To determine the mechanical properties of stainless steel from tensile test experiment.
iii. To determine the effects of significant parameters including sheet thickness and sheet anisotropy on spring-back in V-bending analysis.
iv. To determine the reliability of analytical method in sheet metal bending analysis of stainless steel.

1.5 PROJECT SCOPES

The scopes of the project are limited to:

i. Study the basic understanding of spring-back behaviour from the past researchers.
ii. Conduct experiment for V-bending using press brake bending machine and measure the spring-back angle.
iii. Perform an analytical method to determine the spring-back angle of V-bending.
iv. Compare the experimental result with analytical method.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will discuss about the standard material and it properties used for this project. Then, the theory of tensile and bending test will be study base on the past researched. Lastly, the processes to predict the spring-back angle in experimental and analytical method are study in this chapter.

2.2 MATERIAL

Selecting material for engineering application is important to make sure that material is suitable for the products. In this study, the stainless steel AISI 304 sheet metal has been selected as a material to perform the experimental and analysis for bending test.

2.2.1 Stainless Steel AISI 304

Stainless steel sheet metals have a wide range of application in industry. This material is commonly used for reactor components, consumer products and medical devices. Changes made in the composition of stainless steel to obtain the required mechanical and chemical properties according to the fields used influence their cold shaping. High tensile strength, resistance to corrosion, low thermal conductivity and ductility that stainless steels possess and presence of a great amount of chrome nickel and some amount of molybdenum, strength enhancing elements, are the primary factors that complicate cold shaping compared to other materials. Majority of these products around us are formed by means of a bending apparatus, die or machine, and it is essential that these metal parts be within the required dimensions and tolerance limits. The required dimensions and tolerance limits obtain are depends on the amount of spring back of the material bent. (Özgür, 2008)

2.2.2 Stainless Steel Properties

According to Z. Tourki (2005), the material used in the investigation was the 316 and 304L stainless steel obtained from thin sheet (1 mm) of austenitic stainless steel. The chemical composition of the materials is given in Table 2.1. The mechanical basic characteristics, which are the hardening exponents and their anisotropy coefficients, are described in Table 2.2. The treatment results in a recrystallized structure with an average grain dimension of 100 μm for the 304 steel and 150 nm for the 316 steel.

Table 2.1: Chemical composition of the two studied nuances: AISI304 and AISI 316

Nuances	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**N**	**Cu**	**Fe**
AISI 304	0.05	0.41	1.14	18.04	9	0.193	0.04	0.348	Balance
AISI 316	0.06	0.055	1.85	16.8	12.3	2.59	0.03	0.057	Balance

Source: Z. Tourki (2005)

Table 2.2: Mechanical characteristic of the two studied nuances: AISI 304 and AISI 316

Nuances	**$R_{p0.2}$ (MPa)**	**R_M (MPa)**	**A (%)**	**r**	**n**	**ϕ Grains**
AISI 304	315	690	58	0.94	$n_1 = 0.14$ ($\varepsilon \leq 10\%$) $n_2 = 0.43$ ($\varepsilon > 10\%$)	100 μm
AISI 316	320	625	58	0.94	0.41	150 μm

Source: Z. Tourki (2005)

According to Óscar Martín (2010), the chemical composition and the mechanical properties of the AISI 304 sheets, respectively, are shown in Table 2.3 and Table 2.4. The sheet thickness is 0.8 mm. The metallographic characterization of parental metal, which is obtained by using electrolytic etching with oxalic acid, is according to ASTM A262-91 Practice A.

Table 2.3: Chemical composition of the AISI 304 sheets (wt %)

C	Cr	Ni	Si	Mn	Mo	Al	Co
0.08	18.03	8.74	0.426	1.153	0.36	0.003	0.17
Cu	**Nb**	**Ti**	**V**	**W**	**Fe**	**P**	**S**
0.39	0.02	0.004	0.05	0.03	70.48	0.019	0.002

Source: Óscar Martín (2010)

Table 2.4: Mechanical properties of the AISI 304 ASSI sheets

Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	Micro hardness (HV, 100 g)
290	675	70	162

Source: Óscar Martín (2010)

2.3 TENSILE TEST

According to J.R. Davis (2004), tensile test is one of the most common methods used for evaluating materials. The tensile test is accomplished by gripping the opposite ends of the specimen within the load frame of a test machine. Tensile force is applied by the machine, resulting in the gradual elongation and eventual fracture of the test specimen. During the tensile test process, force-extension data, a quantitative measure on how the test specimen deforms under the applied tensile force, usually monitored and recorded. When the method is conducted properly, the result gain by tensile test force-extension data that can quantify several important mechanical properties of a material such as elastic deformation properties (Young's modulus and Poisson's ratio), yield strength, ultimate tensile strength, ductile properties (elongation and reduction in area) and strain-hardening characteristics.

2.3.1 Specimen

According to the ASTM standard, the specimen of the tensile test can be divided into three types where it is plate type specimen, sheet type specimen and round type specimen. In this project, the test specimen is sheet metal type. Normally, the specimen has enlarged ends or shoulders for gripping. 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 shoulders of the test specimen can be manufactured in various ways to mate to various grips in the testing machine. Both ends of the specimens should have sufficient length and a surface condition such that they are firmly gripped during testing. (J.R. Davis, 2004)

The standard sheet type test specimen according to ASTM standard is shown in Figure 2.1. This specimen is used for testing metallic materials in the form of sheet, plate, flat wire, strip, band and hoop ranging in nominal thickness from 0.13 to 19.0 mm. The detail dimension and specification of the tensile test specimen is shown in the Figure 2.1 and Table 2.5.

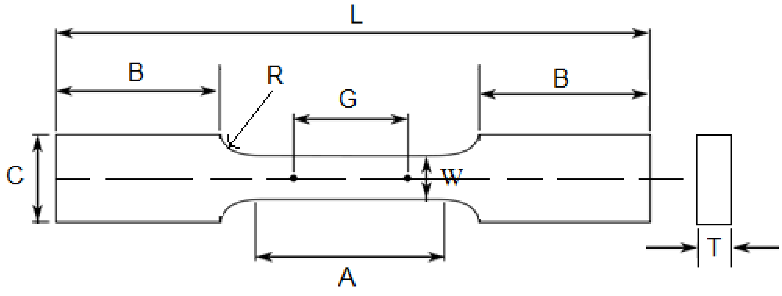


Figure 2.1: Examples of rectangular (flat) tensile test specimen

Source: Annual Book of ASTM Standards (2003)

Table 2.5: Dimension and specification of the tensile test specimen ASTM E8

	Plate type (1.5 in. wide) mm	**Sheet type (0.5 in. wide) mm**	**Sub-size specimen (0.25 in. wide) mm**
Gage length	200 ± 0.25	50.0 ± 0.10	25.0 ± 0.08
Width	40 + 3 - 6	12.5 ± 0.25	6.25 ± 0.05
Thickness	Thickness of Material		
Fillet radius (min.)	13	13	6
Overall length (min.)	450	200	100
Length of reduced section (min.)	225	60	32
Length of grip section (min.)	75	50	32
Width of grip section (approx.)	50	20	10

Source: Annual Book of ASTM Standards (2003)

2.3.2 General Procedures of Tensile Test

After testing specimen has been prepared, the tensile test will be conducted for test the physical behaviour of the sample. The test specimen will be placed properly at the grips and if required, extensometers or strain gauge or any other strain measuring devices can be used with the test specimen for measurement and recording of extension data. To ensure that the test will run at the proper testing speed and temperature, the testing should be monitored all the time. The test is started by applying the force to the test specimen. (J.R. Davis, 2004)

2.4 BENDING TEST

Bending is a common metal forming process used in sheet metal forming to fabricate curve and angle shaped products of various sizes, such as parts of automobiles, ships and aircraft. Furthermore, this process also used in making the various consumer products, such as kitchenware and sanitary products. The bending process concept is based on engineering science and has a wide variety of applications. Furthermore, bending also features in many sheet metal forming processes, such as the deep drawing and stamping processes shown in Figure 2.2.

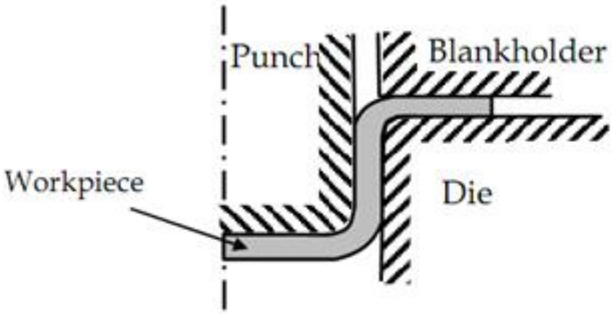
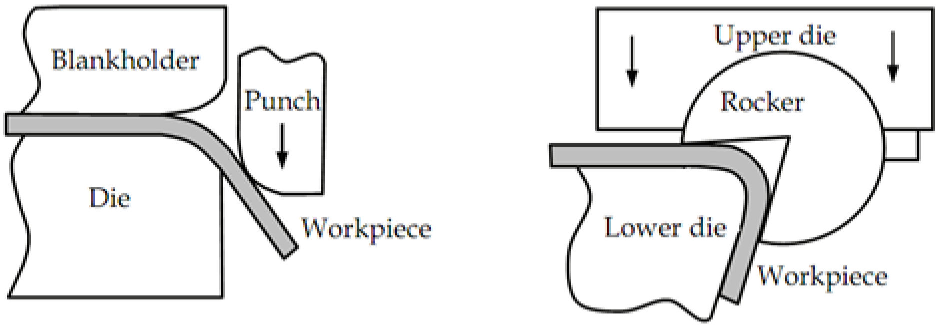


Figure 2.2: Bending in deep drawing process

Source: Sutasn Thipprakmas (2010)

The bending process is divided into two group types which are bending by using a linear die motion and bending by using a rotating die motion. Bending by using a linear die motion is the tool moves linearly to bend the work piece. For example, the wiping die bending and U-bending processes, shown in Figure 2.3 (a). Bending by using a rotating die motion is a tool moves in rotations to bend the work piece, as shown in Figure 2.3 (b). The advantages of rotary bending are elimination of the use of a blank holder, less bending force requirement, and a final bending angle greater than 90 degree.



(a) (b)

Figure 2.3: Classification of bending process (a) Linear die motion (b) Rotating die motion

Source: Sutasn Thipprakmas (2010)

Bending is a manufacturing process where a force, corresponding to a given punch displacement, acts on the work piece. The work piece is initially bent in an elastic region. When the process continues, the work piece is deformed by plastic deformation and changing its shape. The bending load increases until the elastic limit of the material is exceeded in the bending process. Sheet metal can be formed when the material state enters the plastic deformation region. In addition, the stress generated in the work piece is greater than the yield strength but lower than the ultimate tensile strength of the material. The work piece initially deforms where the bending moment is the greatest. For example, the process of permanent deformation starts directly underneath the punch in the case of the V-bending process. During the bending process, the outer surface of the work piece generates the greatest stretch, which then expands inward toward the neutral plane. Similarly, the inner surface of the work piece generates the greatest compression, which also then expands inward toward the neutral plane. These distributions of the stresses are shown in Figure 2.4.

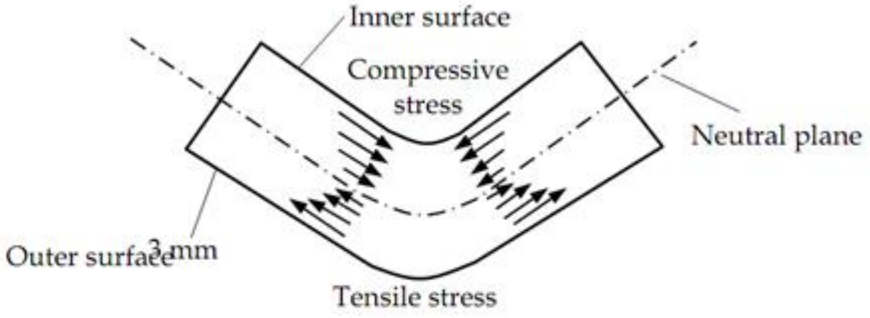


Figure 2.4: Stress distribution in the V-die bending process

Source: Sutasn Thipprakmas (2010)

2.4.1 Principle of V-die Bending Process

The V-bending process can be defined as a bending of a V-shaped part in a single die. The principle of the V-die bending process is shown in Figure 2.5. The work piece is bent between a V-shaped die and punch. The force acting on the punch causes punch displacement and make the work piece is bent. The work piece is initially bent as an elastic deformation. The process continued downward motion by the punch, and when the stresses exceed the elastic limit, the plastic deformation sets in. This plastic deformation start occurs on the outer and inner surfaces directly underneath the punch. The greatest tensile stress is occurred on the outer surface and the greatest compressive stress is occurred on the inner surface. These stresses decreasingly expand inward toward the work piece. In addition, crack formation usually occurs on the outer surface and a wrinkle usually occurs on the inner surface. The initial bending stage is known as Air bending. Air bending is a process that starts from the moment the punch establishes contact with the work piece and is completed either when the legs of the work piece become tangential to the faces of the die or when the smallest internal radius of the work piece becomes smaller than the radius of the punch. As the process continues, after completion of air bending, the bending is focused on the three points of the punch and the two faces of the die. The contact points between the work piece and die are shifted toward the centreline of the die, and the legs of the work piece try to close around the punch. As the punch proceeds further, the legs of the work piece establish contact with the punch, and it is pressed to open up again until the bend angle approaches the die angle (Schuler, 1998). The clearance between the punch and the die in V-bending is commonly dependent of the work piece thickness. The usual thickness of the work piece in the V-bending process ranges from approximately 0.5 to 25 mm.

Initial state Bending state Final state

Figure 2.5: Principle of V-bending process

Source: Sutasn Thipprakmas (2010)

2.4.2 Spring-back Phenomenon

The material is generally divided into two zones according to the plastic deformation theory where it is the elastic and the plastic zones. The elastic property tries to maintain the material in the initial shape, whereas the plastic property tries to retain the material in the deformed shape. In the sheet metal bending process, the bending load increases until the elastic limit of the material is exceeded and then the material state enters the plastic deformation zone. The outer surface of the material generates the tensile stress, which propagates inward toward the neutral plane. Vice versa, the inner surface of the material generates the compressive stress and it propagates inward toward the neutral plane. Because of the stress distributions, this phenomenon causes the formation of a small elastic band around the neutral plane, as shown in Figure 2.6. As the bending force is removed at the end of the bending stroke, the inner surface–generated compressive stress tries to enlarge the work piece and the outer surface–generated tensile stress tries to shrink. In contrast, the elastic band remains in the bent parts trying to maintain its original shape, resulting in a partial recovery toward its initial shape. This elastic recovery is called “spring-back”. Thus, the work piece tries to spring back and the bent part slightly opens out, as shown in Figure 2.7.

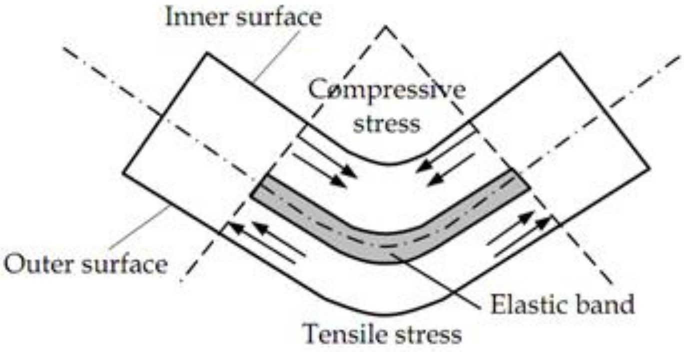


Figure 2.6: Illustration of the elastic band in the bent part

Source: Sutasn Thipprakmas (2010)

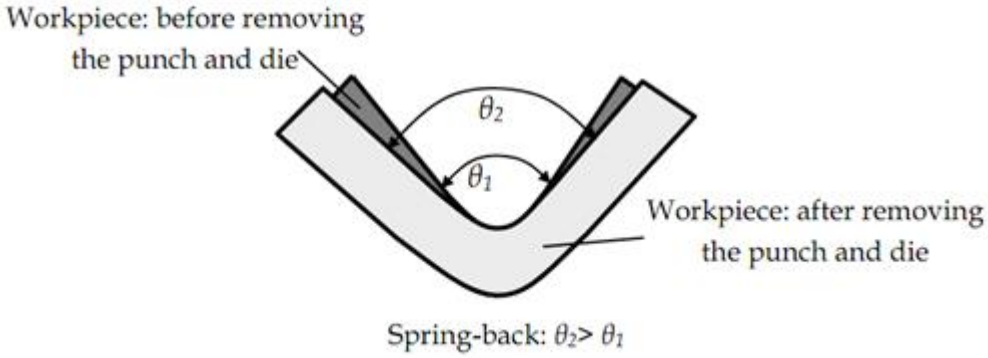


Figure 2.7: Illustration of Spring-back Feature

Source: Sutasn Thipprakmas (2010)

2.4.3 Spring-go Phenomenon

In addition to the spring-back feature, the spring-go feature usually occurs in a bending process. The spring-back characteristic occurs as the bent part slightly opens. In contrast, the spring-go characteristic occurs as the bent part slightly closes, as shown in Figure 2.8.

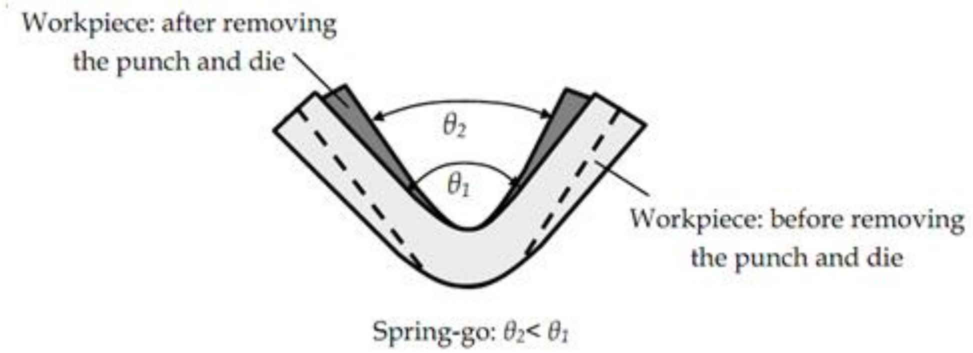


Figure 2.8: Illustration of Spring-go Feature

Source: Sutasn Thipprakmas (2010)

2.4.4 Spring Back Prediction using Experimental Method

According to Özgür (2008), dimensions of the samples were 25x50 mm, and thickness levels are 0.5, 0.75 and 1 mm. Experiments included 10 bending for each material and thickness level at angles of 15, 30, 45, 60, 75, 90 degrees. These sheet metals were bent on a hydraulic press bench with adjustable pressure and time, and each sheet bent was measured finely with a profile meter of “1 min” sensitivity and optical protractor, minimizing measurement error. During the experiments, four different test sets were used, primarily bottom bending technique.

In the first experiment, punch was not thoroughly set to the bottom of the die. A gap equal to the thickness of the sheet material was left between the die and the punch to avoid the effect of the sheet material on spring back, due to the squeezing at the bending section or profile. Punch was held on the sheet metal for 20 seconds, then the load on the material was released as the punch is raised. In the second experiment, a gap equal to the material thickness is left between the die and the punch, but this time the punch was not held on the sheet. As soon as the punch reached the last point of depth, it was removed and the punch load was relieved instantly. In the third experiment, the punch was lowered completely to the bottom of the die. Thickness of sheet metal material between the die and the punch was neglected totally. Here, too, the punch load was kept on the material for 20 seconds. In the fourth experiment, the sheet metal thickness was neglected again to make punch and die contact possible, and the punch was not held on the sheet material. (Özgür, 2008)

First and second of the four methods tested are suitable to determine spring back. In these methods, deformation with the bending profile is avoided by allowing a gap as thick as the sheet metal between the punch and female die, preventing crushing of the metal sheet in the die. In the third and fourth methods, the punch is completely set at the bottom of the female die since the thickness of the metal sheet is disregarded. Related to the thickness of sheet metal, crushing has appeared around the bending area of the part pressed between the punch and female die. Crushing varies according to the angle and types of material. Crushing of bending profile hinders sensitive determination of spring back values. It is clear from the experimental results of the third and fourth methods that they cannot be used in determining spring-back values. Moreover, the time to hold the punch on the sheets affects the spring-back value. The punch must be kept for a definite period of time on the sheets to dispose the elasticity of sheet metal. According to the results obtained, increasing the time to keep the punch on renders decrease in the spring-back value. Thickness of sheet metal must be taken into consideration and the application time of the punch load is important to determine the spring back value. Holding the punch load decreases the spring-back value. Increase in thickness of the material increases the spring-back value. Spring-back value increases in case of an increase in bending angle. (Özgür, 2008)

Regarding to Dongye Fei Nilsson (2006), the air V-bending tests are conducted on an instrumented 100 kN Instron machine with the v free bending tool shown in Fig. 2.10. This machine is speed controlled from 0.1 to 500 mm/min by a desktop computer. The precision of punch force and displacement is ±2.5 N and ±0.001 mm, respectively. The geometric parameters involved are die radius (*Rd*) is 2 mm, die gap (*w*) is 10, 15, 20 and 25 mm, punch radius (*RP*) is 1, 2, 3 and 4 mm and punch velocity (*VP*): 1, 10 and 100 mm/min. The die length is 60 mm and strips of the TRIP steel 90 mm long and 15 mm wide are cut along the rolling direction. No lubricant is used in the bending process. The arms of the bend are free to swivel about the point of sheet contact with the die radius as the bending progressed. The spring-back angle, $\Delta\theta$ is measured by the difference between bending angle θ and unbending angle, θ' ($\Delta\theta - \theta'$).

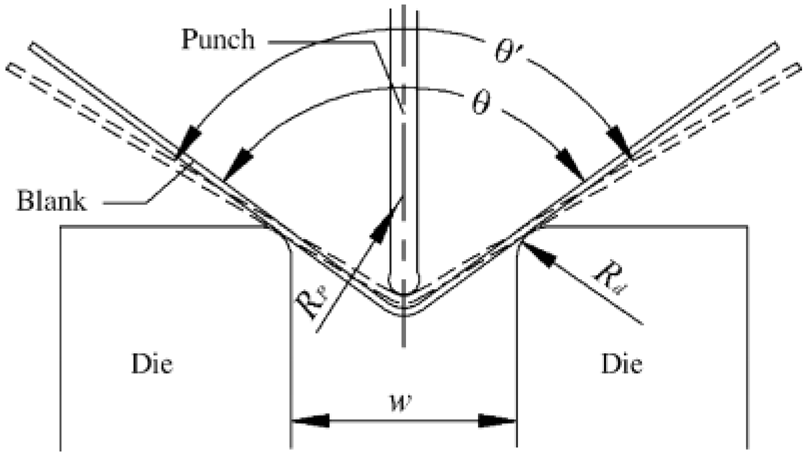


Figure 2.9: Illustration of v-free bending

Source: Dongye Fei Nilsson (2006)

Spring-back for TRIP steels depends strongly on the blank thickness and die gap, while the influence of punch radius and punch velocity on spring-back is negligible. The decrease in Young's modulus during deformation is experimentally shown. Allowing for the variation in Young's modulus with plastic pre-strain gives better correlation between numerical analysis for the spring back simulation and experimental results. Therefore, it is advisable to take into account the variation of Young's modulus for TRIP steels in spring-back simulation. Simulation results show that friction coefficient can influence the punch force, while it does not influence the spring-back angle in the air V-bending process. (Dongye Fei Nilsson, 2006)

2.4.5 Spring Back Prediction using Analytical Method

In the Daw-Kwei Leu (1997) paper, the effects of the normal anisotropic value, *R* and the strain hardening exponent in on the pure bending of sheet metal using the analytical method have been studied. The highlight of this paper is that a simple approach, incorporating the normal anisotropic value *R* and the strain hardening exponent *n*, is developed to estimate spring-back, bendability and the maximum bending moment in pure bending. Comparison between predicted values and published experimental results has been made, a consistent agreement being achieved, reflecting the reliability of the present model. The analysis to estimate the spring back ratio is base on the analysis of the pure bending. A schematic diagram of sheet metal under pure bending is shown in Figure 2.10.

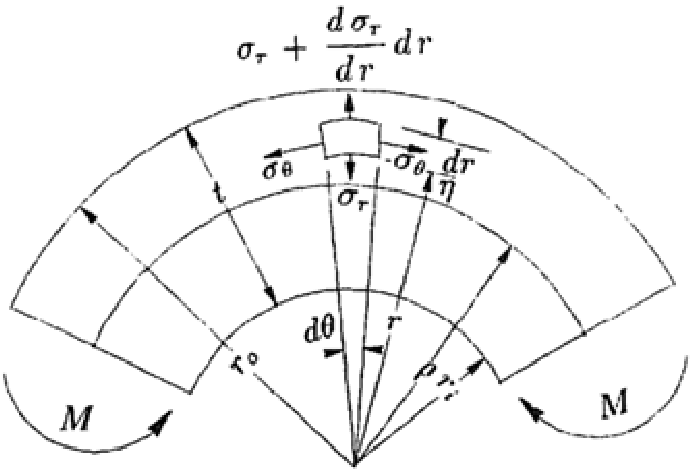


Figure 2.10: Model of analysis of pure bending

Source: Daw-Kwei Leu (1997)

Elastic recovery after unloading causes the spring back phenomenon. The equation for estimate the spring back ratio is base on the bending moment *M* condition. According to the bending moment condition, the spring back equation is written as:

$$\frac{\Delta\theta}{\theta} = \frac{UTS}{e^{-n}n^{n}} \times \left(\frac{1+R}{\sqrt{1+2R}}\right)^{1+n} \frac{3(1-v^{2})}{2E(1+n)} \left(\frac{t}{2\rho}\right)^{n-1} \qquad (2.1)$$

Where $\Delta\theta/\theta$ is the spring-back ratio, *UTS* the tensile strength, *n* the strain hardening exponent, *R* the normal anisotropic value, *v* the Poisson's ratio, *E* the Young's modulus, *t* sheet thickness and ρ is the neutral axis.

As the result, it is concluded that, the spring back is almost proportional to the normal anisotropic value R and it decreases sharply with respect to smaller strain hardening n values or smaller thickness ratio *t*, 2ρ values. At large strain hardening *n*-values or large thickness ratio *t*/ 2ρ-values, the spring back will concentrate to a small range. The minimum bending radius is proportional to the sheet thickness *t*, decreases with the normal anisotropic value *K*, and decreases sharply with the strain hardening exponent *n* to a small range. The maximum bending moment increases with the normal anisotropic value *R*, increases sharply with the sheet thickness *t* but decreases with the strain hardening exponent *n*. (Daw-Kwei Leu, 1997)

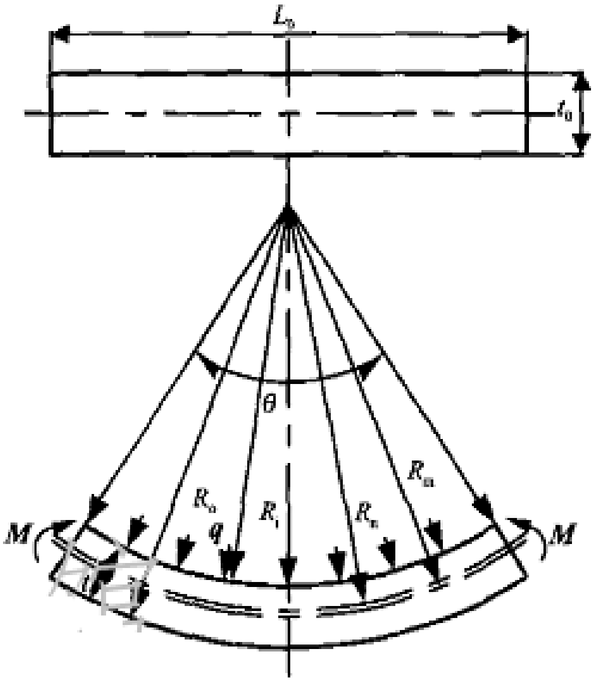


Figure 2.12: The schematic diagram of sheet bending

Source: Zhang Dong-juan (2006)

In the Zhang Dong-juan (2006) paper, an analytical model is been proposed to predicted the spring-back angle in V-bending test. The analytical model is based on the Hill’s yielding creation and plane strain condition. The study of spring-back is account the effect of the contact pressure, the length of bending arm between the punch and die, transverse stress, natural surface shifting and sheet thickness thinning on the sheet spring back of V-bending. In the analysis of sheet bending, the round corner of sheet V-bending can be considered as bending under the action of contact pressure *q* and bending moment *M* as shown in the Figure 2.11.

The non-uniform distribution of stress through sheet thickness during forming process will change the part profile and cause spring back when the loading is removed (Zhang Dong-juan, 2006). Assuming that the arm of V-bending is straight before and after spring back, its spring back can be ignored. Therefore the spring back of sheet V-bending occurs only in the region of the bottom of the corner. The spring back angle of sheet V-bending is calculated using:

$$\Delta\theta = 2\int_0^{\theta} \frac{M(\alpha)}{EI} R_n d\alpha \tag{2.2}$$

Where I is inertia moment of cross-section per unit width, $M(\alpha)$ bending moment along the bending surface, E the Young's modulus and R_n is the neutral layer radius of the sheet.

In this paper, the predict results by the analytical model showed that the contact pressure is related to the length of the bending arm between the punch and die. The shorter the arm length is, the larger the contact pressure is for the same bending ratio (R_i/t_0) which the result in larger sheet spring back of V-bending. The contact pressure has more influence on sheet spring-back for bending ratio$(R_i/t_0) \leq 5$. However for the bending ratio$(R_i/t_0) \geq 5$, its effect can ignore. The effect of neutral surface shifting on the sheet spring-back of V-bending is less than that of contact pressure. The relative shifting amount of neutral surface to sheet thickness $(R_m/R_n)t$ and its effect on sheet-spring back decreases with the bending ratio(R_i/t_0) increases. (Zhang Dong-juan, 2006)

In the Dongye Fei (2006) study, the theoretically calculation also has been use to determined the spring back in air V-bending. The spring back can be theoretically calculated as following:

$$\frac{\Delta\theta}{\theta} = \frac{3K\rho(1-v^2)(1+4t/\omega)}{Et} \tag{2.3}$$

Where K is the ultimate tensile strength, ρ the position of the neutral axial, υ the Poisson's ratio, w the die gap, E the Young's modulus and t is the thickness. The equation can be used to explain the reason that the thinner blank thickness and the wider die gap, the higher spring back angles.

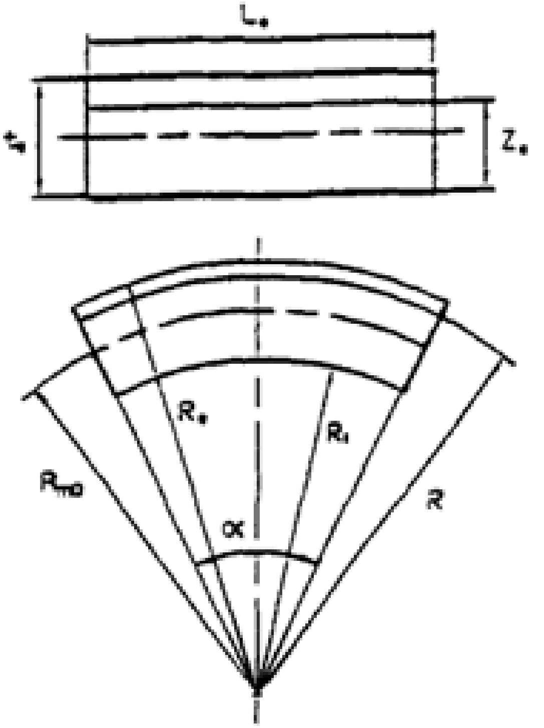


Figure 2.12: Cross sections before and after deformation

Source: Z.T. Zhang, 1995

Regarding to Z.T. Zhang (1995), a new mathematical model is presented for plane strain bending and spring back analysis in sheet metal forming. This model combines effects associated with bending and stretching, considers stress and strain distributions and different thickness variations in the thickness direction, and takes force equilibrium into account. An elastic-plastic material model and Hill's non-quadratic yield function are incorporated in the model. The model is used to obtain force, bending moment, and spring back curvature. A typical two-dimensional draw bending part is divided into five regions along the strip, and the forces and moments acting on each region and the deformation history of each region are examined. Three different methods are applied to the two-dimensional draw bending problems. The first using the new model, the second using the new model but also including a kinematic directional hardening material model to consider the bending and unbending deformation in the wall, and the third using membrane theory plus bending strain.

Spring-back refers to the change in the shape of the sheet geometry after the load has been removed. The stretching force in the sheet causes sheet shrinkage, and the bending moment causes rotation. In sheet metal forming, the shape variation caused by the bending moment is generally much larger than that caused by the stretching force, and therefore the latter is often neglected. Spring back is caused by an elastic deformation, and the unloading process is normally considered as a reverse loading of the same magnitude of the loading force or bending moment, or both. Under plane strain deformation, the spring back curvature caused by unloading of a bending moment is calculated by the following formula:

$$\Delta K = \frac{M(1-v^2)}{LE} \tag{2.4}$$

Where ΔK is the spring back curvature, M bending moment, L is inertia moment of cross-section, v the Poisson's ratio and E the Young's modulus.

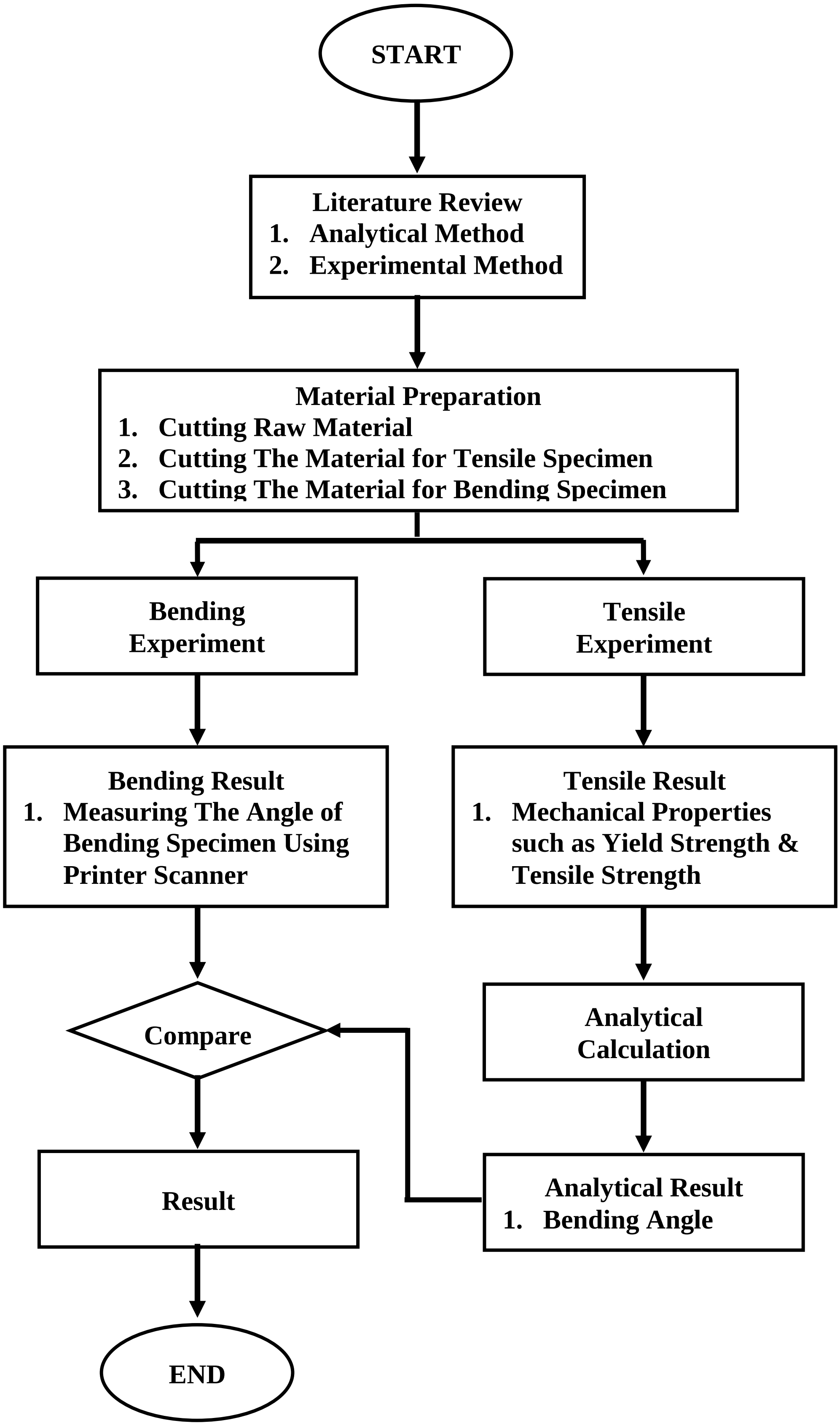
CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter will discuss about the method that used in this project and the process flow of this project. There are two methods used in this project which are analytical method and experimental method. In the analytical method, the process to predict the spring back angle is start with determining the material behaviour using tensile test. Then, by using the result gained, the angle of spring back is calculated using the equation from the past study that has been discusses in Chapter Two. Meanwhile for the experimental method, the methodology of V-bending test will be discussed further in this chapter.

3.2 FLOW CHART



3.3 TENSILE TEST

Tensile test is one of the most common used test for evaluating material properties. In this test, Stainless Steel specimen has been pulled to failure in a relatively short time at a constant rate of 5mm/min. During the tensile test process, force and extension data has been monitored and recorded. The tensile test provides force and extension data that can quantify several important mechanical properties of a Stainless Steel such as elastic deformation properties (Young's modulus and Poisson's ratio), yield strength, ultimate tensile strength, ductile properties (elongation and reduction in area) and strain-hardening characteristics. The mechanical properties that provided from tensile test have been used in the analytical method in solving the spring-back equation.

3.3.1 Specimen Preparation

In this test, two different thickness of specimens have been use to perform tensile test. The thickness is 1.5 mm and 2.0 mm. Each thickness has been cut in the different orientation angle of 0, 45 and 90 degree and each orientation angle has been cut for 3 specimens. Table 3.1 shows the specimens parameter for this project.

Table 3.1: Total tensile specimen

Specimen Thickness (mm)	Bil. of Specimen			
	0°	**45°**	**90°**	**Total Specimen**
1.5	3	3	3	9
2.0	3	3	3	9

3.3.2 Cutting the Raw Material

Stainless steel sheet metal have to be cut into a few specimens according to ASTM Standards, which the raw material of stainless steel sheet metal need to be cut into a rectangular size of 300 mm x 50 mm by using LVD shearing cutting machine.

The material then need to be cut in the angle of 0^{o}, 45^{o} and 90^{o}, which is varies in the direction of the rolling.

Figure 3.1: LVD shearing machine

3.3.3 Cutting Tensile Specimen

The material then requires to be cut into a tensile test specimen based on ASTM Standard as the reference from the 300 mm x 50 mm sheet size. Regarding to the ASTM Standard, the specimen of the tensile test can be divided into three types where it is plate type specimen, sheet type specimen and round type specimen. In this project, the test specimen is in sheet metal type.

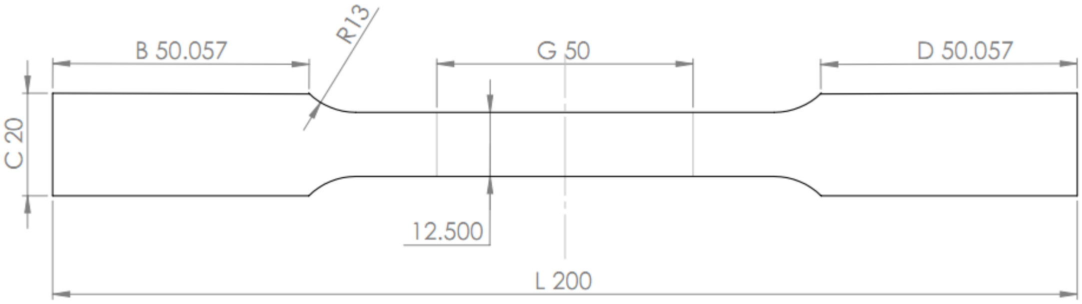


Figure 3.2: ASTM Standard Tensile Specimen Solidworks Drawing

3.3.4 Design Tensile Specimen using Mastercam's

Tensile specimen has been draw using the Mastercam software for generated the G-Code of the CNC milling machine. Mastercam's comprehensive set of predefined tool paths which including contour, drill, pocketing, face, peel mill, engraving, surface high speed, advanced multiaxis, and more else and enable to cut parts efficiently and accurately. The G-Code of the CNC milling machine is attached in the appendices. The scheme 3.1 shown the tensile specimen design processes.

First step, the specimen of tensile test should be drawing in this Mastercam software.

⇩

Then the type of material for specimen should be specifying in the machine group properties toolbar. After that, at the machine group properties toolbar again, set up the raw material size that need to be cut at stock setup.

⇩

Then, at 2D-toolpaths icon select contour as a toolpaths type. After that, select 16 flat endmill as the tool for this process. 16 flat endmill is a 16mm diameter cutting tool for endmill cutting process type.

⇩

The next step is setup the feed rate, spindle speed and plunge rate for this process. The feed rate has been set about 40mm/min while the plunge rate is about 10mm/min. The spindle speed is set to be 900rpm.

⇩

Then, at the linking parameters icon, set up the depth to be cut to the raw material. If the thickness of the material is 2mm, the suitable cutting depth is 2.5mm.

⇩

After all parameter for this process has been setup in the software, the simulation has been run to check the flow of this process. Finally, ganerate the G-code from the simulation process.

Scheme 3.1: Design tensile specimen using mastercam's process

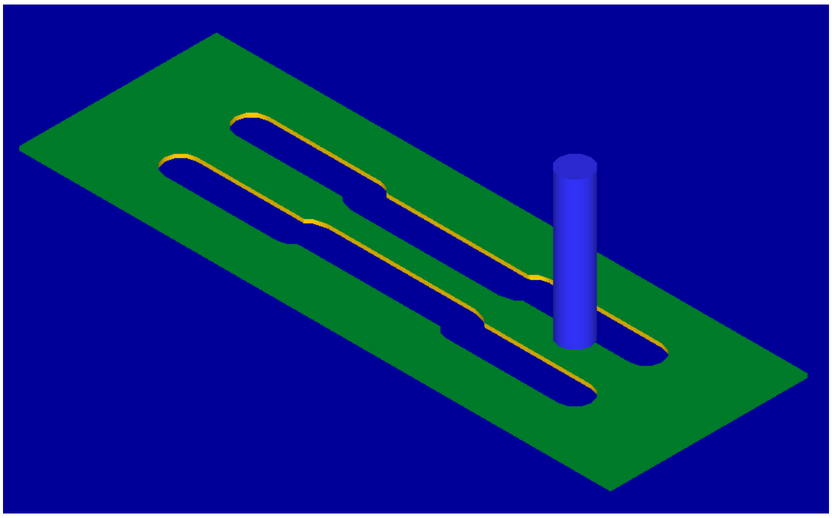


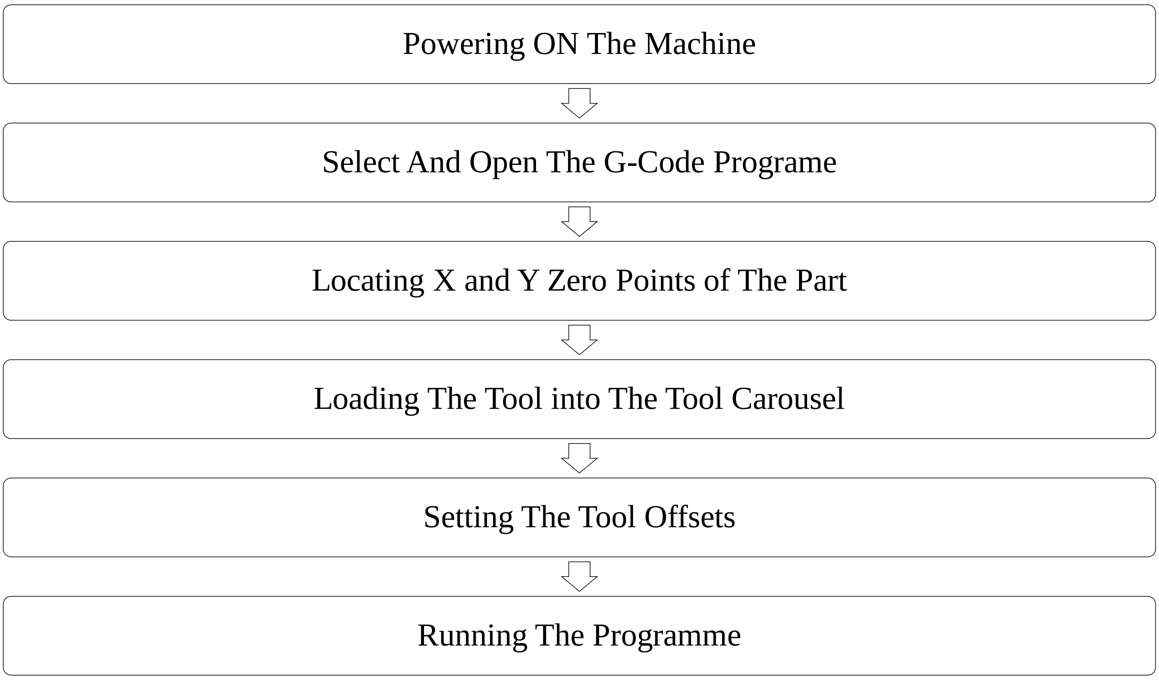
Figure 3.3: CNC Milling Process Simulation using Mastercam's

3.3.5 Cutting Tensile Specimen using CNC Milling Machine

The cutting of tensile specimen will be completed by using Haas CNC Machine. Computer Numerical Control which refers to a computer controller that controls the movement of every axis of the machine using G and M codes instructions and drives the spindle or machine tool into a workpiece to fabricate or to remove the unwanted material from workpiece more accurately without human intervention.

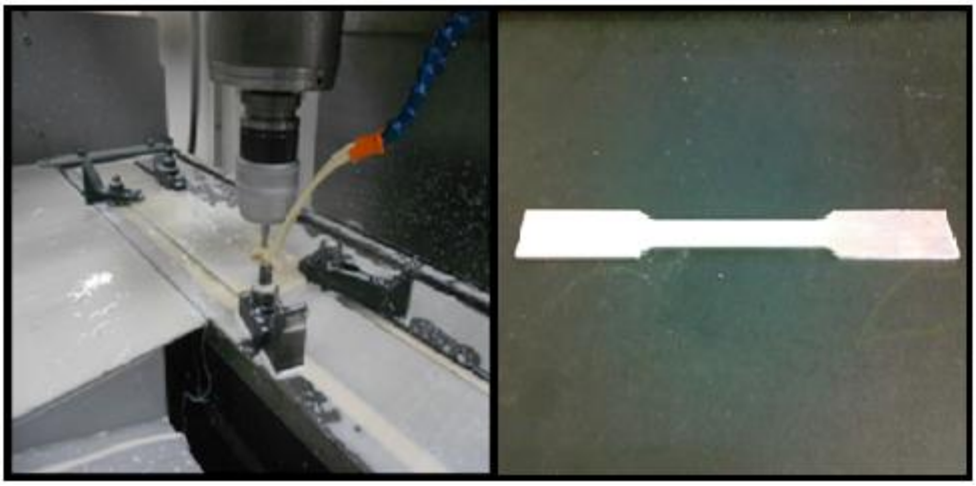
Figure 3.4: Haas CNC Milling Machine

The G-Code that has been generated from Mastercam’s than be imported to the CNC milling machine. Scheme 3.2 has shown the basic processes to run the milling machine.



Scheme 3.2: Basic processes to running the milling machine

The HAAS milling machine will be on when the green POWER ON button in the upper left of the control is pressed. After that, closed the front doors and press the POWER UP/RESTART button to set up the zero available axes. Then press the LIST PROG key and this showed a list of any programs available in the control panel. Import the G-Code programme from USB and press MEMORY and F2 key to select the programme. After the programme was set, clamp the workpiece on the machine and used an edge finder or indicator to locate the part zero point with the jog handle. Press the OFFSET key and PAGE UP until the work coordinate page appears. Then, used the cursor arrows to get to G54 X and pushed the PART ZERO SET key to store the x-axis value as offset. The cursor automatically moves to the G54 Y location. Push again the PART ZERO SET key to set the G54 Y. Usually the z-axis value should be zero.



(a) **(b)**

Figure 3.5: (a) CNC milling process **(b)** Finish tensile specimen

3.3.6 Tensile Test Experiment

After the test specimen has been prepared properly, the tensile test setup recognized to conduct the tensile test. The test specimen was installed properly in the grips in the Instron Universal Testing Machine.

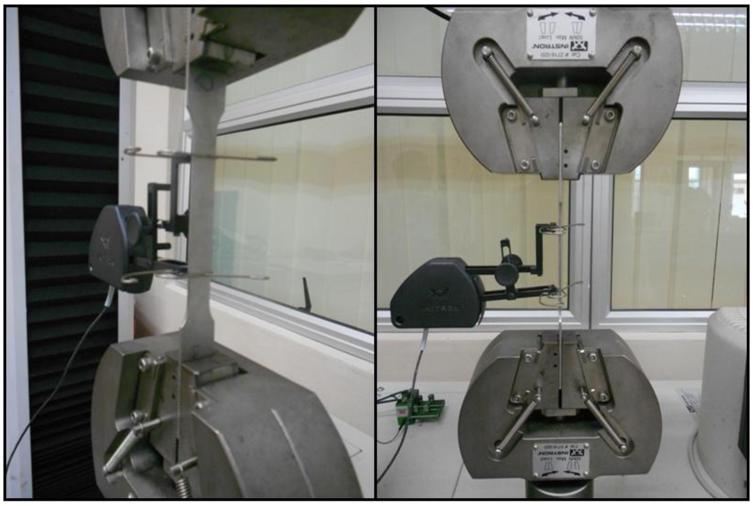


Figure 3.6: Griping specimen at Instron universal testing machine

A check also can be done to ensure that the test will run at the appropriate testing speed and temperature. The test procedure followed the ASTM E8M standard which is the standard tensile test procedure. The test was begun by initiating force application. The data of material properties will be automatically transfer and view in the tensile software in the computer. Scheme below has shown the tensile experiment procedure.

Open BLUEHILL Software in the computer.

Load the specimen into the lower grip and upper grip. Make sure the specimen is straight.

Click METHOD icon and set the specimen parameter (lenght, thickness, width) and crosshead speed (5mm/min).

Click TEST icon and enter the file name. Choose a test method that has been created .

Select the data that should be provided from the test and setting the Stress vs Strain graph in the TEST RESULT and save the method.

Reset the load and strain and click START TEST to start the tensile test.

After the test finished, click to the ULTILITIES in the main screen to view the result and data and save the result.

Finally, measure the final lenght and width of the specimen and record it in the table.

Scheme 3.3: Tensile test experiment procedures

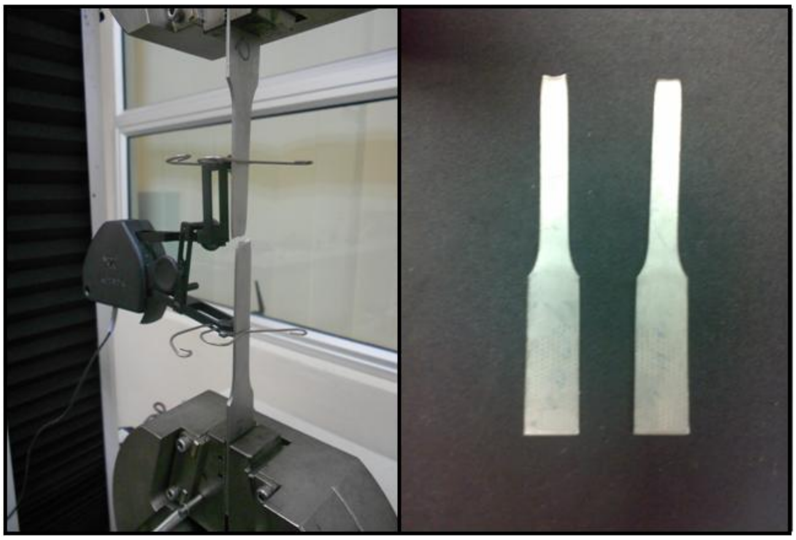


Figure 3.7: Breaking tensile specimen

3.4 ANALYTICAL METHOD

Analytical is one of the methods in predicting the spring-back angle after bending processes. The effect of the anisotropy value *R* (orientation angle) and thickness of the specimen have been studied in this project. The highlight of this paper is that an equation from past studies is used to estimate spring-back angle in V-bending. The equations from Leu (1997) and Dongye (2006) has been used to estimate the values. The mechanical properties that provided from tensile test were used in the analytical method in solving the spring-back equation. The predicted values of the spring-back have been compared with the experimental values and the known experimental results.

3.4.1 Analytical Equations

In the Daw-Kwei Leu (1997) paper, the effects of the normal anisotropic value, R and the strain hardening exponent on the pure bending of sheet metal using the analytical method have been studied. The highlight of this paper that is simple approach, incorporating the normal anisotropic value R and the strain hardening exponent n, is developed to estimate spring back, bendability and the maximum bending moment in pure bending. Comparison between predicted values and published experimental results have been made, a consistent agreement being achieved, reflecting the reliability of the present model. The analysis to estimate the spring back ratio is based on the analysis of the pure bending. A schematic diagram of sheet metal under pure bending is shown in Figure 3.8.

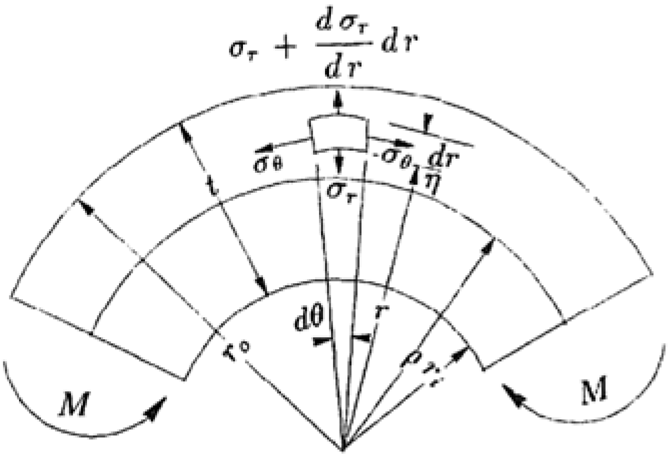


Figure 3.8: Model of analysis of pure bending

Source: Daw-Kwei Leu (1997)

Elastic recovery after unloading causes the spring-back phenomenon. The equation for estimating the spring back ratio is based on the bending moment *M* condition. According to the bending moment condition, the spring-back equation is written as:

$$\frac{\Delta\theta}{\theta} = \frac{UTS}{e^{-n}n^{n}} \times \left(\frac{1+R}{\sqrt{1+2R}}\right)^{1+n} \frac{3(1-v^{2})}{2E(1+n)} \left(\frac{t}{2\rho}\right)^{n-1} \tag{3.1}$$

Where $\Delta\theta/\theta$ is the spring back ratio, *UTS* the tensile strength, *n* the strain hardening exponent, *R* the normal anisotropic value, *v* the Poisson's ratio, *E* the Young's modulus, *t* sheet thickness and ρ is the neutral axis. The neutral axis has been determined by using the equation (3.2):

$$\rho = \sqrt{r_0 r_i} \tag{3.2}$$

Where r_0 is the radius of the outer layer of the bent is sheet while r_i is the radius of the inner layer of the bent sheet.

The normal anisotropic value, R has been determined by using the equation (3.3):

$$R = \frac{R_0+2R_{45}+R_{90}}{4} \tag{3.3}$$

Where R_0, R_{45} and R_{90} is the value of R at 0°, 45° and 90° with the respect to the rolling direction of the sheet.

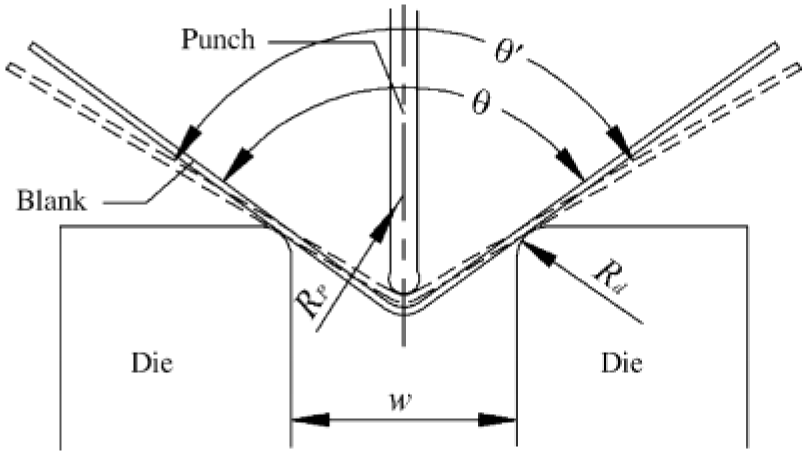


Figure 3.9: Illustration of v-free bending

Source: Dongye Fei Nilsson (2006)

In the Dongye Fei *et. al.* (2006) study, the theoretically calculation also has been used to determine the spring back in air V-bending. The spring-back can be theoretically calculated using equation 3.4:

$$\frac{\Delta\theta}{\theta} = \frac{3K\rho(1-v^2)(1+4t/\omega)}{Et} \tag{3.4}$$

Where K is the ultimate tensile strength, ρ the position of the neutral axial, v the Poisson’s ratio, w the die gap, E the Young’s modulus and t is the thickness. The equation can be used to explain the reason that thinner blank thickness and wider die gap, the higher spring back angles.

3.5 V-BENDING TEST EXPERIMENT

Bending is a common metal forming process used in sheet metal forming to fabricate curve and angle shape products of various sizes, such as parts of automobiles, ships and aircraft. Furthermore, this process also used in making the various consumer products, such as kitchenware and sanitary products. There are many types of bending in industries such as the wiping die bending, U-bending and V-bending process. The bending process concept is based on engineering science and has wide applications. Furthermore, bending also features in many sheet metal forming processes, such as the deep drawing and stamping processes. In this project, V-bending process has been selected as an experimental method to determine the spring-back angle. The experiments were performed using LVD-HD machine. The stainless steel sheet specimens from two different thicknesses were bent and the specimen has been scanned to measure the spring-back angles. The result of this experiment has been used to evaluate the reliability of analytical method in sheet metal bending analysis.

3.5.1 Specimen Preparation

In this test, two different thicknesses of stainless steel have been used to perform the tensile test. The thicknesses are 1.5 mm and 2.0 mm. Each thickness has been cut in the different orientation angle of 0, 45 and 90 degrees and each orientation angles have been cut for 12 specimens. Table 3.2 shows the total specimens in this project.

Table 3.2: Total bending specimen

Specimen Thickness (mm)	**Bil. of Specimen**			
	0°	**45°**	**90°**	**Total Specimen**
1.5	12	12	12	36
2.0	12	12	12	36

The material was cut into a rectangular size of 100 mm x 100 mm by using LVD shearing cutting machine. It was cut followed the angle of 0^o, 45^o and 90^o, which is varying with the direction of rolling.

Figure 3.10: LVD shearing machine

3.5.2 V-Bending Experiment

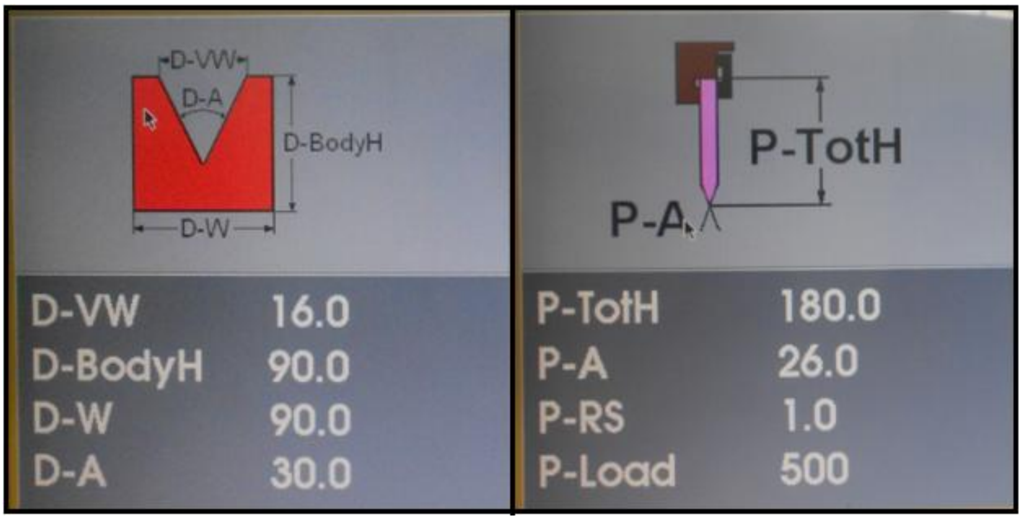
The V-die bending process can be defined as a bending of a V-shaped part in a single die. The specimen was bent into V-shaped die and punch. The force acting on the punch caused punch displacement and made the specimen bent. The specimen was initially bent as an elastic deformation. The process continued downward motion by the punch, and when the stresses exceed the elastic limit, the plastic deformation sets in. This plastic deformation start occurs on the outer and inner surfaces directly underneath the punch. The greatest tensile stress was occurred on the outer surface and the greatest compressive stress was occurred on the inner surface. These stresses decreasingly expand inward toward the specimen. In addition, crack formation usually occurs on the outer surface and wrinkle usually occurs on the inner surface. The initial bending stage is known as Air bending. Air bending is a process that starts from the moment the punch establishes contact with the specimen and completed either when the legs of the specimen become tangential to the faces of the die or when the smallest internal radius of the specimen becomes smaller than the radius of the punch. As the process continues, after completion of air bending, the bending was focused on the three points of the punch and the two faces of the die. The contact points between the specimen and die are shifted toward the centerline of the die, and the legs of the specimen try to close around the punch. As the punch proceeds further, the legs of the specimen establish contact with the punch, and it was pressed to open up again until the bend angle approaches the die angle.

3.5.3 Bending Machine

The LVD-HD machine (Figure 3.11) with a capacity of 800 KN/2500 mm maximum force was used to perform the bending test in this experiment.

Figure 3.11: LVD-HD bending machine

Figure 3.12 shows the specifications of die and punch for LVD-HD bending machine. This specification also can be referred in Table 3.3 for lower die and Table 3.4 for upper punch.



D-VW	16.0
D-BodyH	90.0
D-W	90.0
D-A	30.0

P-TotH	180.0
P-A	26.0
P-RS	1.0
P-Load	500

(a) **(b)**

Figure 3.12: (a) Die specification **(b)** Punch specification

Table 3.3: Lower die specification

Specification	Value
Die Angle (D-A)	30°
Die Gap (D-VW)	16 mm
Die Height (D-BodyH)	90 mm
Die Width (D-W)	90 mm

Table 3.4: Upper punch specification

Specification	Value
Punch Angle (P-A)	26°
Punch Tip Radius (P-RS)	1 mm
Punch Height (P-TotH)	180 mm
Punch Load (P-Load)	500 kN

3.5.4 Bending Process

After the test specimens have been properly prepared, the bending test setup will be established to conducting the bending test. In this project, two different test procedures were used.

i. In the first experiment, punch was lowered completely to the bottom of the die. This process was normally called as a bottoming process in V-bending experiment.
ii. In the second experiment, punch was not thoroughly set to the bottom of the die. A gap between the die and punch was equal to the thickness of sheet material. This process was likely same for the air V-bending process.

The specimens were placed properly on the die at the LVD-HD bending machine. Scheme 3.4 shows the v-bending processes using the LVD-HD bending machine.

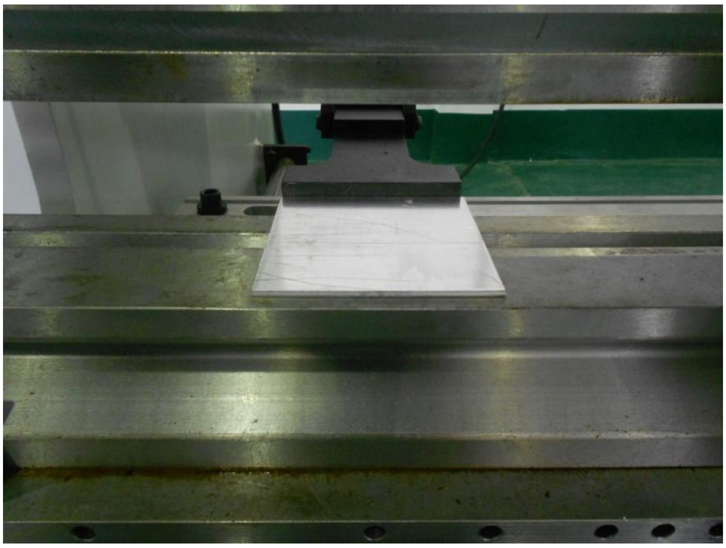
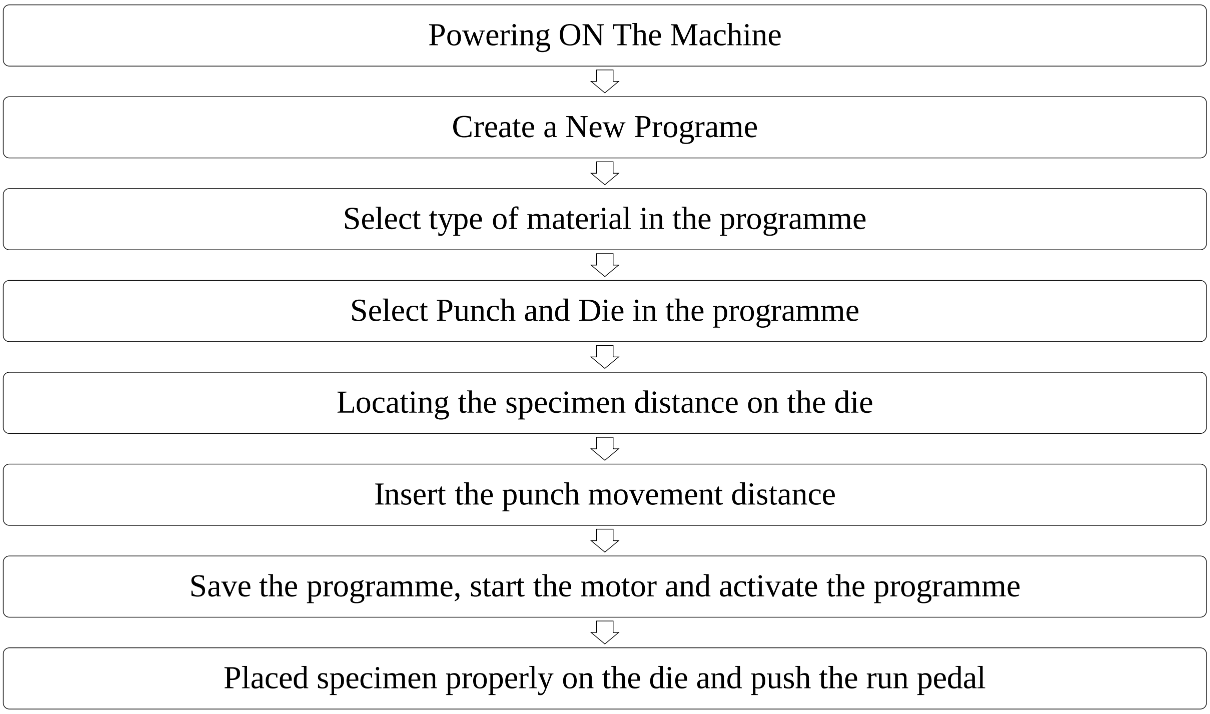


Figure 3.13: Specimen on the die



Scheme 3.4: V-Bending processes using the LVD-HD bending machine

After the LVD-HD bending machine has been ON, opens the new programme in the monitor screen and a new programme created. Click MATERIAL icon and specify the type of material and the thickness. Then, click the DIE icon and select the die type. The 30 degree die angle will be use for this bending test. In this programme, select the die code MV16_30_90 for 30 degree angle die. After that click the PUNCH icon and select the punch code F10. The specimen should be placed centrally on the die after the distance of the specimen stopper has been clarified in the programme. The specimen stopper distance is 50 mm because the specimen size was 100 mm × 100 mm. Then, setup the punch movement distance in the programme. The punch need to be move about 78 mm downward. Finally save the programme and start the motor to run the programme by pushing the run pedal.

(a) **(b)**

Figure 3.14: **(a)** Bending specimen after bending process **(b)** Bending process

3.5.5 Measuring Specimen Angle

The bending angle of the specimen has been measured using the SolidWorks software. After the specimen bent, it was scanned using Canon Inkjet MP 140 Series. The scanning profile was saving in the picture format. The bending specimen figure then was being imported in the SolidWorks software and the angle measured. Scheme 3.5 shows the procedure in measuring specimen angle.

Scan specimen using Canon Inkjet MP 140 Series printer
⇩
Save the scanning profile in picute (JPEG Format)
⇩
Open Solidworks software and import the specimen picture using skecth tool toolbar
⇩
Skecth the v-line on the specimen and measure the angle using smart dimension tool
⇩
Save the result

Scheme 3.5: Measuring specimen angle using Solidworks software

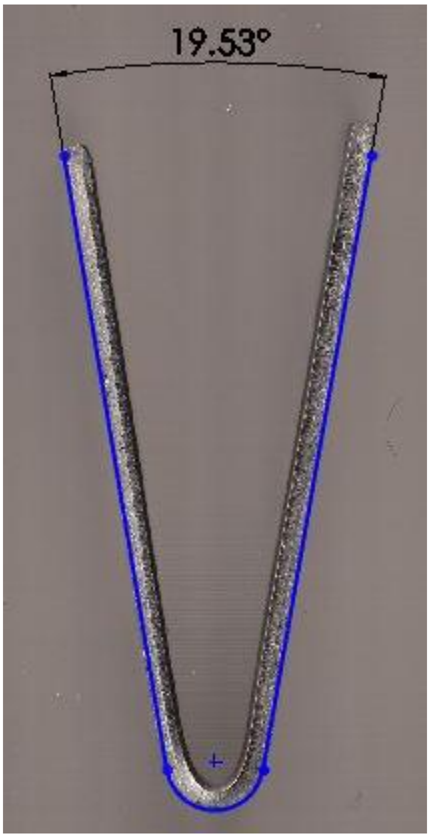


Figure 3.15: Specimen scanning picture

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter will discuss on the end result of this project. In this project, the analytical and experimental methods have been used to determine the spring-back values of V-bending process for stainless steel. For analytical method, the mechanical properties of stainless steel have been found using tensile test experiment. Two different spring-back equations from different references were used in analytical calculation. In the experimental method of V-bending, the experiment was performed using two different procedures and test setups. The results from both methods have been compared and also have been compared with the past result from the past studies. Ultimately, the reliability of analytical methods in sheet metal bending analysis of stainless steel has been evaluated in this chapter.

4.2 TENSILE TEST

Tensile test is one of the most popular that been used for evaluating material properties. In this test, stainless steel specimens were been pulled to failure in a relatively short time at constant rate of 5 mm/min. During the tensile test process, force and extension data has been monitored and recorded. The tensile test provides force and extension data that can quantify several important mechanical properties of stainless steel such as elastic deformation properties (Young's modulus and Poisson's ratio), yield strength, ultimate tensile strength, ductile properties (elongation and reduction in area) and strain-hardening characteristics. The mechanical properties that have been provided by tensile test were used in the analytical method in solving the spring-back equation.

4.2.1 Mechanical Properties of Stainless Steel

In the tensile test process, force (load) and extension data has been monitored and recorded. Force (load) and extension data that provided by this test can be used to find several important mechanical properties of stainless steel such as elastic deformation properties (Young's modulus and Poisson's ratio), yield strength, ultimate tensile strength, ductile properties (elongation and reduction in area) and strain-hardening characteristics. Other than that, the machine also can provide the mechanical properties value directly if the method is set up to determined the values. Table 4.1 shows the mechanical properties values that have been selected in the tensile test method.

Table 4.1: Mechanical properties from tensile test result

Load at Break (Standard) (KN)	**Maximum Load (KN)**	**Modulus (Automatic) (MPa)**	**Strain hardening exponent at n-value (Automatic)**
3.96	13.16	1154	0.47418

Using the recorded data (load and extension), the engineering stress is found by dividing the applied load by the specimen original cross sectional area.

$$\sigma_{eng} = \frac{P}{A_0} \tag{4.1}$$

The engineering strain is found by dividing the change in the specimen gage length by the specimen original gage length.

$$\varepsilon_{eng} = \frac{\delta}{l_0} = \frac{l - l_0}{l_0} \tag{4.2}$$

The true stress and true strain of stainless steel AISI 304 can be found by using the engineering stress and strain value with the equation below:

$$\sigma_{true} = \sigma_{eng}\left(1 + \varepsilon_{eng}\right) \tag{4.3}$$

$$\varepsilon_{true} = \ln\left(1 + \varepsilon_{eng}\right) \tag{4.4}$$

Table 4.2 below show the values of engineering stress, true stress, engineering strain and true strain that can be found by using force (load) and extension data from the test. The data in the table below is initial values of the data in 10 seconds.

Table 4.2: Tensile test result for stainless steel 1.5 mm thickness

Time (s)	**Extension (mm)**	**Load (kN)**	**Eng. Stress (Mpa)**	**True Stress (Mpa)**	**Eng. Strain (mm/mm)**	**True Strain (mm/mm)**
0	0	1.43190	76.3680000	76.3680000	0	0
1	0.08362	2.71182	144.6304000	144.8722799	0.0016724	0.001671003
2	0.16700	3.80415	202.8880000	203.5656459	0.0033400	0.003334435
3	0.25025	4.65057	248.0304000	249.2717922	0.0050050	0.004992517
4	0.33369	5.18077	276.3077333	278.1517559	0.0066738	0.006651629
5	0.41700	5.39963	287.9802667	290.3820221	0.0083400	0.008305414
6	0.50025	5.52776	294.8138667	297.7634794	0.0100050	0.009955281
7	0.58369	5.62730	300.1226667	303.6262387	0.0116738	0.011606187
8	0.66700	5.71148	304.6122667	308.6757943	0.0133400	0.013251806
9	0.75031	5.78725	308.6533333	313.2850470	0.0150062	0.014894721
10	0.83362	5.85621	312.3312000	317.5385107	0.0166724	0.016534941

Based on the tensile test results above, the stress-strain graph can be plotted. The graph can be plotted by using the engineering stress and strain. Figure 4.1 and Figure 4.2 shown stress-strain graph for stainless steel material with different orientation angle (R).

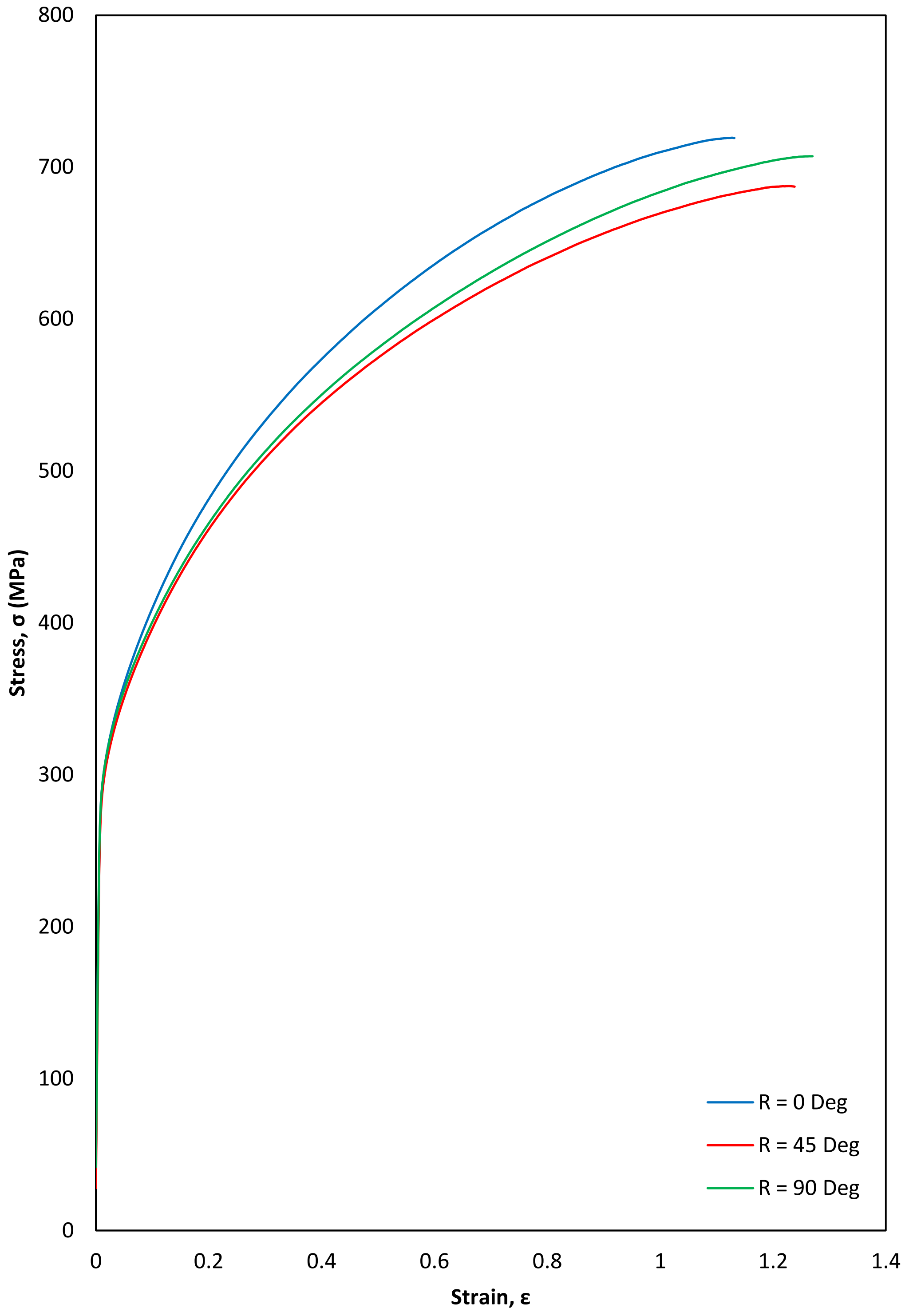


Figure 4.1: Different orientation angle of stress-strain graph for stainless steel 1.5 mm thickness

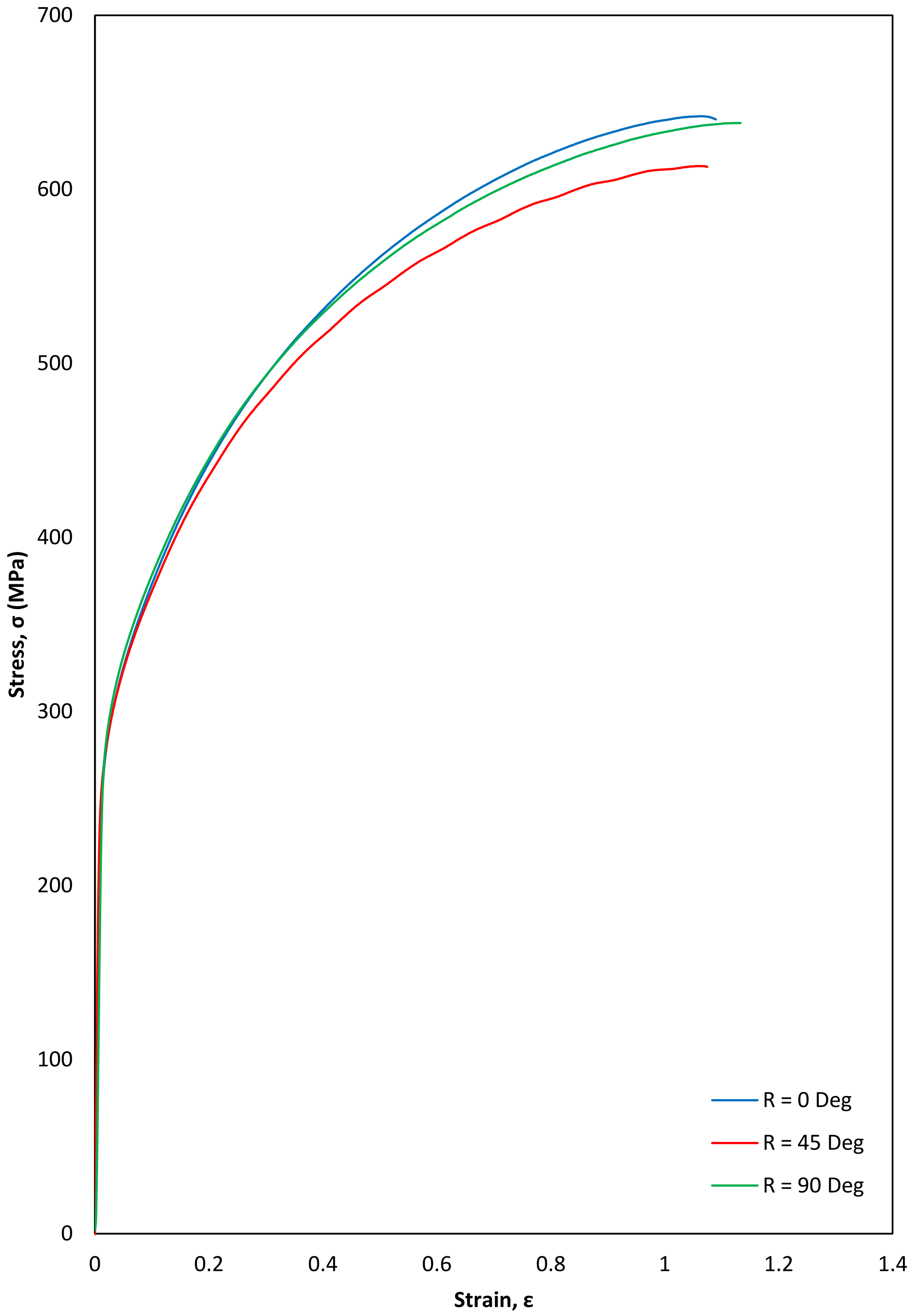


Figure 4.2: Different orientation angle of stress-strain graph for stainless steel 2 mm thickness

Based on the Stress-Strain graph for stainless steel of thickness of 1.5 mm and 2.0 mm, the proportional limit stress, σ_{pl} seems to be much closed values for three different orientation angles. After passes the proportional limit stress point, the test specimens were continuously extent until it reached the maximum stress which is normally known as ultimate tensile strength (UTS) before it break. From the graph, the 0 degree orientation angle specimens have higher UTS values followed by 90 degree and 45 degree orientation angle specimens. For small strain values (the elastic region), the relationship between stress and strain is nearly directly proportional. Within this region, the slope of the stress-strain curve is defined as the elastic modulus or Young's modulus. The slope of the curve was measured before the stress value reached the proportional limit stress σ_{pl} which about 250 MPa. From Table 4.2, the initial data of engineering stress less than 250 MPa was selected and the stress-strain was plotted again to produce a linear stress-strain graph. Figure 4.3 below shows the linear stress-strain graph.

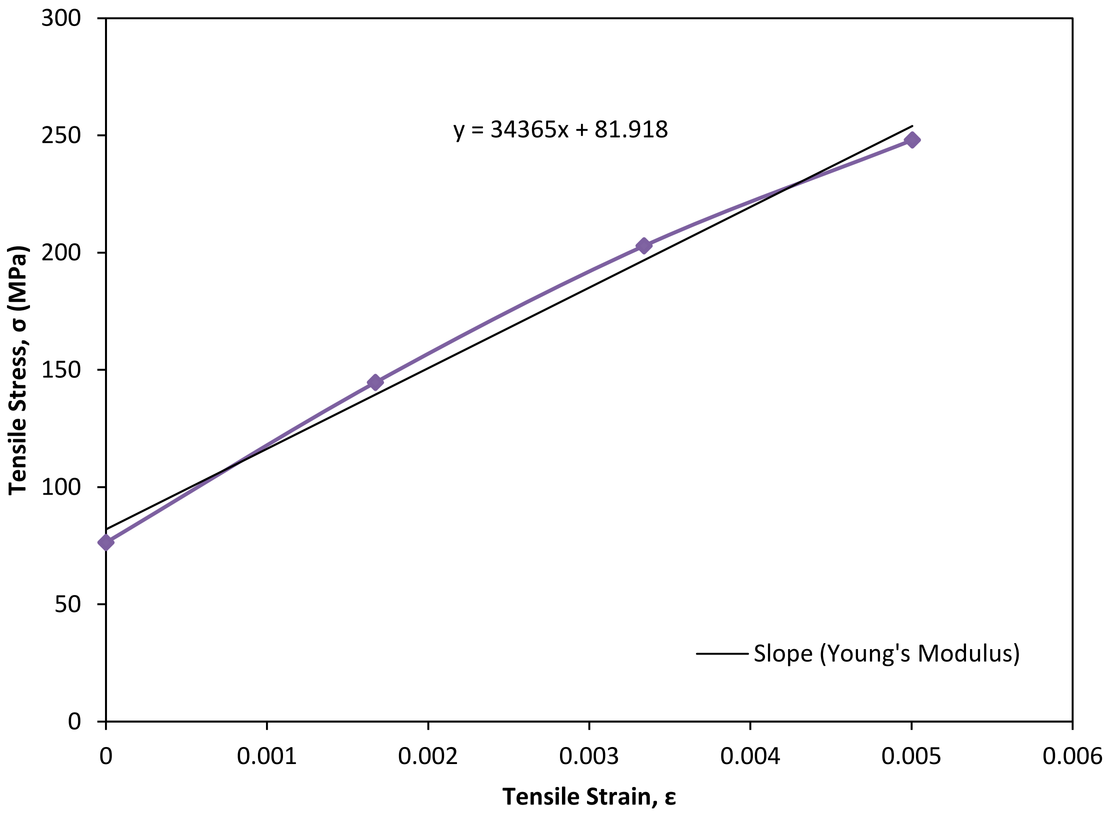


Figure 4.3: Linear stress-strain graph for 1.5 mm thickness

A linear stress-strain graph above shows the slope of the curve estimated was 34365 MPa. A linear stress-strain graph has been plotted for each of the specimens and the average values will produce precise Young's modulus values. Other mechanical properties for stainless steel such as anisotropy values and Poison's ratio can be determined from the final width and length of specimens measured. Table 4.3 had shown the average width and length after the test.

Table 4.3: Final width and length of tensile specimen

Orientation Angle	Average Final Width,	Average Final Length,
Thickness 1.5 mm		
0	8.566666667	108.8057667
45	8.326666667	113.7223667
90	8.493333333	113.3891000
Average	8.462222222	111.9724111
Thickness 2 mm		
0	8.166666667	107.8058000
45	8.086666667	114.2390000
90	8.173333333	111.5279333
Average	8.142222222	111.1909111

Anisotropy value, R is defined to express different contractile strain ratio and is generally applied as an index of anisotropy. Due to the difficulty in measuring gage thickness changes with sufficient precision, an equivalent relationship is commonly used, based on length and width strain measurements:

$$R = \frac{\varepsilon_w}{-(\varepsilon_l + \varepsilon_w)} = \frac{\ln(w_0/w_f)}{\ln(l_f w_f / l_0 w_0)} \tag{4.5}$$

Where ε_w and ε_l are true strains in width and length directions, w_0, w_f, l_0 and l_f are initial and final gage width and length, respectively. With most materials the change of R with strain ε_l is negligible.

The ratio of the two normal strains (lateral and longitudinal) is material constant called the Poison's ratio.

$$v = -\frac{\varepsilon_{lateral}}{\varepsilon_{longitudinal}} = -\frac{(w_f - w_0)/w_0}{(l_f - l_0)/l_0} \tag{4.6}$$

Wherew_0, w_f, l_0 and l_f are initial and final gage width and length, respectively. Table 4.4 had shown the final summaries for the mechanical properties of stainless steel at every orientation angle.

Table 4.4: Mechanical properties of stainless steel

Orientation Angle	**Young's Modulus, *E* (MPa)**	**Strain Hardening Exponent, *n***	**Ultimate Tensile Strength, *UTS* (MPa)**	**Anisotropy Value, *R***	**Poisson's Ratio, *v***
Thickness 1.5 mm					
0	33213.33	0.494603333	712.9808000	0.954668958	0.267547457
45	33361.33	0.499413333	694.1545000	0.979193519	0.261969764
90	29958.00	0.503130000	692.3155667	0.897142772	0.252830008
Average	32177.55	0.499048889	699.8169556	0.943668416	0.260782410
Thickness 2 mm					
0	21921.00	0.503610000	629.0205333	1.242315611	0.299854571
45	20068.33	0.509593333	622.7584000	1.114532146	0.274807101
90	17548.33	0.508286667	620.9714667	1.125732736	0.281281456
Average	19586.88	0.507163333	624.2501333	1.156804141	0.284864383

Based on the result predicted above, the mechanical properties values from the tensile test are closely same to the standard values except the Young's modulus value. The Young modulus values are very small compared to the standard values of stainless steel AISI 304. The standard values are about in between 193 GPa to 200 GPa.

4.3 ANALYTICAL CALCULATION

Analytical calculation is one of the methods in predicting the spring-back angle after bending process. The effect of the anisotropy values, *R* (orientation angle) and the thickness of the specimens have been studied in the study. The highlight of this paper is equations from the past studies are used to estimate spring-back angle in V-die bending. The equations from Leu (1997) and Dongye (2006) has been used to estimate the values. The mechanical properties that provided from tensile test have been used in the analytical method in solving the spring-back equation. The predicted values of the spring-back have been compared with the experimental values and published experimental results. The result of the two different equations have been predicted and discussed. All the data and predicted values were shown in the table and graph.

4.3.1 Daw-Kwei Leu (DKL) Equation

Table 4.5: Daw-Kwei Leu equation data

Orientation Angle (Degree)	Young's Modulus, *E* (MPa)	Ultimate Tensile Strength, *UTS* (MPa)	Strain Hardening Exponent, *n*	Poisson's Ratio, *v*	Anisotropy Value, *R*	Neutral Axis, *ρ* (mm)
Thickness 1.5 mm						
0	33213.33	712.9808000	0.494603333	0.267547457	0.954668958	1.5811388
45	33361.33	694.1545000	0.499413333	0.261969764	0.979193519	1.5811388
90	29958.00	692.3155667	0.503130000	0.252830008	0.897142772	1.5811388
Average	32172.56	699.817000	0.49900000	0.26080000	0.952550000	1.5811388
Thickness 2 mm						
0	21921.00	629.0205333	0.503610000	0.299854571	1.242315611	1.7320508
45	20068.33	622.7584000	0.509593333	0.274807101	1.114532146	1.7320508
90	17548.33	620.9714667	0.508286667	0.281281456	1.125732736	1.7320508
Average	19586.88	624.2501	0.50716	0.2849	1.1492775	1.7320508

Table 4.6: Effect of sheet anisotropy on spring-back value for Daw-Kwei Leu equation

Orientation Angle (Degree)	**Spring-back Ratio, $\Delta\theta/\theta$**	**Spring-back, $\Delta\theta$ (Degree)**
Thickness 1.5 mm		
0	0.084245009	2.527350271
45	0.084765018	2.542950536
90	0.083027703	2.490831097
Average	0.084199435	2.52598304
Thickness 2 mm		
0	0.118012271	3.540368123
45	0.11440602	3.432180613
90	0.114721339	3.441640176
Average	0.115384828	3.461544833

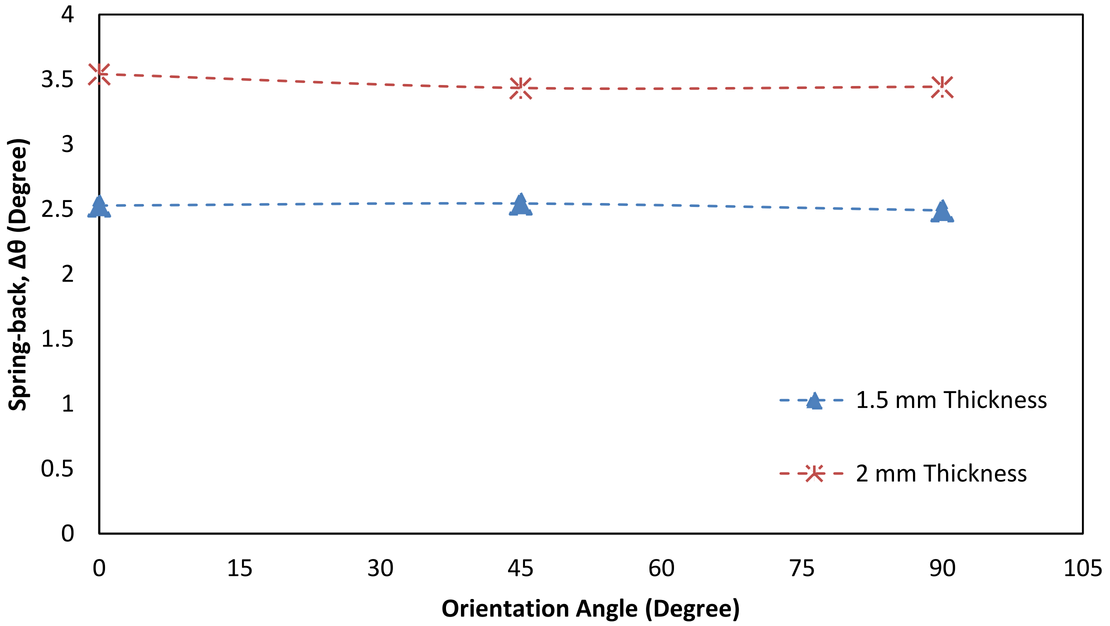


Figure 4.4: Effect of sheet anisotropy on spring-back value for Daw-Kwei Leu equation

Figure 4.4 shows the effect of sheet anisotropy on the spring-back at various thicknesses in V-bending. As shown in the figure, in general, increasing the bending direction to the rolling direction result is a decreased in the spring-back. However, for the 1.5 mm sheet thickness, the spring-back is increases until 45 degree of orientation angle before it start to decrease. For the 2 mm sheet thickness, the spring-back is decreases until 45 degree of orientation angle before it start to increase. Accordingly, it was concluded that the bending of the sheet at orientation 0 degree is suitable condition for spring-back or spring-go reduction in the V-bending process because the spring-back value is smaller compared to other orientation angles. The graph trends are in agreement with the study conducted by other researcher (Bakhshi-Jooybari, 2009).

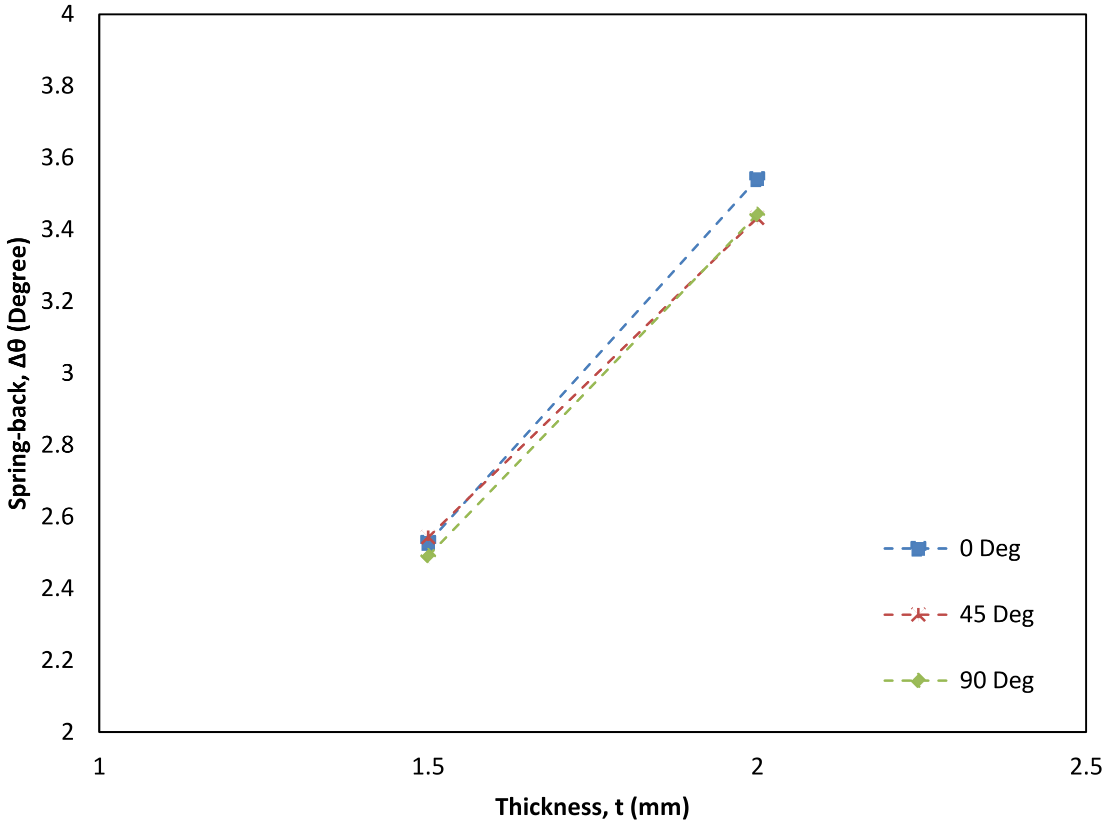


Figure 4.5: Effect of sheet thickness on spring-back value for Daw-Kwei Leu equation

Figure 4.5 show the influence of sheet thickness on spring-back in V-bending at various sheet orientations respectively. As figure 4.5, by increasing the sheet thickness from 1.5 mm to 2 mm, the amount of spring-back is increases. The graph patterns obtained in this result are generally in agreement with the past study (Özgür, 2008).

4.3.2 Dongye Fei and Peter Hodgson (DFPH) Equation

Table 4.7: Effect of sheet anisotropy on spring-back value for Dongye Fei and Peter Hodgson equation

Orientation Angle (Degree)	**Young's Modulus, *E* (MPa)**	**Ultimate Tensile Strength, *UTS* (MPa)**	**Poisson's Ratio, *v***	**Neutral Axis, *ρ* (mm)**	**Die Gap, *w* (mm)**	**Springback Ratio, $\Delta\theta/\theta$**	**Springback, $\Delta\theta$ (Degree)**
Thickness 1.5 mm							
0	33213.33	712.9808000	0.267547457	1.5811388	16	0.027573201	0.827196038
45	33361.33	694.1545000	0.261969764	1.5811388	16	0.026811058	0.804331734
90	29958.00	692.3155667	0.252830008	1.5811388	16	0.029928221	0.897846638
Average	32172.556	699.817000	0.26080000	1.58113883	16	0.02804692	0.84140754
Thickness 2 mm							
0	21921.00	629.0205333	0.299854571	1.7320508	16	0.038164704	1.144941117
45	20068.33	622.7584000	0.274807101	1.7320508	16	0.041925745	1.257772355
90	17548.33	620.9714667	0.281281456	1.7320508	16	0.047622661	1.428679823
Average	19586.875	624.250100	0.28486000	1.73205081	16	0.04279714	1.28391424

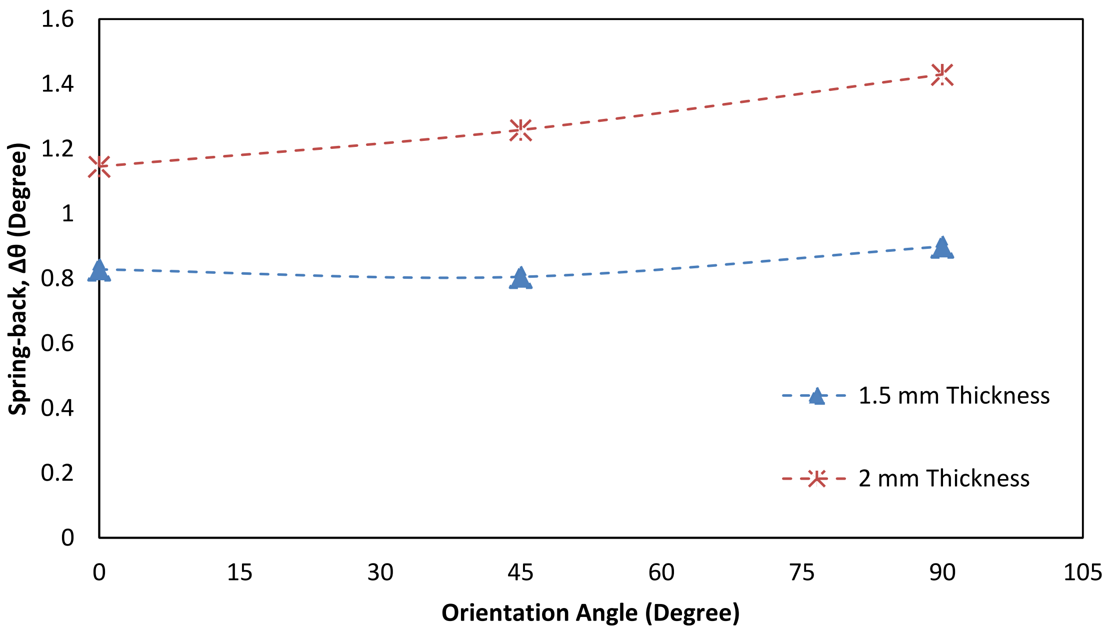


Figure 4.6: Effect of sheet anisotropy on spring-back value for Dongye Fei and Peter Hodgson equation

Figure 4.6 shows the effect of sheet anisotropy on the spring-back at various thicknesses in V-bending test. As shown in the figure, in general, the increasing of the bending direction to the rolling direction resulted in increasing for the spring-back. Except, for the 1.5 mm sheet thickness, the spring-back is decreases at 45 degree of orientation angle before it started to increase. Accordingly, it was concluded that the bending of the sheets at orientation 0 degree was suitable condition for spring-back or spring-go reduction in the V-bending process for the reason that the spring-back value is smaller compared to other orientation angles. The graph trends are in agreement with the study conducted by other researcher (Bakhshi-Jooybari, 2009).

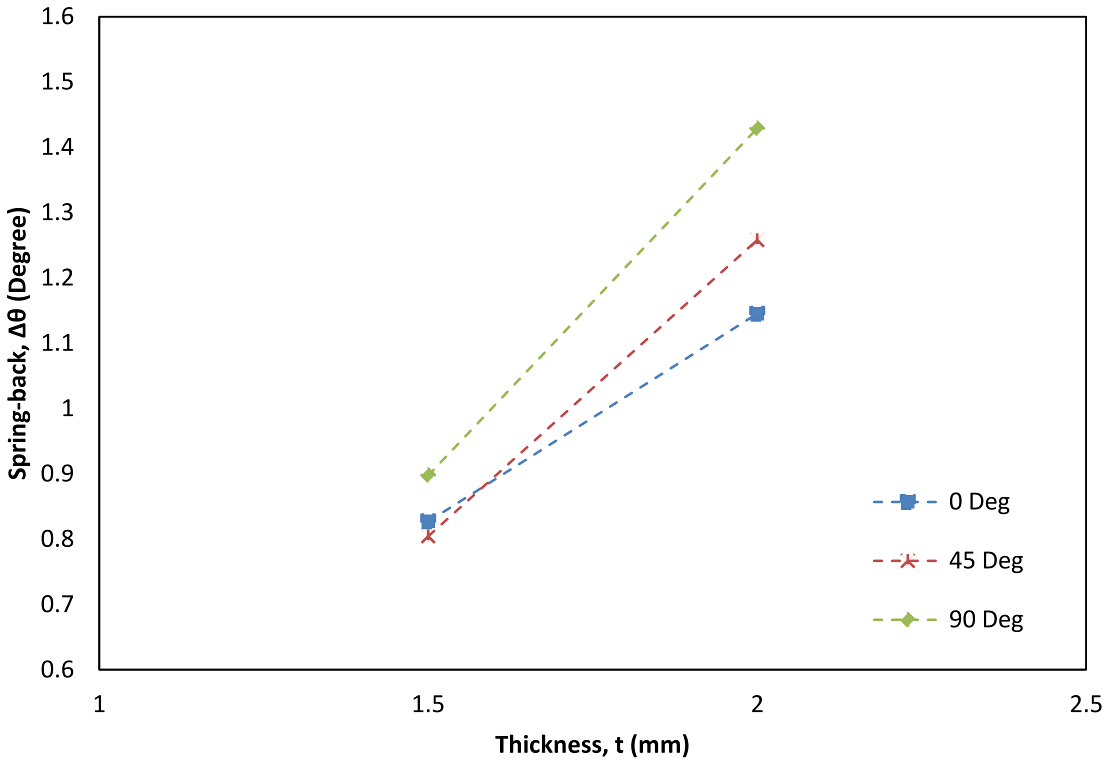


Figure 4.7: Effect of sheet thickness on spring-back value for Dongye Fei and Peter Hodgson equation

Figure 4.7 shows the influence of the sheet thickness on spring-back in V-bending at various sheet orientations respectively. As figure 4.7, by increasing the sheet thickness from 1.5 mm to 2.0 mm, the amount of spring-back is increased. The graph pattern obtained in this result is generally in agreement the past study by other researcher (Özgür, 2008).

4.4 V-BENDING TEST EXPERIMENT

In the bending test, the specimen angle is very important. Normally, the specimen angles for stainless steel material are greater than die angle after bending process. This is due to the elastic recovery characteristic of the material. This elastic recovery is called “spring-back”. Thus, the specimens tried to spring-back and the bent part slightly opens out. However, the experimental result depended on the bending method and procedure. Regarding to Özgür Tekaslan (2006), combination of various materials and process parameters make the exact estimation of spring-back would be hard. Practical results of the experiments are presented in tables. Spring-back graphs also have been drawn according to two different procedures and test setups.

4.4.1 Bottoming Process of V-bending

In this experiment, punch was lowered to the bottom of the die. This process is normally called as bottoming process in V-bending experiment. Table 4.8 has shown the predicted result of the study.

Table 4.8: Bending angles result according to the bottoming process

Thickness (mm)	**Orientation Angle (Degree)**	**Bending Angle (Degree)**						**Average Angle (Degree)**	**Die Angle (Degree)**	**Spring-back Angle (Degree)**
		Sample								
1.5	**0**	18.58	18.30	18.37	18.50	18.38	18.31	18.41	30	-11.59
	45	18.92	19.31	18.99	18.17	18.90	18.89	18.86	30	-11.14
	90	18.22	18.57	18.30	18.25	18.65	18.23	18.37	30	-11.63
2.0	**0**	19.58	19.85	19.70	19.56	21.57	21.36	20.27	30	-9.73
	45	21.25	21.10	21.12	20.79	21.22	20.84	21.05	30	-8.95
	90	20.30	22.79	19.91	19.53	20.91	21.00	20.81	30	-9.19

According to table 4.8, the spring-back value is negative. The negative values are called as a spring-go. The results according to the first experiment setup are generally not in agreement with the past researches. It can be concluded that the different spring-back is possible regarding to the die design and convenience of the material. Combination of various processes makes it difficult to obtain the predicted spring-back. Material parameters such as elasticity, yield stress, hardening property, as well as process parameters for example the load applied, thickness of sheet metal, die angle, punch radius and die gap affect spring back in complex way.

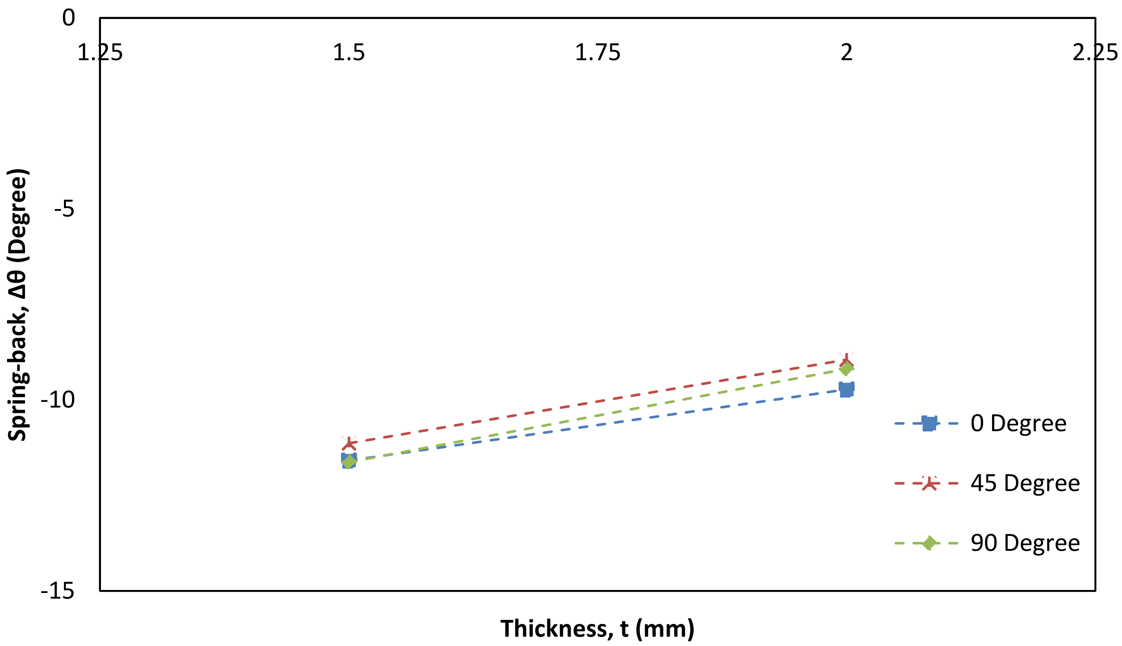


Figure 4.8: Effect of sheet thickness on spring-back value according to the bottoming process

Figure 4.8 shows the influence of sheet thickness on spring-back in V-bending at various sheet orientations respectively. In the figure, the values on the vertical axis are negative. The negative values of spring-back are called spring-go. As figure 4.8, by increasing the sheet thickness from 1.5 mm to 2.0 mm, the amount of spring-back is increased which mean decreased of the amount of spring-go. The graph trends obtained for the result are generally in agreement with the past study (Özgür, 2008).

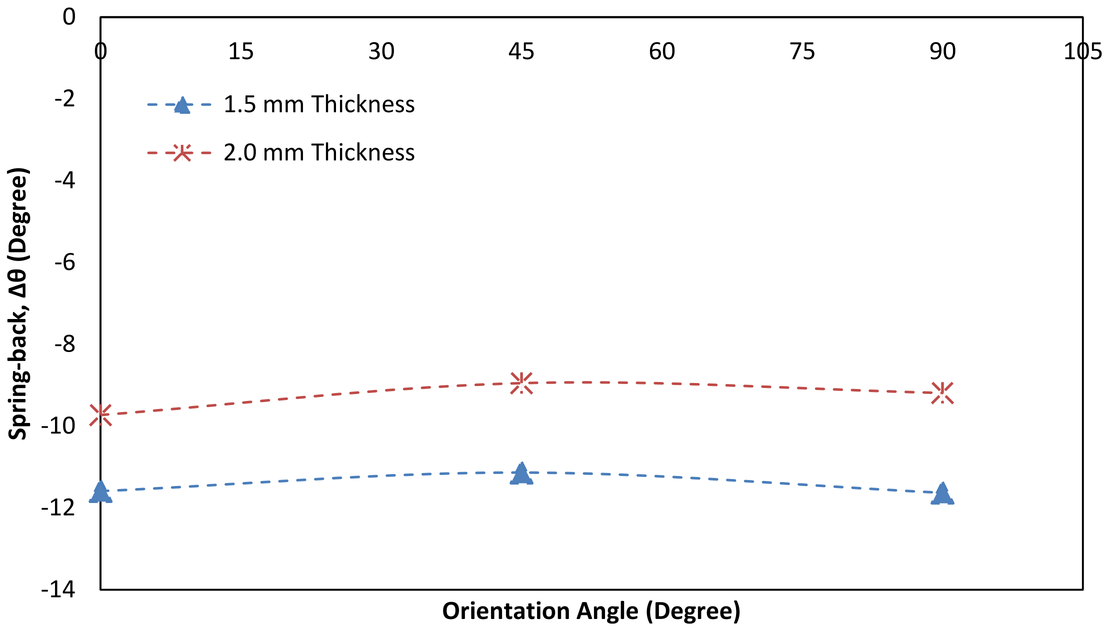


Figure 4.9: Effect of sheet anisotropy on spring-back value according to the bottoming process

Figure 4.9 shows the effect of sheet anisotropy on the spring-back at various thicknesses in V-bending. As shown in the figure, in general, the bending direction increase to the rolling direction resulted in increasing of the spring-back. But the spring-back is increases until 45 degree of orientation angle before it started to decrease. Accordingly, it was concluded that the bending of sheet at orientation 0 degree the best condition for spring-back or spring-go reduction in the V-bending process because the spring-back value is smaller compared to other orientation angles. The graph patterns are in agreement with the study was conducted previous (Bakhshi-Jooybari, 2009).

4.4.2 Air V-bending Process

In the second experiment, punch was not thoroughly set to the bottom of the die. A gap between the die and punch is equal to the thickness of sheet material. This process is likely for the air V-bending process. The predicted result has shown in the Table 4.9.

Table 4.9: Bending angles result according to the air V-bending process

Thickness (mm)	Orientation Angle (Degree)	Bending Angle (Degree)						Average Angle (Degree)	Die Angle (Degree)	Spring Back Angle (Degree)
		Sample								
1.5	**0**	32.0	30.5	30.5	32.0	31.0	31.5	31.25	30	1.25
	45	31.0	31.5	31.5	32.5	31.5	32.5	31.75	30	1.75
	90	31.5	31.5	31.5	31.5	31.5	31.5	31.50	30	1.50
2.0	**0**	33.0	31.5	32.5	33.0	31.0	31.0	32.00	30	2.00
	45	34.0	33.5	33.5	32.5	33.5	33.0	33.33	30	3.33
	90	34.0	33.5	32.5	32.0	31.0	30.5	32.25	30	2.25

In this experiment, the predicted result obtained in the Table 4.9 is commonly closed to the analytical calculation. The angle of the specimen is greater than die angle after bending process. These results are not in agreement with the past study conducted by other researcher.

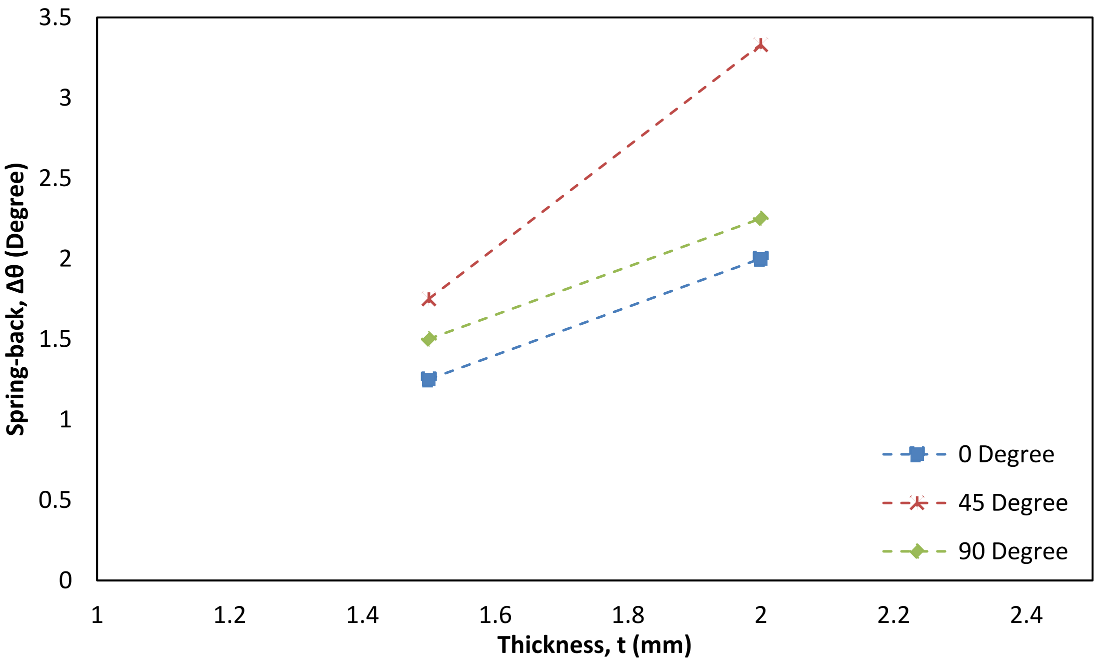


Figure 4.10: Effect of sheet thickness on spring-back value according to the air V-bending process

Figure 4.10 show the influence of sheet thickness on spring-back in V-bending at various sheet orientations respectively. As figure 4.10 shows, by increasing the sheet thickness from 1.5 mm to 2 mm, the amount of spring-back is increased. The graph trends obtained in the result are generally in agreement with the past study by other researcher (Özgür, 2008).

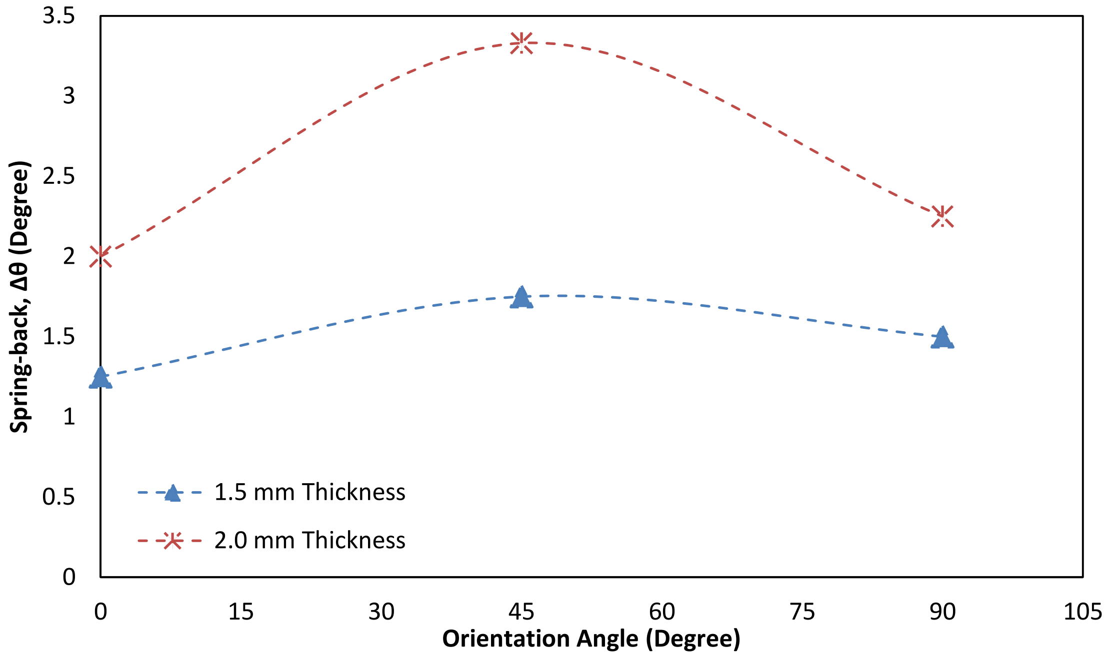


Figure 4.11: Effect of sheet anisotropy on spring-back value according to the air V-bending process

Figure 4.11 shows the effect of sheet anisotropy on the spring-back at various thicknesses in V-bending. As shown in the figure above, in general, increasing the bending direction to the rolling direction resulted in an increase in the spring-back. But the spring-back is increases at 45 degree of orientation angle before the values start to decrease. Accordingly, it was concluded that the bending of sheet at orientation 0 degree was appropriate condition for spring-back or spring-go reduction in the V-bending process because the spring-back value is smaller compared to the other orientation angles. The graph patterns are in agreement with the study conducted by other researcher (Bakhshi-Jooybari, 2009).

4.5 RESULT SUMMARY

This study purposes is to discover out the spring-back values of V-bending for stainless steel material. The spring-back values have been determined using analytical method and experimental method. The results for both methods have been compared and the reliability of the analytical method in sheet metal bending analysis has been evaluated. The result was also been compared with the result of the previous study. The predicted result from the analytical calculation and the result from V-bending experiment are compared with the experimental measurements of Özgür (2008). Table 4.10 shows comparison of the results.

Table 4.10: Comparison between analytical calculation and experimental result with past result conducted by Özgür (2008)

Method	Bending Angle (Degree)	Thickness (mm)	Spring-back, $\Delta\theta$ (Degree)
Experimental Measurements of Özgür Tekaslan (ÖT)	30	0.50	1.01
		0.75	1.89
		1.00	2.00
Analytical Calculation of Daw-Kwei Leu (DKL)	30	1.50	2.53
		2.00	3.46
Analytical Calculation of Dongye Fei and Peter Hodgson (DFPH)	30	1.50	0.84
		2.00	1.28
First Method Experimental Result (Bottoming)	30	1.50	-11.45
		2.00	-9.29
First Method Experimental Result (Bottoming)	30	1.50	1.50
		2.00	2.53

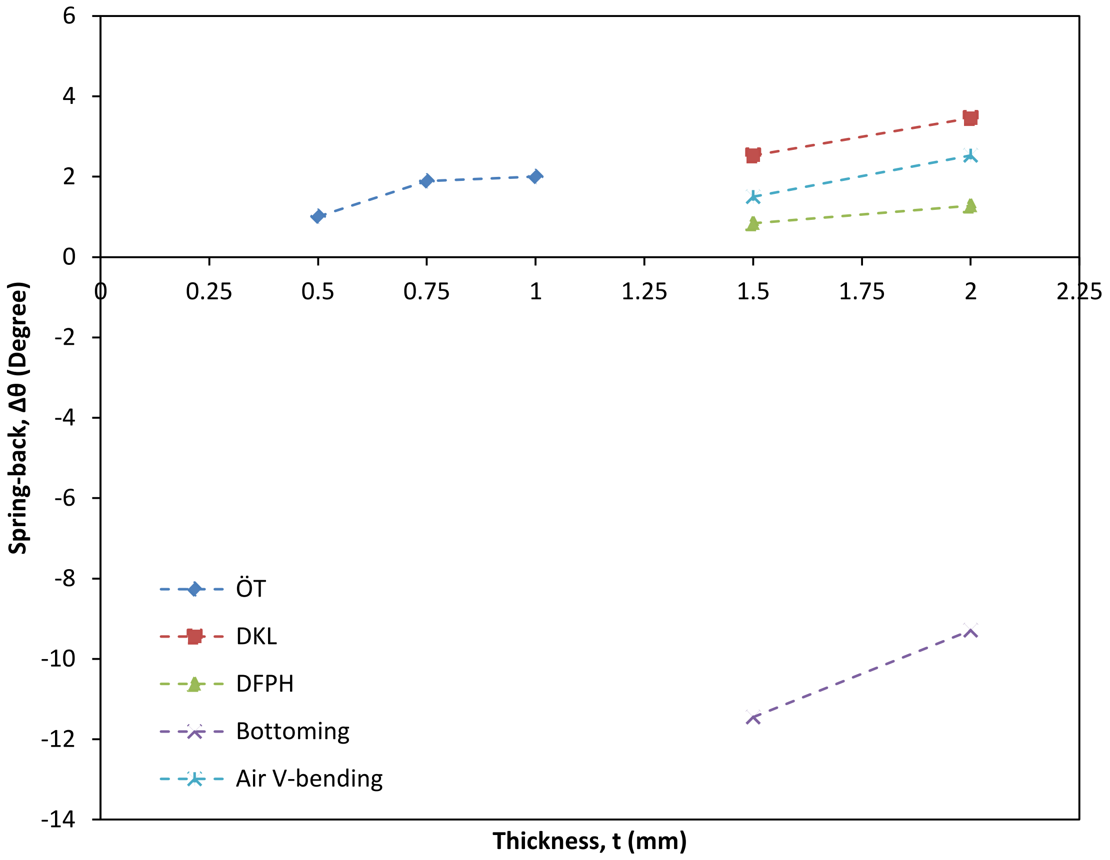


Figure 4.12: Effect of sheet thickness on spring-back value at various methods

As shown in the Table 4.11, the spring-back values for analytical calculation using both equations is closely same to the second experimental (air V-bending) result. Meanwhile the result of the first experiment (bottoming process) is not in agreement with both equations in the analytical calculation. Comparison between analytical calculation and the the experimental measurements of Özgür (2008) shows the close result with the spring-back angle. Even though the thickness is different, it is conclude that the graph trends obtained in this result are generally in agreement with the past study (Özgür, 2008).

Table 4.11: Percentage error of analytical calculation according to the first and second experiment setup (bottoming and air V-bending process)

Thickness (mm)	% Error According to First Experiment Setup (Bottoming)		% Error According to Second Experiment Setup (Air V-bending)	
	DKL	**DFPH**	**DKL**	**DFPH**
1.5	77.90	92.66	40.71	44.00
2.0	62.76	86.22	26.88	49.41

According to the results presented in the graphs and tables, the spring-back values for analytical calculation are generally is not in agreement with the experimental value but the graph trends obtained in this study are generally in agreement with experimental graph patterns. The graph patterns are also in agreement with the past study (Özgür, 2008). This can be concluded that the different spring-back are possible regarding to convenience of the materials and some errors occurred during the tensile specimen preparation, tensile test experiment and V-bending test. In analytical calculations, increasing the sheet thickness resulted increase in the spring-back angle. The orientation angle and anisotropy value *R* will influence the spring-back result. In general, the greater orientation angle makes the larger spring-back angle. Therefore, the orientation 0 degree to the rolling direction provides a suitable condition in V-bending process because the spring-back values are smaller compared to the other orientation angles. The percentage errors are very high because there are some errors happened during the tensile specimen preparation, tensile test experiment and V-bending test. The accuracy and precision of the machine in collecting and determining the data is among the factor for the higher percentage error.

CHAPTER FIVE

CONCLUSIONS

5.1 INTRODUCTION

This chapter summarized the conclusion and presented the recommendations for the project.

5.2 CONCLUSIONS

Analytical is one of the methods in predicting the spring-back angle after bending process. The effect of the anisotropy value *R* (orientation angle) and sheet thickness have been studied in this project. The accuracy of the method has been evaluated by comparing the predicted values with the experimental results of V-bending. The predicted results of analytical method also have been compared with the published experimental values of Özgür (2008). Based on this study, the following conclusion was suggested:

i. Increased of the sheet thickness resulted increased in the spring-back angle.
ii. The orientation 0 degree to the rolling direction provides a suitable condition in V-bending process since the spring-back value is small compared to other orientation angles.
iii. The analytical calculation of spring-back is not in agreement with the experimental value. It is concluded that the analytical method is not suitable in sheet metal bending analysis of stainless steel. This is due to the combination of various material types and process parameters make the precise estimation of spring-back is difficult to gain.

5.3 RECOMMENDATIONS

A few errors have been figured out during the tensile specimen preparation, tensile test experiment and V-bending test. In order to reduce the errors and to improve the study of spring-back prediction on V-bending analysis, a few aspects should be considered as guidelines for further study, for instance:

i. Tensile test specimens should be cut using CNC wire cut machine. These is for the reason that the finish specimens is smoother and will not have any defect at the cutting area compared to finish specimen cutting using CNC milling machine.
ii. Bending specimens also should be cut using CNC machine. The specimens are not flat and have defects at the cutting area if shearing machine is used to cut the specimen.
iii. Extensometer should be used in the tensile test experiment in order to construct the accurate extension data. The Poison's ratio, v and anisotropy value, R also can be directly calculated and produced in the tensile test result from the BlueHill software.
iv. Die and punch tool should be lubricated to reduce the contact friction between the specimens. This is because in analytical calculation, the friction effect can be neglected. The result should be more accurate and the error during the V-bending experiment is able to be minimized.

REFERENCES

Annika Nilsson, lars Melin, and Claes Magnusson. (1995). Finite element simulation of V-die bending: a comparison with experimental results. *Journal of Materials Processing Technology, 65*, 52-58.

Ozgur Tekaslan, Ulvi seker, Ahmet Ozdemir. (2008). Determining springback amount of steel sheet metal has 0.5mm thickness in bending dies. *Journal of Materials and Design, 29*, 1043-1050.

Daw-Kwei Leu. (1997). A simplified approach for evaluating bendability and springback in plastic bending of anisotropic sheet metal. *Journal of Materials Processing Technology, 66*, 9-17.

Dongye Fei and Peter Hodgson, (2006). Experimental and numerical studies of springback in v-bending process for cold rolled TRIP steels. *Journal of Nuclear Engineering Design*.

M.A. Osman,M. Shazly, A. El-Mokaddem, A.S. Wifi. (2010). Springback prediction in V-die bending: modelling and experimental. *Journal of Achievements in Materials and Manufacturing Engineering,* 38, 179-186.

M. Bakhshi-Jooyri, B. Rahmani, V. Daeezadeh, A.Gorji (2009). The study of springback of CK67 steel sheet in V-die and U-die bending processes. *Journal of Materials and Design, 30* 2410-2419.

Z.T. Zhang and D. Lee (1995). Development of a New Model for Plane Strain Bending and Springback Analysis. *Journal of Materials Engineering and Performance,4* 291-300.

Volkan Esat, Haluk Darendeliler, Mustafa Ilhan Gokler. (2002). Finite element analysis of springback in bending of aluminium sheets. *Journal of Materials and Design,* 23, 223-229.

M.V. Inamdar, P.P Date, and S.V. Sabnis. (2002). On the effect of geometric parameters

on springback in sheets of five materials subjected to air vee bending. *Journal of Materials Processing Technology, 123,* 459-463.

A.Behrouzi, B. M Dariani, and M. Shakeri. (2009). A One-step Analytical Approach for Spring-back Compensation in Channel Forming Process. *Journal of the World Congress on Engineering, 2,* 978-988.

Nasim Daemi, and Gholam Hossein Majzoobi. (2011). Experimental and Theoretical Investigation on Notched Specimens Life Under Bending Loading. *Journal of World Academic of Science, Engineering and Technology, 80,* 1175-1179.

Z. Tourki , H. Bargui, and H. Sidhom. (2005). The kinetic of induced martensitic formation and its effect on forming limit curves in the AISI 304 stainless steel. *Journal of Materials Processing Technology, 166,* 330-336.

Óscar Martín, Pilar De Tiedra, and Manuel López. (2010). Artificial neural networks for pitting potential prediction of resistance spot welding joints of AISI 304 austenitic

stainless steel. *Journal of Corrosion Science, 52,* 2397-2402.

Thipprakmas S. and Rojananan S. (2010). Investigation of spring-go phenomenon using finite element method, *Journal of Materials and Design, 29,* 1526-1532.

ZHANG Dong-juan , CUI Zhen-shan, CHEN Zhi-ying, and RUAN Xue-yu. (2007). An analytical model for predicting sheet springback after V-bending. *Journal of Zhejiang University SCIENCE A, 8(2),* 237-244.

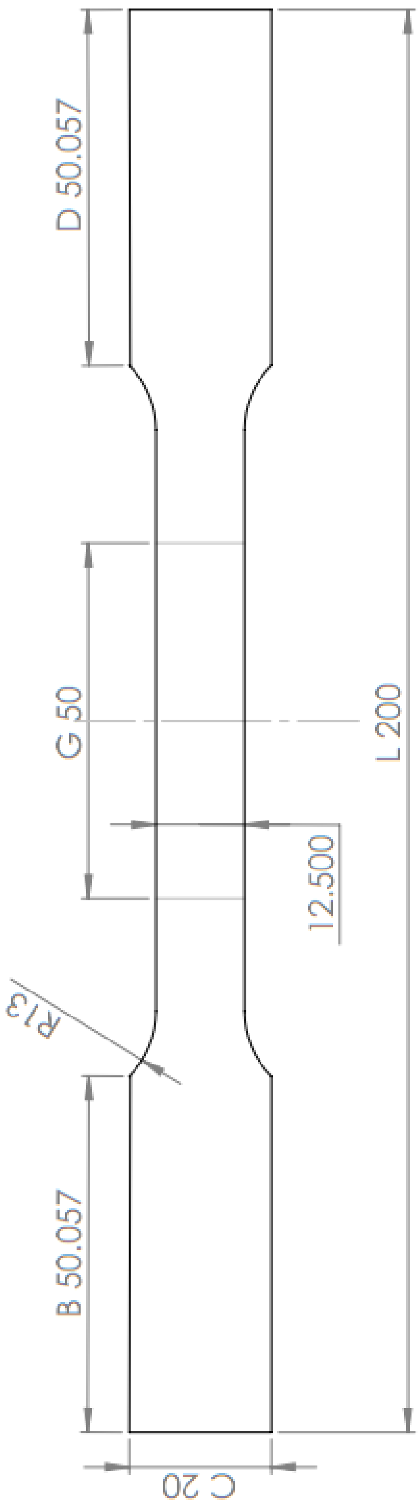
Schuler. (1998). *Metal forming handbook*. New York: Spring-Verlag.

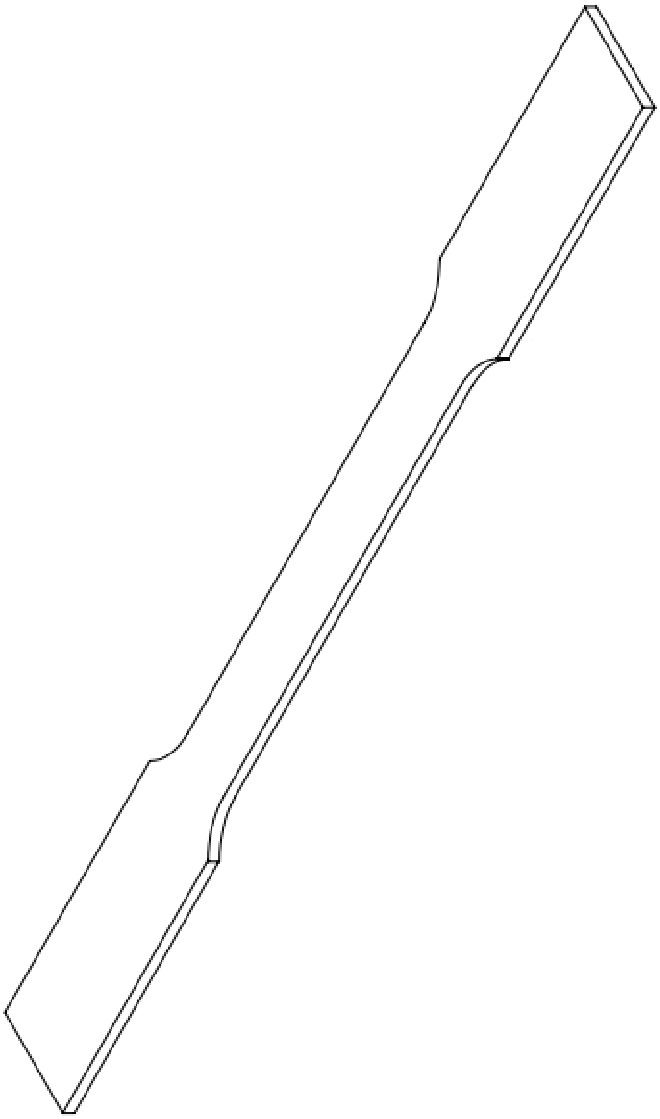
J.R. Davis. (2004). *Tensile testing*. 2nd edition. USA: ASM International.

ASTM. (2003). *Annual Book of ASTM Standards Vol 01.03*, USA: ASTM International

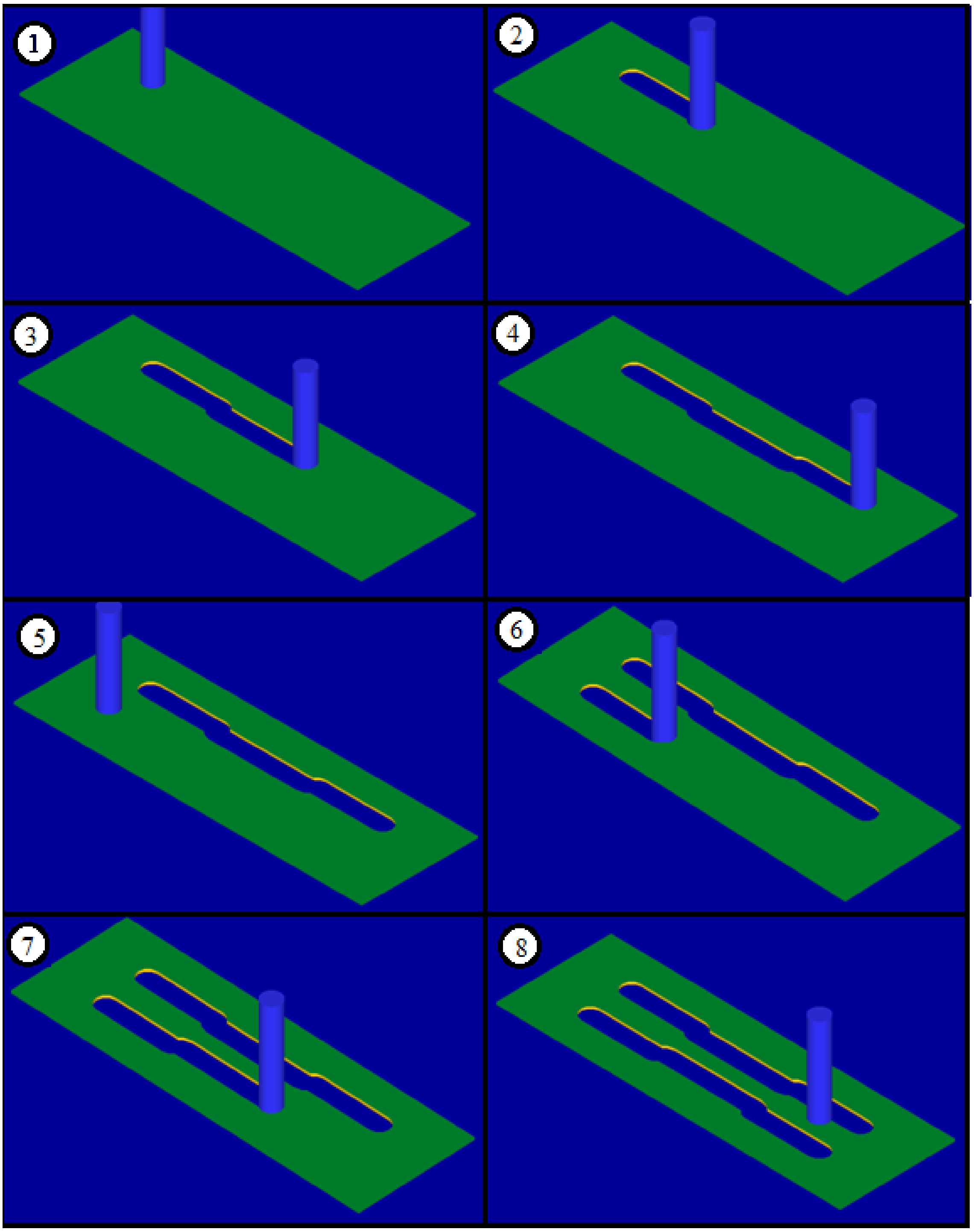
APPENDICES

APPENDIX C





APPENDIX D



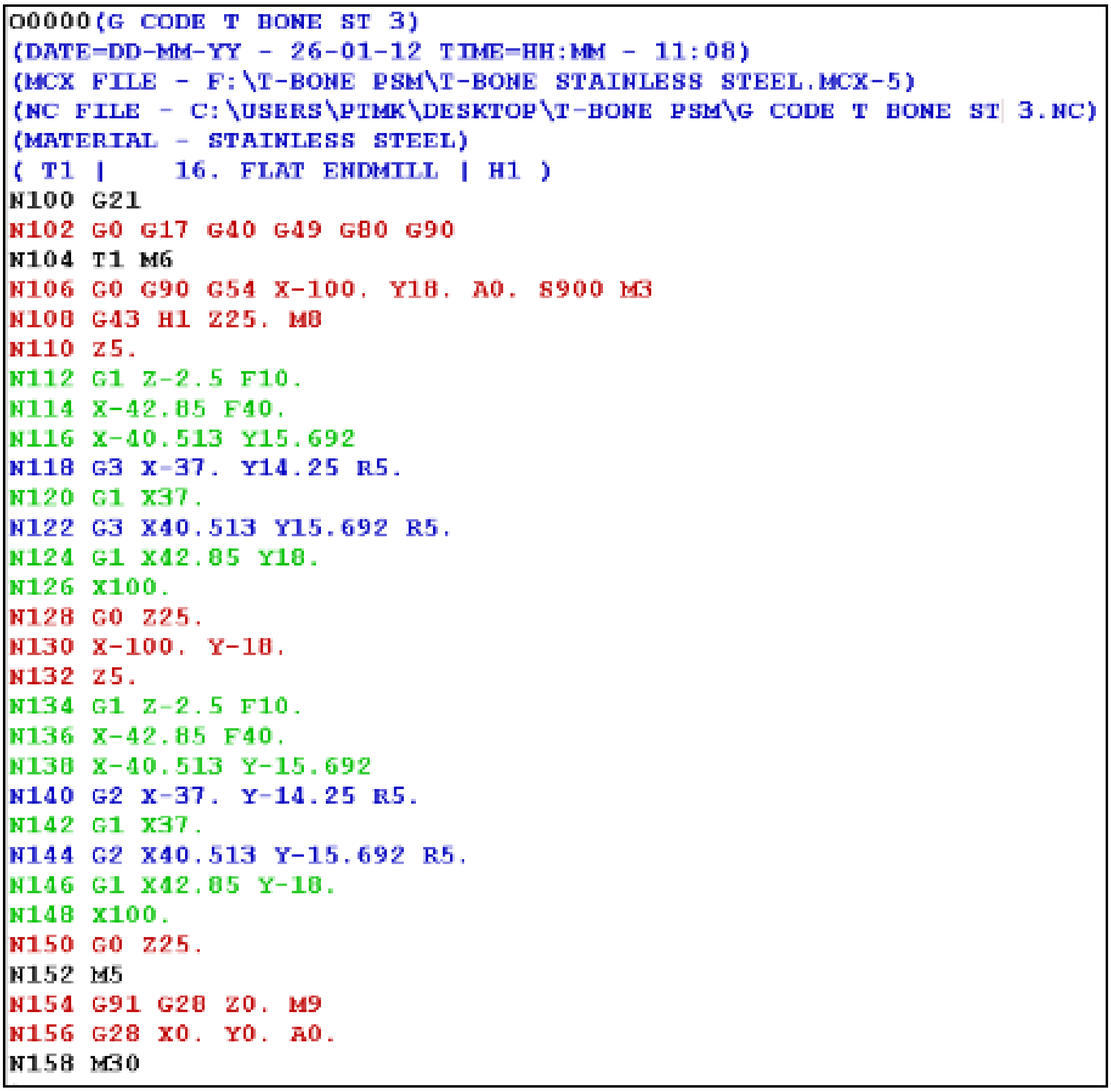
APPENDIX E

Orientation Angle	Final Width (mm)	Final Length (mm)	Young's Modulus (MPa)	Strain Hardening Exponent, n	Ultimate Tensile Strength, UTS (MPa)	Anisotropy Value, R	Poisson's Ratio, v
0	8.5	105.6671	1154	0.47418	701.9323	1.063579332	0.287422912
0	8.5	108.9167	1159	0.49823	719.2565	0.981584521	0.27156986
0	8.7	111.8335	1140	0.5114	717.7536	0.81884302	0.24582144
Average 0	**8.566666667**	**108.8057667**	**1151**	**0.494603333**	**712.9808**	**0.954668958**	**0.267547457**
45	8.34	114.0002	1022	0.5012	687.5243	0.964610429	0.259999188
45	8.5	111.4168	1073	0.48624	694.2539	0.927981985	0.260515038
45	8.14	115.7501	1012	0.5108	700.6853	1.044988143	0.265246745
Average 45	**8.326666667**	**113.7223667**	**1035.666667**	**0.499413333**	**694.1545**	**0.979193519**	**0.261969764**
90	8.58	108.4168	1117	0.4882	660.2448	0.946259856	0.268415935
90	8.5	115.8336	988	0.50533	707.056	0.848599833	0.24303699
90	8.4	115.9169	994	0.51586	709.6459	0.896568627	0.248798108
Average 90	**8.493333333**	**113.3891**	**1033**	**0.50313**	**692.3155667**	**0.897142772**	**0.252830008**
Average Result For 1.5mm Thickness	**8.462222222**	**111.9724111**	**1073.222222**	**0.499048889**	**699.8169556**	**0.943668416**	**0.26078241**

APPENDIX F

Orientation Angle	Final Width (mm)	Final Length (mm)	Young's Modulus (MPa)	Strain Hardening Exponent, n	Ultimate Tensile Strength, UTS (MPa)	Anisotropy Value, R	Poisson's Ratio, v
0	8.5	105.6671	1154	0.47418	701.9323	1.063579332	0.287422912
0	8.5	108.9167	1159	0.49823	719.2565	0.981584521	0.27156986
0	8.7	111.8335	1140	0.5114	717.7536	0.81884302	0.24582144
Average 0	**8.566666667**	**108.8057667**	**1151**	**0.494603333**	**712.9808**	**0.954668958**	**0.267547457**
45	8.34	114.0002	1022	0.5012	687.5243	0.964610429	0.259999188
45	8.5	111.4168	1073	0.48624	694.2539	0.927981985	0.260515038
45	8.14	115.7501	1012	0.5108	700.6853	1.044988143	0.265246745
Average 45	**8.326666667**	**113.7223667**	**1035.666667**	**0.499413333**	**694.1545**	**0.979193519**	**0.261969764**
90	8.58	108.4168	1117	0.4882	660.2448	0.946259856	0.268415935
90	8.5	115.8336	988	0.50533	707.056	0.848599833	0.24303699
90	8.4	115.9169	994	0.51586	709.6459	0.896568627	0.248798108
Average 90	**8.493333333**	**113.3891**	**1033**	**0.50313**	**692.3155667**	**0.897142772**	**0.252830008**
Average Result For 1.5mm Thickness	**8.462222222**	**111.9724111**	**1073.222222**	**0.499048889**	**699.8169556**	**0.943668416**	**0.26078241**

APPENDIX G



```
O0000(G CODE T BONE ST 3)
(DATE=DD-MM-YY - 26-01-12 TIME=HH:MM - 11:08)
(MCX FILE - F:\T-BONE PSM\T-BONE STAINLESS STEEL.MCX-5)
(NC FILE - C:\USERS\PTMK\DESKTOP\T-BONE PSM\G CODE T BONE ST 3.NC)
(MATERIAL - STAINLESS STEEL)
( T1 |     16. FLAT ENDMILL | H1 )
N100 G21
N102 G0 G17 G40 G49 G80 G90
N104 T1 M6
N106 G0 G90 G54 X-100. Y18. A0. S900 M3
N108 G43 H1 Z25. M8
N110 Z5.
N112 G1 Z-2.5 F10.
N114 X-42.85 F40.
N116 X-40.513 Y15.692
N118 G3 X-37. Y14.25 R5.
N120 G1 X37.
N122 G3 X40.513 Y15.692 R5.
N124 G1 X42.85 Y18.
N126 X100.
N128 G0 Z25.
N130 X-100. Y-18.
N132 Z5.
N134 G1 Z-2.5 F10.
N136 X-42.85 F40.
N138 X-40.513 Y-15.692
N140 G2 X-37. Y-14.25 R5.
N142 G1 X37.
N144 G2 X40.513 Y-15.692 R5.
N146 G1 X42.85 Y-18.
N148 X100.
N150 G0 Z25.
N152 M5
N154 G91 G28 Z0. M9
N156 G28 X0. Y0. A0.
N158 M30
```

APPENDIX H

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

This example calculation is for Stainless Steel 1.5mm thickness and 0° orientation angle. The neutral axis has been determined by using the equation below:

$$\rho=\sqrt{r_0 r_i}$$

$$\rho=\sqrt{(2.5)\times(1)}$$

$$=1.5811388mm$$

The spring-back ratio has been determined by using the equation below:

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

$$\frac{\Delta\theta}{\theta}=\frac{712.9808000}{e^{-0.494603333}0.494603333^{0.494603333}}$$

$$\times\left(\frac{1+0.954668958}{\sqrt{1+2(0.954668958)}}\right)^{1+0.494603333}$$

$$\times\frac{3(1-(0.267547457)^{2})}{2(33213.33)(1+0.494603333)}\left(\frac{1.5}{2(1.5811388)}\right)^{0.494603333-1}$$

$$=0.084245009$$

The spring-back angle has been determined by using the equation below:

$$\frac{\Delta\theta}{\theta}=0.084245009$$

$$\Delta\theta=0.084245009\times\theta$$

$$\Delta\theta=0.084245009\times 30^{\circ}$$

$$=2.527350271^{\circ}$$

APPENDIX I

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

This example calculation is for Stainless Steel 1.5mm thickness and 0° orientation angle. The neutral axis has been determined by using the equation below:

$$\rho = \sqrt{r_0 r_i}$$

$$\rho = \sqrt{(2.5)\times(1)}$$

$$= 1.5811388mm$$

The spring-back ratio has been determined by using the equation below:

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

$$\frac{\Delta\theta}{\theta} = \frac{3(712.9808)(1.5811388)(1-(0.267547457)^2)(1+4(1.5)/16)}{(33213.33)(1.5)}$$

$$= 0.027573201$$

The spring-back angle has been determined by using the equation below:

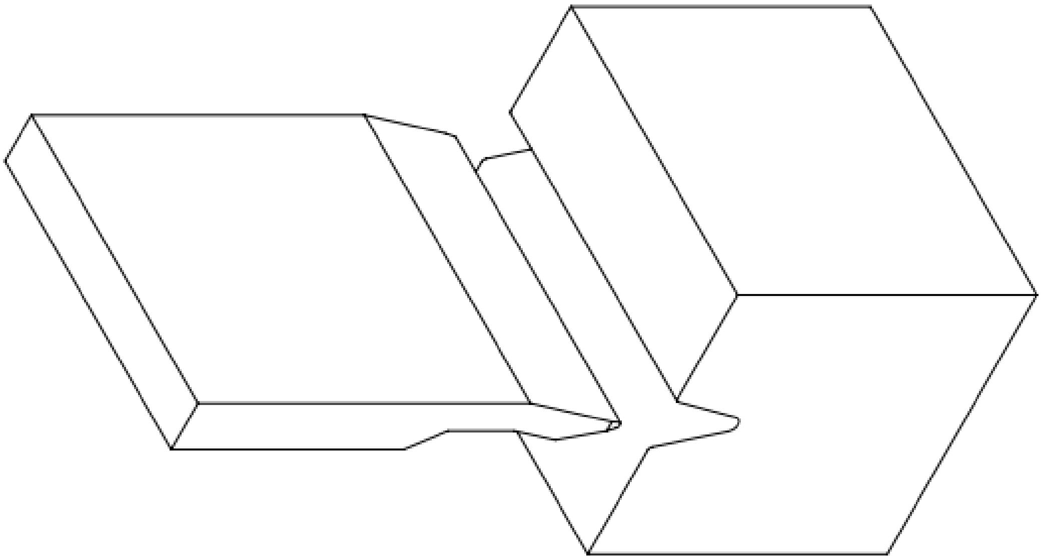
$$\frac{\Delta\theta}{\theta} = 0.027573201$$

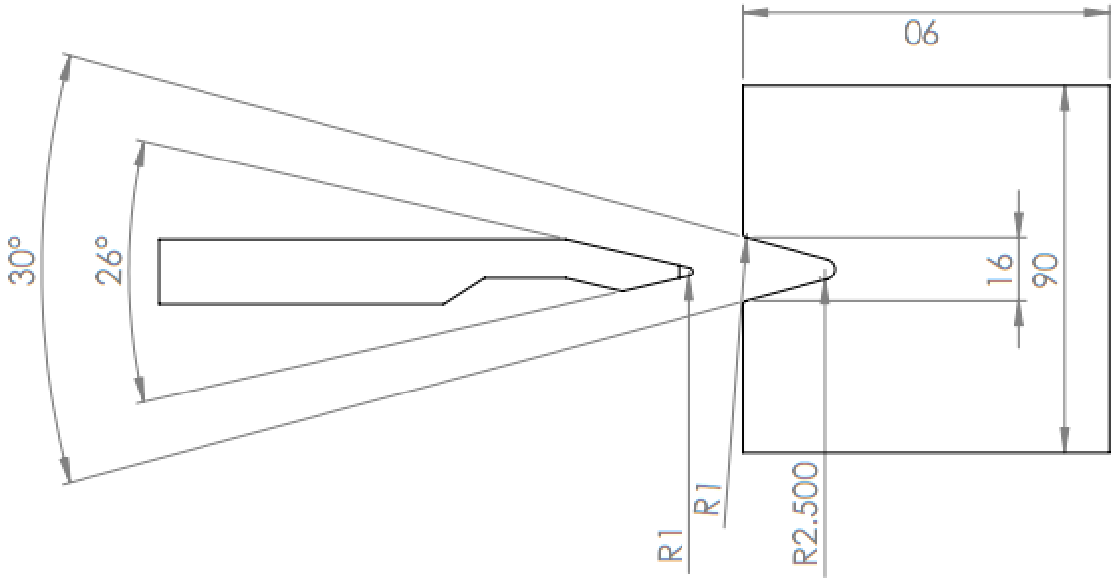
$$\Delta\theta = 0.027573201 \times \theta$$

$$\Delta\theta = 0.0275732019 \times 30°$$

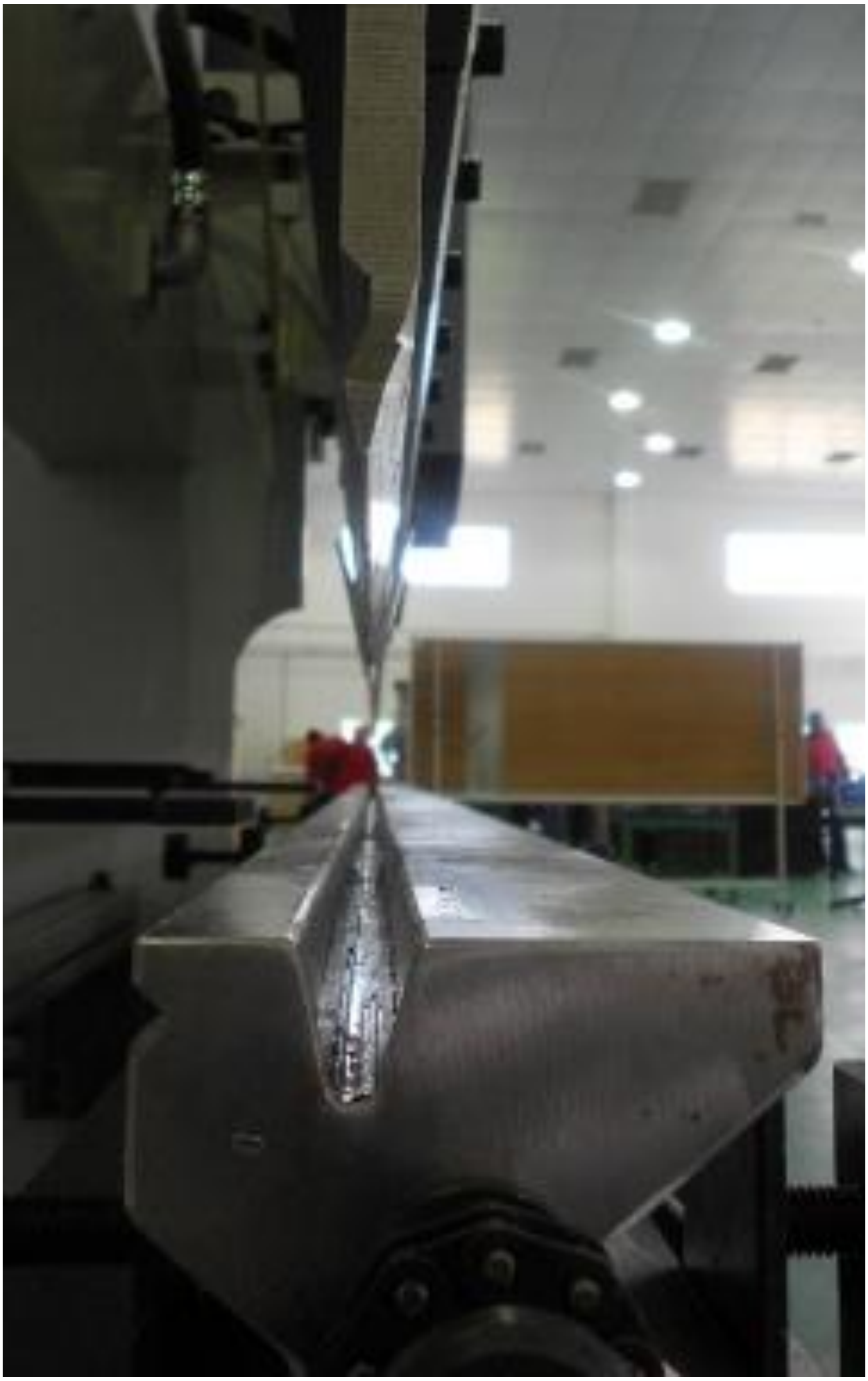
$$= 0.827196038°$$

APPENDIX J





APPENDIX K



APPENDIX L

Bending angle	Measured angle	Stainless steel sheet metal material with 0.5 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	93.01	93.11	93.16	93.05	93.14	93.07	93.06	93.12	93.14	93.18	93.18	93	3.18	3
75	105	107.44	107.55	107.51	108	108	108.01	107.56	107.57	107.59	108.05	107.96	107	2.96	2
60	120	122.03	122.44	122.41	122.4	122.49	122.35	122.35	122.55	122.09	123.01	122.64	122	2.64	2
45	135	136.41	136.51	136.48	136.52	136.53	137.06	137.09	137.08	137.07	137.11	136.99	136	1.99	1
30	160	151.03	151.12	151.07	151.05	151. 35	151.26	151.21	151.22	151.14	151.54	151.30	151	1.30	1
15	165	165.15	165.28	165.42	165.33	165.19	165.41	165.19	165.34	165.17	165.55	165.49	165	0.49	0

Bending angle	Measured angle	Stainless steel sheet metal material with 0.75 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	93.01	93.03	93.06	93.31	93.13	93.11	93.49	93.05	93.04	93.59	93.25	93	3.25	3
75	105	107.36	107.48	108.24	107.52	108.24	107.58	107.49	107.57	108.19	108.25	108.06	108	3.06	3
60	120	122.05	122.54	122.38	122.41	122.38	122.51	122.18	122.21	122.59	123.14	122.67	122	2.67	2
45	135	136.42	136.57	137.111	136.52	136.45	137.11	137.04	137.09	136.59	137.15	137.02	137	2.02	2
30	160	151.04	151.12	151.16	151.25	151.37	151.13	151.41	151.24	151.16	151.59	151.38	151	1.38	1
15	165	165.05	165.25	165.18	165.35	165.48	165.42	165.14	165.56	165.11	166.00	165.52	165	0.52	0

Bending angle	Measured angle	Stainless steel sheet metal material with 1.0 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	93.10	93.26	92.55	93.30	93.45	93.16	93.21	93.30	93.25	93.52	93.39	93	3.39	3
75	105	107.50	107.55	108.08	108.12	107.56	107.56	108.05	108.10	108.30	108.33	108.11	108	3.11	3
60	120	122.20	122.55	122.56	122.48	122.38	122.35	122.40	123.00	122.40	123.00	122.78	122	2.78	2
45	135	136.45	136.56	137.16	137.18	137.00	137.35	137.07	137.06	137.12	137.40	137.19	137	2.19	2
30	160	151.30	151.56	151.35	151.46	151.47	151.45	151.44	151.35	151.36	152.00	151.72	151	1.72	1
15	165	165.20	165.55	165.55	165.40	165.48	165.58	165.42	165.59	165.52	166.40	165.85	165	0.85	0

APPENDIX M

Bending angle	Measured angle	Stainless steel sheet metal material with 0.5 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	93.15	93.45	92.48	93.46	93.47	93.55	93.54	93.54	93.26	93.54	93.66	93	3.66	3
75	105	107.55	108.12	108.10	107.59	108.04	108.05	107.58	108.10	108.18	108.20	108.12	108	3.12	3
60	120	121.40	122.04	121.57	122.10	122.08	121.55	121.55	121.54	122.02	122.16	122.01	122	2.01	2
45	135	136.10	136.16	136.15	136.16	136.15	136.21	136.24	136.24	136.12	136.30	136.30	136	1.30	1
30	160	150.45	151.00	150.58	150.48	150.49	151.10	151.10	151.22	150.46	151.30	151.01	151	1.01	1
15	165	165.45	165.58	166.01	166.00	166.04	165.54	166.05	166.04	165.54	166.10	166.00	165	1.00	1

Bending angle	Measured angle	Stainless steel sheet metal material with 0.75 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	93.45	94.15	93.57	94.11	93.56	93.54	93.58	94.25	93.49	94.42	94.05	94	4.05	4
75	105	107.50	108.11	108.32	108.05	108.46	108.23	108.35	108.55	108.45	108.59	108.53	108	3.52	3
60	120	122.24	123.00	123.04	122.58	122.55	122.56	122.59	122.56	122.51	123.15	122.96	122	2.96	2
45	135	136.45	136.55	136.51	136.48	137.00	136.51	136.58	136.56	137.42	137.55	137.00	137	2.00	2
30	160	151.35	152.00	151.49	151.56	151.43	151.55	151.58	151.49	151.55	152.00	151.89	151	1.89	1
15	165	166.05	166.15	166.05	166.10	166.12	166.05	166.13	166.20	166.14	166.25	166.20	166	1.20	1

Bending angle	Measured angle	Stainless steel sheet metal material with 1.0 mm thickness										Average		Spring-back	
		Samples										Degree	Degree	Degree	Degree
90	90	94.25	94.51	95.05	95.15	94.38	95.06	95.02	94.52	95.12	95.20	95.00	95	5.00	5
75	105	109.00	109.26	109.30	109.10	109.50	109.14	109.25	109.34	109.05	109.50	109.40	109	4.40	4
60	120	123.00	123.45	123.36	123.48	123.38	123.35	123.40	123.04	123.40	124.00	123.60	123	3.60	3
45	135	137.14	137.36	137.26	137.28	137.50	137.35	137.58	137.40	137.16	137.50	137.60	137	2.60	2
30	160	151.40	151.56	152.00	152.12	152.04	151.59	151.44	152.25	151.40	152.45	152.00	152	2.00	2
15	165	166.05	166.10	166.39	166.50	166.48	166.11	166.51	166.14	166.50	167.00	166.57	166	1.57	1