MEASUREMENT OF RESIDUAL STRESS IN COLD WORK AUSTENITIC STAINLESS STEEL 316L WITH DEFLECTION METHOD

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This dissertation is submitted to Faculty of Mechanical Engineering in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering (Structure & Materials)

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May 2017

DECLARATION

"I admitted that this report is truly mine except the summaries and extractions where both I clearly knew its sources."

Signature :...

Supervisor Name :...

Date :...

APPROVAL

"I admitted that I have read this work and from my opinion it is adequately based on the scopes and quality for the degree of Bachelor of Mechanical Engineering

(Structure & Materials)

Signature :……………………………………………..

Writer :……………………………………………..

Date :……………………………………………..

DEDICATION

I dedicated this Final Year Project to my beloved parent, Haji Zulkafli Bin Baharuddin, Hajah Asmah Binti Md. Nor and my family for keep supporting and encourage me throughout my studies. Much appreciation dedicated to my supervisor Dr Wan Mohd Farid Bin Wan Mohamad and my friends for helping and guiding me in completing this project.

ABSTRACT

Residual stress refers to as potential or locked in stress inside an object without the presence of external load. Residual stress also plays an important role in structural integrity. This paper is mainly focussing on measurement of residual stress in cold work austenitic stainless steel 316L with deflection method. A mechanical process is done to produce different thickness of equal sizes specimens.

The thicknesses are reduced to 10% up to 50%. Based on general hypothesis, residual stresses tend to reduce strength. Therefore, a measurement is done using deflection method as it is said to be most precise method to predict the residual stress. This whole process is rather delicate, requiring much time, patience and expenses. In this paper, the effects of thickness reduction with the values of residual stresses are discussed.

ABSTRAK

Tegasan baki merujuk kepada potensi atau tenaga yang wujud di dalam objek tanpa kehadiran daya luar. Tegasan baki juga memainkan peranan penting dalam integriti sesuatu struktur. Risalah ini memfokuskan hanya kepada pengiraan tegasan baki di dalam *stainless steel* austenite jenis 316L menggunakan cara pembengkokan. Proses mekanikal telah dilakukan untuk menghasilkan spesimen yang sama saiz tetapi berbeza ketebalan.

Ketebalan spesimen dikurangkan 10% hingga 50% dari ketebalan awal. Berdasarkan hipotesis, tegasan baki punca cenderungnya kekuatan berkurangan. Oleh itu, pengiraan menggunakan cara pembengkokan digunakan kerana ianya merupakan cara yang paling tepat untuk mengjangkakan tegasan baki. Keseluruhan proses adalah sangat teliti, memerlukan banyak masa, kesabaran and perbelanjaan. Risalah ini membincangkan kaitan diantara ketebalan spesimen dan juga tegasan baki.

ACKNOWLEDGEMENT

Praise to Allah for allowing me to complete my thesis successfully and for giving me good health and mind.

Words of appreciation for my supervisor, Dr Wan Mohd Farid Bin Wan Mohamad, UTeM’s staff, Mr Wan, Mr Rashdan, Mr Mahader, Mr Rafidi, Mrs Rusni and friends who helps and guides me throughout the process.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Residual stresses are the stresses which exist within a body of materials without being subjected to any external forces. As referred, residual stresses are locked-in stresses within a metal object, even though the object is free of external forces (M. Pfeifer). These stresses arise in most metallic objects by four different methods that are mechanical, thermal, plating and machining which cause the metal to yield and deformed to plastic. However, the yielding or plasticity is in-homogenous. Further, these stresses occurred due to some region of the metal objects are being constrained and prevent it from expanding, contracting or releasing elastic strain (M. Pfeifer). They play a critical role for structural integrity of materials in term of service performance, strength, fatigue life and dimensional stability (Tadić and Mišović).

Example of mechanical methods that will induce residual stresses in metal objects are short peening and rolling. This would cause a localized inelastic region that deformed in metal objects. This method uses external loading and unloading which later causes both tensile and compressive residual stress as shown in Figure 1:1. Thermal methods include forging, casting, welding, quenching, carburizing and many other processes. It is the same as machining and plating. However, plating sometimes nullifies the residual stress that occurred within metal objects by combining with some other processes. The goodness of residual stresses may depend on processes and usage. Sometimes residual stresses might be bad for certain usage for example machined metals are prone to fatigue fracture. The integrity of metal objects will vary after some mechanical processes and it is important to know the limitations of the residual stresses.

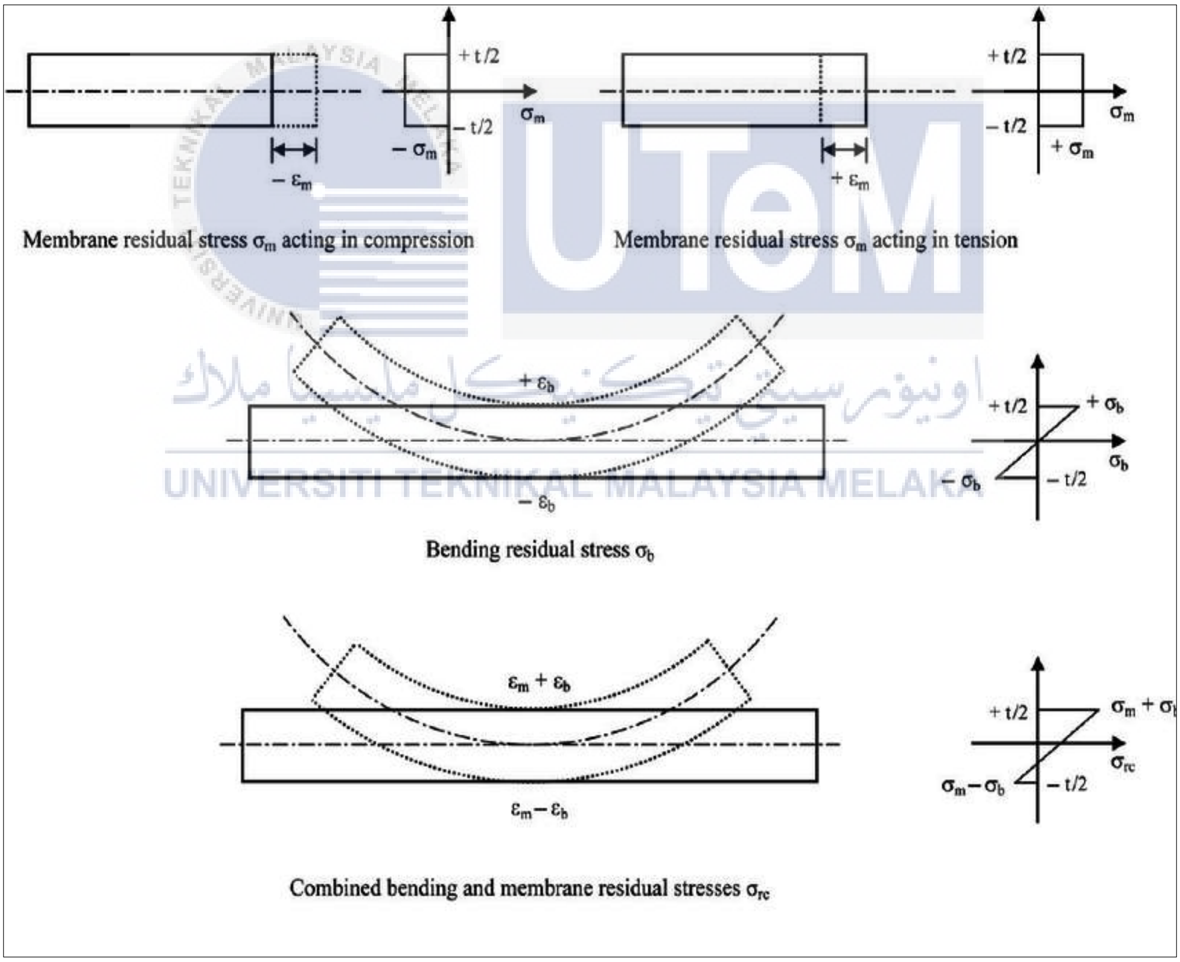


Figure 1:1 : Compressive and tensile residual stress.

Over the years, many researches have been done and experimented to measure the residual stresses. Many techniques can be used to measure the residual stresses as it unforeseen with bare eyes. Measurement techniques can be divided into three categories which are non-destructive, semi-destructive and destructive techniques. For non-destructive techniques, it will be done to analyse the effect of residual stresses with metals' crystallographic properties. For example neutron diffraction, synchrotron diffraction, x-ray diffraction, ultrasonic and magnetic. As for semi-destructive techniques, it follows the "strain release" principle where the specimen used is cut only a bit and measure the deformed shape which leaves the overall materials' integrity remain intact.

This technique includes ring core, deep-hole drilling and centre-hole drilling. The last technique which most costly is the destructive techniques such that they result in a large and irreparable structural change to the specimen (Engineering & Engineering, 2016). This technique also follows the "strain release" principle however the cut specimen is much bigger than the semi-destructive technique. This technique includes block removal, slitting, Sach's boring and contour methods. Residual stresses can be measured by several different methods, as well as by combining various techniques (D. Walker).

1.2 PROBLEM STATEMENT

Residual stress arises mostly in metal that undergoes mechanical process such as rolling and cutting. However, the residual stress cannot be foreseen with naked eyes and this stress unfortunately plays an important role with the integrity of the materials. There is no absolute way to measure the residual stress. So, there are many methods available to estimate the residual stress such as deflection method, x-ray diffraction and crack compliance method.

Rolling process has induced and increased the residual stress, the hardness, tensile strength and the ultimate strength. Both hardness and strength can be measured directly using reliable measurement tools such as tensile test machine and hardness test machine. However, residual stress cannot be measured directly like other properties even though residual stress has large effects on materials' integrity.

There are two ways to estimate the value of residual stress either by experimentally or through simulation.

Therefore, a precise measurement tool is used to predict the value of residual stress through deflection method. Solution (Adlers 300 series stainless steel etchants) is used to deflect the stainless steel sheet. After that, a probe or profile projector can be used to record the deflection.

1.3 OBJECTIVES

The objective of this project is to predict residual stress induced through mechanical process using a deflection method.

1.4 SCOPE OF PROJECT

The scope for this project are :

1. Machining of 80 x 20 mm is done to the metal sheet.
2. To do mechanical treatment to induce residual stress and reduction done are in range.
3. To measure the changes in dimension using precision measurement tools.

4. To do etching process for material to deflect using Adlers 300 series stainless steel etchant.

1.5 GENERAL METHODOLOGY

The action that need to be carried out are as listed :

1. Literature Review

   Anything that related to residual stress and deflection method will be reviewed.

2. Mechanical Process

   Mechanical process such as machining and rolling will be done to create 12 specimens. Each specimen will be in 80 x 20 mm rectangular with different thickness. 12 specimens will be divided equally into thickness of 2.0 mm, 1.8 mm, 1.4 mm, and 1.0 mm.

3. Measurement

   Measurement of important parameters will be measured using precise measurement tools.

4. Analysis

   Analysis will be done to measure residual stress by using different thickness of steel sheets.

5. Report Writing

   A final report will be written at the end of this project.

The methodology is summarized as in Figure 1:2 and as Gantt Chart in Figure 1:3.

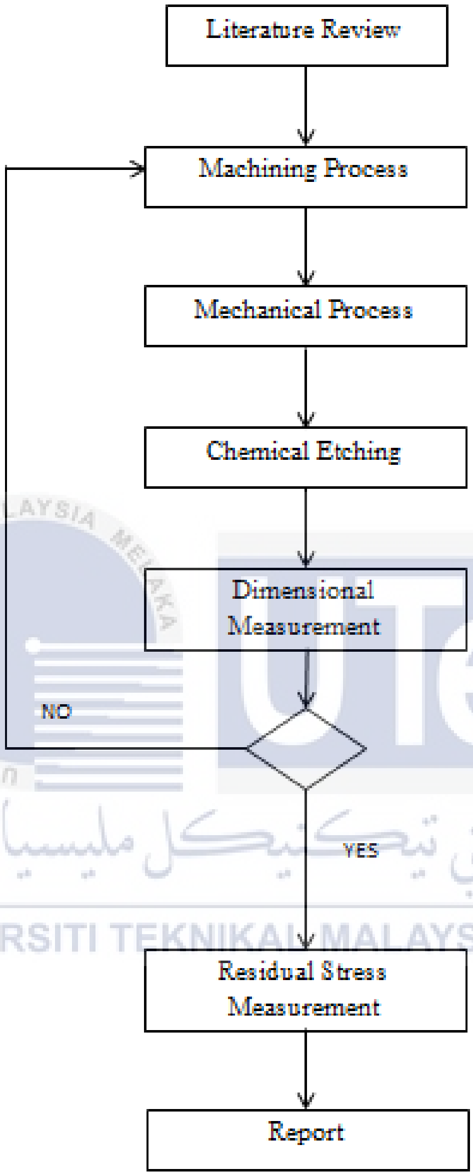


Figure 1:2 : Flowchart of methodology.

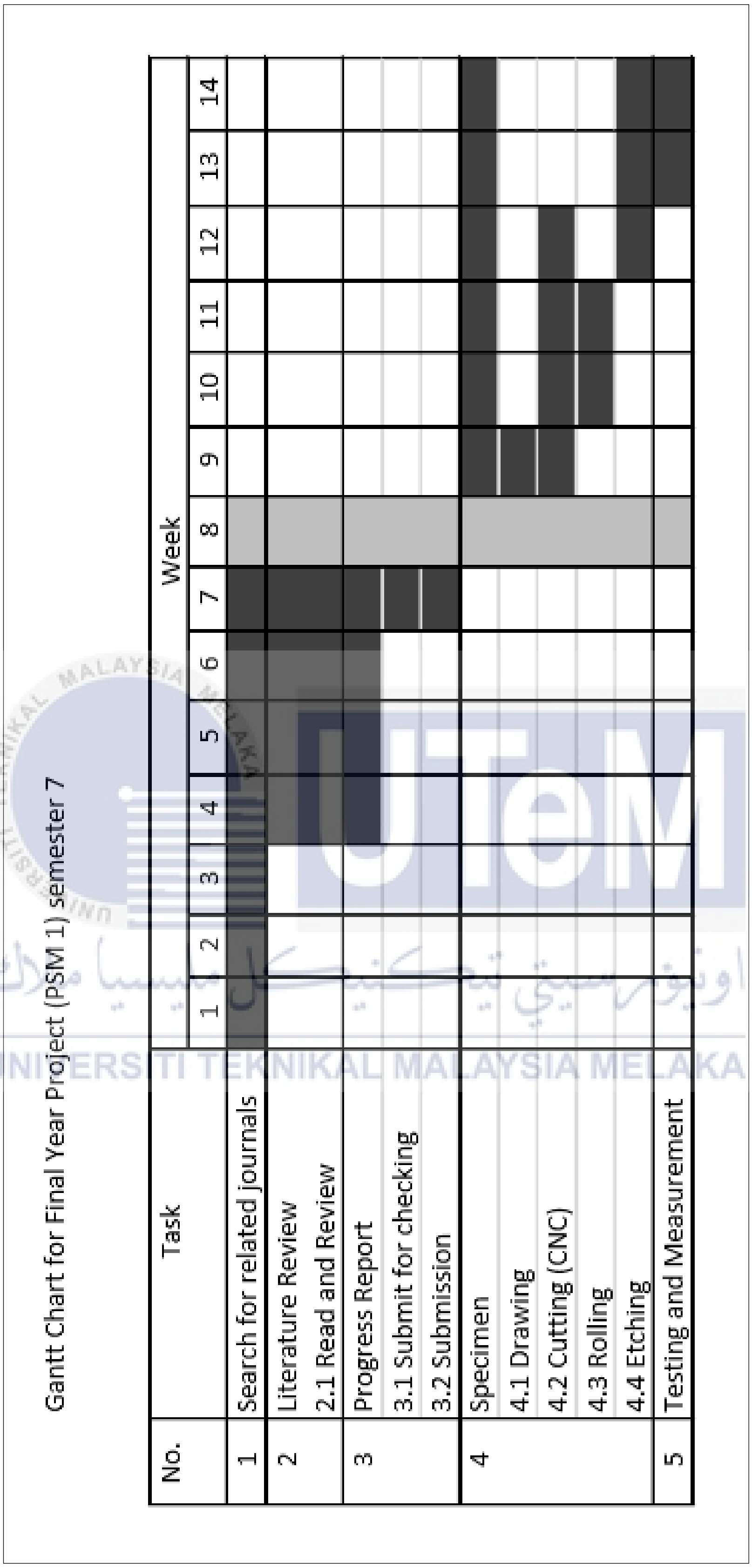


Figure 1:3 : Gantt chart for PSM 1.

CHAPTER 2

LITERATURE REVIEW

The existence of residual stresses would affect the non-homogenous plastic deformation in metals. This occurred due to the irregular distribution of residual stresses. Even though the residual stresses are not affecting the changes of the shape when they were symmetrically balanced in their cross section, they still can affect in future production or mechanical phases. The residual stresses are spatially balanced but they are also latently unstable (Milan, MT., Tarpani, Jr., Bose Filho, 2005).

There are a discussion about residual stresses concerning how it affect the changes of the shape and dimensions when their balance is disturbed by using x-ray diffraction and deflection method. Apparently, the residual stresses needed to be relaxed as if it were exposed to a superposition of external loads might cause the reliability of the component to be damaged or reduced. One way is to remove or completely transform the residual stresses into more appropriate form so that it will not cause any permanent consequences.

Residual stresses are internal stresses exist in metallic components. The value of residual stresses cannot be determined using naked eyes. Therefore, there are many ways to determine the value of residual stresses either by using destructive or non-destructive methods. Mostly, a test or experiment is done using non-destructive methods as it is to reduce cost.

One way to determine both near surface and through the thickness is by applying crack compliance method which is easy yet powerful to implement. The residual stresses that were introduced to the crack or slot area are measured by strain gauges attached to specific region of the part. Assuming the slot is narrow, from that, linear elastic fracture mechanics equations can be employed to establish a relationship between the measured strains, ε, and the corresponding residual stress intensity factor, K_r (Schindler, 1995 cited in Milan.MT. et.al, 2005).

$$K_{Ir}(a) = \frac{E\prime}{Z(a)} \frac{d\varepsilon M}{da} \qquad \text{(Eqn. 2.1)}$$

where ε_M is the measured strain at point M during cutting procedure, a is the slot length, *E'* is the generalized form of Young's modulus *(E' = E for plane stress and E' = E/1-*v^2*)* for plane strain) and *Z(a)* is the "influence function" which depends on the testpiece geometry, cut plane and strain measurement position, but it is independent on the residual stress profile.

For a rectangular plate, where L>2W, and taking strain measurements at the back face point M, Z(a) is given as (Schindler and Bertschinger, 1997 cited in Milan.MT. et.al, 2005):

for a/W<0.2

$$Z(a) = \frac{-2532}{(W-a)}\sqrt{1-25\left(\frac{a}{W}-0.2\right)^2}\left[5.926\left(0.2-\frac{a}{W}\right)^2-0.288\left(0.2-\frac{a}{W}\right)+1\right] \text{(Eqn.2.2)}$$

for $0.2<a/W<1$

$$Z(a) = \frac{-2.532}{(W-a)^{1.5}} \qquad \text{(Eqn.2.3)}$$

$$K_{Ir}(a) = \int_{ao}^{a} h(x,a)\sigma(x)dx \qquad \text{(Eqn.2.4)}$$

where *h(x,a)* is the weight function, which is available for several geometries (Fett and Munz, 1997 cited in Milan. MT et.al, 2005). Therefore, the weight function for a single edge crack in a finite width of rectangular plate is :

$$h(x,a) = \sqrt{\frac{2}{\pi a}}\frac{1}{\sqrt{1-x/a}}\left[1+\frac{1}{(1-\frac{a}{W})^{3/2}}\sum_{v,\mu} A_{v,\mu}\left(\frac{a}{W}\right)^{\mu}(1-\frac{x}{a})^{v+1}\right] \qquad \text{(Eqn.2.5)}$$

where $A_{v,\mu}$ values can be found on Table 2.1.

Table 2:1 Weight function coefficients for rectangular testpieces (Fett and Munz, 1997 cited in Milan. MT. et.al, 2005).

v	μ = 0	μ = 1	μ = 2	μ = 3	μ = 4
0	0.4980	2.4463	0.0700	1.3187	-3.067
1	0.5416	-5.0806	24.3447	-32.7208	18.1214
2	-0.19277	2.55863	-12.6415	19.7630	-10.986

Through Eqn.2.4, the value or residual stress can be obtained. If incremental stress method is used (Schindler, 1995 cited in Milan. MT. et.al, 2005), the stress profile can be depicted schematically by a series of small steps. By applying the prolonging crack hypothetically, discrete form of Eqn.2.4 will be as follow :

$$K_{Ir}\,(a_i) = \sum_{j=1}^{i} \sigma_j \int_{aj-1}^{aj} h(x, a_i)dx \qquad \text{(Eqn.2.6)}$$

These procedures are not only able to determine the initial residual stress profile but also able to determine the redistributing residual stress profiles by changing the integration limits.

Another research has been done regarding on microelectromechanical systems based devices that faced problems caused by residual stress especially during film deposition and post-fabrication processes. During phase transformation, film nucleation occur during deposition process are the causes of residual intrinsic stress, including growth stress. Thermal stress arises from mismatch of film-substrate thermal expansion coefficients developed by the residual extrinsic stress. These would cause undesirable consequences such as cracking, deflection and buckling in the released microstructures.

The residual stress were treated and improved by controlling it, and etch release effects during the fabrication process. This journal studied on how residual stress can be controlled and improved through fabrication and characterisation of suspended microstructure of tantalum. Both wet and dry etching techniques have been examined for the release of the final device in the form of doubly supported beams with length ranging from 100 to 400 μm (A Al-masha'al et al, 2016). The influence of beam geometry, length, width, and thickness is examined by looking on the final deflection profile of the fabricated and simulated structures.

Based on journal, the experiment is done from beams fabrication, buckling analysis and residual stress measurement. During fabrication, the sacrificial layer is considered and cured by heating at 350̊C for 30 minutes and let cooled in room temperature. The second layer, low temperature of SiO_2 is developed by PECVD system at 120̊C. The tantalum has film with thickness of 500 nm deposited by DC magnetron sputtering system. In the analysis, buckling takes place when the axial load exceeds the Euler buckling limit.

$$P_{\mathrm{c}} = \frac{4\pi^2 EI}{L^2} \qquad \text{(Eqn 2.7)}$$

Where L and EI are respectively the length and flexural rigidity of the beam. The buckling occurs at particular length based on the critical stress.

$$\sigma_{\mathrm{cr}} = \frac{E\pi^2 t^2}{3L^2} \qquad \text{(Eqn 2.8)}$$

Where E, t and L are elastic modulus, thickness and length of the beam. Once the beam is release from substrate, it will buckle according to residual stress

$$\sigma_{\mathrm{res}} = \frac{\pi^2 E}{L^2}\left[\frac{A^2}{4} + \frac{t^2}{3}\right] \qquad \text{(Eqn 2.9)}$$

Where A is the amplitude of buckling and can be measured interferometrically. The sinusoidal shape of buckling represent by :

$$y(x) = \frac{A}{2}\left(1 - cos\frac{2\pi x}{L}\right) \qquad \text{(Eqn 2.10)}$$

Where –L/2 ≤ x ≤ L/2, y and x both represent the deflection and position along the beam.

In this experiment, the buckling is measured without considering the post-processing and mechanical applied load effects.

However, this journal discussed the importance of design and fabrication of microstructures of tantalum and how it affected by wet etch and dry etch. The wet etch release approach has produced smaller deformation in the final fabricated devices than the dry etch release method (A Al-masha'al et al, 2016).

Further will explain the machining technique done to create a slot or implementation in the crack compliance method between WEDM and circular abrasive saws that is believed has affects in the residual stress.

Based on the analysis, thin saw and WEDM method is preferable for crack compliance method as they are more likely represent a true crack. This method is preferable due to the efficiency and accuracy of WEDM in controlling the length of each increment. As the experiment is done with the length of the slot, a, must be larger than its width, d, in order to simulate a crack. The thick saw results in larger stress range. Based on the data obtained, it can be said that higher rotational speed of abrasive saws would give larger variations in strain readings, which contribute to a higher level of stress.

As for conclusion, the WEDM is preferable because of its reliability in controlling cut increment length than abrasive saws which provides almost large errors in strain readings which indirectly contribute to higher value of stress.

Another research has been done to determine the value of residual stress in cold rolled narrow strips experimentally and simulation by Nebojsa Tadic and Mitar Misovic.

In this research, a deflection method is used to determine the residual stress in Alloy AA5083. The strips were cut and rolled to achieve different thickness and cut again to get equal length of 80 mm. Later, the strips were equally etched on one side onto a solution contained 20% of NaOH. The chemical composition and mechanical properties are as shown in Table 2.2.

Table 2:2 : Chemical composition and mechanical properties of AA5083 alloy.

Chemical composition, (wt. %)								$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
Mg	Mn	Si	Fe	Cu	Cr	Zn	Ti			
4.23	0.42	0.13	0.26	0.015	-	0.02	-	134.7	289.7	22.86

Due to the nature of deflection method, the residual stress has dominant effects on properties and shape of the sheets. As the sheet went through a cold roll process, the states of residual stresses are in two dimensional. The stress profile as in Figure 2.1 and Figure 2.2, influencing the whole cross section and the maximum is on the surface.

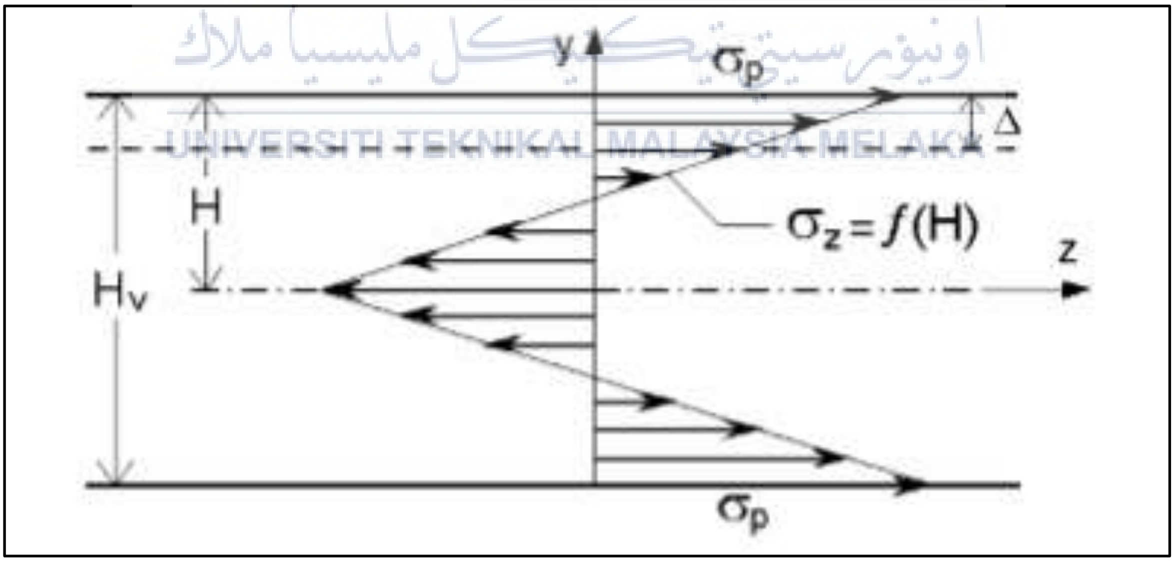


Figure 2:1 : Diagram of longitudinal residual stress.

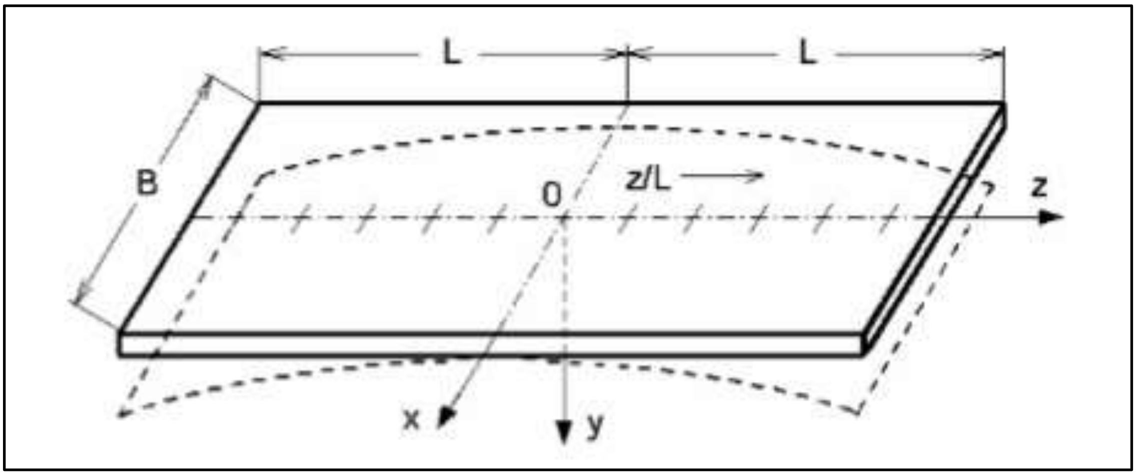


Figure 2:2 : Schematic presentation of elastic bending under influence of residual stress.

The equilibrium diagram can be presented with the equation (N. Tadic and M. Misovic, n.d) :

$$\sigma_z = [A_1 h_r + A_2] \quad \text{(Eqn. 2.11)}$$

where σ_z and σ_p are longitudinal stresses in cross section area and on the surface, h_r is the relative thickness *(y/H)* and A_1, A_2 are the coefficients of determined boundary conditions.

The measurement can be done on the elastic bend of the sample. The bending occurred due to unsymmetrical distribution of stress which represent by Eqn. 2.12.

$$y = a{z_n}^2 \quad \text{(Eqn. 2.12)}$$

where *a* is the coefficient for bend and *z* is the relative longitudinal distance *(z/L).*

The rolling has caused the specimen to have a distributed longitudinal residual stresses and balanced bending moments in relation to the longitudinal axis. However, the etching process has disturbed the balance and the bending occurred symmetrically. Thus, the centre is approximately in the middle of the length that is L (refer Figure 2.2).

An equation is established to relate the bending conditions to residual stress. This equation can estimates the longitudinal residual stress by equalization of cantilever bending moment and residual stresses bending moment (N. Tadic and M. Misovic, N. Tadic, Z. Culafic, 2000 cited in N. Tadic and M. Misovic, n.d) :

$$\sigma_{\mathrm{p}} = \frac{8E(H-\frac{\Delta}{2})^3 f}{H^2\, L^2\left[6(\frac{\Delta}{H}-6(\Delta/H)^2+(\Delta/H)^3\right]} \qquad \text{(Eqn. 2.13)}$$

where Δ is the thickness of removal layer and f is the dimension of elastic bend.

Based on the Eqn. 2.13, the stress σ_{p} can be estimated if the parameters are known. The parameters for chosen dimension of samples, reduction ratio, elastic line, as well as for estimated stress values are shown in Table 2.3.

Table 2:3 : Parameters and results of experimental procedure and FEM simulation.

Sample	Reduction ratio (ε, %)	Δ, (μm)	$y = az_n^2$	mse	f, (mm)	σ_p, (MPa)	FEM			
							Number elements	Number nodes	f, (mm)	σ_{zz}, (MPa)
1	21.1	322	$y = 1823z_n^2$	0.0174	2.446	79.04	12324	16000	2.161	79.93
2	21.5	331	$y = 1622z_n^2$	0.0335	2.243	69.28	25596	32800	1.926	73.03
3	21.8	365	$y = 2012_n^2$	0.0662	2.742	74.57	43344	55245	2.220	77.54

These values is compared between measured and estimated values and the *mse* (mean square error) shown in Table 2.3 defined that the elastic line of bent sample can be described precisely with the equation for bent cantilever elastic line (N. Tadic and M. Misovic, n.d.).

The high values become lower and constant as it reach the elastic line. This is due to the reliability of deflection method depends on the dimension L as the residual stress in the Eqn. 2.13 are proportional to the expression f/L^2. The dissipation of values as in Figure 2.3 is the consequences of measurement errors and elastic line approximation, as well as of non-homogeneity of sample thickness appeared in rolling and chemical etching process (N. Tadic and M. Misovic, n.d.).

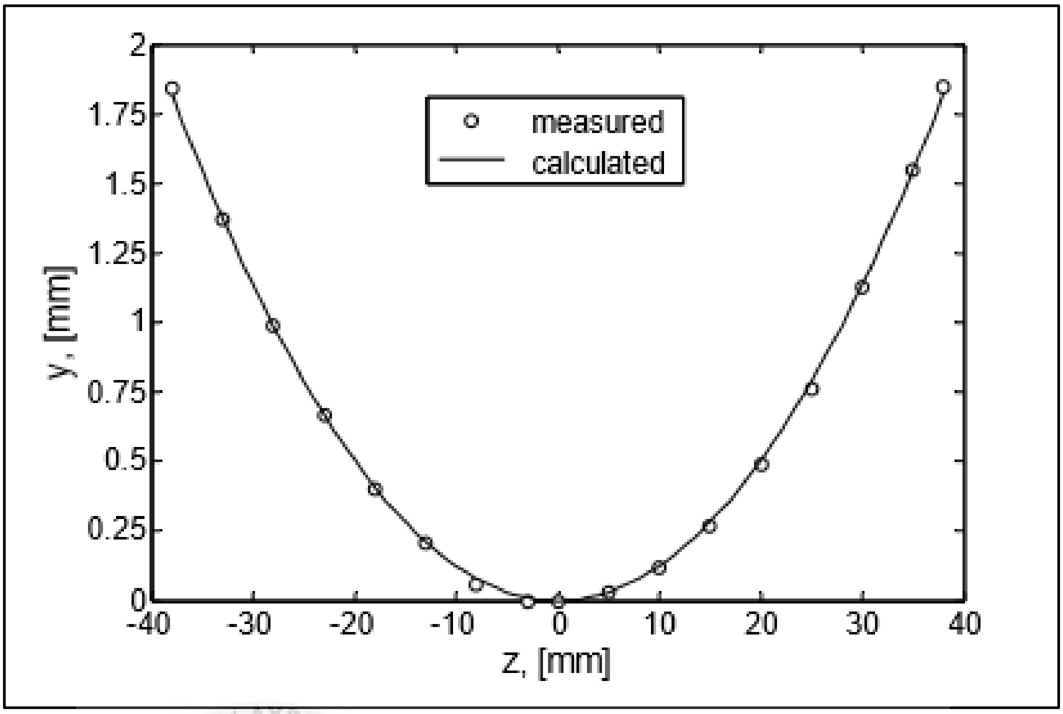


Figure 2:3 : Elastic line of sample.

The determination of residual stress is reliable enough if the total length is twice the length or distance where the stress is nearly constant. The deviation of measured elastic line from the theoretical conditions of cantilever bending can be considered as the error of deflection method and the difference in values satisfy specified criteria. If the difference between bottom and upper curved line is estimated on the basis of stress values the result $\Delta\sigma_p < \pm 5$ MPa is obtained. In that way these values can demonstrate the accuracy in stress determination using the deflection method (N. Tadic and M. Misovic, n.d).

As for the simulation results, the simulation is done with the estimated value of stress on the surface, shape of distribution and shape of the distortion model. Due to rolling effects on the residual stress, it has changed the sample geometry and properties. There are assumption taken account into this simulation that are the position of constrain along the transversal x-axis and couple forces from outside loading opposite direction.

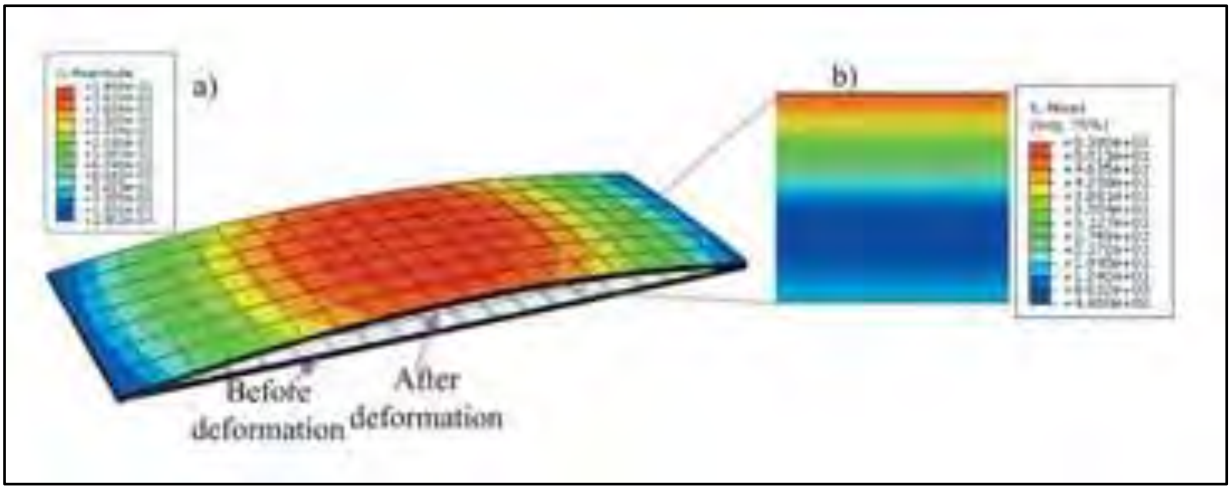


Figure 2:4 : Example of stresses distribution on simulation.

Through simulation, the values of isolated lengths of samples are higher than the experiment. Also, there are absolute difference in longitudinal stresses probably caused by the reduction ratio and residual stresses. This confirms the reliable selection of the relations between sample dimensions in experimental process (N. Tadic and M. Misovic, n.d.).

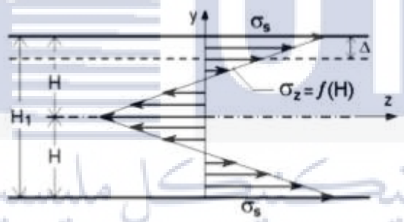
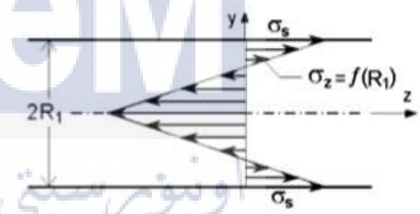
Another reviewed journal is the relaxation of the residual stress written by Nebojsa Tadic, Milos Jelic, Dusko Lucic, and Mitar Misovic in year of 2011. This journal discussing on the measurement of residual of stresses and the control of their complete or partial removal were performed using the deflection method and x-ray diffraction (N. Tadic et.al, 2011). The rolling is done using duo-rolling stand with a diameter of 125 mm and speed of 0.17 m/s.

Two types of residual stresses were experimented and measured. The axisymmetric and two-dimensional residual stresses both occur during mechanical processes. The longitudinal residual stress is measured using a deflection method. This stress disruption occurred due to the removal of thin layer of metal in 20% of NaOH solution in room temperature. However, for drawn bars that contained axisymmetric residual stress is tested using rivet joint removal at one end of the connected halves.

As for the measurement, the elastic line is measured following the bent sample after balance disruption. After further analysis had been done, it shows that the measured elastic lines can be described with high precision by the elastic line of the cantilever bend (N. Tadic et.al, 2011).

If the metal layers of the strips were removed successfully, the elastic line will retain exactly the same properties only if the thickness is reduced up to half of the thickness. However, the residual stress in drawn bars in cyclic bending cannot be measured by deflection method. Therefore, as for drawn bars, x-ray diffraction using DRON-2 type is used. The values and equations can be seen as in Table 2:4 (N. Tadic et.al, 2011).

Table 2:4 : Schemes and equations for elastic line and residual stresses.

	Cold rolled strips	Drawn bars
Scheme of stress distribution through the thickness / cross-section		
Equation for stress distribution	$\sigma_z = \sigma_s\left[2\frac{h}{H} - 1\right]$	$\sigma_z = \sigma_s\left[3\frac{r}{R_1} - 2\right]$
Equation for elastic line	$y = a \cdot (z/L)^2$	$y = a \cdot (z/L)^2$
Equation for surface stress	$\sigma_s = \frac{8E(H - \Delta/2)^3}{\left[6\Delta H - 6\Delta^2 + \Delta^3/H\right]} \frac{f}{L^2}$	$\sigma_s = 12\left(\frac{\pi}{8} - \frac{8}{9\pi}\right)\frac{f}{L^2}$

After being analysed, the relaxation process is done. The thermal relaxation for

Alloy AA5083 strips were annealed up to 140 ̊C for about 10 minutes. These elastically bent strips were placed on 3 mm thick metal plate, attached and aligned before thermally treated. The same thing is done on drawn bars. But for drawn bars, the annealing is using the 370 ̊C/h regime. For both, the processes were repeated by removing the connection after annealing in order to measure the elastic line.

Relaxation will be done if the etched part were deformed in range of 0.5% to 1.65%. The same thing for drawn bars and cyclic bending, after removing the connection, the elastic line is measured.

The thermal relaxation on residual stress can be done using Zener-Wert-Avrami's function as in Eqn. 2.14, where the value of coefficients, temperature (T) and time (t) act as indicator in structural changes.

$$\sigma_{t,T} / \sigma_0 = \exp[-(A.t)^m] \qquad \text{(Eqn. 2.14)}$$

where σ_0, $\sigma_{t,T}$ is the value of the residual stresses for initial state and the after-annealing state in t-T conditions, m is the numerical value that indicates the dominant mechanism and A is the parameter that depends on the temperature, the activation energy and Boltzmann's constant.

After being tested in multilevel of annealing, with different ratios of reduction, different thickness, different thickness of removed layer and the annealing time, an analysis is done using 9 samples. Based on the graph in Figure 2:5, the effect of annealing can be seen in the early process. The curves shows that this thermal treatment stabilizes the high stress existed. However, after within the small area of annealing times, (1 min to 3 min), the stress relaxation is partial, with not very excessive changes, typical for the initial nucleation period (N. Tadic et.al, 2011). Due to the multiple heating, the curve can be considered as linear as the changes are very small because every phase starts with nucleation period.

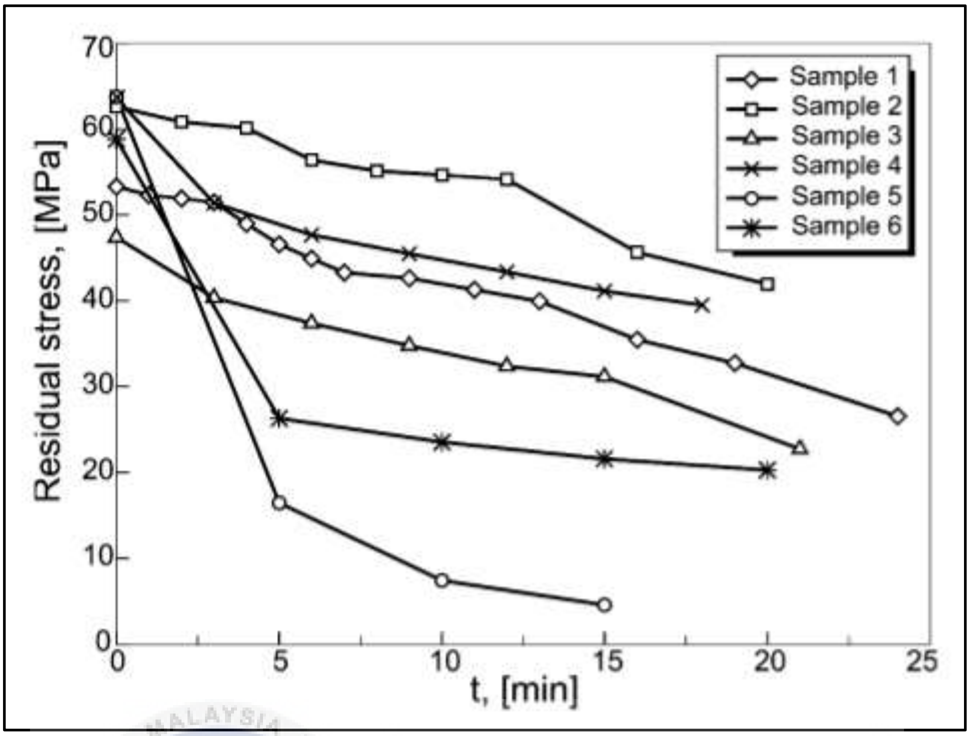


Figure 2:5 Residual stress for different thickness

To be summarized, the residual stresses can be estimated with high precision using deflection method. The induced residual stresses have a lot of advantages and its disadvantages. However in this experiment, the residual stresses are needed to be maintained as it is affecting the structural integrity.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This project is focussing mainly on the experimental results and will not discuss any simulation analysis. The purpose of writing this report is to estimate the value of residual stress existed in 316L stainless steel sheet after undergo machining and mechanical processes. Many journals have been reviewed and have been included in the previous chapter 2 (Literature Review) on how to measure the residual stress and what parameters needed to be taken into account for completing the main purpose. This chapter is about methodology and methods to reach the objectives of this report. The parameters, experimental works, processes and strategies will be further elaborated.

The 316L stainless steel is actually other version of 316 with lower carbon. 316L stainless steel mainly composed of elements as in Table 3:1.

Table 3:1 Composition of 316L stainless steel

Composition	Type 316L (wt%)
Carbon	0.03 (maximum)
Manganese	2.00 (maximum)
Phosphorus	0.045 (maximum)
Sulphur	0.03 (maximum)
Silicon	0.75 (maximum)
Chromium	16.00 to 18.00
Nickel	10.00 to 14.00
Molybdenum	2.00 to 3.00
Nitrogen	0.10 (maximum)
Iron	Balance as type 316 stainless steel

As for the preliminary work, the parameters of mechanical process that is rolling are done in order to reduce the thickness of as-received specimens with 10%, 20% and 50% reduction. In the experimental work, an etching process will be done using appropriate solution for 316L stainless steel to bend. Otherwise, it will not show any bending at all. After being etched, the effects of residual stress can be seen by relating how much the thickness varies with the deflection angle. The thicker the 316L stainless steel sheet, the lesser the residual stress and will have smaller deflection.

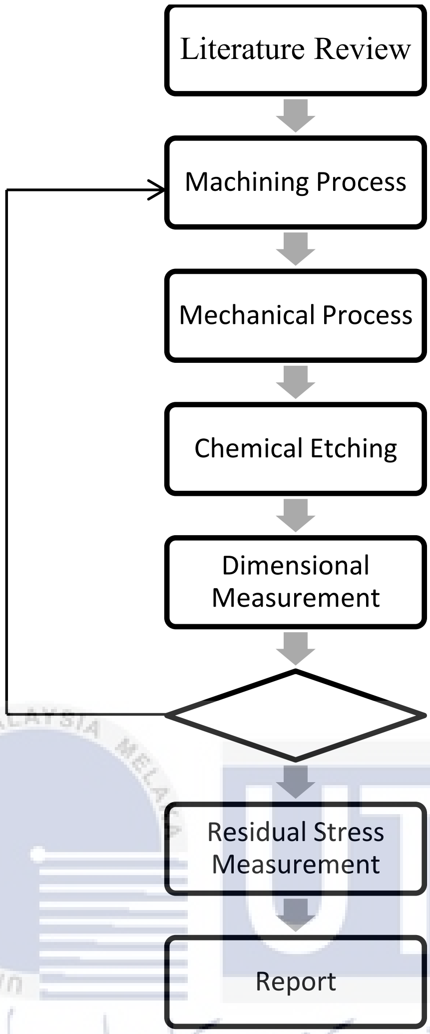


Figure 3:1 Flowchart planning

3.2 SAMPLE PREPARATIONS

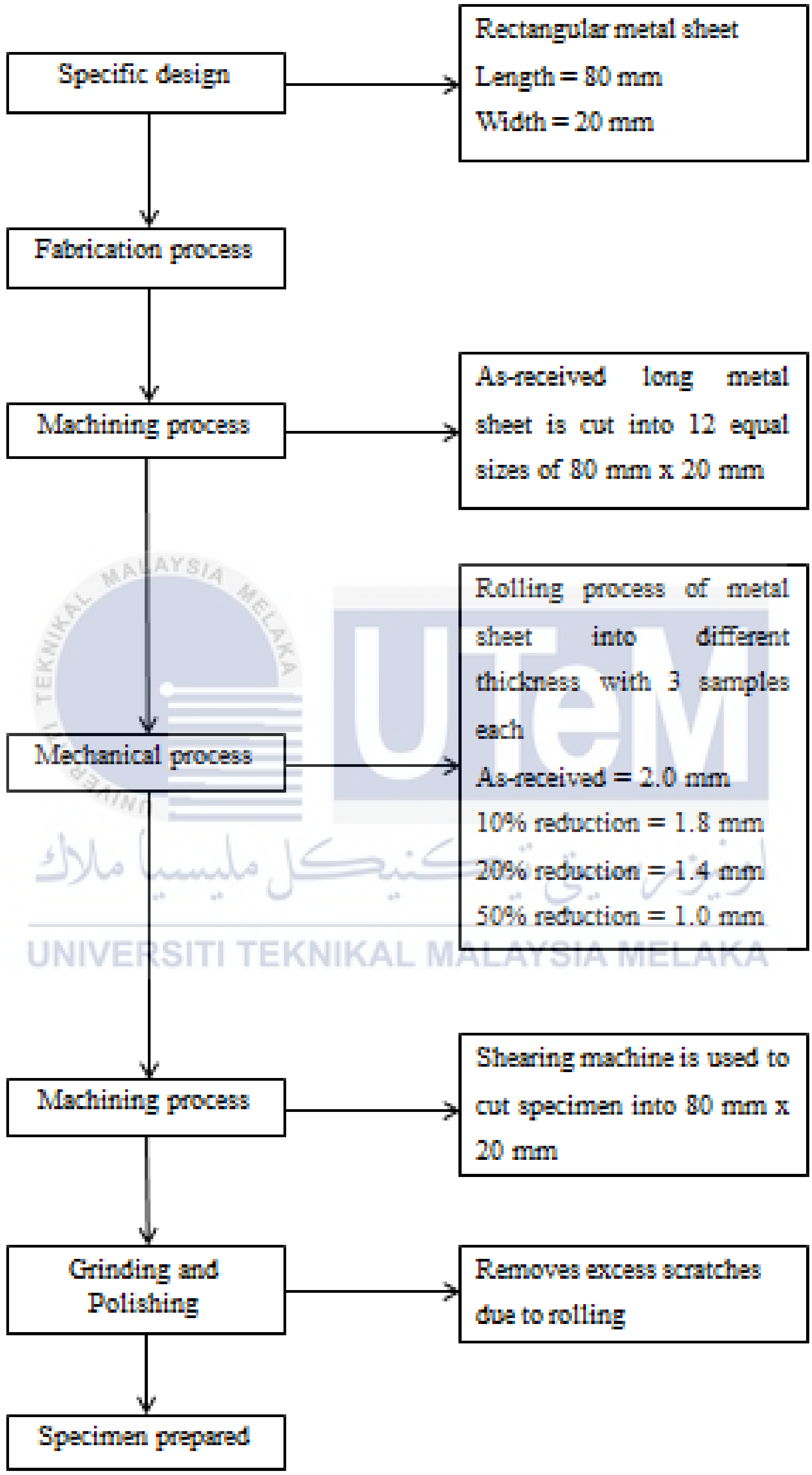


Figure 3:2 Flowchart of specimens preparation.

3.2.1 MACHINING PROCESS

A machining process will be done using a shearing machine in order to produce twelve (12) equal sizes of 80 mm x 20 mm stainless steel sheet. As received stainless steel sheet is approximately 450 mm long, 85 mm width and 20 mm thickness. The shearing machine will create more accurate and smoother product than using other machine. The specimen will be measured and marked using appropriate marker.

The measurement should have a tolerance of at least 1 mm for edge surface finishing later. However, the after-effect of shearing machine is the existence of burr. Burr or shear traces will affect the rolling process as it will gives uneven grain distribution. Therefore, after doing machining process, the specimens will be ensured to have no burr by removing it using fillet and sandpaper.

Final machining is resizing the specimen in 80 mm x 20 mm size by using CNC machine. After being rolled, the specimen will reduce in thickness and obviously increase the surface area.

3.2.2 MECHANICAL PROCESS (ROLLING)

Rolling process is chosen instead of using any other process to reduce the thickness is due to the accuracy of rolling in producing final product. Other processes such as forging are not suitable for small thickness reduction as it might not give accurate final product. Besides, forging might induced crack in the specimens.

Therefore, rolling is the most suitable method can be applied to reduce the thickness until 50% maximum. As-received stainless steel sheet is 2.0 mm and later will be rolled in order to get 1.8 mm, 1.4 mm and 1.0 mm thickness. The parameters for rolling machine will be provided as in Table 3:2.

Table 3:2 Roller specifications

Roller type	Duo-rolling
Roller diameter	125 mm
Roller speed	0.17 m/s

3.2.3 CHEMICAL ETCHING PROCESS

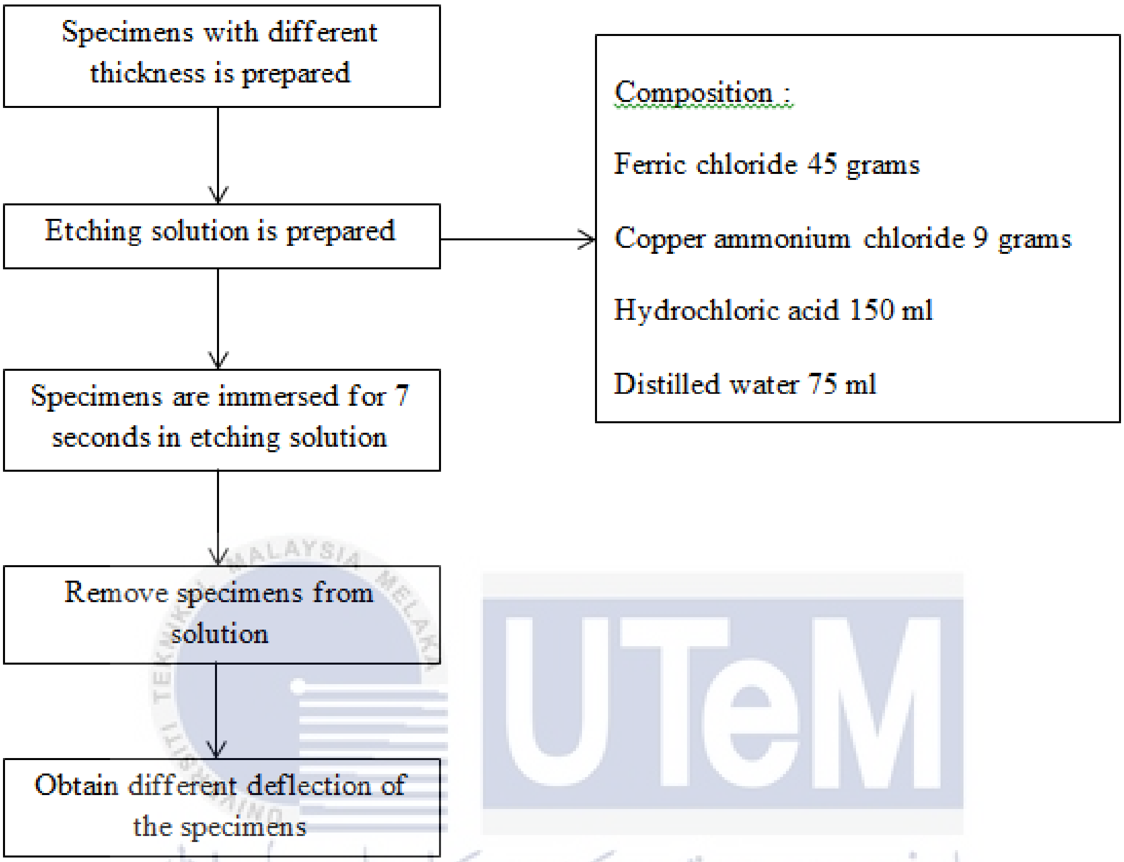


Figure 3:3 Flowchart for chemical etching.

Based on the ASTM E340 -15, Standard Practice for Macroetching Metals and Alloys the most suitable solution for 316L Stainless Steel is the Adler for 300 series stainless steel etchants that contained 45 grams ferric chloride, 9 grams copper ammonium chloride, 150 ml hydrochloric acid and 75 ml distilled water. This solution is very effective for 300 series, austenitic, duplex stainless steel and should be immersed only for several seconds. During etching, it is advised to wear appropriate protective clothing and observed all warnings on chemical manufacturers.

Table 3:3 Metallographic etchants

Echant	Composition	Conc.	Conditions 0	Comments
ASTM No. 30	Ammonia Hydrogen Peroxide (3%) DI Water	62.5 ml 125 ml 62.5 ml	Mix Ammonia and water before adding peroxide. Must be used fresh. Swab 5-45 seconds.	For etching copper, copper alloys and copper-silver alloys.
Adler Etchant	Copper ammonium chloride Hydrochloric acid Ferric chloride, hydrated DI Water	 9 grams 150 ml 45 grams 75 ml	Immersion is recommended for several seconds	For etching 300 series stainless steel and Hastelloy superalloys
Carpenters Stainless Steel Etch	$FeCl_3$ $CuCl_2$ Hydrochloric acid Ferric chloride, hydrated DI Water	8.5 grams 2.4 grams 122 ml 6 ml 122 ml	Immersion etching at 20̊C	For etching duplex and 300 series stainless steel
Kalling's No. 2	$CuCl_2$ Hydrochloric acid Ethanol	5 grams 100 ml 100 ml	Immersion or swabbing etch at 20 ̊ C	For etching duplex and 400 series stainless steels and Ni-Cu alloys and superalloys.
Kellers Etch	Distilled water Nitric acid Hydrochloric acid Hydrofluoric aci	190 ml 5 ml 3 ml 2 ml	10-30 second immersion. Use only fresh etchant	Excellent for aluminum and titanium alloys
Klemm's Reagent	Sodium thiosulfate solution Potassium	 250 ml Saturated	Etch for few seconds to minutes	For etching alpha-beta brass, bronze, tin, cast-iron

	metabisulfite	5 grams		phosphides, ferrite, martensite, retained austenite, zinc and steel temper embrittlement
Kroll’s Reagent	Distilled water Nitric acid Hydrofluoric aci	92 ml 6 ml 2 ml	Swab specimen up to 20 seconds	Excellent for titanium and alloys
Nital	Ethanol Nitric acid	100 ml 1-10 ml	Immersion up to a few minutes	Most common etchant for Fe, carbon and alloys steels and cast iron - Immerse sample up from seconds to minutes; Mn-Fe, MnNi, Mn-Cu, Mn-Co alloys
Marble's Reagent	$CuSO4$ Hydrochloric acid Water	10 grams 50 ml 50 ml	Immerse or swab for 5-60 seconds.	For etching Ni, Ni-Cu and Ni-Fe alloys and superalloys. Add a few drops of $H2SO4$ to increase activity
Murakami's	$K_3Fe(CN)_6$ KOH Water	10 grams 10 grams 100 ml	Pre-mix KOH and water before adding $K_3Fe(CN)_6$	Cr and alloys (use fresh and immerse); iron and steels reveals carbides; Mo and alloys uses fresh and immerse; Ni-Cu alloys for alpha

				phases use at 75 Celcius; W and alloys use fresh and immerse; WC-Co and complex sintered carbides
Picral	Ethanol Picric acid	100 ml 2-4 grams	Seconds to minutes Do not let etchant crystallize or dry – explosive	Recommended for microstructures containing ferrite, carbide, pearlite, martensite and bainite. Also useful for magnetic alloys, cast iron, high alloy stainless steels and magnesium
Vilella's Reagent	Picric Acid Hydrochloric acid Ethanol	1 gram 5 ml 100 ml	Seconds to minutes	Good for ferrite-carbide structures (tempered martensite) in iron and steel

CHAPTER 4

DATA AND RESULTS

This chapter will discuss the results of the experimental works done on the austenitic stainless steel 316L through chemical etching. The residual stress will be measured using deflection method by which the variety of thickness is being considered. The parameters and properties of materials are listed as in table below.

Table 4:1 Properties of stainless steel 316L.

Properties	Dimension
Length	80 mm
Width	20 mm
Thickness	1.0 mm, 1.4 mm, 1.8 mm, 2.0 mm
Young's Modulus, E	193 GPa
Tensile Strength (min)	485 MPa
Yield Strength 0.2% proof (min)	170 MPa
Brinell Hardness (max)	217 MPa
Density (ρ)	8000 kg/m³
Poisson's ratio (v)	0.3

4.1 MACHINING PROCESS

The as-received plate is in 2.0 mm in thickness with area of 450 x 85 mm. The plate is then cut into 12 equal sizes using shearing machine with tolerance of 1 mm. The tolerance purpose is to enhance the cutting surface using fillet and sandpaper. Grinding and polishing is advisable and preferable as it helps reduce the shear effects evenly. Removing the shear effects or burr is essential as it will disturb the grain distribution in the rolling process later.

Figure 4:1 As-received specimen.

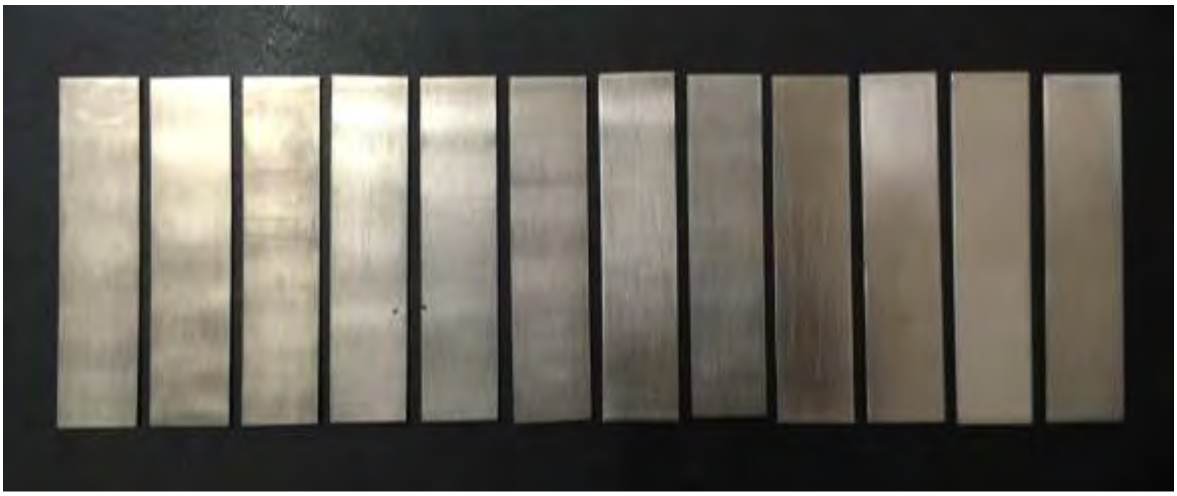


Figure 4:2 After cutting into 12 equal size of specimens.

Figure 4:3 Example of shear effects.

Sandpaper for grinding and polishing used are P150 until P2000. Specimens are later cleaned by wiping using propanol.

4.2 ROLLING PROCESS

For rolling process, the 12 specimens are divided into 4 groups which are with thickness of 2.0 mm, 1.8 mm, 1.4 mm and 1.0 mm respectively.

Figure 4:4 Rolling machine.

Figure 4:5 Different thickness of specimen after rolling process.

After rolling, there are scratches on the surface of the specimens. Therefore, it is advisable to remove necessary amount of scratches before continue to etching process. The specimens were grinding using P150 until P2000 sandpaper and further polished using 3 micron diamond paste.

Figure 4:6 Specimens after cleaned using propanol.

4.3 CHEMICAL ETCHING

This process is done by mixing up the solution that is suitable for deflection of stainless steel 300 series. This solution is composed by few solutions as listed in table below.

Table 4:2 Etching solution compositions.

Solution	Unit
Copper ammonium chloride	9 grams
Hydrochloric acid	150 ml
Ferric chloride, hydrated	45 grams
Distilled water	75 ml

The etching solution is thus placed into a beaker to allow specimens to be immersed approximately 7 seconds. Then, the specimen is taken out and put onto paper on flat surface. Minor deflection can be seen. Latterly, the deflection will be measured using dial gage. Precautions while handling the chemicals as it is contain acid.

Figure 4:7 Etching solution being separated into small amount for usage.

Figure 4:8 Specimen is being immersed for 7 second.

4.4 DEFLECTION MEASUREMENT

After completing etching process which requires the specimens to be immersed for 7 seconds, deflection can be seen even though it is very small. The deflection is then measured using simple dial gage set up.

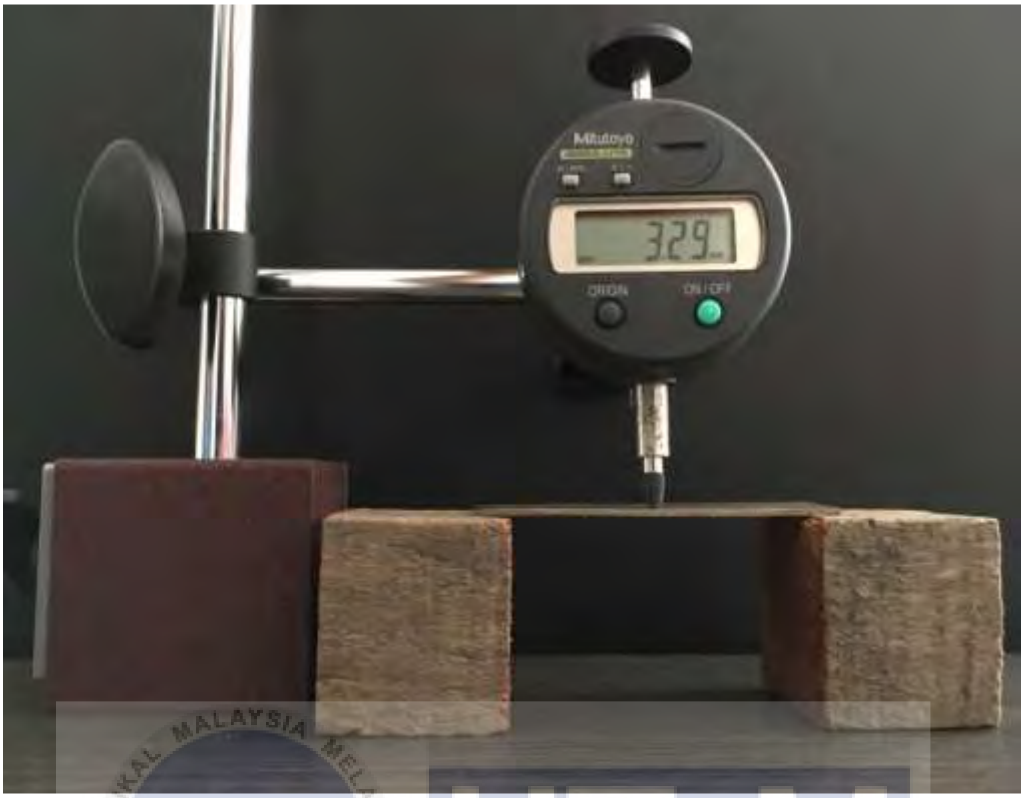


Figure 4:9 Example of measuring the deflection.

The deflection values measured in all specimens are recorded in Table 4.3.

Table 4:3 Deflection values based on thickness.

Thickness, µm	**Reduction ratio, %**	**Sample**	**Deflection, µm**
1000	50	1	160
		2	150
1400	20	1	180
1800	10	1	200
2000	0	1	240

CHAPTER 5

RESULTS AND DISCUSSION

As shown in chapter 4, it can be seen that the thinner the specimen the higher the deflection. This depicts that the specimen contains residual stresses as discussed in chapter 2 and satisfy the hypothesis stated. The state of residual stress is in two dimensional with longitudinal and transverse components. The values of residual stresses are mainly affected by the properties of material and the shape of metal sheets. The profile of residual stress involves through thickness which maximum on the surface. As stated in chapter 2, their profile comprises the whole cross section, and the maximum is on the surface, Figure 5.1, (Tadic and Misovic, n.d)

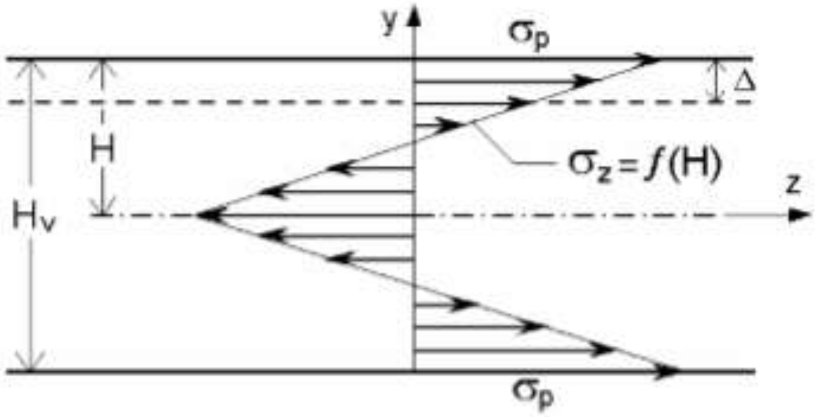
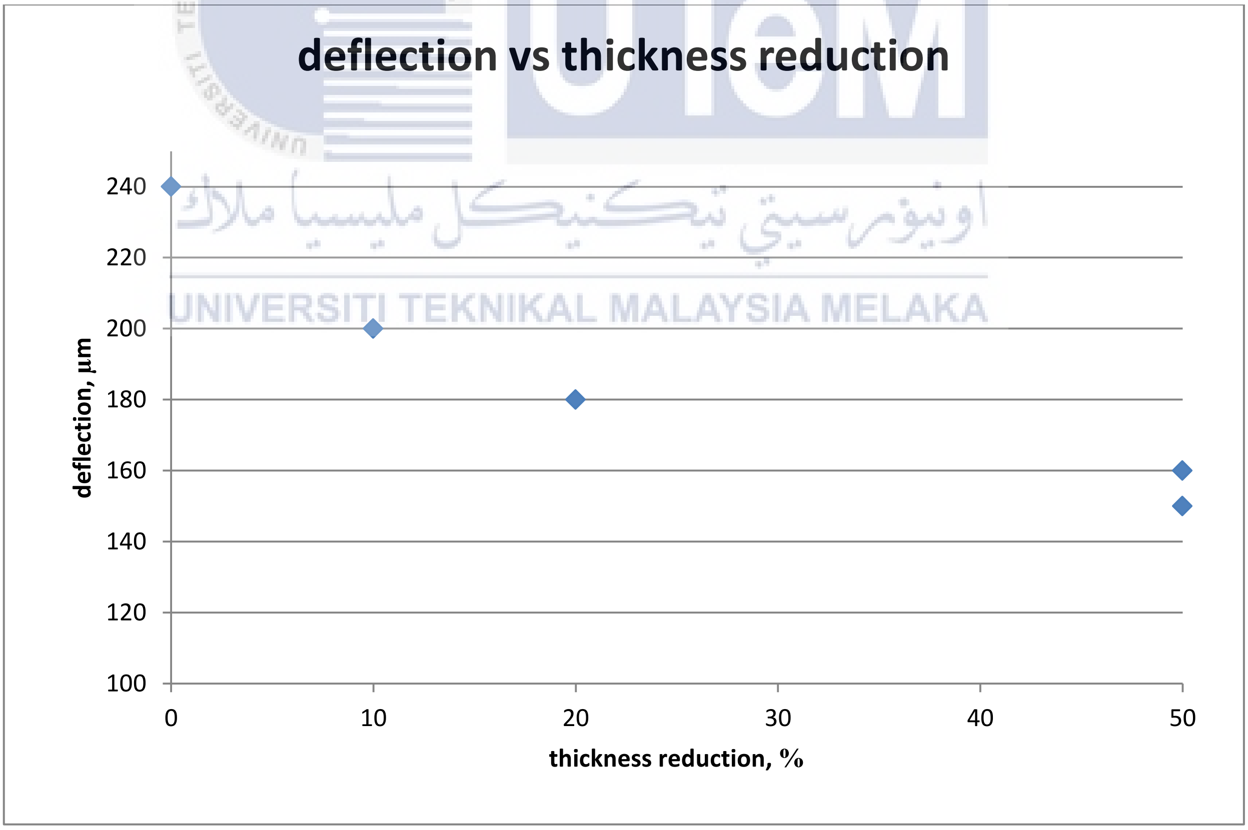


Figure 5:1 Overview and parameters used for residual stress calculation.

The specimens went through cold work rolling process, cut and etched. From Figure 5.1, the thicker the specimen the higher the deflection, thus it can be said that the process created higher residual stress in the specimen.

Table 5:1 Deflection values recorded through experiment based on thickness.

Thickness, µm	Reduction ratio, %	Sample	Deflection, µm
1000	50	1	160
		2	150
1400	20	1	180
1800	10	1	200
2000	0	1	240



Graph 5.1 Deflection versus thickness reduction.

From Table 5.1, the 12 specimens are divided into 4 different thicknesses with each have 3 samples. The specimens went through cold rolled process with original thickness of 2 mm. The reduction ratio are 10%, 20% and 50%. The rolling process has caused few scratches on the surface of the specimens. This would lead to distortion of the grain distribution and eventually caused minor effect on the distribution of residual stress.

However, the scratches were polished before etching process in order to reduce the casualties on the deflection. Etching process took place by immersing the specimen for 7 to 10 seconds.

Based on assumption, the stresses are distributed linearly along the length and constant along the width, and etching process has disturbed the balance. Thus, unsymmetrical bend occurred. Based on the results, the maximum deflection occurred at the centre of the specimens. This proves that the residual stress existed in the specimen as they went through mechanical processes. The slight bend at the edge of the specimen is due to cutting process which induced minor residual stress.

According to cantilever bending, the deflection occurred symmetry to transverse axis, the width. The differences of deflection can be seen that varies slightly even though belong in the same thickness. This is due to un-uniform handling the specimens during mechanical process. With defects arise after each process, lead to different value of deflection. From Table 5.1, the residual stress is determined using Eqn. 5.1.

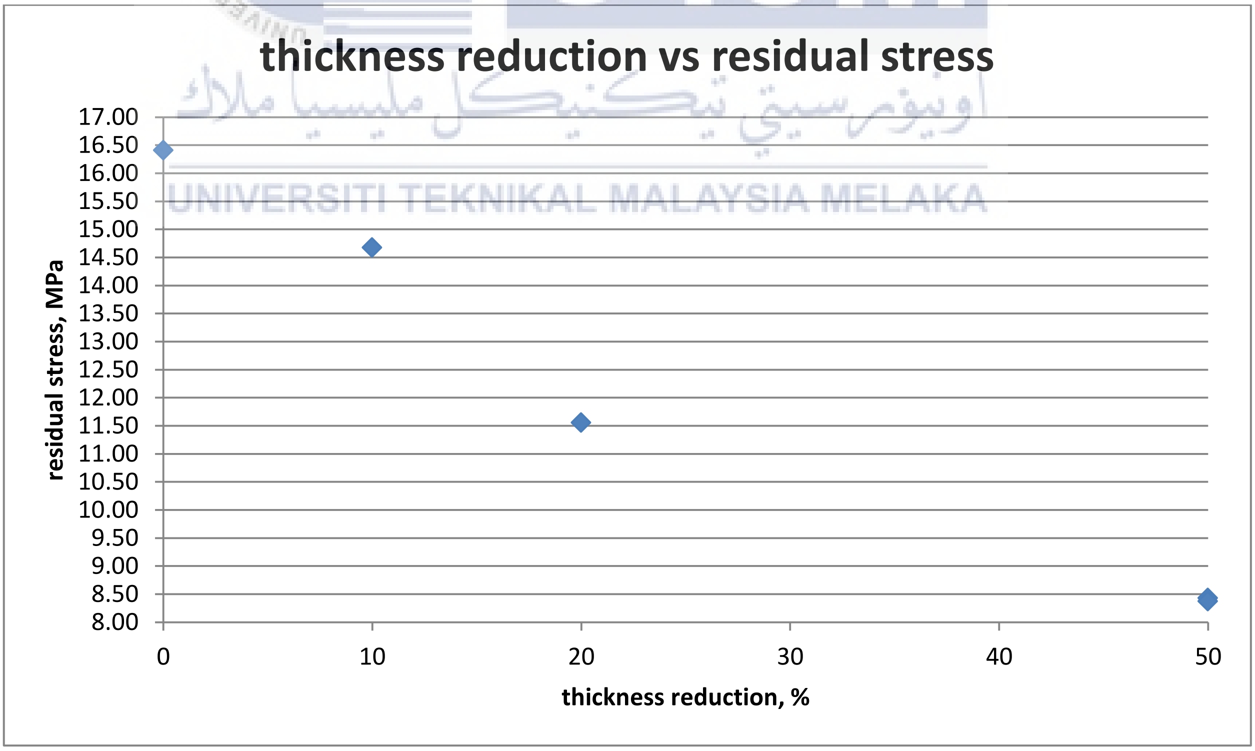
$$\sigma_{\mathrm{res}} = \frac{\pi^2 E}{L^2}\left[\frac{A^2}{4} + \frac{\Delta t^2}{3}\right] \qquad \text{(Eqn. 5.1)}$$

where E is the modulus elasticity of 316L stainless steel, Δt is the thickness of metal sheet, L is the length of metal sheet and A is amplitude of buckling.

Calculation is done based on equation and the result is recorded in Table 5.2 and tabulated in Graph 5.2.

Table 5:2 Residual stress determination through calculation.

Thickness, µm	Reduction ratio, %	Sample	Deflection, µm	Length of the specimen, µm	Elastic Modulus, GPa	Residual stress, σ_{res} MPa
1000	50	1	160	80000	183	8.4279
		2	150			8.3714
1400	20	1	180			11.5525
1800	10	1	200			14.6749
2000	0	1	240			16.4065



Graph 5.2 Thickness reduction versus residual stress.

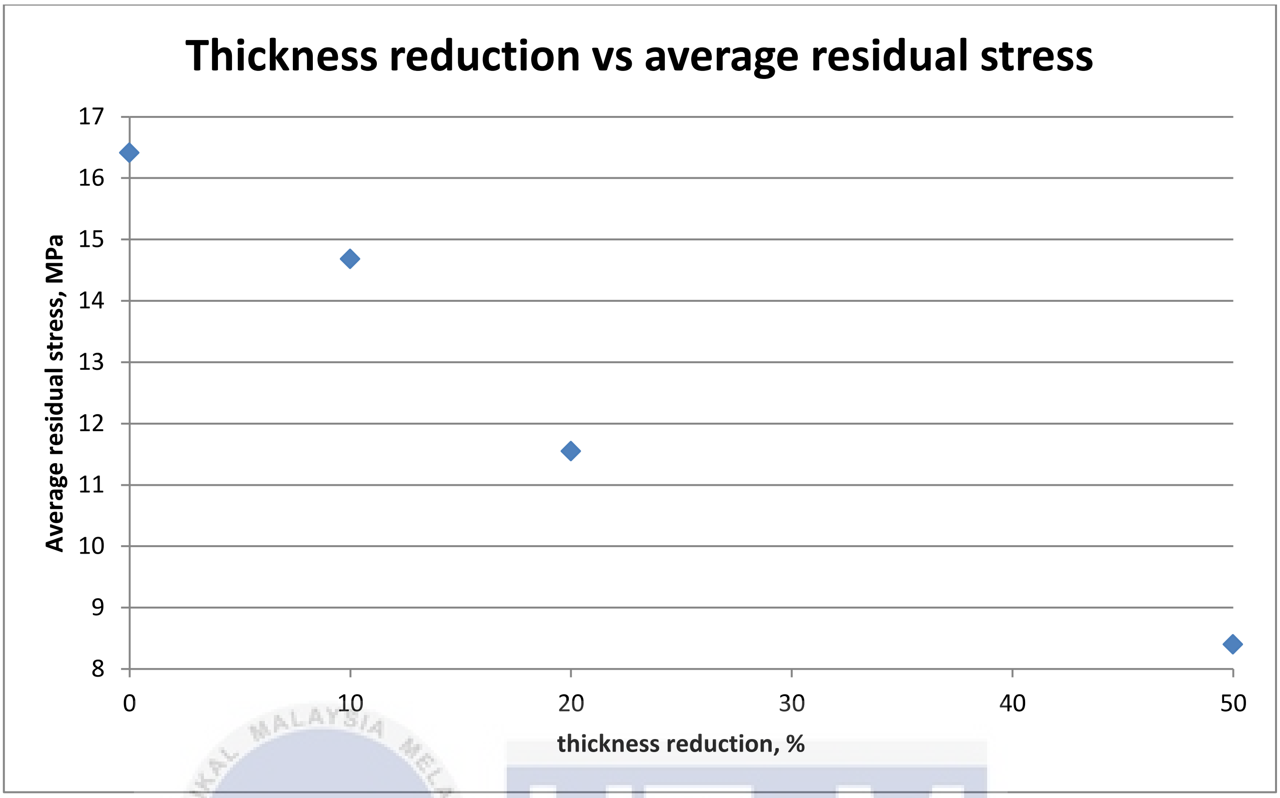
The measured values of deflection after etching process were approximated using Eqn 5.1. The approximation results are shown in Table 5.2.

It can be seen that the value of residual stress differed even though belong to the same thickness. This value affected by processes before etching is done. Rolling process is done one by one with increment as low as 0.05 mm in order to avoid damages. Rolling process has forced the grains to evenly distribute as the thickness is decreased. Cutting using shearing machine induced residual stress around the edge and had caused burr effects.

Based on Table 5.2, the reliability of deflection method greatly depends on the dimension, length and thickness. Based on the graph, the dissipation of residual stresses becomes lower and constant near the transverse axis.

Table 5:3 Average deflection and average residual stress based on thickness.

Thickness, Δt µm	**Average deflection, δ µm**	**Average residual stress, σ_{res} MPa**
1000	155	8.40
1400	180	11.55
1800	200	14.68
2000	240	16.41



Graph 5:3 Thickness reduction versus average residual stress.

From Graph 5.3, it can be seen that the higher the thickness reduction, the lower the residual stress. This is due to the deflection as the balances of residual stresses were interrupted. Higher deflection depicts that the amount needed to deflect the specimen is much smaller compared to thicker specimens.

It is true that the structural integrity of the specimens are enhanced, but that is comparison between two equal dimension of specimens that went through different method of thinning process. The strength, fatigue life and dimensional stability of a 1.0 mm specimen that went through rolling process are much better than 1.0 mm specimen that went through machining process.

However, if compared between 2.0 mm and 1.0 mm specimen, it is obvious that thicker specimen possessed higher strength. Thus, creating higher residual stress.

As for the effects on the structural integrity, the residual stress plays an important role in engineering field from designing to failure. Mostly, the residual stresses tend to be ignored as it has minor effects on structure. Latterly, however, in major structure, residual stresses become major contribution to structural damage, worst, failure.

Residual stress varies with thickness as shown in Table 5.3 and Graph 5.3. The variation of residual stresses decrease as the thickness increase. As its definition, residual stresses are locked in stresses within a metal object, even though the object is free of external forces (M. Pfeifer). 1.0 mm sheet thickness has higher approximated value of residual stress due to quantity of processes it went through.

From observation, many of engineering structure will undergo mechanical or machining process thus induced residual stress. However, through time, with loads, a structure with residual stress will fail. This occurred due to the effects of residual stress on structural integrity.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

Residual stresses are mostly induced through mechanical process, thus a cold rolled process is done in this paper. However, the residual stress cannot be measured precisely. Therefore, based on researches, a deflection method is proven to be most precise method to predict the magnitude of residual stress. The measurement and data is recorded and tabulated in the discussion.

The data recorded is satisfied as stated in hypothesis as through findings, it can be seen that the thicker the specimen, the higher the residual stress. The thicker specimen however, possessed higher residual stress or in other words, require less stress to deflect thicker specimen. As stated by T. Negussie, A. A. Goran and T. Lambert in their book “Residual stresses in thick welded plates”, it is mentioned that residual tends to reduce strength. Even though through mechanical process, has increased the integrity of the specimens in the aspect of strength, fatigue life and dimensional stability, thinner specimens still has lower residual stress compared with thicker specimens. This is due to the thinning process are done mechanically, that is why if the strength is compared between two equal thickness, thinning specimen by rolling would create higher strength than the one done through machining. But if two specimens with different thickness are compared, obviously the thicker specimen possessed higher strength.

However, this paper only discussed on the magnitude of the residual stress and limited to only one mechanical process which is rolling and the results are compared between different thicknesses.

6.2 RECOMMENDATION

As recommendation, from this paper, the value of residual stress should be compared with simulation in order to prove the effectiveness and identify the limitations of deflection method. Not only that, other research also should compare between two methods in order to validate that the deflection method is most precise than the other.

For a bigger scope, it is recommended that further analysis is done on the microstructure of the deflected specimens and relate back the structural integrity and the effects of residual stress.

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