EFFECT OF TOOL ECCENTRICITY ON THE STATIC AND FATIGUE STRENGTH OF THE JOINT MADE BY MECHANICAL CLINCHING PROCESS

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By

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ABSTRACT

EFFECT OF TOOL ECCENTRICITY ON THE STATIC AND FATIGUE STRENGTH OF THE JOINT MADE BY MECHANICAL CLINCHING PROCESS

Kam Heng Keong

The effect of tool eccentricity on the joint strength in clinching process was investigated. The objective is to understand the mechanical behaviour of the clinched joint where proper control on the alignment setting of tools can be considered. In this research, a clinching process to form a round joint was carried out by offsetting the centre line between the upper punch and lower die. The experimental results were compared between offset and without offset conditions. The factors which determine the quality of joint strength such as the interlock and the neck thickness obtained from cross section geometry were examined by opening mode and tension-shearing mode tests. Coated mild steel and aluminium alloy sheets were used for the evaluation. It is found that the strength values by offset clinching exhibit variation in sinusoidal relationship with respect to the in-plane offset direction. These values are generally lower by 10-36% for mild steel and 60-70% for aluminium alloy. The fatigue strength of a clinched joint with offset is generally 5-10% weaker compared to the one without offset. Finally, a 2D rigid-plastic FEM tool is proposed as a first attempt of approximation to investigate the formation of interlock and also to predict the distribution of tool contact pressure caused by the offset condition.

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Last but not least, I wish to thank my parents, my sister and brother-in-law who were beside me all the time and gave me the precious support and encouragement to complete my work and attain my ambition to earn a master degree.

APPROVAL SHEET

This dissertation entitled "**EFFECT OF TOOL ECCENTRICITY ON THE STATIC AND FATIGUE STRENGTH OF THE JOINT MADE BY MECHANICAL CLINCHING PROCESS"** was prepared by KAM HENG KEONG and submitted as partial fulfillment of the requirements for the degree of Master of Engineering Science at Universiti Tunku Abdul Rahman.

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SUBMISSION OF THESIS

It is hereby certified that ***KAM HENG KEONG*** (ID No: ***11UEM06268***) has completed this thesis entitled "EFFECT OF TOOL ECCENTRICITY ON THE STATIC AND FATIGUE STRENGTH OF THE JOINT MADE BY MECHANICAL CLINCHING PROCESS" under the supervision of Dr. Wang Chan Chin (Supervisor) from the Department of Mechanical & Material Engineering, Faculty of Engineering and Science, and Dr. Lim Ying Pio (Co-Supervisor) from the Department of Mechanical & Material Engineering, Faculty of Engineering Science.

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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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Date 24th March 2014

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Mechanical clinching is a cold joining process commonly used to join several metal sheet components into a single piece structure by local hemming. This method is widely used due to its short time and low running cost merits where no additional materials are needed for riveting or heat energy in welding. Besides, the process also acquires flexibleness in joining different types of sheet metal such as aluminium alloy with steel to cut down weight of product's structure such as vehicle and electrical appliances in the industry. Various researches in the mechanical clinching method had been carried out, Varis (2003) inspected the joint strength of various shapes to investigate the suitability for making building frames with high strength structural steel. Varis (2006) continued to study on the economic merit from the aspect of tool service lifespan by comparing the unit cost produced by the mechanical clinching over the self-pierce riveting. Varis and Lepistö (2003) discovered some important parameters for mechanical clinching by using experimental method and finite element method (FEM). Coppieters et al. (2011) reported a set of analytical methods by simplifying the material geometries and stresses to predict the pull-out strength in box-test. Lee et al. (2010) utilized FEM on tool design in order to obtain higher joint strength which fulfils the requirement of automotive industry. Abe et al. (2011) declared that the joint strength of rectangular shape shows higher values than the one of round shape. Abe et al. (2012) introduced a metal flow control method to overcome fracture failure of clinching high strength steel with aluminium alloy sheet. Abe et al (2007) studied the method to join aluminium alloy with mild steel sheets by investigating the flow stress of deformed sheets. Mori et al. (2012) compared the fatigue strength between mechanical clinching and self-pierce riveting, and explained the mechanism of superiority by mechanical clinching method. Carbini et al. (2006) found that a tensile-shear loaded clinched joint can last more than 2 x 10^7 number of cycles at 50% of maximum joint strength.

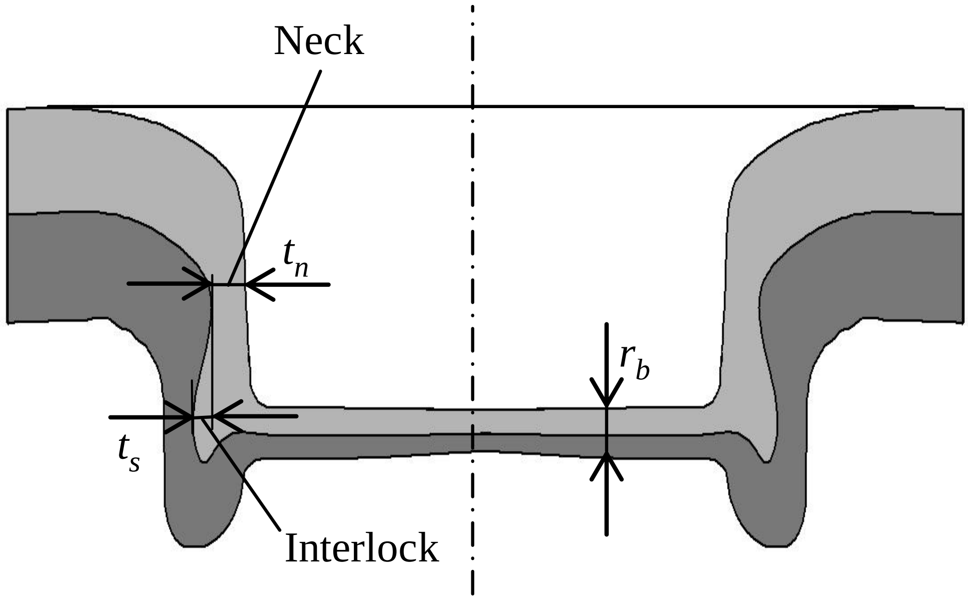


Figure 1.1 The cross section of a clinched joint and parameter terms, Interlock, t_s, neck thickness, t_n, bottom thickness after clinching, r_b.

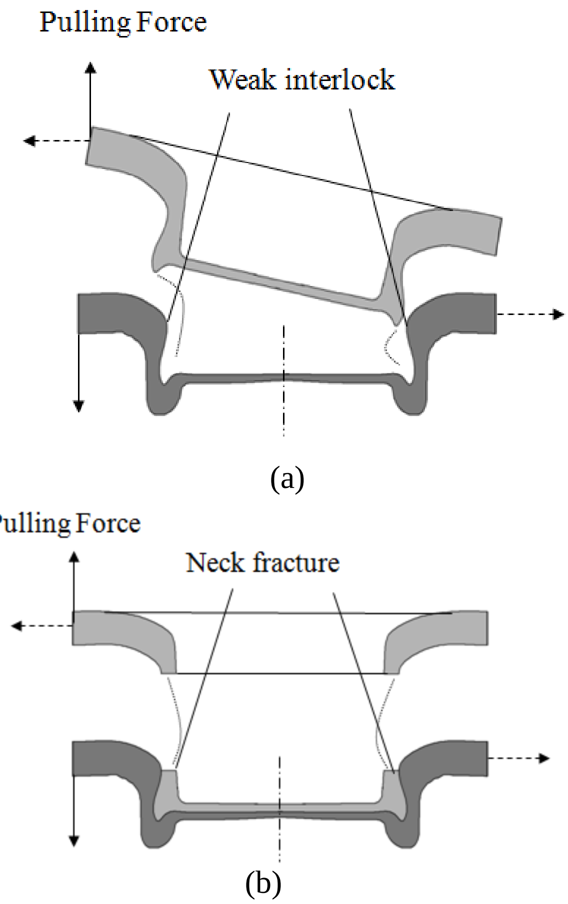


Figure 1.2 Failure modes (a) button Separation (b) neck Failure

The joint strength of a mechanical clinched joint is determined by the parameters: the interlock, t_s and neck thickness, t_n as shown in Figure 1.1, which is measured from the cross sectional geometry of a clinched joint. These parameters are able to determine the structure to hold the resistance against external pulling force. The failure modes of a mechanical clinching joint are illustrated in Figure 1.2. A typical example of a mechanical clinching product is shown in Figure 1.3 where two brackets are clinched with a metal base pan at four locations to form a holding frame for an outdoor air conditioning unit. For joint strength inspection purpose, the samples of the jointed base pan are sent for strength test where a pair of vertical pulling force is applied to separate the joint part at each location by order. This joint strength is determined by the maximum pulling force required to separate the joint part. The author studied a round clinched joint from a commercial product as shown in Figure 1.4. It shows that the cross section is non-symmetrical due to tool eccentricity. It is also found that the upper sheet and the lower sheet are not fully attached as well.

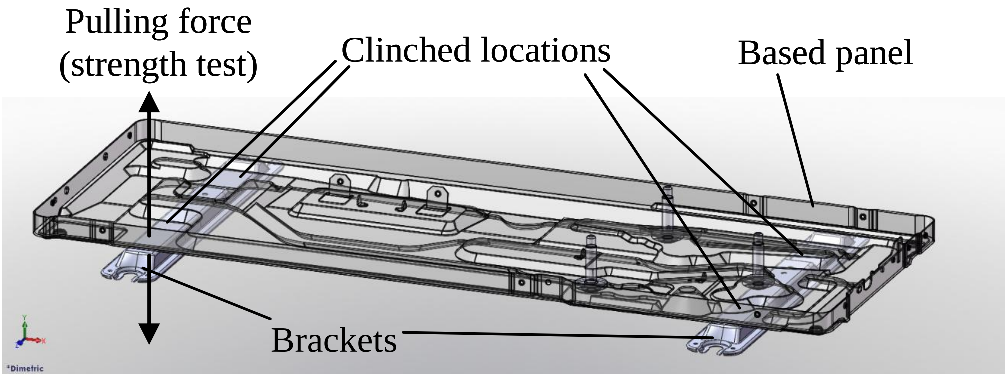


Figure 1.3 Clinched structure and pulling force direction for strength test.

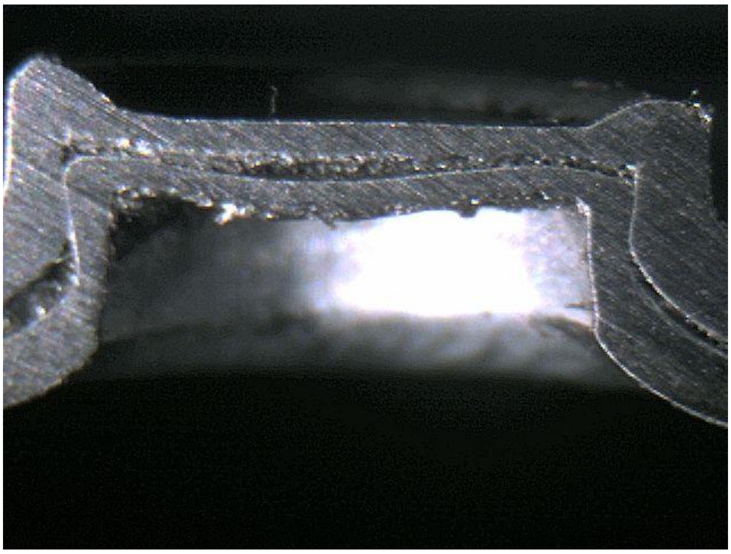


Figure 1.4 Cross section view of clinched joint (sample from commercial product)

In mechanical clinching process, there are many small punches and dies are installed inside a die-set at specific positions to clinch metal sheet parts together in one stroke. Due to the complexity in setting the alignment for many punches and dies inside a die-set, a minor eccentricity due to the displacement between the center axis of upper punch and lower die. Tooling misalignment is typically caused by the following inaccurate assembly of components and distortion due to forces exerted and vibration after a long time of service. Assuming the die clearance is given 1mm, a deviation of 100μm (10% offset ratio) about the center axis is sometimes ignored within the range of tolerance. In addition, the occurrence of minor eccentricity is not easy to be notified during the press operation because of the total forming load shows almost no change and the shape irregularity is not noticeable by simple visual inspection on the spot. Therefore, an evaluation of effect of mechanical clinching tool eccentricity is essential to provide better understanding about the mechanical behaviour of the clinched joint where proper control on the alignment setting of tools can be considered.

1.2 Research Objectives

The objectives of this study are:

1. Investigate the deviation of tool eccentricity in mechanical clinching by evaluating the joint strength (static case) in various conditions of tool offset and to define suitable allowance.
2. Provide a better understanding about the mechanical behavior of the clinched joint where the quality of joint strength can be referred to assist proper setting of tool alignment.

1.3 Thesis Overview

Outline of this dissertation are as shown below,

Chapter 1 presents a brief introduction, problem statement, objectives to be achieved and the layout of the thesis.

Chapter 2 describes a literature review which includes an introduction to mechanical assembling methods such as welding, self-pierce riveting and mechanical clinching. Review on journals on different studies on the behaviour of mechanical clinching.

Chapter 3 covers the experimental setting of mechanical clinching used in this study, including the geometries of mechanical clinching tools, tensile test on the sheet metals, clinching joint loading test and fatigue test, application of FEM software to predict the effect of tooling eccentricity on mechanical clinching joint.

Chapter 4 discussed the result of mechanical clinching joint under different clinching condition. Data collected from different tests was plotted on graphs to study the outcome of mechanical clinching joint under different clinching condition. The discussion of the results is included in this section as well.

Chapter 5 describes the conclusions and the contributions of this dissertation.

Chapter 6 expresses the future prospect of current research.

CHAPTER 2

LITERATURE REVIEW

2.1 Mechanical Assembly

There are a lot of products which are made of more than one parts, engineers need to search for an effective way to assemble the parts into a component. Several joining methods are used in mechanical assembly to mechanically join two or more parts together. Mechanical joining can be categorized into methods of that are temporally such as fastening screws and that are permanent joining such as rivets. The focus of this research work is in the mechanical clinching which is one of the permanent joining method.

2.1.1 Welding

In the welding process, two or more parts are heated and melted or forced together, causing the parts to join as one. Therefore, a lot of energy is required to heat up the material and fumes are produced during the welding process. In some welding methods, a filler material is added to make the joining of the materials easier. One of the limitations of welding process is that this method is not suitable to join dissimilar material because of different material properties especially melting point. Various types of welding operations are used in the industries, such as the spot welding, arch welding, resistance welding and friction stir welding.

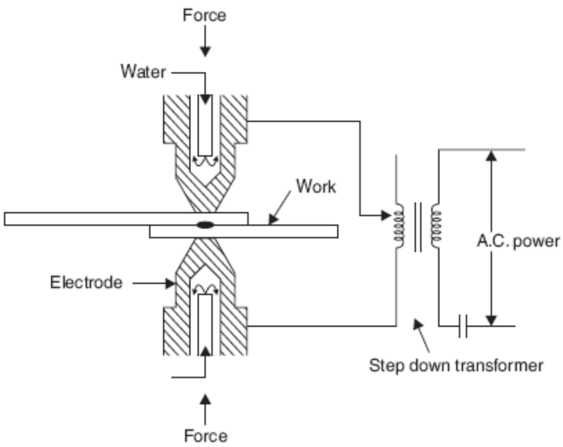


Figure 2.1 Spot welding

2.1.2 Self-piercing Riveting

Self-piercing riveting is a one-stroke mechanical fastening process which is for point joining sheet material such as steels and aluminium alloys. This process generally uses a semi-tubular rivet to join the sheets in a mechanical joint. In addition, there is also a process variant which utilises solid rivets.

As the name suggests, pre-processing holes are not necessary, allowing the joint to be done more rapidly in one operation. The process starts by clamping the sheets between the die and the blankholder. The semi-tubular shaped rivet is punched into the sheet metals that are to be joined between a punch and die in a pressing tool. Mechanical interlock is formed when the rivet pierces the upper sheet and the die shape causes the rivet to flare in the lower sheet. The die shape also causes a button to form at the bottom of the lower sheet and the rivet tail should not pierce the lower sheet.

The advantages of self-piercing riveting include:

- fast and single operation joining process,
- able to use on unweldable materials
- joining dissimilar materials,
- little or no damage to coating layer, no fume or heat is produced, low noise emission, low energy consumption.

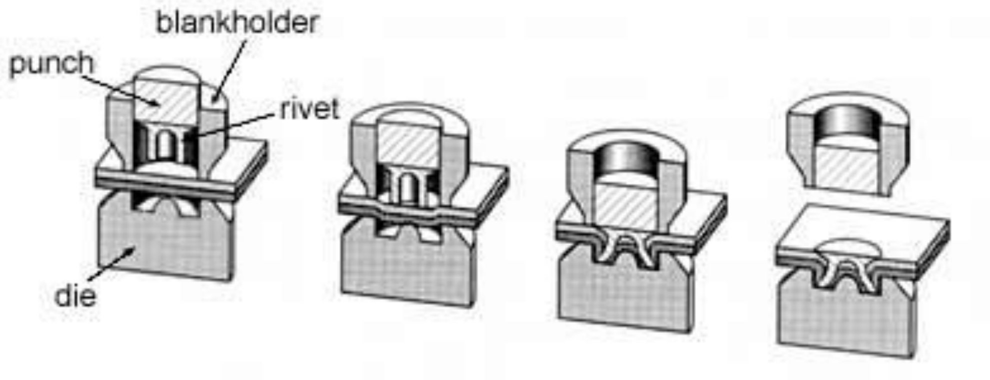


Figure 2.2 Self-piercing riveting

2.1.3 Mechanical Clinching

Clinching (press joining) is a reliable method for joining metal sheets, tubes and profiles. This permanent joint is created by using cold forming technique, without using additional parts or welds. This method offers a decrease in both production and manufacturing cost due to the elimination of the additional parts and 60% reduction of energy used relative to welding. (P.Nesi, 2004)

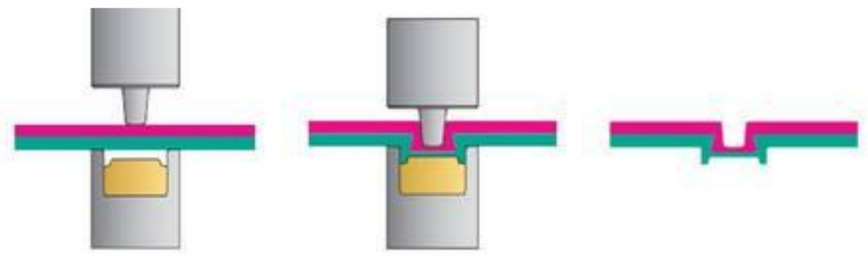


Figure 2.3 Mechanical clinching (TOX®PRESSOTECHNIK, 2009)

The tools require to form a mechanical clinching joint are punch and die. The punch squeezes the two layers of sheet metal into the die. Ultimately the upper sheet forms an interlock within the lower sheet.

Clinching is widely used in the automotive, appliances and electronics industries, where it replaces spot welding in common. Clinching is a cold forming process which requires no electricity and heat. Clinching provides quieter, cleaner and safer working environment for the operators. Maximum lifespan for clinching tools is 300,000 joints and its application for numerous material joining makes it a very economical process (Varis, J., 2006). The operational life of clinching tools can be improved by modifying tool geometry and/or material, and surface treatment of the fastening tool (Lothar Budde, 1994). Clinching has become more popular in joining aluminium panels due to the problems encountered with spot welding of aluminium.

2.1.4 Metal Joining Technique Comparison

The comparisons of clinching, self-piercing riveting and welding under different criteria are stated in Table 2.1.

Table 2.1 Metal joining technique comparison

	Clinching	Self-piercing riveting	Welding
Corrosion of coated material	Little	Little	High
Joint and strength alteration at joining	None	None	Yes
Dynamic load-resistance (shearing)	Very good	Very good	Less good
Static load-resistance (shearing)	Good	Very good	Very good
Process combined with bonding	Optimum	Optimum	Poor
Edges-burring-splinters	None	None	None

Joining consumables required	None	Punch rivet	None
Additional working processes	None	Supply	Post retreatment of treated surface
Cost per joint	Very little	Little	High
Energy consumption	Little	Little	Very high
Economy	Very good	Good	Less good
Handling	Very simple	Simple	Simple
Reproducibility	Very good	Very good	Satisfactory
Dependence of joint result on surface quality	Little	None	High
Pre-processing	None	None	Washing, etching

Among the advantages of mechanical clinching, Varis (2006) draws a conclusion that mechanical clinching is preferred over self-pierceing riveting and welding in term of economic merit which has a lower production cost in the aspect of tool service lifespan.

2.2 Mechanical Clinching Joint Strength Parameters

Several researches had been carried out to study the factors that determine the strength of a mechanical clinching joint. In general, the strength of a mechanical clinching joint is directly proportional to the joint size, the thickness and strength of the blank material.

2.2.1 Material Properties and Thickness

Mucha et al (2011) compared the clinching joint sheering strength of two different materials and made a conclusion that the sheering strength of the clinch joint made of the stronger material is higher than the relatively weaker material. He also commented that thicker sheet metal should be used as the upper sheet in order to obtain higher clinching joint strength when joining materials of different thickness. Neck fracture mode and button separation mode are always found during the joint strength testing. Lee et al (2010) proposed Equation 2.1 and 2.2 to predict joint strength and failure mode. From the equation shown, the joint strength is proportional to fracture stress of the material in neck fracture mode and flow stress in the button separation mode. Besides, these two equations are proportional to interlock, t_s and neck thickness, t_n.

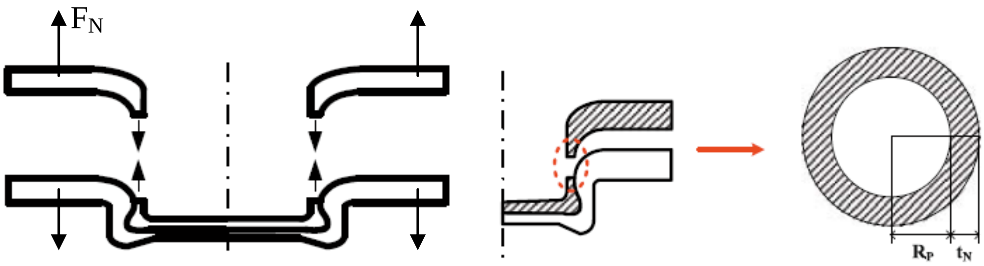


Figure 2.4 Neck fracture mode analysis of clinched joint

$$F_N = \bar{\sigma_f} \cdot A_N = \pi \cdot (2R_P t_N + t_N^2) \cdot \bar{\sigma_f} \tag{2.1}$$

Where $\bar{\sigma_f}$ is the fracture stress of the upper sheet

A_N is the projection area of the neck part

R_p is the clinching punch radius

t_N is the neck-thickness

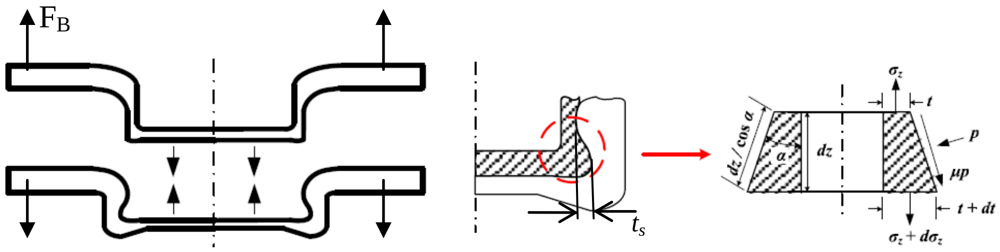


Figure 2.5 Button separation mode analysis of clinched joint

$$F_B = \pi \cdot (2R_P t_N + t_N^2) \cdot \overline{\sigma_Y} \left(\frac{1+\mu/\tan\alpha}{\mu/\tan\alpha}\right) \left[1 - \left(\frac{t_N}{t_s+t_N}\right)^{\mu/\tan\alpha}\right] \quad (2.2)$$

Where $\overline{\sigma_Y}$ is the average flow stress in the clinched region stress

t_s is the length of the interlock

μ is the friction coefficient

Since the strength and failure mode of a clinched joint is determined by the material strength, neck thickness, t_n and interlock, t_s, Figure 2.6 shows the flow chart proposed by Lee et al (2010) to predict the strength of a clinched joint and its failure mode. Equation 2.1 and 2.2 are applied to calculate the strength and failure mode of a clinched joint. A clinched joint will fail at a lower calculated joint strength value from the two equations shown above.

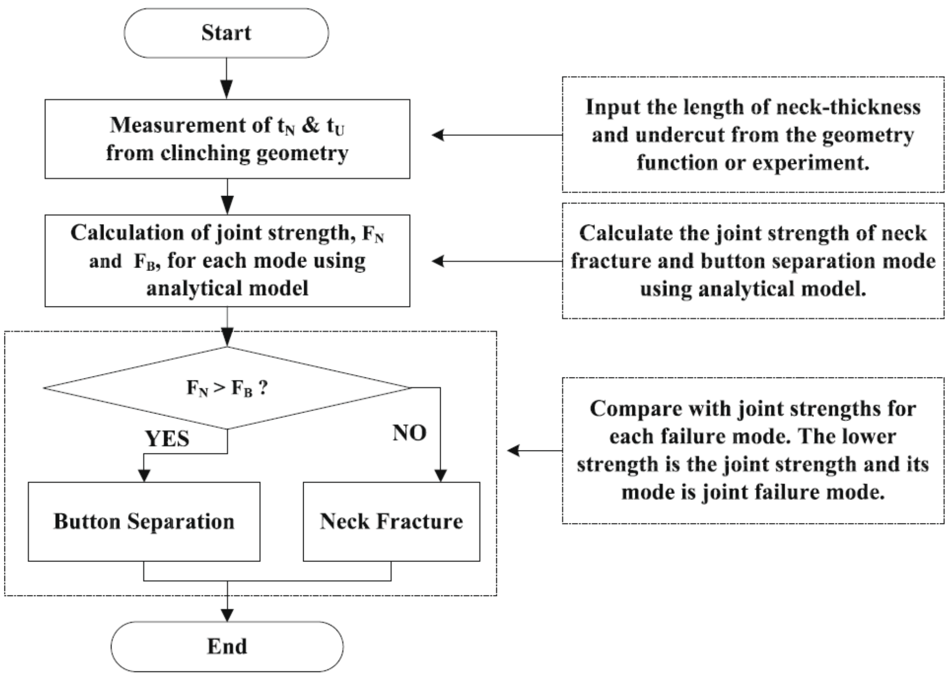


Figure 2.6 Flow chart of joint strength and joint failure mode identification

2.2.2 Tool Geometry

The joinability of the sheet metals is greatly affected by the geometry of the clinching punch and die especially for the metals with low ductility. Several researches had been carried out on the study the effect of tool geometry improving the joinability of high strength steels by modifying the geometry of the clinching die (Varis, J.P..2003, Abe et al. 2008, Abe et al.2012). It was also reported that the geometry will influence the material flow of the sheet metals especially at the neck thickness, t_n and interlock, t_s as shown in Figure 1.1. In general, the segment that stretches the most occurs at the neck part. Lower strain at the neck part is preferred in order to avoid fracture during forming and under loading. Large strain deformation will also wear out the coating layer of clinched joint. This will greatly weakens the corrosion resistance of the clinched joint. By modifying the clinching die, corrosion resistance can be increased by 40% (Abe et al, 2010). In order to achieve the optimum joint strength, FEM is used to predict the outcome by modifying the geometry of punch and die. Due to the curiosity about the effect of tools geometry to the mechanical clinched joint strength, M. Oudjene and L.Ben-Ayed (2008) applied Taguchi Method to study on how parameters of the tools geometry together with FEM software to compromise the shape of the punch and die in order to produce a better quality clinched joint. The result of this method showed an increase of separation force when comparing the initial tools geometry and with the new tools geometry obtained from the Taguchi Method.

2.3 Quality Assurance of Clinched Joint

The quality of a mechanical clinching joint can be reviewed during the clinching process by using an automatic real-time quality control system, and after the clinching process by non-destructive and destructive testing.

2.3.1 Automatic Real-time Quality Control System

This system was developed to gather the information of the punch load and stroke during the clinching process. The punch load curve of a qualified clinching joint should fall within the tolerance range as shown in Figure 2.7. The clinching process will be stopped if the curve shows a deviation from the acceptable range. Typical cases such as clinching inappropriate material or tooling defects can be identified by applying this system.

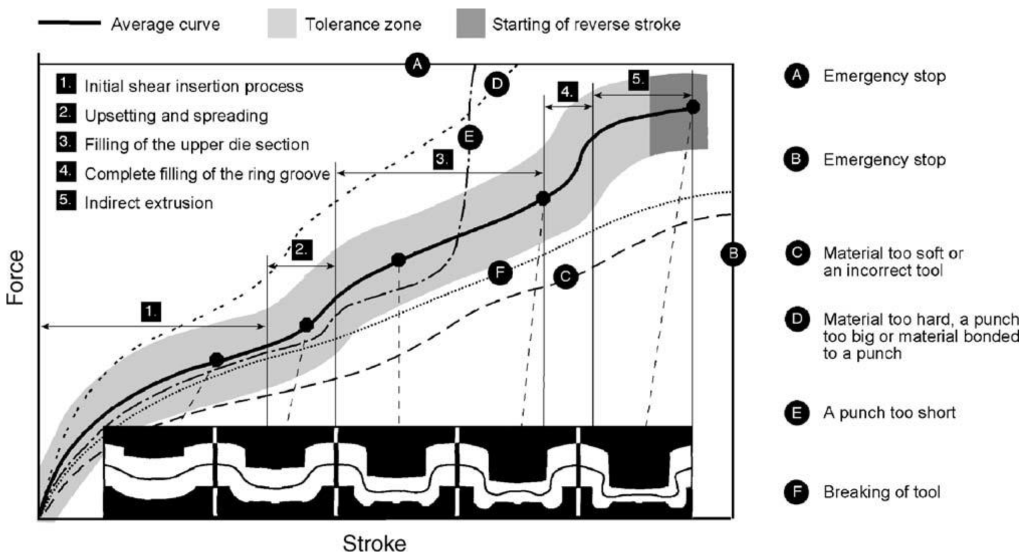


Figure 2.7 Punch load curve collected by real-time process control system [TOX® GmbH]

2.3.2 Non-destructive Testing

The tolerance gauge is a simple tool to monitor joint quality (see Figure 2.8) and both Tog-L-Loc and Lance-L-Loc proposed an inspection standard for clinched joint as shown in Figure 2.9. These tools are made with a maximum and minimum gauge to measure the size of a button of a mechanical clinching joint. The final diameter of the button of a mechanical clinching joint should fall within a specific range for the purpose of optimizing the joint strength.

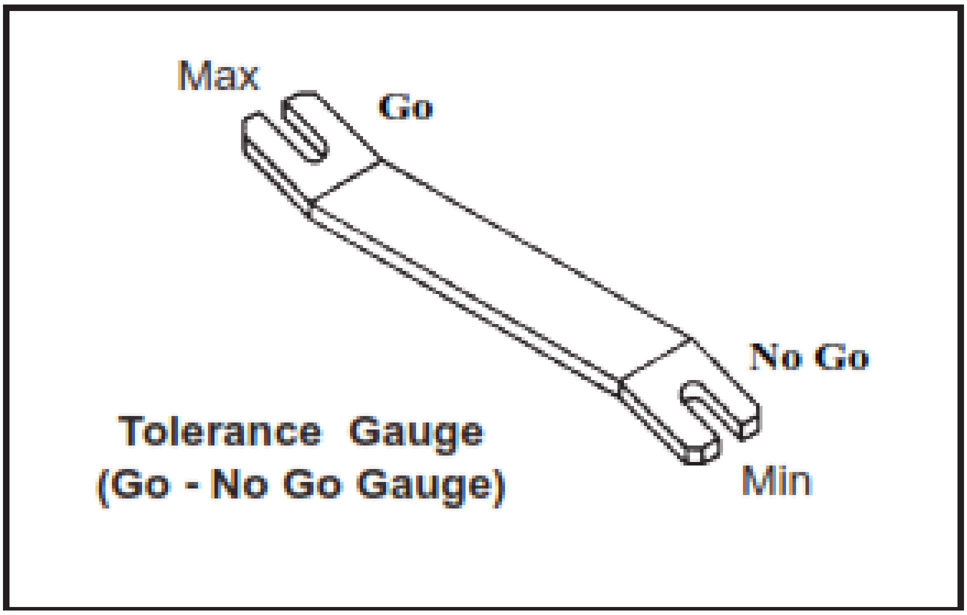


Figure 2.8 Tolerance gauge

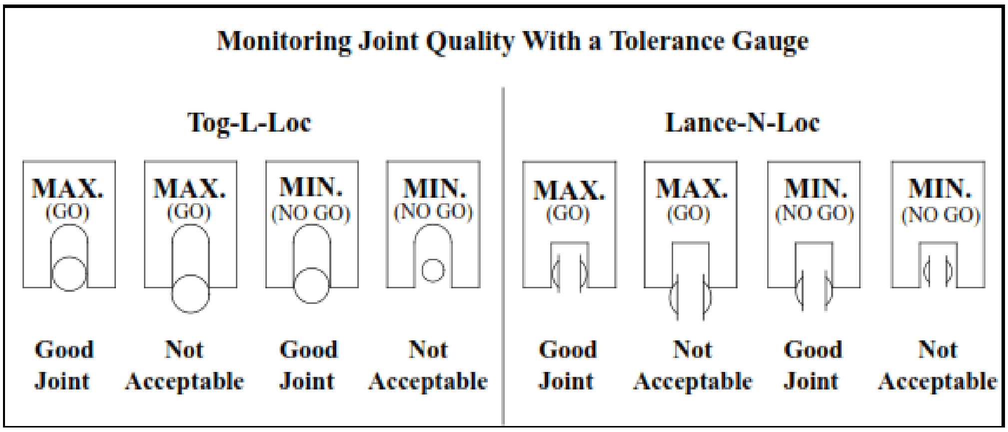
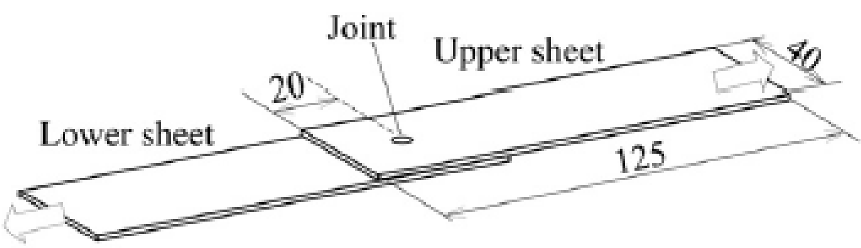


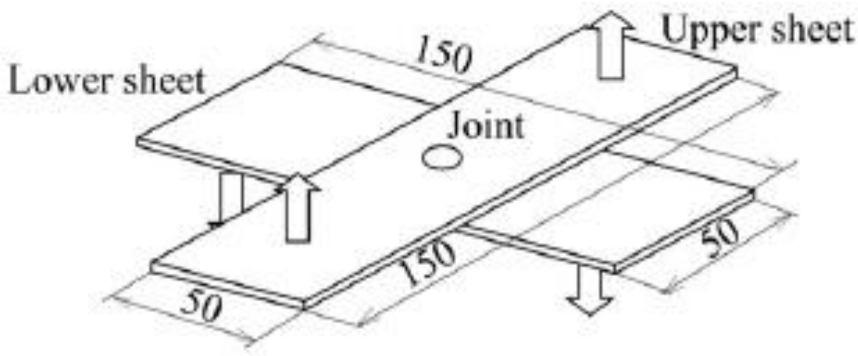
Figure 2.9 Joint quality inspection by Tog-L-Loc and Lance-N-Loc

2.3.3 Destructive Testing

In order to have an accurate study to the quality of the joint strength, the joined metal sheets will undergo tensile test and fatigue test. Two of the most common destructive testing for joint strength inspection are tension-shearing test and cross-tension shearing test. The specimens for these two tests are shown in Figure 2.10. The specimens will be pulled by a pair of external forces until the joint fails. The maximum force that is required to break the joint will be investigated for verification purpose.



(a)



(b)

Figure 2.10 Joined sheets used for destructive testing (a) tension-shearing test (b) cross-tension test

CHAPTER 3

METHODOLOGY

3.1 Tensile Test

Tensile test is carried out by using Instron 5582 universal testing machine to obtain the true stress and true strain of the sheet metals. The sheet metals are coated mild steel GL400 FN AZ150 and aluminium alloy A1100H14. The specimens are cut into the shape as shown in Figure 3.2 for tensile test.

Figure 3.1 Instron 5582 universal testing machine

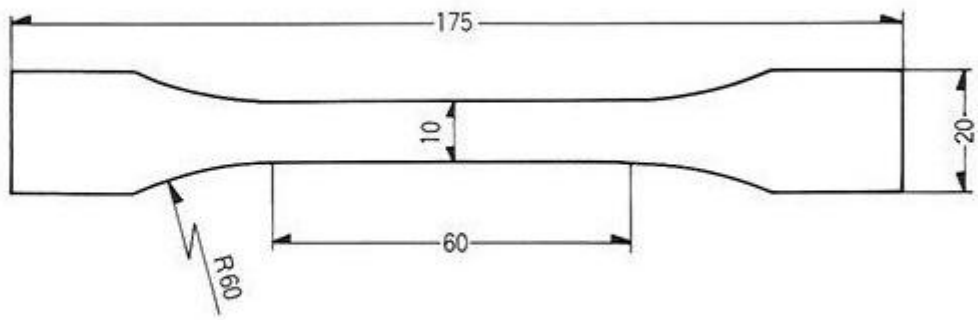


Figure 3.2 Tensile test specimen (JIS K7113-1)

3.2 Experiment Setup

Figure 3.3 shows the layout and dimensions of upper punch and lower die used for the offset clinching experiment. The clinching tools are made of SKD 61. Figure 3.4 shows the top view plane of the center axis position *O* and the loading point at *P*. By considering to move the upper punch in specific direction and increment, two parameters are introduced to define the offset condition for moving the upper punch. The in-plane offset direction, θ shown in Figure 3.4 represents the direction angle about the center point *O* relative to the loading point *P* (Line OP). When $\theta = 0°$, it indicates the punch is moving to the direction away from the loading point *P* (Figure 3.5 (a)), whereas θ = 180° is towards the loading point *P*. (See Figure 3.5 (c)). $\theta = 90°$ and $\theta = 270°$ are in parallel distance (Figure 3.5 (b) and Figure 3.5 (d)). The offset ratio, Δe shown in Figure 3.5 is defined by the value of punch offset distant from the center point *O* with respect to the initial die clearance.

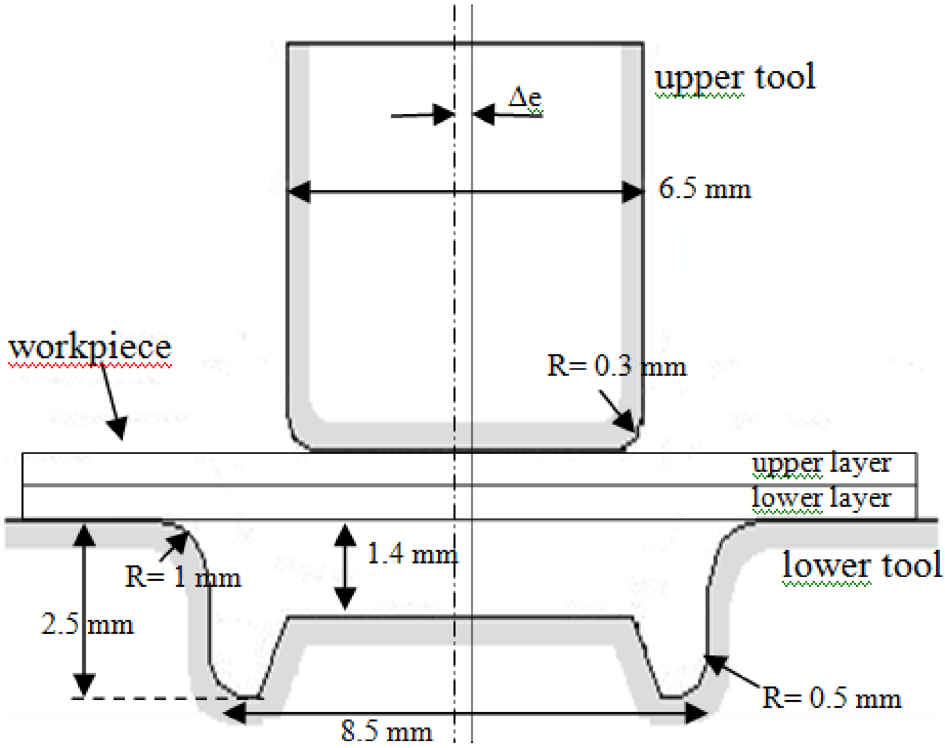


Figure 3.3 Layout and dimension of clinching tool

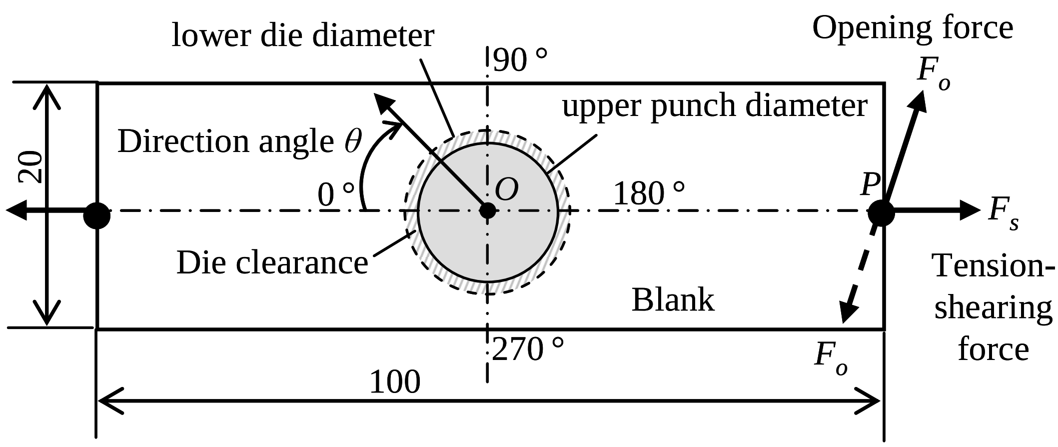


Figure 3.4 Tool center position and loading point

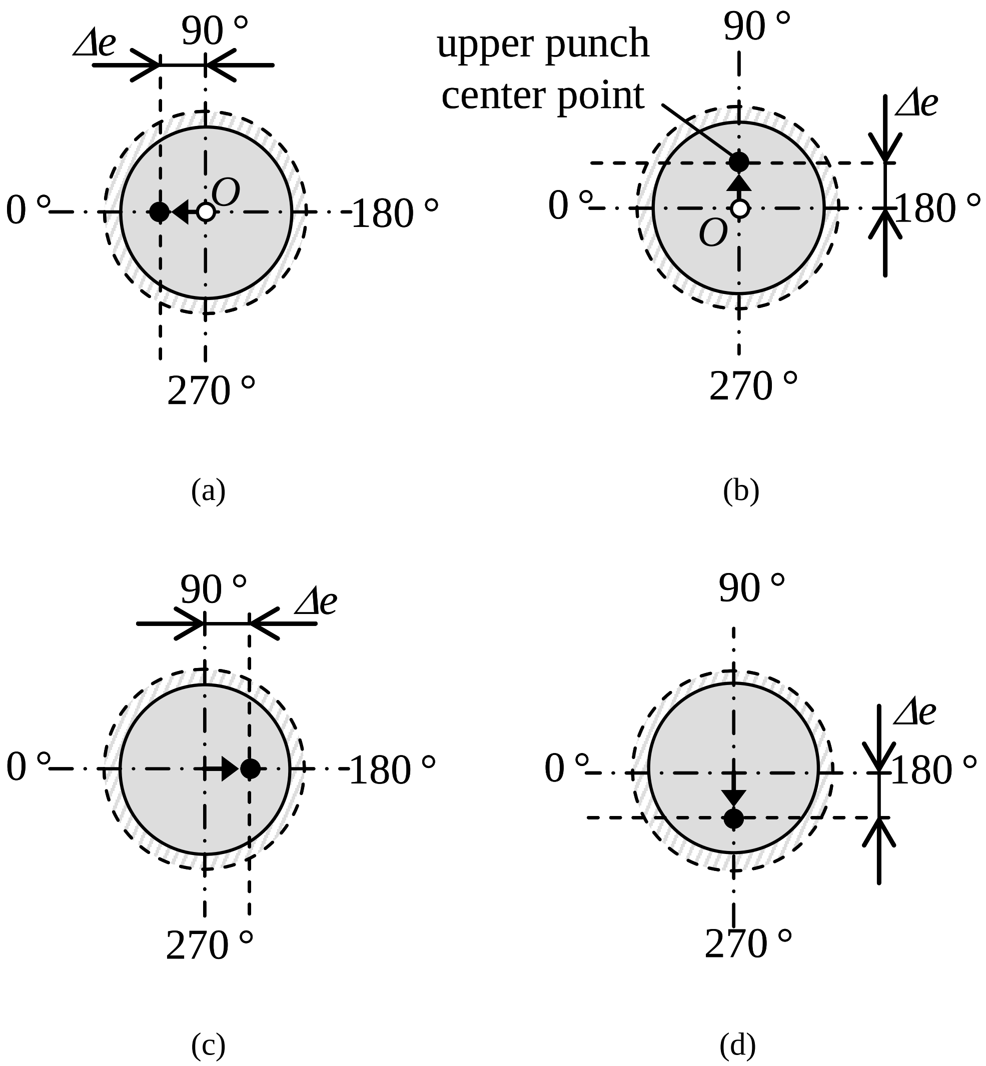


Figure 3.5 Offset direction of upper punch (a) Offset at θ = 0° (b) Offset at θ = 90° (c) Offset at θ = 180° (d) Offset at θ = 270°

Two alignment condition is setup in this clinching experiment in order to study the effect of tool eccentricity to mechanical clinching joint. These conditions are:

a) Without offset (perfectly aligned punch and die setting)

b) With offsetting the punch with 0.25mm, 0.5mm and 0.75mm (25%, 50% and 75% of the clearance) to different orientation of angles (0°, 90°, 180° and 270°)

3.3 Clinching Process Monitoring

Instron 5582 universal testing machine is used to perform the clinching process with the tools shown in Figure 3.3. Forming load history and stroke were recorded for the clinching process under different forming conditions.

3.4 Study of Clinched Joint Cross Section

Different sheet metals of (aluminium with aluminium and steel with steel) 1.0mm and 1.1mm thickness are prepared with standard dimension of 100mm x 20mm. The cross sections of the joints are then observed to analyze the material flow. The punch stroke is varied to study the relation between reduction of bottom thickness, r_b and clinch joint interlock, t_s.

3.5 Loading Tests for Static and Fatigue Strength

Tensile tests are conducted to evaluate the strength of clinched joint specimens with offset and without offset conditions. Two type of loading mode (See Figure 3.6), i.e., opening test and tension-shearing test are considered for the evaluation. The maximum force in opening test, F_o and tension-shearing test, F_s are measured until the joint structure starts to fail. The opening mode chosen in present research is mainly because is much convenient as it is similar to the inspection procedure carried out by the industry in Figure 1.3.

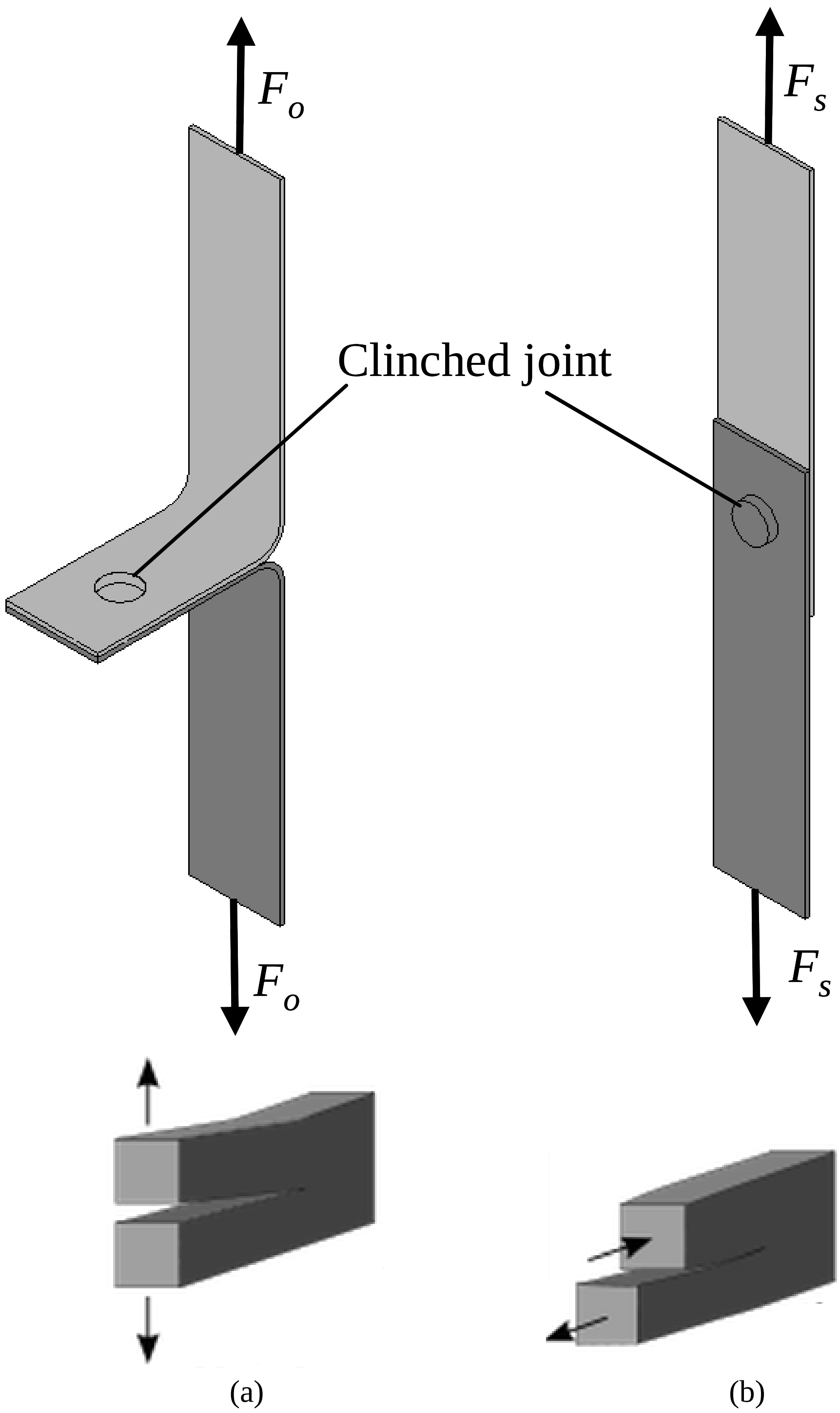


Figure 3.6 Joint strength tests (a) Opening test (b) tension-shearing test

Fatigue test is carried out on clinched joint of with offset and without offset condition at different load level to obtain F-N curves (load vs number of cycle) by using Shidmadzu Servopulse E50 dynamic testing machine as shown in Figure 3.7. Endurance limit is defined as 2 x 10^7 number of cycles which is similar to the work done by Carboni et al. (2006).

Figure 3.7 Shimadzu Servopulse E20 dynamic testing machine

3.6 FEM Model for Offset Clinching

The finite element analysis is applied to investigate the formation of interlock and also to examine the distribution pattern of contact surface pressure caused by the offset condition. In this research, a 2-D rigid-plastic FEM code developed by Osakada et al. (1982) with space elements scheme implemented by Wang (2009) is used as first attempt to simulate the plastic deformation of sheet metal in clinching process. Axi-symmetric and plane-strain models are applied for the case without offset and the case with offset, respectively. Further attempt is made to simplify the FEM model by assuming no slipping and detachment are allowed between the upper sheet layer and lower sheet layer during the process takes place and the blanks are made of same material. By these assumptions, the upper layer and lower layer can be treated as a single deformable body in finite element analysis. However, in this case, a line is drawn to visually represent the two layers. Figure 3.8 shows the FEM model for the simulating the clinching process.

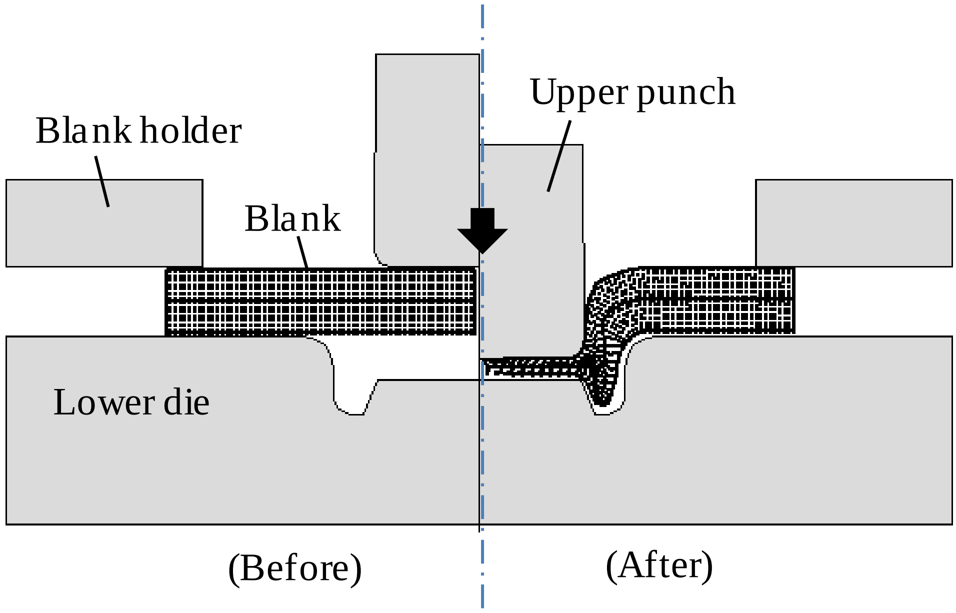


Figure 3.8 2D rigid-plastic FEM model of mechanical clinching

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Offset Clinching

In this research, two types of material used for the blanks are parepared for comparison purpose. Table 3.1 shows the material properties and blank thickness and Table 3.2 shows the offset conditions and blank size for implementation of clinching tests.

Table 4.1 Material properties and blank thickness.

	Coated mild steel GL400 FN AZ150	Aluminium alloy A1100 H14
Thickness (mm)	1.1	1.0
Yield Strength (MPa)	250	118
Tensile Strength (MPa)	380	120
Flow stress (MPa)	$\bar{\sigma} = 503\bar{\varepsilon}^{0.32}$	$\bar{\sigma} = 138\bar{\varepsilon}^{0.024}$
Elongation (%)	28	18
Coating	Zinc (15 μm)	-

Table 4.2 Offset clinching conditions.

In-plane offset direction, θ	0 °, 90 °, 180 °, 270 °
Offset ratio, Δe	0% (without offset), 25%, 50%, 75%
Specimen size	100mm (length) x 20mm (width)
Die clearance	1 mm
Lubrication	Without lubricant

The clinching tests were carried out at different offset direction, θ to investigate the effect of tool eccentricity on forming load. The punch load history curves from each offset condition are compared in Figure 4.1. It is interesting to know that no significant difference in term of forming load can be observed when tool offset is given. The result implies that the tool eccentricity is hard to be detected during the press operation by screening and monitoring at the load indicator during production in progress. Varis, J. (2006) stated that minor defect such eccentricity of tools could hardly be detected by the real-time load and punch stroke monitoring.

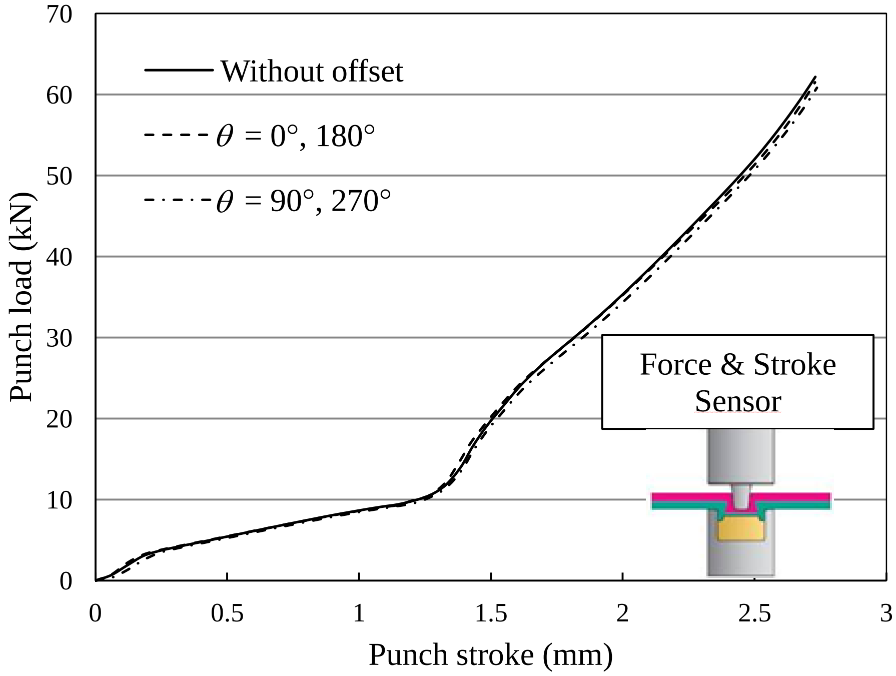
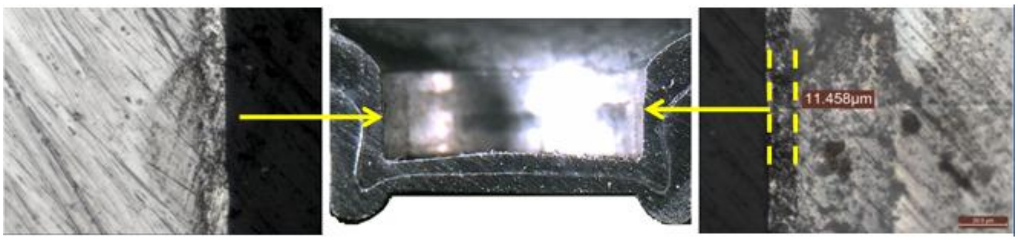
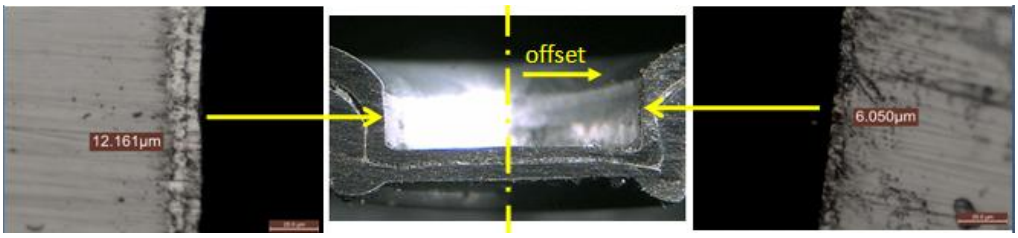


Figure 4.1: Comparison of punch load curves with different offset direction, θ (Δe = 50%, r_b = 60%, coated mild steel).

Figure 4.2 shows the cross section of clinched joint where interlock, t_s, neck thickness, t_n and coated layer at the left and right side of clinched specimens are examined with respect to the offset ratio, Δe. The punch is offset to $\theta = 180°$ direction (moved to the right) to form smaller die clearance on right side. The extruded part (ear shape) at the bottom side can be seen larger on the right side and uneven ear shapes appear at both corners when offset the ratio, Δe is given larger than 50%. The results from examining the cross section are compared in Figure 4.3.



(a)



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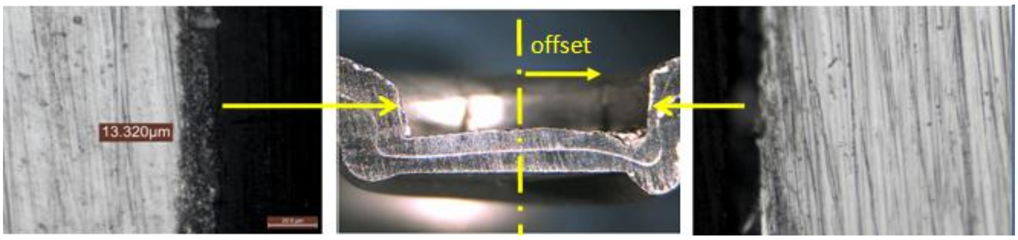
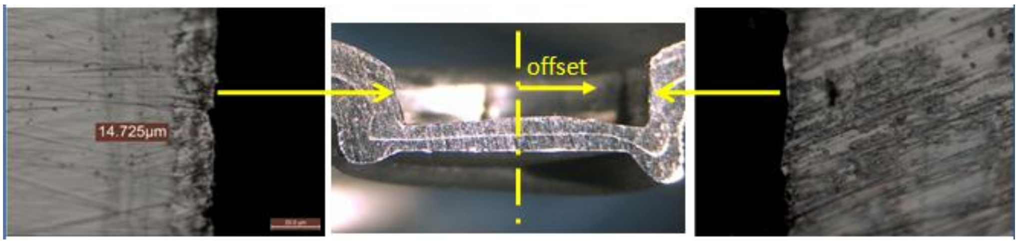


(c)



(d)

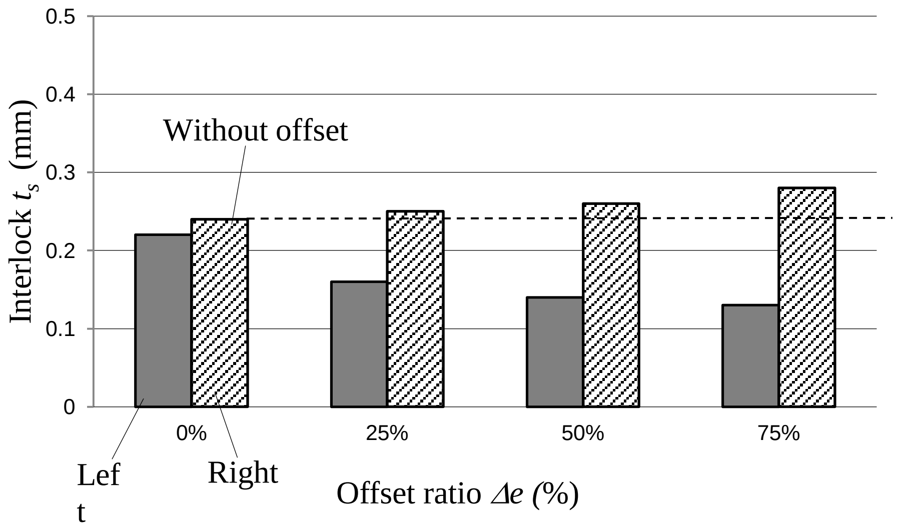
Figure 4.2 Cross section of clinched joint at different offset ratio (θ = 180 °; r_b = 60%, coated mild steel) (a) without offset (b) Δe = 25% offset (c) Δe = 50% (d) Δe = 75% offset

Figure 4.2 (b), (c) and (d) show the distribution of the neck thickness, interlock and the protruding part at the bottom were unevenly formed when compare to the without offset as shown in Figure 4.2 (a). Figure 4.2 (b), (c) and (d) also show some similarity to Figure 1.4. The tooling eccentricity influenced the material flow while forming. The dimension of clinch interlock, t_s and neck thickness, t_n were skewed to one side. The distribution of clinch interlock, t_s and neck thickness, t_n were not uniform around the clinch joint as shown in Figure 4.2 (b), (c) and (d). These two parameters are critical to the joint strength.

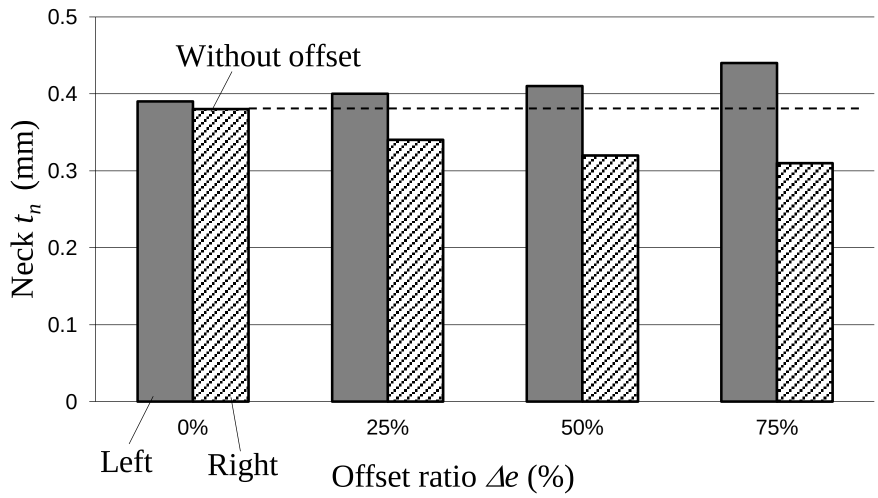
Figure 4.3(a) shows the interlock, t_s value increases on the right side while it decreases on the left side along with increment of offset ratio, Δe. The different is almost 20% at offset ratio, Δe = 75% in respect to the one without offset. This result implies that the pull-out strength (in opening mode) on the left side is higher while it is lower on the right side.

Figure 4.3 (b) shows that the neck thickness, t_n decreases on the right side due to smaller die clearance given while it increases on the left side along with the increment of offset ratio, Δe. The different is almost 15% at offset ratio, Δe = 75% in respect to the one without offset. The thinning occurred at the neck part may easily induce neck failure when loading point is placed on right side.

The coated layer is examined by microscope at the neck part of upper layer since this location is most critical to cause neck failure due to large stretching. Figure 4.3 (c) shows a drastic reduction of the coated layer on the right side when offset ratio, Δe is increased to 50%, while the value on the left side remains intact as its original thickness. The coated layer appeared to be peeled off completely due to severe condition of plastic deformation and surface friction takes place when material is stretched through the narrow die clearance. The neck thickness, t_n, interlock, t_s and coating layer varies around the clinched joint is due to the alteration of tooling geometry that is caused by tooling eccentricity (Varis,J.P..2003, Abe et al. 2008, Abe et al. 2012).



(a)



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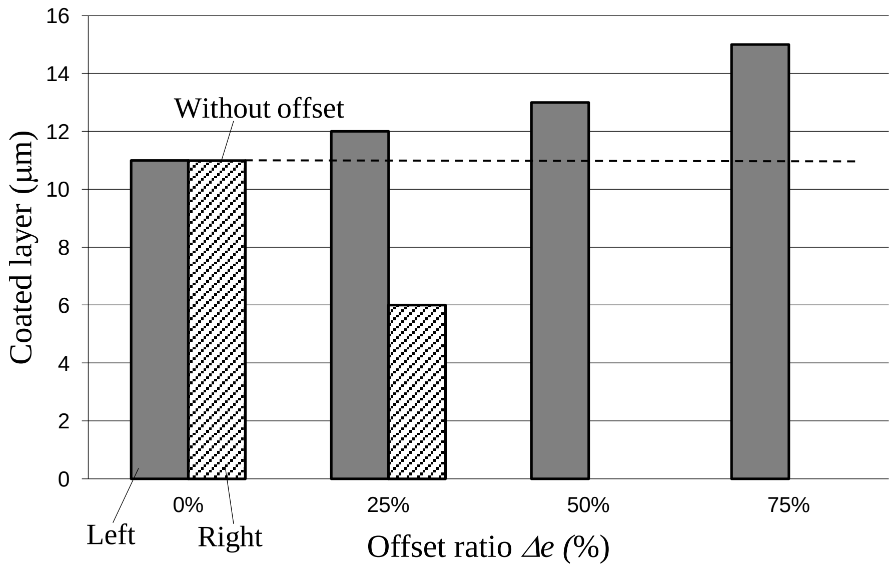


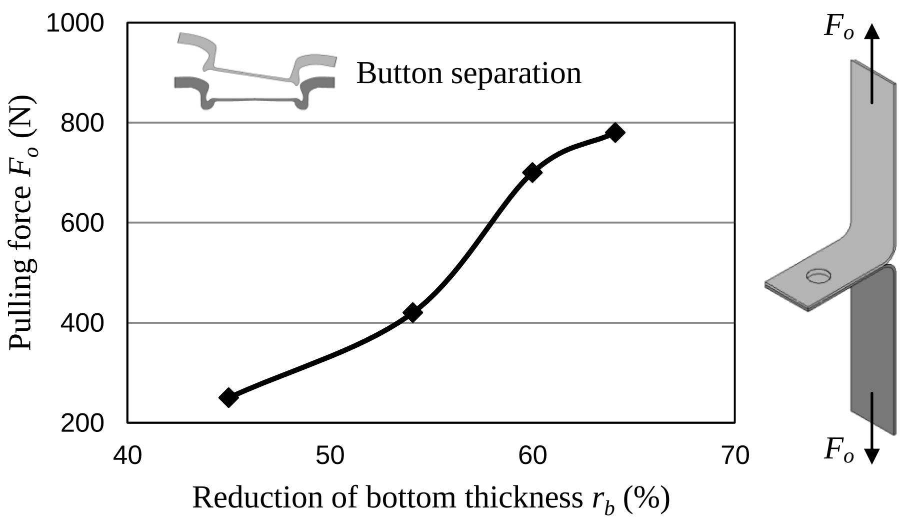
(c)

Figure 4.3 Comparison of thickness parameter between left and right side of offset clinched joints (θ = 180°, r_b = 60%, coated mild steel) (a) interlock, t_s (b) neck thickness, t_n (c) coated layer

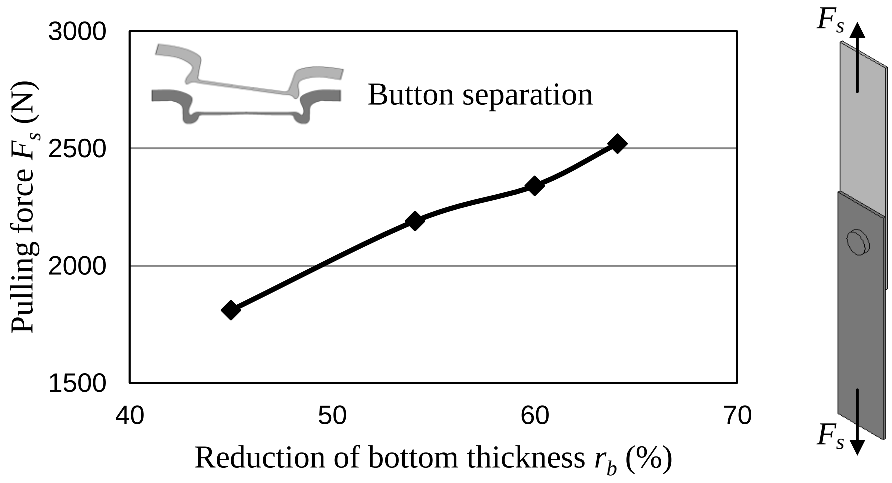
4.2 Static Strength Test

4.2.1 Static Strength and Failure Modes

Two types of failure modes, i.e., button separation and neck fracture can be observed from the joint strength test. In this test, opening mode and tension mode methods are adopted to measure the maximum tension force of clinched joints at each incremental reduction ratio of bottom thickness, r_b, and at the same time to examine the failure patterns for mild steel and aluminium alloy. The reduction ratio is defined by the clinched joint bottom thickness over the initial blank bottom thickness.



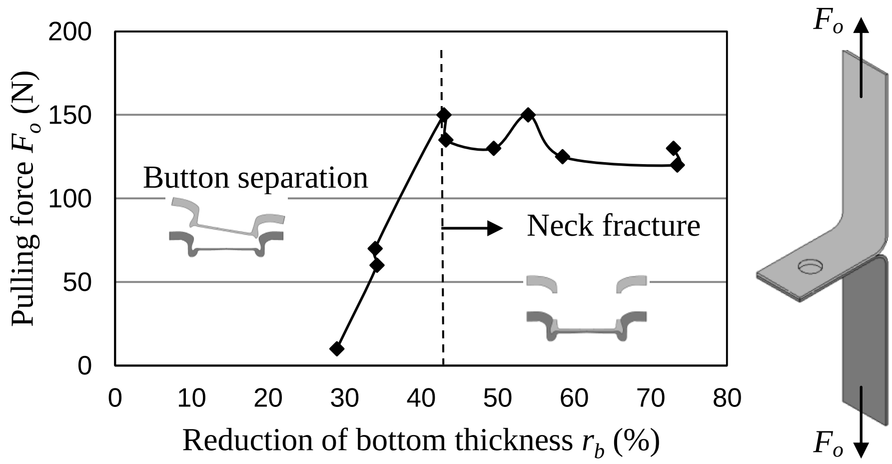
(a)



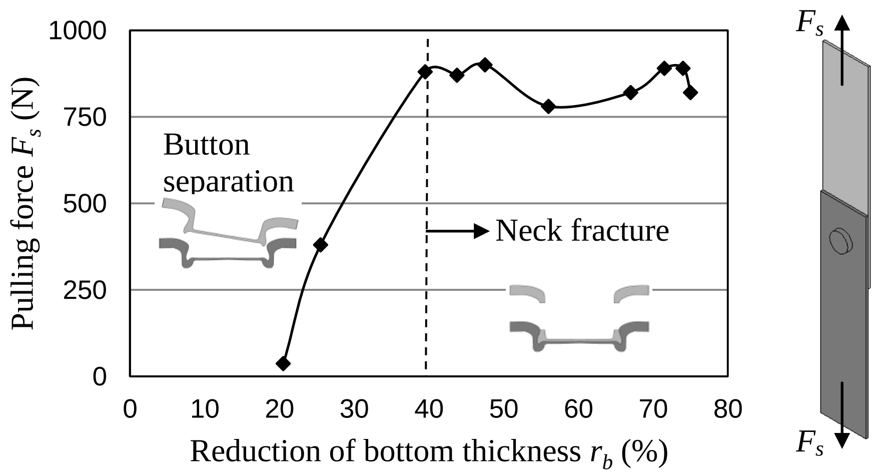
(b)

Figure 4.4 Joint strength test and failure mode for coated mild steel in normal clinching (a) opening test (b) tension-shearing test

Figure 4.4 (a) and (b) show the test results for mild steel in opening mode and tension-shearing mode, respectively. The maximum tension force is measured at each increment of reduction ratio of bottom thickness, r_b. The maximum tension force, F_o in opening test is far lower than the tension-shearing force, F_s in tension shearing test. It can be seen that the opening force, F_o increases in linear trend, and only button separation failure is observed. As reduction ratio goes higher by deeper punch stroke, the bigger size of interlock, t_s is formed and thus, more resistant exerted against the pulling force as it is proportional the size of interlock, t_s (Equation 2.2).



(a)



(b)

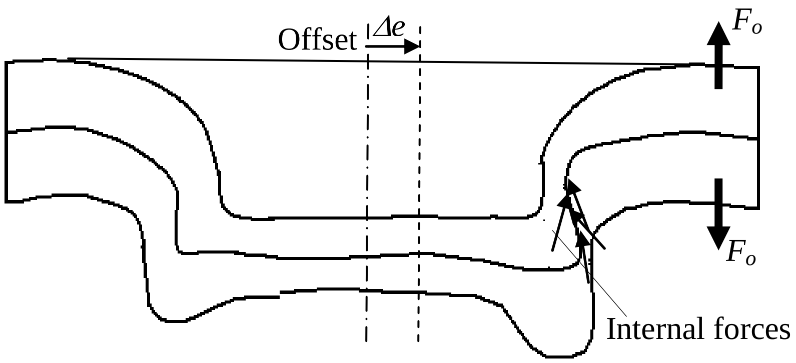
Figure 4.5 Joint strength test and failure mode for aluminium alloy in normal clinching (a) opening test (b) tension-shearing test

Similar tests are carried out for aluminium alloy, and the results are plotted in Figure 4.5 (a) and (b). The failure starts from button separation with the force value of opening force, F_o and shearing force, F_s increased. As the reduction ratio goes about 40%, the failure mode shifts from button separation to neck fracture pattern when the opening force, F_o and tension-shearing force, F_s reach maximum and become constant. The neck fracture is prevailed in later stage because the stress level at the neck part may have reached the ultimate point of tensile stress (Equation 2.1).

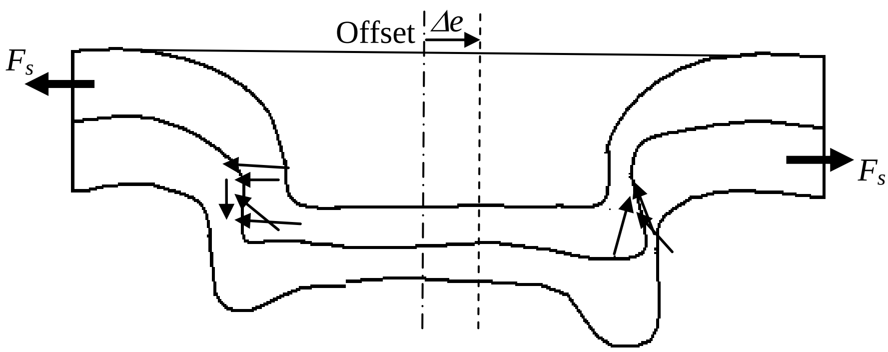
4.2.2 Static Strength Test for Offset Clinching

According to J.Mucha (2011), when a pair of pulling force is applied to the structure, the internal forces will appeared on the layer boundary and react at one side of the corner as illustrated in Figure 4.6. In view of this, it can be assumed that the joint strength will exhibit significant changes for the case of offset clinching where interlock, t_s and neck thickness, t_n of the joint are found varied with respect to offset direction and offset ratio (see Figure 4.3). Thus, the opening test and tension-shearing test are carried out in this study to examine the joint strength behaviour caused by the offset clinching

Figure 4.7 (a) and (b) shows the offset clinched joint strength results for coated mild steel in opening test and tension-shearing test, respectively. The maximum pulling opening force, F_o and tension-shearing force, F_s is plotted against the offset direction, θ by different offset ratio, Δe at 60% bottom thickness reduction ratio, r_b. From the data distribution pattern, it is assumed the opening force, F_o and tension-shearing force, F_s exhibit a sinusoidal relationship with θ with its curve shown minimum at $\theta = 0°$ and maximum at $\theta = 180°$. This can be explained from Figure. 4.6 (a) that at $\theta = 0°$ where the center point is offset to left side, the interlock, t_s formed on the right side becomes smallest and hence weaken the structural strength against opening (Equation 2.2). Whereas in Figure 4.6 the neck thickness, t_n formed on the left side becomes thinnest and hence weakened the structural strength against shearing. The situation is reversed at $\theta = 180°$ with the strength turns to maximum with larger interlock, t_s on the right side and larger neck thickness, t_n on the left side.

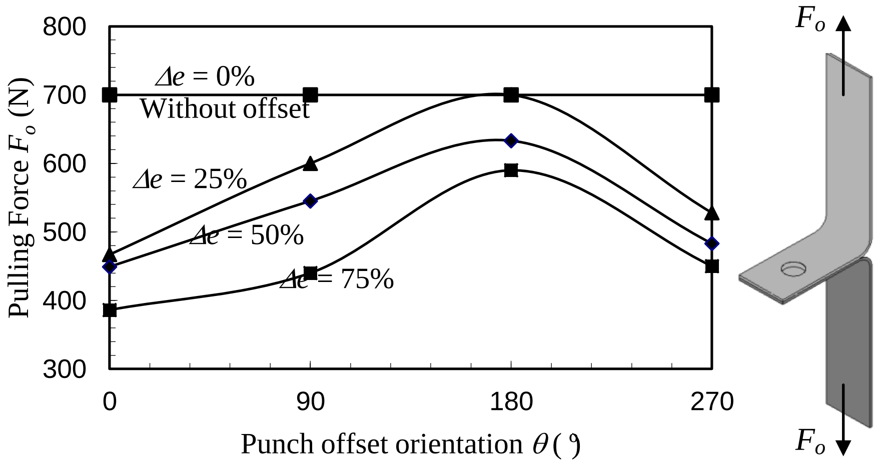


(a)

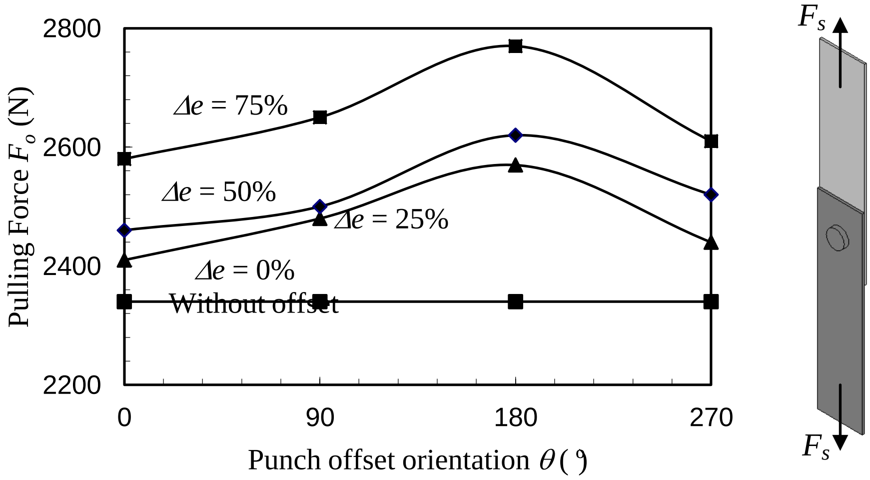


(b)

Figure 4.6 Illustration of internal force interactions at the layer boundary of clinched joint (a) opening test (b) tension-shearing test



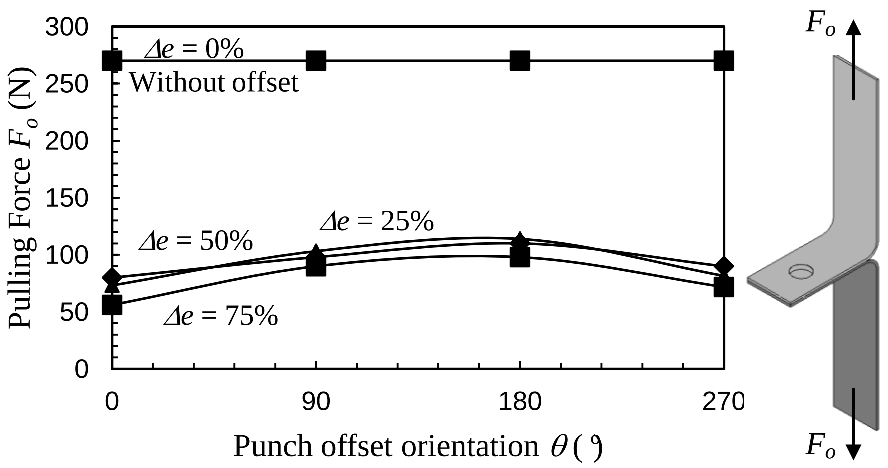
(a)



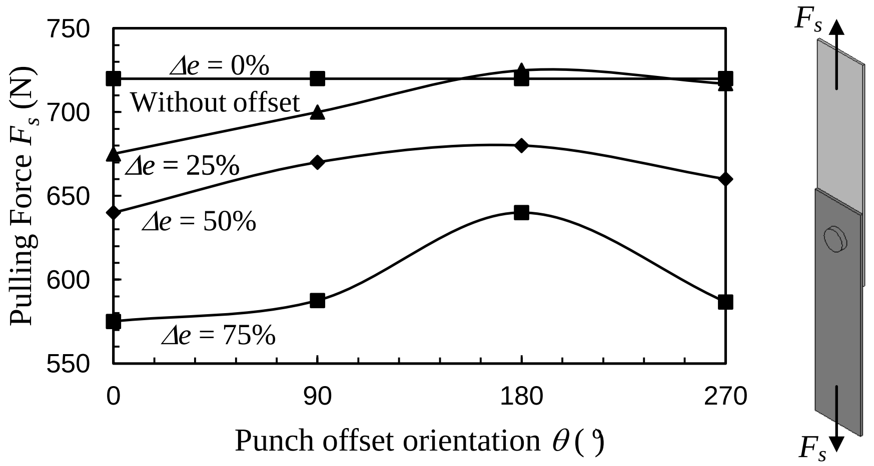
(b)

Figure 4.7 Joint strength tests at different offset conditions for coated mild steel (reduction of bottom thickness, r_b = 60%) (a) opening test (b) tension-shearing test

In the opening test shown in Figure 4.7 (a), the strength curves by offset clinching is generally lower than the one without offset and further reduced by the higher offset ratio, Δe. However, it is interesting to see that offset strength curves shown in Figure 4.7 (b) behave in opposite trend in tension-shearing test. The phenomenon may be due to the strain hardening effect takes place at the neck part for mild steel material and thus exhibits higher resistance against shearing than the one without offset.



(a)



(b)

Figure 4.8 Joint strength tests at different offset conditions for aluminium alloy (reduction of bottom thickness, r_b = 60%) (a) opening test (b) tension-shearing test

For the case of aluminium alloy in Figure 4.8 (a), although the joint strength show similar curve pattern with the one of coated mild steel in opening test, however, the values drop drastically when compared at the same level of offset ratio, e.g., at Δe = 50%. This is because the neck failure occurred at neck part of aluminium alloy, whereas only button separation failure for coated mild steel (see Figure 4.5 (a) and (b)).

In the case of tension-shearing test for aluminium alloy, the offset strength curve shown in Figure 4.8 (b) is lower than the one without offset. The phenomenon is opposed to the case of coated mild steel where it shows higher strength in Figure 4.7 (b). This may due to the neck failure occurred at the neck part for aluminium alloy.

4.3 Fatigue Strength Test

Figure 4.9 shows the comparison of fatigue test result in tension-shearing mode for coated mild steel clinched joint of condition Δe = 0%, θ = 0° and Δe = 50%, θ = 0° for coated mild steel sheet metal. At 50% of maximum joint strength, the clinched joint of without offset completed the fatigue test at 2 x 10^7 number of cycles. This result agree with the finding of Carboni et al. (2006) that concluded the endurance limit of a clinched joint of without offset is 50% of the shearing load. On the other hand, at 50% of maximum joint strength, the clinched joint of Δe = 50% failed at 2.5 x 10^6 number of cycles. It shows a difference of 87.5% by number of cycles when comparing a clinch joint of without offset and Δe = 50%..The clinched joint of Δe = 50% completed the test at 42.5% maximum joint strength in order to achieve 2 x 10^7 number of cycles. The fatigue strength of a clinched joint is weaken due to the tooling eccentricity.

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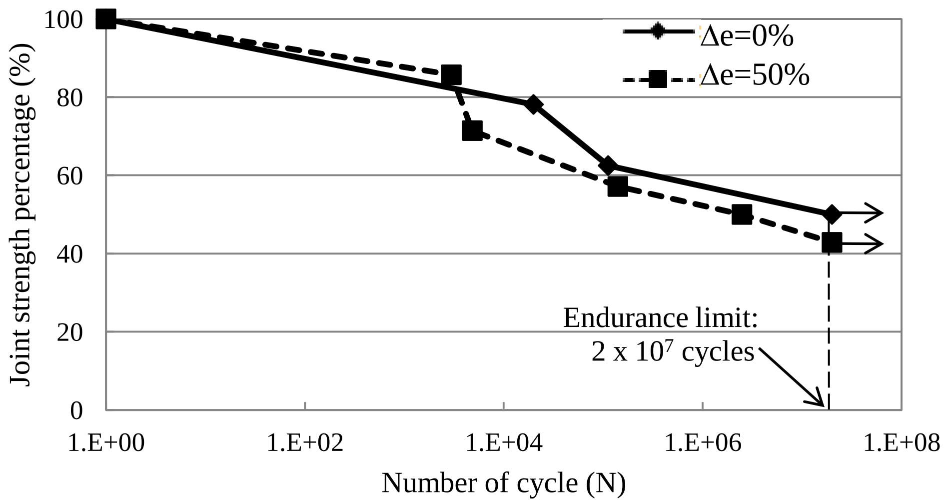


Figure 4.9 Relationship between percentage of joint strength and number of cycles in fatigue tension-shearing test for coated mild steel (reduction of bottom thickness, r_b = 60%).

4.4 Finite Element Simulation for Offset Clinching

Comparisons are made to examine the effectiveness of simulated results by present 2D rigid-plastic FEM model on forming load and the cross section of clinched joint in offset and without offset cases. The flow stress shown in Table 4.1 and the Coulomb's friction coefficient of 0.2 (Abe et al, 2008) between tools and blank are used for perform the FEM analysis.

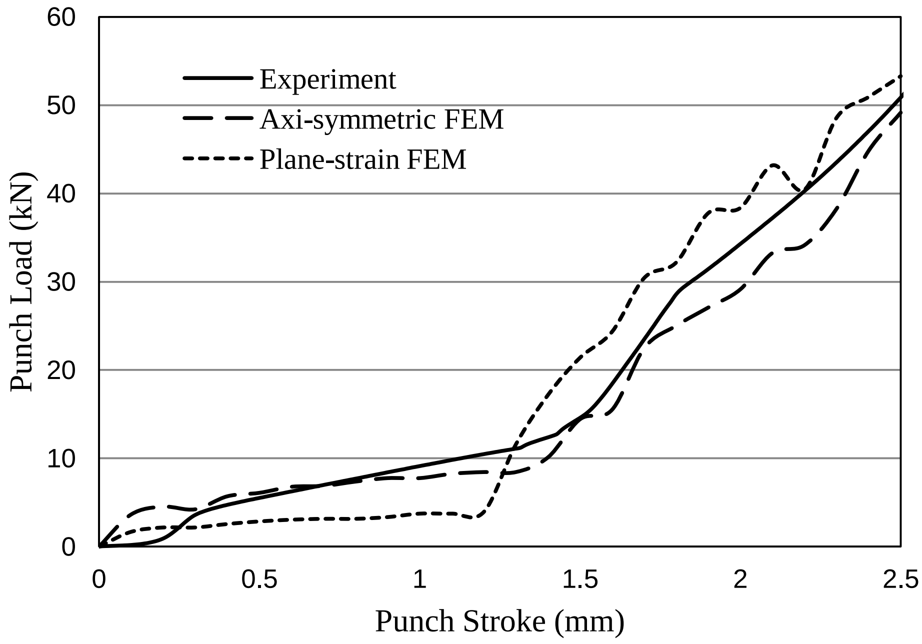
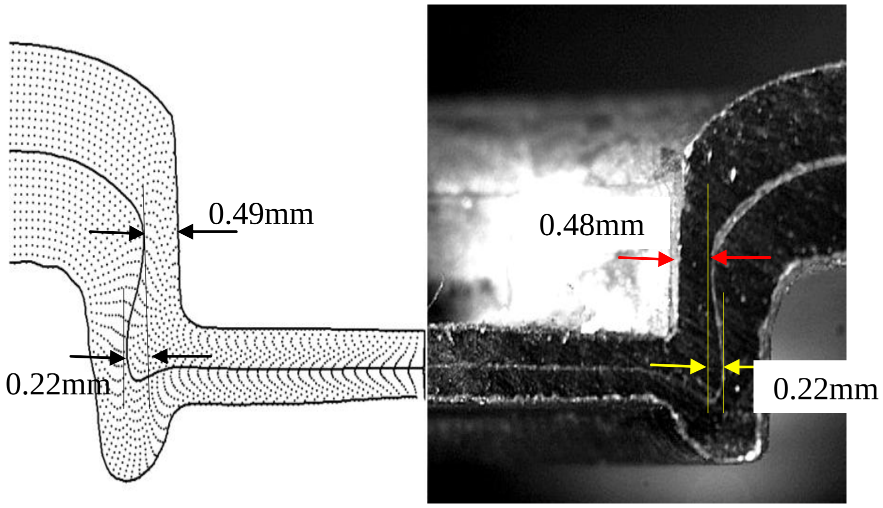
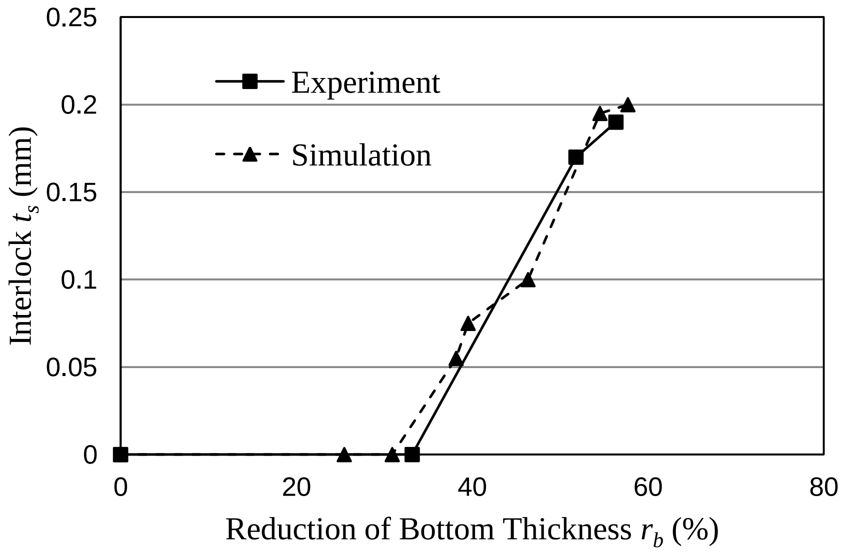


Figure 4.10 Comparison of punch load between experimental and simulated results (reduction of bottom thickness, r_b = 60%, coated mild steel).

Despite a simplified 2D model is introduced, Figure 4.10 and Figure 4.11 (a) shows a fairly closed agreement between the experimental and simulated in terms of forming load curve and cross section profile in clinching. Figure 4.11 (b) shows the present FEM simulation is able to predict the formation of interlock, t_s and the simulated result shows closed agreement with the experimental results.



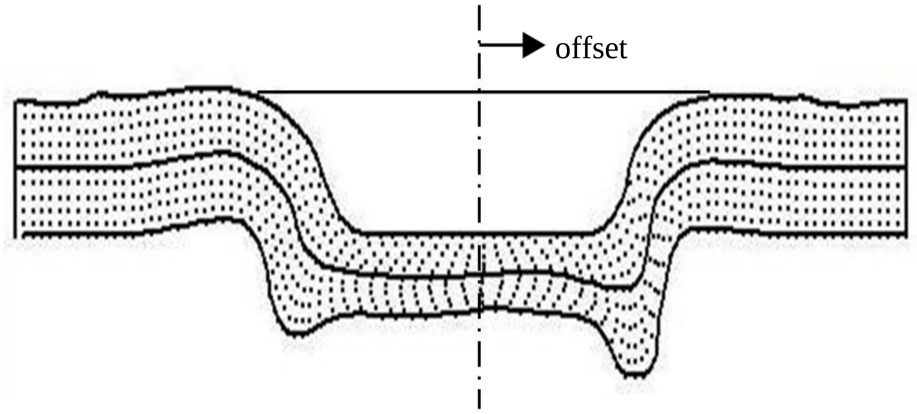
(a)



(b)

Figure 4.11 Comparison of cross section and formation of interlock between experimental and simulated results (a) cross section (b) interlock

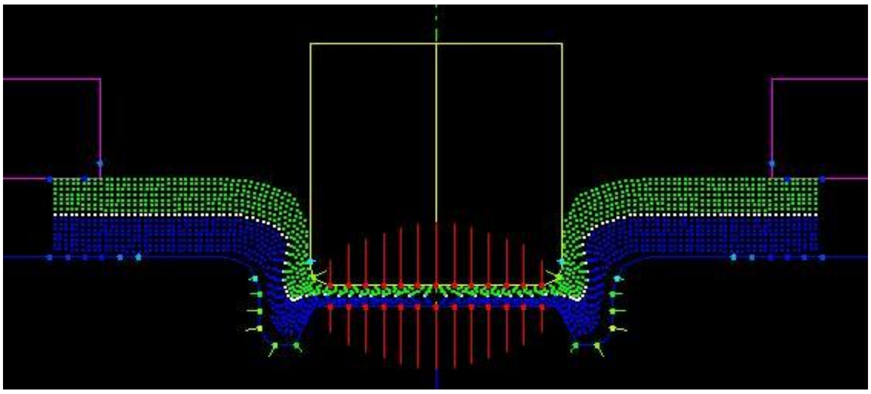
(a)



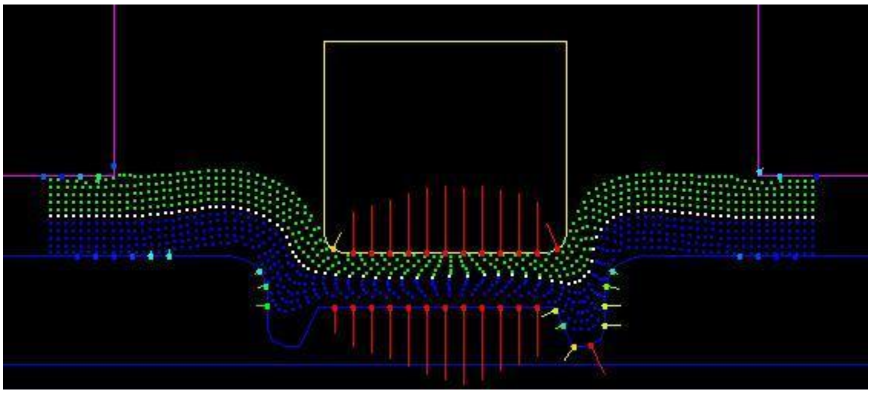
(b)

Figure 4.12 Offset clinching simulation by FEM in plain-strain model (a) experiment result (b) simulation result

From Figure 4.12, it is perhaps a plane-strain model can be used as the first attempt of approximation to study the physical phenomenon in offset clinching. From the offset simulation, it is found that the peak value of tool contact pressure distribution is shifted off from the center axis (see Figure 4.13). This implies an unintended eccentric force exerted on the punch and the peak value can increase up to 12% at Δe = 75% although the total forming load shows no significant different between the one of without offset and with offset (see Figure 4.14).



(a)



(b)

Figure 4.13 Tooling surface pressure distribution (a) without offset (b) with offset

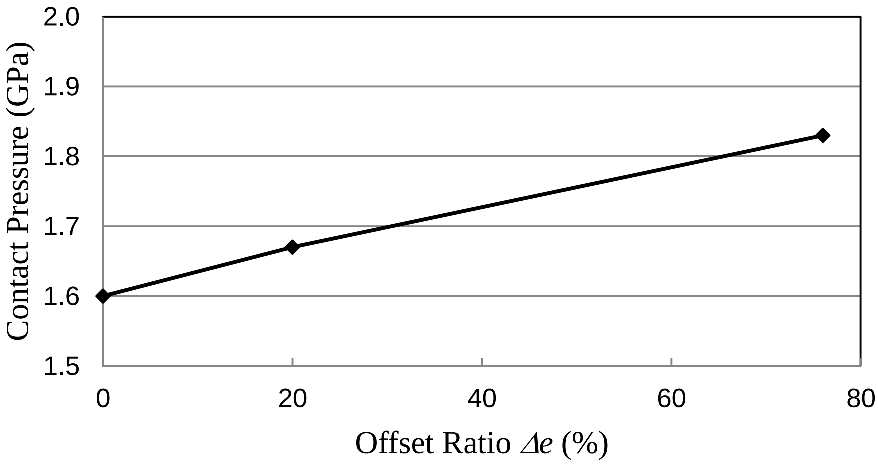


Figure 4.14 Effect of tooling eccentricity to the punch localized maximum pressure

Figure 4.15 Cracked punch

As a result of increasing in local maximum pressure, the punch cracked before achieving the expected tool service lifespan.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusions

In this study, the alignment of the punch and die is purposely offset in order to study the effect of tool eccentricity in mechanical clinching to the strength of clinched joint. Two parameters were introduced, i.e. the in-plane offset direction, θ and offset ratio, Δe to define the orientation and intensity of the offset condition in the misalignment of the tooling. Opening test and tension-shearing test were carried out to evaluate the joint strength.

The punch load curves shows little difference when a joint is clinched under the condition of without offset and with offset even up to offset ratio, Δe of 75%. However, in the study of the cross section of an offset clinched joint, the value of interlock, t_s and neck thickness, t_n varies at different positions around the round clinched joint due to the non-symmetrical deformation.

The coating layer at the neck part is completely peeled off at 50% offset ratio due to the sheet metal is stretched through a smaller die clearance on one side because of tool eccentricity.

The strength of a clinched joint is considered to have achieved maximum level once neck failure mode takes place. Greater reduction of bottom thickness, r_b. will be futile in increasing the joint strength.

In the opening test and tension-shearing test, the maximum pulling force of the offset clinched joint fluctuates in sinusoidal relationship with respect to the offset direction, θ and offset ratio, Δe.

The intensity of offset ratio,Δe and offset direction,θ together alter the pulling force of a clinched joint. In the opening test, the tool eccentricity of 25% to 75% causes in a decrease in joint strength by a range of 60-70% for aluminium alloy and 0-43% for mild steel. While in the tension-shearing test, the joint strength is reduced by 0-20% for aluminium alloy. However, there is a special phenomenon in the tension-shearing test of mild steel where the joint strength is increased by 2-18%, this may be caused by strain-hardening effect.

In the tension-shearing fatigue test, the fatigue strength of a clinched joint with offset condition of $\theta = 0°$ and $\Delta e = 50\%$ is generally 5-10% weaker to a clinched joint without offset.

The use of 2D rigid-plastic FEM as simulation tool is considered sufficient as the first attempt of approximation to investigate the sensibility of design parameters such as offset parameters and the use of different materials. It is predicted that the peak value of tool contact pressure distribution is shifted off from the center axis in offset clinching simulation. This implies that an unintended eccentric force exerted on the punch and the peak value can increase up to 12% at Δe = 75% although the total forming load shows no significant difference with the one without offset. This effect shortens the lifespan of tools.

The tolerance of the tool eccentricity should be limited to Δe = 25% and offset direction of θ = 180° in order to acquire the expected quality of clinched joint and preserve tool service lifespan. Cross section of a clinched joint shall be evaluated to investigate the alignment of the clinching tools. Tools shall be replaced or reconfigure if the neck thickness, t_n and interlock, t_s deviate more Δe = 25% and offset direction of θ = 180°.

5.2 Future Works

Although the effect of eccentricity is investigated, more experiments maybe needed in the eccentricity range less than 25% for industrial use. In current work, the study of tool eccentricity effect is focused more on the static strength of a mechanical clinching joint. Therefore, more fatigue testing at different degree of offset and offset direction should be tested in order to have a better understanding about the effect of tool eccentricity to the dynamic strength of a mechanical clinching joint.

In this research, 2D FEM model was applied to study on the effect of tool eccentricity on clinched joint. Therefore, future research can be conducted to study the effect by using 3D FEM model to provide a more accurate result for the explanation to be accepted about the occurance of neck fracture failure caused by the lower strain hardening effect at the interlock part in case of aluminium over to the steel.

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APPENDIX A

TENSILE TEST RESULT

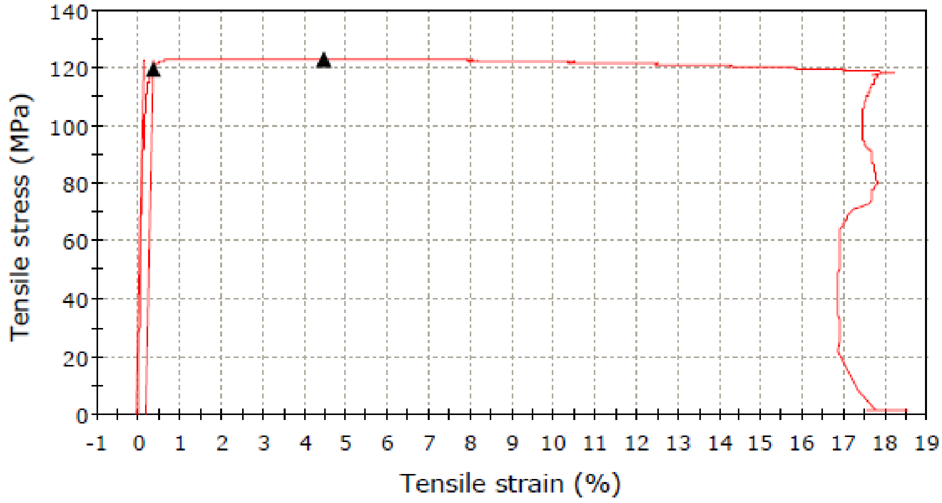


Figure A1: Stress-strain curve of aluminium alloy A1100 H14

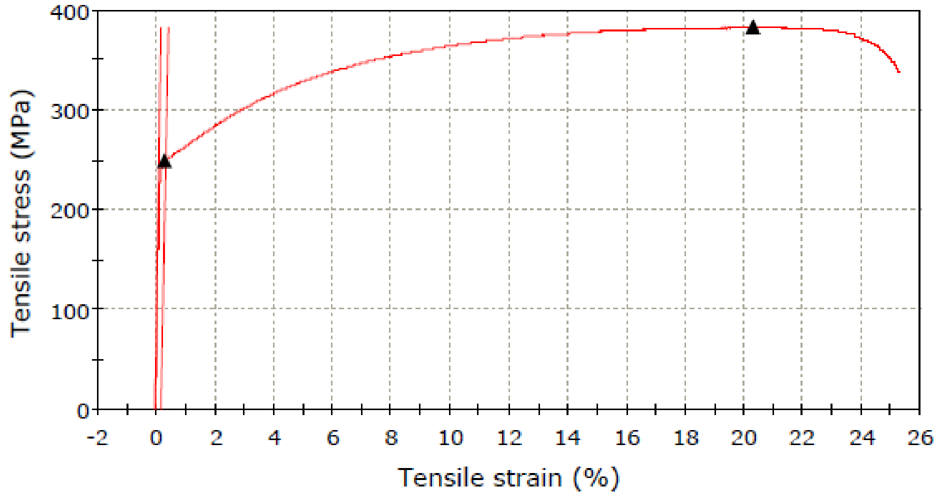
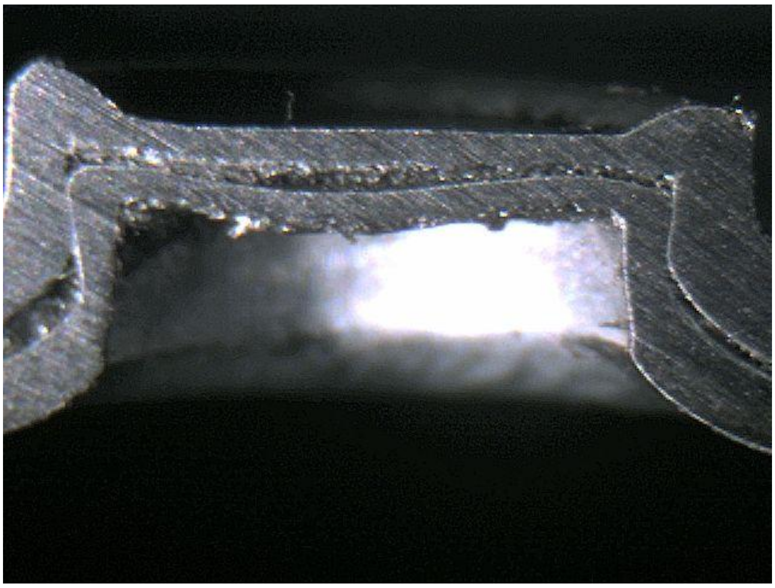


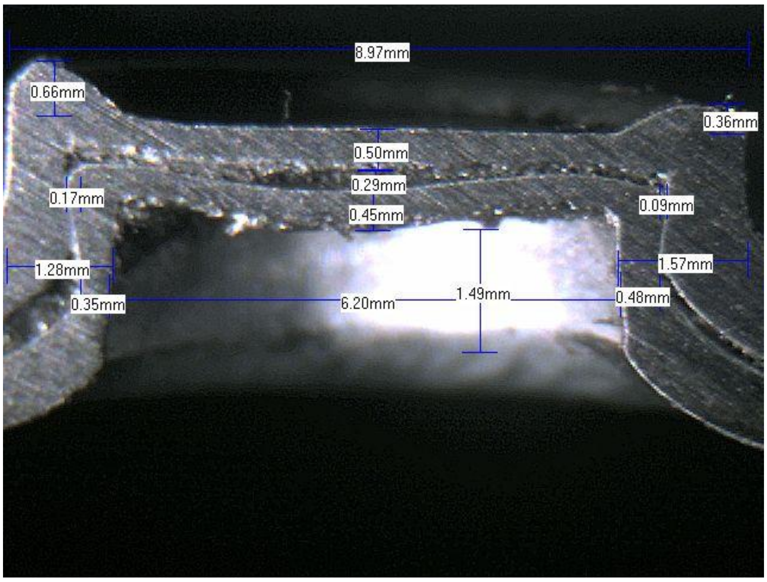
Figure A2: Stress-strain curve of coated mild steel GL400 FN AZ150

APPENDIX B

STUDY OF CLINCHED JOINT OF COMMERCIAL PRODUCT



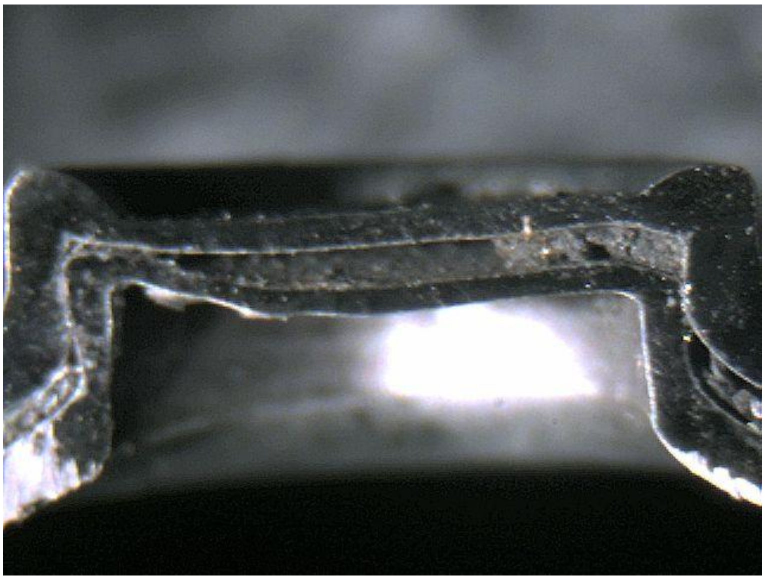
(a)



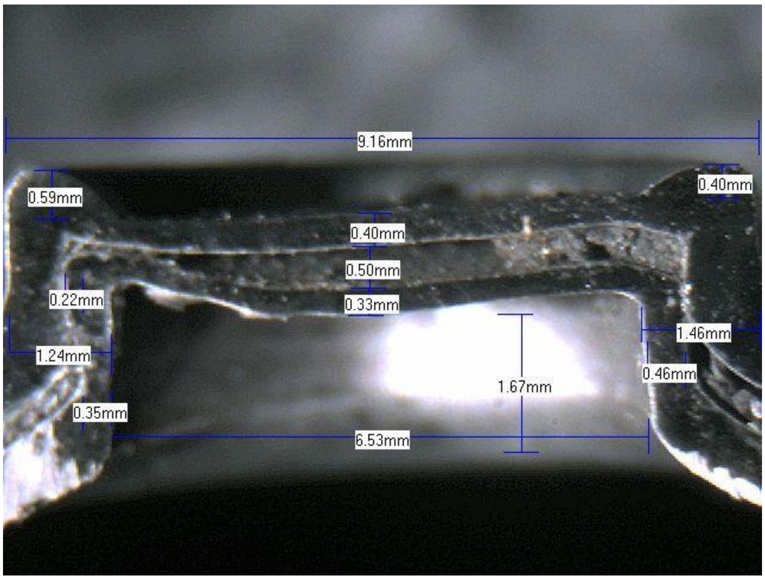
(b)

Figure B1: Cross section view of clinched joint (sample 1)

(a) without dimension (b) with dimension



(a)



(b)

Figure B2: Cross section view of clinched joint (sample 2)

(a) without dimension (b) with dimension

APPENDIX C

EXPERIMENT APPARATUS

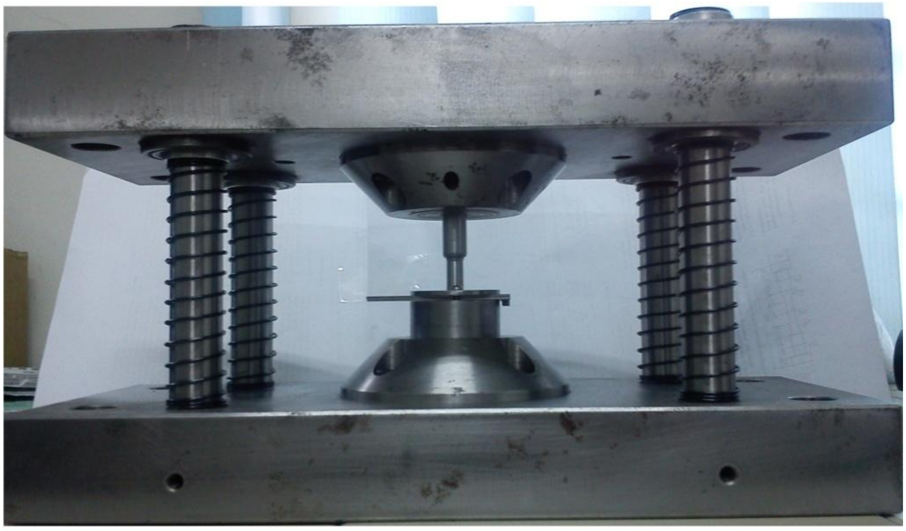


Figure C1: Die set

Figure C2: Punch and die

APPENDIX D

LIST OF PUBLICATION

1.0 Journal Paper

Cheong, W.C., Kam, H.K., Wang, C.C., Lim, Y.P., 2013. Study of cold rotary forming by using rigid-plastic finite element method. *Advanced Materials Research* 626, pp. 662-666.

Cheong, W.C., Kam, H.K., Wang, C.C., Lim, Y.P., 2014. Rigid-plastic finite element simulation of cold forging and sheet metal forming by eulerian meshing method. *Advanced Material Research* 970, pp. 177-184.

Kam, H.K., Cheong, W.C., Wang, C.C., 2013. Development of lubricants evaluation for different friction laws by using rigid-plastic finite element method. *Advanced Materials Research* 626, pp 584-588.

Kam, H.K., Cheong, W.C., Wang, C.C., 2014. Effect of tool eccentricity on the joint strength in mechanical clinching process. *Material Research Innovation*, Accepted (Thomsom ISI indexed journal).

2.0 Conference Paper

Cheong, W.C., Kam, H.K., Wang, C.C., Lim, Y.P., 2012. Application of rigid-plastic finite element method using euler's fixed meshing method for cold forging. *2nd Annual International Conference on Material Science, Metal & Manufacturing* (M3 2012), pp.92-97.

Kam, H.K., Cheong, W.C., Wang, C.C., 2012. Effect of tools eccentricity to the pull-out strength in sheet metal clinching process. *2nd Annual International Conference on Material Science, Metal & Manufacturing* (M3 2012), pp. 57-62.

Kam, H.K., Cheong, W.C., Wang, C.C., 2014. Effect of tool eccentricity on the joint strength in mechanical clinching process. *11th Iinternational Conference on Technology of Plasticity*, 2014, Accepted