STUDY OF FATIGUE BEHAVIOUR OF HIGH SPEED STEEL SKH51 IN FORGING PROCESS

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering

Lee Kong Chian Faculty of Engineering and Science
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May 2020

DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDY OF FATIGUE BEHAVIOUR OF HIGH SPEED STEEL SKH51 IN FORGING PROCESS"** was prepared by **CHAN KING SERN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Mr. Kam Heng Keong for his invaluable advice, guidance and his enormous patience throughout the development of the research. His warm support always fills me up with positivity and makes me continue moving forward. Besides from my research supervisor, I also sincerely appreciate the assistance given by the laboratory assistants, especially Encik Azlan, Encik Mohd Rosnan, Mr. Ho Chan Cheong and many more for their direct or indirect guidance throughout the research.

In addition, I would also like to express my gratitude to my loving parents and loyal friends who had helped and given me encouragement when the research work was not going smoothly. Their encouragement and support are the strongest back up for me to go through the ups and downs.

It would definitely be a hardship for me if there are no fully support, encouragement, guidance and counsel from these great people. So, I would like to thank you from the bottom of my heart.

ABSTRACT

Forging has long been an interest in the metal forming industry due to its low production cost and ability of producing high strength product. It has a wide range of application in producing the product for automobiles, aerospace, machinery, hand tools and hardware, and even the fittings and valves. However, fatigue failure is the main issue of forging tools. Forging tools will fail from time to time due to the effect of cyclic loading that leads to fatigue failure. High speed steel (HSS) SKH51 is one of the popular forging tool steel used in forging industry. Hence, the fatigue behaviour of this tool steel is crucial and in depth study should be done. In considering of this, a series of methodologies have been planned and done to determine the mechanical properties and fatigue behaviour of HSS SKH51 in forging process. Mechanical properties will have a great effect on the fatigue behaviour of this tool steel. From the results obtained, it is proven that HSS SKH51 exhibits a variety of prominent mechanical properties and highly reliable fatigue behaviour. It has a high hardness of HRC 61.1, high ultimate engineering compressive stress of 5920.58 MPa, high critical load of 120 kN and endurance limit of 780 MPa in tensile fatigue test. Fatigue behaviour will in turn affect the fatigue life of a forging tool. There are many types of forging process available in the industry and clinching process is selected as the example in current project for predicting the tool life. The prediction shows that HSS SKH51 square clinching tool is having a higher number of cycles to failure (579 281 cycles) and thus, it is more recommended to be used in the industry instead of HSS SKH51 round clinching tool (63 834 cycles). In conclusion, it can be summed up that HSS SKH51 has a superb fatigue behaviour with long tool life and it could be beneficial when it is used as the forging tool steel. Future work can be done by modifying the validated simulation models to improve the fatigue behaviour of HSS SKH51 in forging process.

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LIST OF SYMBOLS / ABBREVIATIONS

b	fatigue strength exponent
c	fatigue ductility exponent
E	Young's modulus, GPa
K'	cyclic strength coefficient, MPa
N	number of cycles
N_f	number of cycles to failure
n'	cyclic hardening exponent
S	alternating stress, MPa
S_e	endurance limit, MPa
σ_a	stress amplitude, MPa
σ_f	true fracture strength, MPa
$\sigma_f{}'$	fatigue strength coefficient, MPa
σ_m	mean stress in a cycle, MPa
σ_{UTS}	ultimate tensile strength, MPa
ε_a	strain amplitude
ε_e	elastic strain
ε_f	true fracture strain
$\varepsilon_f{}'$	fatigue ductility coefficient
ε_p	plastic strain
$\Delta\varepsilon_e{}^*$	elastic strain at 10^4 cycles
2θ	double angle, °
C	carbon
Cr	chromium
Fe	iron
Mo	molybdenum
V	vanadium
W	tungsten

AFNOR	Association Française de Normalisation (French Standardization Association)
AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Materials
B.S.	British Standards
CESM	continuous electroslag melting
DIN	Deutsches Institut für Normung (German Institute for Standardization)
ESR	electroslag refining
FEA	finite element analysis
FEM	finite element method
HERF	high energy rate forging
HRC	Rockwell hardness test measured on C scale
HSS	high speed steel
JIS	Japanese Industrial Standard
LEFM	linear elastic fracture mechanics
MFPM	Modified Four-Point Correlation Method
M-C	Manson-Coffin
R-O	Ramberg-Osgood
SS	Swedish Standard
VAR	vacuum arc remelting

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Metal forming process has played an important role in the society and metal forming in bulk has been carried out with the help of industrial revolution (Jeswiet, et al., 2008). The agriculture revolution happened in European had fed a large communities. The communities' population increased drastically which made industrialization and urbanization possible at that time. Before the revolution, manufacturing of metal was only available in the level of job-shop. With the invention of power supplies, product manufacturing started to be done in bulk and the complexity of product had increased with the increasing of implementation of automation and innovation. This had led to a rise in production rate of metal working and brought a change to the manufacturing industry (Jeswiet, et al., 2008).

Forging is one of the main bulk metal manufacturing process done to produce complex structures and products (Topa and Shah, 2014). Forging Industry Association (2019) defines forging process as a manufacturing method conducted by squeezing or pressing the metal with extremely high pressure into the parts called as forgings. They have a high strength in nature and it must be noted that forging is not the same as casting since metal is not melted and poured to form the forged parts. Forged parts are generally stronger than the products produced by other metal forming processes. They are mainly used for the application where safety and reliability are critical such as automotive, aircraft and ship (Forging Industry Association, 2019). The other products of forging used nowadays are listed by Cora (2004) such as pin and gear, shaft, crankshaft, camshaft, bolt, ball of bearing and even surgery blade.

According to Karunathilaka, et al. (2018), forging is basically divided into hot, warm and cold forging depending on the temperature of forging process. Superb mechanical properties of forgings, least wastage of material, capability of producing near net shape and net shape products are some of the advantages of cold forging that is done at room temperature. Nevertheless, cold forging tool is always subjected to high mechanical load and abrasive wear that are caused by high flow stress of forged material at room temperature. This will result in mechanical fatigue, which is the main service failure of cold forging process that limits its tool life. Improvement of tool design, surface treatment of forging tool and improvement in forging tool material should be considered since tool cost always occupies a large portion in the production cost of cold forging (Karunathilaka, et al., 2018).

Aluminium, carbon, copper and extremely hard tool steel are commonly used for forging process and in fact, any metal can be applied in this manufacturing process (Forging Industry Association, 2019). Different metal will exhibit different mechanical characteristics which makes it best suited for certain applications (Forging Industry Association, 2019). For cold forging process, the material of forging tool must exhibit high strength, high fracture toughness and high wear resistance to endure the mechanical stress and abrasive wear (Karunathilaka, et al., 2018). In this case, high speed steels (HSS) are usually used as the cold forging tool as it is able to fulfil most of the criteria needed for cold forging process. A high surface pressure of 3000 MPa may be generated in cold forging and HSS SKH51, which is able to withstand a high compressive stress, can be used as the cold forging tool steel to prevent the fatigue failure (Karunathilaka, et al., 2018).

Figure 1.1: Open Die Forging. (Patel, Thakkar and Mehta, 2014)

1.2 Importance of the Study

This project will benefit the forging industry by knowing more about the properties of forging tool. Useful information obtained from the study will help in determining the appropriate working conditions of HSS SKH51 that acts as the forging tool. Proper stress can be applied on the tool in tension or compression loading since the range of working stress is known after carrying out this project. The forging tool will not fail easily by operating the process within the acceptable range of working parameters. Suitable material can be selected and forged by using HSS SKH51 as the forging tool when the valuable data and results are gathered from this study for gaining more knowledge on the behaviour of this tool steel.

Subsequently, fatigue and fracture failure of forging tool can be prevented in the forging and production processes effectively. Tool life of HSS SKH51 will be known after this project is carried out and the forging tool can be replaced before failure. The condition of the forging tool can be monitored from time to time and predictive maintenance can be implemented instead of breakdown maintenance where the tool is only replaced when fracture happens. This can minimize the number of failed product and failure cost significantly. The machine downtime and reworking job of failed product can also be reduced. This results in the reduction of production cost, improvement of production efficiency and increase of industry's profitability after all.

1.3 Problem Statement

Some mechanical properties of HSS SKH51 were established by other researchers. However, they only focused on a few compressive properties of HSS SKH51. In fact, many other compressive and tensile properties of this forging tool steel would also have an effect on its fatigue behaviour. Those properties of HSS SKH51 were still remained unknown.

Besides, the fatigue behaviour of HSS SKH51 was unclear. The fatigue behaviour of this cold forging tool steel was not fully studied by other researchers. Fatigue behaviour of HSS SKH51 is important as this is the main cause that frequently leads the forging tool to failure in the industry. The fatigue behaviour of this tool steel should be understood thoroughly instead of remaining it in doubt.

1.4 Aim and Objectives

In view of the issues mentioned, the main aim of this project is to investigate the fatigue behaviour of HSS SKH51 which acts as the metal forming tool in forging process. For achieving this aim, few objectives have been determined and they are as shown below.

(i) To identify the mechanical properties of HSS SKH51.

(ii) To determine the fatigue behaviour of HSS SKH51.

(iii) To study the feasibility of using HSS SKH51 as clinching tool.

(iv) To predict the fatigue life of HSS SKH51 punch and die in clinching process.

1.5 Scopes and Limitations of the Study

Few scopes and limitations of the current project are listed as below.

(i) HSS SKH51 is taken as the material of forging tool in this project and its relationship with properties of forged material is not considered in the calculation and experimental testing.

(ii) Chemical characteristics of HSS SKH51 such as corrosion and oxidation are ignored. This study is purely focusing on the mechanical properties of the tool steel.

(iii) This project will also focus on analysing the fatigue behaviour of HSS SKH51 in cold forging process. There are a lot of cold forging methods used in the industry and clinching process will be considered, analysed and related to the results of this study.

(iv) Current project is only limited to cold forging but not warm and hot forging process. Thermal fatigue of material must be considered in the study of warm and hot forging, which is not the interest of current project.

(v) Results and data of this project are obtained and tested without considering special conditions and operations of forging process in the industry, such as plating of die surface and skill of forging operator. These conditions will only be known in the industry, which is not the main focus of current project. This limits the outcome of this project to be a conservative result.

1.6 Contribution of the Study

Fatigue behaviour of HSS SKH51 will be determined from this project. Forging industry can take the results of this study as a reference when HSS SKH51 forging tool is used. Suitable working parameters and stress applied on the forging tool can be selected based on the results of this project with extra consideration done by forging operator on the actual service and special operating conditions. Consequently, HSS SKH51 forging tool will not fail easily in the forging process.

Tool life can be prolonged when it is working under the acceptable range of stress level established by this study. It is not needed to replace the forging tool frequently due to fatigue failure. Time and cost can be saved in the industry as the fatigue failure of forging tool has been minimized. This will contribute to the forging industry eventually when effectiveness and efficiency of the forging process is improved critically by utilizing the results of this project.

1.7 Outline of the Report

This report is mainly concerning about the fatigue behaviour of HSS SKH51 that acts as the tool steel in forging process. Chapter 1 Introduction gives a brief idea on the aim, objectives, scopes and limitations of this project. Next, Chapter 2 Literature Review will study the background of HSS SKH51, background of various forging processes implemented in the industry and parameters used to determine the fatigue behaviour of a material.

Planning on the methods that are going to be implemented in this study is explained in Chapter 3 Methodology and Work Plan. Findings of this project will be presented and discussed in Chapter 4 Results and Discussion. For closing, Chapter 5 Conclusions and Recommendations is included to wind up all the results and outcome of the current project and come out with recommendations for exploring more application of HSS SKH51 in forging industry.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review must be done to gain more information and knowledge about the scopes of this project. In order to study the fatigue behaviour of HSS SKH51 in forging process, the composition and classification of steel, especially on HSS, is first studied. Then, it is followed by the literature review on forging, clinching process and study of its defects. As it is suggested by Ku and Kang (2014), forging tools are always subjected to both abrasive wear and mechanical strength during metal-forming processes owing to the high forging loads and tool stresses. Fatigue and fracture failure will be resulted and so, fatigue behaviour will be the third topic that is studied in this chapter. Lastly, forging tool design and tool life prediction are reviewed from the research papers to know more about the ways of reducing fatigue failure.

2.2 Steels

Garrison (2001) states that steels and irons are classified by iron-carbon (Fe-C) phase diagram. Cast irons are the binary Fe-C alloys that have more than 2.06 wt.% carbon. The binary Fe-C alloys which contain less than 2.06 wt.% carbon is called as steels. Steel product is mostly produced in sheet (Garrison, 2001). Steels are ferrite with low carbon contents and usually being formed into complex shapes such as automotive bodies. Their formability can be increased by controlling on the alloying elements and inclusion characteristics and introducing of suitable textures. Coatings can be put onto the steel sheets in many ways to prevent corrosion and for decorative purposes, but this will reduce its formability (Garrison, 2001).

2.2.1 Type of Steels

Steels can be produced by different processes to vary its mechanical and chemical properties and serve for variety purposes. Garrison (2001) claims that low alloy steels, which are called as heat-treated steels, are developed to be used as martensitic steels. The primary concern of them are the hardenability and they are used in tempered condition (Garrison, 2001). Stainless steels are the type of steels with high chromium content of about at least 11 wt.%. Oxide layer will be formed by chromium on the surface of steel that is adhesive and this slows down the oxidation or corrosion of alloys (Garrison, 2001).

Garrison (2001) proclaims that Hadfield steels, tool and die steels and high speed steels are developed for achieving various types of wear resistance. Hadfield steels are having medium to high carbon content with considerable amount of manganese. They are austenitic in room temperature and having high wear resistance due to the transformation of austenite to high carbon martensite when strain is subjected on them. Tool steels are classified into three categories, which are low-alloy, carbon and special purpose tool steels, while die steels are divided into cold-work and hot-work die steels. Most of these steels have large content of strong carbide-forming elements for improving wear resistance and providing strength at both room and elevated temperatures (Garrison, 2001).

2.2.2 High Speed Steels

According to Garrison (2001), the author mentions that high speed steels are primarily manufactured as cutting tools. All of the high speed steels classes are commonly having high carbon, C, content in the range of 0.8 wt.% up to more than 3 wt.%, around 4 wt.% of chromium, Cr, and a huge content of strong carbide forming elements such as vanadium, V, tungsten, W, and molybdenum, Mo (Garrison, 2001). These strong carbide forming elements will provide large carbides after austenitizing which improve wear resistance and contribute to secondary hardening by tempering (Garrison, 2001).

Besides from cutting tools, high speed steels with tungsten carbide are used for cold forging tool manufacturing as commented by Karunathilaka, et al. (2018). This is supported by Mesquita, Barbosa and Machado (2016) that HSS can be used for cold forming which requires high wear resistance, with limited application in moulds and dies. The application of HSS in cold work is limited by its low toughness and relatively course microstructure when it is obtained from bars by conventional metallurgy. Second factor of limitation is about economical, since HSS contains large quantity of alloying elements and more complex heat treatment (Mesquita, Barbosa and Machado, 2016).

In order to break through the limitations, powder metallurgy is suggested by Mesquita, Barbosa and Machado (2016) to produce modern HSS because the microstructure refining of this production process will lead to higher toughness. As a result, HSS will have an excellent performance of high wear resistance, high toughness and finer microstructure. Sitek (2010) affirms that the traditional production processes of HSS is consisting of melting, casting, plastic forming and heat treatment. Nevertheless, it has developed into newer manufacturing processes incorporating with high technology such as electroslag refining (ESR), vacuum arc remelting (VAR) and continuous electroslag melting (CESM) (Sitek, 2010).

2.2.3 High Speed Steel SKH51

One of the popular standard in the category of HSS that is used for cold forging is known as HSS SKH51. Ku and Kang (2014) indicates that high speed tool steel SKH51 is the same as AISI M2 steel grades. Thanks to its high abrasion resistance and toughness characteristics, it is usually used for cutting tools and cold forging dies (Ku and Kang, 2014). This statement is further supported by Murai (2018) who also states that HSS SKH51 is mainly used as cold forging tool. Chromium, tungsten and molybdenum are added to strengthen the carbide in HSS (Murai, 2018). Karunathilaka, et al. (2018) declares that Japanese Industrial Standard (JIS) SKH51 is having the same grade as DIN 1.3343 and AISI M2 standards. It is a molybdenum based HSS used for cold work tool (Karunathilaka, et al., 2018). Table 2.1 shows the equivalent standards of HSS SKH51 in international tool steel classifications as tabulated by Mesquita, Barbosa and Machado (2016).

By considering the hardness and tensile and compressive strength, the material properties of SKH51 tool steel is identical with the mechanical properties of general high-strength steel (Ku and Kang, 2014). It is able to achieve a high hardness of more than 60 HRC and over 3000 MPa of compressive strength (Karunathilaka, et al., 2018). A higher hardness can be achieved by secondary hardening at high tempering temperature of 550 ℃ (Murai, 2018). If the tool always fractures due to high hardness of HSS SKH51, the combination of tempering followed by quenching can be applied to reduce the excessive hardness (Ku and Kang, 2014). For instance, around 3000 MPa of compressive yield stress and 4200 MPa of ultimate compressive stress are obtained by Ku and Kang (2014) after the series of heat treatment. The hardness-controlled SKH51 tool steel is suitable to be used after tempering and quenching and there is no fracture failure observed (Ku and Kang, 2014). All of these mechanical characteristics make HSS SKH51 suitable to be selected for a lot of forging tool applications (Karunathilaka, et al., 2018).

Table 2.1: Equivalent International Standards of HSS JIS SKH51. (Mesquita, Barbosa and Machado, 2016)

United States of America (AISI)	**Germany (DIN)**	**Japan (JIS)**	**Great Britain (B.S.)**	**France (AFNOR)**	**Sweden (SS)**
Molybdenum high-speed steels (ASTM A600)					
M2, reg C	1.3341, 1.3343, 1.3345, 1.3353, 1.3354	G4403 SKH51 (SKH9)	4569 BM2	A35-590 4301 Z85WDCV06-05-04-02	2722

2.3 Forging

Forging process is defined as the metal working process done by using dies and tools where the useful shape of metal is attained in solid state by compressive force (Rathi and Jakhade, 2014). It is the process of hammering and pressing of metal piece (Rathi and Jakhade, 2014). It is also called as a secondary manufacturing process where products are turned into semi-finished or finished parts from primary operation (Mao, 2009). This metal working process can be used for manufacturing of single individual sample parts or for mass production in industry (Cora, 2004).

Rathi and Jakhade (2014) affirms that the forging process will produce a superior mechanical properties product with the least amount of waste of material. This process will start with a material of simple geometry and it will be plastically deformed into a part of complex configuration by one or more operations (Rathi and Jakhade, 2014). During the deformation, the material’s structure of the forged part will align along the direction of deformation, abolishing cast dendritic structure and perhaps grows a fine-grained structure resulting from recrystallization (Mao, 2009). This provides a better toughness and strength to the forged part, which is one of the advantages of forging process (Bharti, 2017).

2.3.1 Forging Processes

As stated in the research of Rathi and Jakhade (2014), hot forging is the mostly used forging process done above metal's recrystallization temperature. New grains will form in the metal and this avoids strain hardening, provides high strain rate and easy metal flow during deformation. Less forging force is required in this process. For cold forging, it is done at or near to room temperature, but below recrystallization temperature. It is used for softer metal and its end product has a better surface finished with little or no finishing work required. A stronger tool is needed which makes the tool and process design critical for cold forging. Whereas for warm forging, the working temperature ranges from above room temperature to lower than recrystallization temperature for reducing the flow stress and forging pressure. This lessens the tooling load and press load while improves the ductility, strength and toughness of the product (Rathi and Jakhade, 2014).

Open-die forging requires simple flat dies to deform the billet in lateral direction of force applied (Rathi and Jakhade, 2014). It requires skilful operator, is only applicable for simple shape and is less accurate in dimension. Impression-die forging will force the material to fully fill the die cavity with some escaped flash. Formation of thin flash will increase the pressure of material to fill out the shapes of cavity, but flash design is very important as extremely thin flash will break the dies. In closed-die forging, high control of material volume and appropriate die design is a must because the forged part is totally constrained in the two half dies without flash. This will lead to zero waste material and high dimensional accurate forged product. This process is done by blocking die and finishing die (Rathi and Jakhade, 2014).

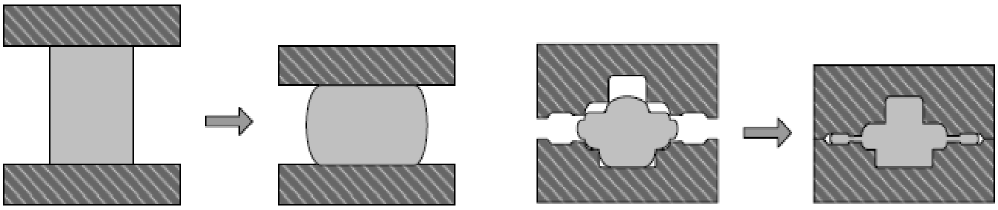


Figure 2.1: Illustration of (a) Open-Die Forging (b) Impression-Die Forging. (Mao, 2009)

In addition, Bharti (2017) suggests few more forging processes such as smith forging. It is the process done by hands on anvil and only used for small-scale lightweight metal forming. The operations involved in smith forging are cutting, bending, upsetting and so on. Press forging is done in a slow manner and continuous force is subjected on the material. Embossments are formed when a thick sheet is squeezed in thickness direction. Upset forging will decrease the length and increase the diameter of wire or rod. It can be used for mass production with multiple dies and cavities. In contrast, roll forging produces a long or thin part with uniform or non-uniform diameter from a thick metal. It is employed to reduce the cross section or distribute the metal over the part. High energy rate forging (HERF) is performed to produce a ductile final product with very high energy applied on the workpiece in a very short time. High ram velocity is generated to provide a greater ram energy (Bharti, 2017).

2.3.1.1 Clinching Process

Mechanical clinching is another process that has become an interest in the recent years in cold forging industry. According to Lee, et al. (2010), clinching is a joining method used to join the materials by plastic deformation. It joins different thicknesses and mechanical properties of metal sheets by using a punch and a die (Eshtayeh, Hrairi and Mohiuddin, 2015). Two or more metal sheets with varies thicknesses can be joined all together at the same time. Forming and drawing are the principal actions involved to create the interlock between the metal sheets. A force that is set according to the strength and thickness of the metal sheets will push the punch down to join and deform the sheets plastically while the die will be fixed at its original position throughout the process (Eshtayeh, Hrairi and Mohiuddin, 2015). Necking will be formed at the upper sheet whereas tensile stress will exist when the lower sheet fills into the die groove (Lee, et al., 2010). No extra heat and extra materials such as fasteners and glue are needed for this process (Eshtayeh, Hrairi and Mohiuddin, 2015).

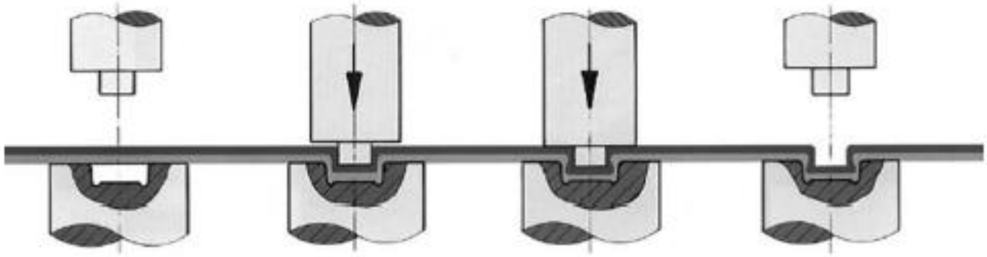


Figure 2.2: Illustration of Clinching Process. (Eshtayeh, Hrairi and Mohiuddin, 2015)

Clinching is applicable in the joining of lightweight sheet material (He, 2017). It is divided into two types, which are shear clinching and press clinching (Eshtayeh, Hrairi and Mohiuddin, 2015). The sheets will be cut and joined together by interlock in shear clinching. For press clinching, the upper sheet surface will be pushed by punch to locally join the sheets and penetrate the materials into the die groove. Neither cutting process is needed nor scrap material is produced in press clinching (Eshtayeh, Hrairi and Mohiuddin, 2015). Other than that, clinching can also be categorised into round or square clinching (He, 2017). However, both round and square clinching are not feasible for brittle material since clinching is a cold forging process in general (He, 2017).

Some factors that affect the strength of clinched joint will be the interlock between the materials, thinning of upper and lower sheet, reduction of thickness of lower sheet and geometries of punch and die (Eshtayeh, Hrairi and Mohiuddin, 2015). As stated by He (2017), the geometries of clinching tools will determine the final geometries of clinched joint, and geometries of joint will influence the strength of it. The thickness of necking, undercut and the final bottom thickness are the main parameters that define the mechanical behaviour of the joint. Neck fracture mode will happen if the neck thickness is too thin (He, 2017). This is because of the low ductility of the clinched material (Eshtayeh, Hrairi and Mohiuddin, 2015). Button separation mode will occur if the undercut is too small (He, 2017). This is because the interlocking exists between the upper and lower sheet is insufficient (Eshtayeh, Hrairi and

Mohiuddin, 2015). The failure that combines two of the modes explained above may also happen (Eshtayeh, Hrairi and Mohiuddin, 2015). Lastly, crack may be found at the bottom of the clinched joint which is caused by tensile stress and this can be avoided by decreasing the depth of the die groove (Eshtayeh, Hrairi and Mohiuddin, 2015).

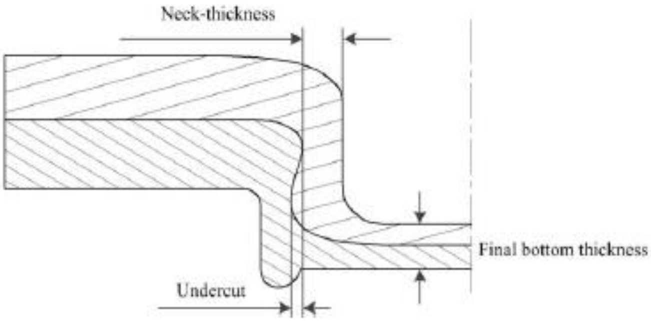
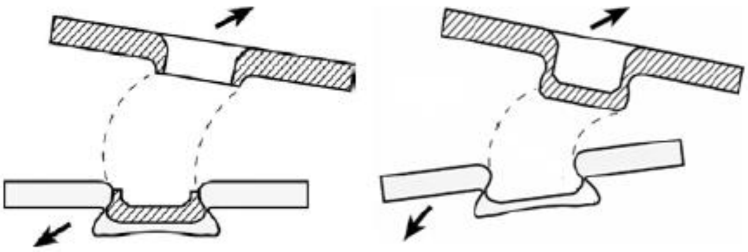


Figure 2.3: Main Parameters of Clinched Joint. (He, 2017)



(a) (b)

Figure 2.4: Illustration of (a) Neck Fracture Mode and (b) Button Separation Mode. (He, 2017)

2.3.2 Forging Equipment

Plenty of forging equipment are available in the market nowadays. As discussed by Rathi and Jakhade (2014), forging hammers and forging presses are the equipment used for the metal working processes. They will determine the production rate, influence the rate of deformation and temperature conditions. The forging machine used must be suited well to all the characteristics required by particular forging process (Rathi and Jakhade, 2014).

Hammer and anvil are used in forging hammer and multiple blows are impacted on the contoured dies (Rathi and Jakhade, 2014). It is the cheapest and most versatile equipment. It is differentiated into gravity- and power-drop hammer. Gravity-drop hammer is further classified into board-, belt-, chain-, air-lift, oil-lift and steam-lift drop hammer. The ram will be uplifted to a height and it is accelerated by gravity during the downstroke which provides the blow energy. This equipment is generally used in hot forging. On top of gravity, air pressure is involved in accelerating the ram for power-drop hammer by using cold or hot air as well as steam (Rathi and Jakhade, 2014). Spring hammer is used in drawing out process where the energy is built up by spring-loaded handle or compressed air (Bharti, 2017). Force is exerted repeatedly on the workpiece when spring oscillates and moves the ram up and down (Bharti, 2017).

Forging presses are used for closed-die forging (Bharti, 2017). It is done by a single continual squeezing process (Rathi and Jakhade, 2014). Mechanical press has a reproducible and preset stroke with various forces being provided at different positions of stroke (Rathi and Jakhade, 2014). It uses an electric motor to drive the large flywheel and ram (Bharti, 2017). This equipment is used for precision die forging, compatible for calibrating large part and high power demand forging (Bharti, 2017). For hydraulic press, it uses fluid pressure to generate the energy and is load restricted (Rathi and Jakhade, 2014). It is flexible, having large capacity and high accuracy, but a slower, space consuming and costly machine in operation (Rathi and Jakhade, 2014). Screw forging press is employed in straightening and bending operation or for upsetting of bolt head (Bharti, 2017). By connecting the discs to a flywheel, the screw can be turned clockwise or anticlockwise to lift or lower down the ram (Bharti, 2017).

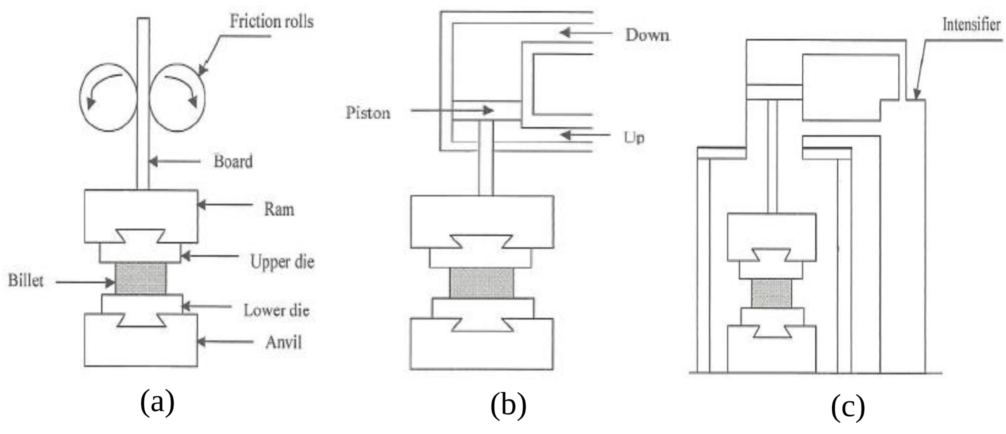


Figure 2.5: Illustration of (a) Board-Drop Hammer (b) Steam Hammer and (c) Hydraulic Press. (Rathi and Jakhade, 2014)

2.3.3 Forging Defects

Even though forging produces the part with higher-level mechanical properties, defects are still possible to occur if the forging process design is not carried out with proper care (Rathi and Jakhade, 2014). Defects are the imperfections of products that exceed some prespecified limits (Soyaliya, Parmar and Kanani, 2015). It is affected by few parameters such as preform of material, material's and die's initial temperature, forming velocity, coefficient of friction, and number and configuration of intermediate forging dies (Mathew, Koshy and Varma, 2013). High speed steels, cold-work die steels and hot-work die steels are the examples of steels used for forging dies. Cold-work die steels and hot-work die steels are further classified by Garrison (2001) as presented in Table 2.2. A suitable forging die steel should always be selected for different type of forging process in order to prevent the forging defect.

There are five common causes of imperfections specified by Sundar, Marathe and Biswas (1987), which are poor billet, incorrect heating, incorrect forging conditions and methods, and uneven cooling of work after forging. Arentoft and Wanhein (1997) have divided the possible forging imperfections into six categories like folds, surface defects, shear defects, cracking, form defects and combination of one or more imperfections stated above. Patel, Thakkar and Mehta (2014) suggest ten forging defects as listed in Table 2.3 with its cause and remedial action that can be taken.

Table 2.2: Classifications of Cold-Work and Hot-Work Die Steels.

Cold-Work Die Steels	Hot-Work Die Steels
Oil hardening cold-work die steels	3-4 wt.% chromium hot-work die steels
Air hardening cold-work die steels	Chromium-molybdenum hot-work die steels
High carbon-high chromium cold-work die steels	Chromium-tungsten hot-work die steels
Wear resistance cold-work die steels	Tungsten hot-work die steels
	Molybdenum hot-work die steels

Table 2.3: Possible Forging Defects with Its Reasons and Remedies.

Forging Defect	Reason	Remedy
Incomplete penetration	Too rapid of light hammer blows	Employ forging press
Cracking of surface	Temperature is too low and excess working on surface	Increase working temperature
Flash cracking	Extreme thin flash	Relieve stress, trimming at high temperature, redistribute flash to uncritical region, thicken the flash
Fold / Cold shut	Sharp corner, excess cooling, friction is too high	Increase die corner fillet radius
Unfilling / Underfilling	Improper forging die design, inappropriate used of forging technique, insufficient heating, less material	Proper design of die, sufficient amount of raw material, appropriate heating
Die mismatch	Misalignment of upper and lower dies	Install half notch on die halves
Scale pits	Inappropriate cleaning of forging material surface	Clean the surface completely before forging
Flakes	Forged part cooled improperly	Practise correct way of cooling
Grain flows improperly	Poor design of die	Improve design of die
Remaining stresses on forging	Inappropriate quenching of work, inhomogeneous material deformation	Slower the cooling of part or cover the part under ash for certain time

2.4 Fatigue Behaviour of Forging Tool

Besides from forging defects found on the forged parts, forging tools will also fail in the forging processes. The main failure mode of forging die is fatigue (Ebara, 2010). Karunathilaka, et al. (2018) defines fatigue as the result of crack or fracture due to the cumulative, localized and irreversible structural change of material caused by cyclic loading of stress and strain after a number of fluctuations. This kind of fracture is owing to the concurrent action of plastic strain, tensile stress and cyclic stress (Karunathilaka, et al., 2018). This die failure is induced by inadequate die material, inappropriate tool design, forging die manufacturing and forging processes (Ebara, 2010). Most of the tool dies will fail at the corner where short crack initiates (Ebara, 2010). Surface quality such as surface roughness, microstructure and residual stress will also be the factor of fatigue failure (Alang, Razak and Miskam, 2011).

Residual stress is the stress exists in the material without the application of external force or thermal effect (Karunathilaka, et al., 2018). The tensile residual stress near to the surface will speed up the crack initiation and propagation whereas the near surface compressive stress will expand the fatigue life. In the forging process, compressive and tensile stress are always present due to die internal pressure of radial stress or circumferential stress (Karunathilaka, et al., 2018). This will lead to unexpected fracture and wear caused by fatigue (Farrahi and Ghadbeigi, 2006). Most of the cracks are initiated from the surface and hence, improving the surface of the die will be beneficial to fatigue behaviour and wear resistance (Farrahi and Ghadbeigi, 2006). Improving on near surface compressive stress is also another method to enhance forging tool fatigue behaviours (Karunathilaka, et al., 2018).

2.4.1 Fatigue Cracking Stages

In forging tool, micro crack is always observed and this starts from the separation of matrix interface of particle or from particle cracking (Hoa, Seo and Lim, 2005). Micro cracking always happens after the application of small strain in plastic deformation (Hoa, Seo and Lim, 2005). Boyer (1986) divides fatigue cracking process into three stages: initiation and nucleation of crack led by initial fatigue damage, crack propagation where crack grows to the uncrack region and final fracture happens at the remaining section. Cracking is usually resulted from the cyclic stress below material's yield strength. Cyclic stress will begin the crack while tensile stress propagates the crack. Compressive force may result to fatigue but compressive stress does not (Boyer, 1986).

Fatigue cracking will originate from the area where high strain exists (Boyer, 1986). This is caused by structural defect which forms the region for stress concentration and high strain intensity. As of the effect of cyclic stress and loading, plastic deformation is developed at this defect tip that acts as the nucleation site of cracking (Boyer, 1986). Crack will initiate from the slip band of a grain which is the outcome of cyclic shear stress, as proposed by Azeez (2013). This forms the slip step and the newly exposed surface of slip step will be oxidized. Slip reversal is inhibited now and it leads to intrusion and extrusion on the material surface. The formation of cyclic slip will generally cause crack initiation (crack nucleation and micro crack growth), crack propagation (macro crack growth) and final fracture (Azeez, 2013). The initiated crack will propagate under the effect of cyclic loading and subsequent to final fatigue failure (Boyer, 1986).

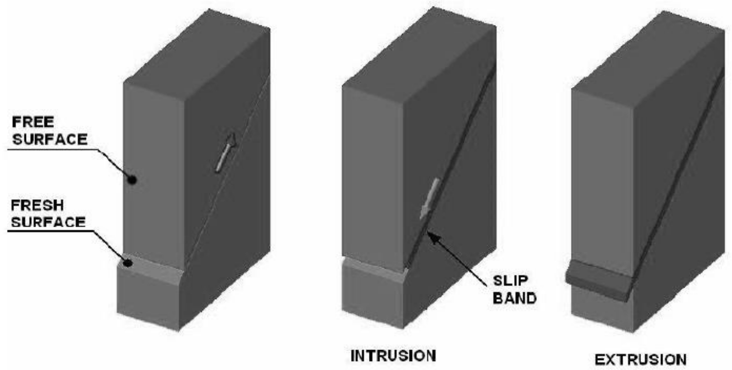


Figure 2.6: Intrusion and Extrusion of Slip Step. (Azeez, 2013)

2.4.2 Fatigue Testing Approaches

In order to avoid fatigue failure, fatigue test has to be done. The primary objective of fatigue failure test is to obtain the fatigue life of a material and its danger point where fatigue failure occurs (Azeez, 2013). Testing can be carried out to investigate the effect of one or more factors which affect the fatigue life by standardizing other testing variables. Two basic fatigue tests are classified as constant- and variable-amplitude test. Constant-amplitude test will subject the testing material to unvaried cyclic stress amplitude until fracture while variable-amplitude test will test the material with different cyclic stress amplitude in simplified stress sequence to simulate the actual environment. In constant-amplitude test, different test piece will be tested by different level of stress, but the stress level will remain unchanged throughout the testing process of an individual test specimen (Azeez, 2013).

There are a variety of machines used for fatigue test and they are specified into general and special purpose fatigue testing machines (Azeez, 2013). Axial loading fatigue test machine is used for general purpose test where purely tension and compression load are applied cyclically between maximum and minimum stresses. Rotating bending test machine is operated to create constant bending and rotating moment on the outer surface of test piece that reversely loaded between maximum tension and compression stresses. In reciprocating bending testing machine, a specimen is clamped in the vice and it is subjected to reciprocating motion of crank drive (Azeez, 2013). Special-purpose fatigue test machine is suggested by Boyer (1986) that is used to test the fatigue fracture of components and special devices such as wire, gear and bearing. Multiaxial testing machine will in turn test the material in biaxial and triaxial stresses (Boyer, 1986).

All the machines specified above are used for testing of fatigue crack initiation (Boyer, 1986). Fatigue crack propagation life will be obtained from facture mechanics (Bannantine, Comer and Handrock, 1990). An initial known crack size is needed for this method. The crack propagation life obtained will be combined with crack initiation life resulted from other testing machine to represent the total fatigue life. Linear elastic fracture mechanics (LEFM) is implemented with the assumptions of elasticity to material that contains defects and cracks. There are three loading modes in LEFM, which are opening, sliding and tearing mode (Bannantine, Comer and Handrock, 1990).

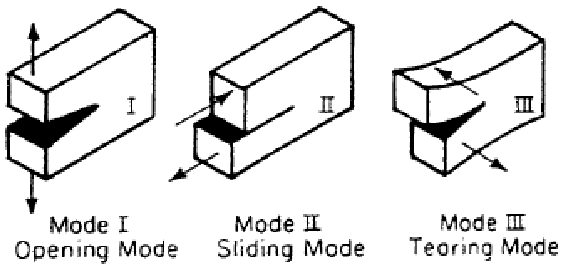


Figure 2.7: Loading Modes of LEFM. (Bannantine, Comer and Handrock, 1990)

2.5 Forging Tool Design

Forging tool design is important to prevent fatigue failure from happening in the manufacturing process. Designing of die is empirical and experience is needed (Chandramouli, 2014). Forging die should be properly designed to increase the tool life and enhance the quality of forged parts (Abdullah, Kam and Samad, 2008). In view of this, the residual stress of die can be minimized by enhancing the properties of die materials by hardening, distributing the flash to suitable location with appropriate shape and size and selecting optimum corner radius in the die. Land width, rake angle and petal angle should also be designed appropriately (Abdullah, Kam and Samad, 2008). McCormack and Monaghan (2001) propose to increase the transition radius for reducing the stress concentration on loaded zone. Changing of profile of die and implementing the pre-stress elements are suggested by Koç and Arslan (2003) to decrease the tensile stress concentrated at fillet and corner.

According to Tomov, Gagov and Radev (2004), gap between half dies should be 3 % of the largest thickness of work piece while the length of flash channel has to be five times longer than the thickness of forged part. The die radii must be enlarged to allow the material plastic flow and reduce the concentration of stress (Ciancio, et al., 2015). Proper design of draft and fillet, lubrication and polished dies for reducing the friction and grinding the curvature edges of die are stated by Thottungal and Sijo (2013) to significantly reduce the laps. Knowledge on ductility and strength of material of work, response of material to deformation and forging temperature, interface frictional properties, deformation of forging tool resulted from huge forging stress and complexity of forged part are all the important criteria in die design (Rathi and Jakade, 2014).

On top of that, it is mentioned by Chandramouli (2014) that a proper die design is depending on the forging process steps, material of forging parts, forging temperature, friction on interface, material flow stress etc. Billet volume should be calculated accurately to prevent underfilling or excess filling. Parting line which is the coincidence line of two half dies must be selected properly to evenly distribute the material. Forging load can be diminished by providing the gutter for flash. Draft angles between 3 ºto 10 ºshould be available for the ease of ejection of forging part. Material of die will be selected based on working temperature and lubrication is vital which determines the surface finished and accuracy of work (Chandramouli, 2014).

2.6 Forging Tool Life Prediction

Tool life should be predicted after knowing the fatigue behaviour of forging tool. Wang, Kam and Wang (2017) once state that tool life is a crucial research study since it will bring a significant reduction in production cost. The life prediction of forging die is critical, especially for forged parts of automobile. This kind of forging process is always done with exceptional high stress applied on forging die surface and finally lead to unforeseen fracture and failure of forging tool (Wang, Kam and Wang, 2017). So, experimental, analytical and numerical methods are usually studied for the forging process (Abdullah, et al., 2007). In order to save the cost of actual modelling, numerical and analytical solutions are validated with experimental outcome (Abdullah, et al., 2007). Numerical approach is more flexible than experimental modelling as the die design can be altered easily (Tong, et al., 2004).

2.6.1 Stress-Life

One of the solution used for understanding of fatigue life cycle is the stress-life approach represented in Wöhler or *S*-*N* curve where *S* and *N* denote for alternating stress and number of cycles respectively (Bannantine, Comer and Handrock, 1990). This approach is normally used for design with operating stress within material elastic region and large number of life cycle. This method must not be used to predict the life below 1000 cycles and its main parameter is called as endurance limit, S_e, that is affected by size, loading type, surface finished and treatment, working temperature and environment (Bannantine, Comer and Handrock, 1990). Boyer (1986) claims that a metal can sustain an infinite number of life cycle without fracture below the endurance limit. The horizontal region of *S*-*N* curve is known as endurance limit, which is the largest force that a material can withstand with 50 % of failure probability (Boyer, 1986).

There are a few strengths and weaknesses listed by Bannantine, Comer and Handrock (1990) for the application of *S*-*N* curve. The estimation and analysis parameters needed for this approach is pretty simple. It performs well for long life cycle and constant amplitude design. Variety data are also available for this method in different applications and conditions. Nevertheless, the solution obtained is purely empirical without considering the fatigue mechanisms provided by other solutions. Problems will be faced when this approach is applied for the loading history of varying stress amplitude. Initiation and propagation of crack is not distinguished by this method as well. This makes the approach to only be the brief estimation of fatigue life and only applicable for unvarying amplitude, long life design (Bannantine, Comer and Handrock, 1990). Various parameters such as surface roughness, mean stress and concentration of stress have to be considered in the curve (Kondo, 2003).

2.6.2 Strain-Life

Other than stress-life approach, strain-life approach can also be used in tool life prediction. Strain-life method is always used since the response of material at critical point or notch usually exhibits a strain (Bannantine, Comer and Handrock, 1990). Stress concentration will cause the plastic strain to form at the notch even though most of the components are designed to remain the nominal load in elastic region (Bannantine, Comer and Handrock, 1990). Strain-life is used to simulate the initiation of crack at notched component (Hafezi, et al., 2012). Strain-controlled condition will be used to model the material response and cyclic stress-strain behaviour under high stress level and low cycle fatigue regime (Bannantine, Comer and Handrock, 1990). Total strain range is the summation of plastic and elastic strain (Brennan, 1994). In the strain-life diagram, the total strain range curve will be asymptotic to both plastic and elastic strain line in low and high cycle regime respectively (Brennan, 1994). The strain-life approach will be implemented when there is a non-uniform loading history or when the effect of mean stress and load sequence is significant (Rahman, et al., 2009).

One of the benefits of using strain-life approach is that it models the plastic strain behaviour accurately at low cyclic fatigue regime and high strain situation (Bannantine, Comer and Handrock, 1990). It accounts the cumulative damage caused by variable amplitude loadings and models the effect of mean stress under different load sequences. It can also be implemented for the application of high temperature where fatigue-creep is important. However, this approach needs a higher level of complex analysis such as Neuber analysis and finite element method (FEM). The strain-life diagram does not consider the crack propagation and only predict the crack initiation life. Some of the aspects of this approach are empirical which are not working based on theories and some of the constants for special conditions of testing specimen such as surface finishing and treatment can only be obtained from additional experimental tests. Strain-life approach should be applied for the conditions when plastic strain forms under high load level or when variable load amplitudes are applied (Bannantine, Comer and Handrock, 1990).

2.6.3 Life Cycle Prediction Criteria

A lot of researchers have done the study to come out with tool life prediction criteria and models in order to relate them to experimental data. Gurson (1977) proposes the criteria and rules of flow of ductile porous metal which presents the effect of hydrostatic stress in plastic yielding and grow of void. Johnson and Cook (1985) suggest the model for cumulative-damage fracture that explains the effect of strain rate, pressure and temperature on the strain growth to fracture. Plasticity model with consideration of Lode parameter and hydrostatic pressure and identification of 3D locus of crack initiation point are performed by Bai and Wierzbicki (2008). Stebunov, Vlasov and Biba (2018) has done the modification on the Cockcroft-Latham criterion by including the influences of stress state and critical plastic strain.

In the study of some other researchers, criterion that is developed depending on critical plastic strain and energy of tensile strain are suggested (Hoa, Seo and Lim, 2005). Ductile fracture criteria with consideration of hydrostatic stress and highest principal stress are also evaluated. Some researchers have examined the feasibility of criteria involving critical tensile strain and maximum value of hydrostatic stress integral (Hoa, Seo and Lim, 2005). Fracture is assumed to happen when the void has grown to certain critical value and this has discussed by Hoa, Seo and Lim (2005) to relate the ductile fracture criteria with phenomenon of void growth and coalescence. It has been proven with the result from finite element program that the criteria developed is able to predict the sites of fatigue fracture with the help of value of cumulative damage (Hoa, Seo and Lim, 2005).

2.6.4 Finite Element Analysis and Finite Element Method

According to Kim and Choi (2009), finite element analysis (FEA) has been commonly used in metal forming issues to predict the life of die. This numerical solution is popular for its flexibility in allowing quick alteration of die design (Abdullah and Samad, 2007). It helps in evaluating the performance of part which would results in cost saving. It is also possible to identify and solve the manufacturing process problems via simulation. Consequently, perfect design of die can be done with the data gathered from fatigue behaviour, stress analysis and FEA tool life estimation (Abdullah and Samad, 2007). For predicting the life of a die, FEA method should be first carried out for forging process, then followed by experimental elastic stress analysis of tool (Kim and Choi, 2009). FEA is also used by some researchers to study for precision forging (Abdullah and Samad, 2007).

Hansen, et al. (1999) have used the finite element method (FEM) for cold forging tool life prediction and the die life of specimen test is assumed to be identical with actual cold forging die with the equivalent strain and stress values. Plastic FEM solution is applied to map the forging contact stress while elastic FEM is done to simulate the growing process of fatigue crack (Hansen, et al., 1999). Falk, Engel and Geiger (1998) use the FEM solution to evaluate the applicability of various fatigue models for tool life prediction of closed die cold forming. FEM is used to quantify and restrict the forging load. The stress-strain distribution obtained is used to calculate the damage parameters and it yields a different life estimation for different models as compared to practical past data (Falk, Engel and Geiger, 1998).

Some FEA and FEM software packages that are commonly used are Ansys, DEFORM, I-DEAS, CAM*form* and FORGE (Abdullah and Samad, 2007).

2.7 Summary

Review of all the research papers have been studied and summarized in this chapter. With the excellent mechanical characteristics, high hardness, high strength and good wear resistance, HSS SKH51 which is the same grade as AISI M2 steel is suitable to be used for cold forging die. This tool steel can be applied in a variety of forging processes and equipment, but forging defects will still happen in the forged parts due to improper working conditions and die design. Fatigue of forging tools is another main problem in all forging processes. Various fatigue testing machines and mechanics are available to investigate the phenomenon of crack initiation and propagation happen in forging tool. Appropriate die design must be considered to reduce the stress concentration, prevent fatigue failure and prolong the tool life. Lastly, prediction of tool life can be done by analytical, numerical and experimental approaches such as stress-life, strain-life, FEM and FEA solutions.

CHAPTER 3

METHODOLOGY AND WORK PLAN

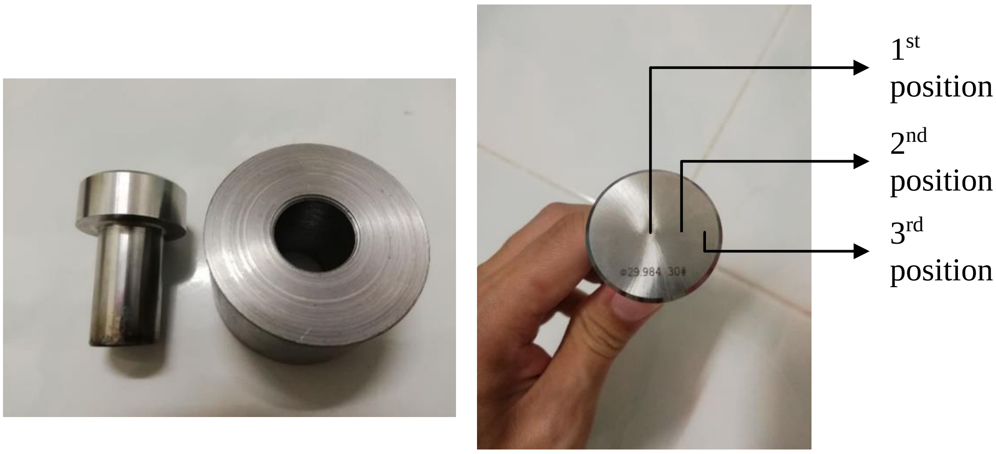
3.1 Introduction

Working plan has been done to conduct the tests, simulation and calculation so that the aim and objectives of this project can be achieved. Hardness test, tensile and compression tests and buckling test are done to determine the mechanical properties of HSS SKH51 as they always have a great effect on the fatigue behaviour. Fatigue tests that are further divided into tensile and tensile-compression fatigue test will next be done to identify the fatigue behaviour of HSS SKH51. Then, it is followed by doing the simulation of clinching process in ABAQUS and lastly, predicting the tool life for clinching process. All these approaches are interrelated with each other and all their results will be linked from one to another in order to complete the methodology and work plan. The methodology of conducting the tests, simulation and calculation are explained as followed.

3.2 Hardness Test

Hardness test will be done on the test specimen of HSS SKH51. Hardness is defined as the resistance of a material to any plastic deformation. Any contamination or surface that is not flat enough will affect the accuracy of the test result. Hence, a perfectly flat and clean surface without scratches will be prepared for the test in order to obtain an accurate result. In this case, the testing specimen is modified from a tensile test specimen. It will be holding upright by a hollow cylindrical block firmly to ensure a secure placement and avoid any movement or slippage of the specimen during the test. This provides a flat surface for the testing and an accurate result will be obtained.

A hardness testing machine with Rockwell hardness tester (as shown in Appendix A) is needed in this case. The Rockwell C scale which is abbreviated as HRC will be used since the C scale is generally used for hardened high speed carbon or tool steels. The tester will be equipped with a diamond cone indenter and load will be applied on the flat surface of test specimen. After applying the load, the depth of indentation will be measured and converted by the machine to a HRC reading. The test will be done on the specimen’s surface at three different positions and three readings will be obtained to calculate for an average HRC reading. This average HRC value will specify the Rockwell hardness of HSS SKH51 and this mechanical property can be used for tool steel selection in forging process.



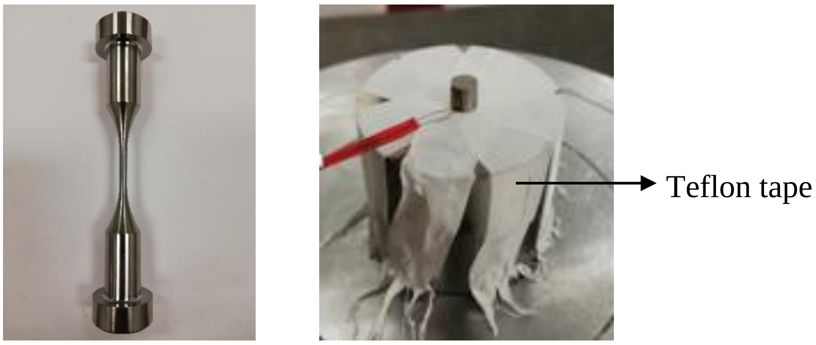
(a) (b)

Figure 3.1: (a) Modified Hardness Test Specimen with Hollow Cylindrical Block (b) Three Testing Positions Labelled on The Specimen Surface.

3.3 Tensile and Compression Tests

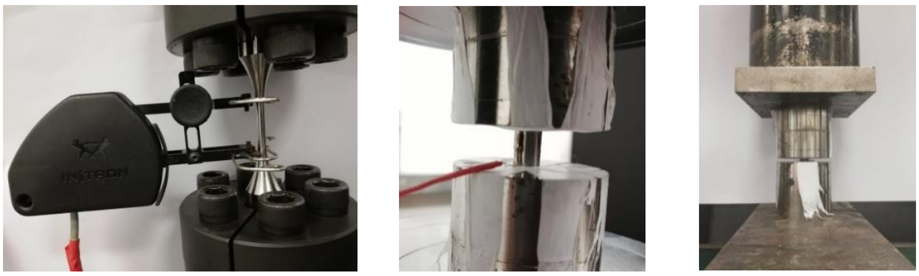
Tensile test is the testing where a pulling or tension force is created on the specimen while compression test is done when a pushing or compressive stress is applied on the specimen. In this project, the tensile and compression tests will be done on the HSS SKH51 test specimen in uniaxial direction. An Instron 5582 universal tester (as shown in Appendix A) will be used for tensile test whereas compression test will need both Instron 5582 universal tester and 60 tons Toyo hydraulic press (as shown in Appendix A). The maximum capacity of Instron 5582 universal tester is 100 kN and the compressive load that HSS SKH51 can withstand is believed to be higher than 100 kN. If the specimen is tested up to the compressive load of 95 kN in Instron 5582 universal tester but it is yet to fail, the testing will be paused and continued starting from the compressive load of 100 kN in Toyo hydraulic press. Extensometer will be used to measure the strain of the specimen in tensile test while strain gauge will be used in compression test. Teflon tape is used in compression test to reduce the friction between the contact surface of testing specimen and testing equipment.

When the tension or compression stress is applied on the specimen, plastic deformation will happen and this leads to final fracture or cracking of the specimen. Strain will be recorded by the strain measuring devices and stress applied will be recorded by the load cell of the testing machine continuously or recorded from the reading of hydraulic press. Once the specimen has fractured in tensile test or cracked in compression test, the testing will be ended. All the data will be represented in stress-strain curves and some mechanical properties of HSS SKH51 such as elasticity, yield strength, ultimate tensile strength and ultimate compressive strength can be obtained from the curves. These characteristics are again useful in the selection and application of HSS SKH51 forging tool. The stress-strain curves and mechanical properties obtained in this section are also helpful in the fatigue tests, simulation in ABAQUS and tool life prediction.



(a) (b)

Figure 3.2: Test Specimen of (a) Tensile Test (b) Compression Test.



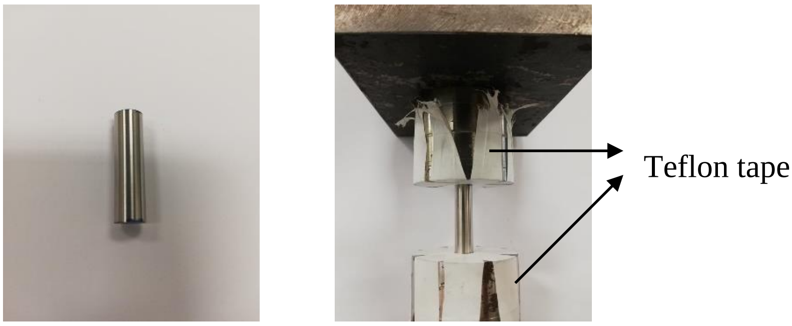
(a) (b) (c)

Figure 3.3: Setup of (a) Tensile Test (b) Compression Test in Instron 5582 Universal Tester (c) Compression Test in Toyo Hydraulic Press.

3.4 Buckling Test

When a material that is long in shape, such as a column, is subjected to compressive stress at two of its ends, the material may become unstable. This instability will cause a deformation and the material will deflect sideway in a sudden. This change in shape will lead the material to failure even though the load applied on it has not reached the ultimate compressive stress yet. Once the material deforms, it is said to have buckled. As it has been mentioned previously, clinching process is one of the scope of this project. The tip of the clinching punch is generally long in shape (as shown in Appendix A). Buckling may happen at the punch tip if the compressive stress applied is too high.

In view of this, buckling test will be done in uniaxial direction on HSS SKH51 specimen by using the 60 tons Toyo hydraulic press. Teflon tape will be used in this test as well. The deformation in length of the specimen will be measured by using vernier calliper and the compressive load applied will be read directly from the scale of the hydraulic press. No load cell and strain measuring device are used in this test as the hydraulic press is unable to be connected to any electronic device. Testing specimen will be set up at the centre of the press. This ensures that the compressive load is applied perpendicularly downward by the press on the contact surface of testing specimen. The compressive load applied will be increased in a constant interval of 1 ton, which is equivalent to 10 kN, manually. The test will be ended when the specimen deflects sideway. This indicates that the specimen has buckled and failed. The critical load that the HSS SKH51 specimen can withstand will be obtained from this test. A graph of load versus deformation in length of the specimen will be plotted to represent the result of the test.



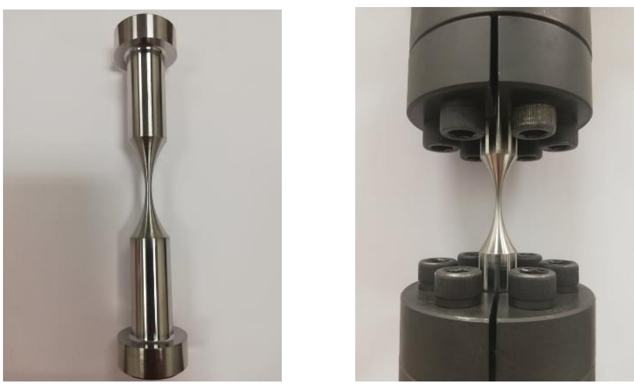
(a) (b)

Figure 3.4: (a) Buckling Test Specimen (b) Setup of Buckling Test.

3.5 Fatigue Tests

Few stress levels will be determined from the stress-strain curve of tensile and compression tests. Then, constant amplitude stress loading will be conducted at these stress levels. The testing machine will apply a cyclic loading at one preselected constant stress amplitude on one HSS SKH51 specimen until fracture. The number of cycles required to fail the specimen is monitored and recorded by the testing machine automatically for that particular stress level. After the first specimen fails, the test will be continued with another specimen being tested at another constant stress amplitude. Once all of the preselected stress levels are tested corresponding to its life to failure, the *S-N* curve can then be plotted for HSS SKH51. This is important in determining the fatigue behaviour of this tool steel and it can be used to predict the number of cycles to failure of forging tool according to the constant stress level applied.

This fatigue test is planned to be done on two types of loading, namely tensile and tensile-compression fatigue test, in the uniaxial direction. Testing machine that will be used is the Shimadzu servo-hydraulic dynamic universal testing machine (as shown in Appendix A) with the capacity of ±50 kN. No strain measuring device is needed in this case as strain is not the concern of the current fatigue tests. A frequency of 10 Hz will be set for the testing. The endurance limit or fatigue limit is defined as 10^7 cycles for both tensile and tensile-compression fatigue test. The testing will be ended manually if any of the specimen is yet to fail even though it has been tested up to 10^7 cycles.

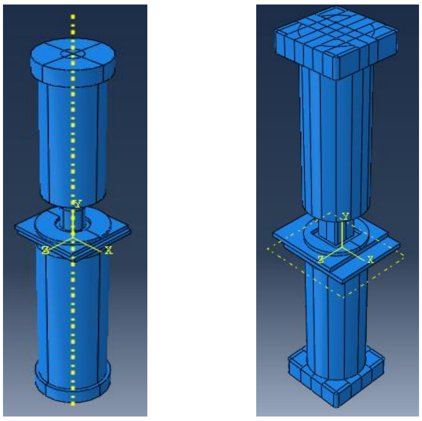


(a) (b)

Figure 3.5: (a) Fatigue Test Specimen (b) Setup of Fatigue Test.

3.6 Simulation in ABAQUS

ABAQUS will be used in this study to perform the simulation of a forging process. This simulation is done to observe the stress distribution happening in HSS SKH51 forging tool during the cold forging process. There are plenty of cold forging processes available in the industry and clinching process is selected as an example in the current project for this simulation. The model of round and square clinching punch and die will first be constructed in the FEA software. Then, the mechanical characteristics of HSS SKH51 obtained from the tests explained previously, such as Young's modulus, true yield stress and true plastic strain, will be inserted for the material properties of clinching punch and die. The interaction properties between punch, die, top steel sheet, bottom steel sheet and blank holder will be specified to consider the friction coefficient exists in between them. Boundary condition will also be set as encastre for die and blank holder while punch will be set to have a negative displacement to simulate the downward motion of punch in clinching process.



(a) (b)

Figure 3.6: Model of (a) Round (b) Square Clinching Process.

Grid independent test is done to obtain the best mesh size that provides the most accurate simulation result. As it is shown in Figure 3.7, simulation for mesh size of 0.3 is stopped halfway due to time constraint. However, the comparison is sufficient to prove that the simulation of mesh size of 0.5 has the most accurate result. Further downsizing of mesh size to 0.3 does not improve the accuracy of result. Therefore, mesh size of 0.5 is used for the simulation in this project.

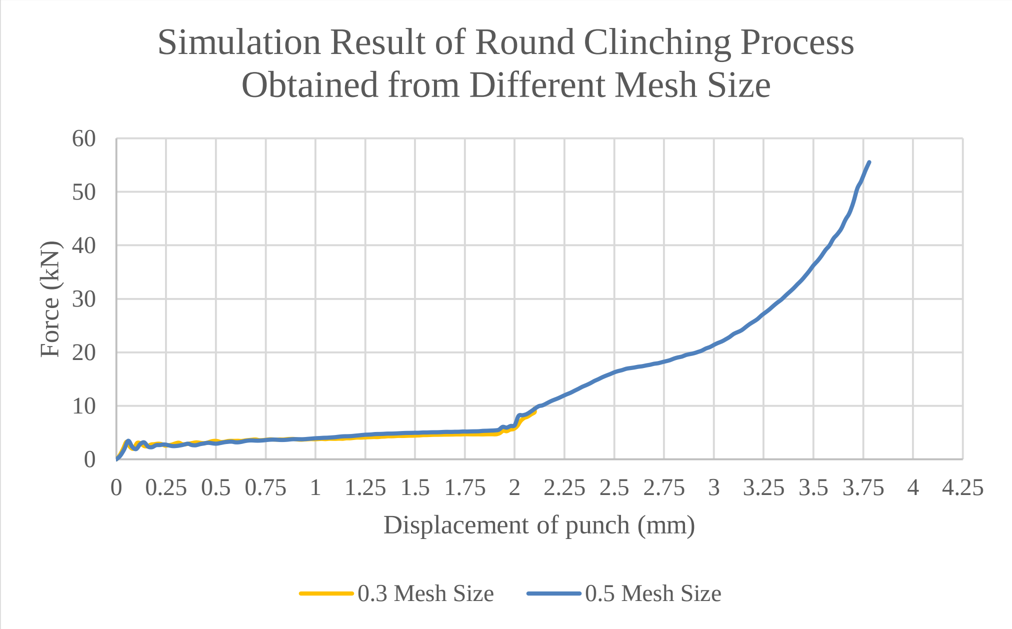


Figure 3.7: Grid Independent Test of FEA Simulation in ABAQUS.

After obtaining the suitable mesh size and completing the simulation, stress distribution happens in the clinching tools can be observed. The exact value of true stress exists in the clinching tools can be determined from this simulation result via von Mises criterion. The true stress value obtained from the simulation can be compared with the true stress-strain curves and true *S*-*N* curves obtained previously to know more about the mechanical properties and fatigue behaviour of HSS SKH51 clinching tool. The fatigue life of punch and die can also be known from the comparison. The true stress exists in the punch and die will then be used for the calculation of tool life prediction in the next section.

Since the cross section dimension of both round and square clinching tool (as shown in Appendix C) are identical in this simulation, their simulation results are in fact comparable. The design with lowest true stress and best fatigue behaviour can be identified among these two types of clinching tool from the simulation results. This determines the best design of clinching tool with a long fatigue life that is suitable to be used in the industry.

3.7 Tool Life Prediction

The tool life prediction of HSS SKH51 clinching tools will be done by comparing the true stress obtained from the ABAQUS simulation with the true *S*-*N* curve of tensile fatigue test. The true stress will be treated as the constant stress amplitude of tensile fatigue test. The number of cycles, *N*, of the clinching tools will be interpolated or extrapolated from the true *S*-*N* curve for that particular constant stress amplitude. As a result, the tool life of HSS SKH51 punch and die can be predicted. Nonetheless, this prediction will only act as a reference because clinching is generally a compression process. A low reliability result will be obtained if the tool life is predicted from the true *S*-*N* curve of tensile fatigue test. Another method with higher accuracy should be applied for this prediction and thus, strain-life equation will be introduced next. The results obtained from these two methods will be analysed and compared afterwards.

The second prediction method of HSS SKH51 clinching tool life will be applied by using the strain-life equation. The strain-life equation suggested by Hartman (2013) is the equation developed by Socie and Morrow (1980) which takes the mean stress of the cycles of loading history into account. This equation will be used in the current project as demonstrated below:

$$\varepsilon_a = \frac{(\sigma_f{}' - \sigma_m)}{E}\left(2N_f\right)^b + \varepsilon_f{}'\left(2N_f\right)^c \tag{3.1}$$

where

ε_a = strain amplitude

σ_m = mean stress in a cycle, MPa

E = Young's modulus, GPa

N_f = number of cycles to failure

$\sigma_f{}'$ = fatigue strength coefficient, MPa

$\varepsilon_f{}'$ = fatigue ductility coefficient

b = fatigue strength exponent

c = fatigue ductility exponent

There are few unknowns need to be determined in Equation 3.1, which are ε_a, *E*, $\sigma_f{}'$, $\varepsilon_f{}'$, *b* and *c*, in order to estimate the number of cycles to failure of clinching tool. The Young's modulus of HSS SKH51, *E*, will be obtained from the stress-strain curves of tensile and compression tests that have been discussed previously. Next, the four constants, $\sigma_f{}'$, $\varepsilon_f{}'$, *b* and *c*, are called as Manson-Coffin (M-C) parameters. These M-C parameters can be calculated by using the empirical formula of Modified Four-Point Correlation Method (MFPM) developed by Ong (1993) as followed:

$$\sigma_f{}' = \sigma_f \tag{3.2}$$

$$\varepsilon_f{}' = \varepsilon_f \tag{3.3}$$

$$b = \frac{1}{6}\left\{\log\left[0.16\left(\frac{\sigma_{UTS}}{E}\right)^{0.81}\right] - \log\left(\frac{\sigma_f}{E}\right)\right\} \tag{3.4}$$

$$c = \frac{1}{4}\left[\log\left(\frac{0.00737 - \frac{\Delta\varepsilon_e{}^*}{2}}{2.074}\right) - \log(\varepsilon_f)\right] \tag{3.5}$$

where

$$\frac{\Delta\varepsilon_e{}^*}{2} = \frac{\sigma_f}{E}\left[10^{\frac{2}{3}\left\{\log\left[0.16\left(\frac{\sigma_{UTS}}{E}\right)^{0.81}\right] - \log\left(\frac{\sigma_f}{E}\right)\right\}}\right] \tag{3.6}$$

and

σ_f = true fracture strength, MPa

σ_{UTS} = ultimate tensile strength, MPa

ε_f = true fracture strain

$\Delta\varepsilon_e{}^*$ = elastic strain at 10^4 cycles

After getting all the M-C parameters, the unknown value of ε_a can then be calculated by using the formula of Ramberg-Osgood (R-O) relationship presented in Equation 3.7. The stress amplitude, σ_a, in Equation 3.7 will be calculated from the true stress value obtained in the simulation results of ABAQUS. K' and n' mentioned in Equation 3.7 are called as R-O parameters.

$$\varepsilon_a = \varepsilon_e + \varepsilon_p = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \quad (3.7)$$

where

$$n' = \frac{b}{c} \quad (3.8)$$

$$K' = \frac{\sigma_f{}'}{(\varepsilon_f{}')^{n'}} \quad (3.9)$$

and

ε_e = elastic strain

ε_p = plastic strain

σ_a = stress amplitude, MPa

K' = cyclic strength coefficient, MPa

n' = cyclic hardening exponent

After getting all the M-C and R-O parameters and the value of E and ε_a, all the constants can be substituted back into Equation 3.1 now for tool life prediction. The mean stress, σ_m, in Equation 3.1 will again be calculated from the true stress value obtained from clinching simulation results of ABAQUS. The number of cycles to failure, N_f, of the HSS SKH51 clinching tools can now be calculated and predicted by using Equation 3.1. The tool life predicted for round and square clinching tool can be compared in this case.

3.8 Summary

The aim and objectives of the current project can be achieved by carrying out all the testing, simulation and calculation stated above. Hardness, tensile and compression tests and buckling test will be done to identify the mechanical properties of HSS SKH51. Fatigue tests will determine the fatigue behaviour of SKH51 tool steel. Simulation done in ABAQUS will study the stress distribution in HSS SKH51 clinching tools while true *S-N* curve and strain-life equation will be used to predict the fatigue life of this tool steel in clinching process. All these results and data obtained must be compared with each and every methodology to prove on the feasibility of using HSS SKH51 as forging tool steel. All the aim and objectives of this study will be fulfilled once the methodology and work plan is carried out accordingly.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results obtained from each and every methodology will be analysed and discussed in this chapter. The data and results obtained from one methodology may be interrelated with another and cross comparison should be done between them. Hardness test, tensile and compression tests and buckling test will determine the properties and characteristics of HSS SKH51. These properties will have a significant effect on the fatigue behaviour of this tool steel. Then, *S-N* curve will be resulted from fatigue tests to investigate on the fatigue behaviour of HSS SKH51. Stress distribution in punch and die and true stress of HSS SKH51 clinching tools obtained from simulation result will next be analysed. Finally, the results of tool life prediction obtained from tensile fatigue true *S-N* curve and strain-life equation will be compared. All of the results will be analysed in detail comprehensively.

4.2 Hardness Test

As it has been planned, the hardness test of HSS SKH51 is done by using the Rockwell hardness tester with C scale. Three positions of the flat surface of test specimen are tested to obtain the HRC readings of the tool steel. The results of this testing is shown in Table 4.1 and Figure 4.1.

Table 4.1: Results of Rockwell Hardness Test of HSS SKH51.

Hardness	**Testing Position**			**Average**
	1st position	**2nd position**	**3rd position**	
HRC	61.1	61.3	61.0	61.1

(a) (b) (c)

Figure 4.1: HRC Reading of (a) First Position (b) Second Position (c) Third Position.

It is observed that three different readings are obtained from three different positions on the flat surface even though the test specimen is the same, which is HSS SKH51. This shows that the material may not be fabricated in a good crystallinity during its manufacturing process, which results in different HRC readings obtained. However, there is only a slight difference of ±0.3 HRC exists between the results. This slight difference will not lead to a huge impact on the mechanical properties and performance of the forging tool steel. An average HRC value is also calculated from these three different readings to consider for this issue of crystallinity of manufactured tool steel. This will provide a reliable result for the hardness test of HSS SKH51 by averaging the three readings obtained.

The result shows that the average hardness of HSS SKH51 is HRC 61.1. This is tally with the statement of Karunathilaka, et al. (2018) that SKH51 tool steel is able to achieve a hardness of more than HRC 60. It proves that HSS SKH51 has a high resistance to abrasive wear and plastic deformation since it has a high hardness as tested. This is supported by Faria, et al. (2007) that, the higher the surface hardness, the higher the wear resistance. Forging process is generally a compression process and compressive stress will be subjected on the forging tool. High resistance to abrasive wear and plastic deformation is crucial for HSS SKH51 forging tool. The forging tool will not be deformed permanently and it will not fail easily under a high compressive stress if it has a high hardness.

So, due to the high hardness of HRC 61.1, this HSS is suitable to be selected as the tool steel for a lot of forging processes, such as clinching.

4.3 Tensile and Compression Tests

Besides from hardness, a lot of other mechanical properties of HSS SKH51 have also been obtained from tensile and compression tests. Stress-strain curves are plotted from the data collected in the tests and the characteristics of this tool steel can be obtained from the curves easily. The stress-strain curves and mechanical properties of HSS SKH51 are shown as below.

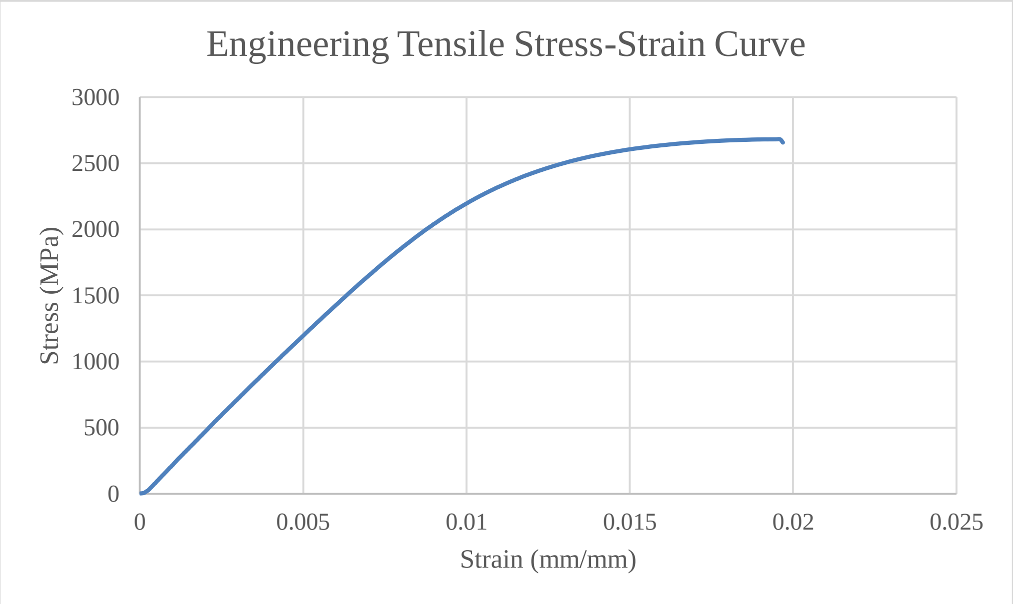


Figure 4.2: Engineering Tensile Stress-Strain Curve of HSS SKH51.

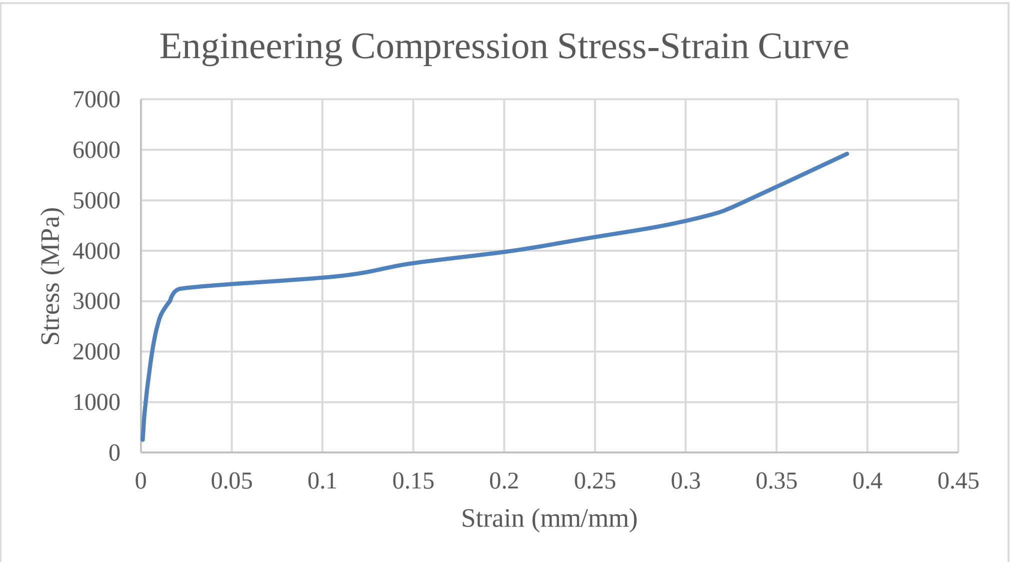


Figure 4.3: Engineering Compression Stress-Strain Curve of HSS SKH51.

Table 4.2: Mechanical Properties of HSS SKH51.

Young's modulus (GPa)	233.68
Ultimate tensile strength (MPa)	2680.18
Tensile yield strength (MPa)	2477.46
Yield strain of tensile test (mm/mm)	0.0126
Ultimate compressive strength (MPa)	5920.58
Compressive yield strength (MPa)	3256.32
Yield strain of compression test (mm/mm)	0.0481

By comparing the results obtained from tensile test and compression test, it is obvious that HSS SKH51 is able to sustain a higher compressive stress as compared to tensile stress. The ultimate compressive strength reported is more than two times of ultimate tensile strength. The yield strain of compression test is much higher than of tensile test. By definition, strain is the ratio of the change in length of a test specimen to its initial length before loading. A higher yield strain obtained from compression test indicates that the tool steel under compressive stress can withstand more deformation in the elastic region before yielding and transforming into plastic behaviour. This is a great advantage for HSS SKH51 to be used as the forging tool steel as it will not be deformed and failed easily under a high compressive stress. The results of compression test are also agreed to the statement of Karunathilaka, et al. (2018) that SKH51 tool steel will exhibit a high compressive stress of over 3000 MPa.

Even though forging is similar to the compression process, the mechanical properties of HSS SKH51 obtained from tensile test should not be ignored too. Tensile and compression stress may exist together in the forging die as circumferential stress and radial stress (Karunathilaka, et al., 2018). Overloading and fatigue will be caused by these stresses and fail the die (Karunathilaka, et al., 2018). A stress that is lower than ultimate tensile stress should be applied for the forging process that uses SKH51 tool steel. The stress limit will not be reached, either for the case of tensile or compression, if the stress applied is lower than the ultimate tensile stress of HSS SKH51. This will ensure that the forging tool is working under the stress limit and the issue of fatigue and overloading will be minimised.

Cabrera (2018) asserts that brittle material will show an elastic part without having the plastic behaviour, as shown by Graph B-1 in Appendix B. The material will have a little or no deformation during the fracture (Cabrera, 2018). This phenomenon is observed from the stress-strain curve of tensile test. There is only a little plastic deformation observed in the curve. Moreover, there is no necking observed from the failed tensile test specimen, which is a trait possessed only by brittle material. These two phenomena undoubtedly show the brittle characteristic of HSS SKH51 and it is reasonable to classify HSS SKH51 as a brittle material.

From the failed compression test specimen, tiny cracks are found when the stress applied on it reaches the ultimate compressive stress. The cracks are slanted at certain angle relative to the horizontal axis. This result can be explained by the theory of 2D Mohr's circle. When a volume element is considered, the plane stress of the element will be the compressive stress applied on the test specimen. When compressive stress increases, the volume element will rotate smoothly in clockwise or anticlockwise direction from the angle of 0° (relative to horizontal axis) to certain angle. When the stress applied reaches the ultimate compressive stress, principal stress and maximum in-plane shear stress will exist in the volume element. The combine effect of these stresses cracks the element and this is the cracking observed from the failed compression test specimen.

The orientation of crack and stresses are determined by the double angle, 2θ, in the 2D Mohr's circle. A rotation of 2θ in the Mohr's circle is equivalent to the rotation of θ for the volume element. By observing the cracks on the failed test specimen, it can be predicted that the volume element is rotated in anticlockwise direction. This is the reason behind for the orientation of slanted cracks noticed in Figure 4.4.

Figure 4.4: Failed Compression Test Specimen with Tiny Cracks Observed.

4.4 Buckling Test

Critical load, P_{cr}, is another vital mechanical property of HSS SKH51 in cold forging process, especially clinching process. Critical load is defined as the maximum axial load that a column can sustain at its verge of buckling before deformation occurs. The critical load that this tool steel can withstand is obtained from the buckling test. A graph of load versus deformation in length is plotted from the data obtained and it is presented below.

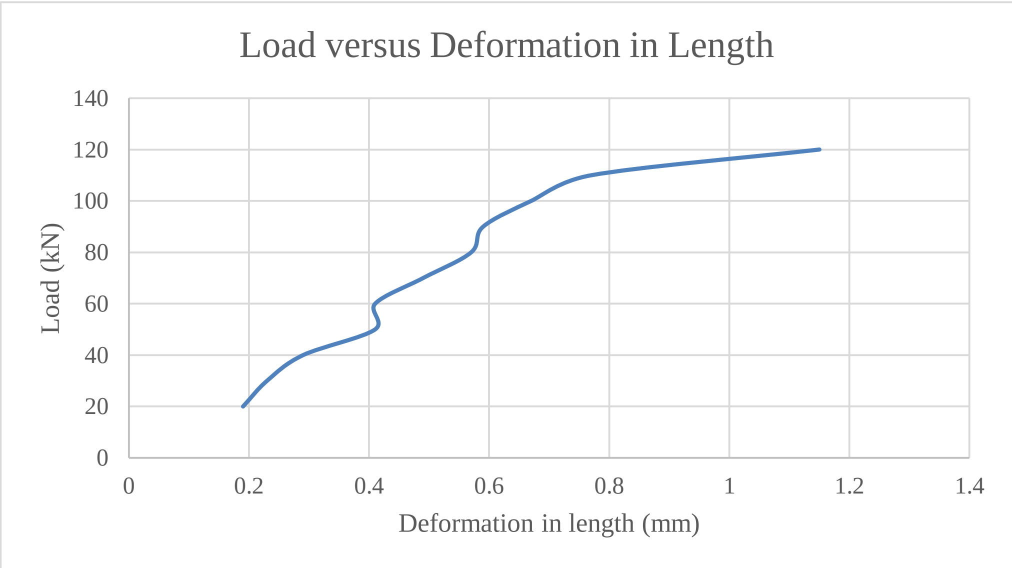


Figure 4.5: Graph of Load versus Deformation in Length of HSS SKH51.

Buckling test is done with the similar procedure as compression test. A uniaxial compressive stress is applied at one end of the test specimen while another end of it is fixed in position. The value of P_{cr} obtained from this testing is 120 kN as shown in the graph of Figure 4.5. Any HSS SKH51 forging tool that is in a column-like shape should not be subjected to a compressive force of over 120 kN. If the compressive force exceeds the P_{cr}, buckling will happen and the forging tool will fail. The shape of the tool will be deformed or deflected and it can no longer produce a forged part with high quality.

The value of critical stress, σ_{cr}, can be calculated by dividing the P_{cr} with the area where the load is applied on. This can help in the design of forging tool to determine the maximum stress that the tool can sustain despite of ultimate tensile and compressive stress. To prevent buckling, the tool should not be subjected to a stress higher than critical stress even if the critical stress is smaller than the ultimate tensile and compressive stress.

According to Türkmen (1995), the buckling resistance of a member will decrease if the length increases. The design of forging tool, especially clinching punch, must consider this concept. The punch tip always possesses a column-like shape. The ratio of punch tip's length to its diameter should not be too large. If there is a high ratio between them, the length of the punch tip may be too long and its resistance to buckling will be reduced. The punch tip may buckle before the applied stress reaches the ultimate tensile and compressive stress. This in turn decreases the service life and fails the clinching punch easily. The resistance to buckling will be high only if the member is chunky (Türkmen, 1995).

By observing the failed buckling test specimen, an obvious deflection of the specimen to the right is noted. The failure pattern of the specimen is the same as the clamped-guided end points constraint illustrated by Figure A-9 in Appendix A. In the 60 tons Toyo hydraulic press, there is a gap noticed in between the press and its supporting structure. When the compressive stress is applied up to the critical load, the gap allows the hydraulic press to translate in a small displacement to the right, which makes the failure pattern similar to the clamped-guided end points constraint.

In fact, the failure pattern of the clinching punch tip will be identical to clamped-clamped end points constraint if buckling happens. Both of the ends of clinching punch tip will be fixed and no rotation or translation are allowed during the clinching process. Buckling will happen at the punch tip with the failure pattern of clamped-clamped end points constraint if and only if the ratio of length to diameter is too large and the compressive force is applied up to the critical load. Hence, these two aspects must be considered in the design of HSS SKH51 forging tool and clinching punch in order to prolong the tool life.

(a) (b)

Figure 4.6: (a) Failed Buckling Test Specimen (b) Buckling Happened in Toyo Hydraulic Press.

4.5 Fatigue Tests

Tensile fatigue test and tensile-compression fatigue test have also been done to investigate the fatigue behaviour of HSS SKH51. The inputs needed for these tests have been obtained from the results of tensile and compression test. The number of cycles to failure of HSS SKH51 at different constant stress amplitude is recorded and the *S-N* curve is plotted based on the result obtained from the test. The *S-N* curve of tensile fatigue and tensile-compression fatigue are plotted together in one graph for comparison.

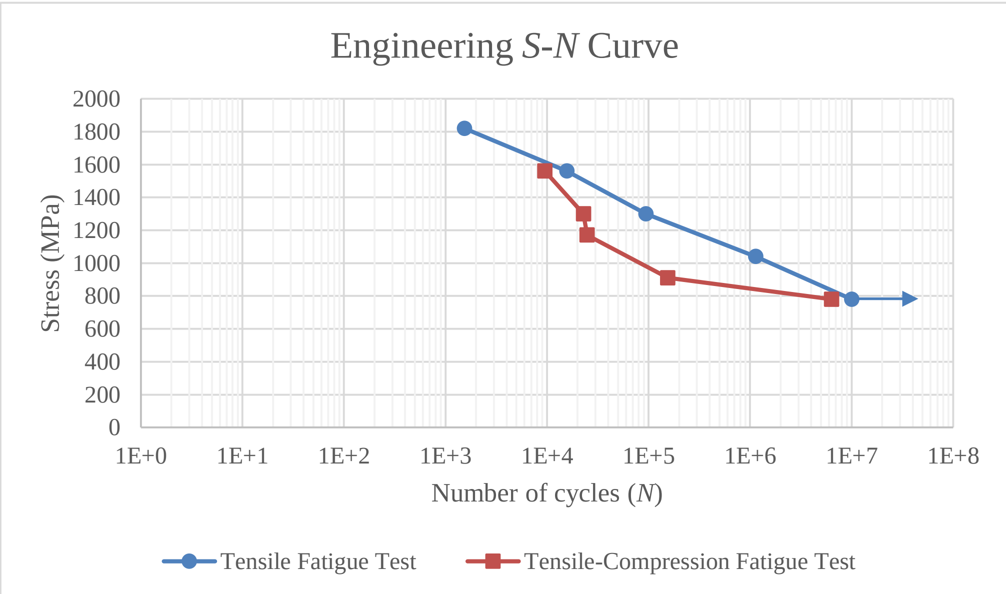


Figure 4.7: Engineering *S-N* Curve of HSS SKH51.

From the engineering *S-N* curve obtained, it is crystal clear that the number of cycles decreases with the increase of stress level. This phenomenon happens for both tensile and tensile-compression fatigue. This result fulfils the expectation of fatigue tests since a higher plastic deformation will be developed when the stress level increases. Plastic deformation will cause the initiation of crack at high strain intensity region. The effect of high cyclic loading will propagate the crack quicker and lead the specimen to final fracture. As a result, the specimen will fail rapidly at a low fatigue life. A small stress amplitude should be applied in the forging process in order to lengthen the life to failure of forging tool.

The result of tensile fatigue test illustrates a linear graph with negative gradient as shown in Figure 4.7. This linear graph indicates that the tool life of HSS SKH51 is predictable if the tool is subjected to tensile stress. A known tensile stress exerted on HSS SKH51 forging tool can be compared with the *S-N* curve of tensile fatigue to obtain the number of cycles to failure. An equation can also be created for this linear *S-N* curve for tool life prediction. Endurance limit is defined in tensile fatigue test when the test specimen has been tested up to 10^7 cycles but it is yet to fail and fracture. The endurance limit obtained for this tensile fatigue test is 780 MPa. If a HSS SKH51 forging tool is subjected to a tensile stress exactly at or lower than 780 MPa, the tool is said to have an infinite tool life and it will not fracture easily.

On the other hand, there is no linear relationship observed from the *S-N* curve of tensile-compression fatigue. Tool life prediction of SKH51 forging tool is unable to be done for this cyclic stress, unless more testing are done at the stress amplitudes presented in Figure 4.7 to obtain a linear *S-N* curve for tensile-compression fatigue. The endurance limit of tensile-compression fatigue test is unable to be determined in the current project due to time constraint. The specimen fractures around six million cycles when it is tested at 780 MPa. The endurance limit of HSS SKH51 for tensile-compression fatigue is believed to be lower than 780 MPa.

All the number of cycles obtained in tensile-compression fatigue is lower than in tensile fatigue even though the constant stress amplitude applied in both tests are about the same. The endurance limit of tensile-compression fatigue is estimated to be smaller than of tensile fatigue as well. A much higher plastic deformation as compared to tensile fatigue is created when the specimen is subjected to cyclic compressive stress in addition of cyclic tensile stress. This speeds up the crack propagation process and the specimen will fracture in a faster pace as compared to tensile fatigue. This shows that the effect of cyclic loading in tensile-compression fatigue is more destructive than in tensile fatigue. Extra measures are needed in designing the forging tool in order to minimize the tensile-compression fatigue effect.

The highest constant stress amplitude applied in these fatigue tests of HSS SKH51 is 1820 MPa. This is much lower than the ultimate tensile strength (2680.18 MPa) and ultimate compressive strength (5920.58 MPa) of HSS SKH51. However, the fatigue test specimen of HSS SKH51 tested at 1820 MPa still fails at 1535 cycles despite the fact that the stress of cyclic loading does not go up to ultimate tensile and compressive strength. This proves that the HSS SKH51 forging tool is possible to fracture at a low stress level below the ultimate tensile strength and ultimate compressive strength. Fatigue caused by cyclic loading effect is thus a significant aspect in the design of forging process. The *S-N* curve obtained from these fatigue tests can acts as a general reference in the design to minimize the issue raised by fatigue of HSS SKH51 forging tool.

4.6 Simulation in ABAQUS

ABAQUS is a powerful and holistic FEA and FEM solution used to simulate the real life forging process. It is impossible to simulate for all types of forging processes available in the industry and so, clinching process is selected as an example in this project. When the clinching process is carried out by using SKH51 tool steel, tension and compressive stress may exist in the clinching punch and die. Stress analysis of clinching tools is important as these stresses may fail the HSS SKH51 clinching tools. As it can be noticed from the simulation results of both round and square clinching process, stress is mainly concentrated at the punch tip and die anvil. Low stress level (contoured in blue colour) is observed in the other regions of punch and die. These regions are subjected to a low cyclic stress and fatigue will hardly happen at these regions. This is the reason that fatigue and failure always happen at the punch tip and die anvil, but not the other regions of the clinching tools.

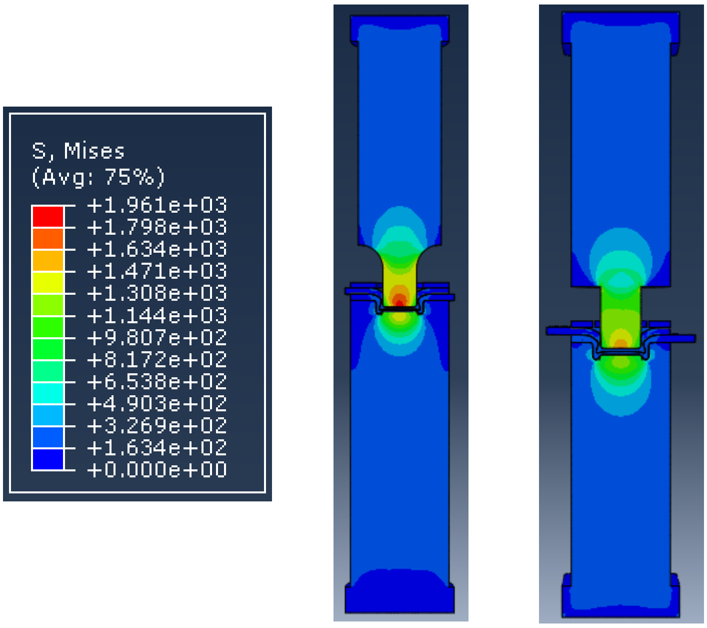


Figure 4.8: Stress Distribution in HSS SKH51 (a) Round (b) Square Clinching Tool.

High stress region is noted from the closer look (Figure 4.9) of both round and square clinching simulation results. The high stress region is located at the centre of the punch tip. The true stresses obtained from this high stress region are 1961.38 MPa and 1703.68 MPa for round and square punch respectively. These true stresses are apparently smaller than the ultimate tensile and compressive strength of HSS SKH51. The punches will not fail easily since they are still in the elastic region of HSS SKH51 when the clinching process is conducted. Care should be taken when the surface area of the punch tip is considered. The critical stress that the round and square punch can sustain are as high as 3.62 GPa and 2.84 GPa respectively. These critical stresses are obviously higher than the stress values obtained in these simulation results and buckling will hardly happen in these clinching punches. On top of that, fatigue is possible to happen at the stress level below the ultimate tensile and compressive stress, as it has been proved in the previous section. So, the tool life of round and square clinching tools should be predicted by using these true stresses to know more about its fatigue behaviour.

Figure 4.9 shows that the high stress region (contoured in red, orange and yellow colour) of square clinching punch is smaller than of round clinching punch. The region of die anvil contoured in yellow colour for round die is also observed, but there is no region contoured in yellow for die anvil of square die. The true stress value obtained from the simulation result for square punch (1703.68 MPa) is lower than for round punch (1961.38 MPa). All of these prove that a smaller stress level will be experienced by HSS SKH51 square clinching tools as compared to round clinching tools. This is because the surface area of square punch tip and die anvil is larger than of round punch tip and die anvil. When a force is exerted on a bigger surface area, a lower stress will be generated on the area. As an outcome, square clinching tools will not fail as frequent as round clinching tools since it is subjected to a lower stress level. The tool life of square clinching tools will be longer than round clinching tools as the cyclic stress applied on square clinching tools are smaller. In view of these, square clinching tools are suggested to be used in the clinching process if the shape of clinch joint is not significant for the clinching product.

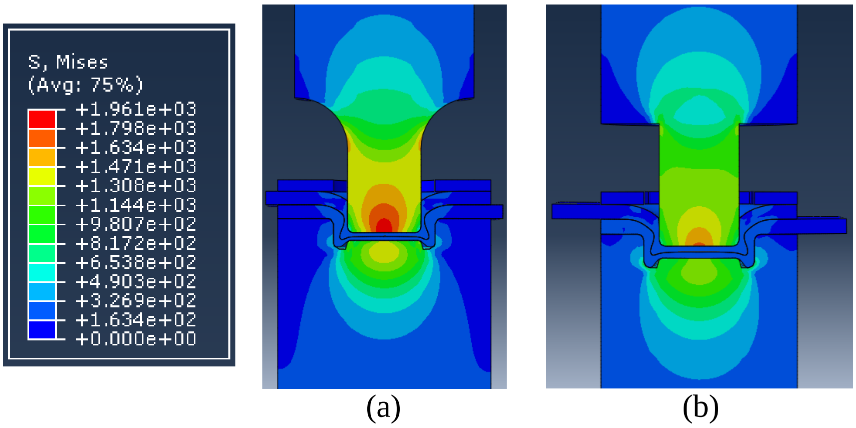
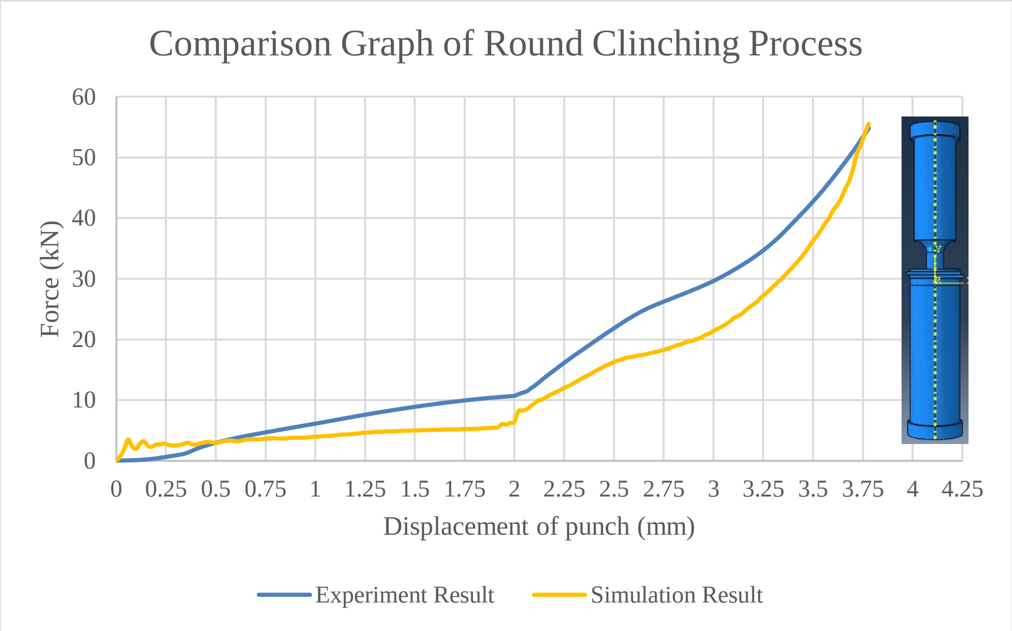
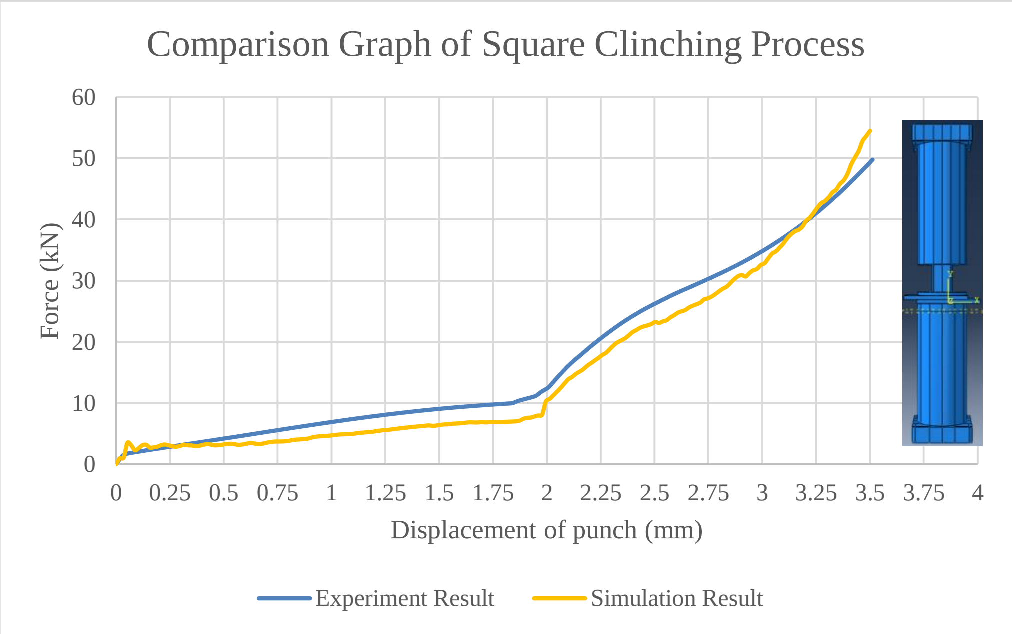


Figure 4.9: Closer Look of Stress Distribution in HSS SKH51 (a) Round (b) Square Clinching Tool.

The graphs of force experienced by the punch against displacement of punch are obtained from the simulation results of round and square clinching process. These graphs are compared with the graphs of load versus displacement of punch obtained from the clinching experiment. This comparison is done to verify the results obtained from ABAQUS simulation. If the graphs plotted from the simulation result is almost the same as the graphs obtained from the clinching experiment, the simulation models are said to have an accurate result. As it can be observed from Figure 4.10, both simulation results of round and square clinching process end at the force around 55 kN. The graphs obtained from simulation results are having the same trend as the graphs of experiment results. They are having a similarity of about 80 % and above. This validates the simulation results and the results are believed to be reliable. The values of true stresses obtained from these simulation models are accurate. These true stresses can next be used for tool life prediction of HSS SKH51 clinching tools.



(a)



(b)

Figure 4.10: Comparison Graph of (a) Round (b) Square Clinching Process.

4.7 Tool Life Prediction

The true stresses obtained from the ABAQUS simulation results are used in this section for tool life prediction of round and square clinching tools. These true stresses are the cyclic stresses exerted on the round and square clinching tools when clinching is conducted in the industry. They are the critical parameters that will fail and lead the tools to fatigue. This makes the fatigue life prediction of HSS SKH51 round and square clinching tools to be the main concern when the tools are subjected to these true stresses. The tool life prediction of round and square clinching tools is done by using two different prediction methods and the results are shown as below.

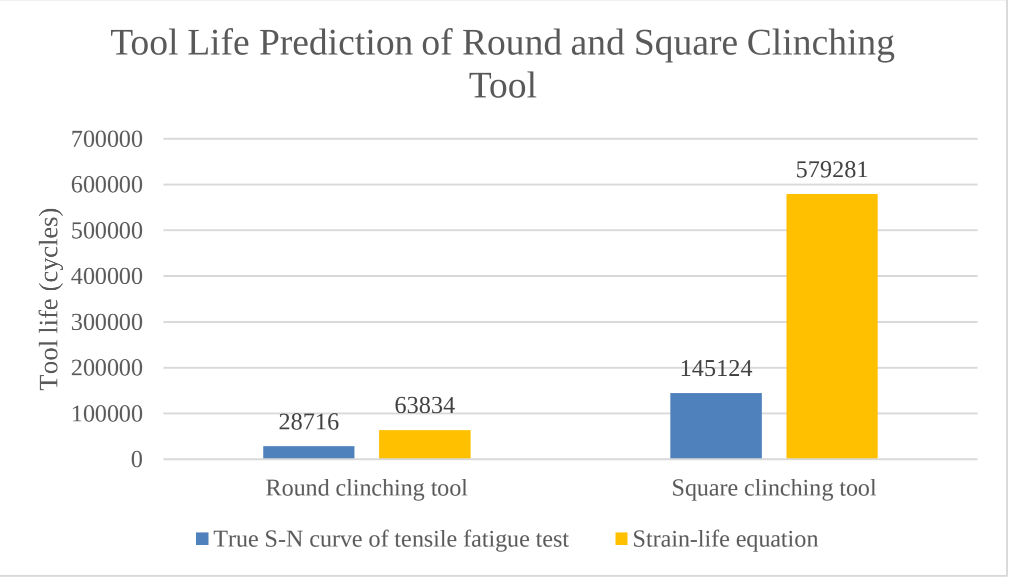


Figure 4.11: Tool Life Predicted from True *S-N* Curve of Tensile Fatigue Test and Strain-Life Equation.

Unsurprisingly, in both of the prediction methods, the tool life predicted for square clinching tools is longer than for round clinching tools. This is because the true stress exists in square clinching tool is lower than in round clinching tool. Less plastic deformation is generated and the crack will propagate slower when a smaller cyclic stress is applied in square clinching tool. This causes the square clinching tool to have a longer tool life as compared to round clinching tool. The tool life predicted for square clinching tool is more than five times of the tool life predicted for round clinching tool. This shows that the square punch and die is having a better fatigue behaviour than round punch and die. Due to this finding, it is again proven that square clinching tool should be used in the industry instead of round clinching tool if the shape of clinch joint is not a significant parameter for the clinching product.

By comparing the results obtained from both prediction methods, the tool life predicted from strain-life equation is much higher than from true *S-N* curve of tensile fatigue test. Since clinching is generally a compression process, it has been mentioned previously that the prediction done by using true *S-N* curve of tensile fatigue test is less accurate. The result obtained from this method is only a general reference and it is not accurate enough for the prediction of clinching tool life. Conversely, some monotonic properties obtained from compression test of this project, such as true compressive fracture stress and fracture strain, are included in the strain-life equation. The actual compressive fatigue behaviour will be represented comprehensively when the monotonic properties obtained from compression test are used to calculate for the M-C and R-O parameters in strain-life equation. From this strain-life equation that fully represents the real compressive fatigue behaviour of HSS SKH51, a more accurate fatigue life of HSS SKH51 clinching tools can be predicted. This results in a longer tool life predicted for round and square clinching tools that is believed to be more accurate. It can be concluded that the tool life predicted from both methods are correct, but the results obtained from strain-life equation is having a higher accuracy.

The highest constant stress amplitude applied in tensile fatigue test discussed previously is 1820 MPa, which is equivalent to a true stress of 1834.24 MPa, and it results in a number of cycles to failure of 1535 cycles. The true stress exists in the round clinching tool is 1961.38 MPa and its tool life predicted from strain-life equation, which represents the actual compressive fatigue behaviour of HSS SKH51, is 63 834 cycles. The tool life predicted from strain-life equation is about 41 times larger than the number of cycles obtained in tensile fatigue test even though the true stress applied on round clinching tool is higher than on tensile fatigue test specimen. This shows that the compressive fatigue behaviour of HSS SKH51 is better than its tensile fatigue behaviour. HSS SKH51 possesses a remarkable fatigue behaviour and long tool life if it is used as the tool steel in the forging process, which is generally a compression process. This makes HSS SKH51 suitable to be used for a wide range of forging processes with its excellent fatigue behaviour.

4.8 Summary

All the results obtained from the methodologies have been presented and discussed thoroughly in this chapter. HSS SKH51 is a forging tool steel that possesses high hardness and strong mechanical properties. HSS SKH51 has a high ultimate compressive strength, which is an advantage for it to be a forging tool steel. It will only buckle at a high critical load when compressive force is subjected on it. HSS SKH51 specimen tested in tensile fatigue test has a longer life to failure than in tensile-compression fatigue test. Simulation of round and square clinching process has also been done by the mean of FEA solution in ABAQUS. Lower stress level is observed from the simulation result of HSS SKH51 square clinching tool. Tool life of both HSS SKH51 round and square clinching tool is predicted by using two different methods. The result obtained from strain-life equation is found to be more accurate and reliable. From that result, it has been proven that HSS SKH51 has a good fatigue behaviour and long tool life in forging and clinching process.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

All in all, the fatigue behaviour of HSS SKH51 in forging process has been studied in this project. The general knowledge of properties of HSS SKH51, forging processes, fatigue behaviour of a material and tool life prediction have been introduced. The researches done by other researchers have also been reviewed in this study. Methodologies have been planned in detail and carried out accordingly to achieve the aim and objectives of the current project. Results obtained from all the methodologies have been discussed to gain more knowledge about the suitability of using HSS SKH51 as the forging tool.

Various testing including hardness test, tensile and compression tests and buckling test have been done to achieve the first objective of this project. HSS SKH51 is found to have excellent mechanical properties. It has a high hardness of HRC 61.1, high ultimate engineering compressive strength of 5920.58 MPa and high critical load of 120 kN. This makes it suitable to be used as the tool steel in a lot of forging processes including clinching process.

To fulfil the second objective of this project, tensile fatigue and tensile-compression fatigue tests have been conducted. A long fatigue life is observed from the result of tensile fatigue test of HSS SKH51. Endurance limit of tensile fatigue of HSS SKH51 is defined as 780 MPa. The combine effect of tensile and compression cyclic loading on HSS SKH51 will result in a shorter number of cycles to failure.

The third objective of this project can be achieved by doing the simulation of round and square clinching process in ABAQUS. HSS SKH51 square clinching punch and die are subjected to a lower stress level (1703.68 MPa) as compared to HSS SKH51 round clinching tool (1961.38 MPa). In view of this, square clinching tool will not fail easily under the effect of low cyclic stress and fatigue.

Tool life prediction is done by using two different methods to attain the fourth objective of the current project. Strain-life equation is having a more accurate prediction on the tool life as compared to the prediction obtained from true *S*-*N* curve of tensile fatigue test. The tool life predicted for HSS SKH51 round and square clinching tool from strain-life equation is 63 834 and 579 281 cycles respectively. This proves that HSS SKH51 is having an excellent fatigue behaviour in forging process.

It can be concluded that HSS SKH51 is suitable to be used as the forging tool as well as clinching tool due to its excellent mechanical properties and outstanding fatigue behaviour. Simulation in ABAQUS and tool life prediction are done for clinching process. HSS SKH51 square clinching tool is recommended to be used in the industry since it is subjected to a lower cyclic stress and having a longer tool life as compared to HSS SKH51 round clinching tool. All the aim and objectives of this project have been achieved successfully.

5.2 Recommendations for Future Work

Due to the time constraint, compression fatigue test is unable to be done in the current project. Even though compression fatigue usually possesses a higher number of cycles to failure and its effect is not as critical as tensile and tensile-compression fatigue, it should still be done in the future work since forging is generally a compression process. The life to failure of compression fatigue is still an interest in studying the fatigue behaviour of HSS SKH51 forging tool.

Since the simulation models built in ABAQUS have been validated, the result obtained from these models is highly accurate. Future work can be done by altering some design of these models to predict for the behaviour of HSS SKH51 clinching tool with other considerations. Same thickness and same material properties are set for the metal sheets that are going to be clinched in the current models. In the future work, the thickness of the metal sheets can be altered such that one sheet will be thicker and another will be thinner. Two different material properties can also be set for the top and bottom metal sheets accordingly. The effect of these alterations on the stress distribution of HSS SKH51 clinching tool can be obtained from the simulation result.

The dimension of punch tip and die anvil can be redesigned in the simulation models too. This is done to reduce the true stress exists in the clinching tool and the result of this improvement can be obtained by running the simulation. Besides from tool design and mechanical properties, chemical properties such as corrosion may also have an effect on the fatigue behaviour of HSS SKH51. The chemical properties of HSS SKH51 can be added into the material properties of these models to simulate the effect on the clinching tool.

All of these changes in the simulation models can be made in the future work. The effect of these changes on the HSS SKH51 clinching tool can be obtained from the simulation result in a faster and cost-saving manner. This will help in exploring more possibility for the application of HSS SKH51 clinching tool.

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APPENDICES

APPENDIX A: Figures

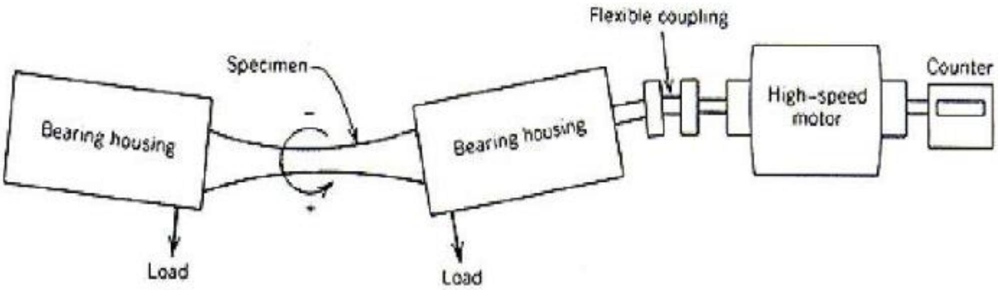


Figure A-1: Rotating Bending Testing Machine. (Azeez, 2013)

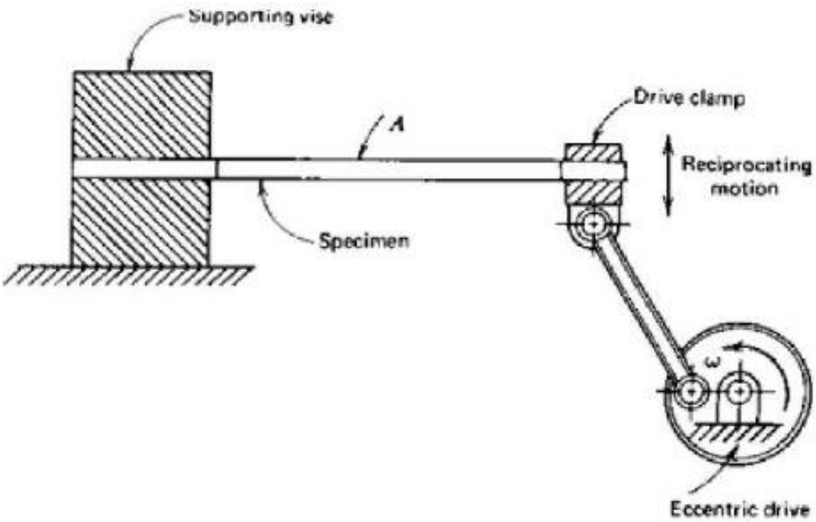


Figure A-2: Reciprocating Bending Testing Machine. (Azeez, 2013)

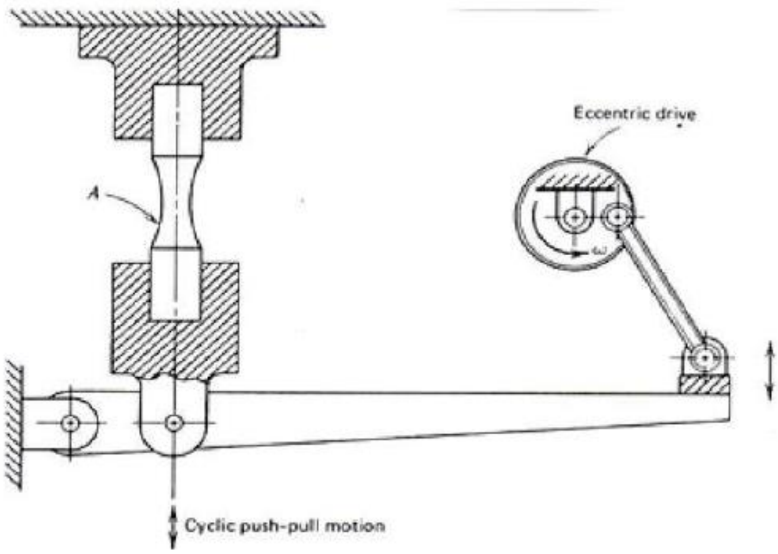


Figure A-3: Direct-Force Fatigue Testing Machine. (Azeez, 2013)

Figure A-4: Rockwell Hardness Tester.

Figure A-5: Instron 5582 Universal Tester.

Figure A-6: 60 Tons Toyo Hydraulic Press.

(a) (b)

Figure A-7: (a) Round Clinching Tools (b) Square Clinching Tools.

Figure A-8: Shimadzu Servo-Hydraulic Universal Testing Machine.

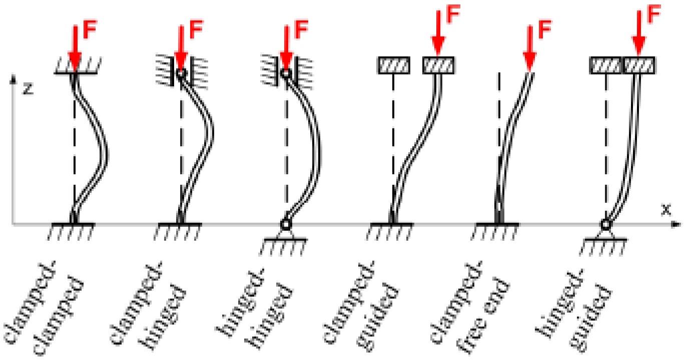
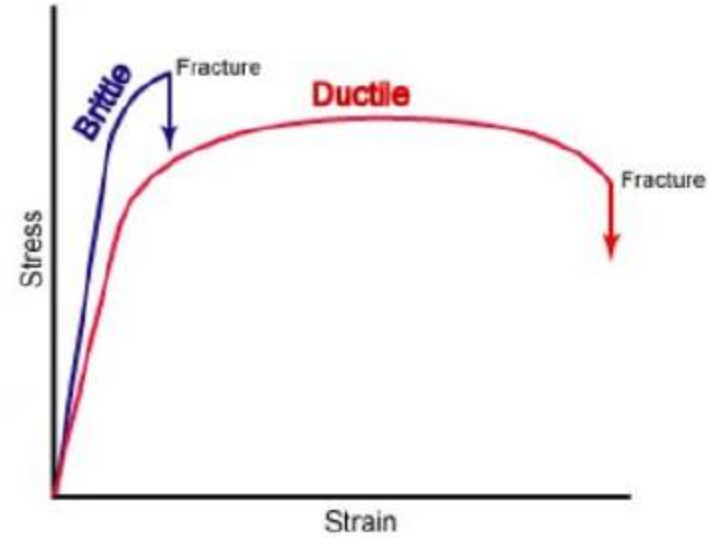


Figure A-9: Failure Pattern of Buckling. (Klimchik, 2011)

APPENDIX B: Graphs



Graph B-1: Engineering Stress-Strain Curve of Brittle and Ductile Material. (Cabrera, 2018)

APPENDIX C: Design of Clinching Tools

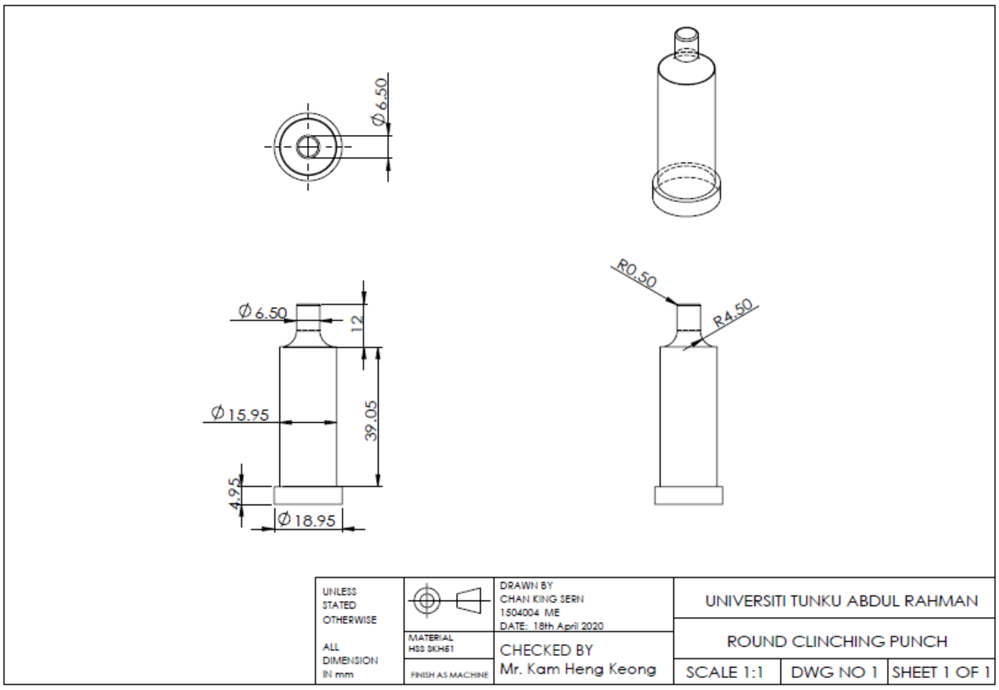


Figure C-1: Dimension of Round Clinching Punch.

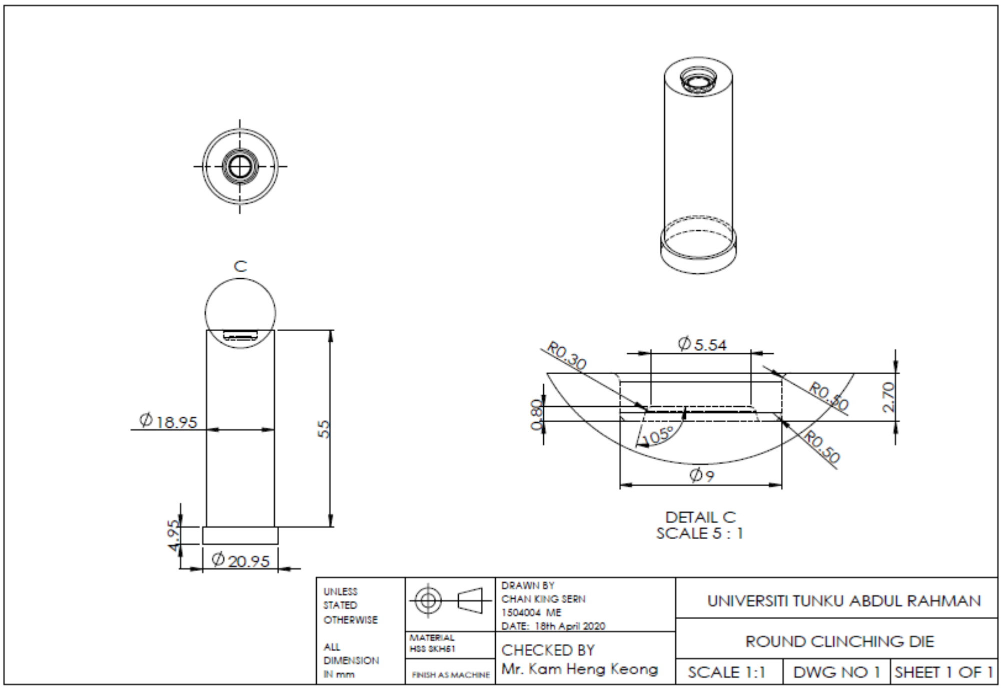


Figure C-2: Dimension of Round Clinching Die.

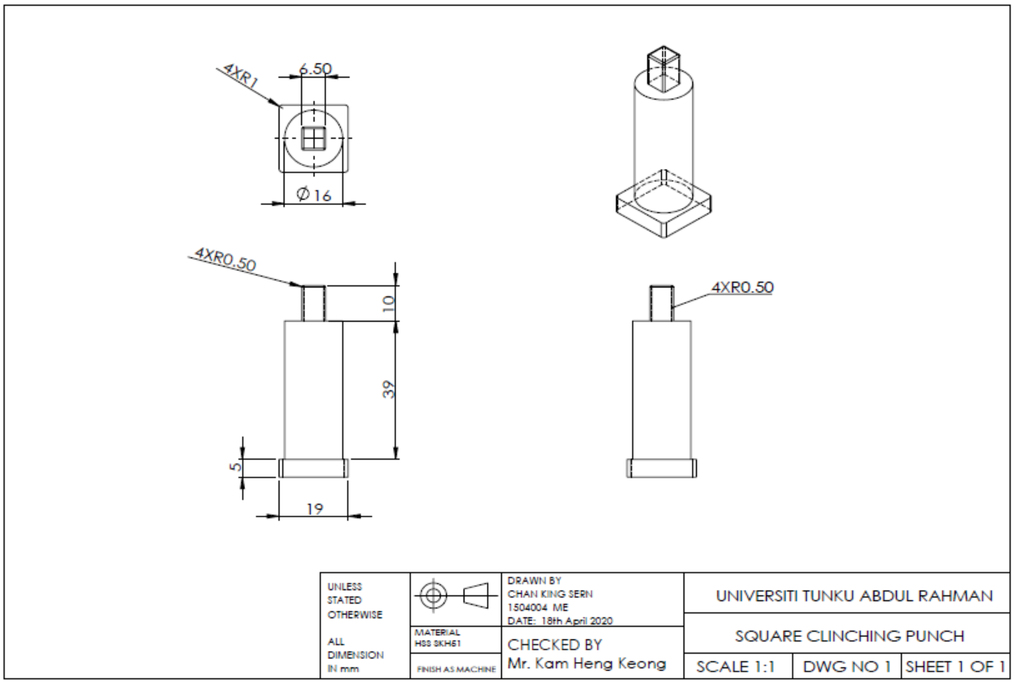


Figure C-3: Dimension of Square Clinching Punch.

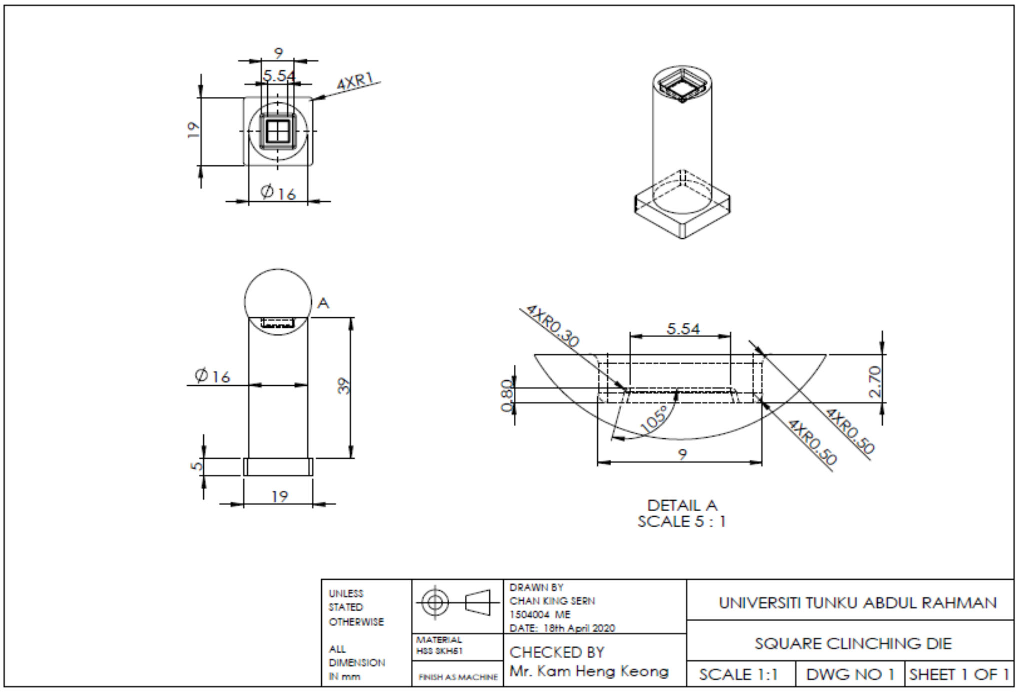


Figure C-4: Dimension of Square Clinching Die.