DEVELOPMENT OF A LOW POWER MICRO-SHEET-FORMING MACHINE FOR MICRO-PRODUCTS PRODUCTION

AKHTAR RAZUL RAZALI

FINAL REPORT

RDU 160355

ACKNOWLEDGEMENT

The researchers would like to address their gratitude to the Universiti Malaysia Pahang for the financial assistance through RDU 160355. Special thanks also go to Mr. Chang Tai Ann, who is very dedicated to keep this project running and successfully graduated his Master Degree. Not to forget, to those helpful teaching engineers, Mr. Aziha, Mr. Asmizam, Mr. Rozikin and Mr. Hafietz for their trust (for the machineries usage), support and helpful advice whenever they were needed. Many thanks too to those who contributed towards this project directly and indirectly.

Finally, to the team, special and warm thanks for the commitment shown to drive this project to success. Without everyone's contribution, this project will never see this happy ending.

ABSTRAK

Permintaan yang meningkat terhadap mikro-produk telah mendorong perkembangan pesat dalam teknologi pembuatan mikro bagi bahagian-bahagian individu dan sistem, yang merangkumi pembangunan baru proses pembuatan, peralatan dan jentera. Banyak usaha yang telah dilakukan hingga kini untuk meningkatkan kecekapan teknologi pembuatan miniatur/ mikro. Walau bagaimanapun, tidak banyak kajian yang dilakukan terhadap penjimatan tenaga semasa pemprosesan bahan. Pengurangan saiz bahan yang diproses dijangka akan turut mengurangkan penggunaan tenaga secara berkadaran dengan skala miniatur. Fokus kajian ini adalah untuk merekabentuk mesin penghasil kepingan mikro yang menggunakan tenaga dalam kuantiti yang rendah bagi tujuan aplikasi pembentukan kepingan logam yang nipis, dan membina mesin penghasil kepingan mikro yang menggunakan arus terus dengan kuasa yang rendah. Di samping itu, kajian ini bertujuan mengukur dan menganalisis keupayaan dan kualiti mesin yang dibina. Beberapa konsep telah dihasilkan dan dinilai dengan melakukan analisis Kaedah Unsur Terhingga (Finite Element Method) dan perbandingan bahan-bahan. Konsep optimum telah dipilih untuk membangunkan reka bentuk yang terperinci. Pembinaan dan pemasangan mesin dilakukan berdasarkan reka bentuk konsep yang telah dipilih. Satu prototaip yang mempunyai sistem penggunaan tenaga yang rendah bagi mesin penghasil kepingan mikro merangkumi elemen-elemen mekanikal dan elektronik telah dibangunkan. Prestasi mesin ini telah diuji dari segi frekuensi asli, daya tebukan, kelajuan dan keupayaan penebukan, penggunaan tenaga (tebukan tunggal dan berdasarkan kekerapan masa). Mesin ini didapati mampu melakukan proses penghasilan kepingan mikro dalam satu peringkat tunggal untuk membentuk bahagian-bahagian kepingan logam yang nipis dengan ketebalan kurang daripada 100 mikron. Selain itu, mesin ini juga berkeupayaan menghasilkan sehingga 600 lejang seminit, dengan kapasiti daya sebanyak 320 N. Sejumlah 0.0038 Wh tenaga telah digunakan oleh mesin ini untuk menghasilkan satu bahagian tunggal. Oleh yang demikian, dapatlah dirumuskan bahawa kajian ini telah berjaya membangunkan sebuah mesin penghasil kepingan mikro yang menggunakan tenaga yang rendah bagi aplikasi pembentukan kepingan logam yang nipis.

ABSTRACT

Increased demands for micro-products have led to rapid development of micro-manufacturing technologies in the manufacture of individual parts and systems, which includes development of new manufacturing processes, tools and machinery. Tremendous efforts have been made, to date, to improve the efficiency of miniature-/ micro-manufacturing technologies. However, there has been lack of research on energy saving during which materials are being processed. It is expected that with the miniaturization of materials being processed, energy consumption is also being 'miniaturized' proportionally. The focus of this study was to design a low energy micro-sheet-forming machine for thin sheet metal application and fabricate a low direct current powered micro-sheet-forming machine. In addition, the research aimed to quantify and analyze the capability and quality of the fabricated machine. Several concepts were generated and these were evaluated by performing Finite Element Method (FEM) analysis and materials comparison. An optimal concept was selected to develop a detailed design. Fabrication and assembly of the machine was made according to the selected conceptual design. A prototype of low energy system for a micro-sheet-forming machine that included mechanical and electronic elements was developed. The machine was tested for its performance in terms of natural frequency, punching forces, punching speed and capability, energy consumption (single punch and frequency-time based). The machine was capable of single stage of micro-sheet-forming processes for thin sheet metal parts with thickness of less than 100 μm. Furthermore, it was also capable of producing up to 600 strokes per minute, with force capacity of 320 N. The energy consumption for the machine to produce a single part was 0.0038 Wh. Thus, it can be concluded that this research has successfully resulted in the development of a low energy micro-sheet-forming machine for thin sheet metal forming application.

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LIST OF SYMBOLS

Ra	Average roughness
Ah	Charge
I	Current
Ω	Electrical resistance measured in Ohms
F	Force
Hz	Frequency measured in hertz
k	Kilo
L	Length
Rz	Mean roughness depth
µm	Micrometer
V_m	Min. Volts
N	Newton
A_p	Peak Amps
W_p	Peak Watts
P	Power rating
V_o	Tapped density
T	Thickness
t	Time consumed measured in seconds
V	Voltage measured in volts
W	Watt
Wh	Watt-hour

LIST OF ABBREVIATION

AC	Alternative current
AFM	Atomic force microscopy
CNC	Computer numerical control
CVD	Chemical vapour deposition
DAQ	Data acquisition
DC	Direct current
ECM	Electrochemical machining
EDM	Electrical discharge machining
EMF	Electro-magnetic filter
FEM	Finite element method
FFT	Fast fourier transform
FRF	Frequency response function
FSR	Force sensitive resistor
LIGA	Lithographie, Galvanoformung, Abformung
MEL	Mechanical engineering laboratory
MEMS	Micro-electro-mechanical systems
NSOM	Near-field scanning optical microscopy

SEM	Scanning electron microscopy
STM	Scanning tunnelling microscopy
PVD	Physical vapour deposition
PZT	Lead zirconate titanate
UTS	Ultimate tensile strength
TEM	Tunnelling electron microscopy

CHAPTER 1

INTRODUCTION

1.1 Research Background

There have been significantly increased demands for the micro-electronic mechanical systems (MEMS) and micro products/ parts in general as a result of fast growth in telecommunication applications. The value of this market was worth USD 197.6 billion in 2005 and anticipated to reach more than USD 492.3 billion in 2016. Wide applications are also seen in biomedical technology, information technology and automotive engineering. For example, typical micro-parts can be formed using micro-forming technology are the connecting pins. They are widely used in computers, communication devices and other electronic products. Together with other micro-products, they shared a market value of USD 45 billion in 2003 and enjoyed an annual growth rate of 20% (Wood, 2005). Increased demands for micro-products have also led to rapid development of micro-manufacturing technologies for the manufacture of individual parts and systems, which includes development of new manufacturing processes, tools and machinery. Currently, the manufacturing technologies, however, still largely rely on the techniques based on the removal of the materials, either by chemical or thermal or mechanical means. Tremendous efforts have been made, to date, to improve the efficiency of miniature-/ micro-manufacturing technologies (Qin et al, 2010; Razali et al, 2011). However, these have not resulted in a radical change in the technologies. Therefore, miniature/ micro-manufacture is still seen as an 'expensive' and 'wasteful' business. Conversion of miniature/micro-materials into engineering products by high-rate plastic deformation (micro-forming) would address two key issues which are of particular importance for the industry, namely, reduction of manufacturing costs and improvement of product quality (Qin et al, 2008; Razali et al, 2009). Besides, the need is proportional to the complexity of forming miniature-/ micro-materials which requires good understanding of machines and processes at micro-scale.

1.2 Problem Statement

Almost all aspects of micro-factory development have been as such because such development is based on a consideration that conventional facilities for manufacturing miniature-/ micro-products are not compatible, in size, to the products to be made in miniature-/micro-manufacturing. Therefore, it is necessary to reduce the scale of the machinery and auxiliary equipment which could correspondingly reduce energy consumption and materials requirement, as well as pollution which eventually create a more user-friendly environment for production. In fact, the present conventional micro-machineries are still big and bulky to produce small-parts/ micro-parts. Big machineries usually consume huge amount of energy to produce small parts, and this is not ideal for the environment. Hence, production of small-parts/ micro-parts has yet to fully embrace the "green" manufacturing concept although the demands for micro-parts production have increased exponentially.

Significant efforts in this field have been devoted to achieving the goals of green manufacturing. With regard to miniature-/ micro-manufacturing, a research group at the University of Strathclyde has developed a micro-sheet-forming machine with proven capability of producing miniature-/ micro-products (Qin et al, 2008). The machine is actuated by a linear motor. Stamping force of 5 kN at a speed of 14 Hz stamping operation has been achieved. The machine consumes 415 VAC of power supply for the actuation system to work. The success story of the University of Strathclyde Research Group however still lacking in terms of effort to tackle energy conservation during the production of the micro-parts. It is expected that with the miniaturization of materials being processed, energy consumption is also being 'miniaturized' proportionally. Miniaturization of materials with a scale of 100:1 of parts, could also possibly mean that the miniaturization of energy may well be achieved using the same ratio.

Thus, this research embarked on a mission to address the unresolved issue of producing micro-parts with low energy consumption. Undoubtedly, a low energy micro-sheet-forming machine which can anticipate saving hundred times less energy than its conventional counterpart is practically a direct solution to the problem of energy conservation in miniaturization process.

1.3 Research Objectives

The research objectives of the present study were as follows:

a. To design a low energy micro-sheet-forming machine for thin sheet metal application;
b. To fabricate a low direct current powered micro-sheet-forming machine; and,
c. To quantify and analyses the performance of the fabricated machine for a thin-sheet-forming application.

1.4 Research Hypotheses

It is expected that a low direct current powered micro-sheet-forming machine with solenoid actuation would be able to be produced at the end of the research. With the low energy actuation, the machine was anticipated to be able to save hundred times less energy than its conventional counterpart in miniature process. Solenoid actuation was proposed as one of the promising solutions to be used for low energy micro-sheet-forming machine development. With rated power at approximately 12 to 24 VDC, the solenoid would be capable of producing thousands of Newton force over acceptable travel distance. Solenoid can be powered by using step-down transformer and controlled using Arduino microprocessor. This has been viewed as a practical solution to miniaturize the energy usage while performing sheet forming process.

1.5 Research Scope

The scope of this research was confined to the following:

a. The development of a machine with stamping capacity of no more than 100 micron thick sheet metal.
b. The use of only direct current electricity for actuation and functioning of the fabricated machine.
c. The limitation of the application to micro-sheet forming operation.

1.6 Gantt Chart

The planning and actual stages of the present research are depicted in the Gantt chart attached in Appendix A of this thesis.

1.7 Research Plan

Fundamental studies and analysis were conducted in the initial stage of study. These include the following: Validation of the micro-sheet-forming process and product-characteristics, and the definition of the specifications required for high-speed forming in micro-sheet-forming, which comprised the development of a classification methodology for high-speed forming considerations; investigation of sheet forming fundamentals to address mass-production requirements, particularly issues related to precision and production rates, which involved participation in forming experiments together with other researchers within the micro-manufacturing research group; qualification of thin-sheet-metal forming methods, processes and equipment for the forming of micro-products, which involved communication with other organizations/ collaborators, simulation experiments and bench-marking. In the light of the foregoing, a methodology for the design of a high-speed forming system for micro-sheet-forming was developed.

Development of new thin sheet system forming concepts for micro-sheet-forming applications was carried out. This included the development of conceptual design models, and analysis methods for assessment. The concept was optimized and the optimal concept was then selected. Detailed design was carried out based on the optimal concept. A prototype of a low energy machine system for a micro-sheet-forming that included mechanical and electronics elements was fabricated. The prototype of the high-speed sheet-forming system was tested, optimized and enhanced with reference to micro-sheet-forming requirements. For this purpose, control to enable synchronization of the machine system was performed. The integrated system was tested with the forming of engineering micro-products. Finally, research entered its end stage which was the completion of the thesis writing process and publications. The flow chart of the research plan is shown in Figure 1.1.

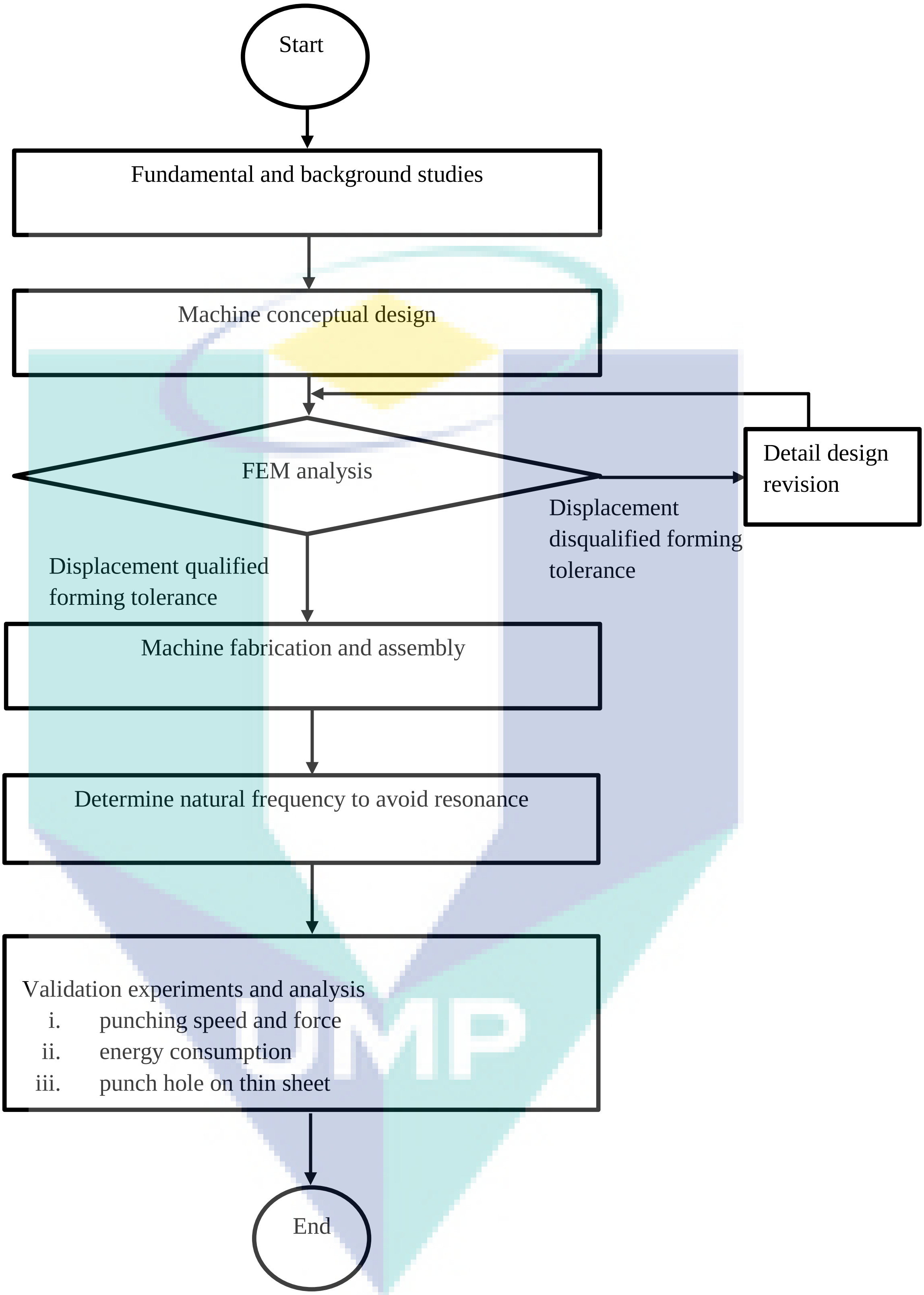


Figure 1.1 Flow chart.

1.8 Structure of the Thesis

In this section, the outline of the thesis, which is structured in seven chapters, is provided. Chapter 1 provides the background of study of this research. The focus concerns the ways in which the understanding of micro-manufacturing technologies trend is shared. Next, the chapter discusses the development of micro-manufacturing with examples of efforts made. The problem statement and objectives of this study are also clearly stated in this chapter.

Chapter 2 covers the review of literature, exploring the fundamental studies on micro-manufacturing, thin sheet metal and sheet forming process. It begins by explaining micro-manufacturing, micro-parts/ products in general. This is done by giving the definition of the terms and also highlighting examples of previous efforts carried out globally. It is then followed by focusing the general manufacturing processes onto one interested manufacturing process which is stamping process. Definition of the stamping is given by highlighting the process parameters. This is followed by examples of stamping machines developed to serve micro-stamping operation. At the end of this chapter, issues related to the field itself are critically examined and summarized.

Chapter 3 presents the development of new thin sheet system forming concepts for micro-sheet-forming applications, which include the development of conceptual design models, FEM analysis methods for assessment. This chapter describes how the concept is optimized and an optimal concept is selected. Detailed design carried out based on the optimal concept is illustrated. The fabrication of a prototype of a low energy machine system for a micro-sheet-forming that includes mechanical and electronics elements is described. The modal analysis performed on the prototype of micro-sheet-forming machine to determine the natural frequency is displayed in Chapter 4.

The performance of fabricated machine was tested with several approaches. Each of these approaches is described separately in individual chapters with its particular methodology, results and discussion. In Chapter 5, the details of description of the testing of energy consumption of the low energy micro-sheet-forming machine and the results are presented. The calculation of the minimum energy consumption to produce single part is also demonstrated. In addition, verification of the speed of forming machine is also made in this chapter.

In Chapter 6, the punching performance of micro-sheet-forming machine is described. The relation between punching force and supply voltage studied, that includes the punching force of forming machine which is controllable by variation of voltage supply, is also shown. Additionally, the performance of hole punching on thin sheet metals is also illustrated in this chapter as well. The results indicating the capability of the machine to perform hole punching on thin sheet metal with thickness of below 100 micron are presented and discussed.

Finally, Chapter 7 provides the s the conclusion of the research achievement, and ends with recommendations for future studies on low energy micro-sheet-forming machine for thin sheet metal application

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is purpose to present the review of literature, exploring the fundamental studies on micro-manufacturing, thin sheet metal and sheet forming process. It begins by explaining micro-manufacturing, micro-parts/ products in general. Definition of the terms is given and also highlighting examples of previous efforts carried out globally. It is then followed by focusing the general manufacturing processes onto one interested manufacturing process which is stamping process. Definition of the stamping is given by highlighting the process parameters. This is followed by examples of stamping machines developed to serve micro-stamping operation. At the end of this chapter, issues related to the field itself are critically examined and summarized.

2.2 Micro-Manufacturing in General

Micro-manufacturing engineering is a general term which concerns a series of relevant activities within the chain of manufacturing micro-products/features, including design, analysis, materials, process, tools, machinery, operational management methods and system. The term 'micro-manufacturing concept' within the context of a miniature factory is understood to be a micro-factory and it is a relatively new concept concerning manufacturing systems. A micro-factory can be defined as a small manufacturing system conceived as a means of achieving higher throughput with less space and reduced consumption of both resources and energy via downsizing of production processes (Claessen and Codourey, 2002). In other words, all of the machines/ equipment have necessarily to be reduced to the micro-scale which may, not only reduce the energy consumptions, but also the preliminary and overhead costs, and materials requirements, along with reduction in pollutions and thus creating a more user-friendly environment for production.

The forming of small parts/ micro-parts is not new, as industry has experienced this for many years. The effect of miniaturization of production systems was studied by a research group from the Mechanical Engineering Laboratory (MEL), Tsukuba Japan in 1990. The estimation made was that with a 1/10 size reduction of production machines, it resulted in approximately 1/100 energy reduction compared to that of the conventional factory. Micro-manufacturing has the most significant advantage that is capable of producing parts which have feature sizes of less than 100µm (Byung et al., 2005; Chern and Renn, 2004; Chern et al., 2006; Qin et al., 2008), or slightly greater than the thickness of a human hair. At this scale, the slightest variation in the manufacturing process which can be caused by material or cutting tool characteristics, vibration and any number of minute changes, thermal variations in the machine, will have a direct impact on the ability to produce features of this type on a production scale (Shanahan, 2006).

2.2.1 Micro-Parts & Components

Typical micro-products including MEMS and micro-system are used in automotive and aerospace engineering such as thermal sensors, temperature sensors, pressure sensors, gas sensors, rate sensors, sound sensors, and injection nozzles, and the components comprise those used in magnetic, electrostatic, pneumatic and thermal actuators, motors, valves and gears. Furthermore, such products are also used in micro-heat exchanger, sensor for mass flow, micro-chemical reactors, and tools/ molds for forming. Apart from these uses, the components are made parts of those for miniaturized electronics products such as mobile phone, MP3 player, and CD players. In medicine, the micro-fabricated parts can be found in a wide range for implantable applications in various clinical areas. Some typical examples are sensors for cardiovascular, micro-machined ceramic packages, and implantable devices. Thus, it is fair to say that micro-products/ components are almost everywhere in our lives (Qin, 2010).

A meso-part is defined as a part that is greater than a few millimetres in size (as a reference, the meso-domain is defined as products fitting in a box of 200 × 200 ×200 mm^3) (Kolesar et al., 2000). However, although part-features may be in the micro-meter range, a micro-part is concerned with small parts with typical part-dimensions in the range of sub-millimetres up to a few millimetres, The typical positional precision for such parts is expected to be in the range between 0.1 and 10 µm. The micro-domain allows for, and sometimes demands, the application of methods and techniques that cannot be applied in the meso-domain. Fig. 2.1 shows the range of part- and feature-size machining capability. Miniature parts are known as parts with machined features beyond 100 µm, whereas a maximum size of less than 5 mm can usually be found in MEMS applications.

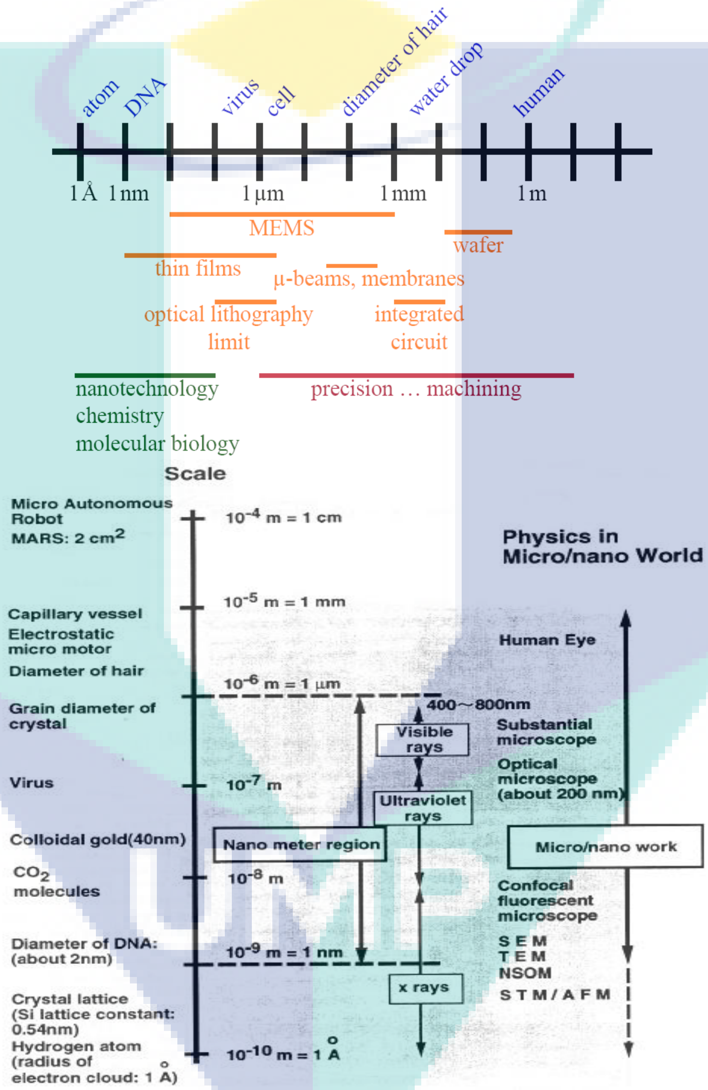


Figure 2.1 Parts scales and dimensions.

Source: Kolesar et al. (2000)

2.2.2 Micro-Manufacturing Methods and Processes

Micro-manufacturing can be defined as "manufacture of micro-products/features with scaled-down conventional processes/technologies" (Qin, 2010). These processes include micro-machining (e.g., mechanical, thermal, electrical-chemicals, and electrical discharge method), micro-forming/ replication, micro-additive (e.g., rapid methods, electron forming, injection molding) and joining. Micro-products have been produced by both conventional and non-conventional methods. Moreover, there are also emerging methods, such as hybrid manufacturing methods, which combine two or more processes together (Chern et al., 2004). According to the methods in which products are to be made, general manufacturing processes can also be classified into subtractive, additive, forming, joining and hybrid processes. The classification of conventional processes is equally applicable to micro-manufacturing. Typical micro-manufacturing processes are shown in Table 2.1.

Table 2.1 Typical methods/processes in micro-manufacturing

Process	Description
Subtractive processes	Micro-Mechanical Cutting (turning, polishing, grinding, milling, etc.); Laser Beam Machining; Micro-ECM; Micro-EDM; Photo-chemical-machining; Electro Beam Machining; etc.
Additive processes	Surface coating (CVD, PVD); Micro-injection moulding; Micro-casting; Chemical deposition; Sintering; Direct writing (ink-jet, laser-guided); Photo-electro-forming; Polymer deposition; Stereolithography; etc.
Deforming processes	Micro-forming (stamping, forging, bending, extrusion, incremental forming, deep drawing, superplastic forming, hydro-forming, etc.); Hot-embossing; Micro/Nano-imprinting; etc.
Joining processes	Micro-Mechanical-Assembly; Resistance; Laser-welding; Laser; Bonding; Vacuum Soldering; Gluing; etc.
Hybrid processes	Micro-Laser-ECM; Shape Deposition and Laser machining; LIGA and LIGA combined with Laser-machining; Micro-EDM and Laser assembly; Efab; Micro assembly injection moulding; Laser-assisted-micro-forming; Combined micro-machining and casting; etc.

Source: Qin (2009)

2.2.3 Micro-Manufacturing Machines/ Tools

Currently, conventional manufacturing in the area of machinery and processes have experienced extensive and rapid development of micro-manufacturing technology.

Numerous researchers and relevance companies have contributed to this continued development by proposed and developed the micro-machine concept.

Japanese researchers and industries were leading the research in micro-manufacturing by focus more on assembly and conveyance processes in the initial stage of micro-manufacturing development (Mishima et al., 2002; Suda et al., 2000; Brussel et al., 2000). Similar development works have performed successfully by European countries, such as Project Miniprod developed by Gaugel et al. (2001). This was later expanded to include the work of the mini-production system by Klocke Nanotechnik (Klocke et al., 2003). The micro-factory uses a nano-robotics module with a repeatability of 50nm. The plant can be a combination of different modules such as force sensors, wafer probers, manipulators, vacuum-grippers and micro-grippers. All of the development works mentioned involved a gluing process, the transportation of parts and a multi-degree-of-freedom assembly process which was realized by various types of micro-manipulators.

Development of micro-manufacturing was focused on the down-scaling of conventional milling and turning processes in the year 2000, and once again was led by the Japanese researchers (Okazaki et al., 2004). For example, the Mechanical Engineering Laboratory, under the National Institute of Advanced Industrial Science and Technology, known as AIST, succeeded in equipping a micro-lathe with a precision digital-control system in the year 2000. In order to give it real machine-tool functionality as depicted in Fig. 2.2 below, it uses a pair of micro-sliders based on a unique step-feed configuration driven by PZT actuators, and a spindle unit mounted on the orthogonally-stacked micro-sliders. For numerical control, the displacement of each slider is detected using an embedded micro linear-encoder with 62.5 nm resolution developed by the Olympus Corporation and fed back to the servo-controller. A single-board custom numerical-controller processes the part programs and feeds the servo-controller with command pulse trains yielding 0.1 µm resolution. The total desktop footprint is approximately 550 ×450 mm.

Figure 2.2 Micro lathe with numerical control.
Source: Okazaki et al. (2004)

The machine has produced good machining results which exceed the standard of ISO 4287/1E (Davim et al., 2005). Turning a brass rod, the surface roughness of the cylinder in the base-line direction and the roundness error were measured as 0.5µm Rz or 60nm Ra, and smaller than 0.5µm, respectively. These values are better than those of the original micro-lathe, and are comparable to those from regular-sized machines. NC motion-control enables programmed shape-generation, as shown in Fig. 2.3.

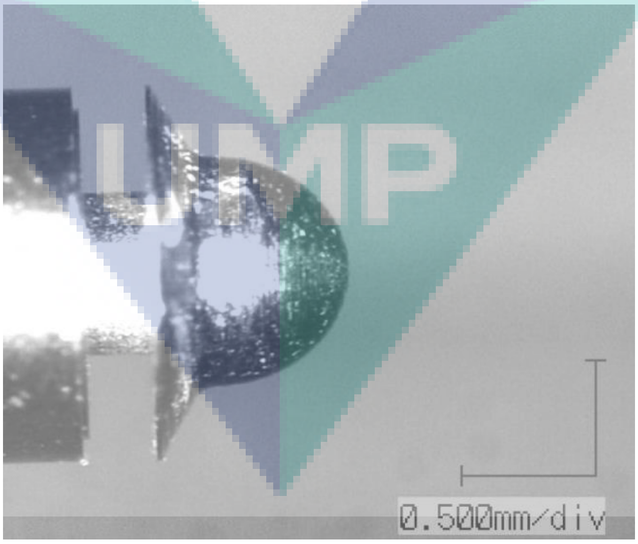


Figure 2.3 Machined 'microhat' by MEL revised microlathe micro-machine
Source: Okazaki et al. (2004)

In the middle of year 2000, Fanuc as one of the world's well-known servo- and machinery-manufacturer, has built up the maturity and raised potential of micro-manufacturing in term of miniaturization of conventional milling and turning process. In 2004, a machine called ROBOnano developed by Fanuc, featuring several combinations of high-precision multi-function machine functions, as depicted in Fig. 2.4, which could function as a five-axis grinder, a five-axis mill a lathe, , a five-axis shaping machine and a high-speed shaper, with this being realized by means of an air-turbine spindle instead of a conventional rotary servo-motor. A friction-free servo system was used as all linear-slides and -screws include static air-bearings. High-speed shuttle unit is used to perform shaping with capability of producing three grooves per second, and a 3 kHz fast speed tool servo by using a lead zirconate titanate (PZT) actuator. Cutting is done with a single-crystal diamond tool. Control of the machine is achieved using a FANUC series 15i control, with error mapping for positional (axial) errors only. The resolution of the linear axes is 1 nm and for the rotational axes is 0.00001°. The design of the machine is such that it experiences no backlash and stick-slip motion.

Figure 2.4 Fanuc ROBOnano versatile micro-machine
Source: Fanuc (2004)

2.2.4 Micro-Manufacturing and Key Issues

In order to succeed compared to the situation with micro-technologies prototype-products, production issues for micro-manufacturing needs to be able to address extensively by the design of micro-products. The mass production of micro-products should be the main target for the design of micro-manufacturing. , Apart from functional requirements, micro-manufacturing-related factors also have to be taken into account during designed of product. It is because manufacturing these products present more significant challenges compared to those for the macro-products manufacturing. Issues related to micro-manufacturing have been highlighted intensively and debated by many researchers (Qin, 2009). Some of the issues typical at the design stage of micro-manufacturing machinery can be summarized as follows:

i. **Conventionally negligible factors** – There is a limitation of scaled down miniaturization for conventional macro-scale machining. When the miniaturization comes to certain dimensions, some negligible factors in micro-manufacturing with conventional machining suddenly play a big impact such as vibration, temperature, tool-offset, chip removal, and the rigidity of the machines structure and tools . Those factors no longer become negligible as they bringing great influence on micro-products.

ii. **Mass production and automation** – Another issue which has occurred in current micro-process technology is related to process automation. Independent and manual processes of the developed prototypes require that every aspect of the process would need manual adjustments. Most of the processes, such as principal processes, turning, pressing, handling and milling processes, tool positioning and aligning material, loading and unloading, are all configured manually and controlled separately by dedicated controllers to obtain precise and accurate motion and alignment. These processes not only time-consuming but also low yield-rate micro-process, and as yet far removed from the potential of conventional processes. Moreover, greater parallax error tend to occurred in manual adjustments compared to present automated closed-loop and programmable controllers that have error-compensation features which highlighted by several relevance of manufacturer such as Fanuc, Kollmorgen, Baldor, Rockwell Automation, Yaskawa, and Parker.

iii. **Machinable materials limitation** – In parallel to the fairly early stage of micro-machine development, only soft- and ductile-materials with low-strength properties have been chosen and studied as the test materials, they are mainly copper, brass, and aluminum (Byung et al, 2005, Chern and Renn, 2004, Chern et al, 2006; Okazaki et al, 2004). The machinability of soft and ductile materials is easily achievable due to the low mechanical strength characteristics and materials tend to deform easily under low applied load/force. The efforts made have shown that only simple micro-features were created successfully, which micro-features were far from being able to be used or applied. Soft materials are very limited in their usage and these materials were found that they are not durable enough to meet the increasing demands of reliability and long life in manufacturing environment. Hence, changing to harder and high strength properties materials will be the only option available.

iv. **Tooling dimension** – Presently, 10 µm end-mill tools made from carbide have been realized by PMT manufacturer. Currently satisfactory on tools used for milling and drilling of sizes are between 25 and 50 micron and can be found commercially available from manufacturer such as Kyocera and Minitools. Nevertheless, micro-tooling development has experienced this more than a decade ago, however there are still limitations which restrict the option of tooling application (Aronson, 2003; Aronson, 2004). The ratio of the tool diameter to the drilling depth as known as aspect ratio have been found suitable between 5 and 10, despite some having aspect ratios of lower than 5. Deeper drilling and plunging will caused tooling breakage, thereby making the tooling improper for automotive- and aerospace-industries; which require very-high-strength material of low mass. None of significant effort studied have found elsewhere regarding this tooling issue. The suitable precision of the drilled holes has not yet been studied extensively. Moreover, the issue regarding the aligning of micro tools of sub-micron precision has not yet been explored widely because no automatic machine at present is available and capable of aligning tools of sub-micron precision (Kibe et al., 2007).

v. **Undesirable external forces** – Precise positioning is also one of the primary problems encountered in the micro-parts handling (Rougeot et al., 2005). The external forces have become key issues, involved in physical contact, such as the sticking or adhesion effect, electrostatic, and Van Der Waals force. Numerous studies have been conducted to comprehend the following situation along with necessary strategy. Mathematical simulation was employed to eliminate those forces (Arai et al., 1995; Arai and Fukuda, 1997; Feddema et al., 1999; Rollot et al., 2000; Bowling et al., 1986; Bowling et al., 1988; Tomas et al., 2007).

vi. **Sensor dimension and performance** – Since the sensors available at present are bulky in size with the achievable precision of the order of tenths of microns, sensor's accuracy need be aimed. Sensor which large in size made the difficulty to be allocated accurately on a constraint workspace. Moreover, this level of sensor precision is not feasible for micro-parts application which requires at least sub-micron precision. In addition, most of the calibration-precision capability of current machines is extremely lagging behind the precision demanded in micro-handling.

2.3 Stamping and Micro-stamping

Stamping process is one of the popular forming processes in industries which offer numerous option of manufacturing product in various applications. Stamping includes a variety of sheet-metal forming manufacturing processes, such as punching machine press or stamping press, blanking, embossing, bending, and coining. In micro-forming field, micro-stamping is on a promising path towards its applications in industrial production. In this section, numerous effort made worldwide covering on this field will be discuss further.

2.3.1 Sheet-Metal Forming and Stamping

Various applications in daily life are made up of sheet-metal components, such as transportation, electronic devices, medical implants, packaging for consumer goods, typical parts/ components including car-panels, aircraft, cans for food and drinks, and frames electronic display. With regard to micro-products, sheet-metal parts comprised of electrical connectors, micro-meshes for masks and optical devices, micro-cups for electron guns and micro-packaging, micro-springs for micro-switches, micro-motor for micro-laminates and fluidic devices, micro-gears for micro-mechanical devices, housings/ casings for micro-device, and micro-knives for surgery. Hence, sheet-metal parts are closely associated with everyday life (Vollertsen et al., 2006).

Fundamental forming process of macro-products include of stamping, blanking, shearing, bending, deep drawing (including mechanical and hydro-mechanical), hydro-forming, super-plastic forming, stretching forming, age forming, spinning, explosive forming, and incremental forming. Out of the numerous forming processes mentioned above, stamping is one of the common and highly in demand forming processes. Metal stamping has been defined as a process employed in the manufacturing of metal parts with a specific design from sheet-metal stock and includes a wide variety of operations such as punching, blanking, embossing, bending, flanging and coining (Kalpakjian and Schmid, 2006). Typical examples are sheet-metal machines, automobile parts, metal components used in audio- and video-devices, aerosol spray cans, and even military tanks. An example in the household is the use of sheets of metal to make pots and pans.

Sheet-metal forming process can be expressed as sheet metal being deformed into difference pre-designed shapes. In order to be transformed into various shapes, the metal material is necessary to be malleable and needs to flow easily. Stamping can be done on materials such as aluminium, steel, bronze, titanium, nickel, copper and other alloys. The process not only mass-production based but also economical and low cycle time. Therefore, it is widely applied in the manufacturing of high-volume products. Sheet metal forming process is also called chipless manufacturing (Sharma, 2007).

In metal-stamping processes, dies and punches are used to cut the metal into the required shape. The punches and dies also called as male and female components respectively. Stamping process is usually realized by press machine-tools. For material, the die normally made up of hardened steel while punch usually made up of hardened tool-steel or carbide. Meanwhile, die has a contour that matches the shape of the finished product whereas punch also matches the contour of the shape of part with slightly smaller clearance between the die and the punch.

2.3.2 Micro-Stamping Processes

Numerous studies have been conducted extensively in the field of micro-forming which indicated that micro-forming is on a promising path towards its application in industrial production (Geiger et al., 2001; Vollertsen et al., 2004; Vollertsen et al., 2006;

Qin, 2006; Geiger et al., 1996). Furthermore, several attractive characteristics offers by metal forming which are superior to those of other processes, for instance, machining at high production-rates, lower manufacturing costs, better material integrity, and less waste. Thus, micro-forming could offer a better option for micro-products with the concern of high volume production and lesser cost, in the case that appropriate manufacturing facility is provided.

Micro-stamping process is literally same as in the conventional stamping process. However, instead of producing macro- and meso-scale products, micro-stamping is mean to produce micro sized products and components. Micro-stamping is viewed as useful to produce parts such as wristwatch and micro handheld-device components, and medical devices (Kalpakjian and Schmid, 2006).

Micro-stamping had demonstrated a gradual development of the process in the early stages of development. Efforts were then extended to automatic with solenoid actuation and hybrid simple punching process on brass strip by researches, as shown in Figure 2.5 (Chern et al., 2004; Chern et al., 2006). The development of a manually-operated micro-stamping machine as depicted in Figure 2.6, further expanded this effort with the capability of employing various punch shapes (Byung et al., 2005).

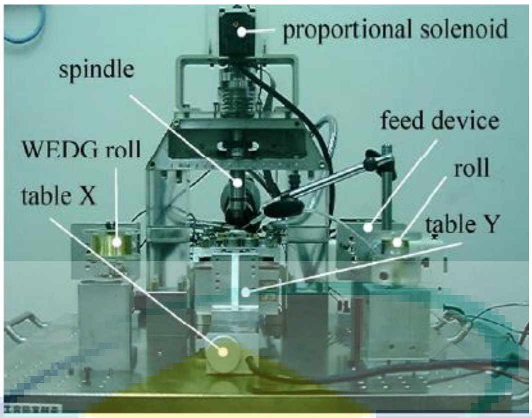


Figure 2.5 Solenoid driven micro-forming machine

Source: Chern et al., (2006)

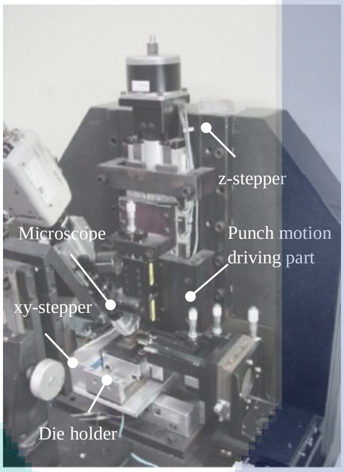


Figure 2.6 Developed micro-punching press machine.

Source: Byung et al. (2005)

The latest efforts in micro-stamping development have demonstrated that multi-stage/ progressive die micro-stamping may be used for the micro-sheet-forming process (Qin et al., 2008). A collaboration between the University of Strathclyde and its European Union partnership have developed micro-stamping machine as shown in Figure 2.7, with linear motor fully automatic driven, and multi-stage/progressive-tool features.

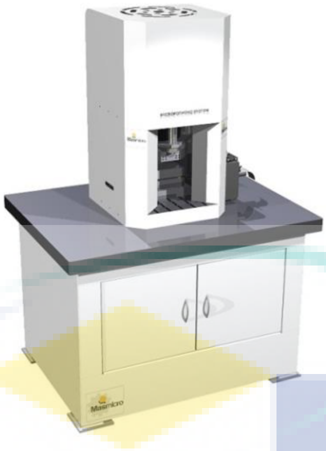


Figure 2.7 A bench-top micro-sheet-forming machine, designed by the University of Strathclyde

Source: Qin, (2008)

From conventional stamping process to micro-stamping process, besides the scaled down of machine itself physically, the tools required for the manufacturing process also have to be scaled down as well to produce the micro-parts. Efforts made by Qin et al. in the year 2008 have demonstrated the successful single-stage operation as shown in Figure. 2.8 and multi-stage/ progressive-tooling for the micro-sheet-forming process shown in Figure 2.9. , Figure 2.10 demonstrated the successfully production of various parts with micro-features.

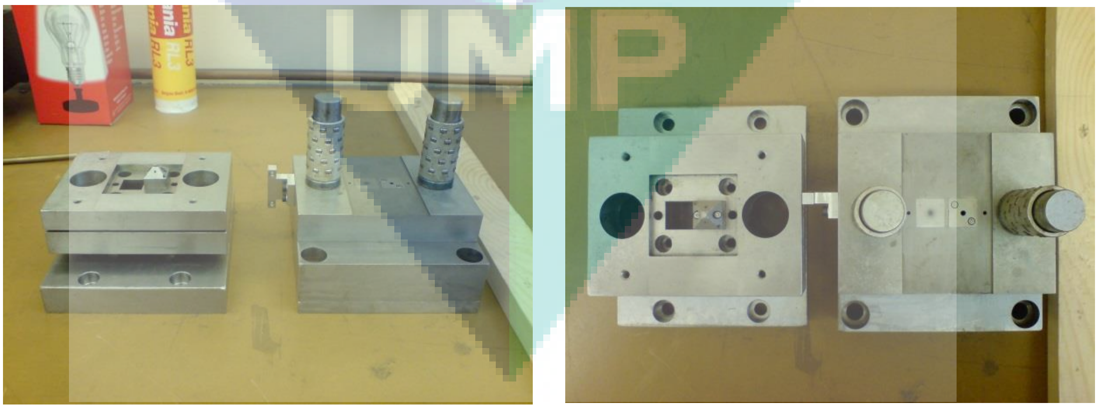


Figure 2.8 Single-stage tool with a square punch and dies for micro-sheet-forming.

Source: Qin (2008)

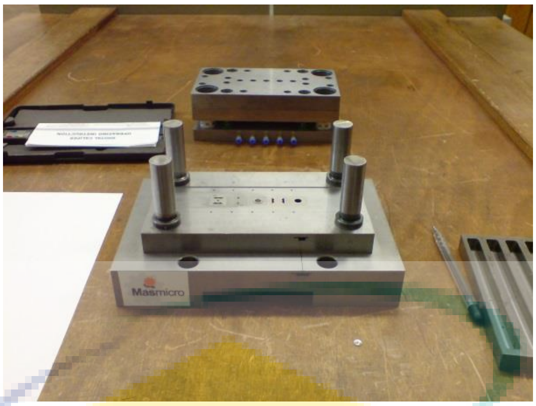


Figure 2.9 Multi-stage tools with various types of forming/blanking punches and dies.

Source: Qin, (2008)

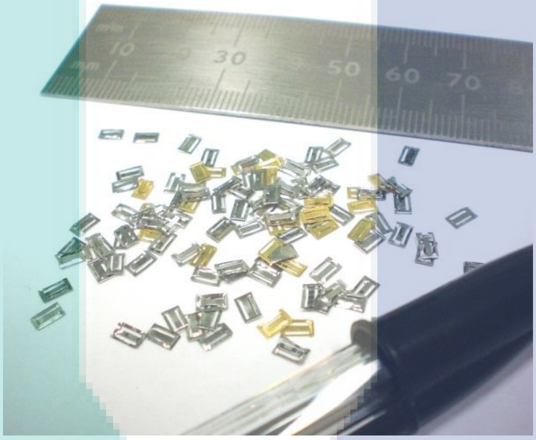


Figure 2.10 Samples of formed micro components in brass and stainless steel

Source: Qin (2008)

2.3.3 Micro-Stamping Machines and Tools

The initial stage of researches studies fundamental of every aspect in micro-forming, including the appropriate tooling and work material (Messner et al., 1994; Geiger et al., 1996; Geiger et al., 2001). The following efforts were then expanded to the development of a micro-forming-machine prototype in middle of 2000, by researchers and joint-venture industries (Qin et al., 2008; Schneider et al., 2004; Vollertsen et al., 2004; Hu et al., 2004).

The preliminary development of the micro-forming-machine prototype was progress based on traditional conventional forming machineries and focused on a multiple range of forming processes, which included bulk-forming processes and stamping. Chern et al. and Byung et al. validated the punching of thin sheet-metal by performing micro-punch in the year 2004 and 2005 respectively. In the studies, Chern et al. (2004) carried out the punching process by actuated a high-force DC solenoid actuation and material feeding from an automatic roll-feeder. The results illustrated a successful punching process, with different punch geometries being used. Meanwhile, Byung et al., (2005) demonstrated punching process by completely manually-controlled with a micro-punch in their study.

A new, low-cost, bench-top machine dedicated for micro-sheet-forming was later developed at the University of Strathclyde (Qin et al., 2008), in collaboration with its EU MAMSICRO consortium partners. This machine uses a linear-motor driving mechanism. The maximum frequency of the machine is 1000 strokes per minute (spm), the maximum force is 5.3 kN, the vertical-position resolution is 0.1 μm, and the load-measurement resolution is 0.1 N. The machine enables the micro-stamping/forming of sheet-metal parts (ideally for sheet metals with thickness of less than 100 m). The machine has a maximum working space of 400mm × 400mm with a flexible set-up, due to having a modular design, in which the ram-driven form/power is changeable without the need of changing other machine set-ups, and four machine-frame columns and supports to the ram guiding bridge can be re-positioned according to the requirements, as well as the sheet-metal feeder, and the part carrier. The bridge for guiding the ram is separated from the main machine frame, and hence it is not affected significantly by the deflection of the main frame and by vibration. Other innovations include monitoring the displacement directly on the tooling (thus offering more accuracy in term of the control of the punch stroke), transporting the micro-parts directly out of the dies by a part carrier, a new sheet-metal holding design, and a new vacuum/ compression-air chamber design. The development of a bench-top machine from the machine design which supported by Finite-Element dynamics analysis, has achieved excellent dynamic performance and machine stability without connection to the bench, and no significant vibration is felt on the shop-floor. A similar machinery-concept was developed by Schneider et al. in the year 2004, proposed that in order to serve the bulk-forming process, the forming tool should drive by a linear motor, a concept which was eventually proven to be successful.

2.3.4 Key Issues Related to Micro-Stamping Quality

Among various type micro-metal components, sheet-metal based components are applied widely in MEMS, micro-electronics/ optical devices, and medical devices/ instruments. There has been significant interest in research on micro-sheet-forming (Qin, 2007; Geiger et al., 1996; Chern et al., 2006; Mishima et al., 2002; Okazaki et al., 2002; Park et al., 2002; Hess, 2000; Schneider et al., 2004; Qin et al., 2008; Kima et al., 2005; Matsushita, 2003; Jeong et al., 2003; Saotome et al., 2001; Oh et al., 2005). However, no sufficient researches have addressed the production issues, in terms of transformation of the laboratory processes or machines into volume production. One of the key issues relates to the automation of the stamping processes by continuously feeding thin sheet-metals with micron-range precision.

2.3.4.1 High-precision handling and product quality

In conventional production, particularly sheet-metals, material feeding in press-working is no longer a major problem (Schuler, 1998). However, challenges arise when thinner metal-strips are to be used in micro-sheet-forming especially in the thickness that lower than 100 µm and the parts/ features to be formed become smaller, for instance, sub-millimetre ranges. In these situation, the material feeding and positioning of the thin sheet-metal underneath the forming tools is require to be as accurate as within one to a few microns during the forming of micro-sheet-metal component. In addition, it is become particularly important in multi-stage progressive micro-stamping, due to the close distance of neighbouring features of a part. Hence, accuracy of the feeding of the sheet-metal is highly required in order to avoid any inaccurate forming or damage to the neighbouring features and connections of the part/ scrap to the strip.

2.3.4.2 High-precision handling to meet volume production

Likewise, for volume production, feeding the thin sheet metal may have to be achieved accurately with a reasonable feed rate, for example 120 strokes per minute, because the stiffness of the thin sheet metal may be a major concern. Conventional sheet-metal feeders with large size cannot applied for precision feeding in micro-sheet-forming. Material feeding in micro-sheet-forming has been addressed occasionally only (Chern et al., 2006; Schneider et al., 2004) in some studies. Detailed study on performance of the feeders in term of positional precision and the feeding mechanism in micro-sheet-forming, considering various forming process conditions and material parameters has yet to be undertaken.

2.4 Forming Analysis on Thin Sheet

The forming of thin sheet is analysed from several perspectives: forces involved in punching, punching clearance, materials and characteristics, energy and force relation. In addition, several actuation systems were also discussed and a qualified actuation system was proposed.

2.4.1 Force Required For Simple Punching Process

Punching is one of the operations in sheet-metal stamping process that uses a punch press to force a tool, called a punch, through the workpiece to create a hole via shearing. The force required to punch is, basically, the product of the shear strength of the sheet metal by the area being sheared (Kalpakjian and Schmid, 2001). The maximum punching force, F, can be estimated from the following equation:

$$F = 0.7TL(UTS) \qquad 2.1$$

where T is sheet thickness, L is total length sheared (such as perimeter of a hole), and UTS is the ultimate tensile strength of the material.

In addition to the punch force, there is also another force required to strip the punch from the sheet during its return stroke. However, this second force is difficult to estimate due to the many factors involved.

2.4.2 Punching Clearance

The major processing parameters in punching are the shape of and the materials for the punch and die, the speed of the punching, the lubrication, and the clearance between the punch and die. The clearance is a major factor in determining the shape and the quality of the sheared edge. As the clearance increases, the sheared edge becomes rougher, and the zone of deformation becomes larger. The sheet tends to be pulled into the clearance zone, and the edges of sheared zone become rougher.

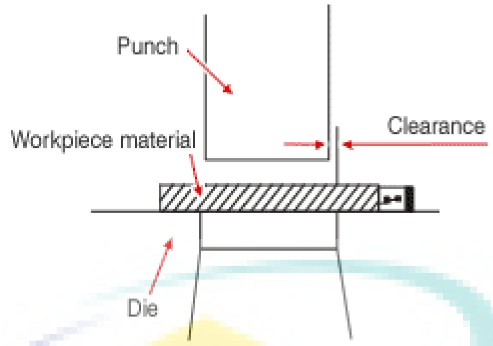


Figure 2.11 Schematic illustration of shearing with punch and die.
Source: Misumi

The appropriate clearance is a function of the type of materials, its temper, and its thickness. As a general guideline, clearances for soft materials are less than those for harder grades. As the clearance increases, the punch force decreases, and the wear on dies and punch is reduced as well. Clearance generally ranges between 2% and 8% of the sheet thickness, but they may be as small as 1% or as large as 30% (Kalpakjian and Schmid, 2001).

The study for quality of sheared edge was carried out by Mori et al (2013) using a slight clearance punching process of ultra-high strength steel sheets using a punch having a small round edge. The onset of cracks in the punching process was delayed by the small round edge of the punch. The concentration of deformation around the edge of the punch was relaxed by the small round edge, the onset of a crack from the edge of the punch was prevented, and thus the burnished surfaces became considerably large. For the punched sheet with the punch having the small round edge, the delayed fracture was prevented and the fatigue strength was improved due to large compressive stress around the sheared edge (Mori et al, 2013).

2.4.3 Materials and Characteristics

Selection of a material for micro-manufacturing will be constrained largely by the availability of the material for volume production, due to the limited number of the suppliers currently operating in this field. However, the trend is improving, such as with nano-material suppliers, the number of which has increased significantly recently (Qin, 2010).

For the sake of micro-product development, new study/ validation of material properties may be needed if the material suppliers are not able to provide the material data relevant to micro-manufacturing, such as size effects and material property descriptions. The properties will have to be validated for design uses, with consideration of size effects, and these have to be available with the inclusion of mechanical, thermal, electrical and magnetic properties, as appropriate, and others including biocompatibility, chemical compatibility, hydrophile and hydrophobe properties. A study was carried out by Wang et al. in 2015 to evaluate the degree of size effects on friction occur in micro-forming process. It was found that the degree of size effects on friction decreased with increase of contact pressure, surface roughness and sliding speed, and also with decrease of the width of the plats of the micro-structured surface (Wang et al, 2015). In addition, grain sizes of the material selected must also be known for most of the micro-manufacturing processes. Selection of materials for suitable processes or available processes will be the ultimate concern for designers.

In metal forming, the most relevant parameters describing the material behaviour are the flow stress and the flow curve (see Figure 2.12). Scaling down the standard tests used to measure the flow behavior reveals that there is a distinct size effect: with decreasing specimen size in general, a decrease in flow stress is observed.

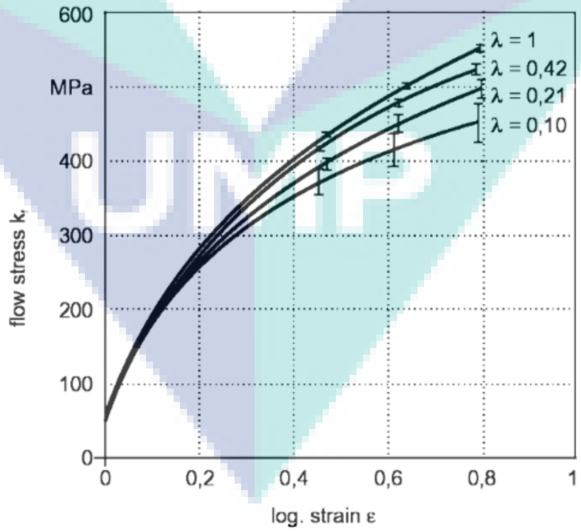


Figure 2.12 Flow stress curve.

Source: Geiger (2001)

The decreasing stresses can be explained by the so-called surface layer model as shown in Figure 2.13. The grains located at the surface of a tensile or upsetting specimen are less restricted than grains inside the material. Dislocations moving through the grains during deformation pile up at grain boundaries but not at the free surface. This leads to less hardening and lower resistance against deformation of the surface grains. With decreasing specimen size and invariant of microstructure, the share of surface grains increases, which leads to lower integral flow curves (Geiger et al, 2001).

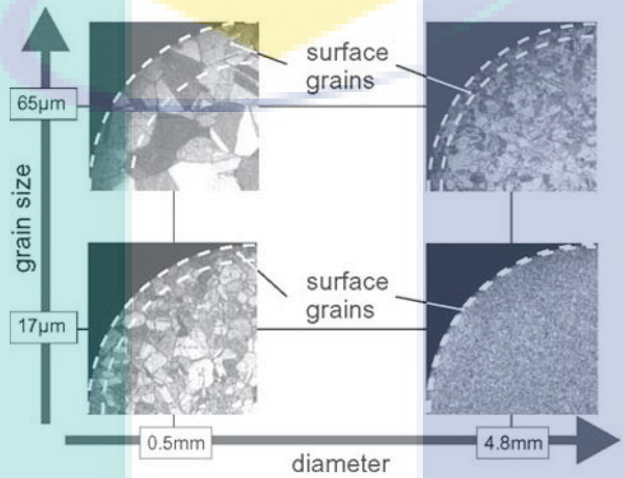


Figure 2.13 Increasing share of surface grain.
Source: Geiger (2001)

Material properties have much more significant impact on the design planning for micro-manufacturing, compared to that in macro-manufacturing. For example, size effects on mechanical, thermal, electrical and magnetic properties, biocompatibility and chemical compatibility. need to be understood, and some of these may be significantly different, compared to the material behaviours in the macro-scale. As a consequence, mechanisms of materials conversion process such as separation, andjoining. will be different, as well as interactions between the materials and process tools.

Compared to the manufacture of macro-products, manufacturing methods and strategies in micro-manufacturing may be different. Manufacturing micro-products may be carried out by non-traditional manufacturing methods. It may scale down or modify the traditional methods, as appropriate, to fully address issues related to manufacturing in the micro-world. Material properties are one of the parameters taken into account in the manufacturing chain. Conventional manufacturing methods may not be able to cope with special material properties, for instance, either they are too hard or too weak for any process. Besides, manufacturing micro-products might also encounter some issues such as materials sticking onto the micro-tools, incompatibility with the mask materials, or original material properties cannot be altered during manufacturing, which may be affected by mechanical work-induced heat or direct heating processes.

Carbon and alloy steels are among the most commonly used metals which have a wide variety of applications. The composition and the processing of steel are controlled in a manner that makes it suitable for numerous applications. The wide range of its properties and generally low cost have made it among the most useful of all metallic materials (Qin, 2010).

2.4.3.1 Carbon Steel

Carbon steels are generally classified by the proportion of their carbon content. They are generally classified as low-carbon (mild), medium-carbon, and high-carbon steels.

i. **Low-carbon steel** – Also known as mild steel, which consists of less than 0.3 % carbon. It is generally used for common industrial products, such as bolts, nuts, sheet, plates, and for machine components that do not require high strength.
ii. **Medium-carbon steel** – Consists of 0.3% to 0.6 % carbon. It is generally used in applications requiring higher strength than low-carbon steels, such as in machinery, in automotive and agricultural equipment part, and in parts for metalworking machinery.
iii. **High-carbon steel** – Consists of more than 0.6 % of carbon. It is generally used for parts which require strength, hardness, and wear resistance, such as cable, wire, springs and cutlery. The parts are usually applied for heat treatment after being manufactured into shapes. The higher the carbon content of the steel, the higher is its hardness, strength, and wear resistance.

In sheet metal forming, low-carbon steels exhibit a behaviour called yield point elongation. After the material yields, the sheet stretches further in certain regions without any increase in yield point, while other regions in the sheet have not produced any yield point yet.

2.4.3.2 Stainless Steel

Stainless steels are characterized primarily by their corrosion resistance, high strength and ductility, and high chromium content. They are called stainless because they develop a thin adherent film of chromium oxide in the presence of oxygen that provides corrosion resistance. In addition, the higher the carbon content, the lower the corrosion resistance of stainless steels. It is due to the formation of chromium carbide in the steel when carbon combines with the chromium. Stainless steels are available in a wide variety of shapes. Typical applications include cutlery, health care and surgical equipment. They are generally divided into five types.

i. **Austenitic** – These steels are generally composed of chromium, nickel, and manganese in iron. They are susceptible to stress corrosion cracking. Austenitic stainless steels are hardened by cold working. They are most ductile of all stainless steels.
ii. **Ferritic** – These steels have high chromium content up to 27 %. They have lower ductility than austenitic stainless steels. They are hardened by cold working and are not heat-treatable. They are generally used for non-structural applications such as kitchen equipment and automotive trim.
iii. **Martensitic** – Most of martensitic stainless steels do not contain nickel and are hardenable by heat treatment. The chromium content might be as much as 18 %. They are typically used for cutlery, surgical tools, and valves.
iv. **Precipitation-hardening** – These steels contain chromium and nickel, along with copper, aluminium, titanium, or molybdenum. They have good corrosion resistance and high strength at elevated temperature. Their main applications are in aircraft and aerospace structural components.
v. **Duplex structure** – These steels have a mixture of austenite and ferrite. They have higher resistance to corrosion and stress corrosion cracking than austenitic stainless steels. Typical applications are in water-treatment plants and heat-exchanger components.

2.4.3.3 Energy, Power Consumption, and Punching Force Relation

As shown in formula 2.1 earlier in Section 2.3.1 of this thesis, the punching forces generally depend on parameters such as type of materials, thickness and the shape of the sheared area. In micro-manufacturing, the thickness of materials are usually below 100 µm, which has insignificant influence on the punch force measurement. Provided that the types of materials used are the same, the shape of sheared area which defines the cross-sectional area for punching process should be taken into account. In addition, energy for a punching process is different from the punching forces and is usually relatively higher than the exact punch forces required. The mechanism of punching process involves the moving of other sub-machinery such as tooling, blank holder, bushing, guide post, and spring. The forces required to encounter the components and bring them together during the punching process must also be included.

Furthermore, in the discussion of energy required for a process step, it is important to consider all secondary energy expenses that are required for its implementation. For example, in the case of cutting process like milling or turning, in which material removal is the primary objective, the specific consumed energy and the specific process power can be computed as objective key figures from the processing power, energy integral, materials removal rate and volume of removed materials (Dietmair and Verl, 2009). Typically, process power is not required continuously while a machine consumes energy at a substantial rate, even if it is standing still. Consequently, the efficiency will be low even for highly efficient processes and machines with high efficiency components, if the machine is not switched off or put into a hibernation mode during periods of inactivity. A general idea of the efficiency of a machine is shown in Figure 2.14. From the diagram, the energy consumed at idle running is actually as much as the actual power required for processing. Most of the input power is consumed for infrastructure and losses. Only 25 % of the input power is actually required for the process.

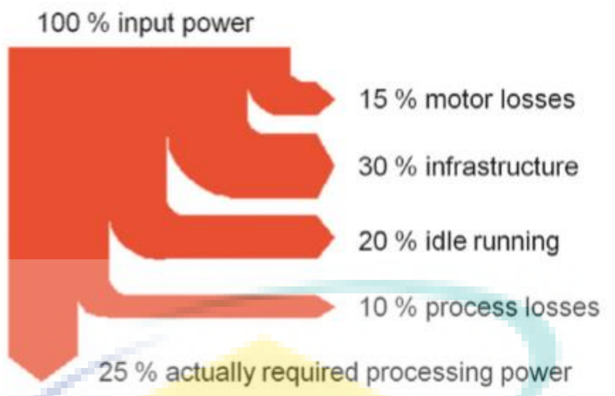


Figure 2.14 Machine tool power flow diagram.
Source: Dietmair (2009)

Moreover, in view of energy decomposition, the use of the machine tools mainly depends on electricity. Energy consumption, namely, the area between machine tool power load curve and time axis, is equal to power multiplied by time, as illustrated in Figure 2.15. Machine tool energy consumption can be divided by the function, composition system, components, operation status and energy consumption attributes. Sometimes, energy consumption of some components or processes can be ignored and some assumptions will be made. For example, in their studies, some researchers may have ignored the energy consumption of feed unit or tool change process while others may have assumed that spindle speed would be constant in the machining process (Zhou et al, 2016). From the diagram (see Fig. 2.1.4), it can be said that high energy is consumed during the machine start-up and even the moment before it is switched off. The power demand goes up to 1200 W. Besides, a certain amount of energy is also consumed during the stand-by status. Nevertheless, the examples given here are mainly for the conventional manufacturing machine, which is bulky and required for high power input. For miniature manufacturing process, it is expected that with the miniaturization of machinery and materials being processed, energy consumption will also be 'miniaturized' proportionally.

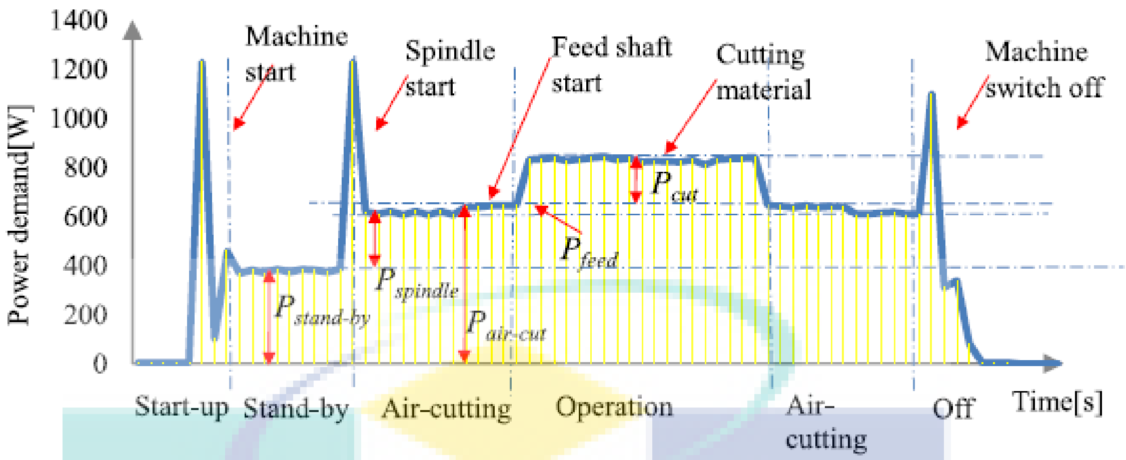


Figure 2.15 A schematic diagram of power profile of the milling process
Source: Zhou (2016)

2.5 Micro-stamping Machine Design and Actuation System

The demands for high productivity, high quality and low energy consumption fundamentally affect the future machine design, and this trend came from the promotion of attention to resource saving and conservation (Neugebauer et al., 2011; Strano et al., 2013). The miniaturization of machine is not new, as the industry has experienced this for many years. Numerous efforts have been made to downsize the scale of machinery design. With the scaling down of equipment/component, the energy required for manufacturing is proportionally reduced as well. As the energy required is miniaturized, the corresponding low energy actuators are introduced for the new actuation system.

2.5.1 Comparison Studies on the Actuation System

Three categories of device have been identified and found to be commercially used by most of the micro-manufacturing researchers: electromechanical actuators, electrical actuators and piezoelectric-actuators.

2.5.1.1 Electromechanical Actuators

The use of hydraulic- and pneumatic-actuators is rapidly replacing by the use of electromechanical actuators due to the cost saving by reducing unnecessary energy-consumption within the manufacturing facilities. Eventually, they have greatly improved control and flexibility and are therefore suitable for multi-positional tasks as they induce no health or caused high noise-levels environmental issues. There are some examples of electromechanical linear-actuation such as solenoids and combinations of electrical motors with mechanical transmissions. Solenoid employs a magnetic concept to move the plunger and actuate. They are used typically in the electrical-transmission field, specifically as relays in high-voltage switches. However, the lack of controllability in accuracy/ precision has become the limitations of solenoids. Besides, travel distance of solenoid is restricted only by limit switches. Solenoids exhibit quite an impressive response-rate, usually in milliseconds, which is suitable for a high-speed punching-process (Chern et al., 2004; Chern et al., 2006).

2.5.1.2 Electrical Actuators

The electrical actuator has been invented to overcome the limitations of the electromechanical systems. An example of electrical actuators is the linear motor. This motor is basically similar to the common rotary-motor apart from its rotational motion which moves in linear motion. It has become a popular trend and has been realized by manufacturers such as Kollmorgen, Rockwell Automation, Copley Controls, Newport, Baldor, Aerotech, Parker Motion, Intellidrives, Hitachi, Linmot, Airex, Yaskawa, Micos, and CAlinear.

The motor in a linear-motor system is connected directly to the moving load. Therefore, there is practically no required any transmission system between the motor and the load. The load will move instantaneously when the motor moves. The linear motor offer quite an impressive resolution and incremental-motion of up to sub-micron precision, depending on the type and resolution of the encoder used. In terms of acceleration and velocity, a linear motor from Kollmorgen manufacturer has outstanding acceleration, in which a minimum of 5 g typical and up to 115 g maximum acceleration may be achieved theoretically, and 0.2 m/s of travel speed can be accomplished easily. However, linear motor applications are used more in the light machinery industry such as for gantries, CNC machining axes, and sub-micro-positioning. Heat build-up may occur in operations that require a long time to be accomplished and in high force-holding processes; therefore, with some linear-motors, a cooling system is employed to overcome the problem.

2.5.1.3 Piezoelectric-Actuators

A later linear-actuation concept is the piezo-actuator which can be found from manufacturer such as Physik Instrumente, Morgan Electro Ceramics, OAO Piezo. When a range of crystalline materials are exposed to an electrical field or charge, the shape change from that generated piezoelectric-motion. The most common of these crystals is quartz (SiO2), but there are others, for example lead zirconate titanate (PZT) and lithium niobate. Quick respond from these materials to changes in the applied voltage and current direction (AC current generates oscillations in the piezoelectric materials). It is also very high accuracy of repeatability from such actuators due to the very little variation in the actuator stroke. This means that such materials can be used in devices which demand highly-precise motion and speed. They also exhibit very fast response times and are suitable for applications which require as low as 1 ms response time. Piezoelectric materials are also shows high efficiency and capability of producing a high force-to-weight ratio, without the effect of ambient temperature. When power is cut-off, the materials will return to its neutral position without the need for any further effort such as cooling. Typical applications of piezoelectric-actuators focus mainly on very light load application such as in the micro- and nano-positioning areas in semiconductors, data storage, fibre optics, photonics, microscopy, lasers, precision machining, aerospace, astronomy and in the field of micro-systems technology.

Research by Mrad et al. (2004) has revealed that although a piezoelectric positioner can satisfy positioning-precision requirements, the positioner naturally cannot provide the stiffness, thrust and speed required for constant micro-manufacturing demands. Such device tends to fail under rapid motion because the nuts and bolts of the equipment would come loose easily. No bearing system is employed in this drive rod and the friction force between moving parts is quite high. This leads to greater heat build-up generated from the rapid motion. Under excessive heat, the device might deform and deflect, and this, in turn, would lead to failure.

2.5.2 Qualified Actuation System

Based on the actuation system discussed previously, Table 2.2 presents a comparative study made on the discussed high-speed and accuracy devices. A proper selection of an actuation system is essential in order to secure high-precision/ accuracy for a high-speed micro-sheet-forming application. Solenoids are viewed to have superior characteristics among other devices in terms of speed, acceleration, force, robustness, and ease of maintenance, as well as their popular use by researchers as an alternative to micro-stamping actuation system.

Indeed, solenoids have the advantages over other devices in respect of their impressive response time and acceleration on short distance. They are also small and compact, making them suitable for use in constrained space applications and appropriate for bench top sized machine. Since there is linear motion in stamping process, where it is realized by linear guide post and bushing that contribute to positioning-accuracies in the system, accuracy is not a major issue and is thus negligible. Therefore, a solenoid actuation is viewed to be a good platform in which the micro-forming process for sheet metal at low energy and high speed forming is concerned.

Table 2.2 Types of linear-displacement devices and their suitability for a micro-press feeding-application.

Device	Accuracy and precision	Acceleration rate (g)	Force (N)	Dimension	Reliability
Solenoid	Inflexibility and uncontrollable on stroke distance	Impressive response time and acceleration on short distance.	Fairly high force inversely proportional to stroke distance. The longer the stroke, the less force it produces.	Small and compact hence suitable for constrained space application.	Reliable in terms of mean time between failure 25,000,000 cycles recorded before failure detected. 24/7 production environment is feasible.
Linear motor and stage	Stroke distance is limited to certain length. Very high precision and accuracy with air bearing. No mechanical transmission;.	Acceleration rate is very impressive. 5-10g acceleration is typical. 40g is available commercially	High thrust force is qualified ranges from tenth up to thousands of Newton force.	Fairly small as ball screw system. Force proportional to the coil size. Larger force requires larger n bulkier coil.	Reliable as demonstrated and used by machineries in early 2000s. 24/7 production environment is feasible.
Piezoelectric-actuator (linear motor)	Very accurate and precise as it has been used in photonics and high precision application but at very limited travel distance.	Response time is better over short distance, hence, reflecting high acceleration rate. Nevertheless, for longer travel distance, 5g is recorded.	Very low force ranging between 7-10N hence limits the application within light weight positioning applications.	Relatively small and compact and suitable for space constrained applications.	Reliability of low speed punching is acceptable. Nevertheless, for high speed punching, heat as well as wear and tear, tend to build up. Not suitable for high speed 24/7 production environment.

2.6 Summary

Based on the studies reviewed in this chapter, it can be summarised that increased demands for micro-products have also led to rapid development of micro-manufacturing technologies for the manufacture of individual parts and systems, which includes development of new manufacturing processes, tools and machinery. Even though tremendous efforts have been made to date to improve the efficiency of miniature-/ micro-manufacturing technologies, they have, however, not resulted in a radical change in the technologies. Therefore, miniature-/ micro-manufacture is still viewed as an ‘expensive’ and ‘wasteful’ business. Conversion of miniature-/ micro-materials into engineering products by micro-forming would address two key issues which are of particular importance for the industry, namely, reduction of manufacturing costs and improvement of product quality. Apart from that, such need is proportional with the complexity of forming miniature/micro-materials which requires good understanding of machine and process at micro-scales.

A research group at the University of Strathclyde has devoted significant efforts to address key issues in this field. A micro-sheet-forming machine has been developed by researchers in the group which has been proven to have the capability of producing miniatures/ micro-products. This machine uses linear motor as a mode of actuation with 5 kN of stamping force achieved at a speed of 14 Hz in stamping operation. Nevertheless, the machine consumes 415VAC of power supply for the actuation system to work. The success story of the University of Strathclyde Research Group is therefore still lacking in its effort to address the issue of energy conservation during the production of micro-parts. Therefore, a low energy micro-sheet-forming machine which can conserve one hundred times less energy than its conventional counterpart is practically a direct solution to energy conservation in miniaturization process. This can be achieved by using low energy actuation device to perform the forming process. Additionally, solenoid actuation is viewed as one of the promising solutions to be used for low energy micro-sheet-forming machine development with the favourable features as thoroughly discussed in this chapter

CHAPTER 3

MACHINE CONCEPT DESIGN AND DEVELOPMENT

3.1 Introduction

Almost all aspects of micro-factory development are as such because conventional facilities for manufacturing miniature-/ micro-products are not compatible, in size, to the products to be made in miniature-/ micro-manufacturing. Therefore, it is necessary to reduce the scale of the equipment which could, in turn, reduce the energy consumption and materials requirement, reduce pollution, and of course, reduce cost as well. At the same time, the mass of mechanical parts will reduce dramatically as the scale of machinery and equipment is reduced. This will result in the increased speed of manufacturing tools. Conventional large scale machines may be optimized/ upgraded especially for the manufacture of miniature/micro-components with enhanced precisions. Machines of smaller size may be built with newly-enhanced elements and designs that are customized for micro-forming application. These machines may also be built in normal size but incorporated with new concepts related to micro-forming, for instance, using linear motor/ piezo-electric actuator, combined with hydraulic or displacement amplifying mechanisms. Thus, the design of a bench sized and high–speed new micro-sheet-forming machine was proposed. Several possible approaches were examined with a view to establishing feasible concepts. Based on the investigation, several concepts for micro-thin sheet-metal-forming have been generated assessed with appropriate applied-loads and force-analysis which eventually formed the basis for designing a micro-forming machine.

In the past decade, micro-forming process development focused on the down-scaling of the conventional process in terms of equipment and tools. With the downsizing of machine facilities, it was expected in the present study that the energy consumption would also be miniaturized. In this chapter, description of the development work process of the prototype of the low energy micro-sheet-forming machine is provided. The development works included materials preparation, design of toolpath for machining, machining plan, fabrication, and assembly components. In addition, fabrication process was carried out by combining accurate measurement and machine with computer numerical control (CNC). Fabrication and assembly of sub-components of the machine were made using actuation facilities.

3.2 Machine Design Consideration

In this study, a prototype of micro-sheet-forming machine system was developed. The development was targeted at low energy actuation along with applicable industry facilities. The following factors were considered by the present researcher in the development of the prototype: forming of thin sheet parts with thickness < 100 µm; forming tolerance set to be 5~10 % of the strip thickness; power rated at approximately 12-24 VDC; use of modular design for easy set-up and changes of the power source, part carrier, tooling, if necessary; scarp collection; environmental friendly process and results; bench-type; low cost equipment.

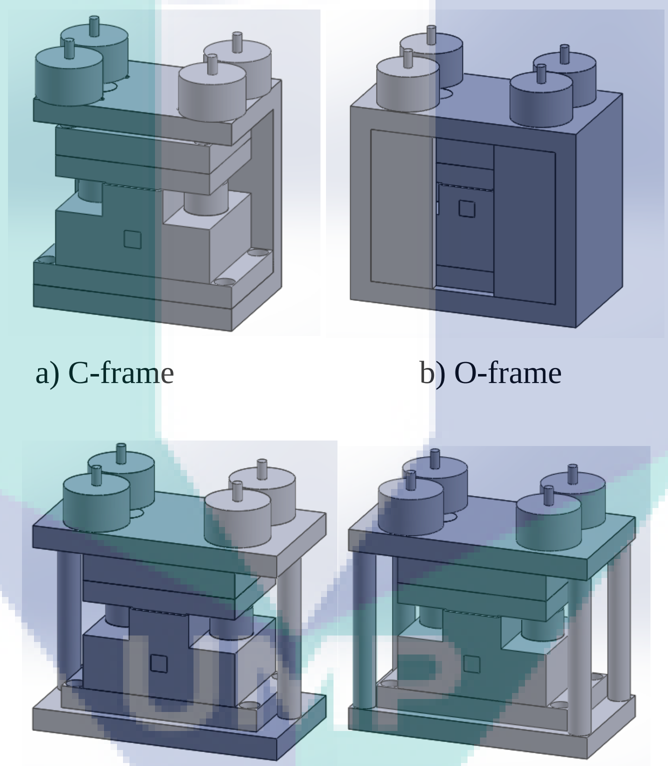
3.3 Machine System Development

Machine system development is concerned with defining machine concept and tool-set and integrated them into sheet-forming application with control system. This section was discussed with the generated of conceptual machine frame design, tool-set feature, and the control system integration.

3.3.1 Machine Frame

Various concepts of machine were examined with regards to the frame design and general design features. As a result of the findings of these examinations, a range of machine concept layouts were generated as shown in Figure 3.1. Evaluation of the various machine concepts was carried out by reviewing the deflection of frame and eliminating the weakest stiffness concepts.

An analysis of various machine frames was carried out using FEM with the purpose of predicting the possible frame deflection during sheet forming process. The FEM analysis was carried out by adding four points of 200 N forces on top of various frame concepts in order to simulate the forces during actuation. The final selection of the machine layout was designed as O-frame, which had the lowest deflection, to provide high stiffness for the frame in order to minimize possible frame deflections.



a) C-frame b) O-frame

c) 2-column frame d) 4-column frame

Figure 3.1 Possible machine layout concept.

3.3.2 Tool Development

The tool set system basically consisted of an upper half die and a lower half die with die-inserts (see Figure 3.2). The forming of die-sets with complex structural features were made up by CNC milling and turning machine. This was driven by four solenoids that were in contact with the top plate of the tool set. The lower half die was connected to the forming machine frame. All components were then assembled and connected together by standard screw fasteners. Upper half die and lower half die were linked by two linear guide post sets with spring and bushing. The guide post set was located at the lower die and the bushing was connected to the upper die by push-fit assembly. Four springs were used to join the punch holder plate with a blank holder. The die insert was located at the middle of punch guide plate aligned with the punch. A tunnel was created across the lower die and below the die-insert for scarp collection.

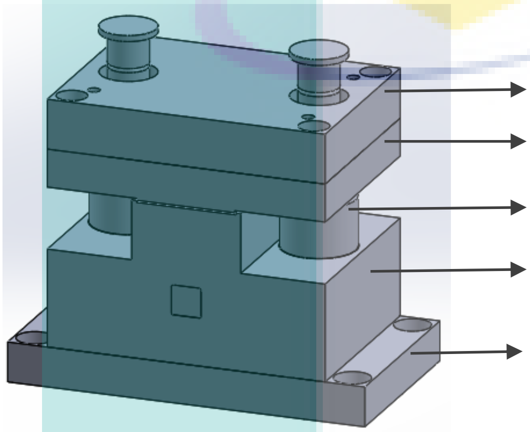


Figure 3.2 Micro-sheet-forming tool-set.

3.3.3 Control System

The linear punch was realized by using four Ledex low profile 6ECM linear solenoids as shown in Figure 3.3. The specification and dimension of solenoid was attached in Appendix C. Each solenoid had the capability of delivering approximately 170 N of thrust at 25 % duty cycle. Lower duty cycle and lower stroke distance would enable more thrust to generate. The variation of solenoid's force with stroke is illustrated in Figure 3.4. Sizing of the solenoids was calculated from the punching force required to punch thin strip metal by using equation 2.1 as indicated earlier in Section 2.3.1 in Chapter 2 of this thesis. The thickness of sheet metal was approximately 100 µm.

Figure 3.3 Ledex low profile 6ECM linear solenoid
Source: Ledex

Besides the simple punching force of thin strip metal, the calculation of the actuation force required also considered the counter force of both compression and tension springs from the machine re-positioning mechanism so that the minimum force required could be determined. The actual force generated by four solenoids was much greater than the minimum force required for punching a single thin sheet metal. The multiplication of the actuation force was necessary to adapt to the requirement of industry production, which would promote the capability of forming on various material options.

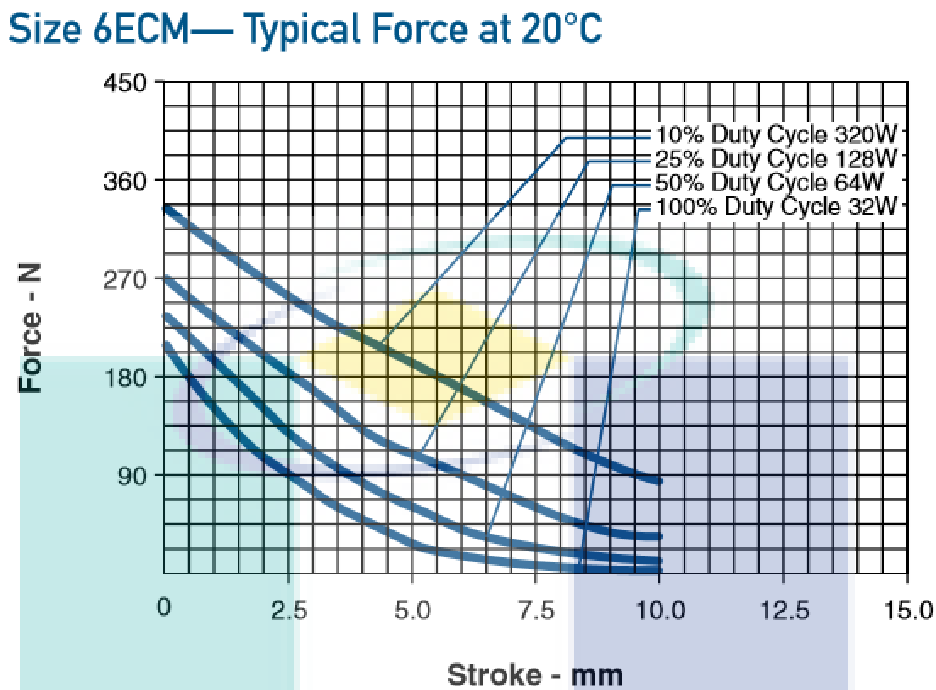


Figure 3.4 Variation of solenoid's force with stroke.
Source: Ledex

Solenoids are powered by 24 V power supply unit and power transmission is controlled by two sets of solid state relays. Each relay connected to the solenoids is controlled by a microcontroller. The microcontroller receives an input signal from a sensor or external switch which detects the presence of the strip material. High input represents the presence of strip material and this automatically triggers the solenoids to actuate and drive the punch. The system receives 240 VAC as an incoming power supply. It is then filtered by EMF to remove electromagnetic noise on the power line. Filtered power line is then fed to an energy meter to monitor energy used by the machine in kWh. Exiting the energy meter, the line is stepped-down to 24 VDC and 12 VDC both for solenoids and microcontroller purposes.

3.3.4 Machine Realization

Fig. 3.5 shows the schematic illustration of designed machine-system for micro-sheet-forming process. The prototype machine-system was built with the integration of the elements/ sub-systems described in the earlier parts of this section.

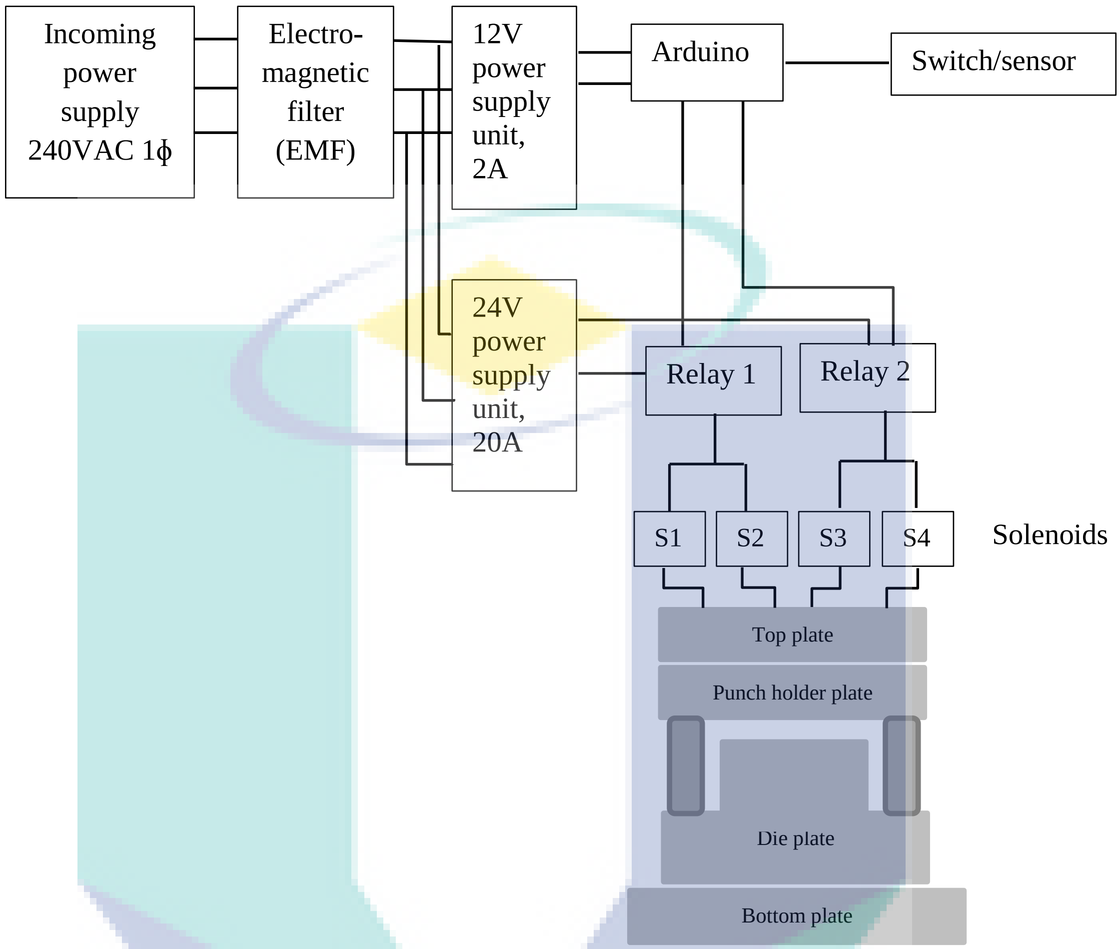


Figure 3.5 Schematic illustration of machine-system connection.

3.4 Finite Element Method (FEM) Analysis

The FEM analysis was done by using *Solidworks SimulationXpress 2014*. It was conducted separately on each individual part and focused on the displacement response of machine frame and moving component such as top plate and punch guide plate. The forces applied simulated the punching force of solenoid during actuation. A comparative study of deflection on materials was also conducted between Aluminium 6061 alloy and carbon steel from the FEM analysis. The displacement tolerance was set to be the same as forming tolerance, which is 5~10% of strip thickness. By taking strip thickness as 50 µm for consideration, the displacement should preferably be not greater than 0.0025 mm.

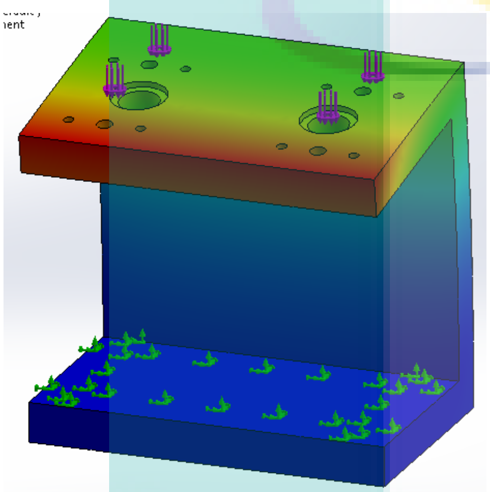
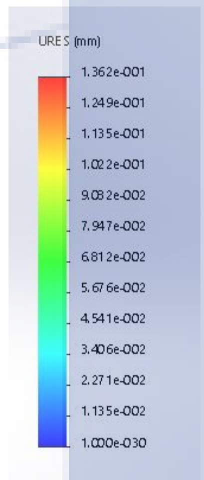
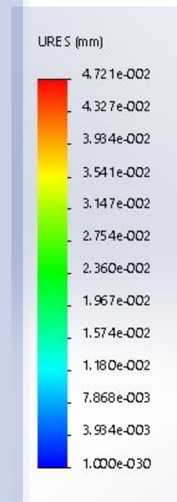
3.4.1 Machine Frame Displacement Responses on Different Materials

Table 3.1a and Table 3.1b present the results of displacement responses of various machine frames on different materials with forces applied. Four 200N forces acted on the top surface of the machine frame where the solenoids were located, to simulate the actuation. Global mesh size for each frame design was generated automatically by software system default. Stiffness of each of the frames was evaluated from the displacement response. C-frame was meshed with 11.03 mm global mesh size with 0.55 mm tolerance. From the results obtained, it can be seen that C-frame demonstrated 0.1362 mm of displacement response for Aluminium 6061 alloy and 0.04721 mm for carbon steel, respectively. The deflection of this frame design was clearly too great from the displacement tolerance since this frame design did not provide strong and equilibrium structure support. In contrast, O-frame with 11.31 mm global mesh size and 0.56 mm tolerance, showed 0.001131 mm of estimated displacement response for Aluminium 6061 alloy and 0.0003835mm for carbon steel, respectively. However, 4-column frame with 10.77 mm mesh size and 0.54 mm tolerance gave 0.01246 mm and 0.004193 mm displacement response each for Aluminium 6061 alloy and carbon steel while 2-column frame with global mesh size 10.49 mm with 0.52 mm tolerance, produced displacement responses of 0.01709 mm and 0.005726 mm for Aluminium 6061 alloy and carbon steel, respectively.

Table 3.2 shows the summary of static displacement response results for the machine frame. By taking tolerance as 0.0025mm, it can be concluded that the equilibrium design of

O-frame provided the highest stiffness structure characteristic from both materials with least displacement within the desired tolerance. In addition, both 4-column and 2-column frames in carbon steel materials also showed high stiffness in their characteristics.

Table 3.1a Comparative study of machine frame displacement responses on different materials.

<table>
<tr><th>Component</th><th colspan="2">Total displacement plot (mm)</th></tr>
<tr><th>Machine frame</th><th>Aluminium 6061 alloy</th><th>Carbon steel</th></tr>
<tr><td>
C-frame</td><td>
</td><td>
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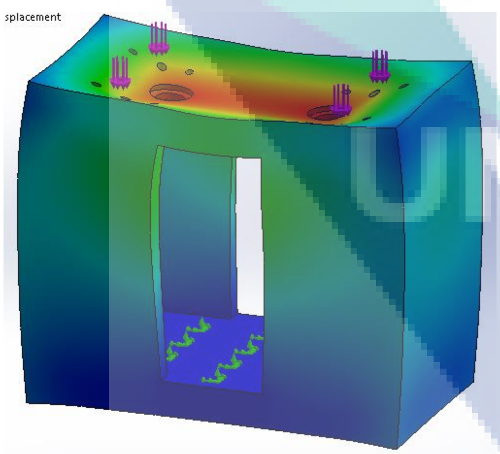
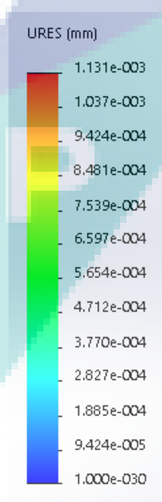
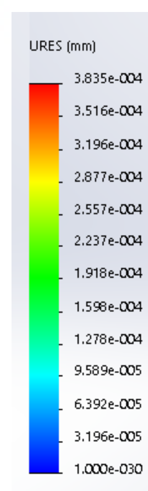
<tr><td>
O-frame</td><td>
</td><td>
</td></tr>
</table>

Table 3.1b Comparative study of machine frame displacement responses on different materials.

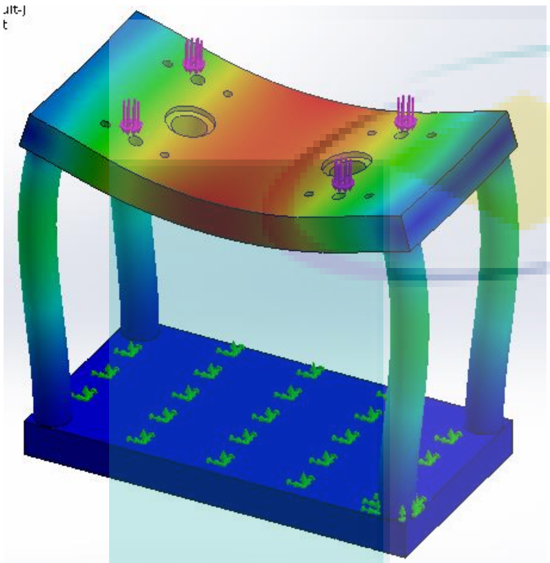
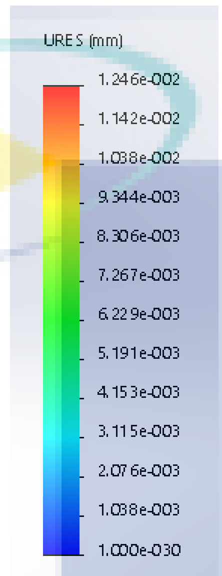
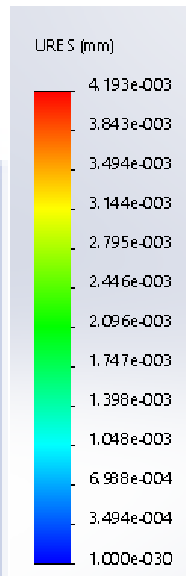
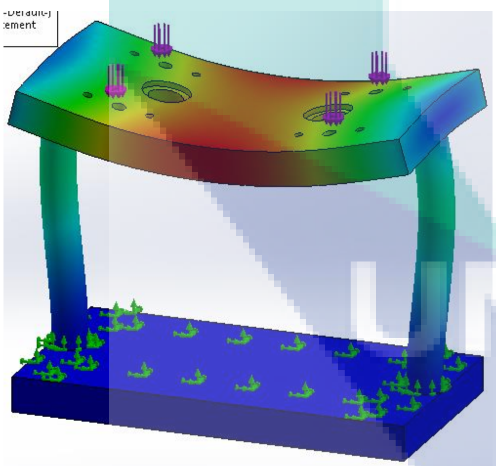
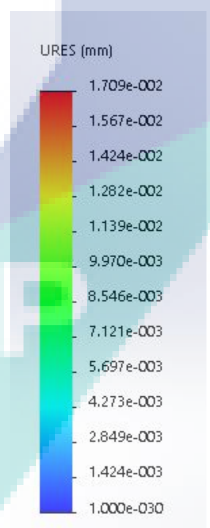
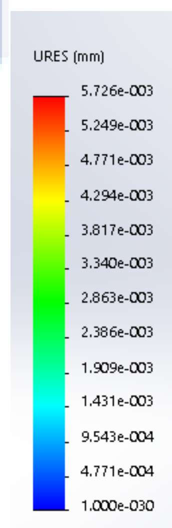
<table>
<tr><th>Component</th><th colspan="2">Total displacement plot (mm)</th></tr>
<tr><td>Machine frame</td><td>Aluminium 6061 alloy</td><td>Carbon steel</td></tr>
<tr><td>
4-column frame</td><td>
</td><td>
</td></tr>
<tr><td>
2-column frame</td><td>
</td><td>
</td></tr>
</table>

Table 3.2 Summary of static displacement responses of machine frame on different materials.

Machine frame	Total displacement (mm)	
	Aluminium 6061 alloy	Carbon steel
C-frame	0.136200	0.0472100
O- frame	0.001131	0.0003835
4-column frame	0.012460	0.0041930
2-column frame	0.017090	0.0057260

3.4.2 Upper Die Displacement Responses

The upper die consisted of top plate and punch guide plate. Upper die plays an important role during forming process as it is the only moving component that transmits force from solenoid to the lower die. The applied force simulates direct contact in solenoid between the top plate and the punch holder plate during actuation. The stiffness of top plate and punch holder plate was evaluated in term of thickness and type of materials. Three different thickness for both plate had selected for evaluation, 15 mm, 20 mm and 25 mm. the global mesh size of simulation for the three thickness are 5 mm, 4.9 mm, and 5.97 mm respectively. The tolerance of mesh size was at average 0.2 mm. Table 3.3 shows displacement characteristic of different thickness of top plate on Aluminium 6061 alloy and carbon steel under four points of 200N applied force. From the results obtained, the top plate with 15 mm thickness showed 0.0072 mm of displacement responses for Aluminium 6061 alloy and 0.002411 mm for carbon steel, respectively. Meanwhile, for 20 mm thickness, top plate demonstrated displacement responses of 0.003267 mm and 0.001093 mm each for Aluminium 6061 alloy and carbon steel. Displacement characteristics of both the top plate and the punch holder plate were found to be within the desired tolerance for both types of material. For 25 mm thickness of top plate, the results showed 0.001869 mm of displacement response for aluminium 6061 alloy and 0.0006242 mm for carbon steel.

Table 3.3 Comparative study of top die displacement responses on different materials.

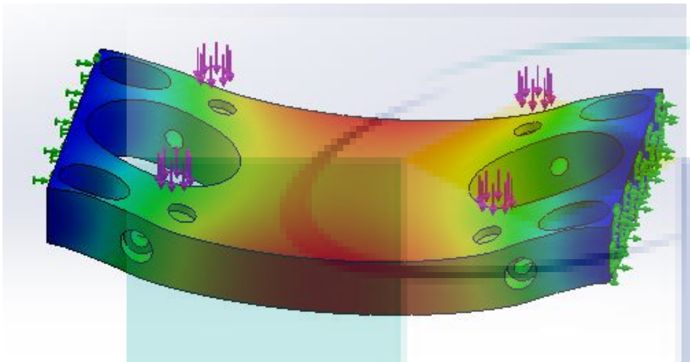
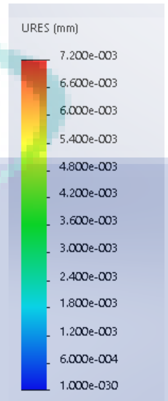
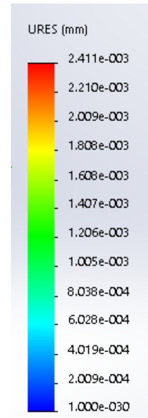
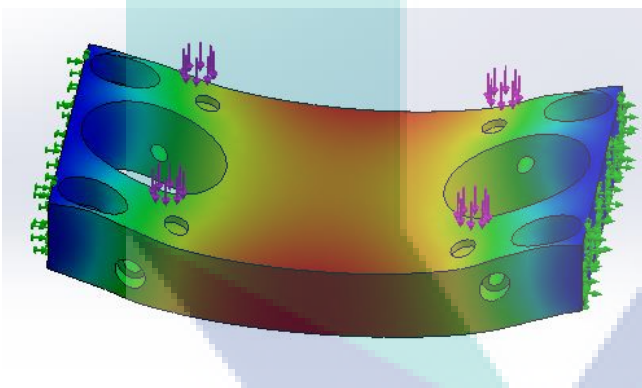
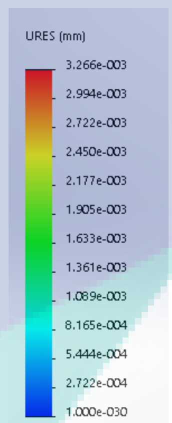
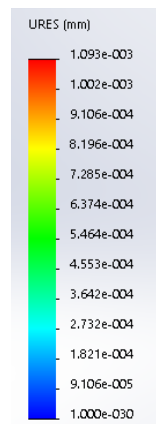
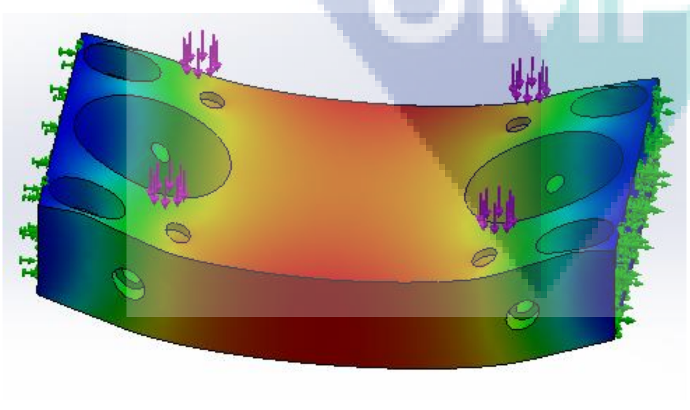
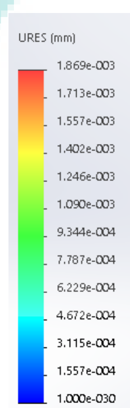
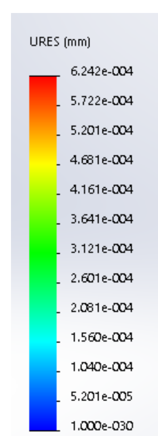
<table>
<tr><th>Component
Top plate</th><th colspan="2">Total displacement plot (mm)</th></tr>
<tr><th></th><th>Aluminium 6061 alloy</th><th>Carbon steel</th></tr>
<tr><td>
15 mm thickness</td><td></td><td></td></tr>
<tr><td>
20 mm thickness</td><td></td><td></td></tr>
<tr><td>
25 mm thickness</td><td></td><td></td></tr>
</table>

Table 3.4 shows displacement characteristic of different thickness of punch holder plate on Aluminium 6061 alloy and carbon steel under 800 N of applied force. The applied force simulates direct contact of top plate with punch holder plate during actuation. For the meshing size creation, global mesh size for the plate of thickness of 15 mm, 20 mm and 25 mm are 4.9 mm, 5.3 mm, and 5.8 mm respectively. The tolerance of mesh size was at average of 0.2 mm. From the results, punch holder plate with 15 mm thickness illustrated 0.009094 mm of displacement response for aluminium 6061 alloy and 0.003071 mm for carbon steel. For 20 mm thickness, punch holder plate demonstrated the displacement response as 0.002474 mm for aluminium 6061 alloy and 0.002014 mm for carbon steel. For 25 mm thickness of top plate, the results showed 0.0008332 mm of displacement response for aluminium 6061 alloy and 0.000595 mm for carbon steel.

Table 3.5 shows the summary of static displacement response results for both top plate and punch holder plate. By taking 0.0025 mm as tolerance, both plate from carbon steel material qualified the simulation evaluation which obtained the displacement response under the tolerance. However, aluminium alloy was taking as priority consideration due to its favorable characteristic and features. The comparison of materials thickness is purpose to avoid over define of component thickness, with the concern of optimization of the usage of materials along with the energy and cost. According to the displacement results, 25 mm of thickness was selected for top plate while 20 mm of thickness was selected for punch holder plate because both values are less than 0.0025 mm.

Table 3.4 Comparative study of punch holder plate displacement response on different materials.

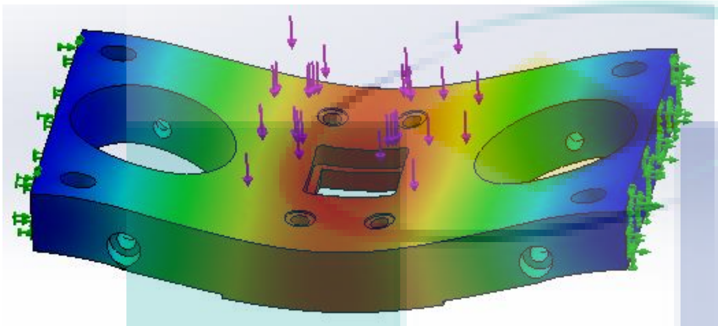
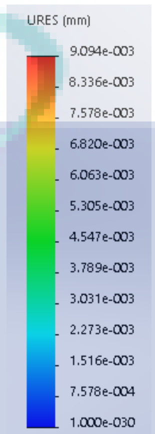
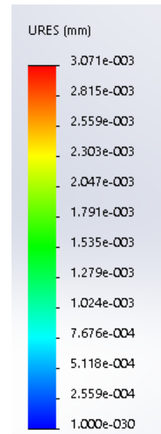
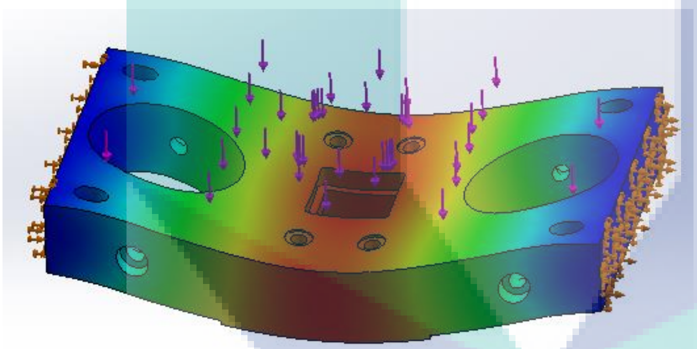
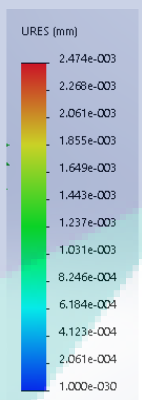
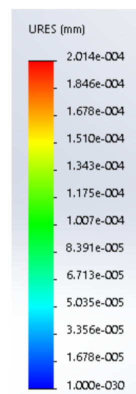
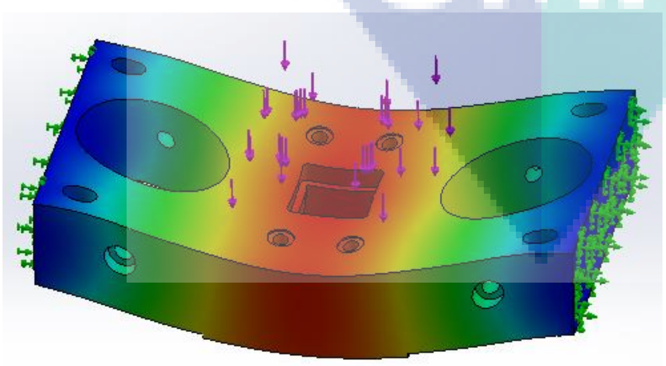
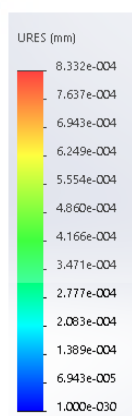
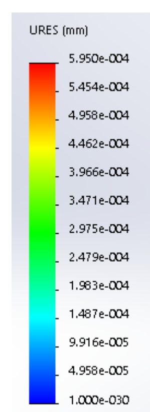
<table>
<tr><th>Component
Punch holder plate</th><th colspan="2">Total displacement plot (mm)
Aluminium 6061 alloy / Carbon steel</th></tr>
<tr><td>
15 mm thickness</td><td></td><td></td></tr>
<tr><td>
20 mm thickness</td><td></td><td></td></tr>
<tr><td>
25 mm thickness</td><td></td><td></td></tr>
</table>

Table 3.5 Static displacement response of upper die components

Upper die components	Thickness (mm)	Total displacement (mm)	
		Aluminium 6061 alloy	Carbon steel
Top plate	15	0.007200	0.002411
	20	0.003267	0.001093
	25	0.001869	0.0006242
Punch holder plate	15	0.009094	0.003071
	20	0.002474	0.002014
	25	0.0008332	0.0005950

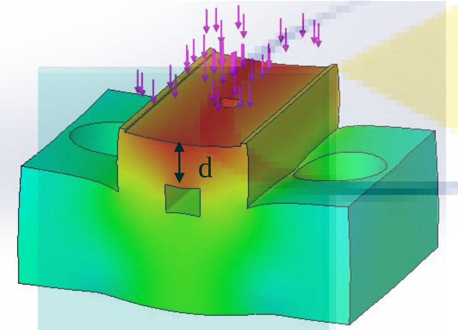
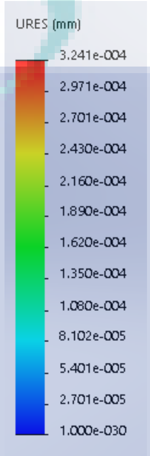
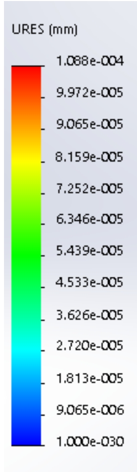
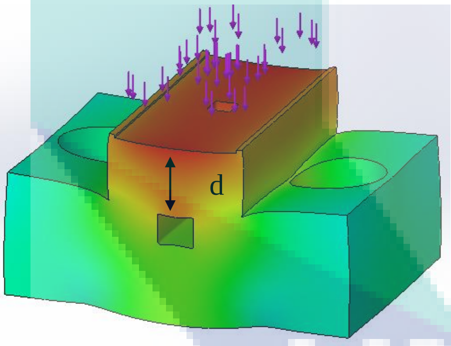
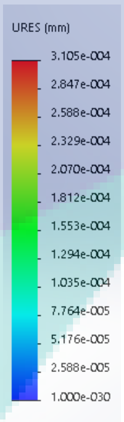
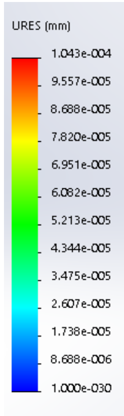
3.4.3 Die Plate Displacement Responses

Table 3.6 shows the displacement response of die plate on different materials. A total of 800N force from four solenoids was applied on the load condition. There was a scrap collection tunnel across the die plate which could weaken the stiffness of the structure. To determine the location of the scrap tunnel position, a study of the relationship between different positions of scrap collection hole and structure displacement responses was conducted. The position of the tunnel would be altered by its distance from the top surface of die plate, indicated as d.

Table 3.7 shows the summary of static displacement responses for different tunnel positions. The results showed that the deflection which occurred on both materials structure met the stiffness requirement. As the tunnel distance, d, increased, the thickness between top surface and tunnel increased the stiffness of structure. From the results obtained, it can be concluded that deflection could be affected by altering the thickness of structure.

O-frame was selected as the appropriate machine concept for the micro-sheet-forming application. In addition, aluminium and carbon steel were selected for comparison as they are the most commonly used and popular materials. Most die shoes are made from steel while aluminium is also a popular die shoe material. Aluminium has one third of the weight of steel and can be machined very quickly, apart from providing greater compressive strength than low carbon steel in alloy form (Hedrick, 2006).

Table 3.6 Comparative study of die plate displacement responses on different materials.

Component	Total displacement plot (mm)	
Die plate	Aluminium 6061 alloy	Carbon steel
 d = 20mm		
 d = 30mm		

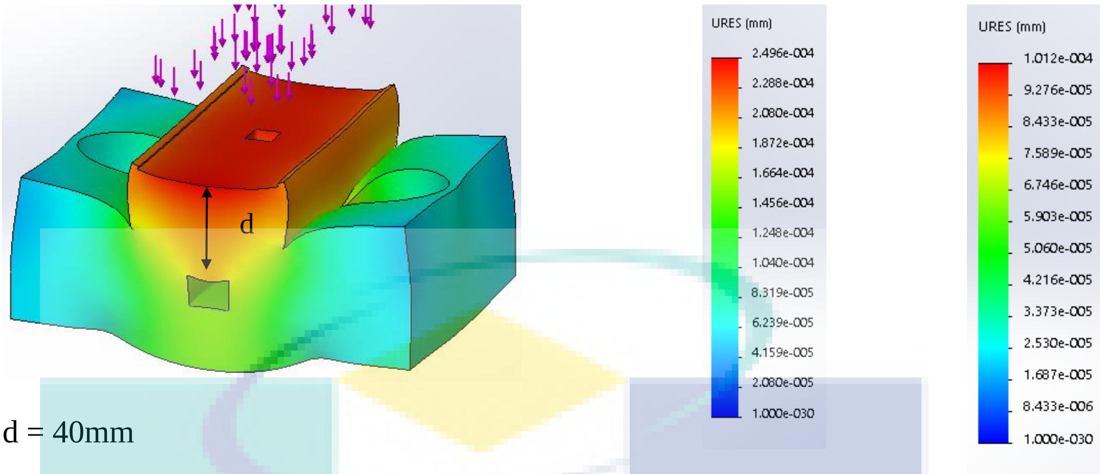


Table 3.7 Summary of static displacement responses of different tunnel distance variation.

Tunnel distance, d	**Total displacement (mm)**	
	Aluminium 6061 alloy	Carbon steel
20	0.0003241	0.0001088
30	0.0003105	0.0001043
40	0.0002496	0.0001012

3.5 Machining Plan

For micro-forming, precision is one of the important issues and a major concern in machine fabrication. In micro-sheet-forming, the tolerance allowed is between 5 and 10 % of the sheet material's thickness. Therefore, quality control of the dimension of the fabrication part becomes crucial to minimize the dimension error in the subsequent micro-forming process.

3.5.1 Technical Drawing

The fabrication was performed according to the selected concept design. Details of the technical drawing of the selected concept design of the micro-sheet-forming machine are presented in Appendix B of this thesis. The machining of sub-components refers to the geometry in the technical drawing.

3.5.2 Material Preparation

Aluminium alloy 6061 was selected as the material for the main structure of die set and machine frame due to its favourable characteristics and based on the results of appropriate examinations which were described in the previous section. Besides, by taking consideration of the continuous and repeatability of the stamping process, the strength of the punch and die needed to be assured. Thus, mild steel was selected for the material of punch and die.

The preparation began with obtaining aluminium from Aluminium 6061 alloy 100 mm × 100 mm square bar. It was sawed into several parts according to the design dimension by band saw machine. The dimensions of sawed parts were slightly greater than the actual dimension so that surface facing could be performed. Moreover, a pair of linear guide posts with bushing from Mingyi manufacturer were used as the connection between tool-set. Bill of materials is shown in Table 3.8. Small components, such as springs and screws, were used for connection and assembly purposes.

Table 3.8 Bill of Materials

Component	Quantity	Materials
Top plate	1	Aluminium
Punch holder plate	1	Aluminium
Die plate	1	Aluminium
Base plate	1	Aluminium
Punch insert	1	Mild steel
Die insert	1	Mild steel
Blank holder	1	Aluminium
Blank holder pin	4	M4 socket cap screw
Scrap collector drawer	1	Aluminium
Linear guide post set	2	Standard part from manufacturer
Fastener	20	M8 socket cap screw
Bushing mounting	8	M4 socket cap screw
Die insert mounting	2	M3 set screw
Compression spring	4	-
Extension spring	4	-
Actuator	4	Ledex low profile 6ECM solenoid

3.5.3 Toolpath Design

Fabrication of the parts was performed by milling process using CNC milling machine. The machining toolpath was designed by computer-aided manufacturing

(CAM) software, called *MastercamX5*. The process began with a 2D CAM system which had tools that allowed designing and creation of the virtual process, with guided CNC machine tools in the manufacture parts. The comprehensive set of predefined toolpaths including contour, drill, pocketing, face, peck drill, and engraving, enable the cutting of the parts efficiently and accurately. In this study, machining toolpath was designed by creating wireframe geometry according to the dimension of parts. 2D wireframe was imported from *Solidworks* into *Mastercam* to act as guide for toolpath. Materials properties of machining part also had been justified beforehand. Volume of stock had been set up as well based on the machining condition. Toolpath was then created by selecting the type of process, and appropriate tool with the corresponding cutting parameter, such as feed rate, spindle speed, cutting speed, and depth of cut. Cutting parameter would be crucial to ensure the precision and accuracy of machining part. Operation was verified by inspecting the step-by-step virtual process. G-code, recognized by the CNC machine, was generated from the compilation of selected operations.

3.6 Fabrication Process

Most of the fabrication processes were covered by CNC milling. Workpiece was clamped at the milling vise to create secure mounting point, allowing support during machining operation to ensure accuracy and precision. Every single workpiece underwent facing process on all surfaces to remove the rough condition and obtained the exact dimensions based on the technical drawing. The facing process was performed by face mill at 600 rpm spindle speed and 0.5 mm depth of cut for every run in order to assure even surface. All the facing process was performed manually by hand jogging.

The continuous punching process of micro-sheet-forming was carried out by the up and down motions in linear direction. These were led by two MISUMI guide post sets with bushing from Mingyi manufacturer. Guide post sets and bushing mounting holes were machined before the machining of all other holes was done. In order to ensure the alignment of mounting positions of the guide post sets and the bushing, the three main structures of the die set, namely, the top plate, the punch holder plate, and the die plate, were clamped together for machining. As the mounting holes were different in diameter, the workpieces were therefore arranged according to the length of the diameter of the hole allocated from the top until the bottom in descending order (i.e., from the biggest to the smallest). Drilling process was conducted using 20 mm drill bit to create the centre slot of the guide post at 1,145 rpm and 50 mm/rev feed rate. The process was selected as peck drilling at 1 mm step to keep chips from detrimentally building up. A conical hole was created beforehand by 10 mm centre drill bit which provided a starting hole for the large sized drill bit and reduced the tendency to wander. In addition, mounting hole for bushing was built by contour process with 14 mm flat end mill at 1,500 rpm and 150 mm/rev feed rate with 0.5 mm depth cuts step.

The punch holder plate consisted of the punch insert and blank holder. The slot of blank holder was created by the pocket process with 4 mm flat end mill at approximately 2000 rpm and 200 mm/rev. The slot for blank holder's pin was drilled by 5 mm drill bit across the plate at 1,500 rpm with 150 mm/rev under 0.5 mm peck drilling. Springs were allocated between the punch holder plate and the blank holder to provide expansion of the blank holder to retract to its original position after every single punching. The pockets counterbored where the spring retained was counterbored 7 mm by 4 mm flat end mill at 1500 rpm and 150 mm/rev with 0.5 mm depth cut step. Furthermore, the punch holder plate and die plate were clamped together for the machining of the punch insert mounting point and the die insert slot. The purpose of clamping together again was to ensure that the positions of the punch and the die were well-aligned so that accurate punching could be performed. In micro-sheet-forming, tolerance was very small at approximately between 5 and10% of the sheet thickness; thus, the precision of punching would be very crucial. The slot was created by the pocket process using 10 mm flat end mill as initial rough step at 1,000 rpm and 100 mm/rev feed rate with 0.5 depth cuts step. Then, 4 mm flat end mill was used to finish the edge by the contour process at 1,000 rpm and 50 mm/rev feed rate with 0.5 mm depth cuts step.

The die plate structure shape was produced by removing the unwanted parts using facing process. The workpiece was cut by 16 mm flat end mill step by step at 1 mm depth cut at 1,500 rpm and 150 mm/rev feed rate. Moreover, a counterbore slot was created at the mounting hole of the guide post to provide space for the movement of bushing. The contour process was conducted by 16 mm flat end mill as well with the same parameters as those in the facing process. In addition, a slot with 50 mm width and 0.5 mm depth of was created on the top surface of the die as the guide for materials feeding. In addition, a tunnel for scrap collection was created across the die plate by using wire electrical discharge machining. A starter hole was drilled by small hole drilling EDM to make a through hole in the workpiece through which the wire was threaded for the wire-cut EDM operation. A hole was drilled from the die insert slot all the way through the tunnel.

Die insert was machined from mild steel obtained from 30 mm x 30 mm square bar. The top surface underwent facing to obtain a fine surface. A 20-mm flat end mill was used to contour the die insert into 20 mm × 20 mm. High spindle speed of 2000 rpm was used with low feed rate at 50 mm/rev. Better surface finish may be achieved by turning carbon alloy steels at low feed rate and high spindle speeds. Roughness of surface is somehow attributed to factors such as vibration of machine, obliqueness in the workpiece, tool wear, and temperature of the workpiece and variation in material composition (Kumar et al, 2012). In addition, smaller depth cuts step, 0.2 mm was used for every single cut all the way down until 25 mm depth. It was necessary to keep the depth of cut as low as possible while machining steel type materials with the concern of tool wear and better surface finish. A single tiny hole was drilled at the centre of die by 1 mm drill bit. Extra care needed to be taken in such micro-scale machining. The drill process was performed under high spindle speed of 5,730 rpm and 150 mm/rev feed rate. For such small diameter of tool bit, peck drill was used and the depth cut was kept as low as 0.1 mm to prevent tool break. Additionally, the punch insert was machined by using 3D milling with 2 mm ball mill. The wireframe geometry was imported from *Solidworks* to create the machining toolpath. The diameter of the punch tips was slightly smaller than that of the die hole for clearance.

Fastener was applied for assembly of the components. Threaded type fastener was applied bearing in mind secure assembly of the components on one hand and also possible occasional dismantling for repair, adjustment, or replacement on the other (Boljanovic, 2005). Fasteners were standardized as M8 socket cap screws for their main component. The counterbore hole was contoured by 6 mm flat end mill at 2,000 rpm and 200 mm/rev feed rate with 1 mm depth of cuts step. The holes of screw were made up of two types of hole: one for the socket cap head and the other for the threaded engagement. The thread hole was then created by hand internal tapping. Three basic configurations of hand tap were applied, namely, taper, plug, and bottoming. Taper tap would act as a starter tap, used to start the thread in a blind hole for another tap to finish or to cut threads all the way on a through hole. Plug tap had tapered threads at the starting end of the tap while bottoming tap cut threads to the bottom of the blind holes. Lubrication was applied throughout the hand tapping to ease the process.

3.7 Assembly Components

In this study, the low energy micro-sheet-forming machine consisted of two main components, namely, tool set and machine frame. The machine comprised parts and subassemblies combined together to perform operation. Every individual part was fit together at a particular part placement by appropriate configuration. Figure 3.6 shows the exploded view of the tool set with the order of assembly of various parts. The main component, that is, the punching section from the upper half of tool set, was assembled initially. The punch insert was assembled by applying the press fit into the punch holder plate. Four compression springs were fit in between the blank holder and the punch holder plate. Bushing was mounted by applying the press fit into the slots at the upper half part of the die and then fixed in its position by eight socket cap screws. In addition, the die insert was mounted by applying the press fit into the provided slot from the die plate and fixed by two set of screws.

Assembly of machine frame was simple, as shown in Figure 3.7. The tool-set was mounted to the frame base plate, followed by two side frame plates and four support plates attached to the frame base. The support plate, as the name suggests, provided extra support to the hollow structure of the frame. Solenoids were fastened on the frame top plate and then mounted to the rest of the structure. In addition, four extension springs connected the machine frame to top plate of the tool-set to provide sufficient force to pull back the upper die to its original position.

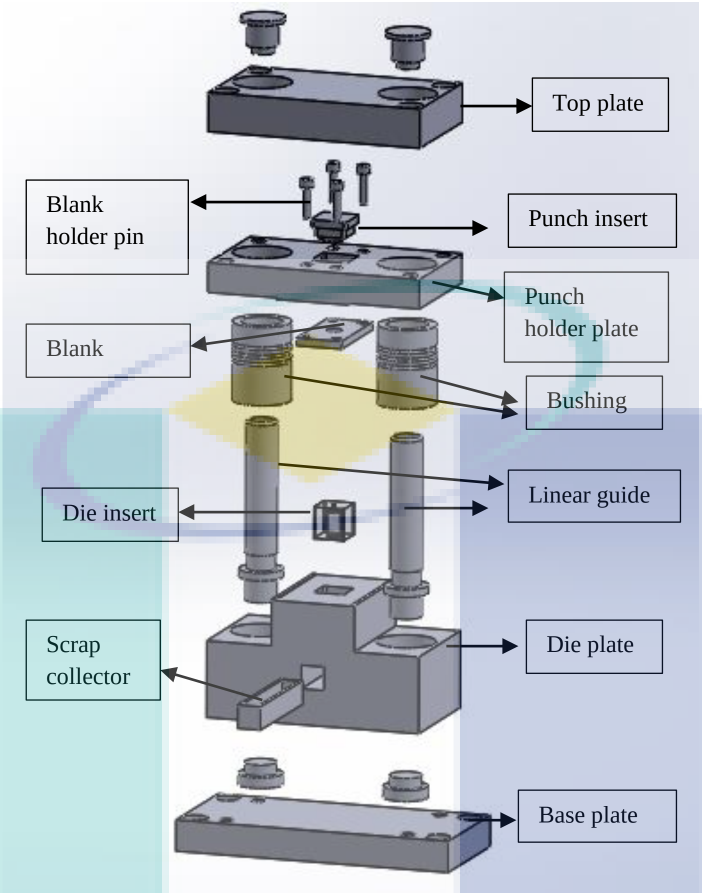


Figure 3.6 Exploded view of the tool set.

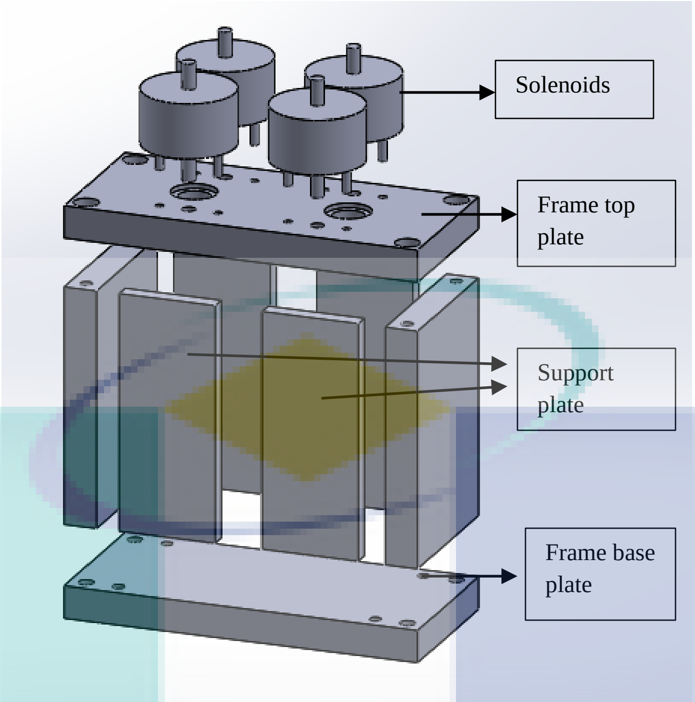


Figure 3.7 Exploded view of the machine frame.

Figure 3.8 shows the assembled tool-set with the close-up of main-subassemblies components. The general structure was built up of aluminium alloy materials whereas the punch and the die were made up of mild steel materials which would have relatively higher strength. Standard parts such as linear guide post set were used to ensure that the die set was accurately located and provide activity during machine operation. Lubrication was applied to the ball cage inside the linear guide post by grease to reduce the friction and ensure operate reliably.

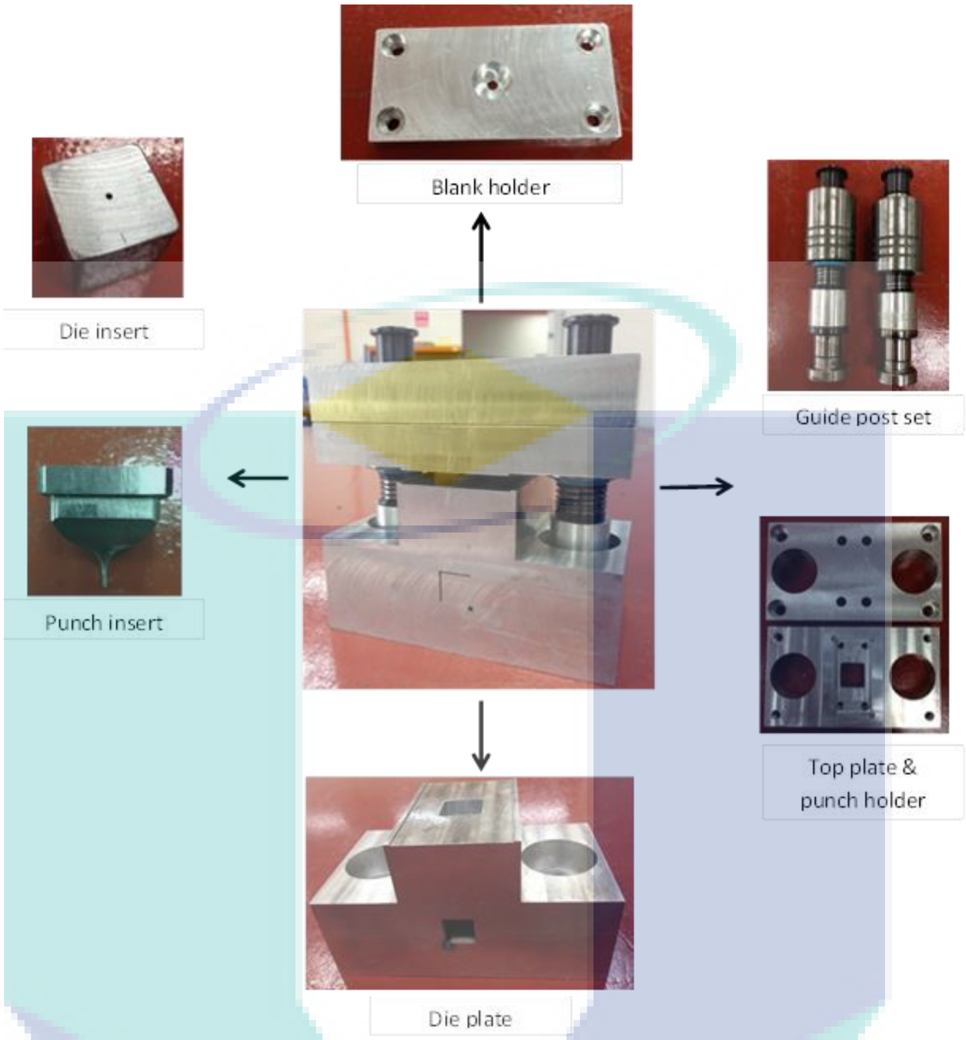


Figure 3.8 Assembled tool-set.

3.8 Conclusion

The design of a bench sized and low energy new micro-sheet-forming machine has been proposed. Several feasible concepts for micro-thin sheet-metal forming have also been established. These were assessed and evaluated with applied-loads and force-analysis. They eventually formed the basis for designing a micro-forming machine. In this study, aluminium alloy was chosen as material because of its characteristics such as machining availability, malleability, better corrosion resistance, and lighter weight. In addition, the machine concept was realized by a simple and low energy control system which corresponded to the objectives of this study.

Consequently, fabrication and assembly of the low energy micro-sheet-forming machine was made possible. The main component of the structure was fabricated from Aluminium 6061 alloy material through CNC process. Precision of the tool-system would be crucial because of narrow tolerances of the dimensions of the micro-components to be formed, which would require the manufacture of die-cavities within the sub-millimeters range in diameter and within a few microns in geometrical accuracy. Thus, the measurement in machining during fabrication was carefully made and repeated to ensure accuracy. Nevertheless, some of the details in the fabrication might have not been possible to be described accurately and thoroughly using words in linear form. Hence, illustrations are made in non-linear form using technical drawing sheets for every component in Appendix A of this thesis which present all the details of the information of the dimensions with annotations. The performance of micro-sheet-forming machine was tested by installing the control system and this will be discussed in the next chapters.

CHAPTER 4

MODAL ANALYSIS

4.1 Introduction

Natural frequency and damping ratio of a machine-tool structure are two parameters which are often examined when determining a strategy for avoiding possible chatter or resonance vibration (Yi Qin, 2012). These two parameters provide the information of structural analysis which is frequently used in machine design. It is one of the fundamental aspects in machine design in which the machine structure is not excited at critical frequencies, or in other words, the operating frequencies must not match the natural frequencies of the machine. The determination of natural frequency is essential which acts as a predictive analysis to avoid some important phenomena such as resonance vibration in the forming process which could result in bad part for the machine, especially for micro-forming application. In micro-stamping, the forming tolerances required may be within the range of sub-microns or at least, less than 5 to 10 % of the strip thickness being used (Razali et al, 2012).

This chapter will describe the experimental modal analysis conducted on the fabricated micro-sheet-forming prototype machine, with the consideration of operational validation in terms of limitation of the operating frequencies for the machine itself. The intention of this chapter is to illustrate the natural frequency of the forming machine that would prevent it from operating under critical frequencies which could result in resonance.

4.2 Experimental Measurement

Modal analysis was performed by using one of the popular modal testing methods, namely, impact testing. It is a fast, convenient, and low-cost way of determining the mode of machines and structures. The principle is to make the examined structure vibrate with an impact hammer with load cell on its tip to measure the force of impact. The impact from the hammer would generate impulses to the accelerometer and spectrum analyser. The excitation and response of particular structure were measured simultaneously. Impact hammer test is depicted in Figure 4.1.

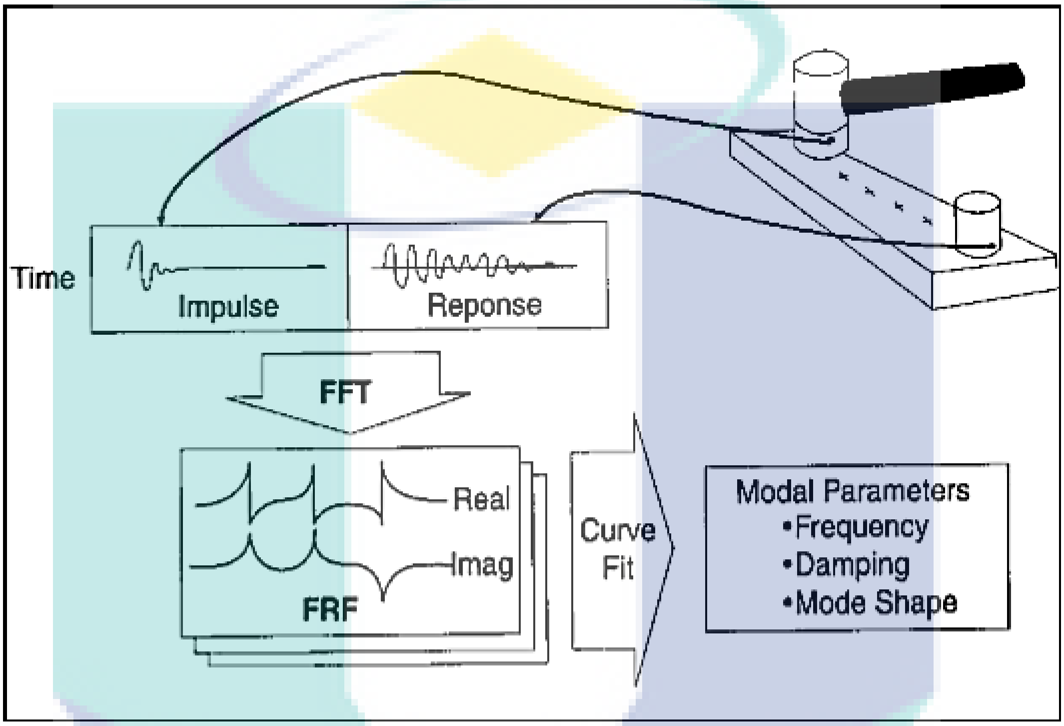


Figure 4.1 Illustration of the impact test.
Source: Schwarz & Richardson, (1999)

4.3 Measurement Tools

Figure 4.2 showed the general purpose modal analysis impact hammer from PCB Piezotronics, with embedded load cell on the tips, along with features: 8 kHz frequency range, 2224 N amplitude range 2.25 mV/N sensitivity, 0.16 kg hammer mass, 0.63 cm head diameter.

Figure 4.2 Modal analysis impact hammer.

Figure 4.3 showed the tri-axial accelerometer used in the experiment. The accelerometer used as 356B18 model of high sensitivity tri-axial accelerometer from PCB Piezotronics, with 0.5 to 3 kHz frequency range, 102 mV/(m/s²) sensitivity, and connected to 1/4-28 4-pin electrical connecter.

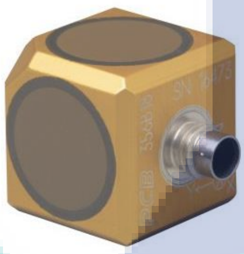


Figure 4.3 Tri-axial accelerometer.

4.4 Roving Accelerometer Test

There are two popular impact tests that are commonly being used: roving hammer test and roving accelerometer test. In this study, roving tri-axial accelerometer test was conducted. The following test method provided one complete column of the FRF matrix as describe the response of the system in a more complete sense. The measurement was taken by impacting the machine structure at a fixed position and moving a single tri-axial accelerometer around several positions. Four positions were selected at each corner of the machine's top surface. In order to perform averaging, five series of impact were performed using the impact hammer for each data capture. The positions for roving accelerometer and fixed impact point are shown in Figure 4.4. The response data were collected simultaneously with Data Acquisition (DAQ) system.

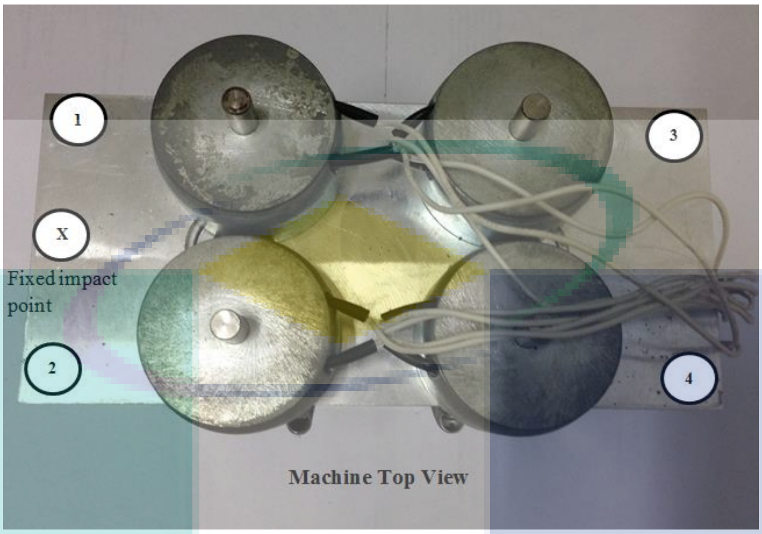


Figure 4.4 Positions for roving accelerometer and fixed impact.

4.5 Data Acquisition (DAQ)

Data acquisition system used was a four-channel National Instruments 9234 type module with one slot compact DAQ chassis as shown in Figure 4.5. One of the channels was connected to the impact hammer and another three channels were connected to tri-axial accelerometer. The DAQ was accessed by *Measurement & Automation Explorer (MAX)* software which was installed automatically with *National Instruments* software. All instruments were synchronized respectively with NI-MAX system in terms of sensitivity, and evaluated for the real-time signal before running the test. *DASYLab* software was used as a monitoring and control application which provided a comprehensive selective of real-time display capabilities. Real-time data were captured and controlled by using *DASYLab* during the impact test. The response data between accelerometer and excitation of hammer were measured in Frequency Response Function (FRF). The FRF data were then imported to *Me'Scope VES* software for further modal analysis.

Figure 4.5 Analog inputs measurement device.

4.6 Results

Figure 4.6 shows the overlap of all of the traces of frequency from every single excitation of impact in linear form. The mode was determined by fitting the frequency curve for mode identified in a frequency range of measurement between 0 and 200 Hz. All of the traces were overlaid, and visually inspected for resonant peaks. The real-time response signals captured various extraneous disturbances known as noise. The noise of frequency capture was expected caused by disturbance of impact hammer connector cable during performing impact. From the overlaid displays, several significant resonant peaks were found in the 50 Hz region.

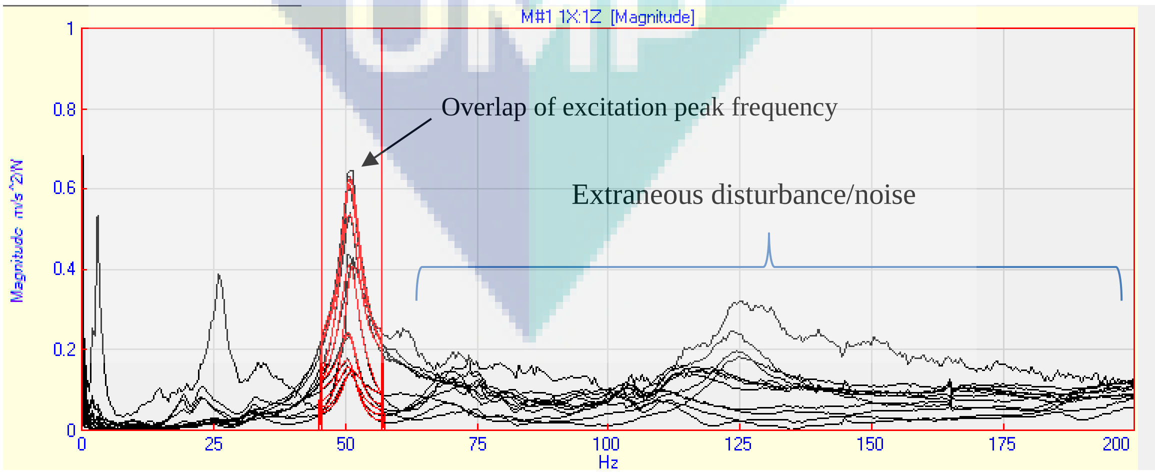


Figure 4.6 Overlap of all of the traces of frequency from excitation.

Experimental modal parameters were estimated by curve fitting the analytical FRF parametric model to a set of experimental derived data. The parameters included the modal frequency, damping, and residue. The resonance peaks data were curve fitted by band cursor and the average modal peaks function results shown in Figure 4.7. In this finding, single mode was identified in the frequency range of the measurements. The outcome of the curve fitting as a set of modal parameters which included frequency damping ratio and residues, is shown in Figure 4.8.

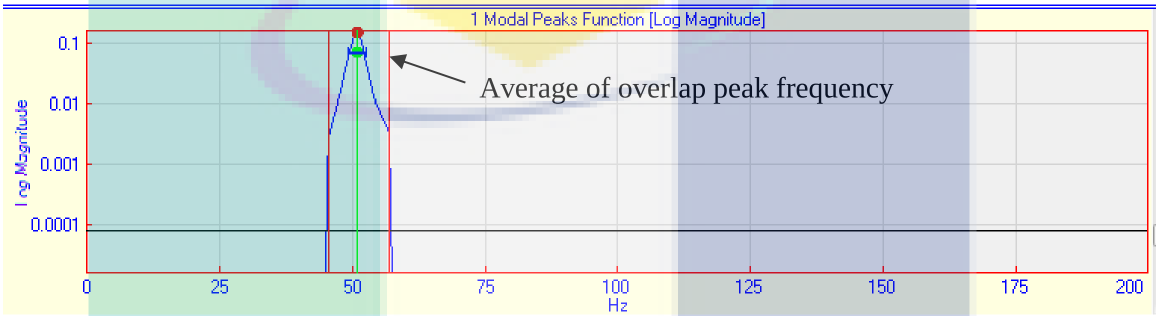


Figure 4.7 Modal peak function

In this finding, single mode was identified in the frequency range of the measurements. The outcome of curve fitting as a set of modal parameters included frequency, damping ratio, and residues was shown in Figure 4.8. The demonstrate 50.9 Hz frequency, 3.58% damping ratio, and residue with 14.2 magnitude and 16.1 degree.

	Select Mode	Frequency (Hz)	Damping (%)	Residue Mag	Residue Phs (deg)
1	Yes	50.9	3.58	14.2	16.1

Figure 4.8 Set of modal parameters for single mode.

4.7 Discussions

The modal frequency result was estimated at 50.9 Hz, which also indicated as the critical frequency of the machine structure at low frequency range. The frequency range below 200 Hz was selected according to the machine operating frequency constraint. The machine was expected to operate below 100 Hz of frequency. The first overlap peak was captured within the range of 50 Hz.

In modal parameter estimation, it concerned typically with estimation of modal frequency, damping and mode shapes. The information regarding to the mode shapes is contained in the modal residues. Modal residue for a particular mode is defined as the product of the modal deformations. In other words, estimating modal residues holds the key to estimating mode shapes and associated scaling factors. However, the mode shape is not the focus in the scope of this study.

It is important to be aware of this and prevent the machine from operating at this critical frequency which could result in resonance. The symmetry design of the machine and good distribution of guide posts as well as solenoid actuators provided relative stability to the machine structure. The result of damping ratio provided the information that it would be necessary to keep the machine operating frequency as far as possible from the critical frequency because of concerns due to safety factor, especially in micro-forming, as forming tolerances may be within the range of sub-microns up to 5 to 10% of the thickness of a thin sheet-metal.

4.8 Conclusion

In a nutshell, it can be concluded from this finding that the natural frequency of fabricated micro-sheet-forming machine tested showed that it was far from the machine's maximum capable operating frequency. The natural frequency is necessary to define as to prevent machine operate under critical frequency which could potentially cause resonance vibration during forming. This estimated natural frequency result can be used as a guideline for alternative process, for instance, high-speed forming process.

CHAPTER 5

ENERGY CONSUMPTION

5.1 Introduction

Scaling down of the machinery and auxiliary equipment may correspondingly reduce energy consumption and materials requirement. Low energy micro-sheet-forming machine which has the capability to conserve hundred times less energy than its conventional counterpart is practically a direct solution for energy consumption in miniaturization process. In this study, micro-sheet-forming machine with low energy solenoid actuation was developed. This chapter describes how energy consumption was measured. It also presents and discusses the results of the experiments conducted and the relationship between energy consumed and operation frequency. In the present study, it was discovered that the micro-sheet-forming machine was capable of operating at a maximum 10 Hz of operation frequency. Verification of the machine punching speed was also made by sound oscilloscope in terms of accuracy of signal transmitted. Energy required for a single punching is also discussed in this chapter before a conclusion is made.

5.2 Measurement Methodology

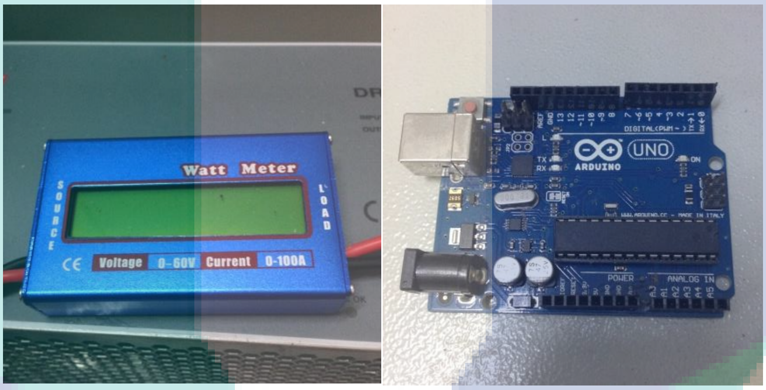
This section demonstrated the setup of experiment with define of equipment used. Experimental procedure was discussed as well with highlighted the verification of machine speed and energy consumption.

5.2.1 Equipment Setup

The actuation of solenoids was manipulated using the popular computing platform Arduino. Arduino UNO board was used to read input signals and turn them into an output, which activated the solenoids. Arduino Uno consisted of 14 digital input/output pins, 16

MHz quartz crystal, and a USB connection. The input signals in this experiment referred to the time interval of ON/OFF conditions of the solenoids. It was powered by plugging in a USB cable to a computer and the output was then connected to the circuit. Solenoids were powered by 24V power supply unit and power transmission controlled by two sets of solid state relays. Each relay connected to the solenoids was controlled by the Arduino UNO board. The inputs were generated using Arduino software by writing the code and uploading it to the board.

A digital LCD 60V/100A power watt meter was used to determine the energy consumed in watt hour units. Figure 5.1 shows the components used for the experiments. The watt meter was installed between the power source and load, which was the solenoids.



(a) (b)

Figure 5.1 Components used for experiments: (a) Watt meter, (b) Arduino UNO board.

5.2.2 Experimental Procedures

A simple test to determine the maximum operating frequency of the micro-forming machine was carried out. It was done by running the machine initially from 1 Hz frequency and increasing the frequency for every test run with 1 Hz increment. The frequency was controlled by the number of ON time of the solenoids within one second which could be manipulated using the Arduino software. The intention was to evaluate the capability of the reaction of the sub-components, such as guide post and spring, to a certain extent of high frequency. The results showed that the machine was able to perform continuous punching at a frequency of up to 10 Hz. Any speed beyond that might cause inconsistent punching of the machine. This was because the springs could no longer provide consistent retraction of punching mechanism at high frequency. Thus, it can be concluded that the micro-forming machine would be capable of operating at a maximum frequency of 10 Hz.

Furthermore, verification of machine speed was also carried out. This was done to evaluate the output signal accuracy. It was intended to validate the precision of the signal transmitted from input to output. Figure 5.2 shows time control and delay plot of energized solenoid for one complete cycle. Solenoid was energized by the control of signal from Arduino through solid state relay. It was known that the solid state relay took 20 µs of time delay for it to respond to energize and de-energize. Although the time response was minimal and insignificant in one cycle time, it should be taken into account when the frequency of ON and OFF conditions increased at higher frequency. A practical way of verifying the time response was conducted by capturing the pulse of the punching of the machine using sound oscilloscope. The highest machine operating frequency of the punching speed, that is, 10 Hz, was selected as the testing parameter.

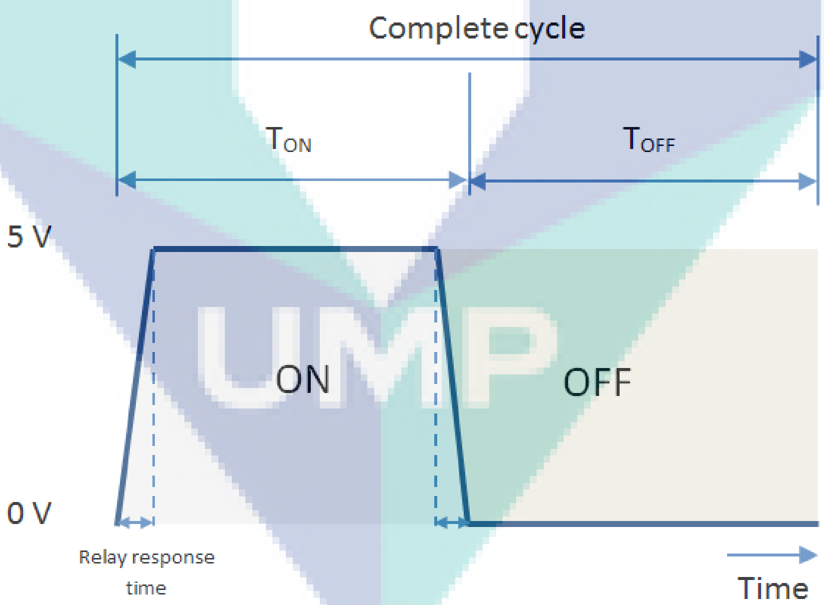


Figure 5.2 Time control and delay plot.

Apart from that, comparison amount of energy consumption at different operating frequencies was carried out by running the micro-forming machine from 1 Hz to 10 Hz. Each frequency was examined by running the machine several times for six different durations: 10, 20, 30, 40, 50, and 60 seconds. The ON time for solenoid was standardized throughout the test as 50 milliseconds. The active time for solenoid during testing was decided from the maximum operating frequency. Energy consumption result in watt-hour (Wh) units was collected three times and discussed.

5.3 Results

The result of experiment was recorded and discussed further. This section was demonstrated the results of experiment in the category of verification of machine speed and energy consumption.

5.3.1 Measure and Verification of Machine Speed

Figure 5.3 shows the results of sound oscilloscope at 10 Hz frequency. Ten pulses were found between every second time interval which suggests that ten successful punches were produced within every second. Therefore, the accuracy of output signal was verified.

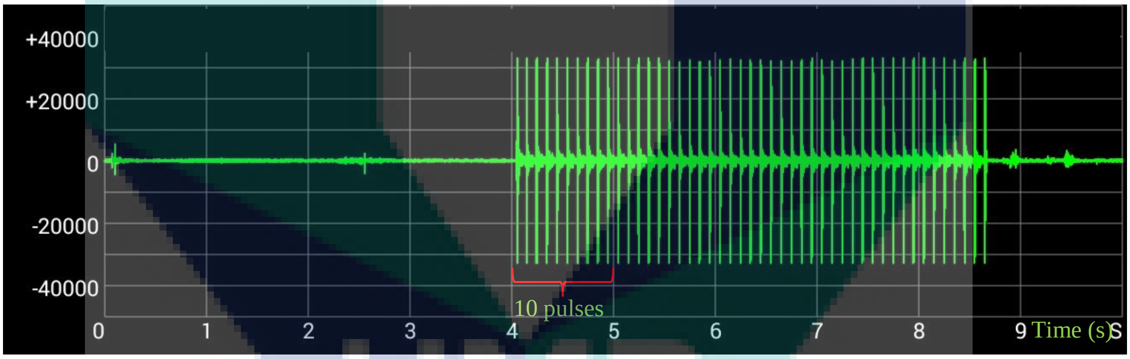


Figure 5.3 Results of sound oscilloscope of machine punching at 10 Hz.

5.3.2 Energy Consumption

The results of energy consumed at different frequencies were obtained. Raw data are presented in Appendix D of this thesis. Figure 5.4 illustrates the results of energy consumption at different operating frequencies. From the result, it can clearly be seen that the energy used generally increases over time. The trend line also clearly illustrates that overall energy consumed increases as the frequency increases, which increased at the initial 10 seconds within the range of 0.1 Wh (1 Hz) to 0.4 Wh (10 Hz), while for the 60 seconds operating time, the range of energy consumed expanded from 0.6 Wh (1 Hz) to 2.3 Wh (10 Hz). However, the trend line also shows a slightly different variation. For frequencies from 1 Hz to 3 Hz, energy consumed increased steadily over the time whereas for frequencies 4 Hz to 6 Hz, there was a slight slope in the trend, before rising steeply for frequencies from 7 Hz to 10 Hz.

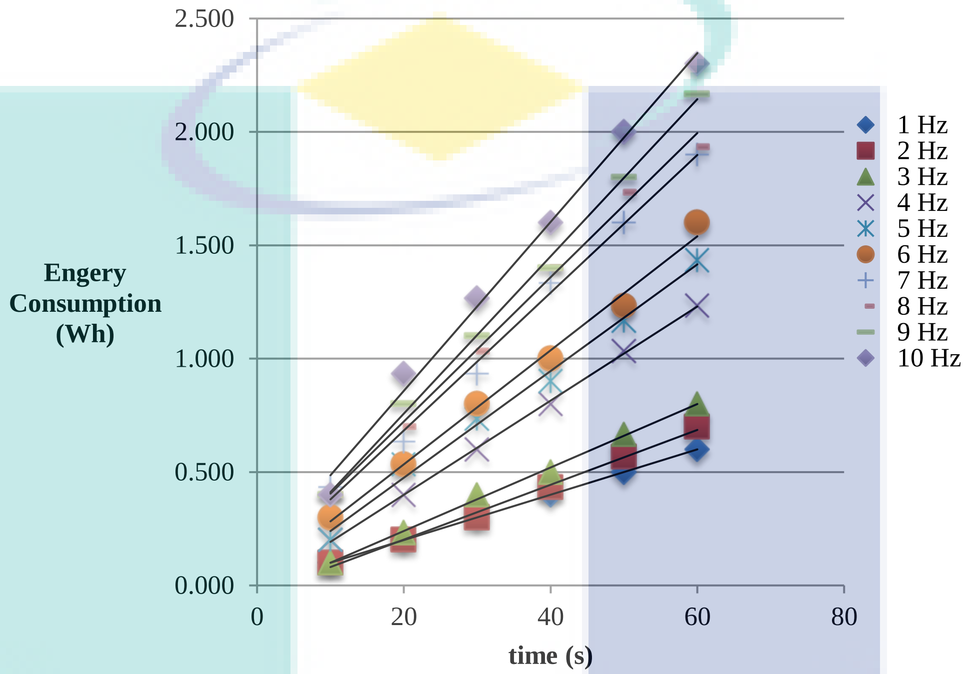


Figure 5.4 Energy consumption results at different operating frequencies.

5.4 Discussions

One of the issues concerned in this study is the collaboration between the input signal generated and the reaction from the output actuation at high frequency and high speed forming. Delay in transfer input signal into output might occur especially at the very short time exchange between ON and OFF during high speed process. In this study, the response of output reaction coordinated well with the input signal at high frequency. The high speed punching was able to generate.

The energy consumed of machine increased with the increase in frequency. This can be explained by the number of ON time of solenoids. At high speed forming, the number of punching required for the forming process became higher. Indeed, the frequencies of solenoids turned on also rose, thereby increasing the amount of energy generated to activate the solenoids. Thus, the total energy consumed by the machine at high frequency forming process also increased. Table 5.2 shows the equations of trend lines in Figure 5.4 at different frequencies. Since the energy consumption depicted linear proportional relationship, the gradient of the trend lines could act as the power factor to estimate the energy consumed over time. From the power factor of each trend line, the operating frequency could be classified into three categories: low speed (1 Hz to 3Hz), medium speed (4 Hz to 6 Hz), and high speed (7 Hz to 10 Hz). The power factor was found to increase proportionally with the increase in frequency. As the frequency increased, the number of complete cycle would increase as well. When the cycle was high, the amount of solenoid energized would also be high. To this extent, it consumed more power to get the job done. Thus, as the operating frequency was high, the power factor was also proportionally high.

Table 5.1 Trend line equation for each frequency.

Frequency (Hz)	Trend line equation	Stroke per minute (spm)	Machine speed categorize
1	y = **0.01**x	60	Low speed
2	y = **0.0121**x - 0.04	120	
3	y = **0.014**x - 0.04	180	
4	y = **0.0208**x - 0.0156	240	Medium speed
5	y = **0.0235**x + 0.0044	300	
6	y = **0.0251**x + 0.0311	360	
7	y = **0.0304**x + 0.0756	420	High speed
8	y = **0.0318**x + 0.0867	480	
9	y = **0.0347**x + 0.0644	540	
10	y = **0.0372**x + 0.1133	600	

Energy consumed in watt-hour (Wh), which is discussed here in this chapter, is a unit of energy equivalent to one watt of power expended for one hour. Watt-hour is not a standard unit in any formal system, but it is commonly used in electrical applications. In addition, it is also the common measurement of electricity rate for pricing. A simple calculation can be done to estimate the energy required for a single punch. By taking the energy consumption of 2.3 Wh at 60 seconds under 10 Hz frequency as reference, an example of calculation is as follows:

Number of punches generated per second: 10

Number of punches generated at 60 sec: 60 x 10 = 600

Energy required for 60 sec punching: 2.3 Wh

Energy required for single punching: 2.3/600 = 0.0038 Wh

The energy required for a single punch at 10 Hz in the present study was approximately 0.0038 Wh. In addition, data for energy consumption could be used as a guide/ reference to know how much energy that would be required for any particular condition. It can also be used as an estimation of electricity pricing. However, research on energy consumption of the punching process of the micro-sheet-forming machine is lacking. In additions, lack of actual value of energy consumption from forming machine could be found elsewhere. Most of the research had successfully downsizing the scale of forming machine in term of machineries and tools towards industrial production, regardless of concerning on the energy usage. For instance, the bench-top machine dedicated for micro-sheet-forming which developed at the University of Strathclyde, consume 415 VAC of power supply for actuation system to work. Thus, by compare with the former, the micro-sheeting-forming machine from this study which power rated at 24 V represented relatively low energy consumption.

5.5 Conclusion

In this study, a low energy micro-sheet-forming machine that was capable of operating at a maximum frequency of 10 Hz was developed. The time control of signal input worked precisely with the output response. In addition, energy usage of the micro-sheet-forming machine was also studied. The experiment results demonstrated that energy consumed increased as the punching frequency of the machine increased. With regard to power factor, the speed of the machine could be classified into three categories: low, medium, and high. Finally, energy required for punching was also studied and discussed. It was observed that there was a positive relationship between energy consumption and frequency.

CHAPTER 6

MACHINE PUNCHING PERFORMANCE

6.1 Introduction

It was anticipated that with the miniaturization of the scale of the machine components and corresponding actuation system, the punching force would also be downsized. In this chapter, the performance of the punching ability of the fabricated low energy micro-sheet-forming machine will be described. A simple test was carried out by thin sheet metal materials punching. The machine was able to punch stainless steel and carbon steel strips up to 100 µm. The relationship between punching force and voltage supply will also be discussed. This was examined by conducting by an investigation into the variations of punching force with the control of voltage supply. The finding revealed the proportional relationship between voltage and punching force: as the voltage supplied increased, the punching force of the low energy micro-sheet-forming machine also increased.

6.2 Equipment and Materials

The equipment and materials used for experiment was demonstrated in this section. Force sensor and controllable power supply unit were defined for the study of punching force and voltage relation. Three different types of punching specimen materials in term of type of materials and thickness also been defined and discussed according.

6.2.1 Force Sensor

Force sensitive resistor (FSR) was used in this experiment to measure the punching force with the variation of voltage supply. FSR as shown in Figure 6.1 is basically a resistor that varies the resistance (measured in ohm, Ω) as the force applied on it either increases or decreases. When there is no external pressure applied, the circuit of sensor is in a high resistance state. As the pressure increases, the resistance goes down. The resistance was read by using multimeter. FSR was powered by 5 V.

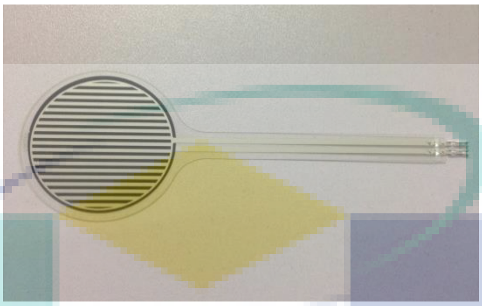


Figure 6.1 Force sensitive sensor (FSR).

6.2.2 Power Supply Unit

The Voltcraft VSP 2405 3x Output Remotely Controllable Variable Switched Mode DC Power Supply (see Figure 6.2) was used to vary the voltage for punching test. This 409W power supply features 3x outputs with setting ranging from 0.1 to 40VDC (0 to 5A), 0.1 to 40VDC (0 to 5A) and 0 to 6VDC (1.5A) with fine adjustment on A-output and B-output for V and I, and adjustment for V on C-output.

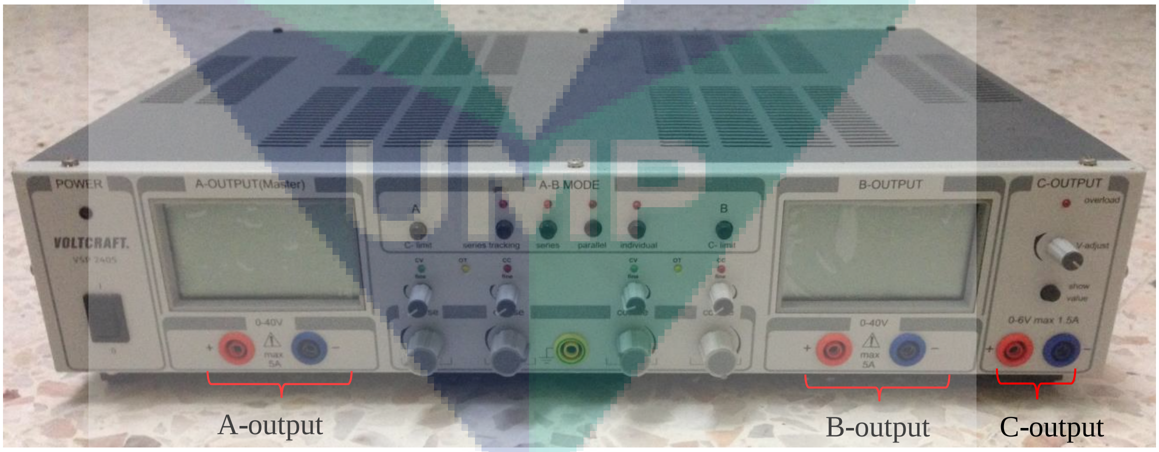


Figure 6.2 Controllable Variable Switched Mode DC Power Supply.

6.2.3 Punching Specimen

The punching test specimen was typically prepared from sheet coil. The sheet coil was cut into 50 mm × 50 mm pieces. Three types of specimens cut into similar pieces in terms of length, were used: 50 µm and 100 µm carbon steel strips and 50 µm stainless steel strips. The specification of materials used are hardened and tempered high carbon steel 1.1274 type, with 293 Brinell hardness and 1015 MPa UTS; and temper rolled stainless steel 1.4310 type, with 217 Brinell hardness and 515 MPa UTS.

6.3 Experimental Procedure

The performance of micro-sheet-forming machine was evaluated using two approaches, namely, force versus voltage and thin sheet punching test.

6.3.1 Force vs. Voltage

Figure 6.3 shows the setup of FSR in circuit. Measurement of the resistive sensor was performed by connecting one end to the C-output from the power supply, and the other end to a pull-down resistor to the ground. The C-output power supply was set at 5 V. The point between the fixed pull-down resistor and the FSR sensor was connected to a multimeter.

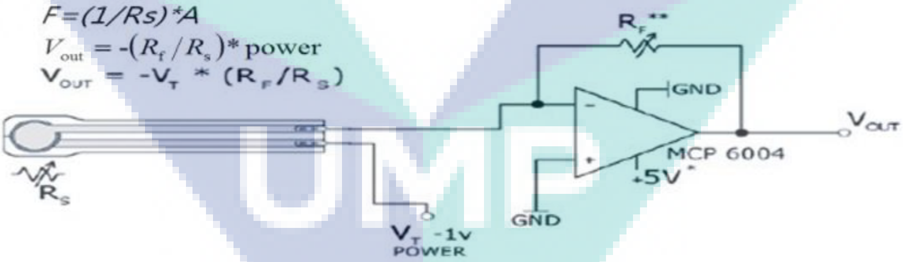


Figure 6.3 Setup of circuit for FSR.

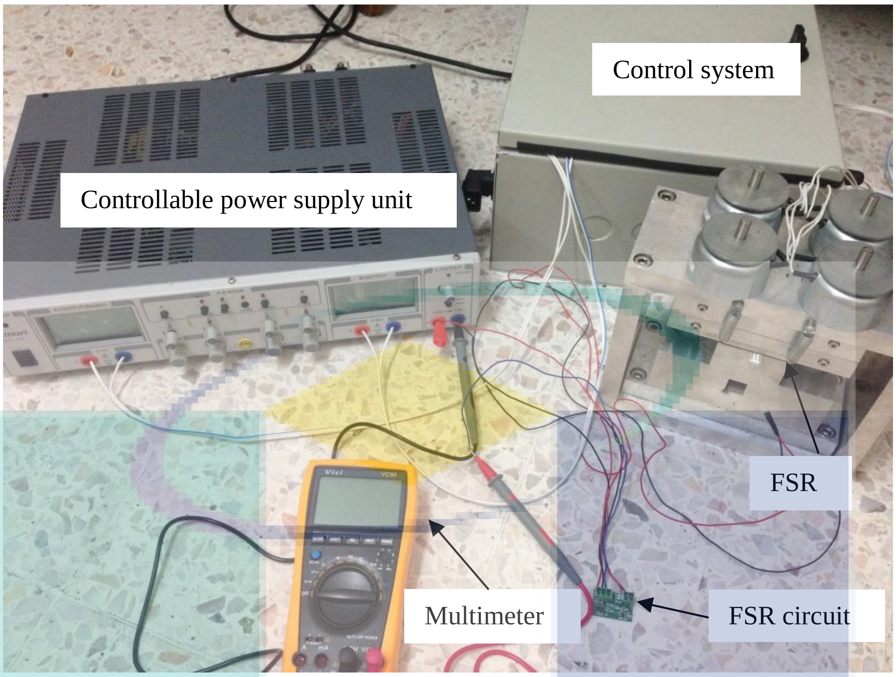


Figure 6.4 Setup of force vs voltage experiment.

Figure 6.4 showed the setup of force versus voltage experiment. The control system of micro-sheet-forming machine was connected to the controllable variable switched mode DC power supply. The circuit was connected to both A-output and B-output. In order to double up the current for solenoids actuation, the mode was set in parallel. The FSR was attached to the top surface of the die plate as shown in Figure 6.5. The punch insert was removed to prevent damage to the sensor. A 24 mm diameter and 1.5 mm thick of impact platform was attached on the force sensor. The blank holder was removed from the spring and kept close to the punch holder plate until the surface was uniform. Force was stimulated from the punching between the upper half die and the lower half die. Moreover, testing parameters for the voltage varied at 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 V. The instant reading of FSR resistance from multimeter was recorded simultaneously during the ram. Reading was recorded for three times to obtain average. The corresponding force value was extracted from the data sheet as shown in Figure 6.6

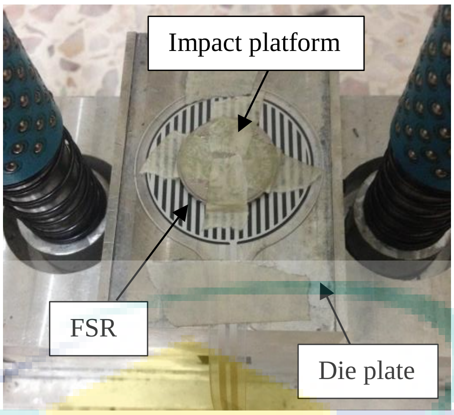


Figure 6.5 Mounting of force sensor resistor.

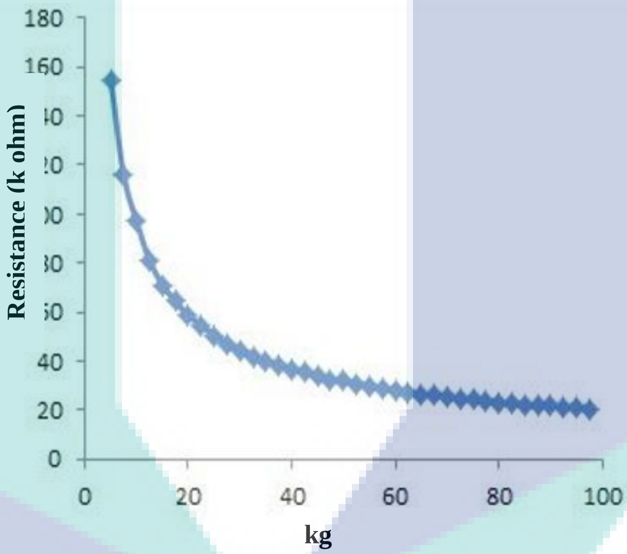


Figure 6.6 Data sheet of FSR measurement from manufacturer.

6.3.2 Punching Performance Validation

The thin sheet punching test was simple and direct. It was carried out by punching the test specimen using the single ram of micro-sheet-forming machine. The power used for this test was 24 V. The results were then evaluated by visual inspection.

6.4 Results

Figure 6.7 shows the graphical results of resistance data when punching was carried out at varied voltages. The trend line demonstrates an inversely proportional relationship between resistance and voltage as expected. The corresponding force for particular resistance was traced out from the data sheet and plotted in graph as illustrated in Figure 6.8. The results show that voltage was proportional to the punching force. For 6 V of voltage, the forming machine produced a punching force of 40 N. When the voltage was increased to 24 V, the machine was able to execute approximately 320 N of punching force. Therefore, it can be said that as the voltage supplied to solenoid increased, the punching force of machine would also increase.

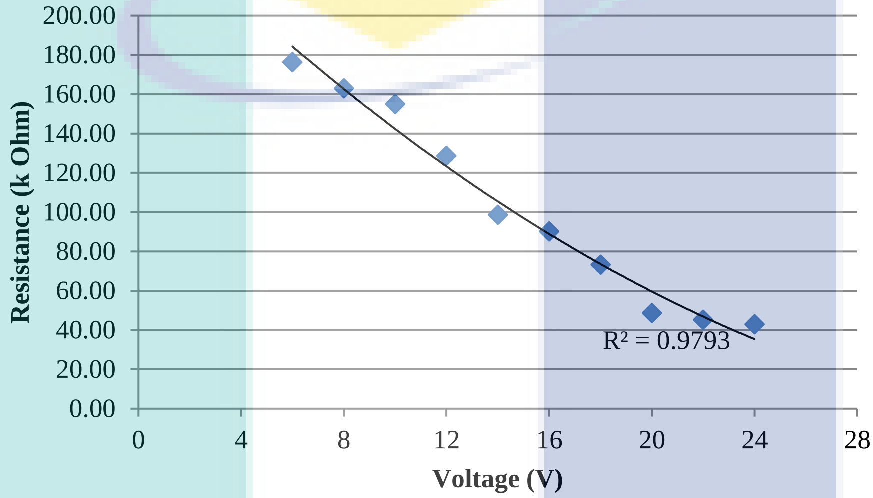


Figure 6.7 Results of resistance with punching at varied voltage.

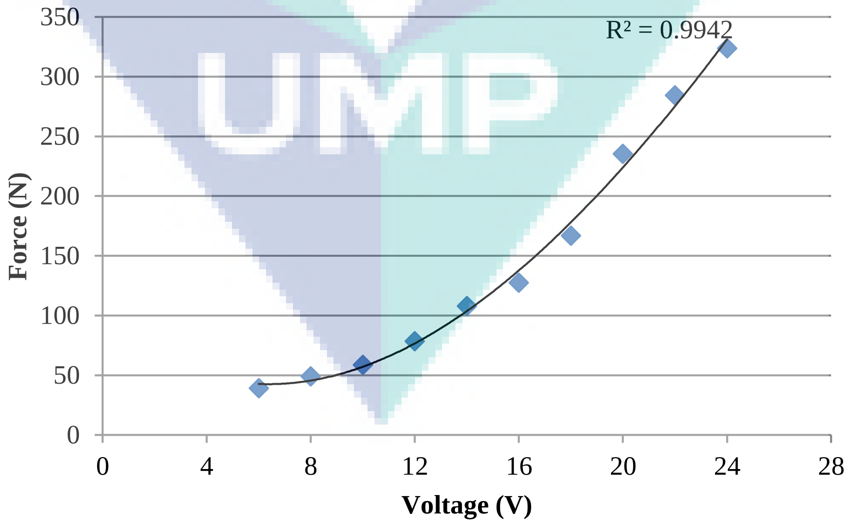
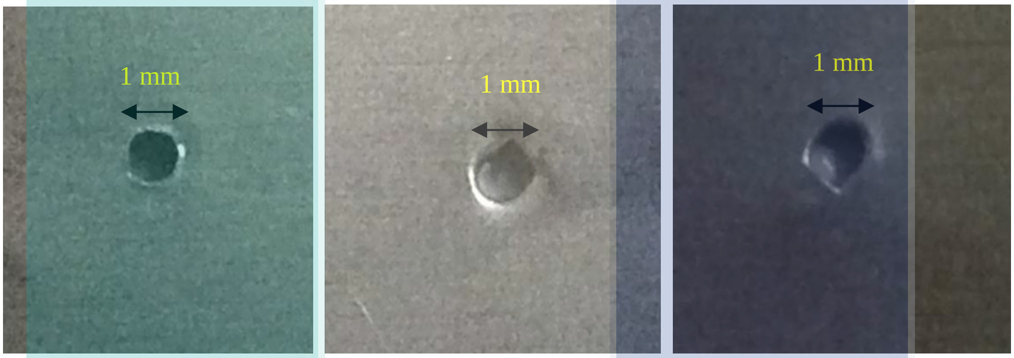


Figure 6.8 Results of punching force at varied voltage.

Figure 6.9 shows the results of punching hole on the three specimens: 50 µm and 100 µm carbon steel strips and 50 µm stainless steel strip. 1 mm diameter of round hole was successfully made on each of the three different strips. By inspecting visually, a round and clean cut of punch hole was observed on 50 µm carbon steel strip. For the 100 µm carbon steel strip and 50 µm stainless steel strip, the hole made was found to be of irregular round shape. Rollover was observed at the upper side of the punch hole. Burr was found on the lower side of the punch hole from the three specimens. For 50 µm carbon steel strip, burr was observed at the periphery of the hole. For both the 100 µm carbon steel strip and 50 µm stainless steel strip, shear fracture hole was found at the lower side of each specimen, and relatively large burr was found as well.



(a) (b) (c)

Figure 6.9 Punching hole on (a) 50 µm carbon steel strip, (b) 100 µm carbon strips, (c) 50 µm stainless steel strips.

6.5 Discussion

In the event of a flow of electrical current across the conductor inside a solenoid, a magnetic field would be generated and the conductor would become an electromagnet. The plunger, located inside the coil, would be attracted towards the centre of the coil by the magnetic flux and this would produce stroke. This is how the solenoid works. The strength of this magnetic field can be altered by controlling the amount of current flowing through it. Although there are a few other ways to control the solenoid forces such as stroke distance and number of coil turns, the method of changing the power of solenoid is more feasible to be conducted without modifying the machine structure. Indeed, the actuation force was decided in advance in machine design consideration. In order to deal with different kinds of materials, it would be necessary to vary the punching force for the forming process. Different materials may have different sizes and physical properties. Optimization of energy usage could be realized by specifying the punching force for the particular materials.

There has been a claim that the number of grains of work metals along the punching direction would decrease as the thickness of work metals decreases (Joo et al, 2005). In this situation, typical mechanism of ductile fracture by the crack initiation and propagation did not work, but rather shear deformation dominated along the hole wall and the scrap was not punched.

6.6 Conclusion

In this study, the relationship between voltage supplied on solenoids and the resulting punching force was examined. The experiment results demonstrated that the punching forces changed with voltage supply: as the voltage increased, the punching force would also increase. It can be concluded that the forming force may be flexibly controlled by manipulating the voltage input to the machine. This relationship was studied with the intention of machining materials with optimum energy. Materials with lower strength properties may require lower force for forming. It would therefore be a feasible solution for micro-sheet-forming machine application to optimize energy usage and make the forming process of the machine become more flexible in terms of voltage. Additionally, the punching performance of the machine was also evaluated. It was found that the machine was capable of forming thin sheet metal from carbon steel and stainless steel measuring not more than 100 µm. Based on the punch hole results, it can be concluded that a larger clearance between the punch and the die hole should be recommended to avoid shear fracture.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

In this study, past literatures on micro-manufacturing, micro-parts/ micro-products in general were reviewed. This is done by giving the definition of the terms and also highlighting examples of the efforts of previous researchers in this field. This was then followed by focusing the bulky manufacturing process narrow down onto one interested manufacturing process which was the stamping process. Definition of stamping was given by highlighting the process parameters. This was followed by examples of stamping machines developed to serve micro-stamping operation. The literature review ended by critically examining issues related to the field itself and a summary of the critical review was made. The present researcher then embarked on a mission to address the problem of production of micro-parts using low energy consumption machine.

The development of new thin sheet system forming concepts for micro-sheet-forming applications included the development of conceptual design models, analysis of methods for assessment, and the mini-experiments. Several concepts were generated and these were evaluated with guided by sound theoretical principles. The concept was then optimized. The optimal concept was later selected to develop a detailed design. A prototype of a low energy machine system for a micro-sheet-forming that included mechanical and electronics elements with synchronization of control with other parts of the machine was required and later produced.

The prototype of the low energy micro-sheet-forming system was tested, optimized and enhanced with reference to micro-sheet-forming requirements. The machine performance was evaluated in terms of natural frequency, punching forces, punching speed and capability, energy consumption (single punch and frequency-time based). The machine was capable of performing single stage micro-sheet-forming processes for forming thin sheet metal parts measuring not more than100 µm. The machine had the capability of up to 600 strokes per minute with force capacity of 320 N. The power consumption for the machine to produce a single part was 0.0038 Wh.

7.2 Recommendations

To further improvise the machine system, a few recommendations are proposed. Firstly, the machine forming process should be developed into multistage forming. In fact, many present micro-products in the market are manufactured by multistage forming, especially those commonly found in sheet metal forming. With the multistage forming feature, the sheet metal forming machine offers the possibility of manufacturing various forming products. It also provides a flexible option for the demands for micro-products. In addition, flexible punch and die for the machine is also proposed to be tested in terms of different shapes and sizes. Flexible punch and die could provide a flexible option for micro-product design.

Furthermore, integration of high-precision feeding system to the forming machine is also suggested. The integration of feeding system could provide the automation processing feature thereby promoting the sheet forming machine toward industry production. High precision of materials feeding is necessary in order to cope with the high speed manufacturing process. Precision feeding is necessary to ensure that micro-parts can be produced with sufficient accuracy, especially in multi-stage forming, while high-speed feeding is inevitable to meet industrial production-rate requirements.

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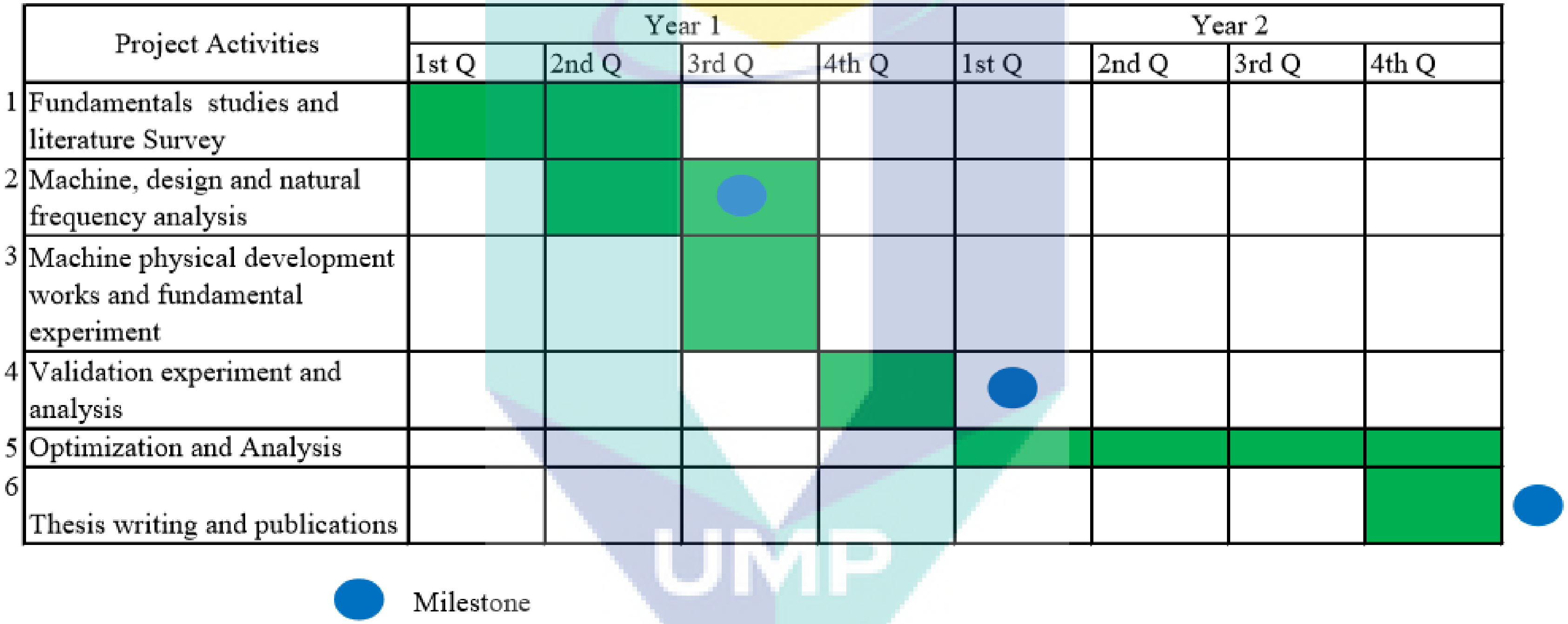
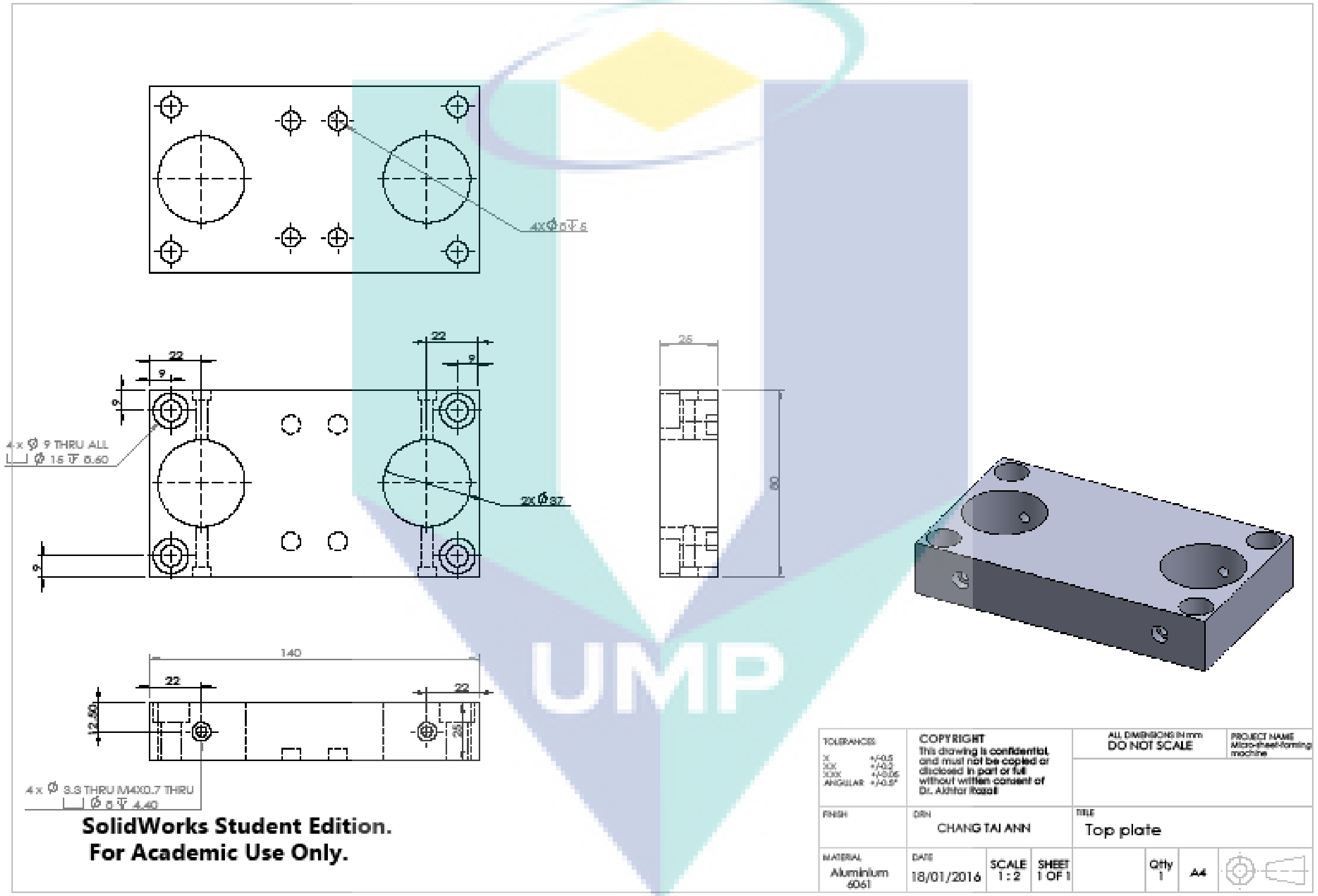
APPENDIX A
GANTT CHART

Gantt Chart with Milestones



APPENDIX B1



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4 x Ø 9 THRU ALL
⌴ Ø 15 ↧ 8.60
2X Ø 37
140
4 x Ø 3.3 THRU M4X0.7 THRU
⌴ Ø 5 ↧ 4.40
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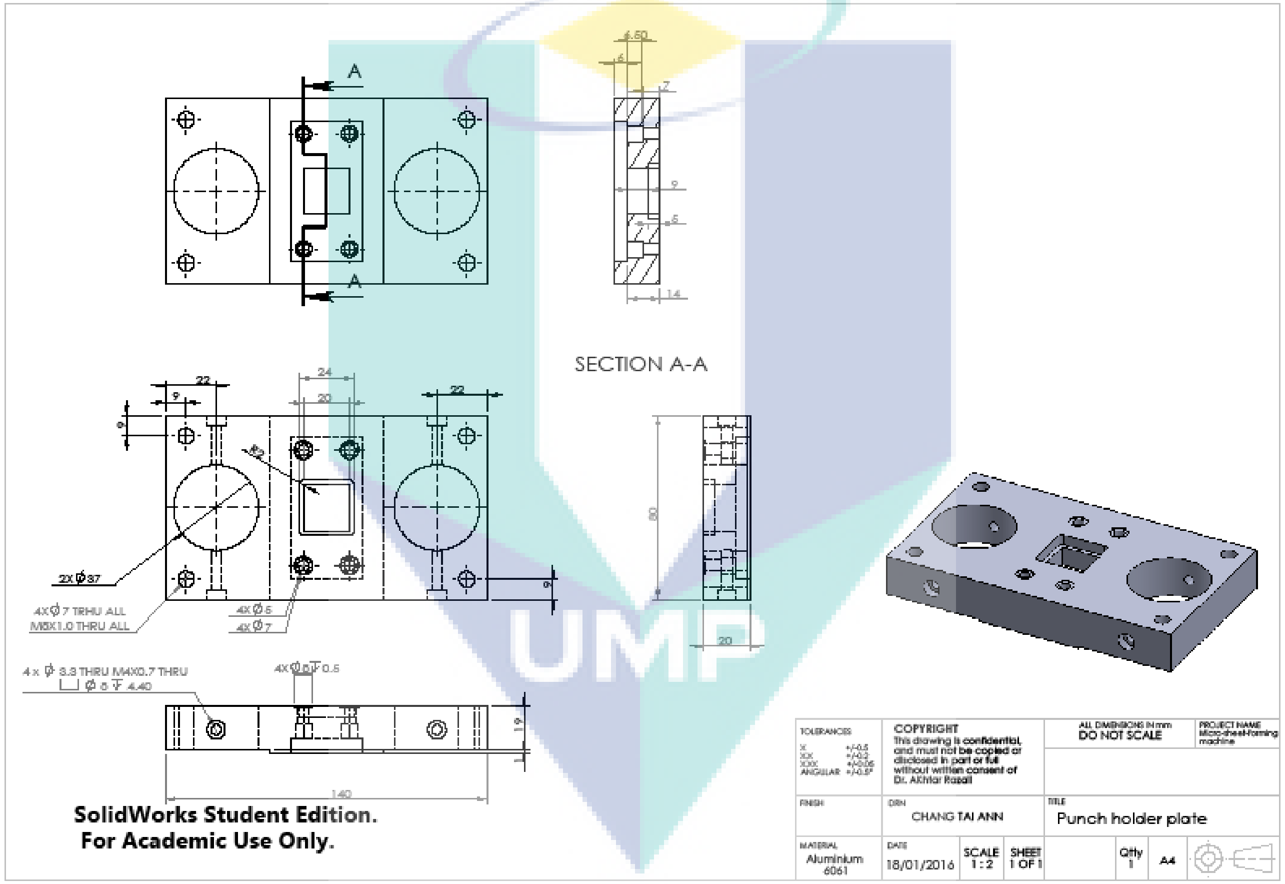
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
DRN
CHANG TAI ANN
TITLE
Top plate
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE
1 : 2
SHEET
1 OF 1
Qtty
1
A4

APPENDIX B2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M8X1.0 THRU ALL
4X Ø5
4X Ø7
140
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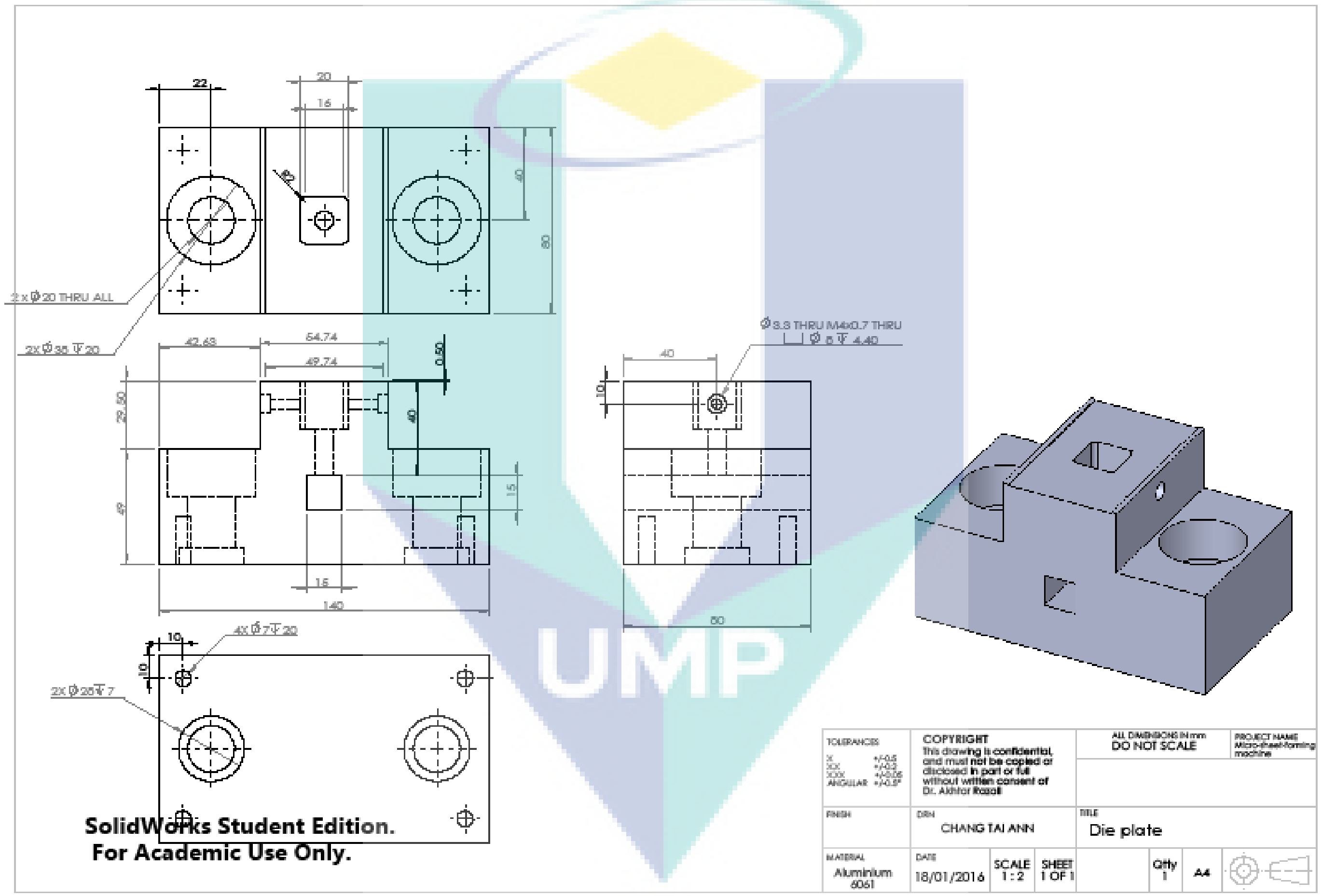
ALL DIMENSIONS IN mm
DO NOT SCALE
DRN
CHANG TAI ANN
TITLE
Punch holder plate
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE 1 : 2
SHEET 1 OF 1
Qtty 1
A4

APPENDIX B3



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Ø3.3 THRU M4x0.7 THRU
⌴ Ø8 ⊽ 4.40
4X Ø7 ⊽ 20
2X Ø28 ⊽ 7
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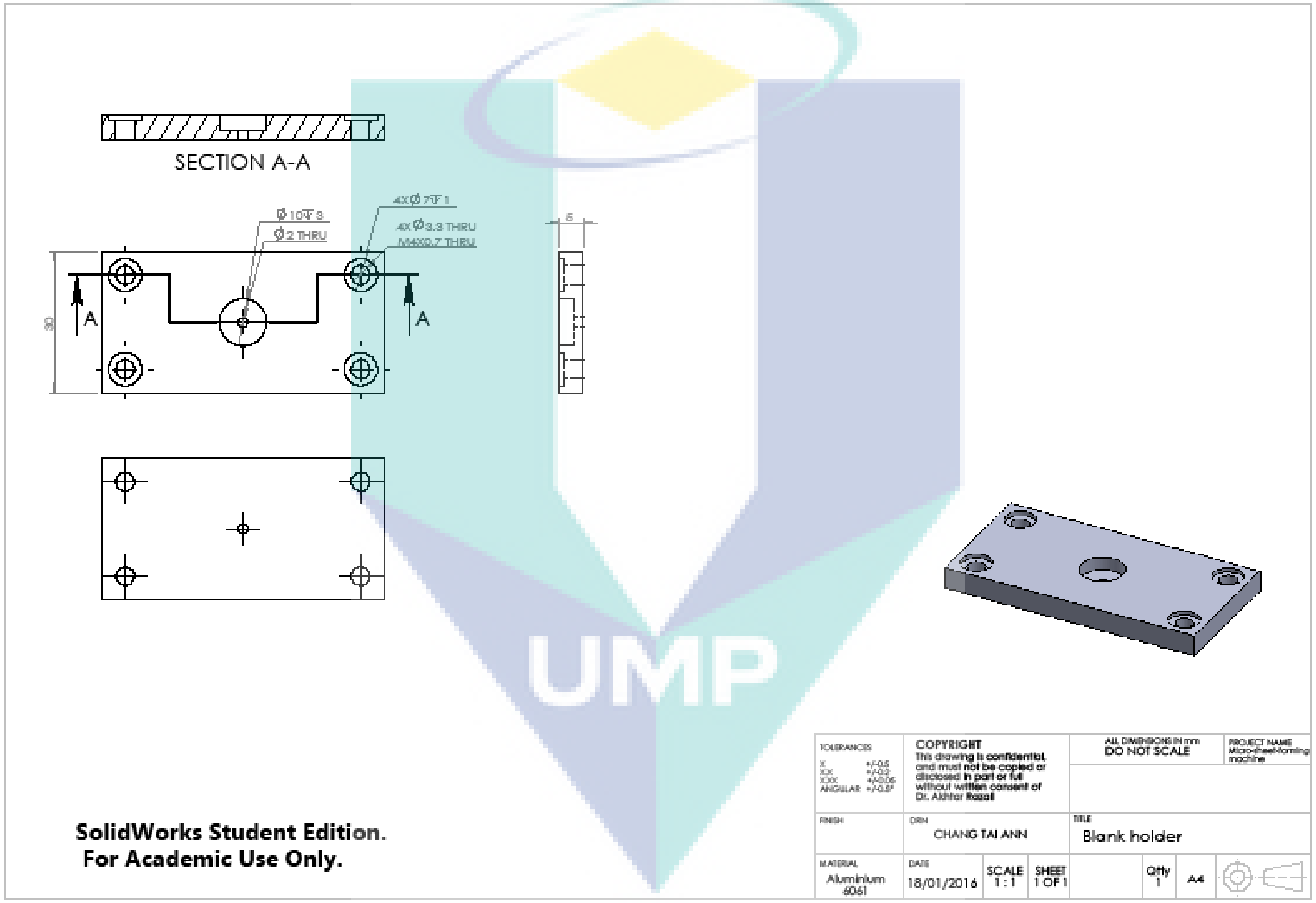
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
DRN
CHANG TAI ANN
TITLE
Die plate
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE
1 : 2
SHEET
1 OF 1
Qty
1
A4

APPENDIX B4


SECTION A-A
Ø10 ▽3
Ø2 THRU
4X Ø7 ▽1
4X Ø3.3 THRU
M4X0.7 THRU
A
30
6
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TOLERANCES
X +/-0.5
XX +/-0.2
XXX +/-0.05
ANGULAR +/-0.5°
COPYRIGHT
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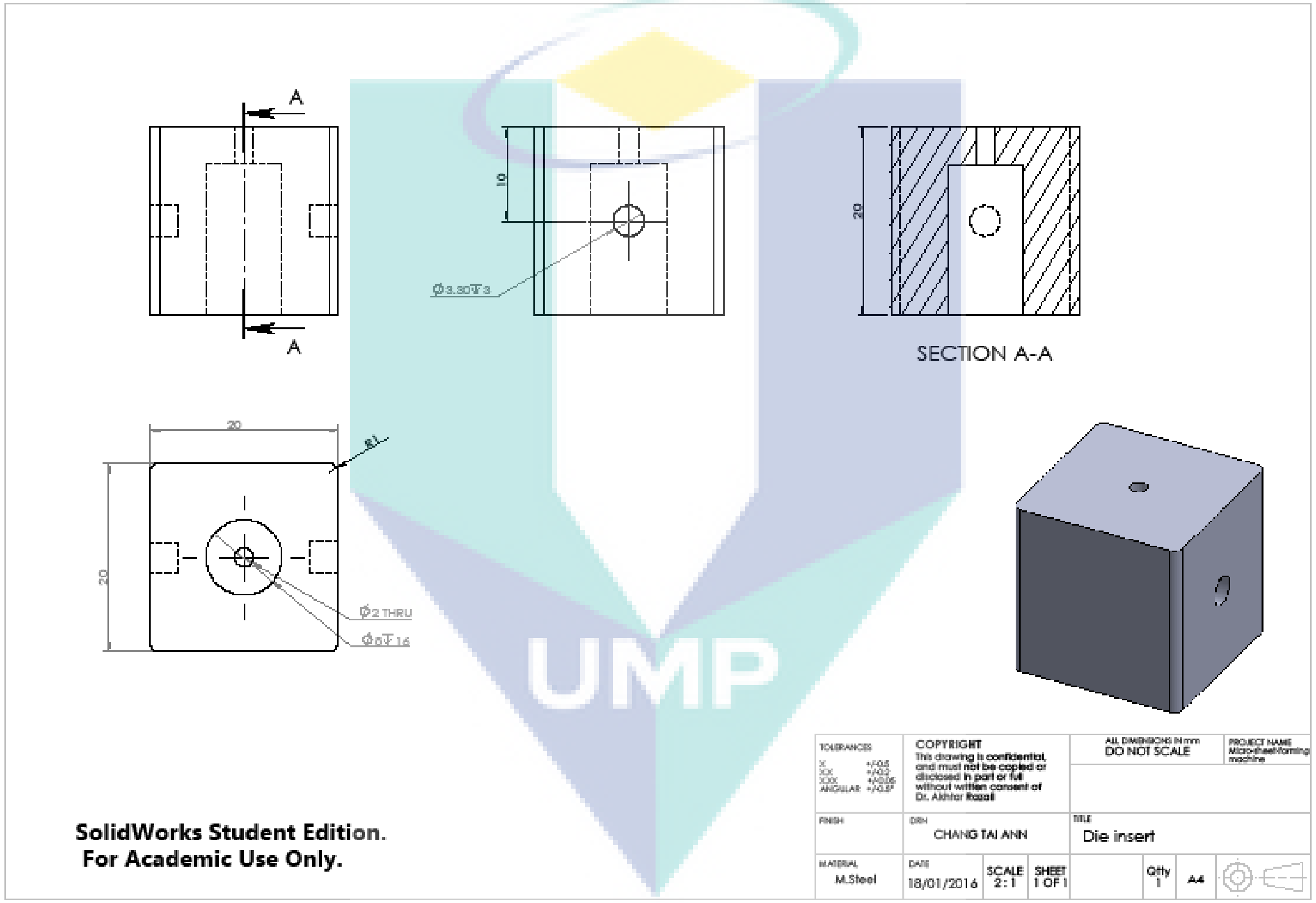
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
FINISH
DRN
CHANG TAI ANN
TITLE
Blank holder
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE
1 : 1
SHEET
1 OF 1
Qtty
1
A4

APPENDIX B5



A
A
10
Ø3.30 ↧ 3
20
SECTION A-A
20
R1
20
Ø2 THRU
Ø5 ↧ 16
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TOLERANCES
X +/-0.5
XX +/-0.2
XXX +/-0.05
ANGULAR +/-0.5°
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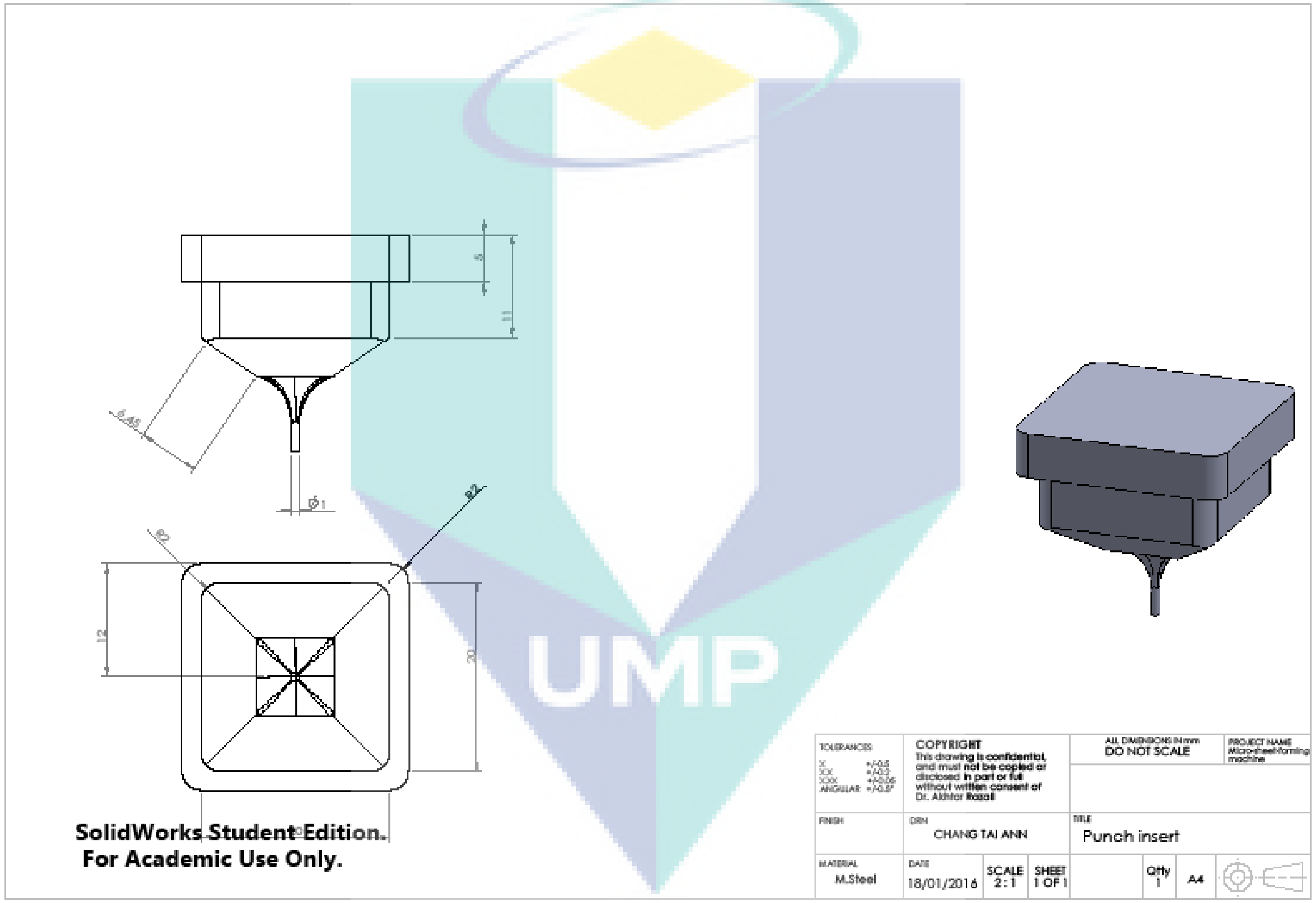
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
FINISH
DRN
CHANG TAI ANN
TITLE
Die insert
MATERIAL
M.Steel
DATE
18/01/2016
SCALE
2 : 1
SHEET
1 OF 1
Qtty
1
A4

APPENDIX B6



5
11
6.45
Ø1
R2
R2
12
20
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TOLERANCES
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XX +/-0.2
XXX +/-0.05
ANGULAR +/-0.5°
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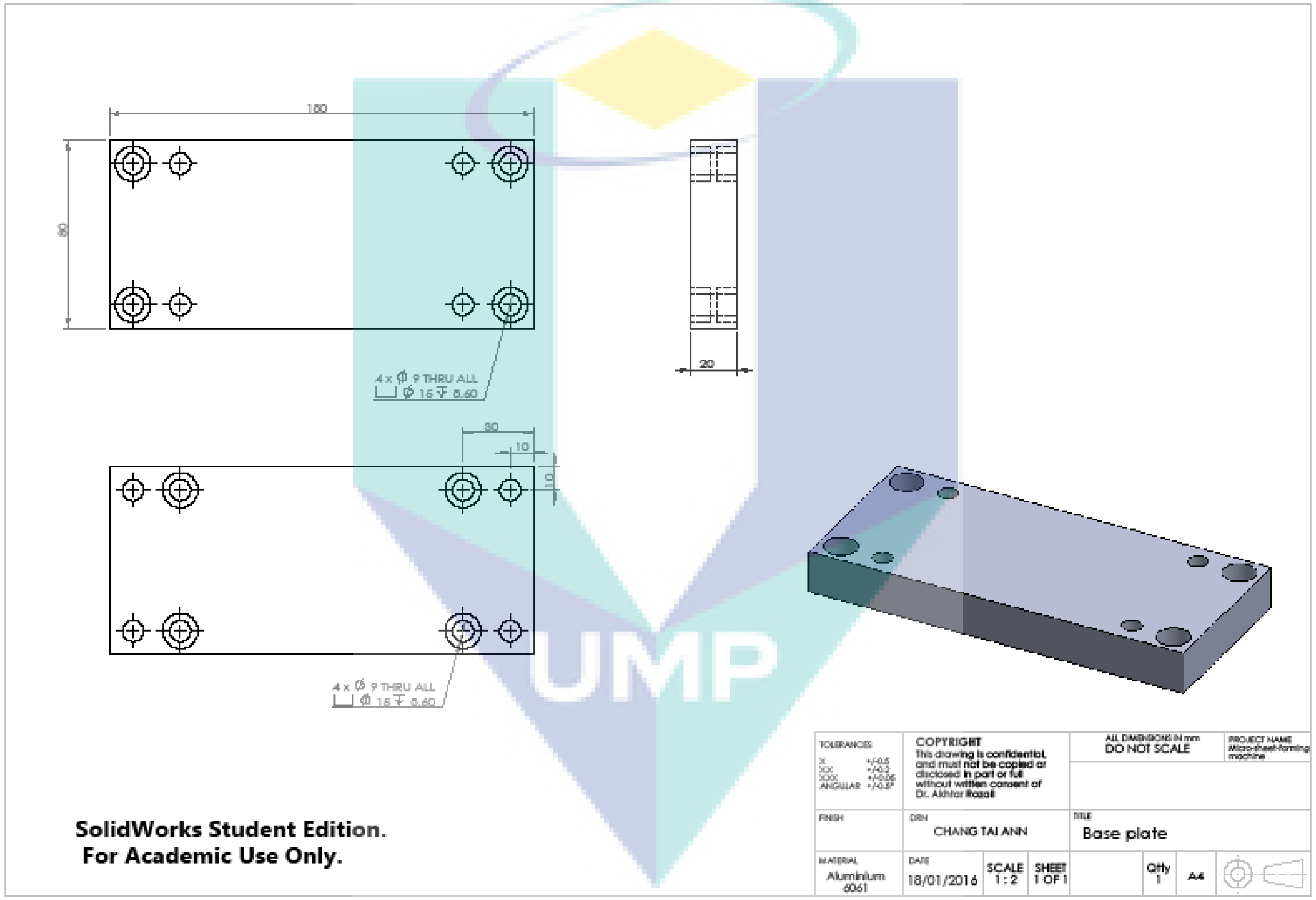
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
FINISH
DRN
CHANG TAI ANN
TITLE
Punch insert
MATERIAL
M.Steel
DATE
18/01/2016
SCALE
2 : 1
SHEET
1 OF 1
Qty
1
A4

APPENDIX B7



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80
4 x Ø 9 THRU ALL
⌴ Ø 15 ↧ 8.60
20
30
10
10
4 x Ø 9 THRU ALL
⌴ Ø 15 ↧ 8.60
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TOLERANCES
X +/-0.5
XX +/-0.2
XXX +/-0.05
ANGULAR +/-0.5°
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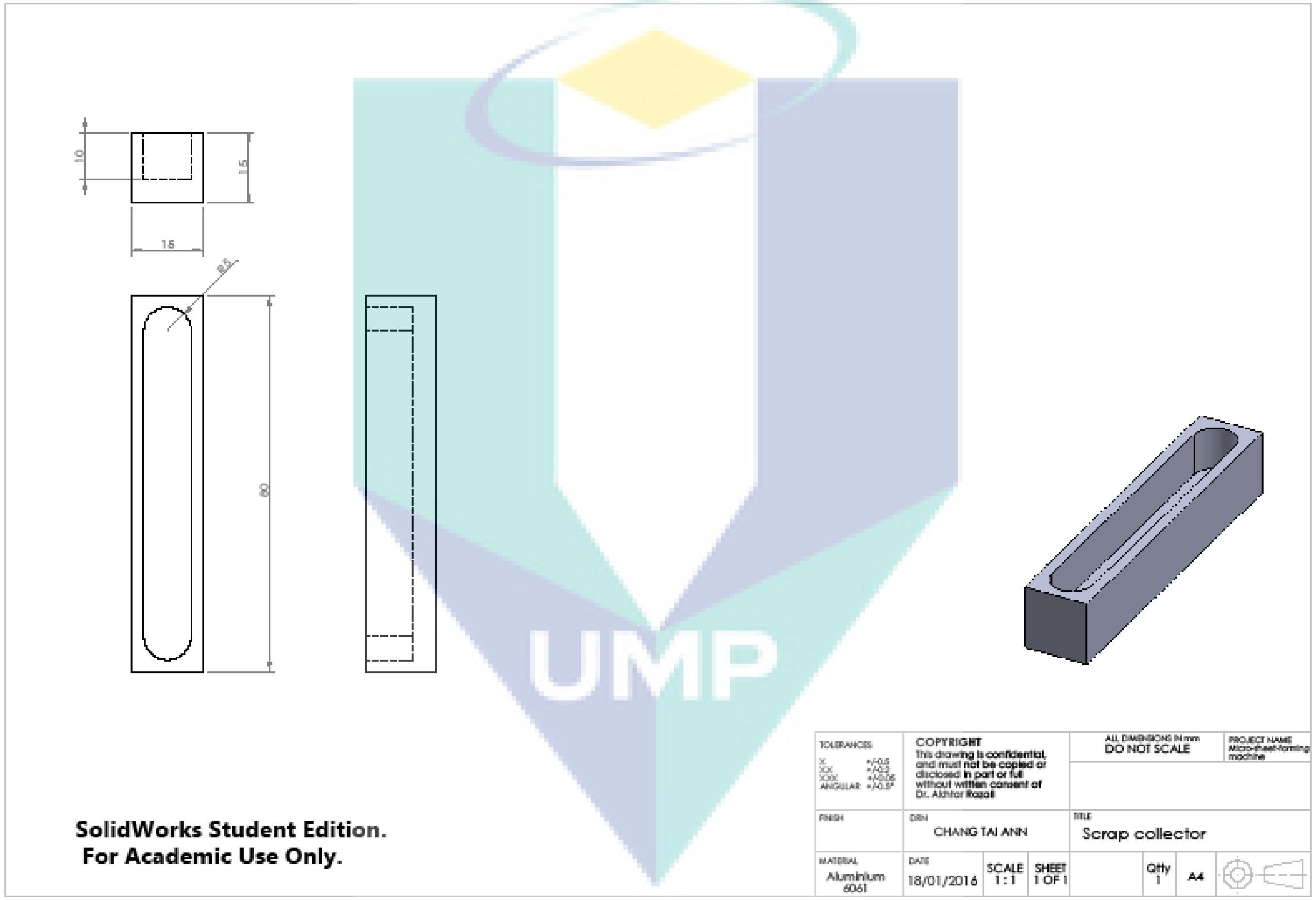
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
FINISH
DRN
CHANG TAI ANN
TITLE
Base plate
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE
1 : 2
SHEET
1 OF 1
Qty
1
A4

APPENDIX B8



10
15
16
80
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TOLERANCES
COPYRIGHT
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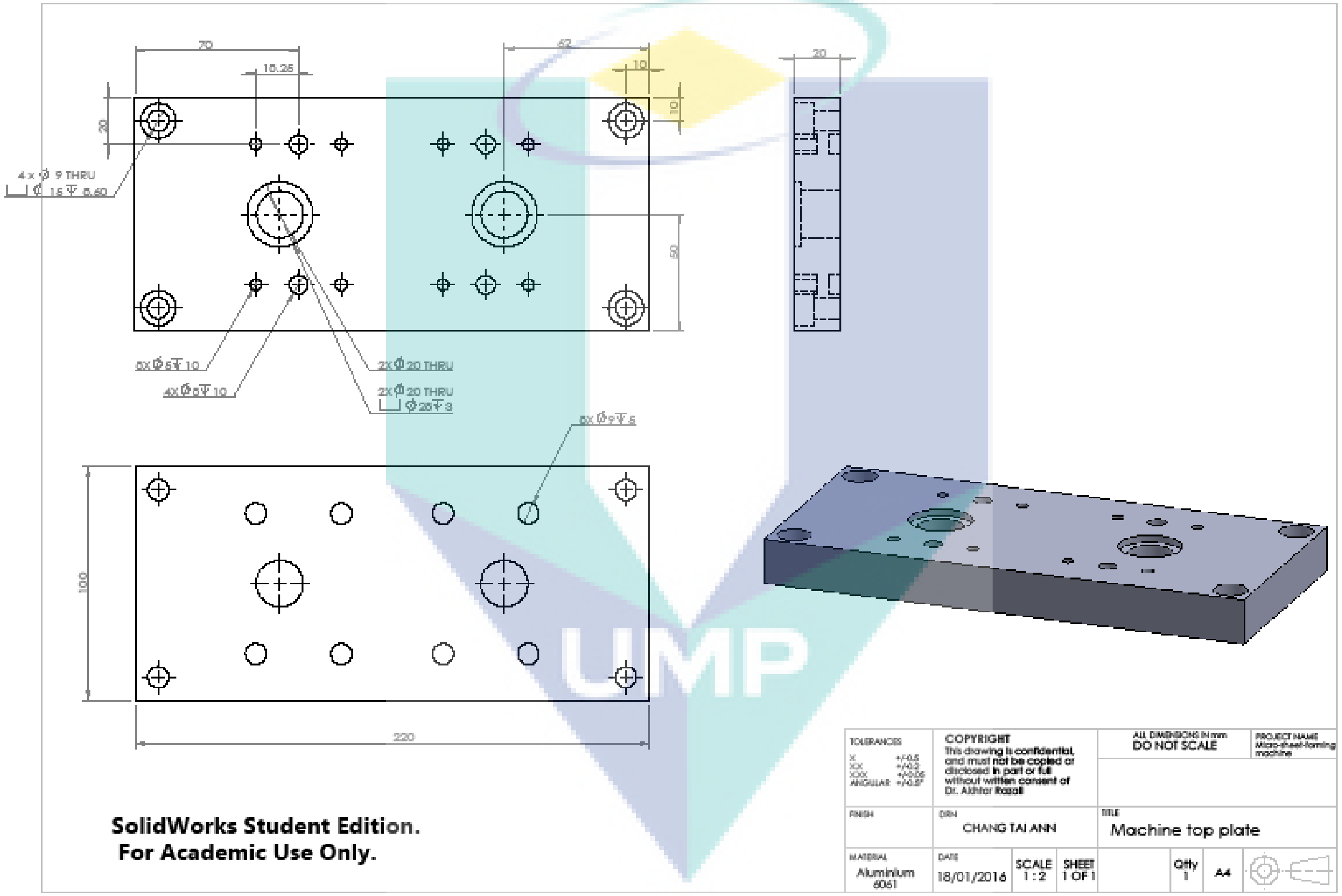
ALL DIMENSIONS IN mm
DO NOT SCALE
PROJECT NAME
Micro-sheet-forming machine
FINISH
DRN
CHANG TAI ANN
TITLE
Scrap collector
MATERIAL
Aluminium 6061
DATE
18/01/2016
SCALE
1 : 1
SHEET
1 OF 1
Qtty
1
A4

APPENDIX B9



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ALL DIMENSIONS IN mm
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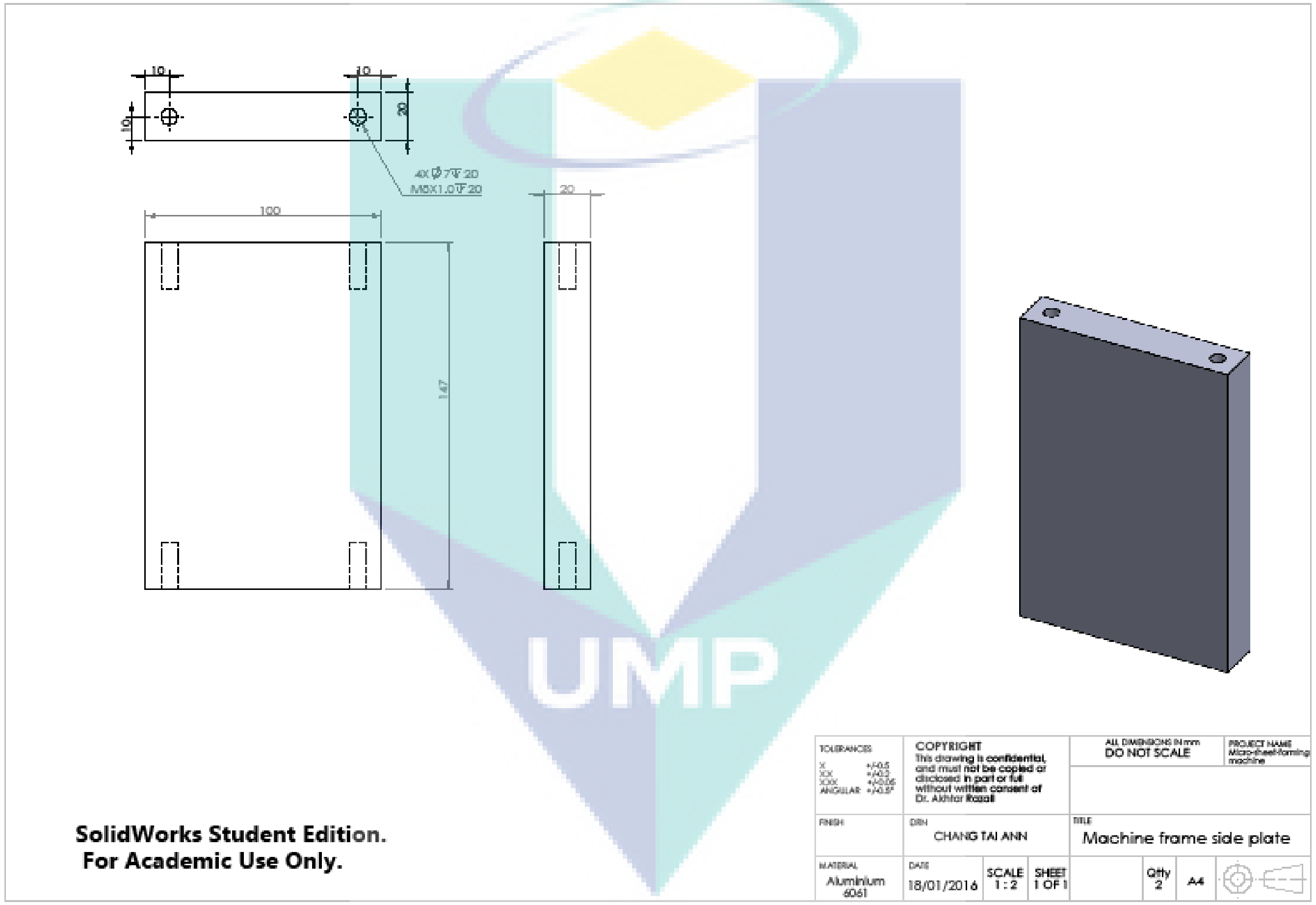
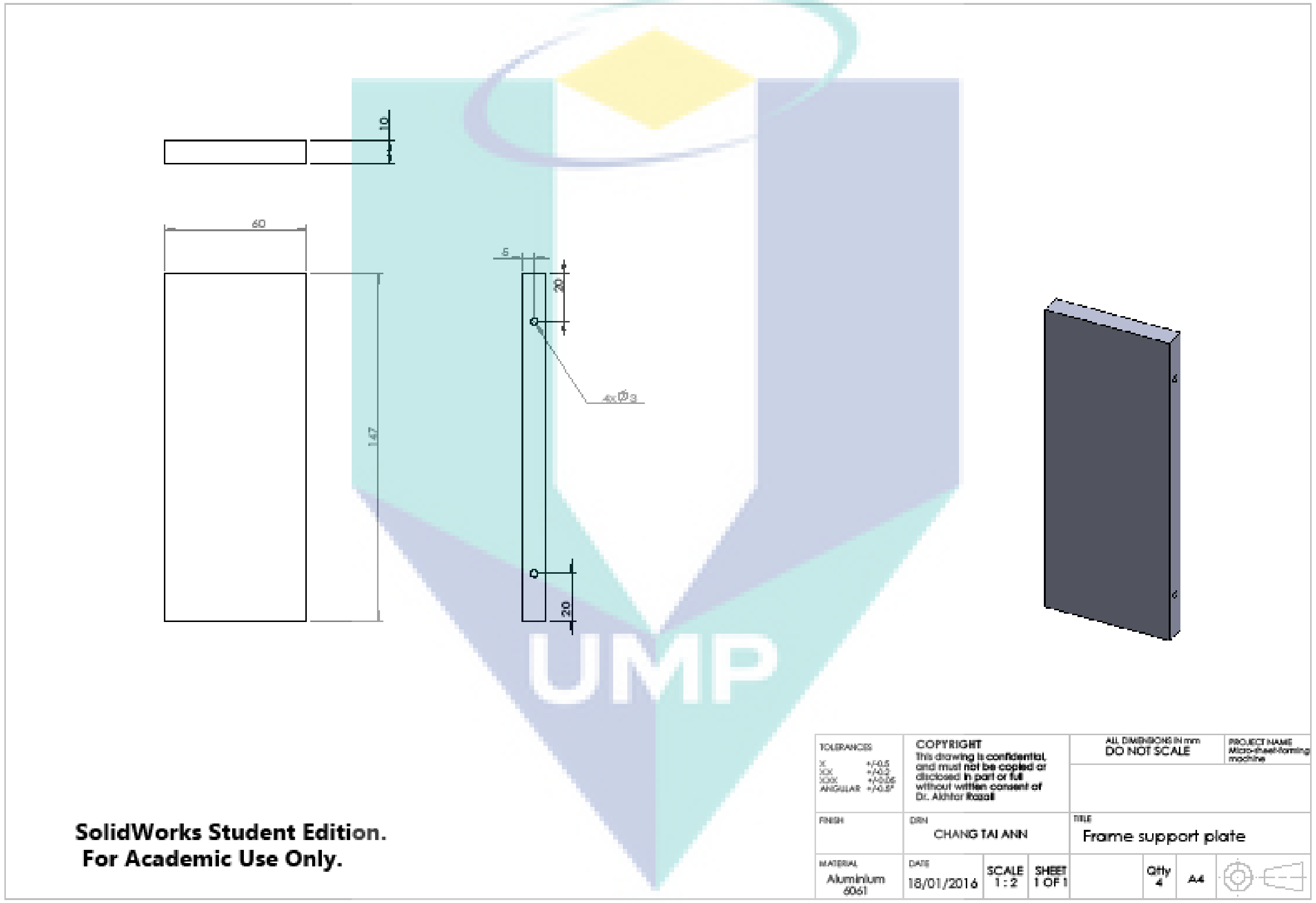
CHANG TAI ANN
Machine top plate
Aluminium 6061
18/01/2016
SCALE 1:2
SHEET 1 OF 1
A4

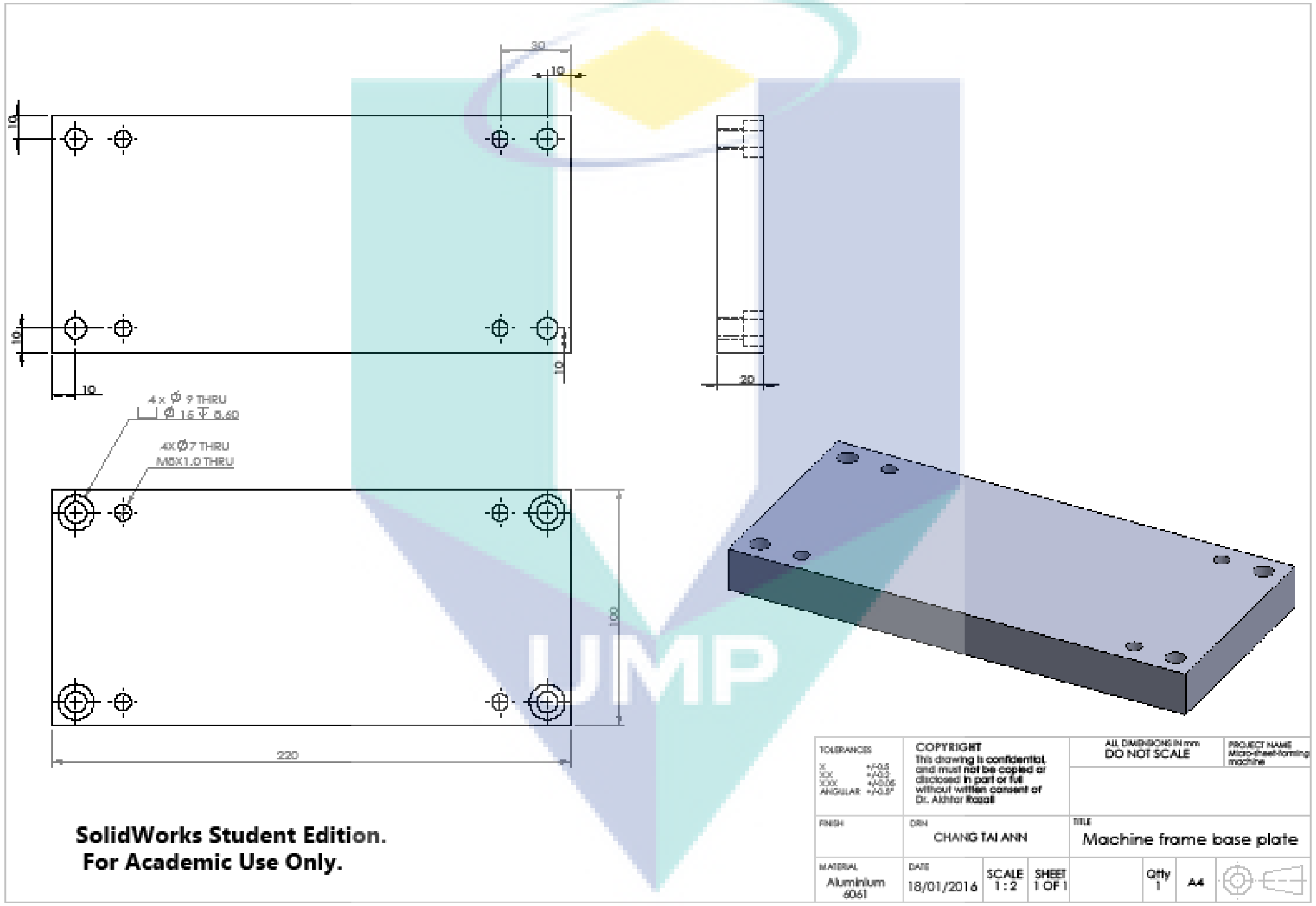
APPENDIX B10



APPENDIX B11



APPENDIX B12



APPENDIX C1
SOLENOID SPECIFICATION

Ledex® Low Profile Size 6ECM — Push or Pull

Medium Stroke, Conical Face
Part Number: 282352-0XX

All catalogue products manufactured after April 1, 2006 are RoHS Compliant

Performance

Maximum Duty Cycle	100%	50%	25%	10%
Maximum ON Time (sec) when pulsed continuously[1]	∞	87	36	13
Maximum ON Time (sec) for single pulse[2]	∞	140	44	16
Watts (@ 20°C)	32	64	128	320
Ampere Turns (@ 20°C)	1480	2080	2940	4620

Coil Data

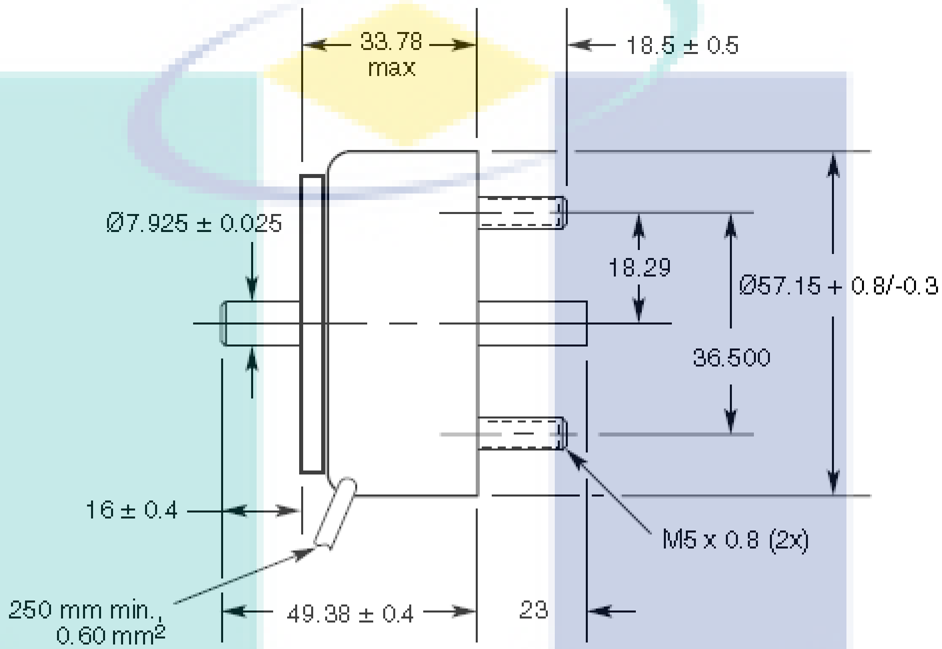
awg (0XX)[3]	Resistance (@20°C)	# Turns[4]	VDC (Nom)	VDC (Nom)	VDC (Nom)	VDC (Nom)
23	4.69	567	12.3	17.2	24.0	38.0
24	7.43	710	15.5	22.0	31.0	48.0
25	12.90	960	19.9	28.0	39.0	62.0
26	19.70	1170	25.0	35.0	49.0	78.0
27	32.00	1500	32.0	44.0	63.0	99.0
28	51.60	1904	40.0	56.0	79.0	125.0
29	74.40	2232	49.0	69.0	98.0	154.0
30	126.00	2940	63.0	89.0	126.0	198.0
31	195.00	3611	80.0	112.0	159.0	250.0
32	288.00	4350	98.0	138.0	195.0	306.0
33	427.00	5010	126.0	177.0	251.0	394.0

Specifications

Dielectric Strength	23-31 awg, 1200 VRMS ; 32-33 awg, 1500 VRMS
Recommended Minimum Heat Sink	Maximum watts dissipated by solenoid are based on an unrestricted flow of air at 20°C, with solenoid mounted on the equivalent of an aluminium plate measuring 314 mm square by 3.2 mm thick
Coil Resistance	23-33 awg, ±5%
Weight	609.5 g
Holding Force	218.0 N @ 105°C

APPENDIX C2
SOLENOID DIMENSION

Size 6ECM



APPENDIX D1
ENERGY CONSUMPTION DATA

Energy Consumption at 1 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.1	2.19	24.21	53.2	0.007
	2	0.1	2.55	24.19	62	0.006
	3	0.1	2.22	24.21	53.7	0.008
20 sec	1	0.2	2.44	24.19	59.3	0.01
	2	0.2	2.55	24.19	62	0.012
	3	0.2	2.57	24.19	62.5	0.01
30 sec	1	0.3	2.5	24.19	60.8	0.015
	2	0.3	2.26	24.21	54.9	0.016
	3	0.3	2.53	24.19	61.5	0.015
40 sec	1	0.4	2.37	24.2	57.6	0.018
	2	0.4	2.23	24.19	54.2	0.019
	3	0.4	2.41	24.19	58.6	0.018
50 sec	1	0.5	2.51	24.19	61	0.024
	2	0.5	2.53	24.18	61.5	0.022
	3	0.5	2.56	24.18	62.2	0.022
60 sec	1	0.6	2.5	24.19	60.8	0.033
	2	0.6	2.55	24.18	62	0.03
	3	0.6	2.53	24.19	61.5	0.03

APPENDIX D2
ENERGY CONSUMPTION DATA

Energy Consumption at 2 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.1	2.27	24.2	55.2	0.007
	2	0.1	2.26	24.2	54.9	0.005
	3	0.1	2.26	24.2	54.7	0.007
20 sec	1	0.2	2.48	24.19	60.3	0.013
	2	0.2	2.5	24.19	60.8	0.013
	3	0.2	2.25	24.2	54.7	0.011
30 sec	1	0.3	2.53	24.19	61.5	0.015
	2	0.3	2.51	24.19	61	0.015
	3	0.3	2.52	24.19	62.3	0.015
40 sec	1	0.4	2.53	24.19	61.5	0.022
	2	0.5	2.5	24.19	60.8	0.024
	3	0.4	2.52	24.19	61.3	0.02
50 sec	1	0.6	2.54	24.1	61.7	0.026
	2	0.6	2.51	24.1	61	0.025
	3	0.5	2.54	24.1	61.7	0.028
60 sec	1	0.7	2.51	24.1	61	0.032
	2	0.7	2.53	24.18	61.5	0.031
	3	0.7	2.54	24.18	61.7	0.029

APPENDIX D3
ENERGY CONSUMPTION DATA

Energy Consumption at 2 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.1	2.99	24.18	72.4	0.007
	2	0.1	2.89	24.19	69.9	0.007
	3	0.1	3.02	24.19	73.1	0.006
20 sec	1	0.3	3.11	24.19	75.2	0.014
	2	0.2	3.05	24.18	73.8	0.012
	3	0.2	3.03	24.18	73.3	0.012
30 sec	1	0.4	3.07	24.18	74.3	0.021
	2	0.4	3.12	24.18	75.5	0.02
	3	0.4	3.02	24.19	73.1	0.02
40 sec	1	0.5	3.12	24.18	75.5	0.023
	2	0.5	3.11	24.18	75.2	0.024
	3	0.5	3.11	24.18	75.2	0.024
50 sec	1	0.7	3.04	24.18	73.6	0.029
	2	0.7	3.03	24.19	73.3	0.03
	3	0.6	3.08	24.18	74.5	0.03
60 sec	1	0.8	3.07	24.19	74.3	0.035
	2	0.8	3.08	24.19	74.5	0.036
	3	0.8	3.02	24.18	73.1	0.036

APPENDIX D4
ENERGY CONSUMPTION DATA

Energy Consumption at 4 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.2	4.73	24.19	114.5	0.013
	2	0.2	4.97	24.17	120.3	0.012
	3	0.2	4.83	24.19	116.8	0.012
20 sec	1	0.4	4.97	24.17	120.3	0.021
	2	0.4	4.84	24.17	117.2	0.022
	3	0.4	4.84	24.18	117.1	0.021
30 sec	1	0.6	4.99	24.17	120.8	0.032
	2	0.6	4.87	24.17	117.9	0.03
	3	0.6	4.93	24.17	119.3	0.03
40 sec	1	0.8	4.93	24.17	119.3	0.04
	2	0.8	4.92	24.18	119.1	0.043
	3	0.8	4.91	24.18	118.8	0.041
50 sec	1	1.0	4.97	24.17	120.3	0.049
	2	1.1	4.89	24.17	118.3	0.056
	3	1.0	4.8	24.17	116.2	0.049
60 sec	1	1.2	4.94	24.17	119.5	0.059
	2	1.3	4.9	24.17	118.6	0.066
	3	1.2	4.93	24.17	119.3	0.059

APPENDIX D5
ENERGY CONSUMPTION DATA

Energy Consumption at 5 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.2	5.09	24.17	123	0.011
	2	0.2	5.01	24.18	121.1	0.012
	3	0.2	5.13	24.18	124.1	0.012
20 sec	1	0.5	4.99	24.18	120.7	0.023
	2	0.5	5.13	24.17	123.9	0.023
	3	0.6	5.04	24.18	121.9	0.027
30 sec	1	0.8	5.05	24.17	122.1	0.037
	2	0.7	5.02	24.18	121.4	0.031
	3	0.7	5.03	24.17	121.7	0.032
40 sec	1	0.9	5.02	24.17	121.3	0.042
	2	0.9	5.1	24.17	123.3	0.043
	3	0.9	5.04	24.17	121.8	0.042
50 sec	1	1.2	5.07	24.17	122.6	0.052
	2	1.2	5.03	24.17	121.6	0.56
	3	1.1	5.01	24.17	121.1	0.052
60 sec	1	1.4	5.09	24.17	123	0.062
	2	1.5	5.03	24.18	121.7	0.067
	3	1.4	5.05	24.17	122.1	0.064

APPENDIX D6
ENERGY CONSUMPTION DATA

Energy Consumption at 6 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.3	5.55	24.14	134.4	0.015
	2	0.3	5.57	24.14	134.8	0.014
	3	0.3	5.64	24.13	136.5	0.013
20 sec	1	0.5	5.61	24.13	135.8	0.026
	2	0.5	5.66	24.13	136.6	0.025
	3	0.6	5.67	24.13	136.8	0.028
30 sec	1	0.8	5.65	24.13	136.7	0.034
	2	0.8	5.65	24.13	136.7	0.035
	3	0.8	5.66	24.13	136.6	0.036
40 sec	1	1.0	5.58	24.13	135.1	0.047
	2	1	5.54	24.13	136.6	0.046
	3	1.0	5.59	24.13	135.3	0.046
50 sec	1	1.3	5.61	24.13	135.8	0.061
	2	1.2	5.55	24.13	134.1	0.057
	3	1.2	5.54	24.13	134.1	0.057
60 sec	1	1.7	5.68	24.13	137.5	0.076
	2	1.6	5.56	24.14	134.6	0.071
	3	1.5	5.53	24.13	133.8	0.068

APPENDIX D7
ENERGY CONSUMPTION DATA

Energy Consumption at 7 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.4	7.69	24.08	180.8	0.018
	2	0.5	7.5	24.08	180.8	0.02
	3	0.4	7.69	24.08	180.8	0.018
20 sec	1	0.6	7.34	24.08	177.2	0.029
	2	0.7	7.41	24.08	178.9	0.029
	3	0.6	7.4	24.08	178.6	0.029
30 sec	1	0.9	7.41	24.08	178.9	0.041
	2	1	7.25	24.08	174.6	0.045
	3	0.9	7.29	24.08	176	0.041
40 sec	1	1.3	7.47	24.08	179.8	0.057
	2	1.4	7.28	24.08	175.8	0.061
	3	1.3	7.47	24.08	179.8	0.057
50 sec	1	1.6	7.34	24.08	177.2	0.069
	2	1.6	7.24	24.08	174.4	0.068
	3	1.6	7.34	24.08	177.2	0.069
60 sec	1	1.9	7.16	24.08	172.9	0.082
	2	1.9	7.22	24.08	174.3	0.083
	3	1.9	7.16	24.08	172.9	0.082

APPENDIX D8
ENERGY CONSUMPTION DATA

Energy Consumption at 8 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.4	7.1	24.06	171.6	0.018
	2	0.4	7	24.06	170.8	0.019
	3	0.4	7.1	24.06	171.6	0.018
20 sec	1	0.7	7.11	24.06	171.4	0.033
	2	0.7	7.19	24.06	173.3	0.034
	3	0.7	7.19	24.06	173.3	0.034
30 sec	1	1.0	7.07	24.06	170.4	0.05
	2	1.1	7.06	24.06	170.2	0.049
	3	1.0	7.07	24.06	170.4	0.05
40 sec	1	1.3	7.11	24.06	171.4	0.063
	2	1.4	7.12	24.06	172.6	0.069
	3	1.5	7.11	24.06	171.4	0.063
50 sec	1	1.8	6.97	24.06	168	0.079
	2	1.7	7.07	24.06	170.4	0.08
	3	1.7	7.07	24.06	170.4	0.08
60 sec	1	2.0	6.96	24.06	167.8	0.092
	2	1.9	6.91	24.06	166.6	0.094
	3	1.9	6.91	24.06	166.6	0.094

APPENDIX D9
ENERGY CONSUMPTION DATA

Energy Consumption at 9 Hz

Time		**Energy (Wh)**	**Peak Amps (Ap)**	**Min. Volts (Vm)**	**Peak Power (Wp)**	**Charge (Ah)**
10 sec	1	0.4	7.29	24.07	175.5	0.017
	2	0.4	7.3	24.08	176	0.02
	3	0.4	7.29	24.07	175.5	0.017
20 sec	1	0.8	7.54	24.07	181.6	0.035
	2	0.8	7.35	24.07	177.1	0.034
	3	0.8	7.35	24.07	177.1	0.034
30 sec	1	1.1	7.44	24.07	179.2	0.048
	2	1.1	7.46	24.07	179.7	0.047
	3	1.1	7.44	24.07	179.2	0.048
40 sec	1	1.4	7.32	24.08	176.2	0.061
	2	1.4	7.39	24.07	178	0.06
	3	1.4	7.39	24.07	178	0.06
50 sec	1	1.8	7.26	24.07	174.8	0.078
	2	1.8	7.33	24.08	176.6	0.076
	3	1.8	7.26	24.07	174.8	0.078
60 sec	1	2.2	7.28	24.08	175.3	0.091
	2	2.1	7.21	24.08	173.6	0.09
	3	2.2	7.28	24.08	175.3	0.091

APPENDIX D10
ENERGY CONSUMPTION DATA

Energy Consumption at 10 Hz

Time		Energy (Wh)	Peak Amps (Ap)	Min. Volts (Vm)	Peak Power (Wp)	Charge (Ah)
10 sec	1	0.4	8.85	24.06	213.1	0.02
	2	0.4	8.8	24.07	211.9	0.019
	3	0.4	8.89	24.07	214	0.019
20 sec	1	1.0	9.45	24.04	227.2	0.043
	2	0.9	0.32	24.04	224.1	0.039
	3	0.9	0.32	24.04	224.1	0.039
30 sec	1	1.3	9.13	24.04	219.7	0.057
	2	1.3	9.19	24.05	221.1	0.061
	3	1.2	9.02	24.04	217.6	0.06
40 sec	1	1.6	9.16	24.04	220.2	0.073
	2	1.6	9.1	24.05	218.9	0.072
	3	1.6	9.16	24.04	220.2	0.073
50 sec	1	2.0	8.77	24.06	211.1	0.088
	2	2.0	9.39	24.04	225.8	0.094
	3	2.0	8.77	24.06	211.1	0.088
60 sec	1	2.3	8.79	24.06	211.6	0.105
	2	2.3	8.75	24.06	210.7	0.105
	3	2.3	8.75	24.06	210.7	0.105

APPENDIX E
LIST OF PUBLICATIONS

Chang, T. A., Razali, A. R., Zainudin, N. A. I., and Yap, W. L., (2015) Size Effects in Thin Sheet Metal Forming. *3rd International Conference on Mechanical Engineering Research (ICMER 2015)*, 18-19 August 2015, Kuantan, Pahang.

Asmara, Y. P., Siregar J. P., Cionita, T., and Chang, T. A. (2016) Improving Efficiency of Aluminium Sacrificial Anode Using Cold Work Process. *IOP Conference Series: Materials Science and Engineering*, 114 (1). pp. 1-6. ISSN 1757-8981 (Print); 1757-899X (Online)