A NEW APPROACH OF DIRECT RECYCLING OF ALUMINIUM ALLOY CHIPS (AA6061) IN HOT PRESS FORGING PROCESS

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A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Mechanical and Manufacturing Engineering

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MAY, 2013

ABSTRACT

This study introduces a new approach of direct recycling using the hot press forging process that eliminates the two intermediate processes of cold-compact and pre-heating. Thereby, it leads to low energy consumption without intervening the metallurgical processes. The mechanical and physics properties of AA6061 aluminium alloy recycled by solid-state recycling were investigated. Amounts of oxide in recycled chips were measured by using oxygen-nitrogen analyser. Oxygen concentration in the recycled specimens increased proportionally with the total surface area of the machined chip per unit volume. The performance of recycled aluminium chip on their mechanical properties and microstructure were compared with the reference specimen. The recycled specimens exhibited a remarkable potential in the strength properties (Ultimate Tensile Strength, UTS = 30.73-117.85 MPa, Elongation to Failure, ETF = 3.84-11.84 %) where it increased with increment of total surface area of chips. This is mainly attributed to grain refinement (7.90-19.50µm) of the microstucture. On the other hand, recycled specimens with medium surface area of chips posed highest elongation to failure (11.84%). Grain size and oxide amount of billet have an effect on the elongation of recycled materials. Analysis for different operating temperatures showed that the higher temperatures (520°C) gave better result on mechanical properties (UTS = 117.85 MPa) and finer microstructure (7.90µm). In this study, the recycled AA6061 chip showed the good potential as the comparison of using only 17.5% of suggested pressure where 70.0 MPa (maximum operating pressure) from 400.0 MPa (suggested optimum pressure) exhibited 35.8% the ultimate tensile strength where 117.85 MPa (maximum tensile strength for recycled billet) from 327.69 MPa (reference). This proved that hot forging process could be an acceptable alternative method for recycling of AA6061 aluminum alloy chips.

ABSTRAK

Kajian ini memperkenalkan pendekatan baru kitarsemula-terus dengan menggunakan proses penekanan tempaan panas yang menghapuskan dua proses iaitu pemampatan dan pra-pemanasan. Oleh itu, ia membawa kepada penggunaan tenaga yang rendah tanpa merubah keadaan metalurgi logam. Sifat-sifat mekanik dan fizikal AA6061 aluminium aloi dikitar semula pada keadaan pepejal. Jumlah oksida dalam cip kitar semula diukur dengan menggunakan penganalisis oksigen-nitrogen. Jumlah oksigen di dalam spesimen kitar semula meningkat dengan jumlah luas permukaan per unit isipadu cip. Prestasi cip aluminium dikitar semula dibandingkan dengan spesimen rujukan bagi sifat-sifat mekanikal dan mikrostrukturnya. Spesimen kitar semula menunjukkan potensi yang luar biasa dalam sifat-sifat kekuatan (Kekuatan tegangan muktamad, UTS = 30.73-117.85 MPa, Pemanjangan untuk Kegagalan, ETF = 3.84-11.84%) di mana ia meningkat dengan kenaikan jumlah luas permukaan per isipadu cip. Ini disebabkan oleh penghalusan bijian (7.90-19.50µm). Namun, spesimen kitar semula dengan kawasan permukaan medium cip memberikan pemanjangan kepada kegagalan tertinggi (11.84%). Saiz dan jumlah oksida memberikan kesan ke atas pemanjangan bahan kitar semula. Analisis untuk suhu operasi yang berbeza menunjukkan bahawa suhu yang paling tinggi (520 ° C) memberikan hasil yang lebih baik bagi sifat-sifat mekanikal (UTS = 117.85 MPa) dan mikrostruktur yang lebih halus (7.90µm). Dalam kajian ini, AA6061 cip kitar semula menunjukkan potensi yang baik sebagai perbandingan hanya menggunakan 17.5% daripada tekanan yang disyorkan di mana 70.0 MPa (tekanan operasi maksimum) daripada 400.0 MPa (tekanan optimum dicadangkan) menunjukkan 35.8% kekuatan tegangan muktamad, 117.85 MPa (kekuatan tegangan maksimum bagi bilet kitar semula) dari 327.69 MPa (rujukan). Ini membuktikan bahawa proses tempaan penekanan panas boleh menjadi kaedah alternatif yang diterima untuk kitar semula AA6061 aluminium aloi cip.

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A	Cross sectional area
doc	Depth of cut
DPH	Diamond Pyramid Hardness
ETF	Elongation to failure
f	Feed
f_r	Feed rate
HSM	High speed machining
HV	Hardness Vickers
n	Number of teeth
N	Rotational per minute
K_f	Forging shape factor
OM	Optical microscope
S	Surface area per unit volume
SEM	Scanning electron microscope
UTS	Ultimate tensile strength
V_C	Cutting speed
YS	Yield strength

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CHAPTER 1

INTRODUCTION

Nowadays, demand for aluminium products is increasing since aluminium alloy offers excellent corrosion resistance with good strength and low density compared to common manufacturing material such as steel. Aluminium is the third most abundant element in the earth's crust after oxygen and silicon. It offers a number of benefits relative to ferrous material in terms of ductile and malleability, corrosion to resistance, better conductivity, low density; and on top of all, its recyclability. This is the critical factor that contributes to wide application of aluminium in manufacturing industry especially in the automotive sector. On the contrary, production of aluminium which involves extraction from aluminium ore called bauxite (primary resource) requires a lot of energy, which is almost 200 gigajoules/ton. This staggering amount is almost the same as 10 times of that required for steel production, supported by the fact that price of virgin aluminium is five times higher than steel. This matter eventually concludes to the importance of recycling aluminium (secondary resources), of which it is significantly more economic rather than using primary resources where it is estimated to produce a given mass of aluminium from recycled scrap (secondary resources) only requires 5% of the energy to produce the same mass from the ore (primary resources) (Schlesinger, 2007).

Since industrial revolution in 18th century, manufacturing sector had known to have an unfavourable impact on environment which had lead to establishment of numerous environmental preservation laws and policies, such as Kyoto Protocol, Montreal Protocol and Environment Quality Act. All of these policies contain regulations that specifically oriented towards reduction of carbon dioxide emissions to prevent global warming due to green house production. Therefore, the need of decrement in energy consumption in industrial processes as well as transportation and production engineering has become a major factor in modern industrial world. Due to rapid growth of local population and daily consumption, the amount of solid waste generated in Peninsular Malaysia went up from 16,200 tons per day in 2001 to 19,100 tons in 2005, an average of 0.8 kilogram per capita per day. For instance, in Kuala Lumpur waste generation is about 3,000 tons a day and forecasts show that this amount will increase further in coming years (Hassan *et al*., 2001). In Malaysia, solid waste problem is one of the most popular all-time debate topics. Other issues that have received extensive public attention are the problems of haze and air emissions from anthropogenic (human impact) sources, water problem both in terms of quantity and quality and indiscriminate dumping of toxic and hazardous wastes (World Bank, 1993). Nowadays, increasing waste management cost, securing final disposal landfills, reduce and clean energy consumption are among the most critical sustainability issues in Malaysia. Sustainable manufacturing is an essential ingredient in ensuring Malaysia to achieve modern urbanization at the same level with other developed countries.

Conventional recycling method involves melting scrap aluminium in a secondary aluminium production process. It uses 10-20 times less energy than primary aluminium production (The Aluminium Federation, 2004). Somehow, by having melting point at 660°C still defines aluminium recycling as an energy intensive process. The waste of aluminium usually comes in form of chip resulted from machining of semi-finished products. Additionally, chip recycling is difficult due to their elongated spiral shape and micro size nature. The apparent density of the chip is low, makes them inconvenient for handling and transportation whereas their surface area is relatively large and covered with oxides and oil emulsion, which is not desirable for recycling through remelting approach. Their large surface area to volume ratio is not conducive to remelting (Gronostajski *et al.*, 1997). Losses occurred at every stage of the recycling process, typically due to metal oxidization during melting, some produced through mixing with the slag from the surface of the melt, and others are scraps resulted from casting and further processing of the aluminium ingots. All these losses contribute to an aluminium yield that can be as low as 54% (Gronostajski *et al.*, 1997). Moreover, conventional recycling is characterized by high energy consumption, high operating costs and a large number of operations.

Hence, this study is aimed to investigate the effect of chip size on the mechanical and physical properties of direct recycling AA6061 aluminium alloy as a potential to be used as secondary resources. It introduces the new approach of recycling which using hot press forging with low energy consumption and cost without intervene the metallurgical processes. In previous studies, less quantitative evaluations were made of the effects of chip size on the mechanical and physical properties integrity of the recycled specimen of AA6061 aluminium alloy particularly in hot press forging operation. Thus, it is indeed practical to investigate the potential usage of waste material. Variety of chip sizes will be prepared by employing high speed milling with different setting of cutting parameters which include cutting speed, depth of cut and feed.

It is hoped that, this study will provide insight into 'Green Technology' program initiated by our government recently by introducing the sustainable recycling technique in such a way to conserve the use of energy and natural resources, promotes the use of renewable resources, reduce the landfill usage, and finally preventing the global warming effects.

1.1 Background of study

Analysis of energy consumption in manufacturing processes have shown that energy is mostly required during production of material such as aluminium or steel and not for further manufacturing steps like forming or cutting (Tekkaya *et al*., 2009). In the area of cutting and forming technology typically, the energy is not majorly spent on manufacturing process, but more on harvesting primary material, from initial melting after mining, to production secondary material, a process involving melting after recycling. Therefore, to reduce energy consumption and carbon dioxide emissions in manufacturing processes, an innovative process chain, combining optimized primary material usage and reduction of process steps is highly needed.

Figure 1.1 shows a simplified diagram of the vehicle life cycle. After the raw material is extracted, it is processed and manufactured into parts before it can be supplied to the consumer. It should be noted that there is a chain of part and component suppliers that contribute to the final manufacturing stage performed by the Original Equipment Manufacturers (OEMs) until recently where suppliers has begun to shift the design responsibility. After the manufacturing stage, the vehicle spends a long time period in the use phase of the life cycle for approximately 16 years with as many as 5% of the vehicles still remaining on the road after 30 years of operation (Sutherland *et al.,* 2008).

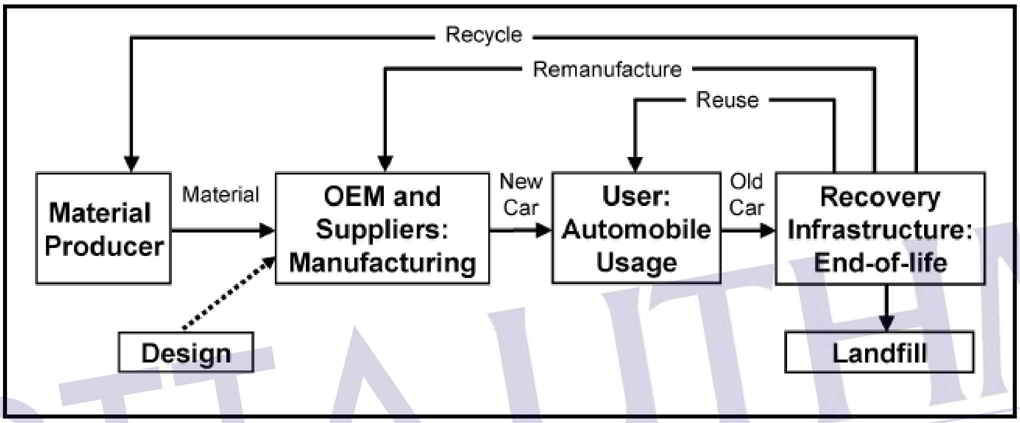

Figure 1.1: Automotive life cycle (Sutherland *et al.,* 2008)

Each life cycle stage shown in Figure 1.1 consumes certain amount of energy as it produces air, water emissions and municipal solid waste (Sutherland *et al.,* 2008).This justifies the effort of automotive manufacturers to use lighter-weight material in production of its vehicles. The fundamental trends and future directions of automotive industry include efforts in reducing vehicle weight and harmful exhaust emission. Since two-thirds of fuel consumption is attributed to vehicle weight, Original Equipment Manufacturers (OEMs) apply lighter material such as aluminium as an alternative to steel and it is usually considered as more convenient choice in terms of fuel economy. As an approximation, a 10% reduction in mass produces a 5% improvement in fuel economy (Sutherland *et al.,* 2008).

Table 1.1 shows the fraction of the total annual US consumption that is used by the automotive industry in 2006 by which, aluminium is depicted as the third main contributor to the total consumption.

Table 1.1: Automotive material as a fraction of total US consumption (Ward's Communications, 2006)

Material	*Percentage of total*
Plastics	4.5
Aluminium	28.2
Copper	10.7
Lead	74.6
Zinc	22.0
Iron	24.6
Steel	13.3
Rubber	72.6

Although there are several benefits resulted from the usage of light weight materials during the life cycle of a vehicle, the recovery infrastructure is likely to decrease despite of the increment in market value. Since the existing automotive recovery infrastructure is more suitable for ferrous-based vehicles, most of current equipment and processes are well suited for steel-based components and a complete redesign of this equipment and processes would be needed to manufacture aluminium components (Sutherland *et al.,* 2008). Therefore, this justifies the significance to further study on the recovery infrastructure and recycling of automotive aluminium.

Recycling of aluminium alloy scraps and chip are usually performed mostly by the melting method. Using the common recycling methods, aluminium alloy chips and scraps are melted, whereby some of the alloy is recovered and reutilized in the production process. Due to the melting characteristics, heating to an elevated temperature of more than 1,000 Kelvin is required (Suzuki *et al.,* 2007). During the melting or recycling of the chip and scraps, a lot of aluminium alloy compositions are lost as a result of oxidation and the costs of labour and energy required for more efficient recovery. Expenditures associated with environmental protection have further increase the general costs (Maoliang *et al*., 2008). To date, several innovative processes have been proposed to recycle aluminium chip using direct hot extrusion. This process chain requires an amount of energy of only 5-10 % of that needed for the conventional process chain including a re-melting step of the scrap to produce new extrusion billets (Suzuki *et al.,* 2005). Recently, Tekkaya *et al*. (2009) proposed a new method of direct recycling aluminium chip which is presented in Figure 1.2. Direct recycled aluminium alloys show high strength due to grain refinement and homogeneous dispersion of oxide precipitates.

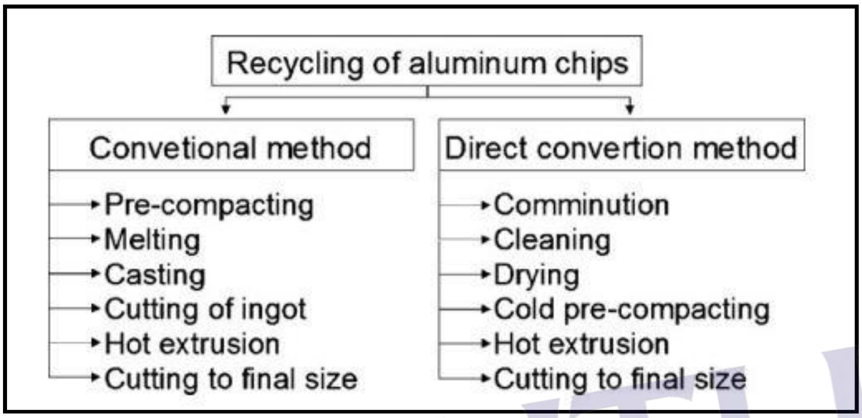

Figure 1.2: A comparison of conventional and direct recycling techniques of Aluminium alloy chip (Tekkaya *et al*., 2009)

Furthermore, as a concern to the global warming, recycling of wrought aluminium alloy by new direct recycling techniques is more preferred instead of conventional remelting method. Solid state recycling process by utilizing compression and extrusion at room or moderate temperature can result in significant energy savings (Jirang and Hans, 2010). From Figure 1.3, there is a substantial loss of aluminium metal during the conventional process that are metal losses during remelting, cross produced from liquid aluminium process, scrap produced from casting process, butts generated during extrusion process which leads to generate a totally new scrap. As presented in Figure 1.4, approximately 10% of aluminium metal will lost during remelting phase and other 35% will be carried out as a new scrap during through the process.

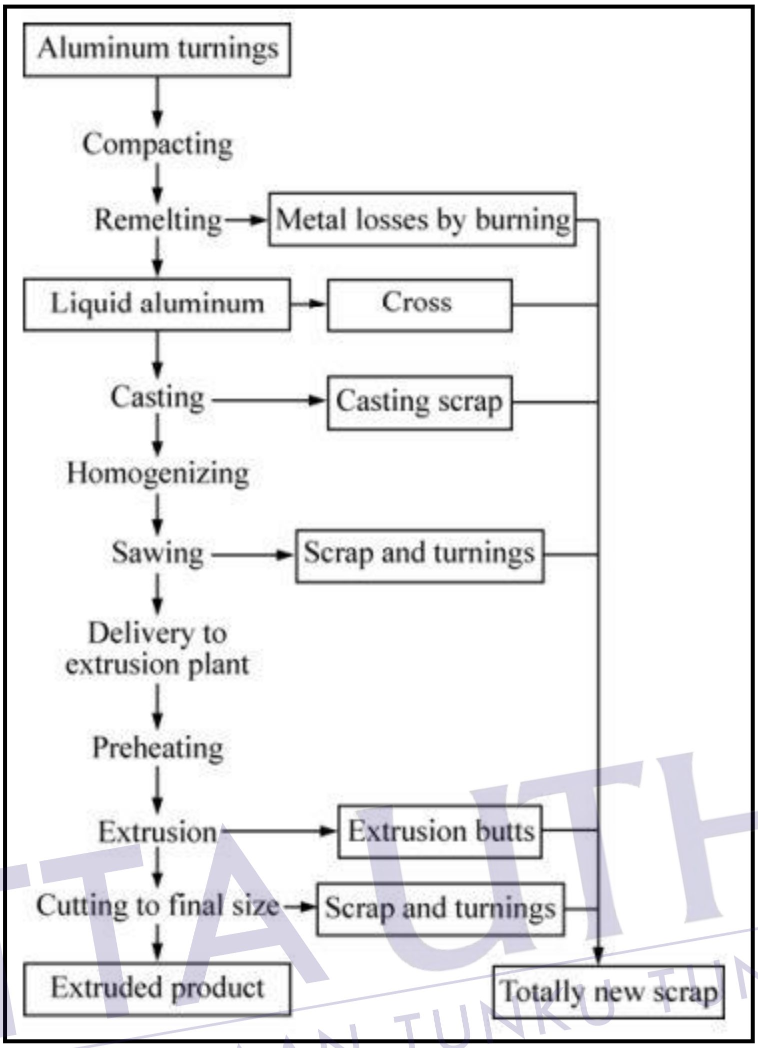

Figure 1.3: Flow chart of conventional process for recycling of aluminum turnings (Jirang and Hans, 2010)

The recycling of aluminium and its alloys by direct recycling method is relatively simple, consumes small amount of energy and does not have a harmful effect on the environment. Material which recycled directly from the chip that formed by hot press forging results in a more economic recycling process. Hence, in order to decrease the energy consumption in industrial process and reduce carbon dioxide emission that causes global warming, it is important to study the direct recycling of aluminium chip as the secondary resources.

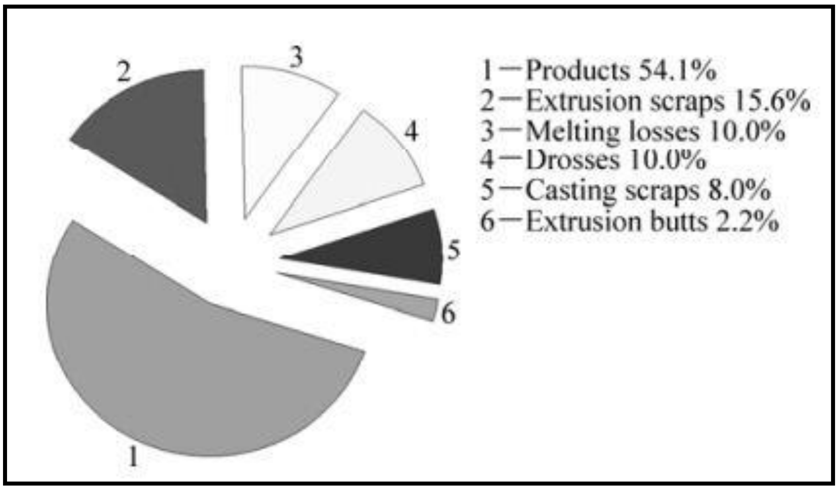

Figure 1.4: Metal yield in recycling of aluminum turnings by conventional recycling process (Jirang and Hans, 2010)

1.2 Problem statement

Government of Malaysia via the 9th Malaysia Plan (2006 – 2010) had been emphasizing on the continuation of reduce, reuse, recovery and recycling of waste as well as greater use of environmentally friendly products. Urgency for conservation of energy and resources through recycling in Malaysian context is profound as Malaysia has the highest per capita energy consumption among the ASEAN countries. As highlighted in one of RMK-10 'Green Technology' criteria which are to conserve the use of energy and natural resources, while promoting the use of renewable resources; therefore, conservation of energy and resources and the practice of recycling are the desired outcomes for future direction (The Economic Planning Unit Malaysia, 2010). On the other hand, demand for aluminium products is increasing since aluminium alloy offers excellent corrosion resistance with good strength and low density. Due to increasing of the demand of this metal, solid waste problem is one of the most popular issues that have received extensive public extension. Finishing process in industry generates waste usually in chip form but recycling of chip is difficult due to their elongated spiral shape and micro size nature. Their surface area is relatively large and covered with oil emulsion which it is not effective for recycling through remelting approach (Gronostajski *et al.,* 1997). Hence, this study was conducted direct recycling techniques by utilizing hot press forging process of aluminum chip for which this process purposely to prevent harm on environmental impact, decreasing energy consumption, as well as reducing the total cost and time production (by reducing the step process). Furthermore, the conditions for consolidation considering chip sizes that affect the mechanical and physical properties in relation to forging products are rarely documented in recent literature. It has been reported that oxide precipitates in the recycled specimen leads to distortion of ductile properties especially at elevated temperature. Oxide precipitation is closely related with recycled aluminium alloy chip size in which increment of oxidization is directly proportional to the increment of chip's surface area (Shuyan *et al.,* 2009). In previous studies, less quantitative evaluations were made on the relationships of the chip size with oxide precipitationon the mechanical properties and microstructure of the recycled AA6061 aluminium alloy. Thus, it is important to clarify this relationship in scientifically distinct, well structured manner.

1.3 Objectives of study

This study embarks on the following objectives:

i) To investigate the effect of different chip sizes and operating temperatures on the mechanical and physical properties of the recycled chip AA6061 aluminium alloy in hot press forging process.

ii) To make comparison and recommendation based on mechanical and physical properties between recycled and reference specimen AA6061 aluminium alloy billets.

1.4 Scope of study

The scopes of this study are focused on the following outcomes:

i) Using AA6061 aluminium alloy (from high speed end milling) and reference specimen AA6061 aluminium alloy billet for comparison.

ii) Running high speed end milling (Sodick-MC430L) machine to produce different chip sizes with the following parameters and conditions:
   a) Tool: 10.0 mm diameter uncoated solid carbide
   b) Dry cutting operation without coolant
   c) High cutting speed: 1100 m/min
   d) Depth of cut, DOC: (0.50, 1.00, 1.50) mm
   e) Feed, f: (0.50, 0.75, 0.10) mm/tooth

iii) Conducting the solid-state direct recycling techniques of aluminium alloy by utilizing hot press forging process based onthe following parameters and conditions:
   a) Three different operating temperature : (460, 490, 520) ˚C
   b) Three different operating pressure (47.0, 58.0, 70.0) MPa.
   c) Close- die types

iv) Investigating and evaluating the responses on mechanical and physical properties as below:
   a) Ultimate tensile strength, yield strength and elongation to failure using Universal Testing Machine
   b) Microstructure analysis including grain size, grain boundary and voids, using Optical Microscope (OM)
   c) Subsurface layer changes consist of microhardness using Vickers Microhardness Tester
   d) Oxide precipitation (oxygen amount) by using Oxygen-Nitrogen Analyzer.

1.5 Expected outcome

The scope of this study introduces the direct technique for recycling aluminium chips instead of conventional method which will be carried out without melting phase. Hot press forging technique is characterized by lower number of steps and gives benefit on low energy consumption and operating cost. It could elaborate technological process details and a systematic characterization of hot forged profiles properties for the recycled of AA6061 aluminium alloy chip of different geometries and will show the technological potential regarding yield behaviour and microstructure. It will reveal the performance of recycled aluminium chip on their mechanical properties and microstructure by comparing them with the original aluminium-base composite. Moreover, it is expected to review the possibility of this recycled aluminium chip as a secondary resources as an alternative to overcome the shortage of primary resources in which it utilizes the metal optimally and able to lower the usage of raw metal. Furthermore, it will help to reduce the land use for mining and provides very low air pollutant emission. This will be an initiative to machining practitioners and industry as a way to support our government on green technology and waste management.

1.6 Significance of study

A global reduction of carbon dioxide emissions is becoming more and more important to prevent global warming caused by green house production. Due to this, the need for decreasing energy consumption of industrial processes as well as transportation and production engineering is a major factor in today’s industrial world. This study introduces the direct techniques of recycling with low energy consumption and cost without intervening the metallurgical processes. It provides potential low air pollution and optimal raw metal utilization as compared to the conventional method.

Therefore, this will be an initiative to support our government in solid waste management as a way to prevent global warming, reduce the landfill of solid waste production and also decrease the energy consumption. This effort can be describe as sustainable manufacturing which is to create the manufactured products using the process that minimize negative environmental impact, conserve energy and natural resources, safe for communities and economically valuable.

CHAPTER 2

LITERATURE REVIEW

Literature review plays an important role during conducting a research. It is highly important to seek a new and better quality in research development of the particular field of study. Focusing on the solid-state recycling aluminium which indicates forming process as discussed in Chapter 1, this chapter briefly explains about the hot forging which brings to the aim of illustrating the fundamental concepts that would be used to explain the method of this study and a reviews on the research trend of previous researcher in this area and understanding the fundamental of hot forging process. The sources of information of this chapter were taken mainly from books and journals. This chapter is divided into four sections, first section discusses about the fundamental of forging. Second section discussed comprehensively about the chronology of the techniques used for recycling aluminium alloy which relates to environment, cost and energy aspect. Third section discussed on the effect of parameter in hot press forging process and consequently shows some guideline to select the suitable parameter for this research. The last section reviews on the effect of chip sizes in recycling of aluminum.

2.1 Forging fundamental

Forging is a deformation process in which the work is compressed between two dies, using either impact or gradual pressure to form the part. It is the oldest metal forming operations, dating back around 500 before century (Groover, 2002). Today, forging is an important industrial process used to produce variety of high-strength components for automotive, aerospace, and other applications.

Forging is carried out in many different ways. One way to classify it is by working temperature. However, they are generally classified by metal temperature whether it is above or below the recrystallization temperature. If the temperature is above material recrystallization temperature it is classified as hot forging. For temperature that falls within the region between 3 over 10 of the recrystallization temperature and material recrystallization temperature is classified as warm forging and finally for temperature below 3 over 10 of the recrystallization temperature then it is known as cold forging (Degarmo *et al.*, 2003).

The primary alloy strengthening precipitate is magnesium silicide (Mg2Si). Thermal cycles throughout the extrusion process promote the growth or dissolution of second phase particles. Many investigations have been performed in order to establish the precipitation sequence in the AA6xxx series aluminium alloys (Kwon *et al.,* 2007). Also the determination and characteristics of every phase has been thoroughly studied.

Figure 2.1 shows the quasi-binary Al-Mg-Si alloy phase diagram. The amount of Mg_2Si that is present depends on the amount of elemental Mg and Si that is in the alloy. Mg_2Si dissolves into solid solution when the temperature is increased from room temperature to (a temperature within the alpha region). Phase transformations reach an equilibrium state when the temperature is maintained for a sufficient time within the alpha region. If the temperature is subsequently reduced below the solvus line, there will be a reduction in the solubility of Mg2Si, and excess Mg2Si will tend to precipitate (Rashid,1997).

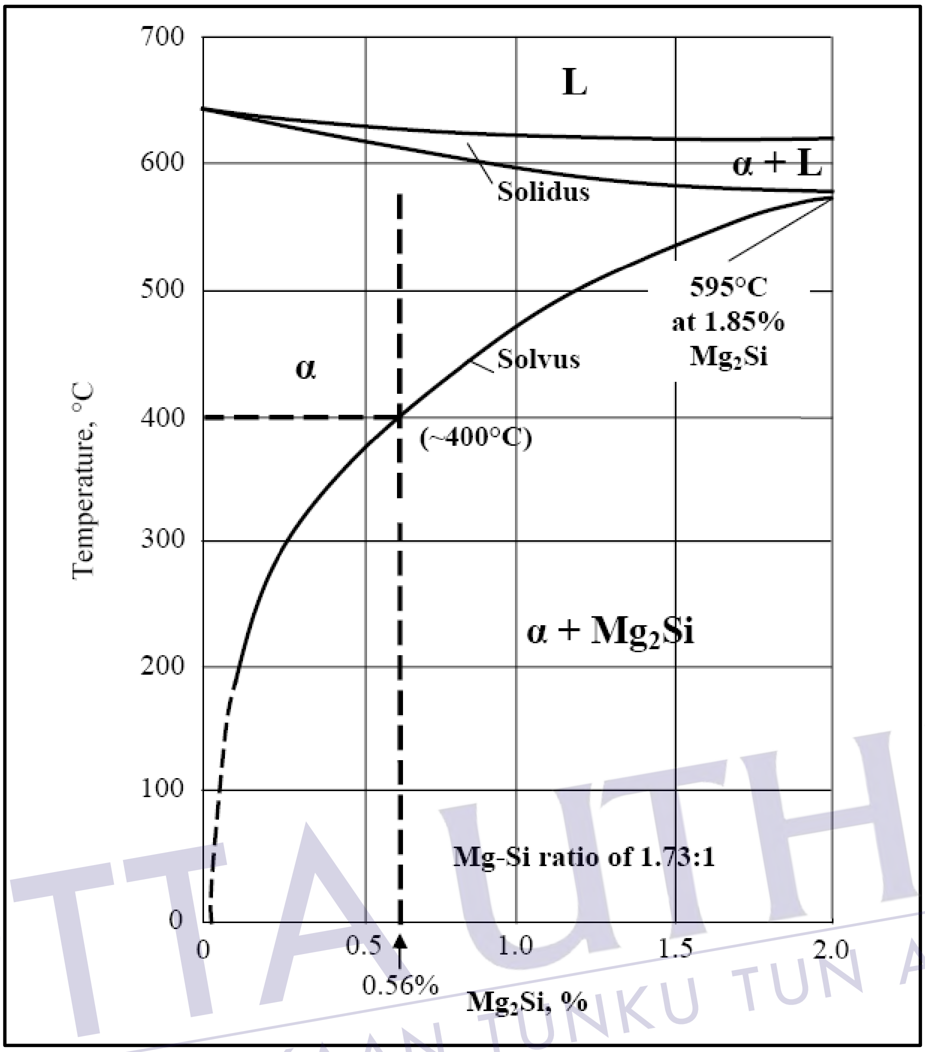

Figure 2.1: Quasi-binary phase diagram for Al-Mg-Si alloy indicating important transition zones (Rashid,1997).

The Mg content of the supplied alloys varies between 0.35% and 0.36%; it would require 0.20% to 0.21% Si to fulfil the stoichiometric requirements for Mg2Si. The Mg2Si would then constitute ~0.56 weight percentage of the alloy as indicated in Figure 2.1. The vertical line in Figure 2.2, showing the Mg2Si content range around 0.56%, intersects with the solid solubility line at about 400°C. Kwon *et al.* (2007) have shown that the main precipitate Mg2Si phase start to dissolve into the matrix at temperatures above 400°C for AA6061 and AA6083 aluminium alloys.

2.2 Recycling aluminium techniques

Aluminum alloys are produced and used in many forms such as casting, sheet, plate, bar, rod, channels and forgings in various areas, especially in the aerospace industry. The advantages of these alloys are lightweight, corrosion resistance, and very good thermal and electrical conductivity. Somehow, production of aluminium from bauxite requires a lot of energy, which is almost 200 GJ/Tons. This amount is approximately 10 times of that required for steel production. In fact, the price of virgin aluminium is five times higher than steel, that leads to the importance of recycling aluminium for which it is more economic instead of using primary resources, supported by the fact that to produce a given mass of aluminium from recycled scrap only requires 5% of the energy to produce the same mass from the ore (Schlesinger, 2007). This section will discuss on the recycling aluminum techniques with concern of environmental impact, energy and cost consumption (Appendices A to B).

2.2.1 Conventional recycling

The elongated spiral shape and micro size in nature have made it difficult to recycle chips due to their large surface area to volume ratio. Apart from that, the chip condition which is prone to be covered in oxide and lubricant is not conducive to remelting. There are losses at every stage of the recycling process, for example, losses caused by metal oxidization during melting, some lost through mixing with the slag from the surface of the melt, and the rest are scraps resulting from casting and further processing of the aluminium ingots (Gronostajski *et al.*, 1997). Gronostajski *et al.* (2000) stated that in the process of melting aluminium and aluminium-alloy waste and scrap, there is about an average of 10% of the metal is burnt and another 10% is lost as the aluminium mixes with the slag removed from the surface of the ladle. These losses are irreversible and able to reach up to 35% if melting takes place in gas- or oil-red furnaces instead of induction furnaces. The main cause of substantial losses of aluminium and aluminium-alloy during conventional recycling is due to its low density (even after the pressing operation) at which it resides longer on the surface of the molten metal and oxidises intensively. There are further losses during casting such as risers, shrink holes and so on, which is estimated about 8%. Later during the processing of aluminium ingots, these losses would amount to about 18%. Therefore there is ultimately no more than 54% of the metal recovered at the end of the process.

Lazzaro and Atzori (1992) analyzed the metal losses in conventional recycling of aluminum turnings. It shows approximately about 45% of the aluminum metal will be either lost or being carried into a new scrap phase. Furthermore, generation of new scrap takes place about 25% during remelting and requires about 6000 kcal/kg energy consumption. Traditionally re-melters used a degreasing fluid to clean the machining swarf followed by heating operation to dry it, which often lead to the development of new oxide films. The melting operation is usually performed in fossil fuel rotary furnaces with high energy consumption, and uses up to 20% of low melting point salt based in equimolar mixtures of potassium and sodium chlorides to improve de-oxidation, as well as fluorides in the form of CaF_2 and Na_3AlF_6 (Tenorio and Espinosa, 2002). The liquid salt break the oxide structure and transform the oxide net in a great number of small fragments that turn into the shape of plates or small clusters of plates. The aluminium freed from the oxides starts to coalesce forming small drops of liquid which is also coalesces among them and accumulate. The oxide-salt reaction generates a by-product, known as “salt-cake” (Gruzleski and Closset, 1990), which is consider as hazardous waste. After melting, the liquid metal is degassed and refined using suitable products for each type of alloy, normally TiB_2 and Al-10 Sr (and poured into metallic moulds (Gruzleski and Closset, 1990). In short, melting techniques generates dangerous residues that require elimination usually at high cost, even if some vaporization techniques are arising (Shinzato and Hypolito, 2005).

Recycling of aluminium alloys swarf by melting requires several operations in order to achieve good ingot quality standards, ranging from conditioning (cleaning, drying and compaction), melting, molten metal treatment (degassing, grain refinement and microstructure modification) to ingot production.

2.2.2 Solid-state recycling

With the concern of global warming, recycling of wrought aluminum alloys via new solid state recycling techniques instead of conventional remelting and subsequent refinement has been taken into account. Solid state recycling process through compression and extrusion at room or moderate temperature may result in significant energy savings. This subchapter discusses the solid-state recycling of which as stated in previous research, it involves two techniques; the powder metallurgy and direct recycling methods.

2.2.2.1 Powder metallurgy technique

This technique utilizes ball mill to grind the scraps of aluminium chip, followed by hot extrusion process. (Gronostajski *et al.,* 2000) prepared the aluminium chips for product manufacturing before chips segregation, continued with cleaning of the chips from impurities and finally commination of the chips to a granulated product. In the case of direct conversion of aluminium and aluminium-alloy chips into compact metal by extrusion, the waste consisted of the part of the chips from which impurities could not be removed (2%) and the extrusion waste itself (3%), leaving 95% of the metal to be recovered. Usually the energy consumed for conventional recycling of aluminium is 16±19 GJ/tons, whereas in the direct conversion of aluminium chip into compact material was only 5±6 GJ/tons.

Additional works were carried out by Fogagnolo *et al.* (2003) when extruding pre-compacted AA6061 reinforced with Al_2O_3 fibres to prevent the necessity of chip transformation into powder. Both Aluminium AA6061 matrixes composite and reinforced Al_2O which was recycled through cold pressing and hot extrusion were compared to the primary material produced by conventional casting process. Fogagnolo *et al.* (2003) found that the ultimate tensile strength (UTS) and hardness were higher for the recycled material than for the former composite. Followed by Samuel (2003), the aluminium scrap was ball milled and mixed with the green density particle before its sintered. Measured properties included green density, compressive strength and hardness. Experimental result obtained shows that recycled aluminium triggered higher productivity. Samuel (2003) stated that this technique caused relatively low air pollution and more metal saving compared to conventional method.

Geertruyden (2005) showed an industrial application of a consolidation technique, which was recycling of secondary aluminium in the form of fine aluminum scrap, turnings, and borings consolidated by aluminum powder. Here, in this work aimed at substituting primary aluminum for loose scrap with high surface area to volume ratio consolidated by an extrusion process. It was estimated that by using this process, an energy savings of 522 billion kilo Joule/year could be achieved in an aluminum rolling plant with an annual sheet production of 226,500 tons/year. Due to the focus on billet production for the melting phase, no final products like profiles were produced.

The recycling of scrap aluminium via cold-bonding was investigated by Allwood *et al.* (2005). Cold bonding demands intimate contact between clean surfaces, requiring high normal pressure to avoid loads being carried by the asperities, and to crack the oxide layers on adjacent pieces of scrap aluminium. Once these layers were broken the softer aluminium was extruded through the cracks. A minimum longitudinal strain of 0.4 was required for this process. Processes that offer the necessary combination of longitudinal extension under transverse pressure are identified as rolling, extrusion and forging. Initial tests were conducted on an annealed 1050 alloy by ball mill as clean sheets of alloy were used as the input. The cold bonding processes were found to have considerably less material loss than conventional recycling, and demand only around 2% of the energy. After all, it was observed that recycling of aluminum scrap by cold bonding during cold extrusion and rolling processes only lead to ingots and not the final products.

The strength of composites without reinforcing differs marginally from those of the corresponding solid materials, and by introducing the reinforcement phase the strength can be improved, especially at higher temperatures. It is discovered that the way in which the reinforcement phase is introduced into the comminute aluminium and aluminium-alloy chips has a significant effect on the quantity and distribution of the matrix.

2.2.2.2 Direct recycling technique

Direct recycling is an innovative process chain, combining optimized primary material usage and reduction of process steps. It is a combination of hot profile extrusion with subsequent turning or machining and hot extrusion of the produced machining chips for semi-finished parts. Several innovative processes have been proposed to recycle aluminium chips using direct hot extrusion. This process chain requires an amount of energy of only 5-10 % of that needed for the conventional process chain including a re-melting step of scraps to produce new extruded billets (Suzuki *et al.,* 2005). This alternative recycling processes poses a little difference from former technique in such way that it does not undergo material transformation from chips into the form of powder. In this work, the new technique employed consist of direct material recycling from the form of chips through cold or hot pressing followed by hot extrusion, avoiding the ball milling step, which results in more economic recycling process. This new technique can also be applied to recycle chips derived from aluminium matrix composite machining, which is still difficult to obtain by other techniques. Figure 3.1, as illustrated from the works of (Tekkaya *et al.,* 2009) shows that this technique is relatively simple, consumes small amounts of energy and does not have a harmful effect on the environment by eliminating the melting and casting process. The material is directly recycled from chips formed by forging, which in some what way results in more economic recycling by skipping two process steps.

Fogagnolo (2003) proposed a method of recycling aluminium alloy chips by employing cold and hot pressing followed by hot extrusion, as well as exploring the possibility of using this method to recycle aluminium matrix composite chips. Hot extrusion of cold or hot pressed samples could satisfactorily promote the consolidation of the chips. Extruding hot pressed samples in high temperature proved to be the best route, from the point of view of mechanical properties. Tekkaya *et al*., (2009) recently studied this method on direct recycling aluminium chips related to cold press and hot extrusion process and showed that no irregularities at the surface were visible due to the individual bonding of chips.

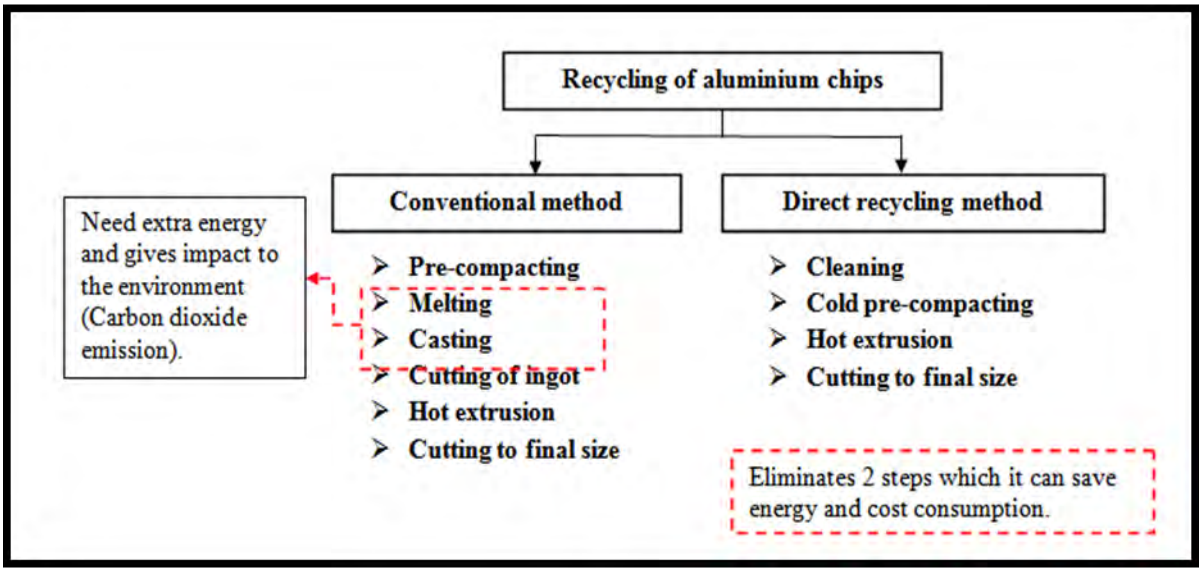

Figure 2.2: A comparison of conventional and direct recycling techniques of Aluminium alloy chips

Tekkaya *et al*., (2009) also stated that during further forming procedures, no reduction in the surface quality of a sample such as opening of pores was detected. The yield strength of extruded chips was comparable to the yield stress of profiles extruded from solid billets, with only a reduction of less than 10% in the stress level was observed. The microstructure showed the seam weld lines developed within the extruded aluminum alloy at the boundaries of the chips. These boundaries were stretched in extrusion direction due to the forming process. No pores or inclusions could be seen at the grain boundaries. Moreover, machining and cutting properties are at least comparable to those of conventionally extruded profiles, sometimes even better because of initial breaking of the chips.

Ryoichi et al., (2011) studied the possibility of solid-state recycling of aluminium alloy machining swarf using cold extrusion and a subsequent cold rolling process is investigated. Cast Al–Si alloy swarf was cold compacted into billets and successfully profile-extruded into square bars with a rectangular cross-sectional aspect ratio of 1:1.8 under an extrusion ratio of 4 or more. It was also found that the strength and density of material recycled through extrusion and an additional rolling process were superior to material recycled using extrusion only. Moreover, it was observed that the ductility of the recycled materials was inferior to that of the original aluminium alloy.

Pantke et al., (2013) studied technological process details and systematic characterization of the hot extruded profiles properties for the reuse of AA-7175 and AA-7475 aluminum alloy chips of different geometries and demonstrated the technological potential regarding mechanical properties of the profiles. The profiles, extruded from mixed scrap material show an improvement of strain. This is based on additional phase boundaries, caused on chip interlocking. Particularly industrial scrap material is suitable for the presented process chain.

Direct recycling technique is expected to be an alternative process that enabled recycling of aluminium chips without the necessity of chips transformation into powder through ball milling.

2.3 Temperature effect in hot forging

Although the aluminum alloys have high-strength to weight ratio and good corrosion resistance, the low formability of aluminum sheets limits their usage in some products with complex shapes, such as automotive body parts. The warm forming process is intended to overcome this problem by using an elevated forming temperature which is below the recrystallization temperature (Tebbe and Kridli, 2004). The warm and hot forming method improves the formability of the aluminum alloys. This improvement at the elevated temperature is principal for the aluminum alloys such as 5082 and 5005 alloys due to the increased strain rate hardening. It was demonstrated that the formability is improved by a uniform temperature increase, but the best results are obtained by applying temperature gradients. The formability depends strongly on the composition of the aluminum alloy. The aluminum which contains 6% magnesium could give a 300% of total elongation at about 250°C, eligible for more application in industry (Altan, 2002). Therefore, this shows that the temperature plays an important role on formability of alloy.

Forging temperature range is carefully selected for each material. The forging temperature for hot working is selected between the solidus and recrystallization temperature. In general, increasing forging temperature will reduce material flow stress and improve the forgability. In some alloy systems, forgeability decreases with increment of grain size. In hot forging, the die is heated up to get little drop in billet temperature when billet is mounted on the die.

This research applied hot forging process in producing sample specimens. Groover, (2002) define hot forming as deformation at temperatures above the recrystallization temperature. Elaboration on recrystallization temperature is about one-half of melting points on absolute scale. In practice, hot working is usually performed somewhat above $0.5T_m$ (melting point). Metal continues to soften as temperature increases above $0.5T_m$, enhancing the advantage of hot working above this level. Groover (2002) also stated that the capability for substantial plastic deformation of hot forging is far more than possible compare to cold working or warm working because the strength coefficient (K) is substantially less at room temperature, strain hardening exponent (n) is zero (theoretically) and the ductility is significantly increased.

2.4 Response of the effect on the chips size

This subchapter reviews the analysis of the responses from the previous study focusing on the chip size effect by using direct recycling process. Three types of responses that were typically analyzed in preceding researches are amount of oxide, mechanical properties and microstructure.

2.4.1 Amount of oxide

It is well known that certain alloys are easy to be oxidized. Oxide films will form naturally on chip surfaces during machining, therefore oxide residues are readily settled on aluminum alloy fabricated from machined chips by solid-state process. Oxide precipitation will inevitably affect the microstructure and properties of recycled materials. Shuyan *et al.,* (2009) investigated the effect of oxide amount with respect to other parameters in hot extrusion process of AZ31B magnesium alloy. AZ31B is a wrought magnesium alloy with good room-temperature strength and ductility combined with corrosion resistance and weld ability. AZ31B finds application in wide variety of uses including aircraft fuselages, cell phone and laptop cases, speaker cones and concrete tools. AZ31B can be super formed at elevated temperatures to produce a wide variety of intricate components for automotive uses. This paper stated that the amount of oxide was closely related to the size of recycled magnesium alloy chip. Oxide in recycled materials was mainly introduced from chips surface. This work assumed that the shape of the machined chips was cuboids, the amount of oxide in recycled specimens from different chip sizes could be estimated by the following equation:

$$O = Sl = \frac{2(xy + yz + xz)}{xyz} \quad (2.1)$$

where *O* was the volume percent of oxide in recycled specimen; *S* was total surface area of chips per unit volume; *l* was the thickness of oxide film on chip surface; *x*, *y*, and *z* were the length, width and thickness of chip, respectively. Shuyan *et al.,* (2009) concluded that the oxide had few particle-dispersion strengthening effect due to its inhomogeneous distribution whereas the grain refinement was also related to the presence of oxide.

Maoliang *et al.*, (2008) investigated the effect of chip sizes (AZ91D magnesium alloy) on the oxide amount. The three recycled specimens were classified by different sizes. This work showed that from the context of readily oxidized magnesium alloys in the machining process, the oxygen content was different and might be responsible for the differences observed. Figure 2.2 shows the relationship between the accumulated oxygen concentration and the total surface area of the chips in the recycled specimens per unit volume.

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