EFFECTS OF HOT PRESS FORGING PARAMETER AND LIFE CYCLE ASSESSMENT IN DIRECT RECYCLING OF AA6061 ALUMINIUM

NUR KAMILAH BINTI YUSUF

A thesis submitted in fulfillment of the requirement for the award of the Doctor of Philosophy.

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

APRIL 2017
For my beloved family and dearly friends.

So verily, with the hardship, there is relief.

Indeed in the hardship, there is relief.

So when you have finished, then stand up for Allah worship.

And to your Lord turn all your invocation.

(Al-Inshirah: 5-8)
ACKNOWLEDGEMENT

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ABSTRACT

Industrial processes have led to global warming by carbon dioxide emissions and considerable amounts of solid waste. Meltless recycling technique have been utilized to overcome the lack of primary resources, focusing on reducing the usage of energy and materials. Hot press forging was proposed as a novel direct recycling technique which results in astoundingly low energy usage in contrast with conventional recycling. The aim of this study is to investigate the effects of parameter to the functional performance of the technique and analysed the environmental impacts with the corresponding remelting method. For this purpose, recycling aluminium chips AA6061 by utilizing hot press forging process with full factorial $3^2$ design of experiment (DOE) which consists of three operating temperature, $T_o$ and three holding time, $t_o$. Response surface methodology (RSM) was utilized for responses optimization and central composite design (CCD) was applied in designing the experiments to evaluate the effects of hot press forging parameter to three responses; ultimate tensile strength (UTS), elongation to failure (ETF) and global warming potential (GWP). The maximum mechanical properties and surface integrity of recycled chip (T1-temper) are remarkably comparable with theoretical AA6061 T4-temper where the value of UTS and microhardness exhibited greater. As the desired mechanical properties of forgings can be obtained only by means of a final heat treatment, T5-temper; aging after forging process was employed. Heat treated recycled billet AA6061 (T5-temper) are considered comparable with as-received AA6061 T6. Response surface optimization shows the suggested optimal hot press forging parameters in this research. Life cycle assessment (LCA) of direct recycling hot press forging process were evaluated and the GWP value of hot press forging routes gives a notable environmental impact when it significantly reduced as compared to conventional (melting) routes.
ABSTRAK

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<tr>
<td>A</td>
<td>Cross sectional area</td>
</tr>
<tr>
<td>Adeq. precision</td>
<td>Adequate precision</td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>Adjusted $R^2$</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>CCD</td>
<td>Central composite design</td>
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<tr>
<td>Cor. total</td>
<td>totals of all information corrected for the mean</td>
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<td>CR</td>
<td>Conventional recycling</td>
</tr>
<tr>
<td>CTP</td>
<td>Compressive torsion process</td>
</tr>
<tr>
<td>C.V. %</td>
<td>Coefficient of variation</td>
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<tr>
<td>DF</td>
<td>Desirability function</td>
</tr>
<tr>
<td>d.f</td>
<td>Degrees of freedom</td>
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<tr>
<td>DR</td>
<td>Direct recycling</td>
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<tr>
<td>DOC</td>
<td>Depth of cut</td>
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<tr>
<td>DOE</td>
<td>Design of experiment</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy-dispersive X-ray Spectroscopy</td>
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<tr>
<td>ECAP</td>
<td>Equal Channel angular pressing</td>
</tr>
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<td>ETF</td>
<td>Elongation to failure</td>
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<tr>
<td>$f$</td>
<td>Feed</td>
</tr>
<tr>
<td>FESEM</td>
<td>Field-emission Scanning Electron Microscope</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Feed rate</td>
</tr>
<tr>
<td>f.u</td>
<td>Functional unit</td>
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<tr>
<td>GHG</td>
<td>Green house gas</td>
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<td>GWP</td>
<td>Global warming potential</td>
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<td>HSM</td>
<td>High speed machining</td>
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<td>HV</td>
<td>Hardness Vickers</td>
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<td>IvsR</td>
<td>Incineration versus recycling</td>
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<td>LCA</td>
<td>Life cycle assessment</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>LCI</td>
<td>Life cycle inventory</td>
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<td>LCIA</td>
<td>Life cycle impact assessment</td>
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<tr>
<td>LvsR</td>
<td>Landfill versus recycling</td>
</tr>
<tr>
<td>n</td>
<td>Number of teeth</td>
</tr>
<tr>
<td>N</td>
<td>Rotational per minute</td>
</tr>
<tr>
<td>Kf</td>
<td>Forging shape factor</td>
</tr>
<tr>
<td>LOM</td>
<td>Light optical microscope</td>
</tr>
<tr>
<td>PM</td>
<td>Powder metallurgy</td>
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<tr>
<td>Pred. $R^2$</td>
<td>Predicted $R^2$</td>
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<td>PRESS</td>
<td>Prediction error sum of squares</td>
</tr>
<tr>
<td>Prob. &gt; F</td>
<td>Proportion of time or probability you would expect to get the stated $F$ value</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Coefficient of determination</td>
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<td>$R_{mvsR_s}$</td>
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<td>Response surface methodology</td>
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<td>SDR</td>
<td>Semi-direct recycling</td>
</tr>
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<td>SEM</td>
<td>Scanning electron microscope</td>
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<td>SHT</td>
<td>Solution heat treated</td>
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<tr>
<td>SPS</td>
<td>Spark plasma sintering</td>
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<tr>
<td>Std. Dev.</td>
<td>Square root of the residual mean square</td>
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<td>$T_a$</td>
<td>Aging temperature</td>
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<tr>
<td>$t_a$</td>
<td>Aging time</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Operating temperature</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Holding time</td>
</tr>
<tr>
<td>T1-temper</td>
<td>Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition</td>
</tr>
<tr>
<td>T4-temper</td>
<td>Solution heat treated and naturally aged to a substantially stable condition</td>
</tr>
<tr>
<td>T5-temper</td>
<td>Cooled from an elevated-temperature shaping process and artificially aged</td>
</tr>
<tr>
<td>T6-temper</td>
<td>Solution heat treated and artificially aged</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate tensile strength</td>
</tr>
</tbody>
</table>
YS  Yield strength

$V_c$  Cutting speed
CHAPTER 1

INTRODUCTION

Environmental concerns have long gained attention as the world's population continues to grow, putting heavy pressure on the Earth's resources. Greenhouse effect that caused the atmosphere to retain heat is one of the factors that contribute to the climate change. An increase in the global average temperature will have significant adverse impacts not only on humans, but the ecosystems and nature such as extreme weather, ocean acidification, extinction of species, drought, desertification, melting of glaciers and rising of global average sea level (Bekkelund, 2013).

In recent years, the increasing of waste management cost, securing final disposal landfills, reduce and clean energy consumption are among the most critical sustainability issues in the whole world. Consequently, sustainable manufacturing is essential in ensuring Malaysia achieving the modern urbanization to be at par with other developed countries (Agamuthu, 2013). The report from the International Energy Agency (2013) stated that, the Association of South-East Asian Nations exhibits total consumption of energy-related carbon dioxide emissions that has almost doubled, from 1.2 gigatons in 2011 to 2.3 gigatons in 2035 or from 3.7% to 6.1% of global emissions as shown in Figure 1.1. Unfortunately, Malaysia is the third-largest carbon dioxide emissions and energy consumer in the ASEAN region. Final energy consumption rises by 76% in 2011-2035.
In the New Policies Scenario, Malaysia's population are forecasted to increase at an average annual rate of 1.2% by 2035, reaching up to 39 million people. Due to the rapid growth of the local population and daily consumption, the amount of solid waste generated in Peninsular Malaysia has skyrocketed from 16,200 tons per day in 2001 to 25,000 tonnes generated per day in 2012 which come to an average of 0.8 kilograms per capita per day (Said, 2012).

Consequently, the Malaysian government has been embarking on several initiatives to counter these issues which one of them is implemented green technology. For instance, strategies in promoting green technology in the country have been detailed out in the 11th Malaysia Plan and 2016 Budget entitled "Pursuing Green Growth for Sustainability and Resilience". Similarly, the Ministry of Energy, Green Technology and Water has been advocating green technology by the formulation of the National Green Technology Policy and the establishment of the National Green Technology Council which is spearheaded by the prime minister himself. One of the major concerns of green technology in Malaysia was focusing on industrial sector where industry remains as the largest end-user, with its demand growing just over 90% (International Energy Agency & International Aluminium Institute, 2013).

Recently, industrial processes have led to global warming by carbon dioxide emissions and considerable amounts of solid waste, affecting human activity, as shown in Figure 1.2 (Yusuf, 2013). The industrial revolution in the 18th century, manufacturing sector had known to have an unfavourable impact on the environment
which had led to the establishment of numerous environmental preservation laws and policies, such as the 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 greenhouse production (Smith, Brown, Ogilvie, Rushton, & Bates, 2001). Various industrial processes has been identified to be accounted for approximately 14 % of the total carbon dioxide emissions and 20 % of the total greenhouse gas emissions in 2010 (United States National Academies, 2010). According to Jayal et al., (2010) the manufacturing sector, which lies at the core of the industrial economy, must be made to be sustainable so that the high standard of living can be preserved. This in turn is achieved by the industrialised societies and to enable developing societies to achieve and maintain the same standard of living. Therefore, the need of the decrement in energy consumption especially in several key industries such as industrial processes, transportation as well as production engineering.

![Global Warming Diagram](image)

**Figure 1.2: Effects of industrial processes on human activities (Yusuf, 2013)**

In comparison to other material categories, metals have the highest potential for systematic recycling, due to i) their high economic value, ii) their large volumes enabling manufacturing at bigger scale and iii) their distinctive feature of excellent recyclability (Paraskevas, Kellens, Renaldi, Dewulf, & Duflo, 2012). Of all the metals, Aluminium is the third most abundant element in the earth’s crust after oxygen and silicon. The demand for aluminium products is increasing because
aluminium alloys possessed excellent corrosion resistance with high strength and low density compared with steel. The use of a lighter-weight material, such as aluminium, as an alternative to steel is usually considered a positive choice especially in fuel economy. As an approximation, a 10% reduction in mass led to 5% improvement in fuel economy (Kumar & Sutherland, 2008).

Aluminium offers several benefits relative to ferrous material in terms of ductility and malleability, resistance to corrosion, better conductivity, low density; and on top of all, its recyclability. This is the critical factor that contributes to broad applications of aluminium in manufacturing industry especially in the automotive sector. On the contrary, production of aluminium which involves the extraction of aluminium ore called bauxite (primary resource) requires profuse energy, which is almost 200 gigajoules/ton. This staggering amount is almost 10 times of that required for steel production, supported by the fact that price of virgin aluminium is five times higher than steel. Thus, the importance of recycling aluminium as secondary resources, of which it is significantly more cost effective rather than using primary resources. Recycling the aluminium was estimated to utilize 5% of the energy used to produce the same amount of aluminium from the ore (Schlesinger, 2013). Recycling of aluminium alloys have shown to provide major economic benefits, thus it is necessary for the aluminium industry to develop and implement all technologies that optimize the benefit of recycling. Hence, this study will focus on the benefits of recycling aluminium and the research gaps of the previous and current techniques involved in the process.

1.1 Background of Study

Transportation is the most notable industry that make use of aluminium worldwide. In 2012, approximately 3.6 million tonnes of wrought and casting alloys were used for the production of cars, commercial vehicles, aeroplanes, trains, ships, and that figure is steadily rising as shown in Figure 1.3 (European Aluminium Refiners, 2012). Increasingly, aluminium products are being employed to reduce vehicle weights without loss of performance, improving safety as well as reducing greenhouse gas emissions from vehicle use-phase. Based on the scenario forecasts,
aluminium content per vehicle will continue to grow to nearly up to 190 kg by 2020. In addition, the use of aluminium Auto Body Sheet is expected to increase by 110% over the next 10 years (Ducker Worldwide, 2016). Consequently, the transport sector is also a major source of aluminium from the end of a vehicle’s lifetime. Hence, this study will focus on automotive aluminium application of AA6061 alloy.

![Aluminium End-use Markets in Western Europe](image)

Figure 1.3: Aluminium End-use Markets in Western Europe (European Aluminium Refiners, 2012)

The recycling of aluminium alloys has proven to be advantageous especially it is cost effective. Thus, it is crucial for the industry to initiate and employ all possible technologies related to aluminium recycling. Therefore, this study will focus on recycling the automotive aluminium chip and scrap from the machining process. There were various techniques in recycling aluminium. The most viable aluminium recycling practices in most industries is based on the melting technique, which is called conventional recycling (CR). CR produce secondary ingot by controlling the composition of the alloy to match the standardized grades. Hatayama et al. (2012) forecasted that in 2030, 6.1 megatons of scrap will not be recycled due to the high concentration of aluminium alloying elements, caused by their inefficient and/or problematic removal during re-melting. As illustrated in Figure 1.4, there is a substantial loss of aluminium metal during the conventional process which include metal losses during re-melting, cross produced from a liquid aluminium process, scrap produced from the casting process, butts generated during the extrusion process.
which in turn leads to generate new scraps. In addition, as presented in Figure 1.5, approximately 10% of aluminium metal will be lost during remelting phase and other 35% will be carried out as a new scrap throughout the process. Consequently, about 45% of the aluminium metal will be either lost or carried into a new scrap phase. Puga et al. (2009) also stated that the process was characterised by a very low metal recovery rate, high-energy consumption, and release of high levels of smoke and gases to the environment.

Figure 1.4: Flow chart of conventional process for recycling of aluminium turnings (Cui & Roven, 2010)

Figure 1.5: Metal yield in conventional recycling of aluminium (Cui & Roven, 2010)
Several innovative processes have been proposed to recycle aluminium chips using solid-state recycling techniques. Initially, the solid-state recycling techniques employ the powder metallurgy processes by Gronostajski et al., (1997) followed by a research from Fogagnolo et al., (2003). However, the solid-state technique has recently improved by utilizing direct recycling method, eliminating the ball-milled process that produce fine granulated particles. As the ball-milling step is eliminated, the process is called direct recycling. This process chain requires only 5-10% energy of that needed for the conventional process chain that includes a re-melting step of the scrap to produce new extrusion billets (Tekkaya et al., 2009). This is due to material being recycled directly from the chips by hot press forging, resulting in a more cost-effective process.

The study that utilized direct recycling using hot forging process shows that recycled aluminium exhibits good strength and plasticity potential, proving that the solid-state technique with hot forging is a viable alternative for recycling aluminium alloy chips. Additional research in this particular study area is highly recommended for further environmental conservation (Lajis, M.A., Yusuf, N.K., Noh, M.Z. Ibrahim, 2013; Yusuf, Lajis, Daud, & Noh, 2013). Hence, hot press forging, however, showed promising alternative method for recycling aluminium as the waste from the machining process exhibit excellent potential in terms of strength and plasticity (Ahmad, Lajis, Yusuf, & Wagiman, 2016). However, the desired mechanical properties of direct recycling using hot forgings can be obtained only by means of a final heat treatment. In general, the best properties in hot forged parts of heat-treatable aluminium alloys are obtained by including heat treatment in the forging cycle that provides strengthening by precipitation hardening mechanisms. The treatment consists of a solution treatment of the alloy in the single-phase region to allow the formation of solid solution, followed by water quenching to room temperature that produces an unstable supersaturated solid solution. When such material is aged at relatively low temperatures, a second phase will precipitate out as a controlled distribution of fine particles. (Forcellese & Gabrielli, 2000) and (Tanner & Robinson, 2008). Therefore, in this research the heat treatment after direct recycling using forging process will be implemented in order to obtain the desired mechanical properties.

Additionally, Life Cycle Assessment (LCA) is one of the most widely used and internationally accepted method for the evaluating the impacts of products and
systems towards the environment (Georgesen, 2006). LCA works by calculating the environmental burden of a material, product or service during its lifetime. Therefore, this research using LCA as a method to study the parameters that influence the meltless direct recycling through hot press forging process to disclose the impact of this alternative towards environment conservation. Moreover, this research also contains a comparative analysis of an alternative material recycling route, starting from the same waste materials as the conventional recycling route, analysing the technical feasibility as well as the possible material and energy savings. Corresponding to these, estimations of the total Global warming potential of both routes will be analysed in details using Life Cycle Assessment (LCA).

Hence, this study aimed to investigate the effect of operating temperature and holding time on the mechanical properties, physical properties, as well as Global warming potential of direct recycling of AA6061 aluminium alloy that is potentially to be used as secondary resources. This in turn help to develop the new approach of recycling, which utilized the hot press forging with low energy consumption and cost without intervening the metallurgical processes. It is indeed practical to investigate the potential usage of waste material.

1.2 Problem Statement

Current practice of recycling which used melting techniques to produce a secondary ingot by controlling the composition of alloy resulted in a nonrecyclable scrap. Since the removal of alloying element during remelting is very difficult in comparison to other elements, a different approach, focusing on solid state recycling of aluminium scrap has been employed that could provide significant environmental benefits, mainly by avoiding metal losses during remelting. The conventional recycling of aluminium is recently less favourable as the method require high energy and large number of operations which led to increase of cost. Hence, this research has conducted solid-state direct recycling technique by utilizing hot press forging process of an aluminium chip for which this process was employed to purposely prevent any harm to the environment, decreasing energy consumption, as well as reducing the total cost and time of production (by reducing the step process).
Furthermore, the conditions for consolidation of aluminium recycling by considering forging parameter that affects the mechanical and physical properties in relation to forging products are rarely documented in recent literature. Therefore, in this research the heat treatment after forging process has been implemented in order to obtain the desired mechanical properties. In heat treatment of aluminium, the selection of temperature and duration of solution and aging treatments are key issues that need to be addressed. In order to obtain optimum mechanical properties, a suitable production procedure should be selected. This justifies the need to investigate the effect of temperature and duration of solution heat treatment that used hot press forging process.

Identifying the sustainable strategies for metal shaping technologies, which promotes energy and resource efficient approaches for aluminium-based component manufacturing is a research topic that should be explored with some urgency. LCA studies on metal waste recycling through solid-state are very scarce and there is almost no database recorded so far in direct recycling aluminium using a hot press forging process. Therefore, this research aimed to estimate and compare the environmental impacts of solid state recycling (hot press forging technique) with conventional recycling (melting technique) route through LCA. The study focused on identifying the available opportunities in alternative recycling routes for the production waste with higher recycling values. Hence, this approach seeks to minimize the need for primary material flows and in turn reduce the adverse environmental impact.

1.3 Objectives of Study

This study aims to explore the effects of hot press forging parameters and Life Cycle Assessment in the direct recycling of aluminium AA6061 which specifically focused on the following objectives:

i. To investigate the mechanical properties and surface integrity which consist of comparison and recommendation for both recycled chip and as-received billet.
ii. To quantify the value of Global warming potential (GWP) for hot press forging parameters of the recycling process and compare the environmental benefits with conventional recycling (melting/casting).

iii. To develop the modelling and optimization of hot press forging parameters’ effect over the mechanical properties responses and Global warming potential (GWP) by employing the Response surface methodology (RSM).

1.4 Scope of Study

The scope of this study 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 chips 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: 1100m/min
   d) Depth of cut, DOC: 1.00mm
   e) Feed, f: 0.05mm/tooth

iii) Conducting the solid-state direct recycling techniques of aluminium alloy by utilizing a hot press forging process (solution heat treatment) as a T1-temper based on the following parameters and conditions:
   a) Three different operating temperature, T1: (430, 480, 530) °C
   b) Three different holding time, t1: (60, 90, 120) minutes
   c) Close-die types

iv) Performing T5-temper heat treatment process immediately after hot press forging process based on the following parameters and conditions for selected sample:
   a) Quenching rate: 100°C/s
   b) Aging temperature: 175 °C
   c) Aging time: (1 to 8) hours
v) Investigating and evaluating the responses on mechanical and physical properties:
   a) Tensile analysis, including Ultimate tensile strength, Elongation to failure using Universal Testing Machine
   b) Microstructure analysis, including grain size, grain boundary and voids, using Light optical microscope (LOM)
   c) Subsurface layer changes consist of microhardness using Vickers Microhardness Tester
   d) Chemical composition using Energy-dispersive X-ray Spectroscopy (EDX)
   e) Relative density using Density Balance
   f) Fracture surface using Field-emission Scanning Electron Microscope (FESEM)

vi) Assessing the life cycle of the environmental impacts of solid state recycling for each experimental trial (hot press forging technique) with conventional recycling (melting technique) route based on the following parameters and conditions:

   a) Scope:
      - Functional unit – unitary (1kg of raw material)
      - Boundaries – secondary products and final residuals

   b) Life cycle inventory (LCI)
      - Data sources – primary and database
      - Database – Ecoinvent v3.1
      - Software – Simapro 8.0.4

   c) Life cycle impact assessment (LCIA)
      - Methods – ReCiPe
      - Impact category – environmental impact
      - Damage category – human health, resource depletion, ecosystem quality

   d) Response
      - Carbon footprint: Global warming potential (GWP) value
vii) Developing a robust modelling and optimization on the effects of operating
temperatures and holding times over the mechanical properties responses and
Global warming potential (GWP) from Life Cycle Assessment by employing
the Response Surface Methodology (RSM) properties:

a) Software: Design Expert 8.0
b) Face centred – Central Composite Design
c) Full factorial - 2 factors and 3 levels

1.5 Significance of Study

This research introduces a direct technique for recycling aluminium scrap instead of
conventional method which will be carried out without melting phase. This technique
is characterized by fewer steps and gives benefit on low energy consumption and
production operating cost. It is hoped that assessment of the performance of recycled
aluminium chips on their mechanical and physical properties by comparing them
with the original aluminium-base alloy. This study also aimed to evaluate the
potential of the recycled aluminium chip to be used as a secondary resource and
hence, as an alternative to overcome the shortage of primary aluminium resources.

In addition, the usage of the recycled aluminium chip helps to reduce the land
use for waste disposal as well as lower the air pollution. This will be an initiative to
machining practitioners and industry to support our government strategy on green
technology and waste management solutions.

Moreover, a mathematical modelling technique was used to determine the
optimal forging condition with respect to various objectives and response criteria.
Hence, modelling and optimization technique called response surface methodology
(RSM) could be used to provide optimal or near-optimal solutions to the overall
optimization problem formulated, and subsequently implemented in actual hot
forging process.

The heat treatment process after direct recycling aluminium using a hot
forging process is needed to improve the material forgeability and strength. The
proposed sequence consists of a solution treatment, followed by water quenching and
then aging that produces a fine precipitate structure characterised by high mechanical properties. This will be the guidance for practitioners to employ alternative way to achieve a maximum strength of recycled aluminium.

Finally, this work contains a comparative analysis of an alternative material recycling route, starting from the same waste materials as the conventional recycling route, analysing the technical feasibility as well as the possible material and energy savings. This assessment can detect significant changes in the environmental effects between the life cycle phases. It can also estimate the effects of materials consumption and environmental emissions on human and the ecosystem. This effort has the potential to structure the flow of quantitative information between different stakeholders (industry, researchers, governmental agents, and other groups). It can be used internally within an industry for process improvement, technology selection and reporting, and externally to support green technology.

Therefore, this will be an initiative to support our government in solid waste management to prevent global warming, reduce the landfill of solid waste production and decrease the energy consumption. This effort can be described as sustainable manufacturing, which aimed to manufacture products using the process that minimize negative impact on the environment, conserve energy and natural resources, safe for communities and economically valuable.
CHAPTER 2

LITERATURE REVIEW

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 review on the research trend of previous research in this area and understanding the fundamental of the hot forging process. The sources of information of this chapter were taken mainly from books and journals. This chapter is divided into five sections, first section reviews comprehensively about the chronology of the techniques used for recycling aluminium alloy. Second section discusses about the fundamental of hot forging and parameter selection. Third section discusses about heat treatment of aluminium which related to hot press forging process. The fourth section reviews the fundamental of response surface method for design of experiment and optimization. The fifth section reviewed and highlight the effect of the related parameter in this study, whereas the sixth section discussed the life cycle assessment of aluminium waste management option and last section summarized overall review.
2.1 Recycling Aluminium Techniques

Recycling of aluminium alloys has been shown to provide major economic benefits; as a result, it is appropriate for the aluminium industry to develop and implement all technologies that will maximize the benefits of recycling. There are three main techniques available for recycling aluminium, conventional recycling (CR), semi-direct recycling (SDR) and direct recycling (DR). Figure 2.1 shows a comparison of the basic steps for the three main recycling techniques. The classification was based on the number of steps and processes included in each technique.

Figure 2.1: Comparison of conventional, semi-direct recycling and direct recycling techniques for aluminium alloy chips
The common aluminium recycling practices in most industries use a melting technique (operating at a temperature exceeding the melting point) to produce a secondary ingot by controlling the composition of the alloys to match the standardized grades. In this research, this approach was classified as a conventional recycling. The SDR technique is characterized by the presence of a compulsory pre-processing step before entering the main process. As shown in Figure 2.1, there are three main forming processes in SDR: powder metallurgy, hot extrusion and spark plasma sintering. Ball milling and cold pre-compaction are the pre-processing steps required for the powder metallurgy, hot extrusion and spark plasma sintering processes, respectively. On the contrary, DR is a single-step process to produce a final product without the necessity of any pre-processing. Currently, there are only three processes that have been recognized as DR techniques: cold forging, hot forging and compressive torsion.

2.1.1 Conventional Recycling

Melting technique is a current aluminium recycling practices in most industries to produce a secondary ingot by controlling the composition of alloys to match the standardized grades. Refiners and remelters play integral roles in aluminium recycling, establishing links with collectors, dismantlers, metal merchants and scrap processors who deal with the collection and treatment of scrap. Aluminium recycling uses aluminium scrap as raw material. After scrap is collected, it is sorted and cleaned before it is used in metal production. Scrap is fed into melting furnaces to liquefy the metal, which is subsequently purified, adjusted to the desired alloy, and produced in a form suitable for processing and fabrication. The types of furnaces used to melt scrap include rotary and electric furnaces. The general structure of secondary aluminium production from secondary raw materials is summarized in the process diagram presented in Figure 2.2 (López & Tayibi, 2007).
Before the melting process, chips must be cleaned, dried and compacted. Traditionally, remelters use a degreasing fluid to clean the fine machined chips, which is followed by a heating operation to dry the chips. This process often leads to the development of new oxide films. However, there are losses at every stage of the recycling process, such as losses caused by metal oxidation during melting, losses through mixing with the slag from the surface of the melt, and scraps resulting from casting and further processing of the aluminium ingots (Gronostajski, Kaczmar, Marciniak, & Matuszak, 1997).

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 with oxide and lubricant is not conducive to remelting. There are losses at every stage of their cycling 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 (1991) analysed the metal losses in conventional recycling of aluminium turnings. It shows approximately about 45% of the aluminium 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 remelters 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 on equimolar mixtures of potassium and sodium chlorides to improve de-oxidation, as well as fluorides in the form of calcium fluoride, CaF₂ and sodium hexafluoroaluminate Na₃AlF₆ (Tenorio & Espinosa, 2002). The liquid salts breaks 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 & Closset, 1990), which is considered as hazardous waste. After melting, the liquid metal is degassed and refined using suitable products for each type of alloy, normally titanium diboride, TiB₂ and Al₁₀Sr (and poured into metallic moulds) (Gruzleski & Closset, 1990). In Europe the landfill disposal of this waste is forbidden because of the slag soluble (Gwinner, 1996). Salts represent a potential source of pollution to surface and groundwater supplies.

However, there are several treatment to recover the loss of aluminium after the melting process, the liquid metal is degassed and refined using suitable products
for each type of alloy, normally TiB₂ and Al₁₀Sr (Gruzleski & Closset, 1990), and poured into metallic moulds. Although melting techniques generate dangerous residues that the re-melting companies must eliminate, usually at a high cost, even if some vaporization techniques are arising (Shinzato & Hypolito, 2005), the salt-cake can be eliminated, the liquid metal is degassed and refined using suitable products for each type of alloy, and poured into metallic moulds. So, the addition of other material is needed to be included into the process for the treatment. Besides, research done by Mashhadi et al. (2009) has used salt flux to recover aluminium alloy. From the recyclability standpoint it is shown that using protective salt flux gave the best route to recycle the aluminium alloy turning scrap, from the point of view of recyclability which is made by cold pressing and melting the compressed aluminium alloy with salt flux. Mechanical properties and chemical analysis of samples were approximately the same as the primary material produced by a conventional casting process.

Another alternative of melting technique that can preserve the environment was done by Puga et al. (2009). Traditionally remelters use a degreasing fluid to clean the machining swarf followed by a heating operation to dry it, which often leads to the development of new oxide films. The study discovered an environmental-friendly aluminium swarf recycling technique avoiding the use of salts during melting, by using induction melting and performing degassing by a novel ultrasonic technique. Those techniques and procedures are the major advantages in the current industrial practice. In order to attain considerable decreasing into manufacturing costs, the final recovered product is introduced in the production cycle together with remaining raw materials. The result shows that the recycling efficiency depends on the swarf conditioning for melting, the melting technique and the metal treatment methodology. David and Kopac (2013) also found one of the alternatives to avoid the environmental problems and to recovery aluminium which a processing method was developed and aluminium was recovered as an added value product as alumina. The method refers to a process at low temperature, in more stages: acid leaching, purification, precipitation and calcinations. At the end of this process aluminium was extracted, first as Al³⁺ soluble ions and final as alumina product. The compaction of the aluminium dross and alumina powder obtained was measured by applying the leaching test using the atomic absorption spectrometry and chemical analysis. The method presented in this work allows the use of hazardous aluminium solid waste as
raw material to recover an important fraction of soluble aluminium content as an added value product, alumina, with high grade purity (99.28%).

In short, although there is improvement suggested in this technique, there still a lot of consideration to take into action. Melting technique generates dangerous residues that require elimination usually at a high cost, even if some vaporization techniques are rising (Shinzato & Hypolito, 2005). As for Samuel (2003), aluminium loss can easily reach 50 % and it is in line with Puga et al. (2009), at the end, the aluminium loss is very high, making this traditional recovery procedure highly inefficient. Recycling of aluminium alloys crap 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.

2.1.2 Semi Direct Recycling

Instead of using CR techniques that use a very high temperature to reach the melting point, recycling of wrought aluminium alloys by SDR is preferable. High energy consumption for conventional aluminium recycling and subsequent refinement has been considered in previous studies (Gronostajski et al., 1997; Tekkaya et al., 2009). The SDR method is defined as a partially direct recycling process that requires additional steps before the recycling process is completed. The three SDR techniques involve powder metallurgy, extrusion and spark plasma sintering techniques under solid-state conditions and can result in significant energy savings. In both techniques, additional steps are required for the recycling process to be completed. The powder metallurgy technique utilizes ball mills before the cold compaction to grind the aluminium chip scraps, whereas the hot extrusion techniques requires ball mills, pre-heating and cold compaction to produce cold billets and spark plasma sintering needed cold compaction to produce billets.
a. Powder Metallurgy Technique

Powder metallurgy (PM) is the process of blending powdered materials, pressing them into a desired shape or form (compacting), and subsequently heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: powder manufacturing, powder blending, compacting, and sintering. Compacting is generally performed at room temperature, and the high-temperature process of sintering is usually conducted at atmospheric pressure. Figure 2.3 shows the general flow of PM processing (Upadhyaya, 1997).

![Diagram of powder metallurgy process]

Figure 2.3: General flow sheet of powder metallurgy processing (Upadhyaya, 1997)

Among many other manufacturing processes, powder metallurgy is also highly ranked because it can produce near net shape products with properties that are comparable with those of conventionally produced products and require less or no secondary machining other than increased mass production rates (Warikh et al., 2014). Many components used in automobiles, aircrafts, spacecraft, nuclear reactors, computers and household appliances are also produced using powder metallurgy.
Powder metallurgy appears to be a flexible and versatile manufacturing process because of its ability to process various types of materials to produce porous products with uniform porosity, electric and magnetic properties from a combination of different materials, refractory metals with high melting points, which are difficult to process using conventional methods, hard metals for cutting tools, frictional materials and dispersion strengthen materials, such as aluminium with the addition of alumina as the strengthening particles (Angelo & Subramanian, 2008).

Powder metallurgy is considered to be a good technique for aluminium recycling. In comparison to the melting method, powder metallurgy offers important advantages, including low processing temperatures compared to the melting process in conventional methods.

b. Extrusion Technique

Hot extrusion is an innovative process chain that combines optimized primary material usage and a reduction in process steps. This technique is a combination of hot profile extrusion with subsequent turning or machining and hot extrusion of the produced machining chips for semi-finished parts. This concept was introduced and patented by Stern in 1945 (Misiolek, Haase, Ben Khalifa, Tekkaya, & Kleiner, 2012). This method is possible due to the joining of the aluminium under high pressure, high strain and a temperature just below the melting point. The strain results in cracking of the oxide layer, and the high pressure and temperature lead to joining caused by contact with the pure aluminium surface.

This process chain requires a small amount of energy compared to conventional process chains and uses only 5-6 gigajoule/ton, which is only 5-6 % of that needed for the conventional process chain. During the complete semi-direct conversion of aluminium chips into a compact metal by extrusion, a portion of the chip from which impurities cannot be removed is wasted, amounting to approximately 2 %; the extrusion waste can be as high as 3%. Thus, 95 % of the aluminium chips are recovered (Tekkaya et al., 2009). These alternative recycling processes both include material transformation from chips to powder via ball milling. In this work, a new technique were employed that consists of directly recycling the
material from the chips via cold or hot forging, which is followed by hot extrusion. As a result, the ball milling step is avoided, resulting in a more economic recycling process. This new technique can also be employed to recycle chips derived from aluminium matrix composites, which are even more difficult to obtain using other techniques.

Figure 2.4 shows the recycling aluminium chip flow process as a secondary resource. The extrusion process is also affected by a combination of optimum ram speed, preheat temperature and preheat time (Rahim, Lajis, & Ariffin, 2015). According to Pantke et al. (2013) recycled aluminium chips with different sizes and shapes can be obtained through different cutting depths during chip production. Higher cutting depths during the rough machining processes require lower cutting depths during the finishing processes. The billets’ structural stability is dependent on the chip geometry and compacting process parameters due to the interlocking of the chips. But there is no significant influence on the mechanical properties of the extruded profiles. The hardness of each profile is similar, and there are no significant differences that depend on the used raw material.

![Figure 2.4: Recycling aluminium chip flow process as a secondary resource](image-url)
c. Spark Plasma Sintering

Spark plasma sintering (SPS) is a new approach of SDR. It consists cold pressed as pre-process and SPS as a main process to consolidate and recycling the aluminium chip. The main characteristic of SPS is that the pulsed DC current directly passes through the graphite die, as well as the chip being compacted as shown in Figure 2.5. The dynamic scrap compactions, combined with electric current-based joule heating, achieved partial fracture of the stable surface oxides, desorption of the entrapped gases and activated the metallic surfaces, resulting in efficient solid-state chip welding eliminating residual porosity (Paraskevas, Kellens, Dewulf, & Duflou, 2014).

![Spark Plasma Sintering schematic](image)

Figure 2.5: Spark Plasma Sintering schematic (Paraskevas, Kellens, et al., 2014)

The heat generated is internal, in contrast to the conventional hot pressing, where the heat is provided by external heating elements. This facilitates a very high heating rate where the sintering process generally is very fast. Spark plasma sintering
REFERENCES


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