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HOT PRESS FORGING AS THE DIRECT RECYCLING TECHNIQUE OF ALUMINIUM – A REVIEW

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ABSTRACT
Aluminium is totally recyclable with no downgrading of its qualities, but in the process of typical conventional aluminium recycling, there are quite a number of negative impacts. The recycling of aluminium and its alloys by direct recycling method is relatively simple, consumes small amount of energy, produce small amount of waste and does not have a harmful effect on the environment. This approach use hot press forging which eliminated two pre-process steps which typically introduce in conventional and semi-direct recycling. Hot press forging of aluminium 6xxx series is hot working process which means that the alloys should be heated around 460-520 °C, slightly above the recrystallization temperature. After heating the material, 1 to 2 hours of soaking times are sufficient to redissolve the aluminium under the flow stress less than 47 MPa. Review on recycling aluminium chips using hot press forging show that there are good potential of strength and plasticity. This is proved that such recycling technique could be employed as an alternative method to replace the conventional aluminium recycling process.

Keywords: aluminium, direct recycling, hot press forging.

INTRODUCTION
Industrial revolution totally changed the environmental landscape for the whole world. Although the invention through the industrial revolution aims to ease the human in many aspects, but at the same time, it also disappoints the environment in tremendous elements. This disappointment had urged the authority to promulgate laws and regulation to avert global warming from the greenhouse effect. As there were saying of “The world is sick” being referred to the number pollution that had dominated the environment green and fresh surrounding.

According to the report by United Nations Conference on Trade and Development (1995), Lake Batata which originally was a typical unpolluted water ecosystem has been tainted by bauxite washing activities. In over ten years, the waste from bauxite beneficiation was discharged into the lake and the effluent contains 6 – 9% of solid waste. This irresponsible doing of tailing disposal into the lake result the dynamics of the nutrients were affected, mainly in the area where tailings were discharged. Such misbehave activities should be avoided before it went far and create catastrophic toward the nature.

Demand from the highly populated world nowadays is directly contributing to the tumour that had been bared by the earth. The industry is trying their best in suiting people demand and indirectly put metals and alloys to be in the top list. Aluminium demanding for various purposed for such machinery, building, packaging, electrical application, consumer durables and transport has been increasing ever since the beginning of the industrial revolution in 1760. This is due the bound of the aluminium properties which are low weight, high strength, superior malleability, easy machining, excellent corrosion resistance and good thermal and electrical conductivity.
Conversely, the whole process of producing the aluminium is hugely energy-intensive. Aluminium is originally produced from bauxite. The world consumed primary aluminium for the total of 800 Mt from 1900-2006 and it is forecasted to increase to 1200 Mt by the year 2030 (Hunt, 2007). Under those circumstances, it is crucially important to recycle secondary resources aluminium, whereby it is pecuniary advantage than processing the primary aluminium resource. Recycling aluminium only required upmost 95% less energy than to produce primary aluminium and it is also dissipate unpleasant effect toward the environment (“The International Aluminium Institute,” 2014).

This review aims to prompt ideal parameters selection to produce optimal responses for mechanical and physical properties of recycled aluminium. The review covers the discussion on pre-process elimination, chip studies base on sizes, forming process by hot press forging, suitable operating temperature, flow stress and also heating time for aluminium 6xxx series. Furthermore, this review also confers about modelling and optimizing the hot press forging parameters to achieve optimum mechanical and physical responses.

ALUMINIUM RECYCLING
Aluminium recycling had been triggered in the early 1900’s where it aims to reduce the energy consumption and to preserve the environment. The primary aluminium production (mining bauxite from ore) required 113 gigajoule per tonne of energy but on the other hand, secondary production (conventional aluminium recycling from scrap) need only 13.6 gigajoule per tonne of energy (Rombach, 1998). Figure-1 illustrates the differentiation of energy consumption. This significant reduction of 88% of energy is contributing to the reduction of secondary aluminium price due to it lower energy consumption.

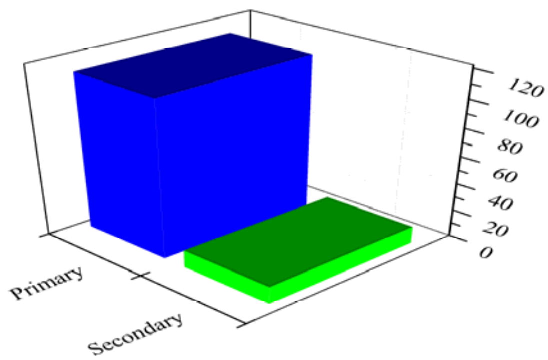

Figure-1. Comparison of energy requirement for aluminium production.

There are several techniques that had been studied in the recycling of aluminium namely as conventional, semi direct and direct recycling. Conventional recycling technique comprises of melting the scrap and cast it into new products.

Lazzaro & Atzori (1992) analyzed the metal losses during the conventional recycling of aluminum turnings. Figure-2 dipicted the distribution of metal yield in conventional recycling of aluminium. Approximately 45% of the aluminum metal is either lost or carried into a new scrap phase. Furthermore, approximately 25% of new scrap is produced during re-melting, consuming approximately 6,000 kcal.kg-1 of energy.

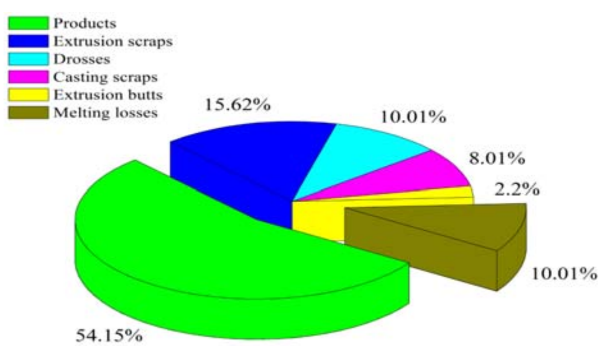

Figure-2. Metal yield in conventional recycling of aluminium (Lazzaro & Atzori, 1992).

Followed, there are solid-state recycling (semi direct) which entail of turning scrap into new forms through powder metallurgy or hot extrusion process. Hot extrusion is the most popular recycling techniques for the past 19 years (Rahim, Lajis, & Ariffin, 2015). Yet, there are direct recycling techniques which directly turn aluminium chips without changing its shape into new form by utilizing hot press forging.

In direct recycling method, average metal loss during the remelting phase could be avoided approximately 20% by preventing intensive oxidation on the molten metal surface, burning and mixture with the slag removed from the surface of the ladle (Gronostajski & Matuszak, 1999).

For that, aluminium is needed to have alternative recovery instead of conventional aluminium recycling as the demand increasing and to prevent the shortage of the primary sources of aluminium that cause extensive cost of operation (Khamis, Lajis, & Albert, 2014). The recycling of aluminium and its alloys by direct recycling method is relatively simple, consumes small amount of energy, produce small amount of waste and does not have a harmful effect on the environment (Yusuf, Lajis, Daud, & Noh, 2013).

Therefore, an efficient process should be properly construct in order to improve the present procedure of aluminium recycling so that the environment do not too prone to the pollution and at the same time, produce better product properties.

HOT PRESS FORGING

Pre-Process Elimination

The new approach of direct recycling aluminium using hot press forging will eliminate two pre-process step which is typically introduce in conventional and semi direct recycling. The two pre-processes step that had been eliminated were cold-compaction and ball-milling (Yusuf, 2013). By eliminating the two pre-processes, the time, cost and also energy consumption can be reduce.

Chip Preparation

Material removal process (machining) permits the cutting tool to remove unwanted material from a workpiece to produce the desired shape. During the machining process, waste is produced in chips form. Coincide with the name of direct recycling, the chips were directly cleaned and dried as soon as it leave the machining process. This typical preliminary process (presence in any recycling technique) is to remove impurity (lubricant from the machining) that in the end will result clean aluminium scrap without the intrusion of other substance. The solution used for cleaning the aluminium scrap is 99.5% purity Acetone (C_3H_6O) and drying process took about 30 minutes in thermal oven at 60 ºC temperature.

Lajis *et al.* (2013) studied and categorized chips into three type namely as small, medium and large. The chips produced by manipulating the machining parameter for High Speed Machining (HSM). The chip types and size are tabled in Table-1 dan Figure-3 according to the average measurement of length, width and thickness.

Table-1. AA6061 chips parameter (Yusuf, 2013).

Type	Chip parameter (mm)		
	Length, l	Width, w	Thickness, t
Small	6.10	0.535	0.021
Medium	5.20	1.097	0.091
Large	4.30	1.535	0.145

(a) (b) (c)

Figure-3. Selected chip sizes for recycling process a) small-sized, b) medium-sized, c) large-sized (Yusuf, 2013)

Hu *et al.* (2008) said that if the shape of the machined chips is taken as cubic, the relationship can be satisfied using Equation-1 to calculate the surface area per unit volume, S. This then result the S value for small, medium and large chips equal to 99.30, 24.19 and 15.56 mm2/mm3 respectively.

$$S = 2\,(\,l.w + w.t + t.l\,)\,l.w.t \qquad (1)$$

Forming Process

Cleaned aluminium chips were poured into the bottom mould (Figure-4a) and the top mould (Figure-4b) will be fixed accordingly. The top mould will act as plunger to press the aluminium chips. The mould is then being placed inside the hot press forging machine (Figure-4c) to execute the forging operation. The operation identified as flashless forging because the raw workpiece (aluminium chips) is completely contained within the mould cavity during compression, and no flash is formed.

(a) (b) (c)

Figure-4. Forming equipment (a) bottom mould, (b) top mould, (c) hot press forging machine.

Flashless forging able to minimize waste associated with post-forging operations. Therefore, the final product needs little or no finishing process. Cost savings are gained from the use of less material, and thus less scrap generated.

Operating Temperature

The heating of a metal workpiece reduces the flow stress and thus leads to a corresponding decrease in the force and work required for deformation. Moreover, Lajis *et al.* (2014) and Shahrom *et al.* (2014) showed that the operating temperature is identified as the second most significant factor (after chip size) influencing the mechanical properties.

Aluminium 6xxx series have the melting temperature ranged from 550-650ºC. Direct recycling technique involves deformation at temperatures somewhat above the recrystallization temperature or namely as hot working (Groover, 2010). For this particular hot working process, the optimum forging temperature for aluminium 6xxx series should range from 460-520 ºC (ASM International, 1996).

As the mould is placed inside the hot press forging machine, the machine is turned on and temperatures will begin to increase. For the first 120 minutes, the mould was heated at 4.33ºC/min. When it reaches the desired temperature, the holding stage took place for 30 minutes to stable and distribute the heat into the entire working area (furnace, mould and aluminium chips). At that point, the temperature is maintained during pre-compacting cycle (PCC) stage until the end of the soaking time. Finally, the temperature is turn off to begin the cooling stage. Figure-5 illustrates the operating temperature flow for the whole process.

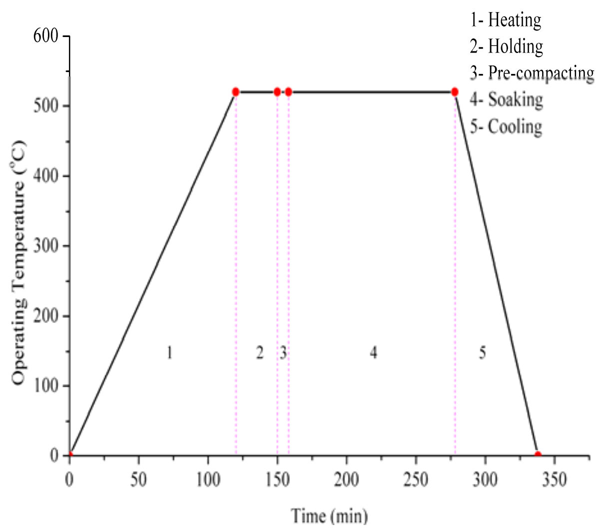

Figure-5. Operating temperature flow.

Flow Stress

The deformation imparted to this recycling technique is relatively slow by utilizing hydraulic presses at the strain rate of 10 s-1. A highly forgeable aluminium alloy 6xxx is suggested to have a flow stress less than approximately 47 MPa or 369 kN in force (ASM International, 1996). This flow stress is parallel with the suggested optimum operating temperature (as mention earlier) for 6xxx series that should range from 460-520ºC. The flow stress could be interpolated by the mentioned temperature and strain rate in Figure-6.

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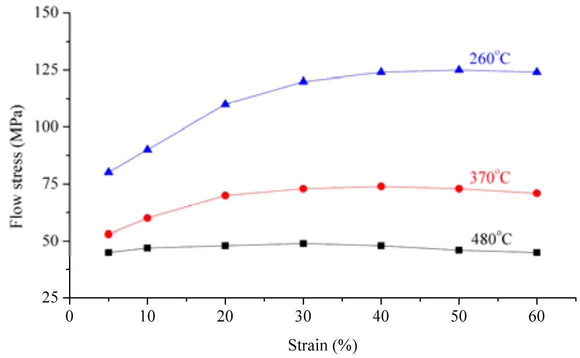

Figure-6. Flow stress versus strain rate for alloy 6061 at the strain rate of 10s-1 (ASM International, 1996).

During the PCC stage, the plunge is repeatedly pressed with the force of not more than 369 kN. The process is done for several cycles with constantly delay time for each cycle is 2 minutes. When the cycle is finished, it will start the soaking stage with the same force. As soon as the soaking stage finish, the plunge is let to press the aluminium from the beginning, until the end of the cooling stage. Figure-7 illustrates the force for the whole process (a) and at PCC stage for 4 cycle (b).

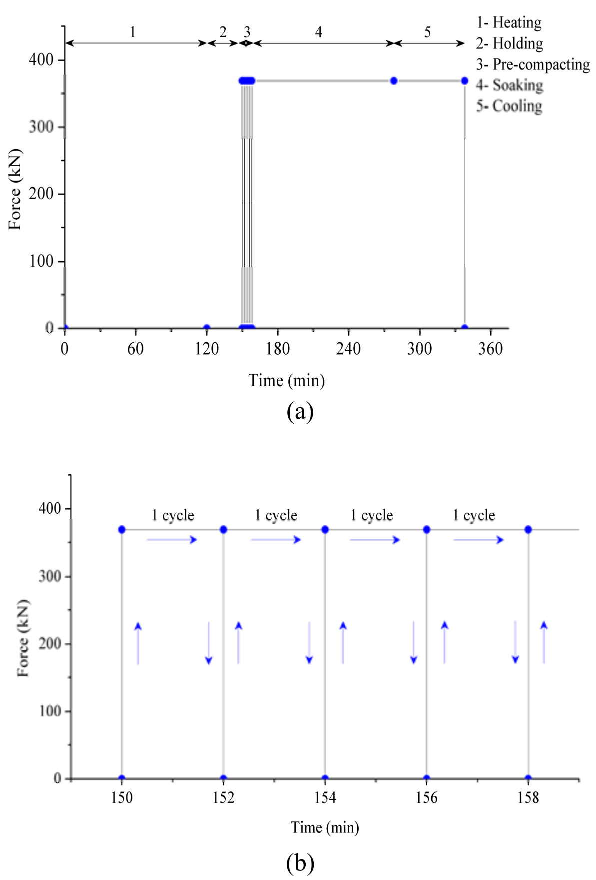

Figure-7. Force for the (a) whole process and (b) PCC stage for 4 cycle.

Heating and Soaking Time

The section thickness and the furnace capabilities is the dependence factor for aluminium alloys heating time. Yet, because of the increased thermal conductivity of aluminium alloys, the required preheating times are shorter than with other forged materials (i.e. steels). Commonly, 10 to 20 min per inch of section thickness is sufficient to ensure that the aluminium alloys have reached the desired temperature (ASM International, 1996). Since the mould measured as 3.0 inches in thickness, the holding time is fixed for 30 minutes.

After heating the material above the solvus temperature, sufficient time namely soaking time, must be given to completely redissolve the second phase. Generally, soaking times of 1 to 2 hours are sufficient for aluminium alloys (ASM International, 1996). Figure-8 merged the force and operating temperature with the function of time.

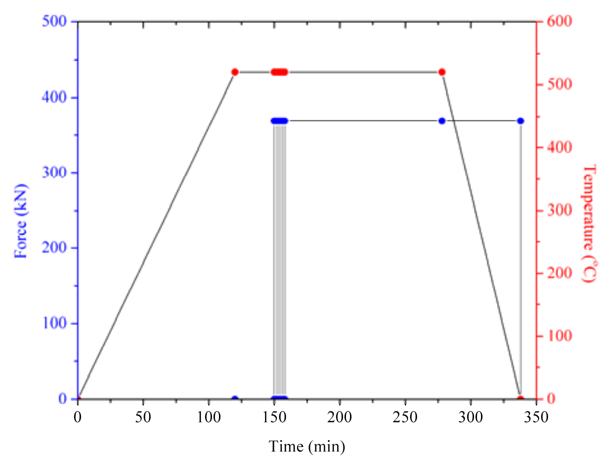

Figure-8. Force and operating temperature with the function of time.

RESPONSES

Mechanical Properties

Ultimate tensile strength (UTS) provides information on the strength and ductility of materials under uniaxial tensile stresses. This information may be useful in comparisons of materials, alloy development, quality control, and design under certain circumstances.

The mechanical properties achieved in the alloys depend on control of the temperature and duration during processes (Meng, 2010). Yusuf *et al.* (2013) discussed on the operating temperature of direct recycling aluminium chips (AA6061) in hot press forging process. It is found that there were raised of UTS and YS when the operating temperature increased from 460-520°C. As shown in Figure-9, at maximum temperature of 520°C and force of 78 kN, the specimen exhibit the highest UTS and YS of 90.43 MPa and 84 MPa respectively. The UTS has linear trend with increment of temperature which is similar to the YS trend. Increasing of YS and UTS are affected by increment of heating temperature (Naka, Nakayama, Uemori, Hino, & Yoshida, 2003; Tiryakiouglu, Campbell, & Staley, 2003; Zhang, Li, Yuan, & Peng, 2007).

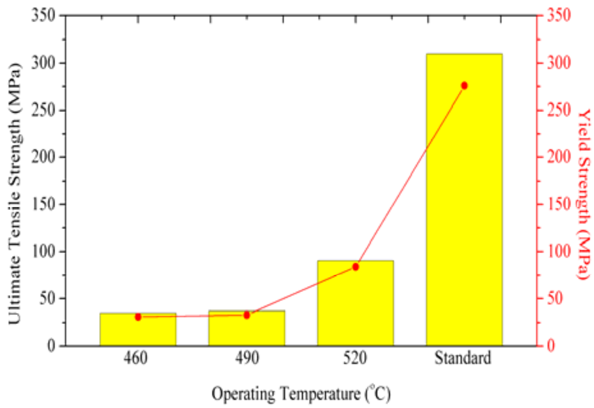

Figure-9. UTS and YS for different operating temperature.

Lajis, Yusuf, & Noh (2013) stated that all physical and mechanical material properties primarily depend on the structure of the material. It is established that the difference in grain size should be responsible for the variation of the UTS for the recycled specimens. In the studies of mechanical properties and surface integrity of recycled AA6061 chips, Lajis, Yusuf, & Noh (2013) also stated that the size of machined chips is an important factor for the control of oxide contamination in solid-state recycling. This is because oxide in the recycled specimen contributes to higher tensile strength and ETF, while excessive oxide can adversely affect the ETF.

In the other study on the same years, Lajis, Yusuf, Noh, *et al.* (2013) conclude that the reason of marginally different between the recycled specimen and the standard AA6061 was due to the effect of low force applied (78 kN) to the alloys during the hot press forging process. Although it is suggested to have force less than 369 kN for 6xxx aluminium; a highly forgeable alloy, still there are limits of lower force that should not be surpassed.

Physical Properties

Some alloys are readily known for their tendency to be oxidized. Oxide film will form naturally on chip surfaces during machining and subsequent lay out. Thus, there is always some oxide in aluminium alloy fabricated from machined chips by the solid state process. The accumulated oxygen concentration increases linearly with the total surface area. These oxide precipitations have bad influence, in such way that it will inevitably affect the microstructure and properties of the material (Lajis, Yusuf, Noh, *et al.* 2013). Still, oxide suppresses grain growth during hot forming (Wu, Ji, & Zhang, 2009).

The grain size decreases with the increasing of the operating temperature. The forging temperature for hot working is selected between the solidus and the recrystallization temperature. For AA6061 alloy, recrystallization temperature started from 450°C and solidus region started at 580°C (ASM International, 1996). In general, increased forging temperature will reduce material flow stress and improve the forgeability.

Yusuf *et al*. (2013) found that the grain size was coarser due to the insufficient operating temperature (430°C) during the hot press forging process. However, the microstructure became finer at the temperature of 460-520°C (above recrystallization point). Figure-10 shows the microstructure at different temperature. At recrystallization temperature, the structure started to enter the second phase of precipitation. In this process solute atoms diffuse to form small precipitates (Rashid, 1997). These fine precipitates act as a barrier for dislocation movement, causing an enrichment of initial strength (Meng, 2010).

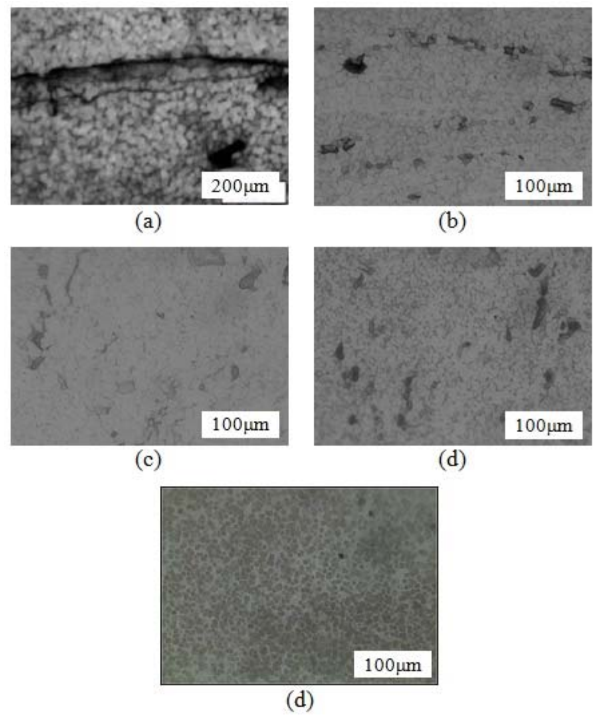

Figure-10. Microstructure at different temperature (a) 420 °C, (b) 490 °C, (c) 520 °C, (d) AA6061 As-received (Yusuf *et al.* 2013).

The finer grain size can be due to the dynamic recrystallization that occurs during the hot forming of Al-Mg aluminium alloys (Sheppard, McShane, Zaidi, & Tan, 1983). According to Lee *et al.* (2005), obvious distortion was produced around oxides during hot conditions, resulting in high dislocation density and larger orientation differences of grain boundaries in distorted areas. Distortion areas became the cores of dynamic recrystallization. Therefore, more oxidation will lead to higher dynamic recrystallization, leading to a finer grain size Lajis, Yusuf, & Noh (2013).

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MODELLING AND OPTIMIZATION

Proper data handling means that the data to be treated should be acquired in a suitable way. The use of experimental designs makes it possible to define the experiments to be executed and the data to be collected. Taguchi Method and Response Surface Methodology (RSM) commonly used as the experimental design and optimization of the response investigated. Both carried out the same objective but in a uniquely different technique.

Shahrom *et al.* (2014) had utilized Taguchi method by varying the chip size (CS), operating temperature (OT) and operating pressure (OP). CS present a higher ranking compared to the OT and OP. The main effect graph is illustrated in Figure-11. The optimal suggested parameters are CS1, OT3 and OP3 which is 99.3 mm, 520 °C and 70 MN/m2 correspondingly.

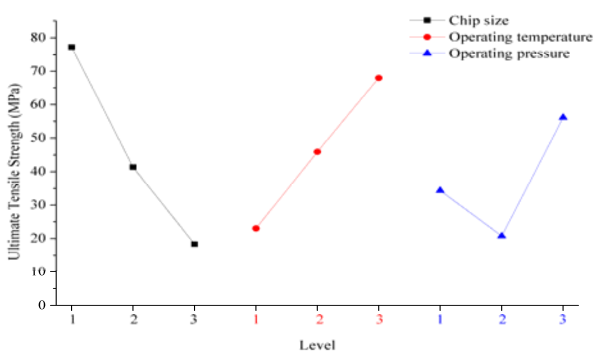

Figure-11. Main effect factor graph (Shahrom *et al.* 2014).

On the other hand, Lajis et al. (2014) employed RSM in their study by executing central-composite-design (CCD) which was found that it is useful to investigate the quadratic effects. Chip size (A), temperature (B) and pressure (C) were choosen as the parameter. It is shown that chip size has more significant effect over UTS, followed by temperature. The solution suggested for desirability are (1) small chip size, (2) 520 °C of operating temperature and (3) 48.0 MPa of pressure. The result should give UTS value of 116.559 MPa with 99% desirability. The 3D contour graph for chip size and temperature with respect to the UTS is shown in Figure-12.

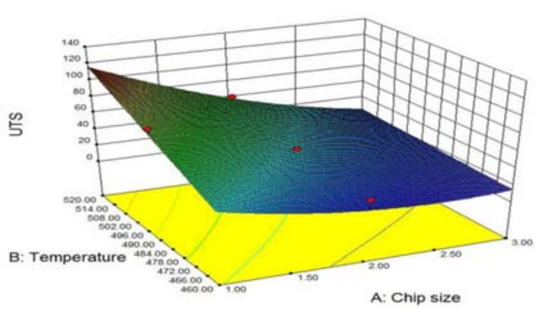

Figure-12. 3D surface graph for solution desirability (Lajis *et al.* 2014).

Khamis *et al.* (Khamis *et al.* 2014) also done RSM by using CCD. A full-factorial of 33 is executed with the parameter model of chip size (A), PCC (B) and holding time (C). The final empirical model in term of coded factor for UTS was given in Equation-2.

$$UTS = +79.74 + 10.30A + 16.29B + 22.48C + 14.47AC + 7.87BC - 29.91A^2 \quad (2)$$

Thus, it is established that the holding time (C) is the most significant factor associated with UTS, followed by the PCC (B) and then the chip size (A). Khamis *et al.* (Khamis *et al.* 2014) suggested that holding time of 120 minutes, 4 cycles of PCC with large chip size will improve the UTS. This is based on the desirability of 98%, which will give UTS value of 113.369 MPa. The 3D contour graph for chip size and pre-compaction with respect to the desirability is shown in Figure-13.

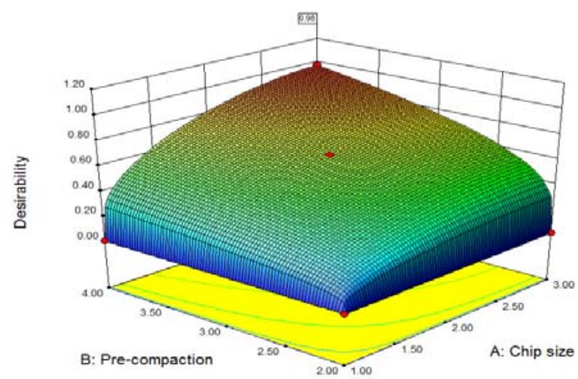

Figure-13. 3D surface graph for solution desirability. (Khamis *et al.* 2014).

CONCLUSIONS

Several studies have been carried out to explore the techniques in recycling of aluminium since the early 1990's. This is due to the reason to reduce the overreliance on the primary aluminium source since mining bauxite from the ore required extensive energy, higher cost as well as giving bad impact toward the environment. The new approach of direct recycling aluminium using hot press forging eliminated two pre-process step (cold-compaction and ball-milling) which is typically introduce in conventional and semi direct recycling.

Aluminium waste which normally produced during machining process was classified as in chips form. Due to metal contact with oxygen molecules, oxide film will naturally formed on the chip surface during the machining process. Oxide on the alloys will affect UTS and ETF, while excessive oxide can adversely affect the ETF.

Hot press forging of aluminium 6xxx series is hot working process which means that the alloys should be heated slightly above the recrystallization temperature (around 460-520 °C for 6xxx series). When the material is heated above the solvus temperature, it should be soaked for 1 to 2 hours to completely redissolve the chip. Based on the previous studied, microstructure became finer with the increment of the operating temperature. The finer particle dispersion enable the incremental of UTS and YS.

Prior studies exerted small force of 78 kN. It is approximately 79% less than the suggested force (369 kN for aluminium 6xxx series). The small force applied is insufficient for the chips to have proper bonding. Though the force is advised to be lower than 369 kN for a strain of 10 s-1, still it cannot be too low which make the specimen fail at lower UTS and have insignificant ETF value.

Above all, the studies of recycling aluminium chips by utilizing hot press forging proved that such solid state recycling is possible as an alternative method for recycling aluminium. This is based on the evidence of the experimental material exhibited good potential of strength and plasticity. For the beneficial of the environment, further and comprehensive research in this distinctive technique is highly recommended.

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