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A Sustainable Direct Recycling of Aluminum Chip (AA6061) in Hot Press Forging Employing Response Surface Methodology

S.S. Khamis[a], M.A. Lajis[b,]*, R.A.O. Albert[c]

[a,b,c]*Sustainable Manuf. And Recycling Technology (SMART) Research Cluster, Advanced Manuf. And Materials Centre (AMMC), University Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor Darul Takzim, Malaysia*

* Corresponding author. Tel.:+607-4538313; fax:+607-4538399.*E-mail address:*amri@uthm.edu.my

Abstract

The present study is aimed at investigating a new approach of direct recycling using the hot press forging process. In the study, the chip sizes of AA6061 that produced from high speed milling were used and the mechanical property of the recycled chip of AA 6061 was studied. Response surface methodology (RSM) was used as the appropriate approach for the experimental design and optimization of the response investigated. Central composite design (CCD) based on face centred cubic design was applied in designing the experiments to evaluate the effects of three main operating variables. Three main operating variables investigated i.e. chip size, pre-compaction, and holding time was used to determine the mechanical properties by measuring the ultimate tensile strength (UTS)as the response variable. The results of mechanical property of the recycled chips were compared with the original AA6061 aluminium billet. Result of mechanical properties shows holding time has the most influential effect followed by pre-compaction, and chip size has the least effect on UTS. Hot pressed AA6061 aluminium alloy at holding time 120 minutes, 4 times pre-compaction cycle, and large chip size shows the best UTS with reasonablePred R^2 of 0.8866 and 98% suggested solution for desirability. Therefore, it can be concluded that, hot press forging could be one of the alternative metal waste recycling processes instead of conventional method that has been carried out without melting phase which contributes to a sustainable manufacturing process technology in the future.

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*Keywords:*Direct recycling; Aluminum AA6061; Hot press forging; Mechanical properties; Response surface methodology

1. Introduction

Total primary aluminum consumption in the world was of 50.2 million tonnes in 2013. China is the main user of primary aluminum worldwide, with 23.2 mil tonnes in 2013. Europe (7.2 mil tonnes) and North America (5.5 mil tonnes) continue to be key regions for the consumption of primaryaluminum[1].These happen due to outstanding application of aluminum in the world. However, lack of control caused primary resources become shortage day by day and in fact give many pollution effects to the environment.Aluminium is the most heavily consumed non-ferrous metal in the world, with current annual consumption at 24 million tonnes. About 75% of this total volume, or 18 million tons, is primary aluminium (that is, extracted from ore) as opposed to secondary aluminium which is derived from scrap metal processing [2]. However, there are losses at every stage of conventional aluminium recycling process, such as losses caused by metal oxidation during melting, some losses thought mixing with the slag from the surface of the melt, and the rest are the scraps resulting from casting and further processing of the aluminium ingots. Ultimately not more than 54% of the metal is recovered [3]. Conventional recycling techniques generate dangerous residues that require elimination usually at high cost, even some vaporization techniques are arising [4]. Aluminium loss can easily reach 50% and at the end, the aluminium loss is very high, making this traditional recovery procedure highly inefficient [5, 6]. For that reason, aluminium is needed to havealternative recovery instead of conventional aluminum recycling as the

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demand increasing and to prevent the shortage of the primary sources of aluminium that cause expensive cost of operation. At the same time, pollution to the environment can be reduced when the nature of recycling is adapted.

Hot forging product proved to have better properties by previous studies compared to other different techniques of recycling. The conventional aluminum recycling carried out with a melting phase at the same time require pre-processing of the scraps to remove impurities. There are loses at every stage of recycling process due to metal oxidation, slag mixing and scraps resulting from casting [7]. [8]analyzed that metal loses in conventional recycling process was approximately 45% of the aluminum metal. Consequently, this study introduces a new approach of solid-state direct recycling of aluminiumusing hot press forging technique which leads to simpler steps and give benefits on low energy consumption and operating cost due to the process that implies above the recrystallization temperature [9]. This alternative process was tested and developed and is able to recycle aluminium chips without the necessity of chips transformation into powder through milling [10]. In addition to that, hot forging process shows the best microstructure, largest densities and giving strongest material. Although less energy will be used, hot forging process even could be used to fabricate automotive pistons with high productivity and without limitation in the chemical compositions of the alloy [11].

In conventional multifactor experiments, optimization is usually carried out by varying a single factor while keeping all other factors fixed at a specific set of conditions. It is not only time-consuming, but also usually incapable of reaching the true optimum due to ignoring the interactions among variables. Response surface methodology (RSM) is a collection of mathematical and statistical techniquesthat are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimise this response [12]. RSM also quantifies relationships among one or more measured responses and the vital input factors [13]. With RSM, the interactions of possible influencing parameters on treatment efficiency can be evaluated with a limited number of planned experiments [14]. RSM method is now widely use in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost [15]. For that reason, RSM was employed in this study for the optimal experimental design of direct recycling aluminium chip AA 6061. Different chip sizes, pre-compaction and holding time was the input variables used as the factors investigated that needed to be optimizedin the process while, ultimate tensile strength (UTS) was the response variable.The experimental plan for this study was developed by Design Expert software version 8.0.

Nomenclature

A	factor 1-Chip size (S_c)
B	factor 2-Precompaction cycle (PCC)
C	factor 2-Pre-heating time (t_H)
Adeq precision	adequate precision
Adj R^2	adjusted R2
Cor total	totals of all information corrected for the mean
Pred R^2	predicted R^2
Prob>F	proportion of time or expected to get the F value
UTS	ultimate tensile strength
R^2	coefficient of determination

2. Experimental Procedure

2.1. Experimental design

Response surface methodology (RSM) using a sequence of designed experimentswas employed in this study to obtain optimal responses. RSM is a method of optimization using statistical and mathematical techniques useful for developing, improving and optimization process [16]. Central-composite-design (CCD) was chosen as the RSM design that is useful for investigating the quadratic effects. The version 8.0 of the Design Expert software was used to develop the experimental plan for RSM. Table 1 shows the experimental parameter model.

Table 1.The experimental hot press forging factors and levels in the actual form.

Factor	Low level (-)	High level (+)
A: Chip (size)	Small	Large
B: Pre-compaction (cycle)	2	4
C: Holding time (minutes)	60	120

2.2. Chip preparation

AA6061-T6 alloy was used as the study material to produce three different chip sizes as in Fig. 1. Bulk of the AA6061-T6 alloy received was cut into 5 pieces of dog bone shape as in ASTM E8/E8M [17] using EDM wire cut for used as the reference specimen and the left pieces was dry milled using Sodick-MC430L high speed machiningto producethree differentrecycling chips size [18]. All the recycling chips was then cleaned by ultrasonic bath using acetone solution and finally dried in thermal oven at 60°C.

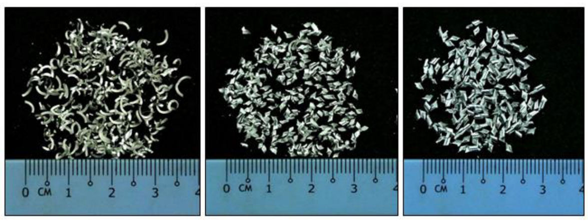

Fig.1 Three different ship sizes: (a) small, (b)medium, (c)large

2.3. Hot press forging

Cleaned AA6061-T6chips which are employed as wasted materials were weighted ~8g and load into dog bone shape close die according specified dimension following ASTM

E8/E8M [17].Pre-heating was done afterthe temperature reach 480°C. The heating time or so called holding time is required to soften the materialbefore the press forging process.It is important tominimize the coarsening microstructure and recovery of matrix [19].After 480°C constant temperature reached, the hot press forging process was carried out by pre-compacted the specimen at constant pressure of 15tonnes.Three different pre-compaction; 2, 3, 4 cycles, and pre-heating time; 60, 90, 120 minutes were used to conducted the solid-state direct recycling of AA6061-T6 alloy using three different chip size produced. All the parameters were carried out base on RSM experimental design. Fig. 2 shows the appearance of the hot press forged AA6061-T6 in a dog bone shape.

The ultimate tensile strength (UTS)was examined tosee the mechanical properties of the sample. Themetallographic investigation to see the physical properties of the recycling specimen were carried out using the optical microscope.

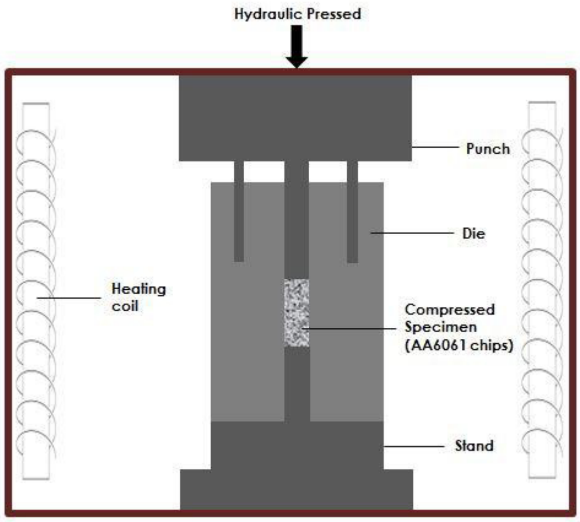

Fig. 2.Hot press forged AA6061-T6 recycling chip.

3. Result and Discussion

3.1. RSM Mathematical model

The adequacy of the developed empirical relationship for the response variable UTSwas tested using the analysis of variance (ANOVA) technique [20]. The result from the recycling chips AA6061-T6 trials are shown in Table 2. The results were inserted in the Design Expert software for further analysis. Without performing any transformation on the response, examination of the Fit Summary output revealed that the quadratic model is statistically significant for both responses and therefore it will be used for further analysis [15].

Table 2.The result of recycled AA6061 using hot press forging process.

Run	A (Size)	B (Cycles)	C (Minutes)	UTS (MPa)
1	Small	4	60	40.3
2	Small	2	60	24.58
3	Small	3	90	28.78
4	Medium	3	90	81.30
5	Medium	3	90	82.30
6	Large	4	60	26.62
7	Medium	3	60	64.20
8	Medium	3	90	82.30
9	Small	2	120	30.95
10	Small	4	120	72.99
11	Large	2	60	17.55
12	Medium	3	90	84.4
13	Large	2	120	76.64
14	Medium	2	90	35.96
15	Medium	3	90	85.40
16	Large	3	90	57.49
17	Medium	4	90	64.97
18	Large	4	120	122.33
19	Medium	3	120	95.14
20	Medium	3	90	86.30

3.2. ANOVA Analysis

A statistical method used to test differences between two or more means which the inferences about means are made by analyzing variance is called Analysis of Variance (ANOVA). In this study, theANOVA statistical method was used to test differences between the chip sizes; pre-compaction and holding time to developed empirical relationship for the response UTS. The summary of the design performed is shown in Table 3after the model was modified.The Model F-value of 21.89 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AC, A^2 are significant model terms after the model is reduced to improved the quadratic model.

Table 3Modified ANOVA table for response quadratic model for the response UTS.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	14918.70	5	2983.74	21.89	< 0.0001	significant
A	*1061.52*	*1*	*1061.52*	*7.79*	*0.0144*	
B	*2655.27*	*1*	*2655.27*	*19.48*	*0.0006*	
C	*5053.50*	*1*	*5053.50*	*37.08*	*< 0.0001*	
AC	*1674.47*	*1*	*1674.47*	*12.29*	*0.0035*	
A^2	*4473.94*	*1*	*4473.94*	*32.83*	*< 0.0001*	
Residual	1907.85	14	136.28			
Lack of Fit	*1907.85*	*9*	*211.62*	*319.63*	*< 0.0001*	*significant*
Pure Error	*3.31*	*5*	*0.66*			
Cor Total	16826.55	19				

$$UTS=+79.74+10.30A+16.29B+22.48C+14.47AC+7.87BC-29.91A^2 \quad (1)$$

The "Lack of Fit F-value" of 319.63 implies the Lack of Fit is significant. There is only a 0.01% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Pred R-Squared" of 0.7243 is in reasonable agreement with the "Adj R-Squared" of 0.8866. "Adeq Precision" measures the signal to noise ratio greater than 4 that is desirable. The ratio of 16.654 indicates an adequate signal. Therefore, this model can be used to navigate the design space.

The final emperical model in terms of coded factor for UTS was given in Eq. 1. From the equation, it can be seen that the holding time (C) is most significant factor associated with UTS, followed by the operating pre-compaction (B) and then the chip size (A).It can be confirm according to the pertubation plot in Figure 3 where the plot indicated that holding time (C) has the most influential effect (steepest slope) UTS followed by pre-compaction (B), whereas, chip size (A) has the least effect on UTS.

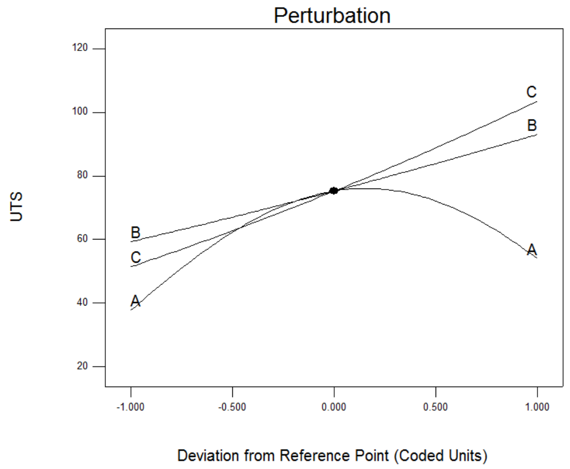

Fig.3. Pertubation plot for UTS

3.4. Optimization desirability

The aim of this investigation was to maximize the UTS of the AA6061 recycled chip and to see which parameters that are optimum through the recycling process. The best and most effective parameter will be shown in the optimization. Table4 shows the suggested solution for desirability in order to get the maximum UTS. Fig. 4 Fig. 5shows contour plot and the optimization graphfor solution desirability. The contour plot is a 2D representation of the response across the select factors. Whereas the optimization graph is a 3D surface plot that is a projection of the 2D plot giving shape that can easily understand. From the optimization, the predicted value of the response UTS is 113.369MPa with 98% desirability. The experimental result indicates that hot pressed AA6061 aluminium alloy using larger S_c, 4 times of PCC and 120 minutes of t_H has the response UTS 122.3MPa. It was found that the experimental value can reach higher UTS than the predicted value.

Table4 Suggested solution for desirability

Solutions No	Chip size	Pre-compaction	Holding time	UTS	Desirability	
1	3.00	4.00	120.00	113.369	0.98	Selected

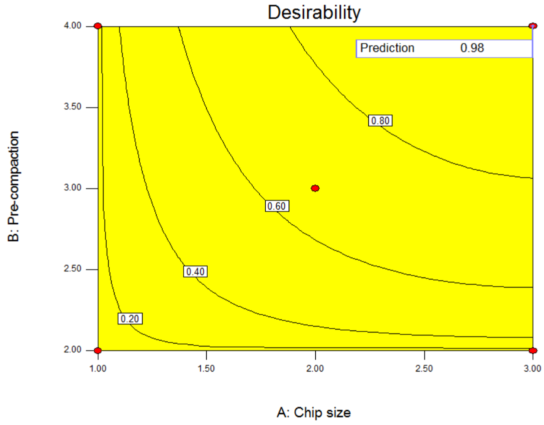

Fig. 4 Contour for solution desirability function

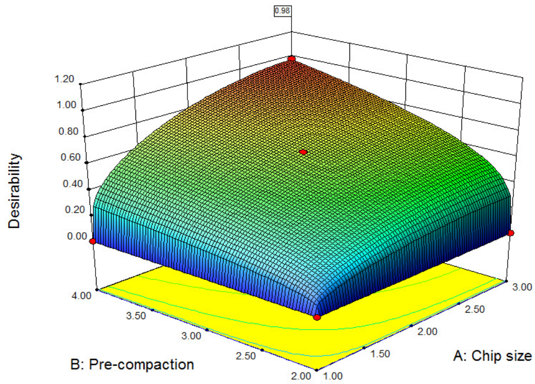

Fig 53D surface graph for solution desirability

4. Conclusion

In this work, the chip sizes of AA6061 that produced from high speed milling are used and the mechanical property of the recycled chip of AA 6061 was studied. Response surface methodology was employed to maximize the UTS and the optimization that coupled with ANOVA analysis shows holding time (C) has the most influential effect (steepest slope)followed by pre-compaction (B), whereas, chip size (A) has the least effect on UTS.From the suggested solution for desirability, it can be conclude that longer holding time and more pre-compaction with large chip size will higher the UTS value. The physical properties of hot pressed AA6061 at maximum parameter shows the best microstructure with more grain boundary occurs with higher degrees of consolidation. Therefore, this study can be used as an alternative for recycling aluminium chips instead of conventional method which has been carried out without melting phase.

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