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Analyses and Optimization of Physical and Mechanical Properties of Direct Recycled Aluminium Alloy (AA6061) Wastes by ANOVA Approach

Mohammed H. Rady, Mohd Sukri Mustapa, S Shamsudin, M. A. Lajis, A. Wagiman

***Abstract*—**The present study is aimed at investigating microhardness and density of aluminium alloy chips when subjected to various settings of preheating temperature and preheating time. Three values of preheating temperature were taken as 450 °C, 500 °C, and 550 °C. On the other hand, three values of preheating time were chosen (1, 2, 3) hours. The influences of the process parameters (preheating temperature and time) were analyzed using Design of Experiments (DOE) approach whereby full factorial design with center point analysis was adopted. The total runs were 11 and they comprise of two factors of full factorial design with 3 center points. The responses were microhardness and density. The results showed that the density and microhardness increased with decreasing the preheating temperature. The results also found that the preheating temperature is more important to be controlled rather than the preheating time in microhardness analysis while both the preheating temperature and preheating time are important in density analysis. It can be concluded that setting temperature at 450 °C for 1 hour resulted in the optimum responses.

***Keywords*—**AA6061, density, DOE, hot extrusion, microhardness.

I. Introduction

ALUMINUM production has been broadly used for many application accordingly recycling of aluminum prompts an immense number of cost and environmental advantages. In examination with different materials, aluminum production has one of the biggest energy differences between primary and secondary production at 186 MJ per 1 kg and 10– 20 MJ per 1 kg respectively [1]. From this reason various manufactures have now centers of growing and expanding the utilization of secondary materials [2]. Aluminum chips produced by machining are the most champion among a wide range of scrap to reuse by remelting, as the oxidation of the material is increased in view of the high surface to volume extent of the chips [3]. A direct recycling of aluminum alloy machining chips into finished or semi-finished product is an alternative method to overcome the issue of losing material by using remelting of aluminum chips and to additionally build up the energy balance of the aluminum production [4]-[6]. Aluminum as chips can be directly changed into semi-finished or finished items through mechanical operations, for example, hot extrusion, hot forging, rolling, severe plastic deformation forms, friction extrusion, conform process etc. [1], [7]. Products by solid-state recycling of aluminum chips in hot extrusion process are controlled by many factors such as die geometry, extrusion ratio, temperature related parameters and etc. in which each of them could influence the extrudates' quality [8], [9]. This study investigates the effects of preheating temperature and preheating time on the response variable (microhardness and density).

Mohammed H. Rady is with the University of Wasit, Iraq (phone: 00601117650654; e-mail: mradhi@uowasit.edu.iq).
Mohd Sukri Mustapa, S. Shamsudin, M. A. Lajis, and A. Wagiman are with the University Tun Hussein Onn, Malaysia (e-mail: sukri@uthm.edu.my, shazarel@uthm.edu.my, amri@uthm.edu.my, abdulla@uthm.edu.my).

II. Working Procedures

A. Preparing the Chips

Preparing the chips was by comminuting the aluminum block through high-speed milling. Selection of the milling type was because of their having a thinner shape which can result in better deformability [8]-[10]. The size of the chip particles was examined by a Toolmaker measuring microscope equipped with a digital Nikon MM-60 camera and are presented in Fig. 1. The chips obtained by face milling were curled up and discontinuous. The material selected for the study was aluminum AA6061-T6 heat-treated, which has vast applications in an automotive industry. The mechanical properties of the aluminum alloy selected in this study are summarized in Table I.

B. Cleaning and Drying the Chips

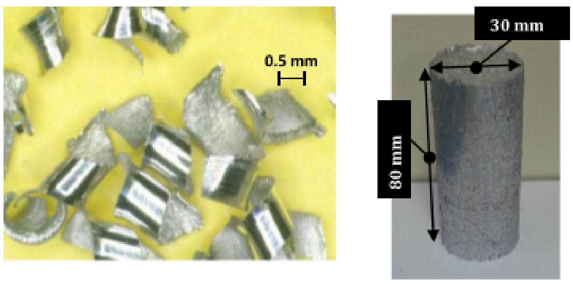
The chips were degreased with acetone inside an ultrasonic bath for ten minutes for vanishing any dirt and impurities. The cleaning of the chips method followed ASTM G131-96, the standard practice applicable to clean materials by ultrasonic methods. Lastly, the drying process used was with conventional drying oven for 1 hour to dry up the acetone solution or any moisture left on the chips made earlier.

C. Cold Press Process

The cleaned machining chips were then put in a cylindrical container and compacted at room temperature by a cold press approximately 80 mm. The sequence of the chip preprocessing is shown in Fig. 2.

D. Hot Extrusion Process

The billets were extruded through the designated conditions as shown in Table II. The ranges of temperature and preheating time selected were between 450 and 550 °C and 1 and 3 hr, respectively. The maximum temperature was limited to 550 °C because heating the billet above 550 °C leads to hot cracks in the surface of the extrudates, while the ram speed setting was limited to below or equal to 1mm/s to avoid an in homogeneous material flow due to the influence stick-slip resulting in chatter marks on the profile surface at higher speeds [11]. The heat was generated using a ceramic heater installed around the container. A graphite-based lubricant was used over the inner surface of the container and the die at every cycle of extrusion in order to forbid the increase in extrusion load as an effect of friction.



Chip appearance	Chip-based billet	Chip Characteristics: Type	Geometry	Size (mm)
		Milling-type chips	Length (l)	≈ 3.10-3.20
			Width (w)	≈ 1.097
			Thickness (t)	≈ 0.091
			Surface area	≈ 24.43

Fig. 1 Characteristics of milling type of chips and chip-based billet appearance after compaction

Fig. 2 Preprocessing of chips before consolidation

TABLE I
MECHANICAL PROPERTIES OF AA6061-T6

Mechanical properties	Value (all values measured under T = 25 °C) Max.	Min.
Density (g/cm3)	2.70	2.66
Tensile strength (MPa)	319	315
Yield strength (MPa)	292	291
Elongation (%)	13	12

TABLE II
PARAMETER SETTING OF HOT EXTRUSION PROCESS

Parameter	Value/type
Extrusion die	Round
Extrusion ratio R	5.4
Billet ϕ (mm)	30
extrusion speed (mm/s)	1
Container temp (°C)	300
Die temp. (°C)	300
Preheating temp. (°C)	450,500,550
Preheating time (hr)	1,2,3

E. Experimental Design

Experimental runs based on the 3^2 full factorial design were performed to investigate the effects of two process parameters as aforementioned. Three center points were included in the design to check the curvature effect of the model and the interactions between parameters were also considered. The design scheme is listed in Table III. Only single run was implemented in each corner and total 11 runs were involved. The details of the experimental run are given in Table IV. Responses in this study were microhardness and density of the fabricated samples. Analysis of variance (ANOVA) was applied to rank the main effects and to analyze the interactions between the input parameters. The DOE results can suggest an insight of further experimental direction for process optimization.

TABLE III
DESIGN SCHEME OF PROCESS PARAMETERS AND THEIR LEVELS

Parameter symbol	Parameter	Levels Low (-1)	Center (0)	High (+1)
A	Preheating temperature	450	500	550
B	Preheating time	1	2	3

III. RESULT AND DISCUSSIONS

Total eleven runs were carried out according to the full factorial design with three center points. The overall results of the experiments are presented in Table IV. The data shows that the minimum preheating temperature gives the high resulting microhardness and density.

A. Microhardness Test

Microhardness testing was carried out at load of 0.9807 N and holding time of 10 seconds at room temperature. In this way, the hardness test was achieved by using the micro Vickers hardness machine. It is extremely useful for testing on a wide kind of materials as long as specimens are carefully prepared. A square base pyramid formed diamond is utilized for testing in the Vickers scale. three times of the test were inspected for each sample. Then, the average was taken of these outcomes. The result of microhardness was that the extrude sample at a lower preheating temperature is found to be harder than the extrude sample at a high preheating temperature, noticing that the microhardness is sensitive to the extrusion preheating temperature because the grain size in entire regions is large at higher temperatures while extruded samples at lower preheating temperature are found to initiate that amounts of normal stress and shear strain at the zone neighbouring to the die wall are high to frame a hard skin on the extrudates. On the hard skin layer, the plastic flow of the chips is limited to a generally small region underneath the indenter to bring about higher hardness.

TABLE IV
RESULTS OF MICROHARDNESS AND DENSITY

Sample Designation	Std. Order	*A* (°C)	*B* (hr)	Micro hardness	Density (g/cm^3)
S1	1	450	1	50.9254	2.70000
S2	2	550	1	44.9448	2.68942
S3	3	450	3	49.9987	2.70005
S4	4	550	3	44.2872	2.55555
S5	5	450	1	55.6886	2.77777
S6	6	550	1	44.3944	2.68825
S7	7	450	3	50.9192	2.70000
S8	8	550	3	44.3572	2.63583
S9	9	500	2	44.8555	2.70000
S10	10	500	2	42.2784	2.70000
S11	11	500	2	51.4043	2.69577

*Note: *A* = Preheating Temperature, *B* = Preheating Time

B. Density Test

Density test by using Archimedes' water immersion principle in distilled water was used to fulfil the density testing of the extruded products. The cross section of cutting samples was a circular. The samples were cut to approximately 1 mm in diameter. we can be seen from analyses of DOE that the value of density increase with decreasing preheating temperature for all extruded samples. Therefore, it was noted the maximum value of density was at 450 Ċ. This result indicates that the chips were compacted to outrageously dense but obtained in poor inter-chip bonding; therefore, the higher amount of stress produced at lower preheating temperature was only able to eliminate the voids and was incapable of improving chip welding. For samples extruded at high temperature, their strength resulted was relatively high [12] but they had a lower density because of encountering the residual voids and cracks.

TABLE V
RESULTS OF ANOVA FOR MICROHARDNESS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	126.185	31.546	3.37	0.090
Linear	2	114.243	57.122	6.10	0.036
Preheating Temp	1	109.138	109.138	11.65	0.014
Preheating Time	1	5.105	5.105	0.55	0.488
2-Way Interactions	1	3.127	3.127	0.33	0.548
Curvature	1	8.815	8.815	0.94	0.369

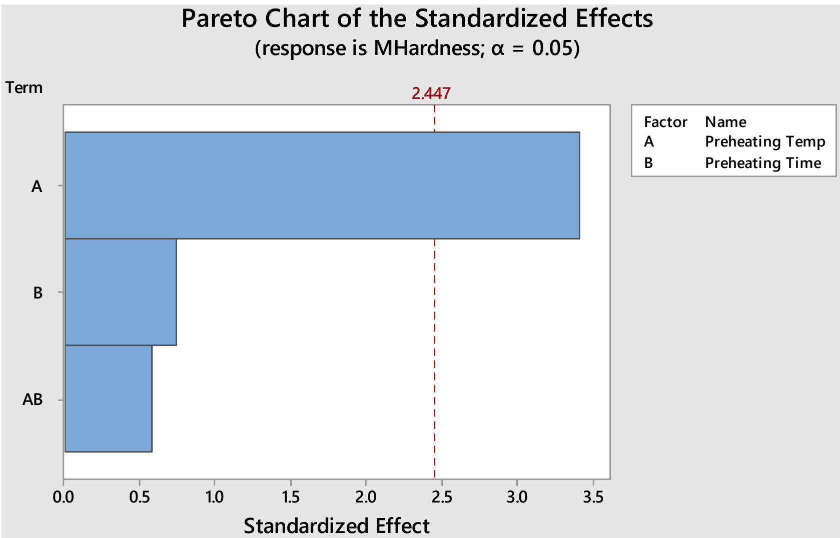


Fig. 3 Pareto chart of microhardness

C. Analysis of ANOVA Results

The ANOVA results indicate that the significant term contributing to microhardness in direct hot extrusion of aluminium AA6061 is preheating temperature, it indicated by $p < 0.05$ as shown in Table V and Fig. 3 (Pareto Chart). The remaining factors, preheating time and interaction of preheating temperature and preheating time are not significant. For the density, we can note that significant terms are preheating temperature and preheating time ($p < 0.05$) but preheating temperature is more influential factor towards the density than the preheating time. The interaction of preheating temperature and preheating time is not significant as shown in Table VI and Fig. 4.

In DOE analysis, the main effect plot and interaction plot of microhardness are as shown in Figs. 5 and 6 respectively. The main effect plot is clearly shows that preheating temperature is significant parameter in which the response is influenced while preheating time is unimportant parameter toward microhardness. As can be seen in interaction plot that it depicts the same trend. It shows that the final model selected is appropriate for the observed data. On the other hand, the curvature effect is insignificant on the response and also confirmed by the ANOVA results in Table IV, where $p > 0.05$ for the curvature term. Therefore, linear model is enough to fit all the data.

For the density, the main effect plot and interaction plot are as shown in Figs. 7 and 8 respectively. The main effect plot indicates that preheating temperature and preheating time are significant parameters where they effect on the response. Also, we can note from interaction plot same trend and the curvature effect is unimportant.

TABLE VI
RESULTS OF ANOVA FOR DENSITY

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	0.022790	0.005698	5.46	0.034
Linear	2	0.020631	0.010315	9.89	0.013
Preheating Temp	1	0.011917	0.011917	11.42	0.015
Preheating Time	1	0.008713	0.008713	8.35	0.028
2-Way Interactions	1	0.001474	0.001474	1.41	0.280
Curvature	1	0.000686	0.000686	0.66	0.448

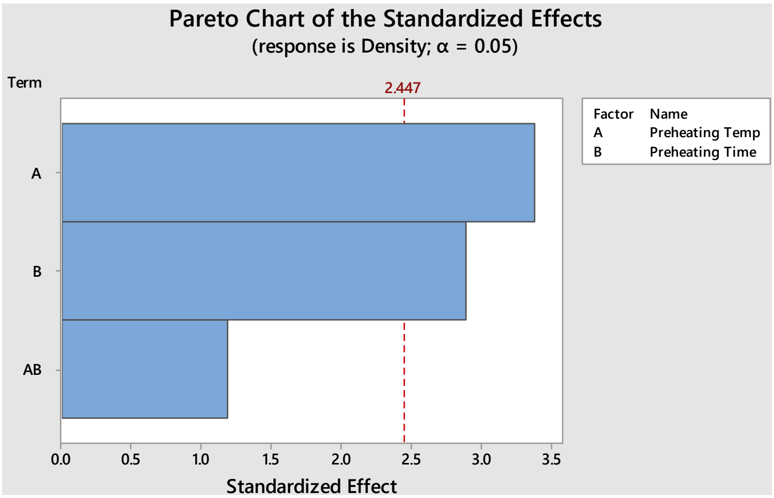


Fig. 4 Pareto chart of density

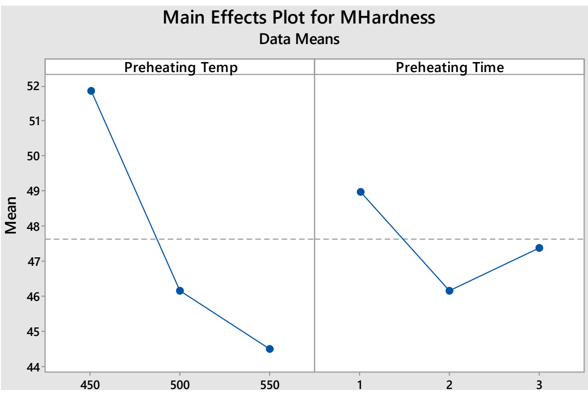


Fig. 5 Main effect plot for microhardness

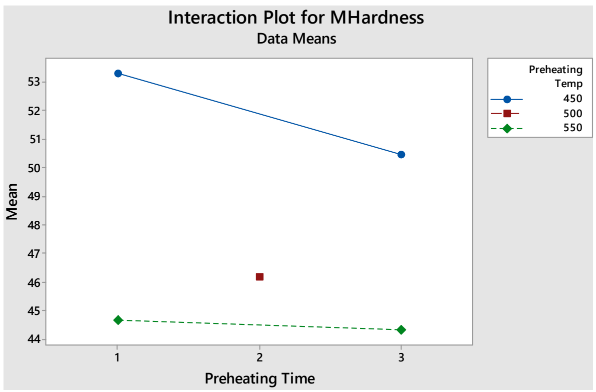


Fig. 6 Interaction plot for microhardness

D. Response Optimizer

The response optimizer method is used to show which factors have effect on extrudates product separately and their impact on the response variables (microhardness and density). This method gave the best value for these responses. Figs. 9 and 10 represent the analysis of optimizer response from

Design of Experiment for microhardness and density respectively.

IV. Conclusion

The study discusses intensively the effects of preheating temperature and preheating time on the resulting microhardness and density of the extruded profiles in direct recycling of aluminum AA6061 wastes. The ANOVA results infer that the factor of preheating temperature is very significant to microhardness performance and the preheating time is unimportant while in analysis of performance of density, both the preheating temperature and preheating time are considering as important factors. The microhardness is sensitive to the extrusion preheating temperature because extruded samples at lower preheating temperature are found to initiate that amounts of normal stress and shear strain at the zone neighboring to the die wall are high to frame a hard skin on the extrudates. Because of hard skin layer, the plastic flow of the chips is limited to a generally small region underneath the indenter to bring about higher hardness. For density, it is high at low preheating temperature because of the higher amount of stress produced at lower preheating temperature was only able to eliminate the voids but was incapable of improving chip welding.

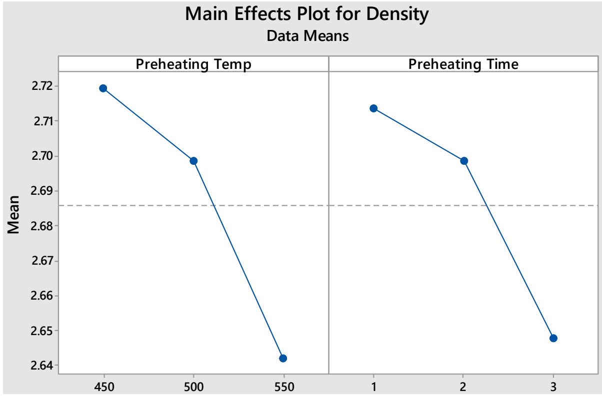


Fig. 7 Main effect plot for density

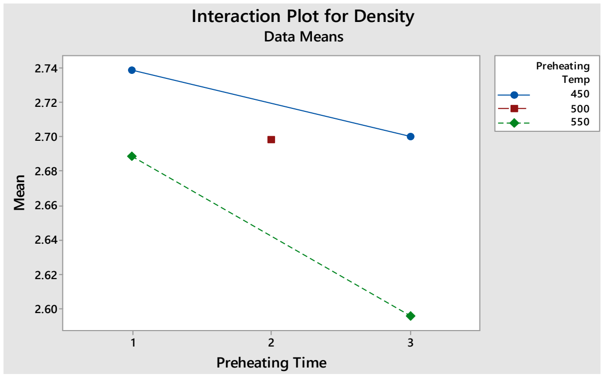


Fig. 8 Interaction plot for density

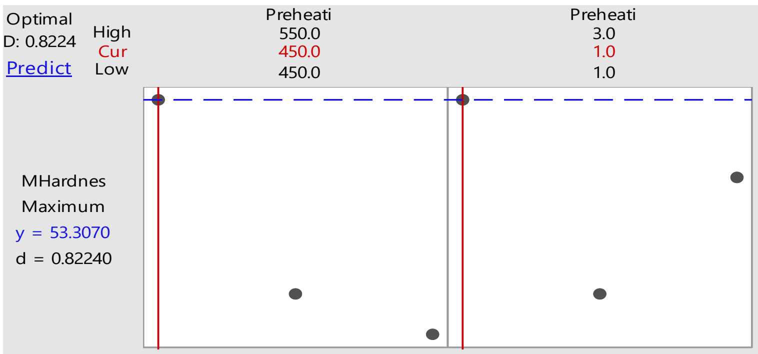


Fig. 9 Optimization plot for microhardness

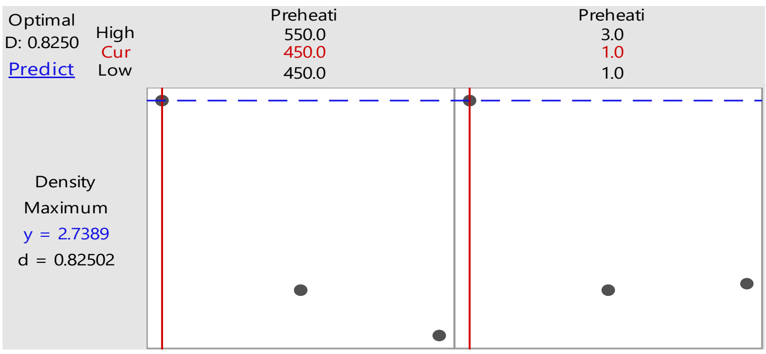


Fig. 10 Optimization plot for density

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