Analyses of Fatigue Resistance of Recycled AA 6061 by Hot Extrusion Using ANOVA Method

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Abstract

This study focuses on analyzing the fatigue life recovery in solid-state recycled (direct recycling without remelting) aluminium AA 6061 processed via the hot extrusion operation. The analyses were achieved by varying the factors of preheating temperature (PHT) at 450, 500 and 550^{0}C and preheating time (PHti) at 1, 2, and 3 hours respectively. The effect of these parameters was analyzed on the fatigue of the produced alloy using the ANOVA technique in addition to the full factorial design with 2 replicates and 3 center points. From the result, it is indicated that the PHT parameter is more significant to be controlled rather than the PHti. An increase of PHT produced higher fatigue resistance. Among the selected parameters, extrudates show the best fatigue resistance at 550 °C and for 3 hours preheating. The analyses revealed that PHT was the main key parameter that takes control of the fatigue resistance in the recycling of the AA 6061 chip. Analysis of optical micrographs of the extrudates was also illustrated and discussed.

Keywords: Aluminium AA 6061, ANOVA, extrusion, fatigue resistance, metal recycling

1. Introduction

Aluminum alloys have been extensively used for structural applications and transportation such as automobile parts, electrical, electronic, household and frames of windows and doors in building applications [1]. It is important to develop recycling procedures in order to derive relevant areas of application of the recycled products. The study of key influential parameters is relevant to report on the mechanical property and fatigue performance of the recycled product. The relevance of recycling spans from cost, effect on environment to energy and climate change.

When direct recycling was employed, losses associated with materials machining and finishing, oxidation of metals and slag mixing are avoided. Parts of the metal are wasted by the traditional method of recycling as a chip during the stage of finishing process [2]. Now a days, an economical recycling technique has been found instead of the conventional method, and this technique includes the direct recycling of the chip of the metals alloys [3,4]. The direct recycling of aluminum alloys chips is an alternative procedure to solve the problem of the material losses as chips are converted to other products without melting. The energy balance is achieved in the aluminum production process, when aluminum chips are converted directly into finished or semi-finished segments through a mechanical operation, like hot extrusion, hot ECAP, severe plastic deformation forms, rolling, conform process, friction extrusion, and hot forging process [5-9]. The quality of profiles produced using solid-state recycling by the hot extrusion way are affected by several parameters like extrusion ratio, volume fraction, die geometry, and temperature related parameters [10,11]. The most significant parameter for extrusion procedureis temperature as it provides required welding of the chips and has directly affected the strength of the material. Researchers studied the effect of the temperature and preheating time on mechanical properties in extrudes profiles. The findings indicate that the strength of the tensile is very sensitive to preheating temperature [2, 12]. The study of direct recycled composite AA 6061 chips and environmental evaluation using multi response optimization of AA 6061 chips is reported by Yusuf et al. [13, 14]. Ho et al. studied the deformation, damage and tensile properties of recycled aluminium alloys AA6061 [15, 16]. A number of components made from AA 6061 are subjected to cyclic stresses and should possess the appropriate fatigue resistance.

From the available few research works, the authors have identified that the fatigue characteristics of such recycled AA 6061 are important and should be studied for sustaining the cyclic stresses sufficiently. This research also indicates the use of direct recycling procedures of aluminium alloy AA6061 with low cost and energy consumption without intervention in the metallurgical process. In the hot extrusion process used for AA 6061 direct recycling, preheating temperature (PHT) and preheating time (PHti) are the important factors affecting the fatigue resistance. It is also important to study the effect of various combinations of these variables.

Hence, the present research is aimed to present the effect of two main variables, namely, preheating temperature and preheating time on fatigue resistance using Analyses of Variance (ANOVA) and determination of optimum values of these variables using the response optimizer method. The further objective of this paper is to study the change in the microstructure of recycled AA 6061 due to change in preheating temperature and preheating time.

2. Experimental Procedure

2.1 Billet Preparation

Blocks of aluminium alloy were cut to obtain the aluminium chips with the aid of the high speed milling machine. A toolmaker estimating microscope machine which has a digital Nikon MM-60 camera installed was used in measuring the dimension of the alloy chips. The chips were reported to have a normal measure of (3.12 - 3.20 mm) length × (1.098 mm) width × (0.092 mm) thickness with a surface area (24.45 mm^2). The chemical composition of the aluminium alloy used in this study is summarized in Table 1.

Table 1: Composition of alloy 6061 wt.% [5]

Element	% Present
Magnesium (Mg)	0.95
Silicon (Si)	0.6
Iron (Fe)	0.25
Copper (Cu)	0.02
Chromium (Cr)	0.06
Manganese (Mn)	0.05
Mg_2Si	0.97
Aluminium (Al)	Balance

The next step was to remove the grease from the chips and clean it up. An ultrasonic bath was done using acetone liquid with the aid of the chemical which lasted for 10 minutes as the impurities were also removed. The ASTM G131-96 was used in conducting the cleaning operation. The removal of moisture content as a result of the solution bath was done by exposing the chips to high temperature using the conventional oven. This was also to remove the acetone solution. The billets were formed by cold compaction of the cleaned and dried chips. Here, cold compaction was done at room temperature using a cylindrical container. The billet had a size of 80 mm long and 30 mm diameter.

2.2 Hot Extrusion Process

The splendid chip's consolidation method was acquired by hot extrusion because this operation is able to crush the layer of oxide surrounding the surfaces of chips and promote weld bond sufficiently under the pressure and excessive plastic strain generated during the method. Extrusion operations were done at an extrusion ratio (R = 5.4), billet diameter (ϕ = 30 mm). The temperature of the container and die was fixed at 3000°C. The preheating temperature was maintained between 450 °C and 550 °C while preheating time was between 1 and 3 hours in that order. The justification for limiting the maximum preheating temperature at 550 °C was to avoid the hot cracks which may occur when the temperature exceed 550 °C. Again, to guide against the inhomogeneous flow of the aluminium chips, the speed of the pressing ram speed was regulated to ensure it as below 1 mm/s. This was also a key in avoiding the stick-slip effect resulting in chatter marks on the extrudates surfaces at a higher speed [18]. The ceramic heater fixed close to the container generated the required heat. Lubrication of the inner circumference of the die was achieved using the graphite-based lubricant in suitable quantity. The aim of the lubrication was to guide against excessive friction that may occur during the extrusion as the extrudates move in the cylinder.

2.3 Fatigue Testing

Specimens for fatigue test were fabricated according to ASTM E466-15 standard. The surfaces of fatigue specimens were polished using different wet silicon carbide papers in order to obtain smooth finished samples. For accuracy and perfect dimensions of the specimens and to avoid mistakes, all the specimens were machined on the CNC machine. During manufacturing of the specimens, careful control was taken to produce a good surface finishing and to minimize residual stresses. The fatigue resistance test was carried out using high cycle fatigue on SHIMADZU fatigue test machine at a frequency of 20 Hz. The stress ratio was equal to 0.1 at room temperature. This was to avoid buckling on the samples and to ensure stability in cyclic load. The fatigue test apparatus used in this research has the capability of applying different stress levels with zero mean stress. The specimens were subjected to an applied axial load. Therefore, the surface of the specimen was under succession tension-tension stress. In this test, the specimen was held at two ends and loaded cyclically between two extreme (maximum and minimum) values.

The microstructure of the recycled alloys was observed by using Light Optical Microscope (LOM).

The sequence of preparing the billets and the samples is shown in Fig.1.

2.4 Design of Experiment

Design of Experiment (DOE) is a method that combines the process of experimental design. It provides a unique layout that supports an organized way of implementing an experiment when the relationship between the responses and the parameters to be measured are not clearly known. The advantage of using DOE is to save materials, time and financial resources.

The experimental design is applied using the 2^2 full factorial system to show the influences of 2 process factors PHT and PHti. Three center points were involved in DOE to check the effect of model curvature. In each corner, a single run was applied and a total eleven runs were included. The details used in DOE are shown in Table 2. During the process of DOE, ANOVA were achieved to provide the Key Effect along with Interaction Plots to study the relationship between the PHT and PHti and fatigue resistance. The result of DOE can activate a view for an optimizer method to show the optimal.

Table 2: Factors and levels used in DOE

Factor sign	Factor	Levels		
		Lower (-1)	Center (0)	Higher (+1)
A	PHT	450°C	500°C	550°C
B	PHti	1 h	2 h	3 h

3. Results and Discussion

3.1 ANOVA Results

A total of eleven runs and the experimental results are presented in Table 3. From the table, it is observed that the highest value of PHT provides a high fatigue resistance. The implications of the result were further elaborated using clarified from ANOVA of the DOE.

The results demonstrate that the important term contributing to fatigue resistance in the direct recycling of AA 6061 by hot extrusion is preheating temperature and preheating time. These two parameters indicated by p-value < (0.05) as displayed in Table 4 and also in the Fig. 2 represented the Pareto Chart. The remaining parameters, interaction of PHT and PHti is not considerable and the preheating temperature is the main parameter that impacts towards the fatigue resistance and this influence is more than that of the preheating time.

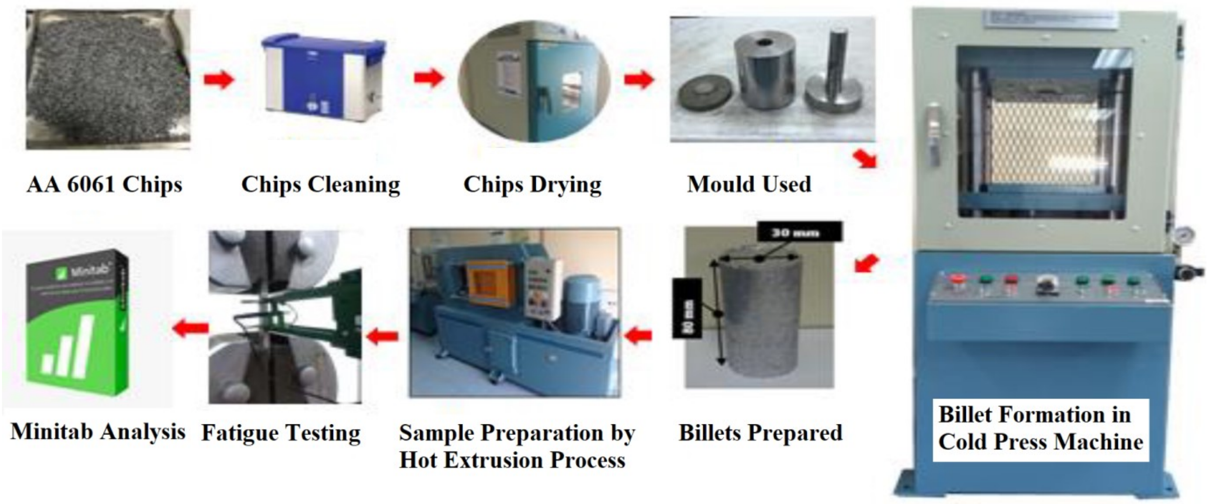

Fig. 1: Sequence of various activities used in the present research

Table 3: Fatigue resistance results

Specimen Symbol	Std. Order	PHT (A) (°C)	PHti (B) (hour)	Fatigue Resistance (MPa)
S 1	1	450	1	90.570
S 2	2	**550**	**1**	**117.087**
S 3	3	450	3	102.428
S 4	4	550	3	125.229
S 5	5	450	1	88.878
S 6	6	**550**	**1**	**119.893**
S 7	7	450	3	98.451
S 8	8	550	3	127.680
S 9	9	500	2	109.293
S 10	10	500	2	115.052
S 11	11	500	2	112.514

Table 4: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	1705.60	426.40	77.67	0.000
Linear	2	1674.95	837.48	152.54	0.000
Preheating Temp.	1	1500.48	1500.48	273.30	0.000
Preheating Time	1	174.47	174.47	31.78	0.001
2-Way Interactions (Preheating Temp.*Preheating Time)	1	3.78	3.78	0.69	0.438
Curvature	1	26.87	26.87	4.89	0.069
Error	6	32.94	5.49		
Total	10	1738.55			

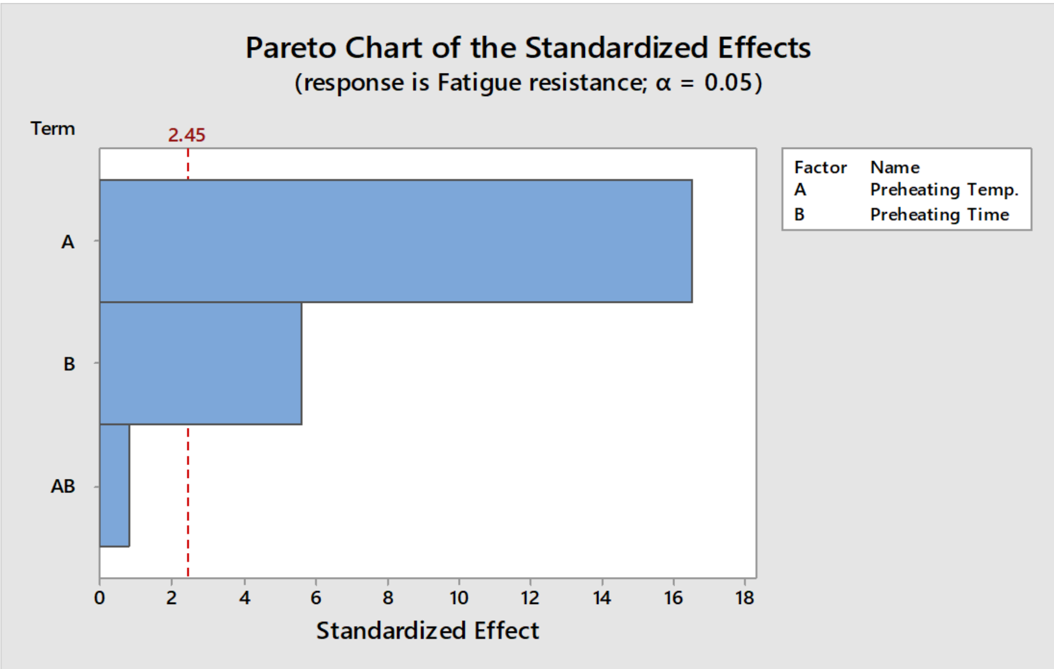

Fig. 2: Pareto chart of fatigue resistance

The DOE analysis revealed that the main effect plot basically showed that overall center points positions are close to the lines associated with the mean fatigue resistance. This was demonstrated in Fig. 3 where the values of low to high setting of the factors are noticed. A similar trend was maintained in the interaction plot in Fig. 4. The graph showed that the final model chosen is capable of describing the experimental result well. Apparently, the insignificance of the effect of curvature on the parameters measured just strengthened the observed pattern in ANOVA outcome in Table 4. The $p > (0.05)$ in relation to the term of curvature parameters revealed a close relationship. The implication was that a linear model saw sufficient in describing the relationship observed in the data.

Investigation of the parameter with higher influence on producing profiles was using a response optimizer method separately and its impact on the fatigue behavior. This procedure found out the best value for fatigue resistance was at 550 °C and 3 hours. Fig. 5 clarifies the analyses of optimizer response derived from DOE of fatigue resistance.

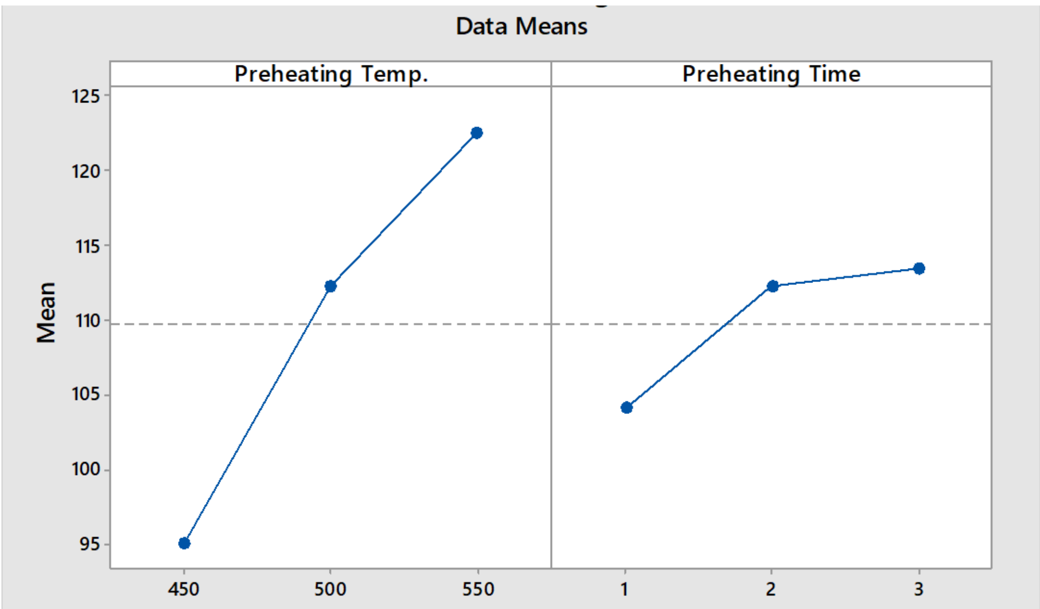

Fig. 3: Main effects plot of fatigue resistance

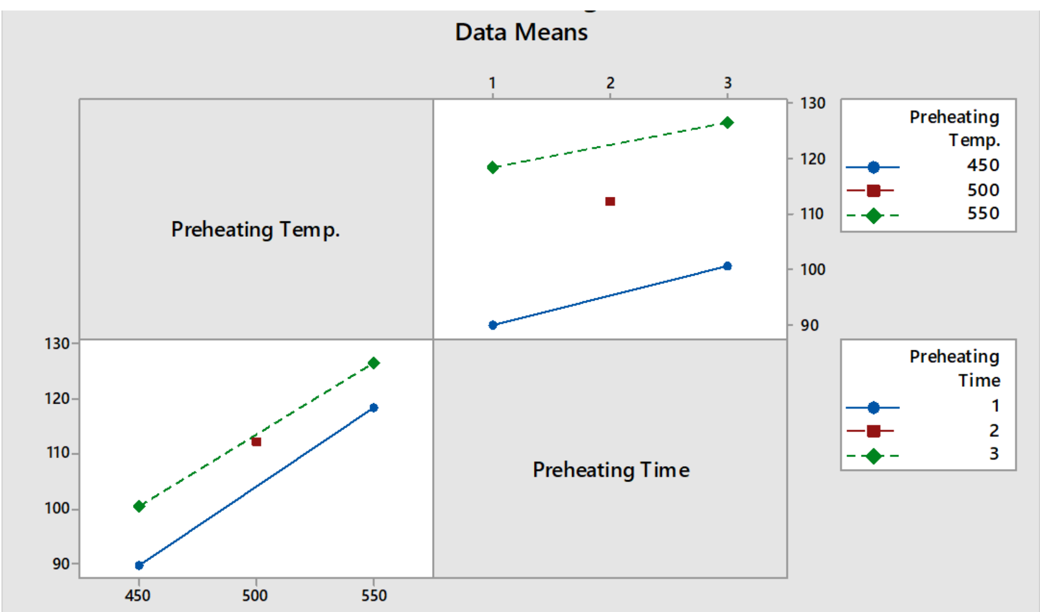

Fig. 4: Interaction plot of fatigue resistance

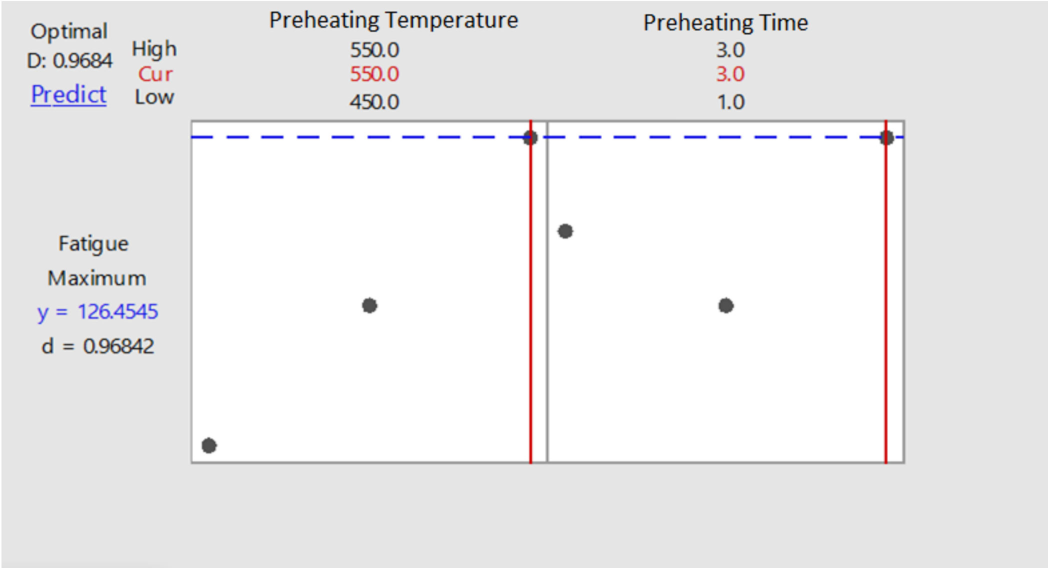

Fig. 5: Optimization plot of fatigue resistance

3.2 Analysis of Microstructure

The specimens are at the lowest PHT indicated low fatigue resistance and conversely. The parameter of temperature created an influence on the chip strengthening. Increasing the PHT to 550 °C enhances solely the characteristic of fatigue resistance. Furthermore, the results deduced that the direct recycling by the hot extrusion process at a low preheating temperature had the bad behavior in terms of strength and could not efficiently make the consolidation of chips, since temperature stimulates phases and matter transformation.

The Typical Optical Micrograph (TOM) of the aluminium alloy chips extruded at different PHT and PHti are shown in Fig. 6. The morphology revealed fine grain the microstructure of specimens heated at 450 °C, 1 hour as displayed in Fig. 6 (a). The dynamic recrystallization through hot extrusion process was liable for the fine grains noticed, but the boundaries of chips and the grain sizes are small. There are voids and less cracks can be observed in these extrudates. Similarly, for samples extruded at 450 °C, 3 hours shown in Fig. 6 (b) revealed a microstructure in that of 6 (a) with a very slight difference. The difference was increased in voids and cracks because of the increase of the PHti from 1 to 3 hours, which was responsible for more crystallization and the increase in voids. Clearly, the fatigue resistance is poor in the recycled alloy of this case as a result of generating cracks and voids formation. A similar investigation was reported by Chino's work [19].

When the preheating temperature was increased to 500 °C, non-uniform and unrecognized forms were illustrated in the case of new micrographs. It can be observed that the boundary lines are smooth, minimal voids and the specimens contain a very dense microstructure as given in Fig. 6 (c). A similar microstructure was reported in the study conducted by Huo's work [20].

An increase in PHT from 500 to 550 °C revealed a change in the microstructure as presented in (d) and (e) from Fig. 6. It could be observed that the shape of the grain is more recrystallized and equiaxed an indication that the case of the coarsening had occurred in the grain at this temperature. The coarsening property of grain structure is beneficial to get high tensile strength at high preheating temperature [2] and there is a direct relation between the tensile strength and fatigue resistance and in addition to the absence of the voids and cracks in this condition led to increase of fatigue resistance.

4. Conclusion

This paper presented the effect of preheating temperature and preheating time on the fatigue resistance of direct recycled AA 6061, determined the optimum values of these parameters and studied the microstructures of the extrudates obtained for these parameters.

The first part of the study concentrated on investigating the effect of preheating temperature (450 °C, 500 °C, 550 °C) and preheating time (1 hour, 2 hours, 3 hours) on the fatigue resistance of

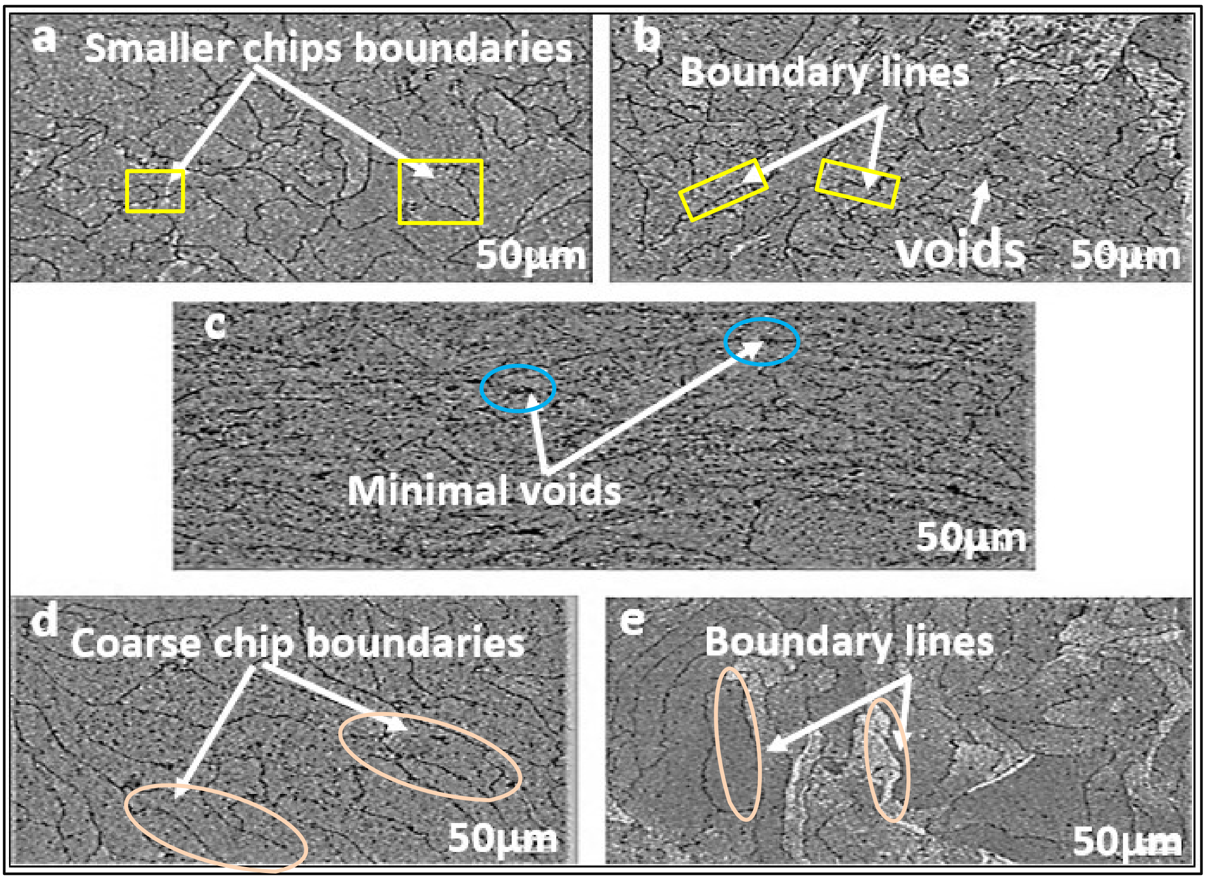

Fig. 6: Microstructure of extrudates at different PHT and PHti (a) 450°C and 1 hour (b) 450°C and 3 hours (c) 500°C and 2 hours (d) 550°C and 1 hour (e) 550°C and 3 hours

the products extruded from the direct recycling of aluminium alloy AA6061. The ANOVA investigation confirmed the statistical significance of PHT in order to obtain outstanding performance of fatigue resistance. As for the PHti, it has less significance on the fatigue behavior of the extruded alloys when compared to that of PHT. Obviously, high temperature has the capacity to support efficient consolidation of the chips. Temperature also enhanced the bonding of chips based on the diffusion transport principles.

The second part is concerned about determining the optimum (preheating time and preheating temperature) parameters of the hot extrusion process for recycled aluminium chips by the response optimizer method. This procedure found out the best value for fatigue resistance was at 550 °C and 3 hours and the fatigue resistance in this case is 126.45 Mpa.

The third part of the research is on the microstructure of the extruded aluminium alloy chips, hot extrusion parameters produced varying micrographs of extruded profiles whereas grain coarsening and the absence of the voids and cracks occurred at the higher preheating temperature which led to increase in the fatigue resistance.

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