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The Impact of Heating Temperature and Flux Ratio on the In-Situ Casting Technique as a Direct Recycling of AlSi7Mg Machining Chips

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ABSTRACT

Recycling aluminium and its alloys is gaining popularity in reducing energy consumption and associated manufacturing expenses. The fluxing process is the preferred and often-used technique in the recycling sector for removing oxide inclusions from molten aluminium. The present study investigates the influence of flux ratio and heating temperature on the behaviour of aluminium alloy chips (AlSi7Mg) during in-situ casting. The primary objective is to create a more efficient and economical approach to recycling aluminium waste. The chips underwent heating for 30 minutes inside a controlled laboratory furnace. The temperatures used during this procedure were 750°C and 800°C. The chips were combined with flux in ratios of 1:0.1 and 1:0.2. The number of melted chips rose due to increasing the temperature and flux ratio. The heated samples were subjected to surface morphology and elemental analysis using a scanning electron microscope with energy-dispersive spectroscopy (EDS). The Energy Dispersive Spectroscopy (EDS) examination indicated the presence of oxygen on the surface of the unprocessed aluminium alloy machining chips. On the other hand, the X-ray diffraction (XRD) revealed that the observed condition may be attributed to the oxidation process, proven by the presence of Aluminium Oxide (Al_2O_3).

1. Introduction

Aluminium (Al) alloys have recently seen a notable surge due to their advantageous properties [1]. The exceptional specific characteristics, good corrosion resistance, and electrical and thermal conductivity of aluminium have positioned it as a competitive preference across various industries, such as electrical, packaging, building, construction, and transportation sectors [2]. Aluminium (Al) is a metal extracted from bauxite and used to manufacture various industrial products. The bauxite mining industry began with little concern for the potential adverse environmental impacts,

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socioeconomic factors, and human well-being. For instance, surface mining is one of the primary techniques whereby the extraction process entails the removal of plants [3].

Consequently, there is a corresponding rise in aluminium waste, including swarf or chips. The recycling of aluminium alloy chips has emerged as a crucial concern and a subject of scholarly investigation, primarily driven by the growing awareness of environmental sustainability [4]. This disparity may be attributed to the fact that in 2010, the worldwide production of aluminium metal amounted to around 56 million tonnes, but only 18 million tonnes of scrap were successfully recovered. According to estimations, the worldwide demand for aluminium in 2020 reached around 97 million tonnes, necessitating the recycling of roughly 31 million tonnes of waste [5].

Abdullah Wagiman *et al.,* [6] found that aluminium chips from machining processes typically exhibit greater intrinsic worth than post-consumer product scrap. This distinction arises from the chips' diminished contamination and elevated purity levels. There are many methods for recycling machining chips, one of which is called in-situ melting or in-situ casting. Casting is considered a favourable method for fabricating aluminium (Al) alloys due to its ability to produce complicated components with superior surface finish and few metallurgical limitations. The in-situ casting method used in investment casting of metal alloy has shown exceptional outcomes and has promise as a viable technique for a pouring-free casting process. This technique was introduced by Jafari *et al.,* [7]. Furthermore, an innovative technique entails in-situ microwave casting for metallic materials has been introduced by Mishra *et al.,* [8], presenting an alternative means of casting metal objects. This technique can achieve a densely cast product with less than 2% porosity, but it is considered a costly and intricate procedure.

The casting process discussed is characterised by its simplicity and cost-effectiveness, making it a promising approach for directly recycling aluminium alloy chips. Nevertheless, the recycling process of aluminium alloy machining chips is intricate due to the active oxidation during in-situ casting, impeding the chips' thorough melting. Therefore, Capuzzi *et al.,* [9] found that using flux during in-situ casting may enhance the recovery and quality of aluminium while also serving as a covering flux for the liquid aluminium. The fluxing process is one of the preeminent and extensively embraced methodologies for refining molten aluminium and eliminating oxide inclusions, including oxide films. Fluxes typically comprise solid substances designed to eliminate impurities and enhance the fluidity of the molten metal [10]. Shi *et al.,* [11] also have found that the salt flux, comprising equimolar NaCl-KCl, can utilized to reclamation aluminium from waste aluminium and aluminium dross. This flux encases the molten aluminium, restraining further oxidation, eliminating the oxide layer, and augmenting the amalgamation of aluminium droplets.

Without suitable molten aluminium refining methods, these oxide inclusions will endure in the aluminium post-casting, giving rise to various difficulties, such as diminished mechanical properties, compromised surface quality, and inferior machinability [12]. Máté *et al.,* [13] found that the frequently encountered inclusions in aluminium alloy melts are the double oxide films or bifilms, which can easily form due to disturbances to the surface oxide layer. Gyarmati *et al.,* [14] conducted an experiment that utilised solid fluxes on melted aluminium alloy with an appropriate ratio and found that this technique can effectively diminish the inclusion content in aluminium melts.

Adopting alternative methods and configurations is imperative to enhance the efficiency and cost-effectiveness of recycling aluminium alloy waste. As a response, in-situ casting utilizing a standard laboratory furnace with flux application has been devised. The study aims to explore the impact of the flux ratio and heating temperature on the behaviour of aluminium alloy chips (AlSi7Mg) in the process of in-situ casting. The main objective is to develop a more effective and cost-efficient method for recycling aluminium alloy waste.

2. Methodology
2.1 The Heating Process of Aluminium Alloy (Al-Si7Mg) Chips

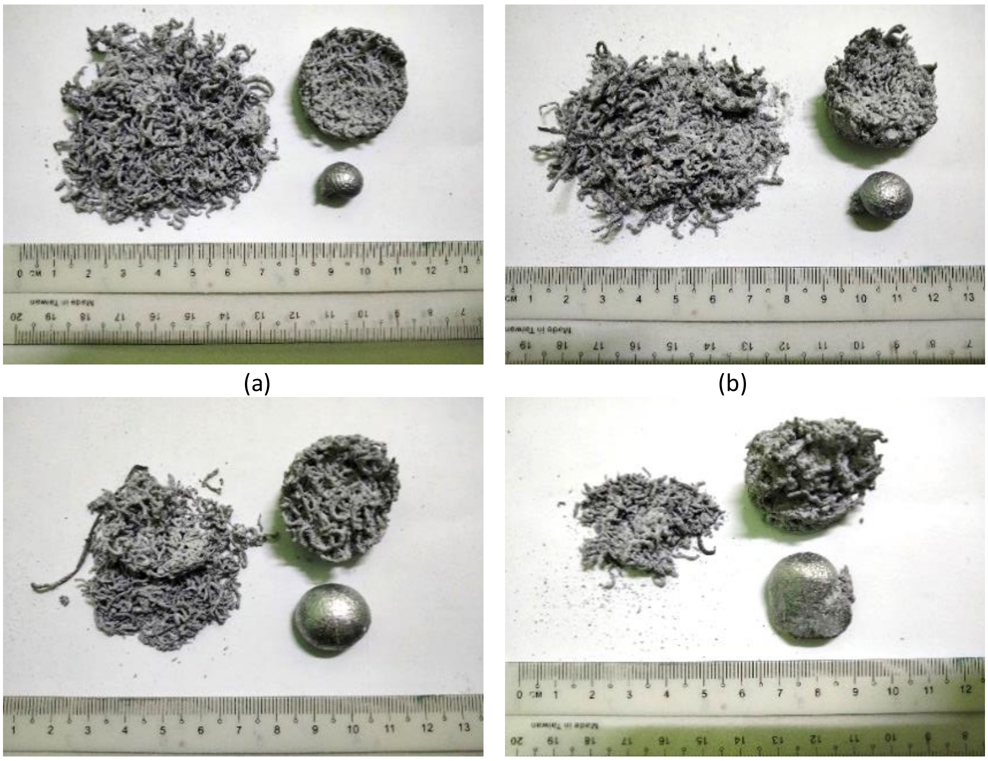
In-situ casting was performed using Al alloy (AlSi7Mg) machining chips combined with flux and put within an investment casting ceramic mould. The four samples of machining chips underwent a 30-minute heating process at diverse temperatures and flux ratios. The initial sample, with a flux ratio of 1:0.1, was heated to 750°C, while the subsequent sample, featuring a slightly adjusted ratio of 1:0.2, was also subjected to a temperature of 750°C. The third sample was maintained at a flux ratio of 1:0.1 but exposed to an elevated temperature of 800°C. Finally, the fourth sample experienced the same temperature of 800°C, albeit with a flux ratio of 1:0.2. A combination of 50wt% sodium chloride (NaCl) and 50wt% potassium chloride (KCl) was used as the flux. Samples of heated machining chips were cooled to room temperature and prepared for metallography analysis and physical evaluation.

2.2 Physical Evaluation and Oxidation Analysis

The visual evaluation of heated machining chips was conducted using direct observation without optical instruments. The purpose of this examination was to assess the visual characteristics of the machining chips. Furthermore, the weight of the chips was gauged using an electrical balance, aiming to ascertain the percentage of chips that had melted during the in-situ casting experiment. The surface morphology and elemental analyses were conducted using a scanning electron microscope (SEM) model EVO LS10, equipped with Energy Dispersive Spectroscopy (EDS). X-ray diffraction (XRD) model Bruker D8 was used to analyse the compounds and phases of oxide found on the heated machining chips.

3. Results
3.1 Physical Evaluation

Figures 1(a-b) provide visual representations of AlSi7Mg machining chips after a 30-minute exposure to a temperature of 750°C. Conversely, Figures 1(c-d) illustrates visual depictions of machining chips subjected to a temperature of 800°C, with varying flux ratios. Figure 1(a) shows the phenomenon whereby only a small amount of machining chips melted like a liquid droplet. On the contrary, other machining chips underwent fusion, emulating the investment casting mould, while the remaining machining chips remained fragmented. The dimensions of the molten machining chips shown in Figures 1(b) and 1(d) were observed to be more prominent in comparison to the molten chips illustrated in Figures 1(a) and 1(c). This phenomenon indicates a positive correlation between the rise in flux ratio and the number of melted machining chips across both heating temperatures. Widyantoro *et al.,* [15] found that the participation of the flux in the process of binding oxide inclusions from the molten metal to the surface is the underlying cause. When subjecting a metal to a heating process, variations in the resulting outcomes may be seen between samples that have been heated to various temperatures [16]. The physical evaluation was tabulated in Table 1 and Figure 2.

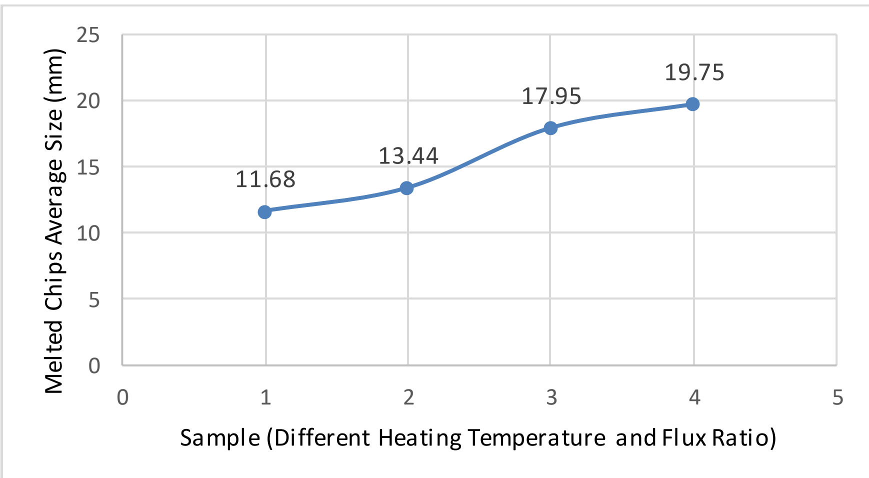


(a) (b) (c) (d)

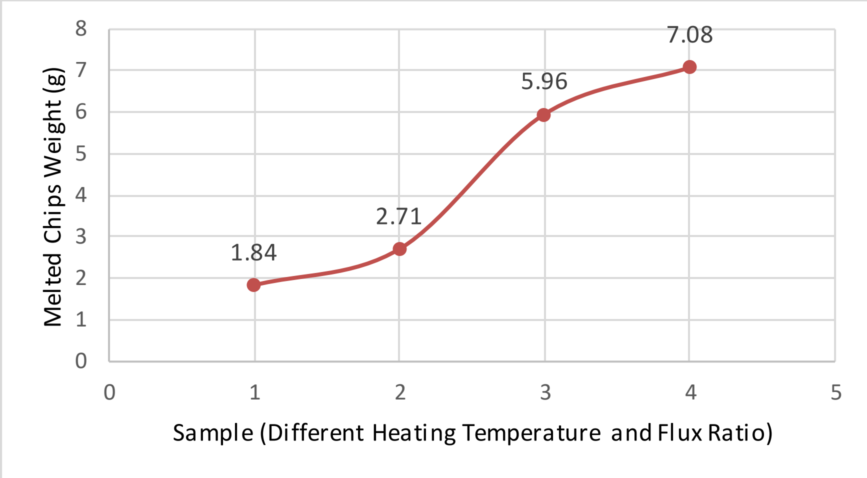
Fig. 1. Heated AlSi7Mg machining chips (a) at the temperature of 750°C with a flux ratio of 1:0.1 (b) at the temperature of 750°C with a flux ratio of 1:0.2 (c) at the temperature of 800°C with a flux ratio 1:0.1 (d) at the temperature 800°C with flux ratio 1:0.2

Table 1
AlSi7Mg machining chip's sample number with different heating temperatures and flux ratio

Sample number	Heating temperature (°C)	Flux ratio
1	750	0.1
2	750	0.2
3	800	0.1
4	800	0.2



(a)



(b)

Fig. 2. The chart of the relationship between four different samples that had a temperature rise from 750°C to 800°C, while the flux ratio rose from 0.1 to 0.2 with the (a) melted chips average size and (b) melted chips weight

3.2 Oxidation of the Heated AlSi7Mg Machining Chips

Figures 3(a-d) present the scanning electron microscope (SEM) cross-sectional images depicting the melted AlSi7Mg machining chips in a liquid droplet state. Meanwhile, Figures 3(e-h) show the cross-section of the fused AlSi7Mg machining chips after heating at temperatures of 750°C and 800°C, employing flux ratios of 1:0.1 and 1:0.2, respectively, for 30 minutes. The absence of an oxide layer on the surface of the molten alloy machining chips, observable in Figures 3(a-d), is notable. This observed phenomenon can be ascribed to the influence of the flux, which functions as a covering agent, facilitating the melting process of the chips. Zhang *et al.* [17] found that the flux mixture of NaCl-KCl demonstrates the capability to decrease the relative porosity of the AlSi7Mg alloy while also exhibiting the ability to remove the oxide layer. Figures 3(e-h) show the presence of an oxide layer between the machining chips of the fused alloy. The fused aluminium chips are identified and designated as Chip A and Chip B. The in-situ casting experiment was impeded by the presence of an oxide layer on the surface of the alloy machining chips, preventing the chips from fully melting into a liquid droplet of molten aluminium.

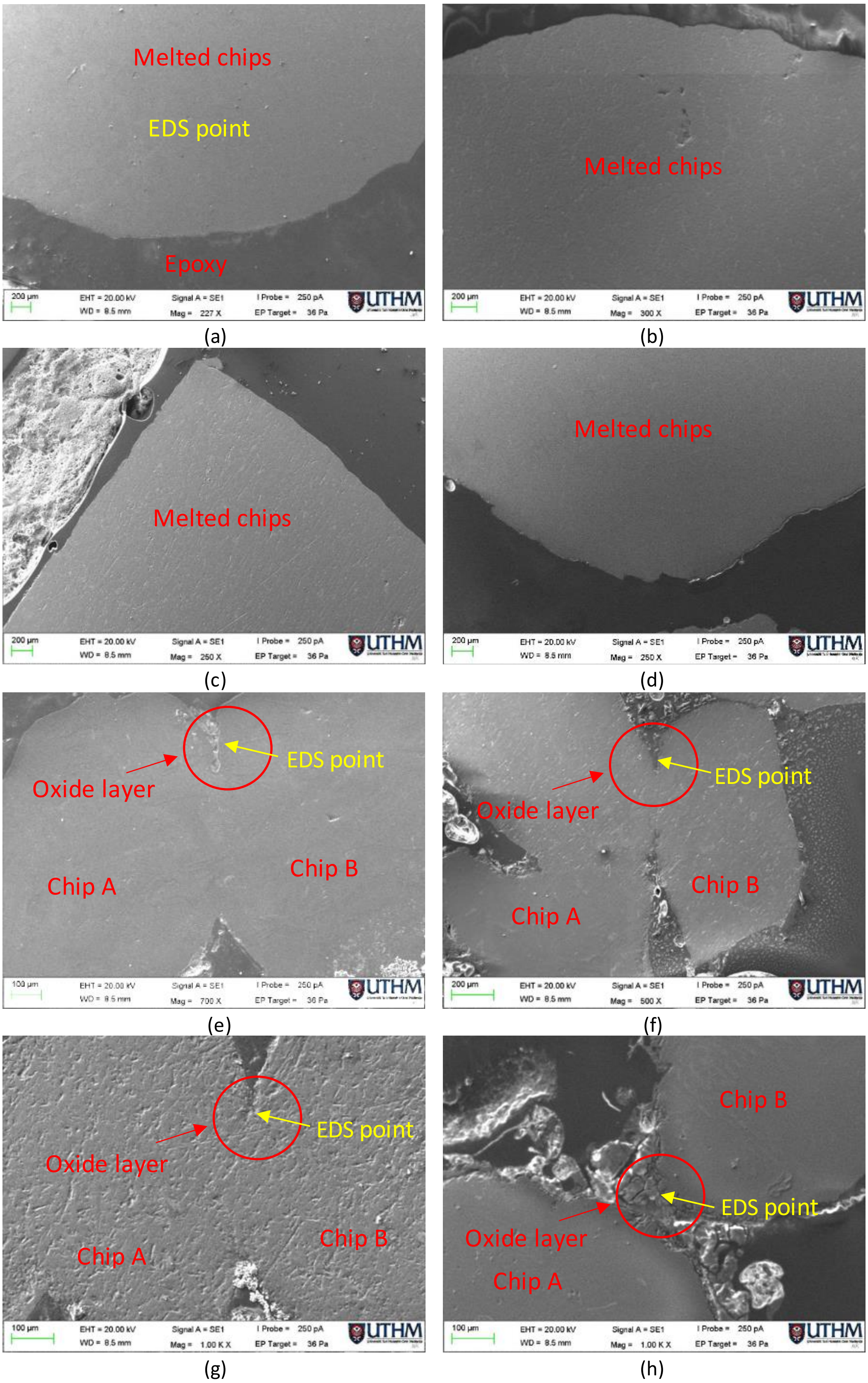
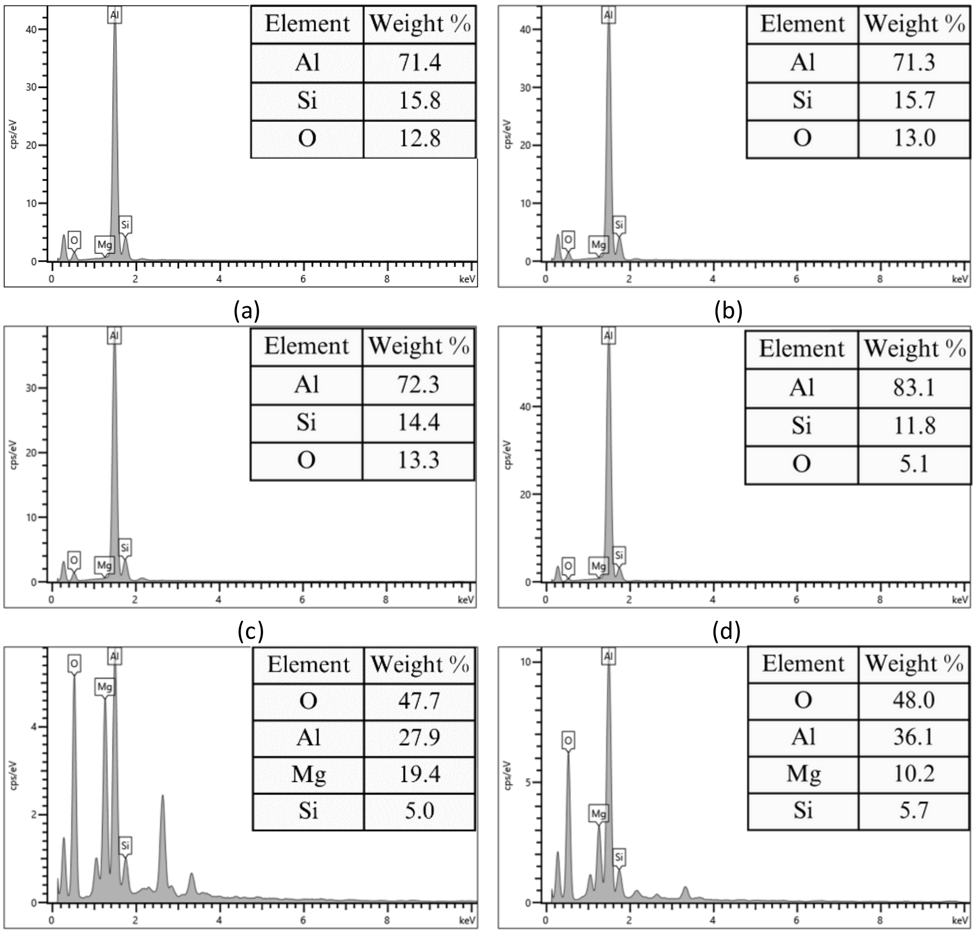


Fig. 3. SEM cross-section images of the melted AlSi7Mg machining chips (liquid droplet) and fused AlSi7Mg machining chips, respectively at temperature of (a) 750°C and flux ratio 1:0.1 (b) 750°C and flux ratio 1:0.2 (c) 800°C and flux ratio 1:0.1 (d) 800°C and flux ratio 1:0.2 (e) 750°C and flux ratio 1:0.1 (f) 750°C and flux ratio 1:0.2 (g) 800°C and flux ratio 1:0.1 (h) 800°C and flux ratio 1:0.2

Figures 4(a-h) present the results of Energy Dispersive X-ray Spectroscopy (EDS) analyses conducted at multiple points. In Figure 4(a), the EDS spectrum of melted machining chips, gathered from the location identified in Figure 3(a), reveals an aluminium weight percentage of 71.4% and an oxygen weight percentage of 12.8%, indicating substantial melting of the chips. Similarly, Figure 4(b) illustrates the EDS spectrum of melted machining chips collected at the EDS point in Figure 3(b), displaying an aluminium weight percentage of 71.3% and an oxygen weight percentage of 13%. The EDS spectrum in Figure 4(c) corresponds to melted machining chips from the EDS point in Figure 3(c), with an aluminium weight percentage of 72.3% and an oxygen weight percentage of 13.3%. Furthermore, Figure 4(d) shows the EDS spectrum of melted machining chips from the EDS point in Figure 3(d), revealing an aluminium weight percentage of 83.1% and an oxygen weight percentage of 5.1%.

The subsequent EDS analyses in Figures 4(e-h), performed at the oxide layer areas between machining chips as illustrated in Figure 3(e-h), demonstrate elevated oxygen concentrations, ranging from 47.7% to 59.6%, with corresponding aluminium percentages varying between 27.9% and 44.8%. The discernible increase in oxygen concentration in the surrounding region implies an oxidative process in AlSi7Mg at elevated temperatures, forming a protective layer. This layer acts as a barrier, preventing the escape of the molten material and impeding the creation of a molten alloy pool during the in-situ casting experiment. A thin oxide layer within the melt might be attributed to the active surface oxidation of chips during the melting process, as found by Saleh [18].



Element	Weight %
Al	71.4
Si	15.8
O	12.8

(a)

Element	Weight %
Al	71.3
Si	15.7
O	13.0

(b)

Element	Weight %
Al	72.3
Si	14.4
O	13.3

(c)

Element	Weight %
Al	83.1
Si	11.8
O	5.1

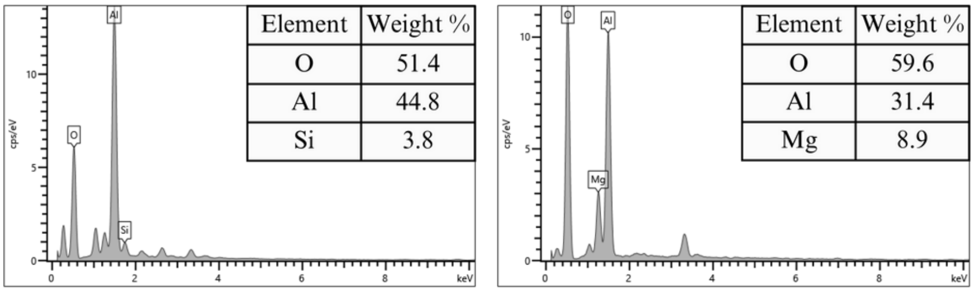
(d)

Element	Weight %
O	47.7
Al	27.9
Mg	19.4
Si	5.0

(e)

Element	Weight %
O	48.0
Al	36.1
Mg	10.2
Si	5.7

(f)



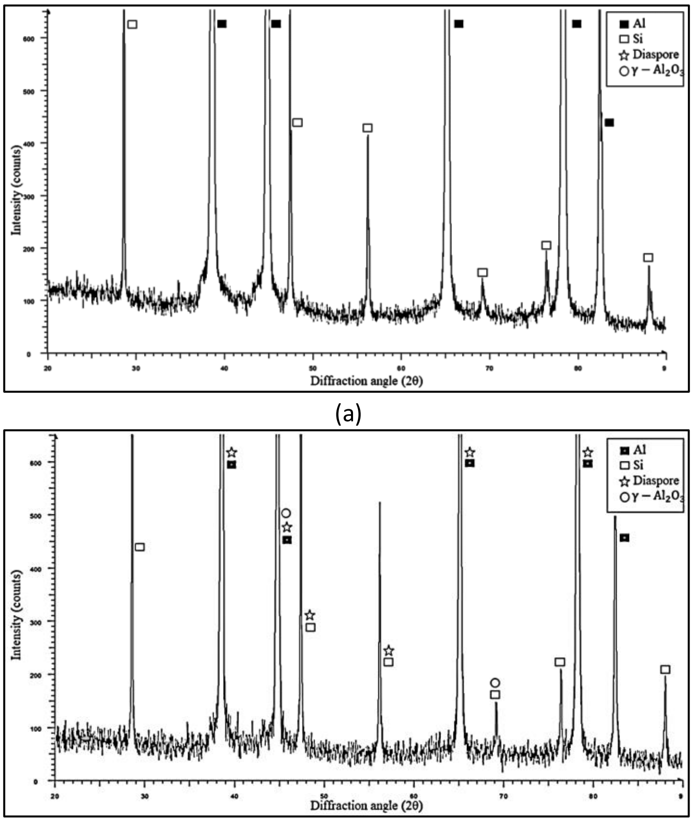
(g) (h)

Fig. 4. EDS analyses results taken from melted AlSi7Mg machining chips (liquid droplet) and fused AlSi7Mg machining chips, respectively, at the temperature of (a) 750°C and flux ratio 1:0.1 (b) 750°C and flux ratio 1:0.2 (c) 800°C and flux ratio 1:0.1 (d) 800°C and flux ratio 1:0.2 (e) 750°C and flux ratio 1:0.1 (f) 750°C and flux ratio 1:0.2 (g) 800°C and flux ratio 1:0.1 (h) 800°C and flux ratio 1:0.2

3.3 Oxide Compounds and Phases Analysis

Figure 5(a) illustrates the X-ray diffraction (XRD) analysis outcomes of aluminium alloy chips before the heating process. In Figure 5(b), the XRD analysis reveals peaks for AlSi7Mg machining chips subjected to 30-minute heating at 750°C with a flux ratio of 1:0.1. The X-ray diffraction spectra of the aluminium alloy chip sample before heating manifested distinctive peaks corresponding to crystalline aluminium. These peaks were observed at 2θ angles of 38.47°, 44.74°, 65.14°, 78.23°, and 82.44°, as depicted in Figure 5(a). The X-ray diffraction spectrum derived from the aluminium alloy chip sample exhibited discernible peaks corresponding to crystalline aluminium at specific angles of 38.47°, 44.74°, 65.14°, 78.23°, and 82.44°, as illustrated in Figure 5(b).

Through a comparative analysis of the X-ray diffraction (XRD) pattern of the heated samples, it was observed that the peaks associated with crystalline aluminium exhibited a notable correlation with the existence of diaspore [α-AlO(OH)]. The findings indicate that the diaspore formation occurred due to the hydration process undergone by the aluminium during the in-situ casting experiment. Moreover, the conversion from boehmite (γ-AlO(OH)) to metastable γ-Al_2O_3 occurred upon the hydration of aluminium. The investigation revealed the presence of gamma alumina oxide (γ-Al_2O_3) as a notable phase. The progression from aluminium hydroxide to alumina in the oxide phases was postulated to align with the transitional phases [19]. The existence of γ-Al_2O_3 indicates the presence of a thin oxide layer that enveloped the AlSi7Mg alloy during the in-situ casting process. Furthermore, Saleh *et al.* [20] found that the observed phenomenon may be attributed to the elimination or detachment of the oxide layer present on the surface of the aluminium alloy chips. This occurrence results from the impact of the NaCl-KCl flux during the heating procedure, as seen under the specified conditions.



(a)

(b)

Fig. 5. XRD analysis of aluminium alloy chips (a) before heating (b) after 30 minutes of heating at the temperature of 750°C and flux ratio 1:0.1

4. Conclusions

It can be inferred that the in-situ casting technology represents a cost-effective and straightforward method for the direct recycling of aluminium waste. Despite some limitations, the findings suggest that using flux in the in-situ casting process has significant potential for product manufacturing. The optimisation of this process may be achieved by the augmentation of the amount or flux ratio, as well as the sequential application of flux with layers of aluminium alloy chips. Based on the conducted studies, it has been determined that elevating the flux ratio during the in-situ casting process results in a reduction of the oxidation of AlSi7Mg. The observed effect of raising the temperature from 750°C to 800°C was an increase in the melting behaviour of AlSi7Mg machining chips when subjected to flux application at the corresponding ratios. The process of in-situ casting was impeded by the occurrence of active oxidation of aluminium, specifically resulting in the formation of gamma aluminium oxide (γ-Al_2O_3), hence preventing the complete melting of AlSi7Mg.

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