

Analysis of the Effect of Cupola Furnace Slag Addition as Reinforcement on Aluminum Metal Matrix Composites Fabricated by Stir Casting Method

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Abstract

This study aims to investigate the effect of adding foundry slag waste from a cupola furnace as a reinforcing particle in Aluminum Metal Matrix Composites (AMMCs) on the casting characteristics of recycled aluminum scrap-based alloys. The cupola slag furnace was added at weight fractions of 2%, 4%, and 6%. The composites were fabricated using the stir casting method, with aluminum scrap frame serving as the matrix and foundry slag as the reinforcement. The aluminum was melted in a gas furnace, and mechanical stirring was initiated 5 minutes before adding the slag into the semi-solid molten metal. After slag addition, stirring was continued for another 5 minutes, followed by the addition of magnesium (Mg) as a wetting agent. The molten composite was then poured into molds to produce test specimens. The experimental evaluation included density measurement, impact toughness testing (J/mm^2), and fracture surface observation of the impact-tested specimens. The results revealed that increasing the slag content significantly affected the material's toughness. At lower concentrations (2–4%), the slag particles were uniformly dispersed within the aluminum matrix and acted as effective micro-reinforcements that hindered crack propagation. However, at higher concentrations (6%), particle agglomeration occurred due to increased surface energy and weakened interfacial bonding, leading to a noticeable decrease in impact toughness.

Keywords: aluminum metal matrix composites; cupola slag furnace, stir casting

Abstrak

Penelitian ini bertujuan untuk mengetahui pengaruh penambahan limbah slag *foundry* dari tungku kupola sebagai partikel penguat pada *Aluminium Metal Matrix Composite* (AMMC) terhadap karakteristik hasil pengecoran berbasis limbah aluminium *scrap*. Variasi fraksi berat slag yang digunakan adalah 2%, 4%, dan 6%. Proses fabrikasi dilakukan dengan metode *stir casting*, menggunakan aluminium *scrap* kusen sebagai matriks dan slag *foundry* sebagai partikel penguat. Peleburan aluminium dilakukan dalam tungku gas, dengan proses pengadukan dimulai 5 menit sebelum penambahan slag ke dalam logam cair pada kondisi semi-padat (*semi-solid*). Setelah slag ditambahkan, pengadukan dilanjutkan selama 5 menit, kemudian ditambahkan magnesium (Mg) sebagai *wetting agent*. Setelah proses pengadukan selesai, logam cair dituangkan ke dalam cetakan untuk pembuatan spesimen uji. Pengujian meliputi pengukuran densitas, uji ketangguhan impak (J/mm^2), serta pengamatan morfologi patahan hasil uji impak. Hasil penelitian menunjukkan bahwa peningkatan fraksi berat slag berpengaruh signifikan terhadap ketangguhan material. Pada kadar rendah (2–4%), partikel slag terdispersi merata di dalam matriks aluminium dan berperan sebagai penguat mikro (*micro-reinforcement*) yang efektif dalam menghambat perambatan retak (*crack propagation*). Namun, pada kadar tinggi (6%), terjadi aglomerasi partikel slag akibat meningkatnya energi permukaan dan melemahnya ikatan antarmuka, sehingga menyebabkan penurunan nilai ketangguhan impak material.

Kata kunci: Aluminium metal matrik komposit; slag tungku kupola; *stir casting*

1. Introduction

At current, materials engineering research is concentrated on creating materials with great mechanical strength and low weight. Composite materials have been created to accomplish these goals by combining two or more constituents with different properties, which leads to better performance than single constituent [1]. The development of metal matrix composites (MMCs) aims to provide a range of characteristics, including increased specific strength, greater wear resistance, and improved thermal stability, that are not possible with metals alloys [2]. One of the most popular varieties of metal matrix composites is aluminum metal matrix composite (AMMC), which was created to satisfy the needs of materials that combine high mechanical strength and low density [3]. AMMCs are attractive materials for engineering applications involving severe mechanical and thermal loads because they are strong, lightweight, and have good stiffness, toughness, and wear resistance [4].

Aluminum serves as the matrix and ceramic particles serve as the reinforcement in the creation of Aluminum Metal Matrix Composites (AMMCs) [5]. Even while pure ceramic reinforcements like SiC and AlO_3 offer superior mechanical performance, their expensive cost of production prevents widespread use. As a result, recent research has concentrated on using ceramic materials produced from waste as a more cost-effective substitute [6]. Numerous waste sources have been investigated, such as red mud that contains FeO_3 , SiO_2 , and Al_2O_3 [4], fly ash that is primarily composed of SiO_2 and Al_2O_3 compounds [7], and other industrial by-products. Foundry slag, which comes from furnace melting processes and is produced by the metal casting industry, is one promising waste source [8]. SiO_2 and AlO_3 make up much to 58% of the slag composition in cupola furnaces, whereas only around 11% of the slag in induction furnaces comprises these oxides [8].

Pure ceramics like alumina (AlO_3) and silicon carbide (SiC) or geopolymer-based ceramics like alumina oxide and silica oxide can be used as reinforcement in aluminum metal matrix composites (AMMCs). In comparison to composites reinforced with pure ceramics, AMMC reinforced with geopolymer-based ceramics employing an AA6010 aluminum alloy matrix demonstrated reduced porosity and almost 50% greater hardness (Akbar, 2021). The weight fraction (Fw)-based reinforcement addition has a major impact on the composite's mechanical properties. For example, adding 2% Fw sea sand particles to AA6010 aluminum increased its hardness relative to 4% and 6%, whereas 6% Fw produced the best tensile strength [2, 6]. Furthermore, the wettability between the reinforcement particles and the aluminum matrix is improved when up to 1% magnesium (Mg) is added as a wetting agent. However, adding too much magnesium (>1%) causes the molten metal to become more viscous during stirring, which reduces particle dispersion [2,6,9,10].

Although the stir casting technique is frequently used in a semi-solid state to achieve better particle distribution and bonding homogeneity [11], the manufacturing of aluminum metal matrix composites (AMMCs) is typically done in a liquid [6]. The final qualities of the composite are determined by a number of crucial elements that impact the stir casting process. The stirrer's design and operation, especially the size of its blades and its rotational speed, are important factors. The Ratio of Crucible to Blade (R_{CB}), which is the ratio of the furnace diameter to the blade diameter, is commonly used to denote the stirrer size. According to reports, a more even distribution of reinforcing particles inside the aluminum matrix results from an R_{CB} value of 1.5, improving the material's hardness and bending strength [12]. Additionally, the porosity and homogeneity of the semi-solid mixture are greatly influenced by the stirring speed; 500 rpm has been demonstrated to provide low porosity, improving the composite's tensile and impact strength [9].

Although pure ceramic materials like SiC and AlO_3 offer superior mechanical performance, their application as reinforcements in aluminum metal matrix composites (AMMCs) comes at a high cost of manufacture. The use of more

affordable alternative, waste-derived ceramic reinforcements has been prompted by this [6]. These include fly ash, which is primarily composed of SiO_2 and Al_2O_3 compounds [7], red mud, which contains Fe_2O_3 , SiO_2 , and Al_2O_3 [4], and other industrial wastes. The metal casting sector, which generates slag as a by-product of furnace melting operations, is one possible source of this waste [8]. SiO_2 and Al_2O_3 make up up to 58% of the slag from cupola furnaces, while only around 11% of the slag from induction furnaces has these oxides [8].

Waste from the usage of aluminum and its alloys is frequently produced, which could present environmental problems [13]. In contrast to primary aluminum production [14], such trash can be recycled by remelting methods [15], which can cut carbon emissions by up to 95%. Scrap aluminum frames with a 95% aluminum composition are classified as low-alloy aluminum [16]. Through composite material engineering techniques, this scrap could be used as a base material for medium- to high-performance components despite its poor economic value and limited mechanical qualities.

Aluminum scrap from frame waste has the potential to be utilized again as a matrix material in aluminum metal matrix composites (AMMCs). Meanwhile, because of its high oxide concentration, foundry slag, a by-product of metal casting processes, exhibits encouraging potential as a reinforcement material. The purpose of this study is to examine how the properties of aluminum scrap castings made by the stir casting process are affected when cupola furnace foundry slag is used as reinforcement in AMMCs with weight fraction changes of 2%, 4%, and 6%. Improving the mechanical qualities of aluminum scrap from frame waste is crucial for this research in order to produce lightweight, highly durable materials at a cheap cost of manufacture. Furthermore, by using a sustainable material engineering method, this study is anticipated to increase the economic worth of both foundry slag and aluminum waste.

2. Material and Method

The experimental steps outlined in earlier research, such as the stir casting procedure, material and equipment characteristics, and changes in reinforcement weight fractions, are referred to in this study. Figure 1 depicts the entire fabrication and testing process used in this investigation.

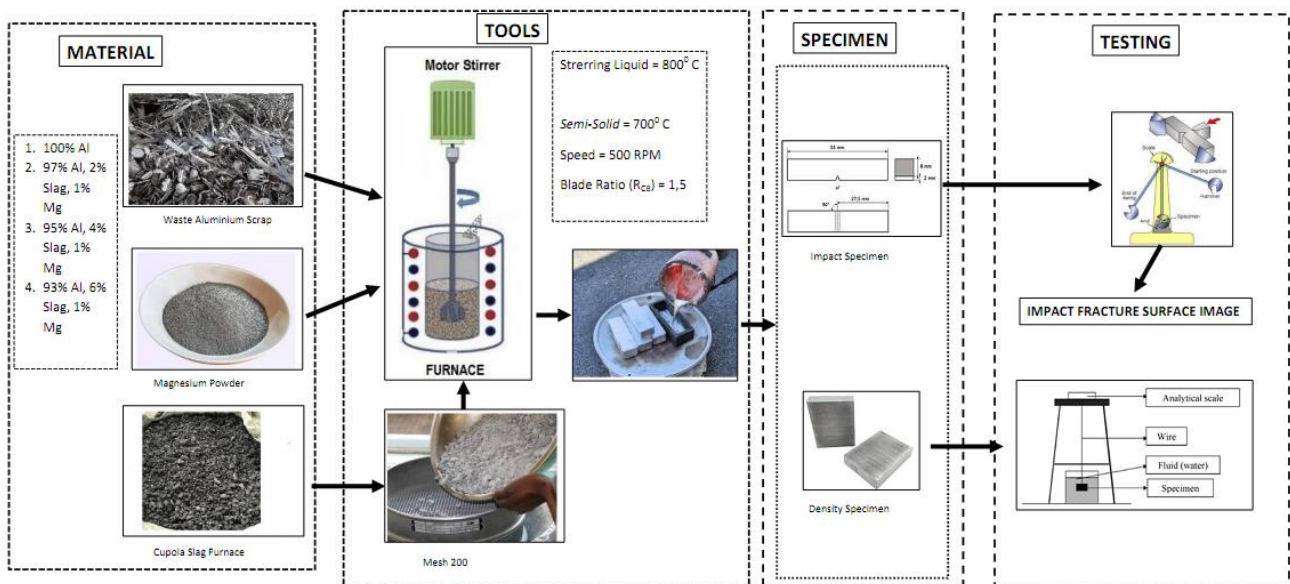


Figure 1. Illustrates the fabrication and testing in this investigation

This study's melting furnace is based on the design by Lashmikanthan *et al.* [11], which consists of a gas-based heat source, an electric motor-driven stirrer, and a heat-resistant crucible furnace. With a crucible-to-blade diameter ratio (R_{CB}) of 1.5, as suggested by Andryanto *et al.* [12], the stirrer blade design adheres to the arrangement suggested by Akbar *et al.* [6]. The matrix, reinforcement, and additive components are the main materials utilized in this investigation. Aluminum scrap from window frame waste that contains more than 95% aluminum makes up the matrix, which acts as the basic material [16]. Cast iron foundry slag from cupola and induction furnaces, which mostly contained SiO_2 and Al_2O_3 compounds, was utilized as reinforcement in the AMMC [17]. 200 mesh was the fineness at which the slag particles were processed [5,6]. To improve the wettability between the reinforcement particles and the aluminum matrix, pure magnesium (Mg) was used as a wetting agent as an additive with a weight fraction of 1% [5,6,9]. The slag reinforcement, additive materials, and aluminum scrap matrix composition were taken from research Akbar *et al.* [6].

Three primary materials were used in the experiment: additive, reinforcement, and matrix. Aluminum scrap frames was used as the matrix; it was cleaned and then cut into tiny bits to facilitate melting. Slag from a cupola furnace, dried and powdered to a fineness of 200 mesh, used as the reinforcement material. As a wetting agent, pure magnesium (Mg) powder was added at a constant weight fraction of 1%. The following four compositions were created: 100% Al (no reinforcement), 1% Mg, 2% Slag, 97% Al, 4% slag + 1% Mg + 95% Al, and 6% slag + 1% Mg + 93% Al. The stir casting method was used to create the Aluminum Metal Matrix Composite (AMMC). A gas-heated crucible furnace was used to melt aluminum scrap at a temperature of about 800°C. After cooling the melt to 700°C until it was semi-solid, it was agitated using a motor stirrer set at 500 rpm and with a blade-to-crucible diameter ratio of 1.5. To increase particle wettability, magnesium was added after slag powder was gradually added to the semi-solid aluminum melt while stirring. To achieve uniform particle dispersion, the stirring operation was carried out for approximately five minutes. The molten composite was homogenized, then poured into metal molds to solidify.

Density measurement, impact toughness testing, and macro-fractographic analysis of the shattered surfaces were among the experimental tests carried out in this investigation. The purpose of the density test was to compute the porosity level of the composite specimens and to ascertain the theoretical and real density values. The microstructural features, such as the dispersion of slag reinforcement particles inside the aluminum matrix, were observed using metallographic investigation. The Charpy method was used in the impact toughness test to assess the material's capacity to absorb energy under abrupt loading. In order to determine fracture modes and surface morphology associated with the variation in slag reinforcement content, macro-fracture surface observations were also carried out on the impact-tested specimens.

To ascertain the true density and calculate the porosity level of the material, a density test was performed on specimens made of aluminum metal matrix composite (AMMC). As seen in Figure 2, the testing process was founded on Archimedes' principle and referenced to the approach put forward by Akbar *et al.* [6]. Equation (1) was used to determine the theoretical density, Equation (2), and Equation (3) was then used to get the percentage of porosity. The purpose of the metallographic analysis was to observe the specimens' microstructural features. The Charpy method was used to conduct the impact test, adhering to the ASTM E23 standard and the process outlined by Harahap [19]. The absorbed energy in joules per square millimeter (J/mm^2) was measured using a pendulum impact testing equipment after the specimens were cut with a standard V-notch (Figure 3). Following testing, the fractured specimens undergo macroscopic surface observation in order to assess the failure characteristics and fracture.

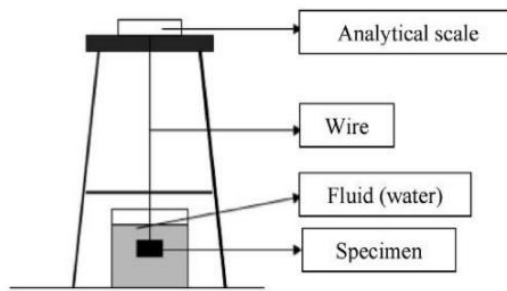


Figure 2. Density test measurement schematic [6]

$$\rho_{th} = \rho_m v_m + \rho_p v_p \quad (1)$$

$$\rho_a = \frac{m_s}{m_s - m_g} \rho_{H_2O} \quad (2)$$

ρ_{th} : theoretical density; ρ_m :matrix density; ρ_p :reinforcement density; ρ_a : actual density; v_m :volume fraction of the matrix; v_p : volume fraction of the reinforcement; m_s : specimen mass in air; m_g : specimen mass in water.

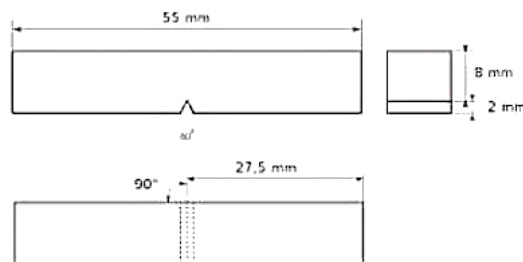


Figure 3. Impact test specimen schematic [19]

3. Results and Discussion

Table 1 displays the findings of the compositional analysis of recycled aluminum scrap (before slag was added). With alloying elements of 0.65% Si and 0.361% Mg acting as strengthening components, the sample shows a high aluminum purity of 98.44%. At 0.326%, the Fe content is still below the crucial threshold for impurity levels. The recycled aluminum scrap can be categorized as a member of the 6xxx series aluminum alloy based on its chemical composition. According to Table 2, the foundry slag's composition shows that ceramic oxides—mainly SiO_2 , Al_2O_3 , and CaO —dominate. These oxides make up around 89% of the cupola slag, with 46% of that being SiO_2 and 39% being Al_2O_3 . Table 2 also reveals the presence of metallic oxides, such as FeO and MnO , in addition to these main ceramic phases. These oxides are usually formed as by-products of the oxidation process during iron melting.

Table 1. Analysis of the Chemical Composition of Remelted Aluminum Scrap

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	Al
Composition (%)	0,65	0,326	0,078	0,025	0,361	0,0013	0,088	0,033	0,028	0,005	98,44

Table 2. Foundry Slag Oxide Composition

Element	SiO_2	Al_2O_3	CaO	Fe_2O_3	Coke Ash
Composition (%)	0,65	0,326	0,078	0,025	0,361

The percentage difference between the actual and theoretical densities is known as the error density, and it can be used to determine the porosity level of a material. The number of voids or internal flaws that emerge within the metal matrix is closely correlated with this value [20]. As increasing cupola slag fractions are added, the density test results (Figure 4) demonstrate an increase in error density, which suggests a rise in porosity inside the material. The material is still quite thick with just little micro-defects at 0% slag addition (error 2%). When 2% slag (error 5%) is added, reinforcement particles are introduced into the aluminum matrix, which causes a minor increase in porosity. Additionally, raising the slag content to 4% (error 9%) and 6% (error 11%) enhances particle agglomeration and decreases the melting process's wetting capacity, which raises porosity [21].

According to the impact toughness test findings shown in Figure 5, foundry slag added to the aluminum matrix typically improves impact toughness up to an ideal concentration. The impact toughness, however, declines with increasing slag content, indicating a decrease in the effectiveness of reinforcement as a result of particle agglomeration and a reduced capacity of the matrix to absorb impact energy [6]. The lowest impact toughness value, 0.19 J/mm², was shown by pure aluminum without slag. Slag up to 2 weight percent was added, increasing both cupola slag's impact toughness (0.21 J/mm²). This improvement shows how well the slag's ceramic oxide particles (SiO₂ and AlO₃) improved the matrix's capacity to absorb impact energy under dynamic loading. At 4 weight percent cupola slag, the maximum impact toughness of 0.31 J/mm² was attained. The impact toughness of cupola slag, on the other hand, decreased by 0.25 J/mm² at 6 weight percent. This suggests that adding too much slag causes particle agglomeration and poor interfacial bonding, which lowers the material's capacity to absorb energy [6].

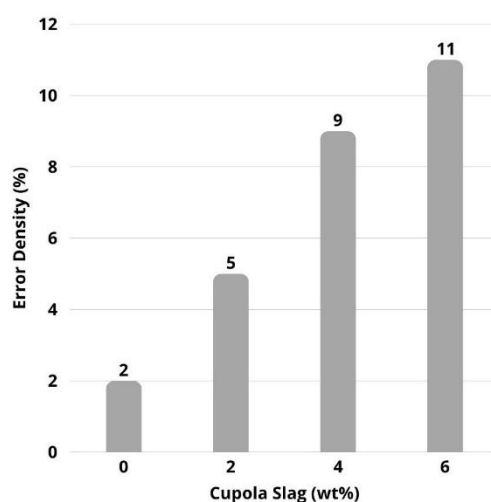


Figure 4. Effect of cupola slag addition on error density

Figure 6a shows the fracture surface of a pure aluminum sample (0%) as a relatively clean crystalline fracture, with no visible cavities or protrusions. Based on this surface area, brittle fracture is the dominant fracture mechanism [14]. Without reinforcing particles, impact energy is not absorbed properly, allowing fracture growth to proceed unhindered. Consequently, at 0% slag content, there are no particles to hinder crack propagation [14]. In comparison to the pure aluminum (0%), the fracture surface of the sample with a 2 weight percent cupola slag addition (Figure 6b) has a rougher and more varied shape. Apart from the crystalline regions, there are also smooth, shiny patches with micro-protrusions, granular textures, and small dimples, which suggests that there was some plastic deformation before the fracture [15]. These characteristics imply a shift in the fracture mechanism toward a semi-brittle or mixed-mode fracture

[18]. The rise in impact toughness to 0.21 J/mm^2 is consistent with this transition, suggesting that the addition of ceramic oxide particles from the slag improved the matrix's capacity to absorb impact energy and prevent cracks from spreading inside the aluminum structure.

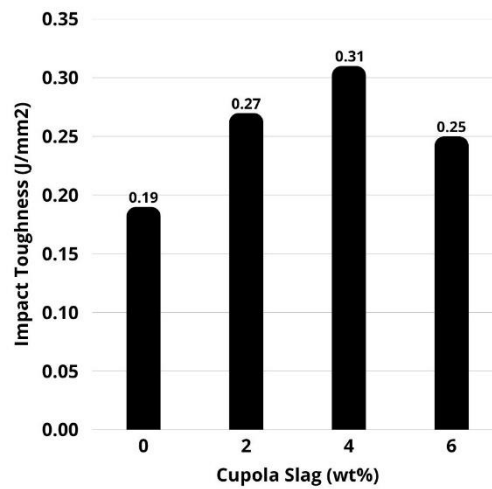


Figure 5. Addition of cupola slag affects impact toughness

At 4 weight percent cupola slag addition, the impact toughness value peaked at 0.31 J/mm^2 , showing an ideal composition with evenly dispersed slag particles throughout the aluminum matrix. In comparison to the 2% slag sample, the macro-fracture image (Figure 2c) shows a notably rougher surface with uneven textures, along with the presence of micro-protrusions and fine dimples. According to these morphological traits, the fracture process changes in favor of a ductile fracture mode, in which the material experiences more plastic deformation before failing. This response demonstrates that the evenly distributed ceramic oxide particles successfully improve the matrix–particle bonding and energy absorption capacity under impact loading at the 4% reinforcing level [1]. The macro-fracture impact (Figure 5d) changes after 6 weight percent cupola slag addition, showing a rougher and more heterogeneous surface. Particle agglomeration and oxide inclusions that are not evenly distributed throughout the aluminum matrix are indicated by the presence of fine black patches and contrasting regions. This condition reduces the material's capacity for plastic deformation before fracture by causing an uneven distribution of stress and serving as locations for crack initiation. By increasing the number of granular fracture areas and decreasing plastic deformation, the agglomeration process affects the fracture mechanism toward a semi-brittle (quasi-brittle) behavior [3]. Impact toughness decreased from 0.31 J/mm^2 at 4 weight percent cupola slag to 0.25 J/mm^2 , this suggests that too much slag reduces ductility by causing particle agglomerates to gather.

The research results show that the macro-fracture impact, impact toughness, and error density of aluminum matrix composites are all severely affected by the addition of cupola slag. Low error density levels between 0 and 4 weight percent slag suggest a denser and more homogeneous matrix with evenly distributed slag particles. The maximum impact toughness of 0.31 J/mm^2 at 4 weight percent slag addition is achieved by this ideal distribution, which also improves load transmission efficiency and initial crack blockage [6]. In contrast, increasing the slag's thickness by up to 6 weight percent results in a decrease in the error density due to porosity and particle agglomeration [6], a rough and heterogeneous fracture surface and the appearance of granular areas that act as the first site of crack initiation are signs of this phenomenon. Impact hardness drops to 0.25 J/mm^2 as a result of the fracture mechanism changing from ductile

to quasi-brittle. Because an excess of cupola slag particles weakens the material's structural integrity and capacity to absorb impact energy, there is a negative correlation between impact toughness and an increase in error density [6].

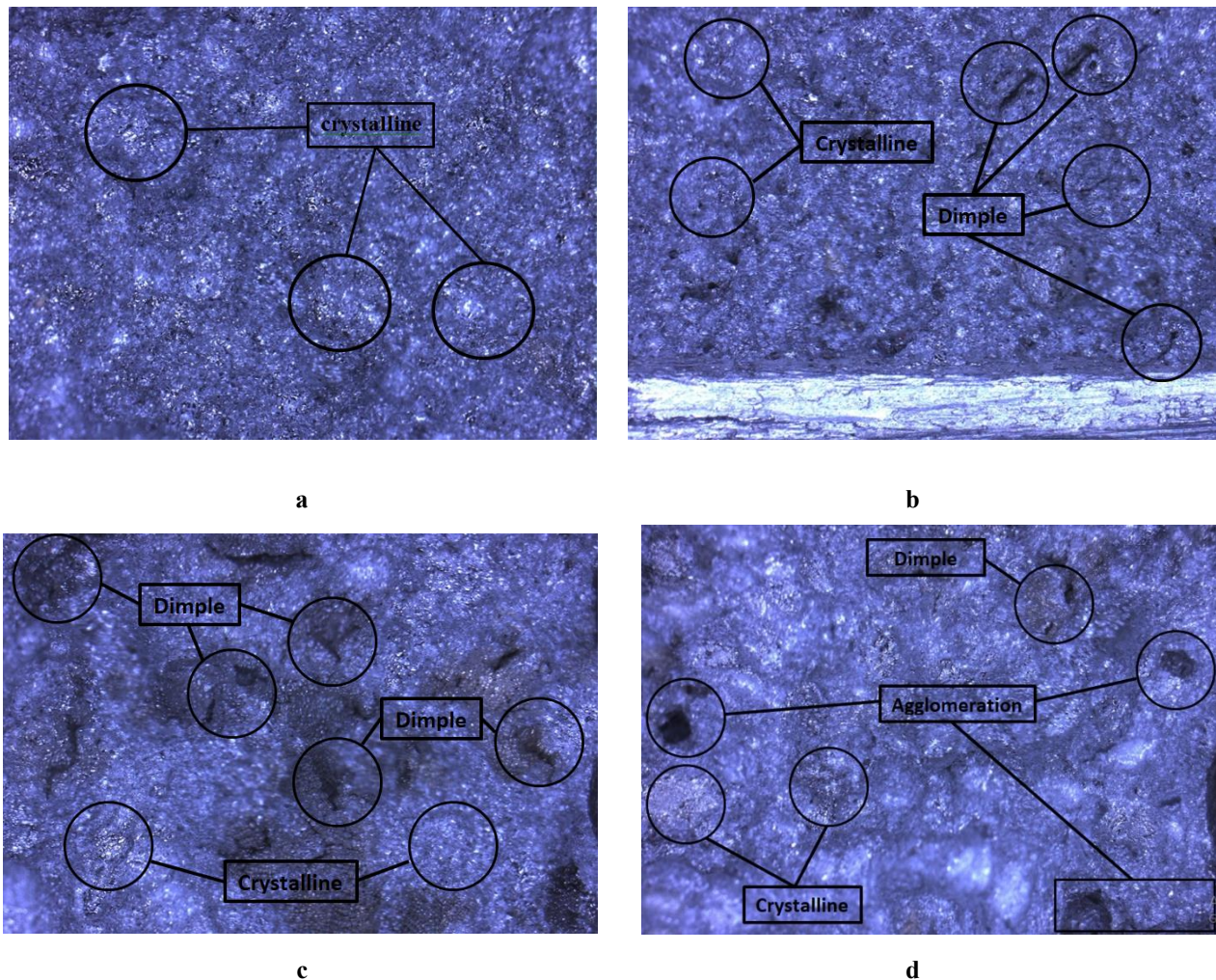


Figure 5. Macro photo of impact fracture : (a) 0% slag (b) 2% slag (c) 4% slag (d) 6% slag

4. Conclusion

The results of the research show that the density, impact toughness, and fracture surface of aluminum matrix composites are all affected by the addition of cupola slag. The composite shows moderate impact toughness with a relatively smooth fracture surface and the lowest error density of 2% at 0% slag addition. With a little higher impact toughness and a more rough fracture surface, the 2% slag addition produced an error density of 5%. The impact toughness peaked at 0.31 J/mm², which is characterized by a rough and dimpled fracture surface, and the error density increasing to 9% with 4% slag addition. With a coarse and rough fracture surface, the 6% slag addition resulted in the greatest error density of 11% and a decreased impact toughness of 0.25 J/mm².

It recommended that further study be done to examine the microstructural improvement of aluminum matrix composites enhanced with cupola slag using advanced characterization methods such as XRD and SEM-EDS to detect interfacial bonding and potential oxide formation.

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