



RESEARCH ARTICLE

DEVELOPMENT OF METAL MATRIX COMPOSITES VIA STIR CASTING USING RECYCLED ALUMINUM ALLOY REINFORCED WITH SPENT CATALYTIC CONVERTER (SCC) PARTICLES

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Abstract. This study introduces an eco-friendly and sustainable approach to developing metal matrix composites (MMCs) by utilizing locally sourced scrap aluminium engine head (SAEH) as the matrix material, reinforced with powdered spent catalytic converter (SCC) particles and Al₂O₃. The stir casting method was chosen for composite fabrication due to its simplicity and cost efficiency. Microstructural analysis was performed using optical microscopy (OM), scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDAX). The mechanical properties of the MMCs, including tensile strength, compressive strength, hardness, and impact resistance, as well as physical properties like density and porosity were investigated. The results demonstrate significant enhancements in the mechanical properties of the composite compared to the as-cast SAEH. The ultimate tensile strength increased from 70.3 MPa (as-cast SAEH) to 158.7 MPa (SAEH+SCC). Similarly, the ultimate compressive strength rose from 513.7 MPa to 717.85 MPa, while hardness improved from 32.56 HB to 45.5 HB. The impact strength also increased from 1.4 Joules to 1.7 Joules. Moreover, porosity was reduced from 14.28% to 8.3%, indicating improved material density and fewer defects. These findings suggest that reinforcing SAEH with SCC particles via stir casting leads to the development of a stronger, more durable composite. The research underscores the potential of using recycled materials to produce sustainable MMCs, aligning with the goals of minimizing environmental impact and enhancing mechanical properties for a variety of engineering applications. Additionally, the study supports the sustainable development goals (SDGs), advocating for environmentally responsible material development that contributes to global sustainability efforts.

Keywords: Sustainable, scrap aluminium engine heads, spent catalytic converter, stir casting, mechanical properties.

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1. INTRODUCTION

The rising demand for advanced materials with superior mechanical properties, coupled with the global emphasis on sustainability, has driven the exploration of metal matrix composites (MMCs). MMCs offer an attractive solution for numerous engineering applications due to their improved strength, durability, and resistance to wear. However, traditional production methods often rely on virgin raw materials, which contribute to environmental degradation and resource depletion. In this context, the use of recycled materials to fabricate MMCs presents a promising path forward, aligning with sustainability goals and reducing environmental impact [1].

One of the key challenges in the development of metal matrix composites (MMCs) is selecting matrix, reinforcement materials and fabrication method to achieve the desired mechanical properties while ensuring environmental sustainability. Recent studies indicate that stir casting is a promising technique for producing MMCs. Arunachalam et al. [2] highlighted that stir casting is a cost-effective method and able to incorporate various reinforcements, including waste materials. Similarly, Al Orami et al. [3] emphasized the potential of using scrap aluminium alloys combined with other waste products, such as borosilicate glass, to enhance MMC properties. These studies point to a growing trend of utilizing recycled materials in MMC production, reducing both costs and environmental impact. Researchers are focusing on identifying reinforcement particles that are cost-effective, sustainable, and practical for enhancing aluminum composites [4].

The automotive and petrochemical industries produce significant quantities of scrap materials and spent catalysts. If properly repurposed, these materials can aid in resource conservation and reduce environmental impact [5]. One such material of interest is the scrap aluminium engine head (SAEH) from automotive scrap yards, which offers potential for further use due to its inherent properties [6]. Catalytic converter is component in automotive exhaust systems which is critical for reducing emissions, containing precious metals (like platinum, palladium, and rhodium) and a ceramic or metallic honeycomb structure. Over time, catalytic converters lose effectiveness due to contamination and material degradation, becoming spent. Disposing of spent catalytic converter (SCC) poses environmental challenges due to their metal content and chemical residues [7]. However, recycling and repurposing these materials offer a valuable resource for enhancing material properties while reducing landfill waste [8]. Industrial waste elements are typically harder and can be used as reinforcement for softer materials [9].

Spent catalytic converters contain valuable metals such as platinum, palladium, and rhodium [10]. These metals are highly resistant to oxidation and high temperatures, making them suitable for use in metal matrix composites (MMCs). Spent catalytic converters are often recycled to recover precious metals as this process is economically and environmentally beneficial, as it reduces the demand for new mining and prevents valuable materials from ending up in landfills. Precious metals like platinum, palladium, and rhodium have excellent thermal stability, corrosion resistance, and wear resistance. When incorporated as reinforcements in MMCs, they enhance the hardness, strength, durability, wear resistance and resistance to high temperatures, making the final product more robust for demanding applications. Additionally, the incorporation of SCC reinforcement particles reduces the density of aluminum composites [11].

Eco-friendly materials that repurpose industrial waste are essential for minimizing environmental impact. However, incorporating waste materials may affect the mechanical and physical properties of composite materials. This research used scrap aluminium engine heads (SAEH) as the matrix material and reinforces it with spent catalytic converter (SCC) particles. The study aims to assess the effectiveness of SCC in enhancing the mechanical and physical properties of SAEH-SCC composites, contributing to sustainable MMC development and advancing high-performance engineering applications.

2. MATERIALS AND METHODS

The metal matrix composite (MMC) was produced using scrap aluminium engine head (SAEH) as the matrix material and spent catalytic converter (SCC) particles as reinforcement using stir casting technique.

2.1 Preparation of SAEH

The SAEH was obtained from a local car scrap yard within Oman. The SAEH was cut into small pieces. Then, SAEH was cleaned to remove any impurities.

2.2 Preparation of SCC

The SCC was taken from abandoned catalytic converters of automotive exhaust systems at Oman city. The SCC was crushed, grinded into fine particles and then was sieved to obtain uniform particles size. The SCC was preheated to 300 °C to remove moisture and prevent thermal shock before added in the mixture.

2.3 Fabrication of Composite Using Stir Casting

The small size of SAEH was placed in the crucible before heating process. Magnesium chips (1 wt.%) were added as a wetting agent to improve bonding between aluminium matrix and SCC particles since wettability in aluminum composites is promoted by magnesium. The mixture was heated to a temperature of 850 °C. The parameters for stir casting are tabulated in Table 1. Once the aluminium alloy (SAEH) was fully molten, the furnace temperature was reduced to 750 °C and 2.5 wt.% SCC + 2.5 wt.% Al₂O₃ were added to the melt. The molten composite was stirred at 650 rpm for 10 minutes to ensure uniform distribution of the SCC and Al₂O₃ particles throughout the aluminium matrix. The molten then was poured in a steel die that was preheated at 250 °C. Samples were then removed from the mould after they had solidified and sent for characterization.

Table 1: Process parameters for composite fabrication

| Fixed process parameters | Values |
|--|---------------|
| Furnace temperature | 850°C |
| Melt temperature/Stirring temperature | 750°C |
| Stirring time | 10 mins |
| Preheat temperature of reinforcement particles | 300°C |
| Stirrer speed | 650 rpm |
| Die temperature | 250°C |

2.4 Characterizations

Microstructural characterization and phase analysis of the fabricated MMCs were performed using optical microscopy, scanning electron microscopy (SEM) equipped with energy-dispersive X-ray analysis (EDAX), and X-ray diffraction (XRD). Mechanical testing included assessments of tensile strength, compressive strength, hardness, and impact resistance. Tensile strength was determined with a universal tensile testing machine, while compressive strength was evaluated through compression testing. Hardness was measured using a Brinell hardness tester, and impact resistance was assessed with a Charpy impact testing apparatus. Additionally, the density of the composite materials was measured using an Archimedes density measurement setup.

3. RESULTS AND DISCUSSION

3.1 Density and Porosity

Figure 1 presents the theoretical and experimental density and porosity of the composites and as cast SAEH. It was observed that the experimental density of both the aluminum composite and as-cast samples consistently fell below the theoretical density values [8]. This difference is due to the theoretical density not accounting for porosity and other defects within the composites. The findings indicate a reduction in porosity, from 14.28% in the as-cast SAEH to 8.3% in the SAEH+SCC composite. This decrease in porosity reflects an increase in material density, attributed to better packing and dispersion of SCC particles and Al_2O_3 within the aluminum matrix. This improvement is likely due to enhanced wettability, which facilitates nucleation, crystallization, and the reduction of shrinkage porosity [12].

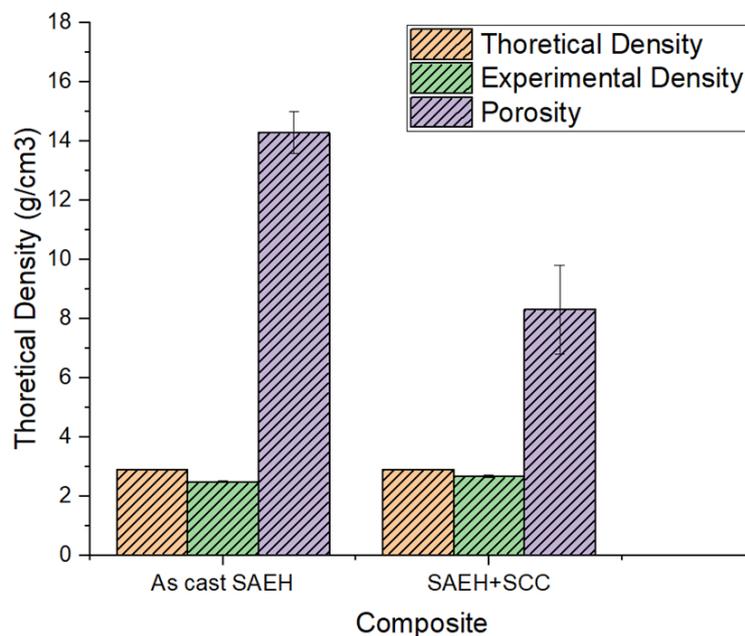


Figure 1: Theoretical and experimental density and porosity of the produced composite

3.2 Microstructure Evaluation

The fabricated MMCs were examined using optical microscopy, as shown in Figure 2. The as-cast SAEH and composite consist of a white aluminum matrix and a black eutectic phase containing a mixture of Si, Al_2O_3 , and SCC. These mixed particles are primarily located at the grain boundaries [13]. As cast SAEH sample contains large size of pore as displayed in Figure 2(a). In contrast, Figure 2(b) shows the SAEH+SCC composite with a more uniform microstructure, less porosity, and a well-distributed reinforcement phase, contributing to improved mechanical properties.

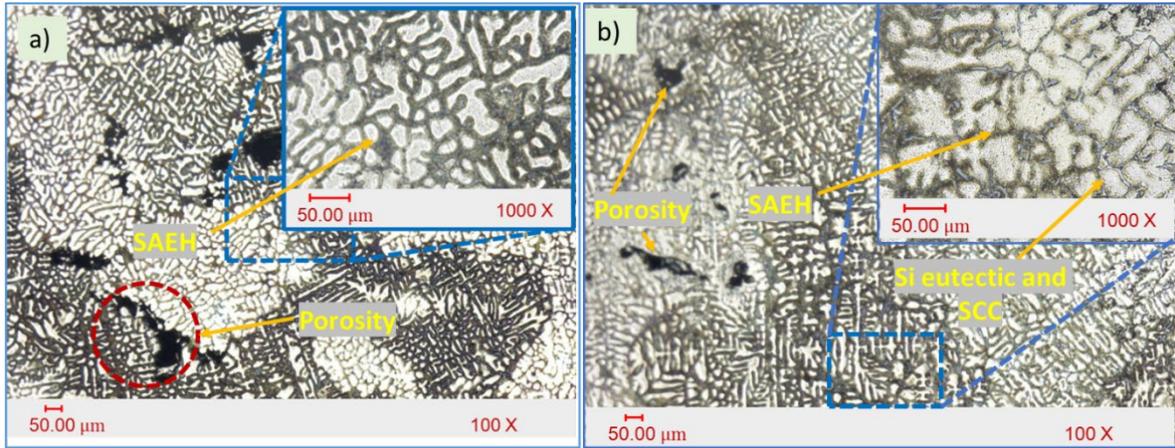


Figure 2: Optical microscopic images of produced samples (a) as-cast SAEH, and (b) SAEH + SCC

3.3 Scanning Electron Microscopy (SEM) Analysis

SEM analysis, depicted in Figure 3, provided further microstructure analysis of the MMCs. In Figure 3(b), the SCC particles show a uniform distribution within the aluminum matrix. In contrast as cast SAEH sample in Figure 3(a) exhibits higher microporosity and cracks. This confirms the enhanced structure of the SAEH+SCC composite, which demonstrates better particle-matrix adhesion and fewer voids, contributing to its superior mechanical properties.

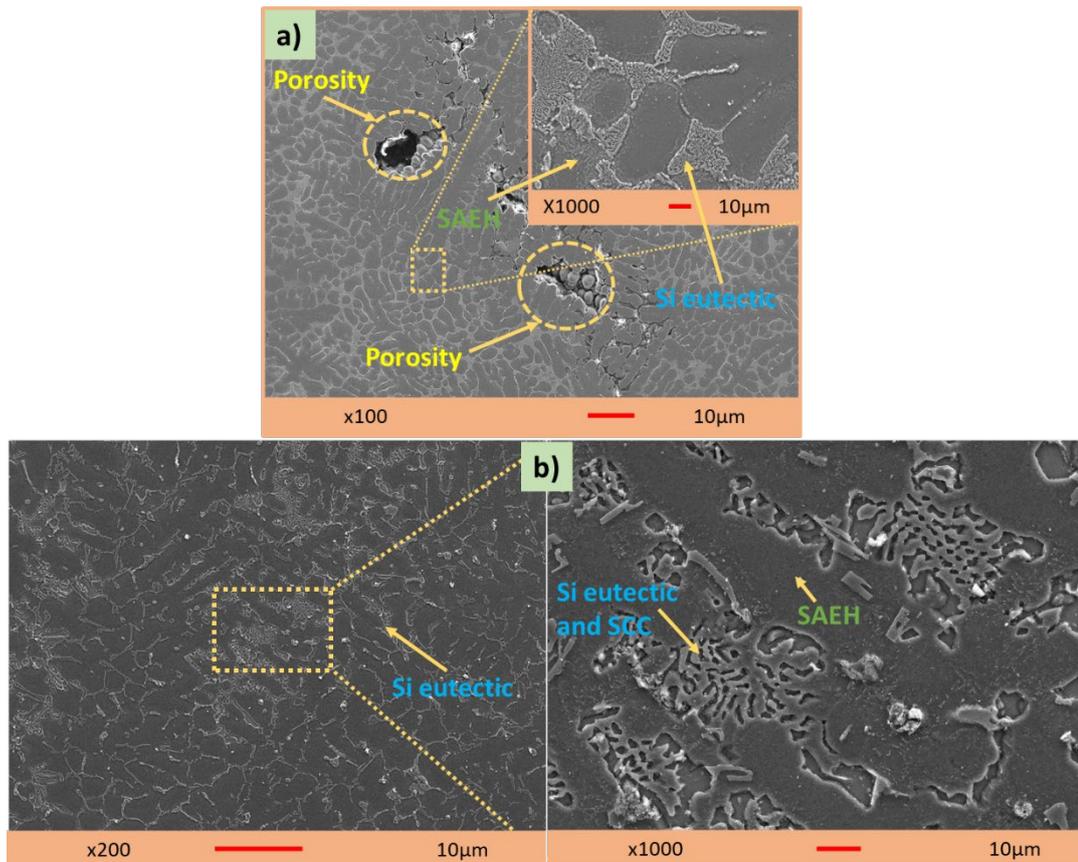


Figure 3: Scanning Electron Microscopy (SEM) images of produced samples (a) as-cast SAEH and (b) SAEH + SCC

3.4 Elemental Mapping Analysis

Energy-dispersive X-ray spectroscopy (EDAX) was performed to analyze the elemental composition of the composites. As illustrated in Figure 4, the EDAX spectra revealed that aluminum, silicon and are the predominant elements in the SAEH+SCC composite. This indicates that the SAEH contains high elements of Al, Cu and Si that fall under 2XX series. The highest element of Al is present at the matrix (spectrum 1,2,3,13,14) while Si is high at the interdendritic region (spectrum 12). However, platinum, palladium, and rhodium that is contained in SCC was not detected. This may be due to the small amount present in SCC.

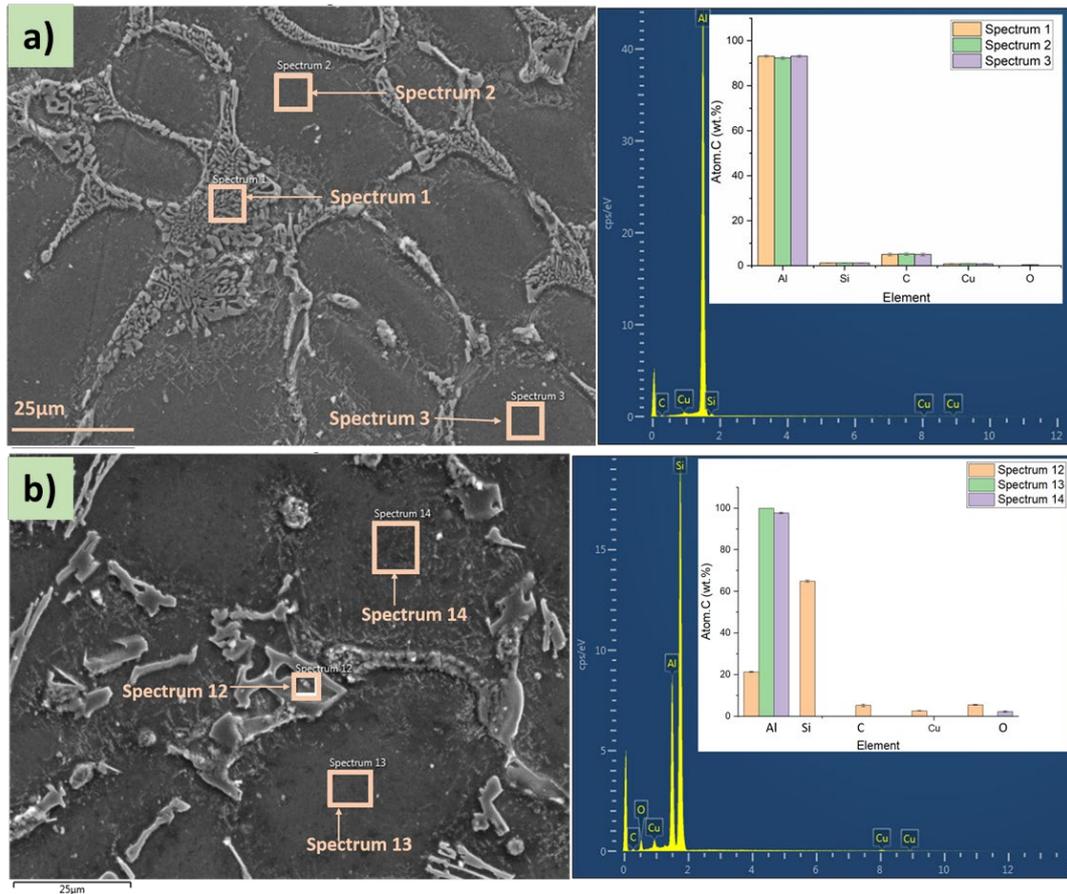


Figure 4: Energy Dispersive X-ray Spectroscopy (EDS) analysis of (a) as-cast SAEH, and (b) SAEH + SCC.

3.5 Tensile Strength

The tensile properties of the produced composites were investigated using a Universal Tensile Testing machine as shown Figure 5. The ultimate tensile strength (UTS) of the SAEH+SCC composite was significantly higher (158.7 MPa) than as-cast SAEH. The improvement can be attributed to the uniform distribution of SCC and Al_2O_3 particles. Both Al_2O_3 and SCC are hard that resist the deformation and increasing load-bearing capacity. These particles tend to accumulate at grain boundaries, serving as barriers to dislocation movement. The restriction of dislocation impedes plastic deformation, thereby strengthening the material [14]. Furthermore, the enhanced load transfer capacity of the composites, due to the addition of reinforcing particles at the particle-matrix interface, significantly strengthened the material and increased its tensile strength. This illustrates the clear correlation between hardness and tensile strength in the composite [15].

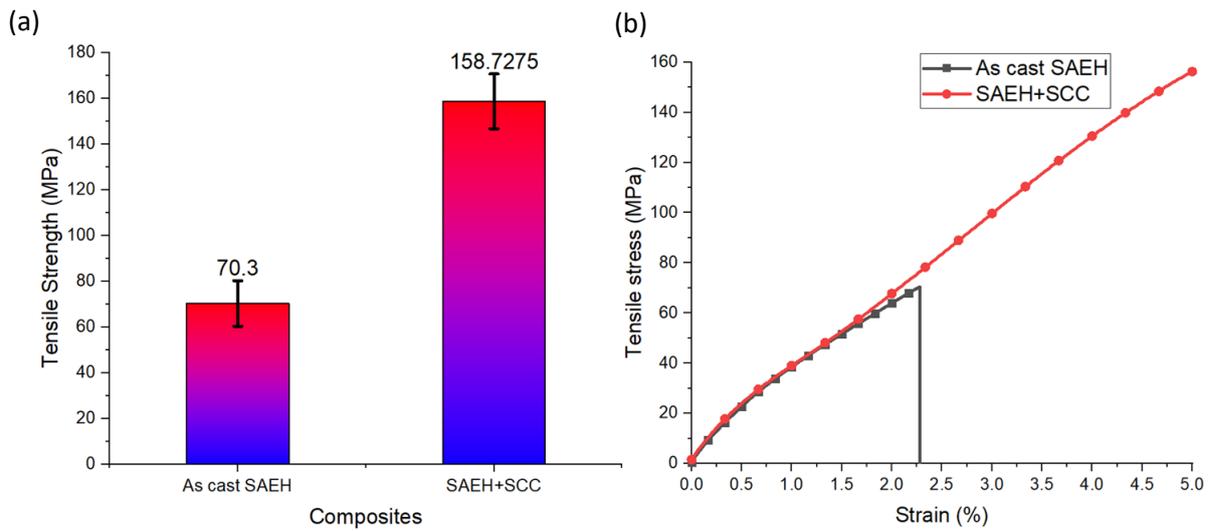


Figure 5: (a) Tensile strength, and (b) Tensile stress-strain of as-cast SAEH and composite (SAEH+SCC)

3.6 Compressive Strength

As shown in Figure 6, the compressive strength results demonstrate that the SAEH + SCC composite exhibited a notable improvement compared to the as-cast SAEH. The composite achieved a compressive strength of 717.85 MPa, whereas the as-cast SAEH had only 513.7 MPa. This enhancement is primarily attributed to the hardness and strength of the SCC particles, which reinforced the aluminum, increasing its resistance to compressive forces.

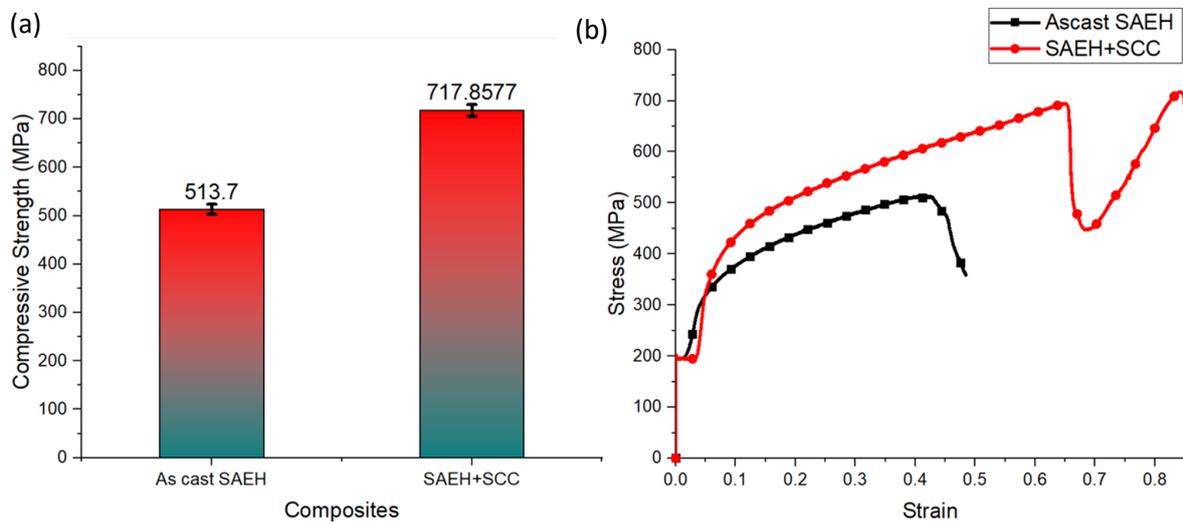


Figure 6: (a) Compressive strength, and (b) compressive stress-strain of as-cast SAEH and composite (SAEH+SCC)

3.7 Hardness

Figure 7 shows the hardness value of SAEH+SCC composite and as cast SAEH. The hardness increased from 32.56 HB to 45.5 HB after reinforced with SCC indicating improvement of This could be attributed to introduction of hard SCC particles and Al_2O_3 that increased resistance of the surface in the composite. The Al_2O_3 and SCC improve wettability and bonding strength between the aluminum matrix and the reinforcement particles. The reinforcement restricts the dislocation movement [14].

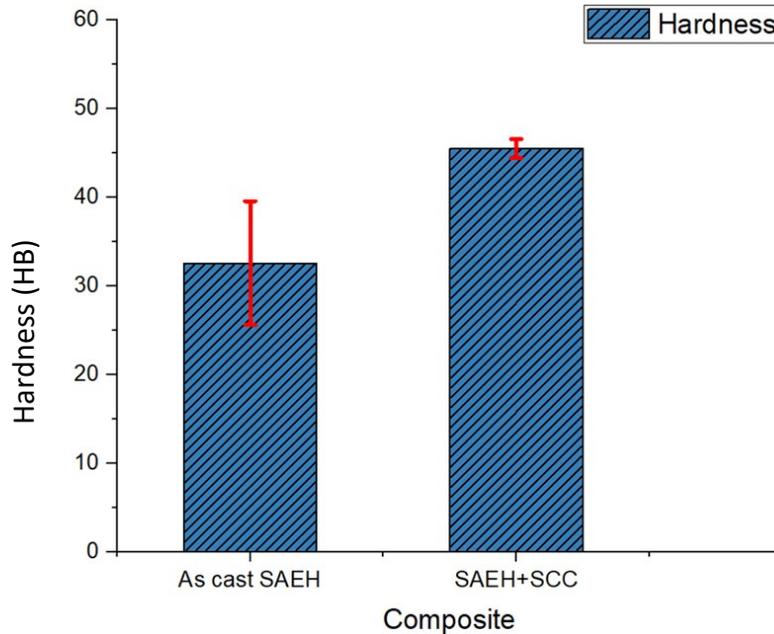


Figure 7: Hardness of as cast SAEH vs composite

3.8 Impact Strength

Impact test was performed using a Charpy impact testing apparatus, indicating an increase in the energy absorption capability of the SAEH+SCC composite. As shown in Figure 8, the impact strength of the composite increased from 1.4 Joules for the as-cast SAEH to 1.7 Joules for the reinforced composite. Alumina being hard and tough, along with SCC containing platinum, palladium, and rhodium, resists crack propagation, enabling the matrix to absorb more energy during impact. By strengthening grain boundaries and preventing weak points, the composite can better withstand dynamic loads, leading to superior impact resistance compared to the as-cast material. Table 2 shows the comparison of mechanical properties of the as-cast scrap aluminium engine heads (SAEH) and the SAEH reinforced with spent catalytic converter (SCC) particles composite.

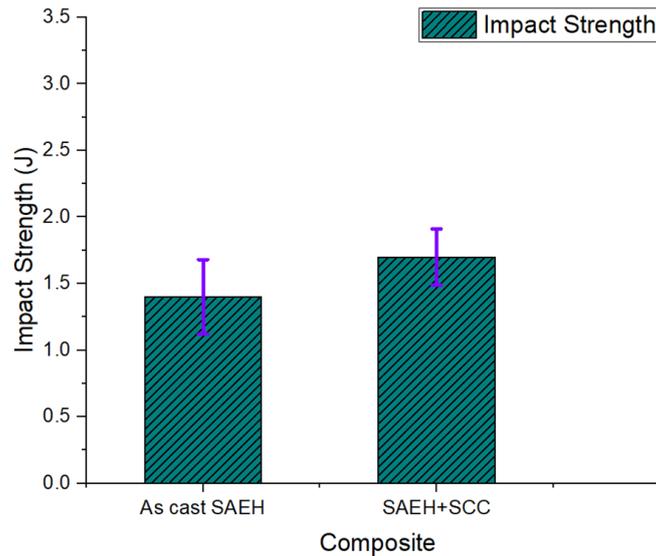


Figure 8: Impact strength of as cast SAEH and composite

Table 2: Mechanical properties of as cast SAEH and SAEH+SCC Composite

| Property | As-cast SAEH | SAEH +SCC Composite |
|---------------------------------|--------------|---------------------|
| Ultimate tensile strength (MPa) | 70.3 | 158.7 |
| Compressive strength (MPa) | 513.7 | 717.85 |
| Hardness (HB) | 32.56 | 45.5 |
| Impact strength (Joules) | 1.4 | 1.7 |

4. CONCLUSIONS

This research successfully developed a sustainable composite with improved properties. Overall, the mechanical characteristics of the SAEH+SCC composite showed significant enhancements compared to the as-cast SAEH. The tensile strength increased by 125%, and the compressive strength rose by 39%. Additionally, the hardness improved from 32.56 HB to 45.5 HB. Impact tests demonstrated greater energy absorption by the composite. Optical microscopy, SEM, and EDAX analyses confirmed a uniform distribution of the reinforcement phase and a reduction in porosity. These results highlight the benefits of incorporating SCC into the composite and support the advancement of environmentally friendly materials.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare

Compliance with Ethical Standards

The work is compliant with ethical standards

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