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ENHANCED CORROSION RESISTANCE AND MECHANICAL INTEGRITY OF AL6061/BERYL METAL COMPOSITES: AN ELECTROCHEMICAL STUDY IN ACIDIC CHLORIDE AND ALKALINE MEDIA

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ABSTRACT

Al6061 aluminium alloy has been widely used in aerospace, automotive, and marine industries for its low density, excellent mechanical properties, and medium corrosion resistance. Nevertheless, its structural reliability is still limited by the susceptibility to localised corrosion in severe environments. In the present investigation, beryl (Be3Al2Si6O18), a natural beryllium aluminium cyclosilicate, is utilised as a reinforcement phase to enhance corrosion resistance and mechanical properties of Al6061 alloy. In order to make the aluminium/boron balide MMCs more homogeneous and have better interface bonding, these stir-cast MMCs with 2, 4 and 6 wt% of beryl were successfully extruded. The mechanical properties, such as hardness, density and porosity, were initially determined, then the corrosion behaviour was explored electrochemically in 0.5 M HCl and 0.1 M NaOH solutions by means of Tafel extrapolation and EIS methods. The microstructure and phase characteristics were systematically investigated using a scanning electron microscope (SEM) and an X-ray diffractometer (XRD). Results showed that the composite with 6 wt% beryl had the smallest current density and maximum LIN, described by a higher resistance to polarisation, which proved an improved stability of the passive film. These results indicate that the incorporation of beryl reinforcement via CEP effectively enhances not only the corrosion resistance but also the structural property of Al6061 alloy, and thus its potential for use in corrosive, aggressive, and high-simultaneous property engineering conditions.

Keywords: Al6061, Beryl Reinforcement, Mmcs, Corrosion Resistance Index, Stir Casting, Extrusion and Electrochemical Analysis.

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INTRODUCTION

Aluminium and its alloys, particularly Al6061, are highly appreciated for their corrosion resistance, wear resistance, thermal stability, and high specific strength-to-density ratio, which make them great candidates to be used in automotive, marine, and aerospace areas.[8] The inclusion of ceramic and nano-sized reinforcements has been investigated by researchers to further strengthen these properties.[2,3] $Be_3Al_2Si_6O_{18}$, or beryl, is a silicate-based ceramic that has emerged as an exciting candidate for an efficient reinforcement in aluminium matrix composites because it exhibits significantly high hardness, excellent wear performance, and several other advantageous thermal properties. However, very limited research has been conducted to investigate the electrochemical corrosion behaviour of Al6061-Beryl composites, specifically in extreme conditions like chloride and alkaline environments. Post-processing, such as extrusion shrinking already known to enhance microstructural uniformity and grain size while minimising porosity, hence resulting in excellent mechanical properties.[12] Simultaneously, the extrusion itself can also change corrosion, including reinforcement bonding state, not only stress distribution, but also the nature of grain boundaries. Corrosion is the dominant mode of failure in AMCs, generally because of micro-scale galvanic coupling in the aluminium matrix and the conductive reinforcements, which are prevalently responsible for localised damage, especially in chloride-rich environments. Although the inherent stabilisation of Beryl probably helps these effects be less severe, the effect on corrosion kinetics caused by extrusion is complex. New research highlights the importance of reinforcing with post-processing to improve corrosion resistance 711. One of the studies selected in this case is edited about the production of Al6061 composites with Beryl of 2, 4, and 6 wt%. % after extrusion for gaining a uniform structure.[13] The corrosion resistance of the composite is studied through an electrochemical study in NaCl and NaOH solutions, whereas the microstructure and hardness are studied using SEM, EDAX, and a microhardness test. The objective is to study the effect of Beryl reinforcement within extrusion on corrosion behaviour and further provide a perspective for designing lightweight, highly resistant corroded material in marine and industrial applications.

EXPERIMENTAL

Materials Employed

Aluminium 6061 (Al6061), which possesses excellent strength, corrosion resistance and demonstrates wide application in the structural fields and aerospace applications, was employed as the matrix material. The composition of the alloy is given in Table-1, which shows typical key elements of Si, Mg and Cr. Beryl ($Be_3Al_2Si_6O_{18}$), a natural Be–Al silicate mineral having a hexagonal crystal structure, was employed as reinforcement. Applied in powder (~140μm), beryl is composed of major oxides such as SiO_2, Al_2O_3 and BeO (Table-2). Its density (2.75 g/cm³) is near Al6061 (2.70 g/cm³), enabling smooth distribution as well as good wettability in the casting process.

Composite Fabrication

Al6061/beryl composites were processed by stir casting. Al6061 ingots were used. The material was molten with Electric Resistance Heating in a graphite crucible at approximately 720 °C. Magnesium (1 wt%) was added to the liquid to promote wetting and minimise oxide formation. The beryl particles were thermally treated at 400°C for one hour and added to the liquid-phase aluminium at addition levels of 2, 4, and 6 wt% % using two-stage introductions with continuous stirring (300 rpm) over ten minutes. This solution was then poured into preheated steel moulds (25 mm × 200 mm) and left at room temperature to solidify. The as-cast ingots were homogenised at 530°C for 2 hours, then furnace cooled.

Sample Preparation

Cast bars were machined into cylindrical specimens for corrosion and mechanical testing. Standard metallographic polishing using SiC papers and alumina slurry ensured mirror finishes. Samples were cleaned with ethanol and deionised water before testing.

Density and Porosity Measurement

Density was determined using Archimedes' principle (ASTM D792). Theoretical density was calculated using the rule of mixtures, and porosity (%) was determined by:

$$\text{Porosity (\%)} = \left(\frac{\rho_{\text{theoretical}} - \rho_{\text{measured}}}{\rho_{\text{theoretical}}}\right) \text{ X } 100$$

Microstructural and Phase Analysis

SEM was used to evaluate the microstructure and distribution of beryl particles in the Al6061 matrix. XRD analysis (Cu-Kα, λ = 1.5406 Å) was conducted over a 2θ range of 20°–80° for phase identification.

Hardness Testing

Vickers microhardness testing was performed per ASTM E384 using a 500 g load and a 10-second dwell time. Five indentations per specimen were averaged for accuracy.

Electrochemical Corrosion Testing

Corrosion behaviour of the composites was investigated using electrochemical methods in two aggressive environments:

0.5 M HCl – representing an acidic chloride medium.

1 M NaOH – representing an alkaline environment.

A CHI660E electrochemical workstation with a three-electrode cell setup was used: the composite as the working electrode (1 cm² area), platinum as the counter, and Ag/AgCl as the reference electrode. Tests were performed at ambient temperature under static conditions.

Potentiodynamic Polarization

Samples were immersed for 30 minutes to stabilise at the Open Circuit Potential (OCP). Polarisation scans were conducted ±250 mV from OCP at 1 mV/s. The Tafel extrapolation method was used to determine:

Corrosion potential (Ecorr) – indicating susceptibility to corrosion.

Corrosion current density (Icorr) – directly related to corrosion rate.

Electrochemical Impedance Spectroscopy (EIS)

EIS was performed at OCP with a 5 mV AC signal across 0.01 Hz to 10^4 Hz. Nyquist plots were analysed using ZSimpWin 3.21. An equivalent electrical circuit (EEC) model was used to extract:

Charge transfer resistance (Rct) – higher values imply better corrosion resistance.

Double-layer capacitance (Cdl) – associated with passive film thickness and electrochemical behaviour.

These electrochemical techniques provided comprehensive insights into the corrosion performance of Al6061/Beryl composites in both environments.

RESULTS AND DISCUSSION

Tafel polarisation indicated that the addition of beryl content (0–6 wt%) in Al6061 matrix has improved the corrosion resistance of the composites, Ositains 0.5 M HCl and NaOH as discussed. The consumption of metal was lower with the inhibition rate increasing the corrosion resistance, considering the reduction in Icorr.

Table-1: Tafel Polarisation Results for Al6061/Beryl Composites

Beryl Content (wt%)	Ecorr (mV) – HCl	Icorr (μA/cm²) – HCl	Rate (mm/yr) – HCl	Ecorr (mV) – NaOH	Icorr (μA/cm²) – NaOH	Rate (mm/yr) – NaOH
0	-699.1	24.1	0.279	-734.2	33.4	0.387
2	-676.3	15.5	0.181	-711.5	21.8	0.252
4	-654.2	9.7	0.113	-688.2	12.6	0.145
6	-631.4	6.89	0.079	-671.1	9.14	0.106

The corrosion rate also decreased (Table-1), and the corrosion potential (Ecorr) nobly shifted towards hydrogen evolution, which means that graphene in this case showed an improvement in the thermodynamic stability. The protective effect of beryl particles and the possibly formed passivation film, which prevented both the Fe and Al from being dissolved, was more distinct in HCl solution than in NaOH solution due to the amphoteric nature of aluminium; it is more susceptible to a corrosion environment with alkalinity fragments (pH = 12) that will dissolve Al faster.

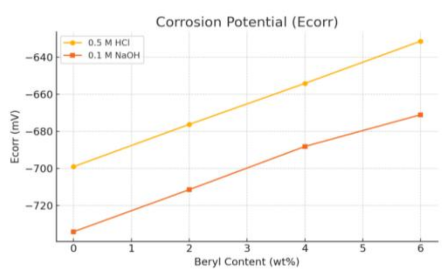

Fig.-1: Corrosion Potential (Ecorr)

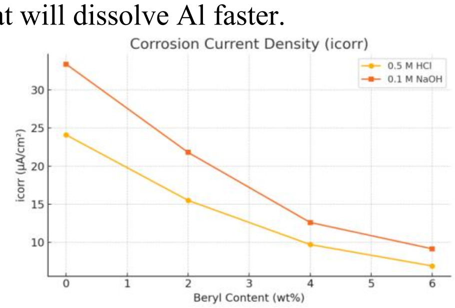

Fig.-2: Corrosion Current Density (Icorr)

Referring to Fig.-3, the corrosion rate of Al6061 matrix decreases with an increase in beryl content; however, the unreinforced alloy demonstrates a high level of corrosion in both acidic and basic media. The corrosion rates in HCl and NaOH dissolve at 0.079 mm/year and 0.106 mm/year for the beryl composites, which make up 6 wt%, and show the lowest among them, which is an obvious improvement. The stability and thickness of a bery Particles passive layer is attributable to these two effects: physical barrier property and surface refinement. These effects together restrict the ion transfer and corrosion reactions, verifying that beryl reinforcement not only improves strength but also enhances resistance to corrosion under aggressive environments.

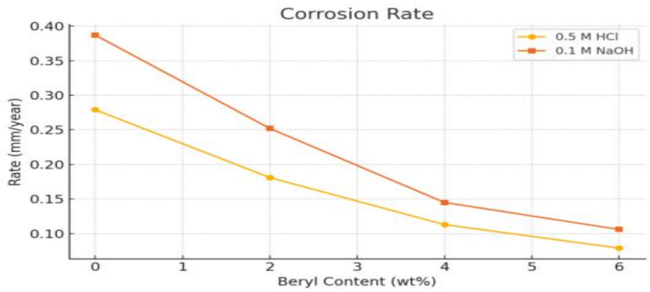

Fig.-3: Corrosion Rate vs. Beryl Content

The Nyquist plots (Fig.-3) demonstrate that the impedance arc diameter increases with beryl content in both corrosive media.

Table-2: Nyquist Diameter (Impedance) Values

Beryl Content (wt%)	Nyquist Diameter (Ω·cm²) – HCl	Nyquist Diameter (Ω·cm²) – NaOH
0	258.7	209.3
2	372.4	317.6
4	481.2	428.5
6	598.4	511.8

The increasing impedance values indicate improved corrosion resistance. The larger semicircles in Nyquist plots confirm the higher polarisation resistance and reduced charge transfer, suggesting that beryl reinforcement positively influences the electrochemical stability of Al6061.

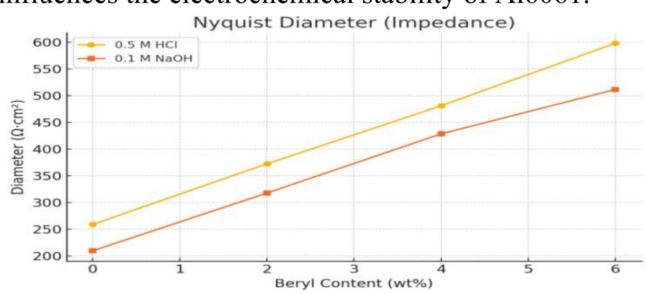

Fig.-4: Nyquist Diameter vs. Beryl Content

CONCLUSION

In this work, the corrosion behaviour of Al6061/Beryl composites was critically studied in an aggressive environment (H_2SO_4 and NaOH). Nasicon Beryl particulate-filled composites were prepared by stir casting and then extrusion for microstructure optimisation and better mechanical properties. Among the studied materials, Al–B–6 Ex composite (6 wt% Beryl) showed a promising combination of density, hardness, and porosity properties with other composites. Tafel-extrapolation and electrochemical impedance spectroscopy (EIS) results indicated that the addition of Beryl resulted in notable improvements in the corrosion resistance of Al6061, especially in Accreditation-Nist-based-6 Ex which exhibited both minimal I corr along with maximal R p. The observations from scanning electron microscopy (SEM) regarding surface morphology further endorsed these findings as an insignificant damage or pitting on surface was observed to be developed while displaying a stable and protective passive layer as a result in reinforcement by Beryl. These results indicate that Al–B–6 Ex composite is a very useful material for highly corrosive areas, including ship engine components operating in acidic or alkaline conditions. The outcomes are in harmony with the United Nations Sustainable Development Goal SDG-9: Industry, Innovation and Infrastructure, toward the development of sustainable high-performance materials facilitating sustainable industrial progression. The application prospects of these composites in industry could be exploited.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-9: Industry, Innovation and Infrastructure*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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