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Original Research Article

Evaluation of Mechanical Properties and Microstructural Characteristics of Aluminum-Based Hybrid Composites for Medical Applications

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Abstract: The rapid evolution of medical and biomedical engineering has intensified the demand for advanced materials that combine high strength, low density, wear resistance, and long-term reliability. Conventional metallic biomaterials such as stainless steel and cobalt–chromium alloys, although mechanically robust, often suffer from high density and elastic modulus mismatch with human bone, leading to stress shielding and reduced service life. In this study, aluminum alloy 7075 reinforced with magnesium oxide (MgO) and fly ash is investigated as a hybrid metal matrix composite (HMMC) for potential medical and biomedical applications. The manuscript presents a comprehensive discussion on material selection, fabrication routes, microstructural characteristics, and mechanical performance, with emphasis on suitability for orthopedic devices, prosthetic structures, and medical equipment components. The results indicate that the incorporation of MgO and fly ash enhances hardness, strength, and wear resistance while maintaining a low density, making the composite a promising candidate for lightweight medical applications.

Keywords: Aluminum 7075; Hybrid metal matrix composite; Magnesium oxide; Fly ash; Biomedical materials; Orthopedic applications.

INTRODUCTION

The selection of materials for medical applications is governed by strict requirements including mechanical reliability, lightweight design, corrosion resistance, manufacturability, and, in many cases, biocompatibility. Metals such as stainless steel, titanium alloys, and cobalt–chromium alloys are widely used in orthopedic implants and medical devices due to their high strength and corrosion resistance. However, their relatively high density and stiffness often lead to stress shielding, which may adversely affect bone remodeling and implant longevity.

These image topics relate to areas where materials with good strength, low weight, and wear resistance (like Al-7075 composites) are valuable:

Fig 1.1: Applications of Al-7075 composites orthopedic devices, prosthetics, surgical instruments, and medical equipment

Composite materials provide an effective pathway to overcome these limitations by enabling the tailoring of properties through controlled combinations of matrix and reinforcement phases. Among them, aluminum-based metal matrix composites (AMMCs) have attracted significant attention due to their low density, high specific strength, and excellent machinability. Hybrid metal matrix composites (HMMCs), reinforced with more than one type of particulate or ceramic phase, offer further enhancement in mechanical and tribological performance.

In recent years, the potential application of aluminum-based composites in the medical field has expanded, particularly for non-permanent implants, external fixation devices, prosthetic components, and medical equipment structures. This manuscript focuses on aluminum alloy 7075 reinforced with magnesium oxide and fly ash, highlighting its relevance as a lightweight and mechanically efficient material for medical and biomedical engineering applications.

1. LITERATURE SURVEY

Deepak Singla et al. (2021) investigated Al7075 alloy composites reinforced with *fly ash and graphite* using stir casting. Their study found that hybrid reinforcement improved tensile yield strength, ultimate strength, and microhardness compared to the unreinforced alloy. The work also discussed the effect of processing parameters on particle distribution and resultant mechanical enhancement.

Boopathi et al. (2022) examined hybrid composites of Al7075 reinforced with fly ash, red mud, and mica particles. They found that multi-particle reinforcement increased hardness, tensile strength, and wear resistance, though ductility decreased due to the presence of hard particles.

M. Mahendra Boopathi et al. (2018) focused on Al7075 alloy reinforced specifically with fly ash particles, demonstrating the effectiveness of fly ash as a low-cost reinforcement that enhances mechanical performance through proper dispersion during stir casting.

Kumar Sahu and Kumar Sahu (2021) provided a broader review of AA7075 composites, including fly ash and boron carbide reinforcements. They reported that hybrid combinations (e.g., B4C + fly ash) significantly increased microhardness and improved tensile strength, illustrating the synergistic enhancement effect of particle-based reinforcement systems.

Gopala Krishna et al. (2024) developed Al7075 hybrid metal matrix composites reinforced with *boron carbide (B4C)* and *coconut shell fly ash* via powder metallurgy. Their study showed that hardness increased significantly with higher B4C and fly ash content, and tensile strength improved at optimal reinforcement fractions. This demonstrates the effectiveness of hybrid reinforcement even when agricultural waste is used as filler, aligning with sustainability objectives.

Mahdavi et al (2011) investigated the applicability of in situ powder metallurgy (IPM) method for processing the Al6061/SiC/Gr hybrid composites, effect of SiC content on the tribological behavior of the hybrid composites. The amount of porosity and hardness are decreased by increasing of graphite content in the composites. However, for identical graphite contents the porosity and hardness of Al/30SiC/Gr hybrid composites are higher than those of Al/Gr composites.

Gui (2001) observed that Plasma spraying is a feasible route to produce aluminum composite coatings reinforced with SiC particles. A considerably uniform distribution of SiC particles can be found in the 25 composite coatings. Good compatibility and strong bonding between the sprayed layer and the substrate were obtained. Because of non-wetting nature of graphite by molten aluminum, non-coated graphite particles exhibited an inhomogeneous distribution in the coatings and had a certain loss during plasma spraying. Al/SiC and Al/Gr had clear interfaces, and undesirable reactions were not found.

Lin et al (2010) investigated the 10%SiCp/Al-Mg composites by semi-solidmechanical stirring technique. The distribution of SiCp reinforcement in matrix is improved by the superior wettability between reinforcement and matrix, with increasing Mg content. The composites exhibited superior tensile strength compared with Al-Mg alloys. In addition, the mechanical properties of the composites increased with the addition of Mg content.

Hassan et al (2008) studied the dry sliding wear behaviour of some powder metallurgy (PM) Al–Mg–Cu alloys manufactured by powder metallurgy with different weight percentage of Cu. The wear study of the metal matrix composites reinforced with 5 or 10 vol. % silicon carbide particles (SiC) have been carried using pin-on-disk apparatus. From the study, they observed that both hardness and wear resistance were enhanced by the addition of Cu and/or SiC to the Al-4 wt% Mg alloy. The formations of mechanically mixed layer (MML) as a result of material transfer from counter face disk to the samples and vice versa were observed in all tested specimens.

Karamis et al (2012) made an attempt to improve the strength of Al 6061 Al metalmatrix composites by Reciprocating Extrusion (RE). The billets were extruded under a pressure of 17.5 MPa at 573 K with a 10:1 extrusion ratio. The reciprocating extrusions were carried out by using up to 15 passes. A homogeneous dispersion of SiCp and refined grain structure of the test materials were obtained by RE.

MATERIAL AND METHODS

MATERIALS AND COMPOSITE DESIGN

3.1 Aluminum Alloy 7075 as Matrix Material

Fig 3.1: **Aluminum Alloy 7075**

Aluminum alloy 7075 is a high-strength Al–Zn–Mg–Cu alloy known for its excellent mechanical properties and fatigue resistance. Its high strength-to-weight ratio, combined with good machinability, makes it suitable for precision components required in medical devices and prosthetic systems. Although aluminum alloys are not traditionally used for permanent implants, surface modification techniques such as anodization, ceramic coatings, and bioactive layers enable their application in temporary implants and biomedical structures.

3.2 Magnesium Oxide Reinforcement

Magnesium oxide (MgO) is a ceramic material characterized by high hardness, thermal stability, and chemical inertness. In biomedical contexts, magnesium-based compounds are widely studied due to their favorable interaction with biological systems. When incorporated into aluminum matrices, MgO acts as an effective reinforcement, improving hardness, wear resistance, and microstructural stability—key attributes for load-bearing and sliding medical components.

Fig 3.2: **Magnesium Oxide**

3.3 Fly Ash Reinforcement

Fig 3.3: Fly Ash

Fly ash is an industrial by-product rich in silica, alumina, and calcium oxide. Its use as a reinforcement material contributes to weight reduction, cost effectiveness, and improved wear resistance. In medical engineering, fly ash–reinforced aluminum composites are particularly attractive for non-implantable applications such as prosthetic frames, mobility aids, and medical equipment housings, where lightweight and durability are critical.

2. FABRICATION METHODOLOGY

Stir casting was selected as the primary fabrication technique due to its simplicity, scalability, and cost effectiveness. In this process, aluminum alloy 7075 is melted in a crucible furnace and mechanically stirred to create a vortex. Preheated MgO and fly ash particles are gradually introduced into the molten alloy to ensure uniform distribution. The composite slurry is then poured into preheated molds and allowed to solidify under controlled conditions.

The stir casting technique is well suited for medical component manufacturing as it allows the production of near-net-shape components, minimizes material wastage, and is compatible with conventional machining and finishing operations.

Fig 4.1: Bottom pouring stir casting

Aluminum alloy 7075 matrix material was received in the form of a 1000 g ingot. The ingot was cut into smaller pieces of about 3–5 g to minimize dwelling time and enable faster melting, as well as to obtain more accurate weight measurements. Cutting was carried out using a cut-off machine with a grade HH cutting wheel suitable for non-ferrous metals and continuous coolant flow to avoid overheating. After cutting, the ingots were washed using warm water. The required weight percentages of Al 7075, magnesium oxide (MgO), and fly ash were measured using an analytical balance.

The graphite crucible was placed inside a steel chamber fitted with a J-type thermocouple to monitor the temperature. The furnace was preheated to 100 °C, and nitrogen gas was supplied continuously at a flow rate of 3 cc/min. The aluminum alloy and reinforcement powders were placed in the graphite crucible, which was then positioned inside the stainless steel chamber. The furnace temperature was increased stepwise to 200 °C, 500 °C, and finally 850 °C over a period of approximately 4 hours to achieve controlled heating.

The experimental setup consisted of the main furnace and a stirring system with mild steel stirrer blades. The crucible and reinforcement powders (MgO and fly ash) were preheated prior to mixing. The aluminum alloy was melted completely and maintained at a temperature of 830 ± 10 °C. The stirring mechanism was lowered into the crucible, and vigorous mechanical stirring was carried out at 550 rpm for 10 minutes to ensure uniform dispersion of the reinforcement particles in the aluminum matrix.

RESULTS AND DISCUSSIONS

The composite specimens fabricated should be characterized by conducted various tests such as tensile and hardness.

5.1 Tensile Test

The tensile test is a common test performed on metals, wood, plastics, and most other materials. Tensile loads are those that tend to pull the specimen apart, putting the specimen in tension. They can be performed on any specimen of known cross-sectional area and gage length to which a uniform tensile load can be applied. Tensile tests are used to determine the mechanical behavior of materials under static, axial tensile or stretch loading.

ASTM standards for common tensile tests may be found in sections E8 (metals), D638 (plastics), D2343 (fibers), D897 (adhesives), D987 (paper), and D412 (rubber).

Ultimate Tensile Strength the maximum tensile stress that a material is capable of developing during a test.

5.1.1. TENSILE TESTING PROCESS:

Tensile testing was carried out according to the ASTM E8–2009 standard to determine the tensile properties of the material, including tensile strength. Tensile strength is defined as the maximum tensile stress a material can withstand before failure. ASTM-standard specimens were prepared and mounted in a tensile testing machine using appropriate grips. A steady and continuous tensile load was applied during the test.

Data were collected at predetermined intervals, including applied load and change in gauge length. The applied load was recorded directly from the machine, while deformation over the gauge length was measured using an extensometer attached to the specimen. Data collection continued until yielding was observed, characterized by continued deformation without an increase in load. The extensometer was then removed, and loading was continued until fracture to determine ultimate tensile strength and rupture strength.

Fig 5.1: Tensile testing machine

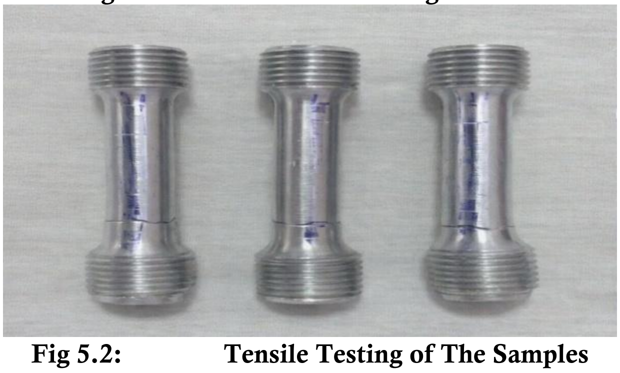

Fig 5.2: Tensile Testing of The Samples

Stress and strain values were calculated from the recorded data. Stress was obtained from the applied load and cross-sectional area, while strain was calculated as the ratio of change in length to the original gauge length. The tensile strength values for different specimen compositions are presented below.

Table 5.1 Tensile Test Values

	Sample 1	sample 2	Sample 3
Ultimate tensile strength	115Mpa	198Mpa	104Mpa

5.2. Hardness

Hardness is the resistance of a metal to penetration by a pointed tool. It is a property that enables a material to resist permanent deformation such as bending, breaking, or shape change when a load is applied. Higher hardness indicates greater resistance to deformation.

Hardness Measurement Methods

- Rockwell hardness test
- Brinell hardness test
- Vickers hardness test
- Knoop hardness test
- Shore hardness test

5.2.1 Brinell Hardness Test

Brinell hardness is determined by forcing a hard steel or carbide ball of specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation produced. The Brinell hardness number (BHN) is calculated by dividing the applied load (kg) by the surface area of the indentation (mm²). Although the result represents pressure, units are generally not stated.

- EN ISO 6506-3:2005 – Calibration of reference blocks
- EN ISO 6506-4:2005 – Table of hardness values
- ASTM International standards

The Brinell scale characterizes indentation hardness based on the penetration of an indenter into the test material.

Fig 5.3: Brinell Hardness Testing Machine

5.2.2 Test Parameters

A 5 mm diameter steel ball indenter is commonly used. Standard loads applied are 250 kg, 1500 kg, and 3000 kg. The loading time is typically 15 seconds for ferrous materials, 30 seconds for non-ferrous materials, and 120 seconds for magnesium alloys.

Fig 5.4: Samples After Testing Of Hardness

Table 5.2: Hardness Tests Values

Sample ID	OBSERVED VALUES IN BHN(5mm ball/250 kg load)		
Sample 1	83.6	85.9	82.9
Sample 2	92.9	95.1	97.3
Sample 3	63.4	65.2	64.6

5.3 IMPACT TESTING

5.3.1 IMPACT TEST

The variation of impact strength with the composite content, in samples S1, S2 and S3). in this case, the S3 sample composite exhibition better impact properties, the impact strength increases with increasing volume fraction of fibres, reaching a maximum value at 33.2%. beyond 30%, the impact strength shows a decreasing trend. The maximum impact strength of the composites 2 joules.

Fig 5.5: Impact Strength Machine

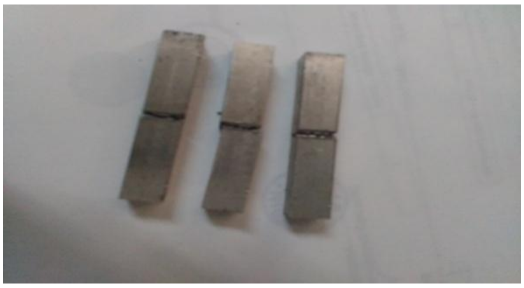

Fig 5.6: After impact testing samples

Table5.3: Impact Test Data

Samples	Impact strength(joules)
S1	2
S2	2
S3	2

CONCLUSION

The present work investigated the fabrication and mechanical characterization of aluminum alloy 7075 reinforced with magnesium oxide (MgO) and fly ash for potential medical and biomedical applications. Based on the experimental results, the following conclusions are drawn:

Tensile test results revealed that Sample 2 exhibited the highest tensile strength of 198 MPa, which is significantly higher than that of Sample 3 (117 MPa). The tensile strength of all samples ranged between 100 and 200 MPa. The improvement in tensile strength is attributed to effective interfacial bonding and load transfer between the aluminum matrix and the MgO and fly ash reinforcements. Such strength levels are desirable for non-implantable medical components such as orthopedic fixation frames, prosthetic structures, and surgical instrument parts.

Hardness values were also found to be maximum for Sample 2, with a hardness value of 97, while the hardness of all samples ranged between 60 and 99. The increased hardness is due to the strong adhesion between the aluminum matrix and the ceramic reinforcements, which is beneficial for medical applications requiring wear resistance, such as prosthetic joints, assistive devices, and medical equipment components.

Impact strength was observed to be identical for all samples, with a value of 2 J. This uniform impact behavior indicates consistent energy absorption capability across the composites, which is important for medical devices subjected to sudden or accidental loading.

Microstructural analysis revealed improved and uniform reinforcement distribution in Sample 2, confirming strong matrix–reinforcement adhesion. Such microstructural integrity enhances mechanical reliability and supports the use of this composite in biomedical structural applications.

Overall, the developed Al-7075/MgO/fly ash hybrid composite exhibits a favorable combination of strength, hardness, impact resistance, and microstructural stability, making it a promising material for lightweight, non-implantable, and temporary medical and biomedical applications.

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