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Mechanical, Thermal, and Tribological Performance of AL7075–Fe_2O_3 Metal Matrix Composites for Marine Applications

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***Abstract*—The mechanical, thermal, tribological and microstructural properties of metal matrix composites (MMCs) made of Al7075 aluminum alloy and Fe_2O_3 reinforce by varying its percentage 3 %, 6 % and 9 % by weight are investigated in this study. Various tests such as tensile, compression, hardness, impact, wear and fatigue tests were conducted, all in accordance with ASTM protocols. The Laser Flash Method and dilatometry were used for the thermal characterisation. The microstructural features were investigated SEM/EDX and XRD. ANSYS finite element analysis (FEA) was used to simulate a marine propeller shaft sleeve for an axial loading of 1000 N. The ultimate tensile strength (521-583 MPa), compressive strength (408-464 MPa), Vickers hardness (167-205 VHN) and fatigue endurance (203-258 Mpa) of Fe_2O_3 content increase monotonously, while the wear resistance increases as Fe_2O_3 content improves. On the other hand, impact toughness (26↓15 J), thermal conductivity (152–118 W/m·K) and coefficient of thermal expansion (22–14×10^{-}6 K^{-1}) also decreases. SEM shows some ductile fracture behavior at certain locations and the rest as mixed-brittle fracture behavior and EDX confirms the uniform dispersion of Fe_2O_3 in the material. FEA indicates the safety factor should be 2.74 and the maximum deformation of 1.47 mm under marine loading conditions. The 9 % Fe_2O_3 composite is concluded as the best composition material for the marine structural parts which are used for high dimensional stability, wear resistance and strength.**

***Index Terms*—AL7075; Fe_2O_3; metal matrix composite; stir casting; marine engineering; SEM; fatigue; FEA**

I. INTRODUCTION

Materials needed for marine engineering should be able to resist with the corrosive effect of sea water cyclic mechanical loading, with temperature, biofouling and cavitation erosion. Although the monolithic aluminium alloys have a low weight, the conventional carbon steels can corrode very quickly in chloride corrosive environment and have to undergo repeated expensive cycle of cathodic protection and recoating but on the other hand the conventional carbon steels are subject to frequent expensive cycles of cathodic protection and recoating, they have low sliding or erosive contact performance and are prone to pitting or stresscorrosion cracking in chloride corrosive environment.

The metal matrix composites that lie in between these extremes are based on a composite consisting of a weaker (less stiff) metal matrix and stiffer (harder) ceramic particulates to deliver greater amounts of specific strength, stiffness, wear resistance and thermal stability. The best suited of aluminium alloys is AL7075 which is known for possessing most extreme tensile strength (up to 570 MPa in T6 condition) and fatigue resistance, which is why it is considered for the propeller hubs, propellers shaft sleeves, deck fittings etc. [2] Its main drawbacks – moderate corrosion resistance, low tribological properties – can be eliminated with the use of ceramic reinforcement.

The naturally occurring iron dioxides (hematite—Fe_2O_3) are quite hard (Mohs's hardness ~ 5.5–6.5), very stable in chemical and thermal effects and even proven as a material incapable of corrosion in saline environments. This seems to be rarely characterised in comparison to SiC-based or Al_2O_3-based material systems when compared to the Fe_2O_3-reinforced AL7075 systems and integrated experimental-simulation based study of the material coupling to marine specific loads has not been reported yet [3].

This paper explores this issue by fabrication and testing of three different levels of reinforcements (0 %, 6,6 % and 11,8 % Fe_2O_3) of AL7075–Fe_2O_3 MMCs using stir casting technique, followed by a full range multi-property test as per ASTM standard, micro-structural characterisation using high resolution SEM/EDX and XRD techniques and conducting ANSYS FEA and validating the structural suitability on a representative marine propeller shaft sleeve.

II. LITERATURE REVIEW

The tabulation of literature studies shown in Table 1 are just a few of studies concerning MMCs used for marine applications as well as for structures. It is very clear that there is a gap; there has been no systematic work to explore the behavior of Fe_2O_3 reinforced - AL7075 under multi properties condition in marine environment coupled with the validated numerical simulation.

Table 1. Summary of Related Literature

Author(s) & Year	Material System	Key Findings	Limitation

Elanchezhian et al. (2018)	Ti-6Al-4V / Kevlar / Carbon Fibre	Superior impact resistance for naval hull panels	No quantitative marine corrosion data
Vijayakumar et al. (2020)	A5083/Fly ash/SiC Hybrid MMC	Improved hardness & tribology via stir casting	Limited to non-saltwater environments
Imran & Khan (2019)	AL7075 + various ceramics (SiC, Al_2O_3, TiO_2)	Systematic review: strength ↑, CTE ↓ with ceramics	No Fe_2O_3 or marine simulation
Krishnan et al. (2019)	Bronze MMC + reinforcement	Hardness & tensile strength ↑; ductility ↓	Not applicable to lightweight marine design
Rubino et al. (2020)	Polymer Fibre-Reinforced Composites	Broad marine review; good corrosion resistance	FRPs lack high-temperature stability
Hamzat et al. (2025)	Fibre-reinforced aerospace/marine composites	Failure mechanisms under combined loading	No MMC or Fe_2O_3 data
Present Study	AL7075 + Fe_2O_3 (3, 6, 9 wt%)	Full multi-property characterisation + ANSYS FEA	—

III. MATERIALS AND METHODS

3.1 Raw Materials

The matrix was commercial AL7075 (composition: Al base, 5.6–6.1 wt% Zn, 2.1–2.5 wt% Mg, 1.2–1.6 wt% Cu). The reinforcement used was analytical grade hematite (Fe_2O_3) powder with the particle size of 1–5 μm (d50 = 3 μm) and pre-dried in dry air cured 2 h at 250°C to remove the moisture absorbed on the surfaces of the powder for improving the wettability.

3.2 Stir-Casting Fabrication

The billets of AL7075 were melted with a graphite crucible under argon atmosphere at a maximum temperature of 730 ± 5°C. Average pre-heated Fe_2O_3 was added (1 wt%/min) and mechanical stirring was continued at stirring speed of 350 rpm for 10 min, which does not affect the homogeneous dispersion. The gases were argon degassed and NaCl/KCl were used as flux to remove any dissolved hydrogen and surface oxides. The melt was poured into the steel moulds which were heated in advance, and quenched under controlled cooling conditions.

Table 2. Key Stir-Casting Process Parameters

Parameter	Value / Range	Rationale
Melting temperature	730 ± 5°C	Above liquidus of AL7075
Particle pre-heat	250°C / 2 h	Moisture removal; wettability ↑
Stirrer speed	350 rpm, 10 min	Uniform dispersion
Particle addition rate	1 wt%/min	Prevent agglomeration
Mould pre-heat	200°C	Reduce thermal shock porosity

3.3 Specimen Preparation and Test Standards

CNC designs and polishing were used to create castings with ASTM specified geometries. Tensile Dog bone, compression cylinders, Charpy V notch were prepared as well as fatigue specimens (same dog bone configuration used for tensile), and pin-on-disc pins (as specified by ASTM G99). Flat sample of the dimensions (50 x 50 x 5 mm) was used for hardness (BHN/VHN) and corrosion testing.

3.4 Characterization Techniques

Methods for obtaining characterization information on the microstructure include SEM (FEI Quanta 250) and XRD (Cu-Kα radiation, 2θ = 20–80°). Density: Archimedes principle. Thermal conductivity: Laser Flash Analysis (ASTM E1461). CTE: push-rod dilatometry (ASTM E831, 25–300°C). Thermal stability: heating up to 800°C in N_2 at 10°C/min. Corrosion: potentiodynamic polarisation in 3.5 wt% NaCl; salt-spray (ASTM B117) with 5 wt% NaCl; at 35°C. Vibration – FEA Modal analysis. The four point probe method is widely used for the electrical conductivity determination.

3.5 ANSYS Finite Element Analysis

The propeller shaft sleeve model has been created in SolidWorks then imported to the ANSYS Mechanical 2023 R2 software for simulation, in this case OD = 140 mm, wall per drawing in reference "Fig. 4.2" in section 4 of the source thesis, length L = 2500 mm. The properties for material used for composite (9 % Fe_2O_3) were assigned. It was tied at one end and a remote load at the other end was 1000 N. A structured hexahedral mesh was used for these static structural, damage and safety factor analyses.

IV. RESULTS AND DISCUSSION

4.1 Mechanical Properties

Table 3. Tensile and Compression Testing Results (Mean ± SD)

Composition	UTS (MPa)	YS (MPa)	Elongation (%)	Compressive Strength (MPa)

Pure AL7075	521 ± 10	353 ± 5	10.0 ± 0.5	408 ± 5
3% Fe_2O_3	541 ± 12	362 ± 8	7.0 ± 0.4	419 ± 6
6% Fe_2O_3	556 ± 14	381 ± 10	6.0 ± 0.3	438 ± 8
9% Fe_2O_3	583 ± 8	403 ± 6	4.0 ± 0.2	464 ± 7

The value of "UTS" of the composite metal has increased by 11.9 % from the base alloy to the 9 % alloy (from 521 to 583 MPa). This increase in the "UTS" is attributed to an effect by the presence of Fe_2O_3 particles in the soft matrix (IV) of U8551, which include dislocation pinning, Hall-Petch strengthening and load transfer. The matching decrease in elongation at break (from 10 → 4 %) is typical of the reduction in dislocation mobility that occurs in particulate MMCs [4] because of the stresses generated by the particles. The compressive strength increased monotonously (408 → 464 MPa; ≦13.7 %), which is important for the properties of the stiffeners (hulls) and assemblies (brackets) of aluminium alloy.

Table 4. Hardness and Impact Testing Results

Composition	BHN	VHN	Impact Toughness (J)
Pure AL7075	148 ± 2	167 ± 3	26 ± 2
3% Fe_2O_3	162 ± 3	178 ± 4	21 ± 1
6% Fe_2O_3	178 ± 4	189 ± 5	19 ± 2
9% Fe_2O_3	193 ± 5	205 ± 6	15 ± 1

VHN increases by 22.8 % (167 → 205 VHN) as Fe_2O_3 increases, which can be explained as dispersion strengthening - lack of local plastic indentation by hard ceramic particles increases the VHN. This is the INVERSE one observed for the impact toughness change (decrease; 26 → 15 J; −42.3 %) and is corroborated by the brittle characteristics caused by the presence of clusters of ceramics as well as by interfacial debonding sites seen in SEM images (Section 4.4). The composition range from 3–6 % might be better suited for marine applications that are related to wave impact.

4.2 Wear and Fatigue Performance

Table 5. Wear (Pin-on-Disc) and Fatigue Endurance Results

Composition	Wear Rate (mm^3/Nm)	COF	Endurance Limit (MPa)
Pure AL7075	0.55 ± 0.02	0.45 ± 0.05	203 ± 6
3% Fe_2O_3	0.50 ± 0.01	0.42 ± 0.04	222 ± 5

6% Fe_2O_3	0.45 ± 0.02	0.40 ± 0.03	238 ± 6
9% Fe_2O_3	0.40 ± 0.03	0.38 ± 0.02	258 ± 7

The mechanical results of the composite material revealed a fairly uniform and dispersed distribution of the Fe_2O_3 particles that effectively improved the tribological and fatigue properties of the composite material produced. The occurring wear rate was found to be reduced from 0.55mm3/Nm to 0.40mm3/Nm and COF, from 0.45 to 0.38. This improvement is the result of the existence of hard reinforcement particles of Fe_2O_3, which plays a load bearing role as asperities, decreasing the metal-to-metal contact of aluminium matrix with counterface surface area. The particles also trigger the oxidation wear mechanism rather than adhesive wear with a consequent increase in the wear resistance. Besides tribological improvement, to low down wear rate and friction, fatigue endurance limit of the product was further enhanced by 27% from 203 MPa to 258 MPa. The grain boundaries with reinforced particles offer higher resistance to crack propagation (lateral) under cyclic loading condition, by delaying crack initiation, and thereby strengthen the crack propagation resistance of these grain boundaries. The increased mechanical characteristics of the composite make it particularly applicable to marine uses like ships' propeller shafts and propeller bearing assemblies, which are subjected to repetitive stresses and corrosive ocean conditions at all times.

4.3 Thermal Properties

Table 6. Thermal Conductivity and CTE Results

Composition	Thermal Conductivity (W/m·K)	CTE ($\times 10^{-6}$ K^{-1})	Thermal Stability (°C)
Pure AL7075	152 ± 5	22 ± 1	450
3% Fe_2O_3	143 ± 5	19 ± 1	>550
6% Fe_2O_3	131 ± 5	18 ± 1	>550
9% Fe_2O_3	118 ± 5	14 ± 1	>550

The decrease is 22.4 % (152 → 118 W/m·K) due to the following reasons: Fe_2O_3 (k ≈ 12 W/m·K) has a much lower thermal conductivity than AL7075 (k ≈ 160 W/m·K), and particle-matrix interfaces scatter phonons. The conductivity's advantage is that there is less to cause heat insulation in engine compartments but the disadvantage is that the high duty-cycling parts require design of heat management thereof. The coefficient of CTE is (22 → 14 × 10-6 K-1), which helps to avoid thermal distortion of precision marine parts when subjected to cyclic heating. The reinforcing of Fe_2O_3 on the degradation of AL7075 degradation during TGA/DSC further confirms that the ceramic particle acts as an oxidation barrier and the onset of significant mass-loss degradation is raised from 450°C (pure AL7075) to more than 550°C in AL7075 reinforced by Fe_2O_3.

4.4 Microstructural Analysis (SEM/EDX/XRD)

Table 7. SEM Fracture Surface Analysis Summary

Fe_2O_3 wt%	Fracture Mode	Key SEM Features	Interpretation
0%	Fully ductile	Deep microvoids, ductile tearing ligaments	Plastic deformation dominant; low wear resistance
3%	Ductile + particle pull-out	Dispersed Fe_2O_3 particles, coarse dimples	Onset of particle strengthening; good toughness retained
6%	Mixed ductile-brittle	Reinforcement clusters, propagating cracks between clusters	Transition region; highest strength-toughness trade-off
9%	Predominantly brittle	Interfacial cracks, cleavage facets, jagged fracture	High stiffness; reduced ductility; best wear performance

The fracture mode changes from completely ductile (0 % Fe_2O_3) to the completely brittle (9 % Fe_2O_3) in comparison with a decrease in impact toughness. The Fe and O elemental mapping images created with EDX confirm that the Fe and O are better distributed in a ll reinforcement levels, further supporting the effectiveness of this protocol, stir-casting. No extra peaks of undesired intermetallic phases (as $Al_2Fe_2O_6$, FeAl or similar) are seen, while the XRD peaks of Al (FCC) and α-Fe_2O_3 (rhombohedral) are present, showing the thermodynamic stability at the casting temperature and the absence of deleterious interfacial reactions.

Table 8. EDX Elemental Distribution at Varying Fe_2O_3 Levels (wt%)

Composition	Al	Fe	O	Zn	Mg	Cu
0% Fe_2O_3	95.0	0.0	0.5	1.0	2.5	0.0
4% Fe_2O_3	91.0	3.0	1.5	1.0	2.0	0.5
6% Fe_2O_3	87.0	5.5	2.5	1.5	2.0	1.0
9% Fe_2O_3	83.0	7.5	3.5	1.5	2.5	1.0

4.5 ANSYS FEA — Marine Propeller Shaft Sleeve

Table 9. ANSYS Static Structural FEA Results (9 % Fe_2O_3 Composite)

FEA Parameter	Value	Remark
Applied axial load	1000 N	Simulated marine assembly load

Boundary condition	Fixed support (one end)	Representative of shaft coupling
Max total deformation	1.47 mm	At free (loaded) end
Min total deformation	≈0 mm	At fixed support — BC validated
Max damage index	2.44×10^7	Central shaft region (load-transfer zone)
Max safety factor	2.74	Majority of shaft length
Min safety factor	0.042	Stress concentration at collar transitions

The maximum of 1.47 mm deformation with 1000 N at the loading end of the shaft is found to be acceptable, thus indicating the stiffness of the shaft to be good. Most of the sleeve length had a high level of structural reserve with an average safety factor of 2.74. The local minimisation of safety factor of 0.042 at the taper transitions, or the collar regions, is an expected geometric stress concentrator that should be given some careful consideration when detailed design decisions are made; either by optimising the fillets in this region or by locally reinforcing the section. The FEA deformation gradient (blue to red from fixed to free end), is consistent with cantilever beam classical mechanics, thus confirming the model. It is concluded that the composite made from 9 % Fe_2O_3 has adequate load-bearing capacity for use in marine propulsion shaft.

V. COMPARATIVE PERFORMANCE AND OPTIMAL COMPOSITION SELECTION

Table 10. Multi-Property Radar Summary: Property Change Relative to Pure AL7075 (%)

Property	Pure AL7075	3% Fe_2O_3	6% Fe_2O_3	9% Fe_2O_3
UTS (Δ%)	Ref.	+3.8%	+6.7%	+11.9%
Compressive Strength (Δ%)	Ref.	+2.7%	+7.4%	+13.7%
Vickers Hardness (Δ%)	Ref.	+6.6%	+13.2%	+22.8%
Fatigue Endurance (Δ%)	Ref.	+9.4%	+17.2%	+27.1%
Wear Rate (Δ%)	Ref.	−9.1%	−18.2%	−27.3%
Impact Toughness (Δ%)	Ref.	−19.2%	−26.9%	−42.3%

Thermal Conductivity (Δ%)	Ref.	−5.9%	−13.8%	−22.4%
CTE (Δ%)	Ref.	−13.6%	−18.2%	−36.4%

All levels of reinforcement showed a result of the holistic property shift to be found in Table 10. 9 % Fe_2O_3 composite is used most in propeller shaft sleeves, deck brackets, pump housing/offshore structural reinforcement where using this type of composite has the advantage of being a combination of high strength and hardness, high fatigue strength, good wear resistance and a reduced CTE range to enhanced dimensional stability. In sensitive locations like that of a hull in the vicinity of the collision area, window has 3-6% Fe_2O_3, which provides useful strength and wear performance, without sacrificing a reasonable toughness.

VI. DISCUSSION

6.1 Strengthening Mechanisms

These mechanical enhancements are provided by (a) load transfer, which tends to put higher stresses on inter particles which are harder than the matrix; (b) dislocation pinning – geometrically necessary dislocations at the particle/matrix interface during processing due to thermal mismatch between particles and matrix; (c) grain refinement – the matrix alloy is heterogeneously nucleated; and (d) Orowan strengthening – stress factors arising due to the sub-micron spacing between the particles. The total effect comes from the combined effects which have led to an increase in the UTS by 11.9 % between 0 and 9 % Fe_2O_3 [7]

6.2 Tribological Behaviour

Wear-rate reduction is in accordance with Archard's law for which W is inversely proportional to the hardness, H, of the composite so that an increase in H will help to suppress the volumetric loss, W. The lower COF noticed at 9 % Fe_2O_3 is due to a solid lubricant in the form of a tribofilm on the surfaces formed due to the in-situ presence of Fe_2O_3. The in-situ presence of Fe_2O_3 has changed the dominant mechanism, from adhesion to mild oxidation wearing mechanism. This is verified by SEM of worn surfaces: the AL7075 composites reveal less adhesive grooves than unreinforced AL7075 but more ploughing marks or crater formation with more dense oxide layer in the composites than that of unreinforced AL7075 with 9 % composite [8].

6.3 Corrosion Performance

The improvement of corrosion resistance due to Fe_2O_3 particles is due to two mechanisms: (i) the particles decrease the effective surface area of Al which is accessible to chloride ions to decrease the surface area, and (ii) formation of a passivation film (Al_2O_3/Fe_2O_3 composite oxide) to increase charge-transfer resistance in EIS measurement. The results of potentiodynamic polarisation showed reduced corrosion dissolution rates (lower Ico) for both reinforced composites when compared with the same solution of 3.5 wt% NaCl solution as would be used in seawater [9].

6.4 Marine Application Suitability Map

Table 11. Recommended Composition by Marine Application

Marine Component	Primary Requirement	Recommended Composition	Justification
Propeller shaft sleeve	Wear + fatigue	9% Fe_2O_3	Max hardness + endurance limit
Hull panel bracket	Strength + impact	3–6% Fe_2O_3	Balance of toughness and strength
Engine mount	Thermal stability + stiffness	6–9% Fe_2O_3	Low CTE; high compressive strength
Pump housing	Corrosion + wear	6% Fe_2O_3	Optimal barrier + tribological properties
Offshore deck fitting	Lightweight + strength	9% Fe_2O_3	Highest specific strength

VII. CONCLUSION

In this study, first ever integrated experimentally to simulated characterization of AL7075-Fe_2O_3 MMCs for marine engineering is presented. The following main conclusions can be drawn:

1. This follows a general trend for mechanical strength and hardness to increase with the increase in Fe_2O_3 content. The 9 % composite achieves UTS = 583 MPa, VHN = 205, compressive strength = 464 MPa, and fatigue endurance = 258 MPa—improvements of 11.9 %, 22.8 %, 13.7 %, and 27.1 % over pure AL7075, respectively.
2. For the tribological performance 2). The composite made with 9 % showed a significant improvement, reducing the COF by 15.6 % and the wear rate by 27.3 % due to the process of particle-hardening and the formation of in-situ oxide tribofilm.
3. In the marine component applications such as thermal fluctuations, the performance such as thermal insulation and dimensional stability are improved by 3. Thermal conductivity, CTE decreased with reinforcement (22.4 % and 36.4 % reduction at 9 %). 4. Thermal conductivity results showed that reinforcement ratio was inversely proportional, as expected. The thermal degradation onset is increased from 450°C to higher than 550°C.
4. SEM/EDX reveals that there are no intermetallic variations and no Fe_2O_3 grains on the matrix-particle interface. The fracture mode transition from ductile (0 %) to mixed/brittle (9 %), correlates with the trends in impact toughness.
5. Validation of the adequate structural performance (safety factor: 2.74, maximum deformation: 1.47 mm under 1000 N) by 5-dimensional ANSYS FEA in on a marine propeller shaft sleeve, the requirement for future design optimization of geometric sizes of the transitions/tapers is identified.

6. The 9% Fe_2O_3 composition is recommended for parts that need the highest strength, wear and dimensional stability, such as propeller-shaft sleeves, fittings for offshore decks and so on. It is recommended to use between 3–6 % for the applications requiring higher impact toughness (hull brackets, structural reinforcement).

The AL7075–Fe_2O_3 composite system is potential to be used as alternative material to the conventional marine aluminium alloy and is able to overcome the one of the existing gaps in the research on Fe_2O_3-reinforced MMC. Further studies are recommended including: Further extended salt spray fatigue tests; Hybrid nano-micro reinforcement; Industry scale up manufacturing trials.

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