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Influence of rare earth elements on aluminium metal matrix composites: A review

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Abstract. In view of the unique characteristics and diverse applications of composite materials; researchers across the world are focusing on the development of a variety of Metal-Matrix Composites (MMCs), particularly in the domain of Aluminium-based MMCs (AMMCs). The present research paper focuses on the study of the influence of rare earth elements (REEs) and rare earth oxides (REOs) on the Tensile Strength, Hardness, and Microstructure of AMMCs. Apart from the fraction, shape, and size of the reinforced particle, the fabrication methods also play a crucial role in the microstructure and performance of the composite. Stir casting and Powder metallurgy are the methods that are commonly used over the globe for processing of AMMCs due to their availability, simplicity, and low-cost production. During stir casting, the nature and characteristics of AMMCs largely depend upon geometrical parameters like impeller design and process parameters such as stirring speed, stirring time, and stirring temperature. However, in Powder Metallurgy, process parameters such as blending time, sintering temperature, and compact pressure have a significant effect on the performance of AMMCs. From previous studies, it has been observed that the tensile strength of AMMCs having REEs and REOs as reinforcement varies in the range of 26 MPa to 562 MPa, and the elongation during tensile tests enhanced up to 33.33 %. It is also observed that the hardness value of AMMCs with REEs and REOs particulates occurred in the range of 46 VHN to 260 VHN. From the survey of microscopic images, it is concluded that grain refinement and the formation of the useful compounds between aluminum matrix and rare earth particles helped in the enhancement of the mechanical properties of the AMMCs. It is also observed that the excessive use of reinforcement particles results in agglomeration that leads to a reduction in mechanical properties.

Keywords: aluminium metal matrix composites, rare earth elements, rare earth oxide, mechanical properties, microstructural properties

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Introduction

In ancient times, from 200 BC to 1200 AD, the clay was reinforced with grass fibers in the Nile valley, straw-reinforced bricks in the Great Wall of China, bonding super and lower quality wood in Egypt, and lamination of horns, wood, and silk on Bows with adhesives were the significant landmarks of composite materials. At the turn of the twentieth century, polymer composites such as glass-fiber reinforced composites and phenolic-resin-asbestos captured the attention of many researchers. But due to higher thermal sensitivity and lower strength, there was a restriction of application in the aerospace and defence sector. So, in the 1970s, the space race between the world's superpowers gave birth to MMCs, which were lighter than base metal or alloy and more robust than polymer composites [1]. The demand for innovative products using superior materials and process technologies is increasing in the age of globalization. Engineers are currently seeking stronger, lighter, and less costly materials. Metallic matrix composites (MMCs) offer the qualities required for various engineering applications.

MMCs outperform traditional composites mechanically, thermally, and electrically. They are also more resistant to extreme temperatures, moisture, radiation, and outgassing in a vacuum. The metal matrix composites consist of at least two different materials, one of which must be metal, as illustrated in Fig. 1. The second component can be another metal, an organic or inorganic compound, or a ceramic [2–5]. Composite materials are more potent and lighter than conventional materials like steel. Rather than using steel, the auto industry is increasingly turning to composite materials to light automobile parts load [6]. MMCs are distinguished by their superior specific strength, low coefficient of thermal expansion, high thermal resistance, exceptional wear resistance, superior specific stiffness, and exceptional corrosion resistance [3-7]. Matrix materials in MMCs often consist of light metals like Al, Mg, and Ti. The production of MMCs is facilitated by the wide availability of matrixed materials, with aluminium and its alloys being particularly popular. Aluminium's many positive qualities make it a popular metal choice, including its light-weight, low cost, economic viability, ease of processing with a wide range of methods, high strength-to-weight ratio, and resistance to corrosion [8]. The AMCs are replacing cast iron components in automotive industries due to enhancement in hardness with a slight compromise in ductility by doping ceramic particles in the base metal matrix [9].

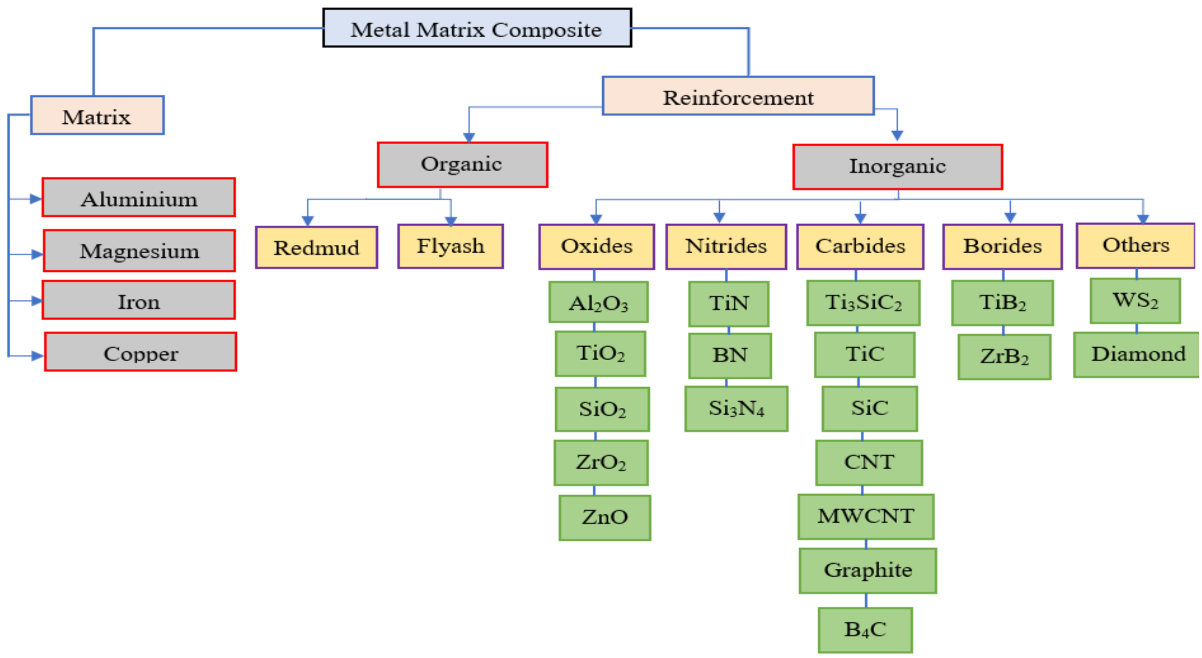


Fig. 1. Classification of Metal Matrix Composites

The current investigation centres on particle-reinforced composites (a reinforcement with discrete form), specifically rare earth elements/oxides (REEs/REOs), because of their availability, low cost, ease of dispersion in the matrix, and relatively uniform distribution. The composite's purposes and uses inform the selection of reinforcement materials. Using lightweight metals as reinforcement paves the way for novel applications where reduced weight is a priority [10–12]. Common reinforcements used in aluminium matrices to improve mechanical and tribological properties include Al_2O_3 [13], ZrO_2 [14], SiO_2/TiO_2 [15], Si_3N_4 [16], TiC [17], SiC [18], B_4C [19], TiB [20], CNT [21] and diamond [22]. But in recent years, researchers have been keen on hybrid metal matrix composites. The hybrid AMCs can be prepared with combinations of two or more ceramic particulates, synthetic and industrial waste, agriculture waste, and synthetic powder ceramic [23]. Because of their superior performance to single-reinforced composites, hybrid AMCs have seen consistent growth in demand from the aerospace and automotive sectors [24].

Similarly, researchers are beginning to pay more attention to the use of rare earth elements and their oxides as an additive/reinforcement in the composites due to their appealing properties, such as high strength at room temperature, excellent magnetic properties, high thermal conductivity, high thermal stability and high mechanical properties [25]. There are a total of 17 rare earth elements and they include the lanthanides (15), ranging in atomic number from 57 (lanthanum) to 71 (lutetium), as well as yttrium (39) and scandium (21). The REEs are widely used in chemical, metal and alloy, medical science, and oil refining industries. Nowadays, the use of REEs is expanding in electronic pieces of equipment, permanent magnets, and the polishing of glass[26–31].

Common materials for AMMCs with REEs/REOs

The most commonly used combinations of materials for AMMCs with REEs/REOs are shown in Table 1.

Table 1. List of matrix and reinforcement material combinations

Matrix Material	Reinforcement
2510 Al alloy	Yb
Al6063	Al_2O_3, Y_2O_3, Al_2O_3/ Y_2O_3, SiC + Rare Earths mixture [CeO_2 (cerium oxide) + La_2O_3(lanthanum oxide)]
AA6082	Y_2O_3, Gr + Y_2O_3
AA7075	Micron-sized yttria, Nano-sized yttria
Al6061	[Al_2O_3 (aluminium oxide) + SiC (silicon carbide)] + CeO_2
AA20240	ZnO, Y_2O_3
AA7017	Y_2O_3

Fabrication procedures

Various techniques have been described in the different works of literature for the fabrication of MMCs, but are mainly categorised into liquid-state and solid-state techniques. However, the two most used methods are described below.

Stir casting. The traditional method of liquid casting, which entails agitating, was the most appealing and widely used of the many processing methods available. Reinforcements, whether added to pure or hybrid composites, can improve the materials' mechanical properties; however, the case depends heavily on the precision with which the materials are fabricated [32]. The quality of the final composite is profoundly impacted by operational parameters like stirring speed, stirring time, melting temperature, and impeller size. The crucial parameters for better functionality of the manufactured composite are the reinforcement weight/volume percentage, shape, and size. At first, the metal is heated in a graphite crucible using a high-frequency induction heater until it reaches a molten or semi-solid state (Stir Rheocasting) [33].

Afterwards, the reinforcements such as metals, organic compounds, ceramic, and REE are incorporated into the molten metal matrix, mainly after preheating, to avoid the decomposition of reinforcement particulates. Titanium carbide, silicon carbide, or graphite stirrers are used to ensure that the reinforcement is evenly distributed throughout the matrix and to prevent the reinforcement from clumping together. In ultrasonic-assisted stir casting, an ultrasonic probe is used in place of a stirrer to prevent reinforcement particles from accumulating [34]. It is standard procedure to include wetting agents of 1-2 wt. %, such as magnesium, calcium, silicon, titanium, zinc, and zirconium, to increase the wettability of reinforcements in the matrix [35]. Degassers like tetrachloroethane, sodium hexachloroaluminate, and hexachloroethane are used to get rid of the hydrogen, nitrogen, and carbon dioxide in the aluminium melt [34,36–40]. The procedure is carried out in an inert gas atmosphere (Argon) to avoid melt oxidation. After the melt has been poured into the die and allowed to solidify, the product is ejected from the die and put through additional quality assurance procedures. The squeeze casting process occurs when pressure is applied during the solidification phase. A schematic arrangement of basic stir casting has been shown in Fig. 2.

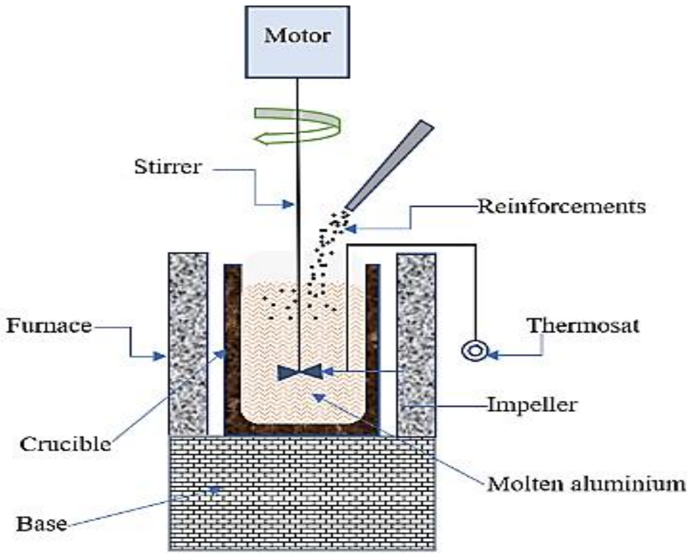


Fig. 2. Schematic diagram of the stir casting process

Powder metallurgy. Mixing, compacting and sintering are the three main stages of the powder metallurgy process shown in Fig. 3. In the mixing stage, the reinforcement materials (discrete phases) and matrix material (continuous phase) are mixed properly using suitable process control agents like toluene (to avoid oxidation) and zinc stearate (lubricant) [41].

The compacting of the mixed material with enough pressure to form the green compact with the desired porosity is prepared in the compacting stage. And then, sintering, wherein the green compacts are heated and held at a high temperature below the melting point of the metal matrix for long enough for a diffusion bond to form. The reinforcement material and PM process parameters (compaction pressure, holding temperature, and holding time) contribute to the final product's characteristics [42]. The physical and mechanical properties of aluminium-based composites are most sensitive to compaction pressure, one of the three parameters of the powder metallurgy process. The sintering temperature and time also affect the mechanical properties of aluminium-based composites. There are several ways to sinter the green compact in PM's sintering stage, including spark or plasma sintering, conventional microwave sintering, hybrid microwave sintering, and gas sintering. Powder metallurgy produces high-quality aluminium-based materials best when compacted at pressures of 600 to 700 MPa, sintered at temperatures of 520 to 600 °C, and given a sintering time of 3 to 4 hours. Compared to other methods of making MMC, powder metallurgy has several benefits, such as lower processing temperatures, less energy use, and better material utilisation [43].

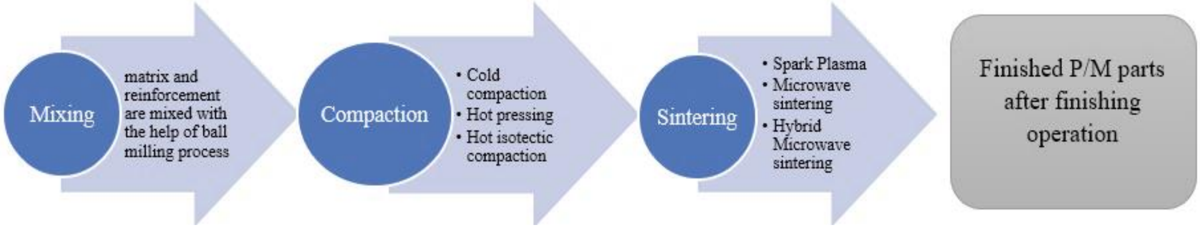


Fig. 3. Processing diagram of Powder Metallurgy

Effect of REEs and REOs on mechanical properties of AMMCs

Mechanical testing is an essential part of estimating the material's mechanical properties. To check whether the given material can meet the desired applications, some mechanical characteristics have to be identified for composites, such as tensile strength and hardness. The Universal Testing Machine (UTM) is commonly used to test the material's tensile strength. The hardness tests such as Vicker hardness and Brinell hardness test are used [44].

Effect of REEs and REOs on tensile strength of AMMCs. Manufacturing components that can withstand tension forces relies heavily on the tensile characteristics of materials. The results of tensile tests can predict how long individual parts will last and lead to the economical production of the parts.

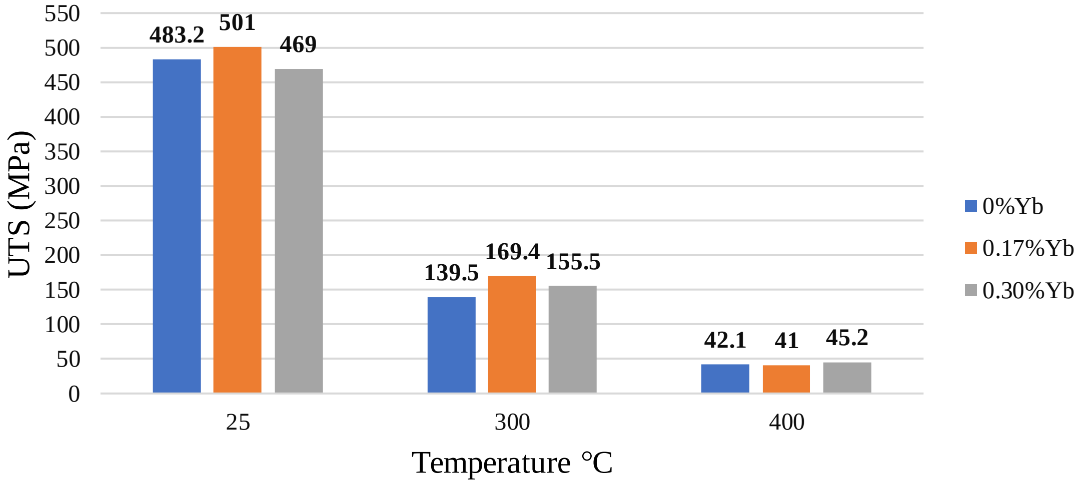


Fig. 4. Different temperatures cause a different amount of change in UTS for 2510A aluminium alloy with varying %Yb (based on data of [45])

Zhang Xin-ming et al. performed a tensile test of the plate of 2519 aluminium alloy doped with rare earth element ytterbium (Yb) (0 %, 0.17 %, and 0.30 % mass fraction) at different temperatures of 25 °C, 300 °C, and 400 °C. Tensile strength was higher for the composite with 0.17 % Yb at both room temperature and 300 ˚C, though elongation was slightly lower. The tensile strength was improved by adding 0.17 % Yb, from 483.2 MPa to 501.0 MPa at 25 °C and from 139.5 MPa to 169.4 MPa at 300 °C as shown in Fig. 4. But the sample underperformed at 400 °C. And the maximum percentage of elongation (65 %) was observed for Yb-free alloy at 400 °C, as illustrated in Fig. 5 [45].

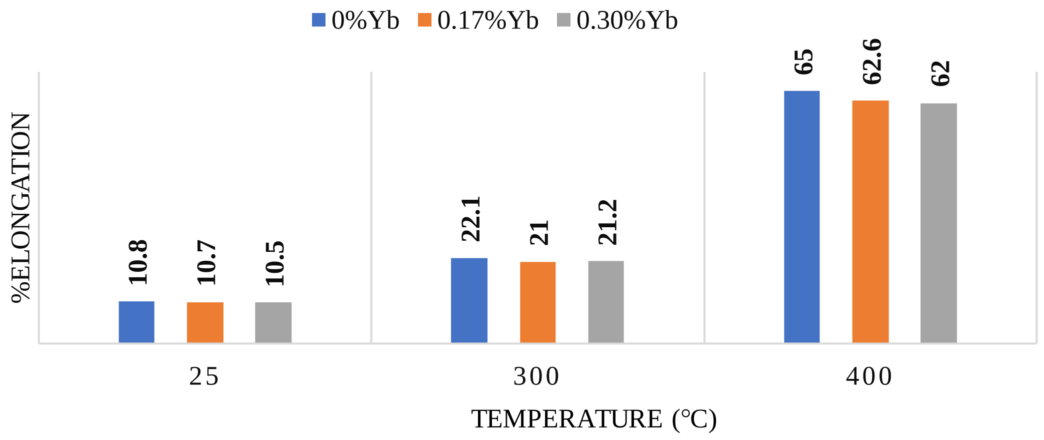


Fig. 5. Different temperatures cause a different amount of change in %elongation for 2510A aluminium alloy with varying %Yb (based on data of [45])

The impact of Cerium (Ce) on Al-Cu-Mg-Ag alloy with varying concentrations of Ce (0 wt.%, 0.2 wt.%, and 0.45 wt.%) was investigated by D.H. Xiao et al. The impact of temperature on the material's tensile properties was investigated through experiments conducted at 250, 200, 300, and 350 °C. In all temperatures up to 350 degrees Celsius, the tensile strength increased from 0 to 0.45 wt.% Ce. At room temperature, tensile strength increased from 516 to 562 MPa, yield strength increased from 482 and 528 MPa, and % elongation decreased from 9.5 to 7.3 % as Ce content changed from 0 to 0.45 %. This improved efficiency was also observed at different temperatures [46]. Similar results were observed by Wei Tian et al. for the Al-Cu-Mn-Mg-Fe alloy, using 0.254 wt.% Ce to study its impact on mechanical properties. The tensile strength was 326 MPa, which rose 15.19 % and the yield strength was 256 MPa, which rose 6.667 %. The elongation has also increased from 3.1 to 4.8 % [47].

Ultimate tensile strength increased with increasing amounts of Er (erbium) in a study by Xiaowu Hu et al. The addition of 0.6 wt.% of Er boosted the sample's UTS to a maximum of 269.35 MPa, a 31.76 % improvement over the UTS of the base alloy [49]. Furthermore, Chen Zhongwei et al. looked at how adding 1wt%Lanthanum (La) and 1.01wt%Samarium (Sm) to Al-Cu-Mn alloy altered its mechanical properties. The formation of the new phase Al_6Cu_6La in the La-containing composite increased the tensile strength from 310 to 405.6 MPa, as shown in Fig. 6(a). There was an improvement over the Sm-containing composite, which only achieved 375.9 MPa [48].

In another study, Oxide Dispersion Strengthened (ODS) alloys were manufactured through stir casting using commercial aluminium and yttrium oxide with various mass percentages of 1, 2, and 3 %, and their mechanical properties were examined by Gwang-Ho Kim et al. The tensile specimen was made using the ASTM-E8M standard. Al-2mass%Y_2O_3 sample reported a maximum UTS value up to 80 MPa, i.e., 1.55 times the base alloy. The UTS value for Al-3mass%Y_2O_3 was 0.6 times lower than pure Al due to oxide particle aggregation [50]. Similarly, Zhi-Qiang Yu et al. utilised the squeeze casting method to prepare modified (yttria-coated alumina) and unmodified (alumina) composites with an Al-Mg-Si matrix. The modified composites had a maximum tensile strength of 527 MPa, yield strength of 428 MPa, and elongation of 0.5 %, while the non-modified composites had maximum values of 406 MPa, 308 MPa, and 0.3 %. A stronger interfacial bond was formed with the matrix in the modified composite, resulting in enhanced characteristics [51]. Regarding tensile examination of nanocomposites, Hafeez Ahamed et al. compared the base alloy, nanocomposite, and a hybrid nanocomposite of aluminium. The material has been put through tensile tests per the ASTM-E8/E8M-09 standard. Increased UTS were observed at 89 % for Al6063/1.5vol%Al_2O_3, 97 % for Al6063/1.5vol%Y_2O_3, and 106 % for Al6063/0.75vol%Al_2O_3/0.75vol%Y_2O_3, respectively, when compared to the base alloy [52].

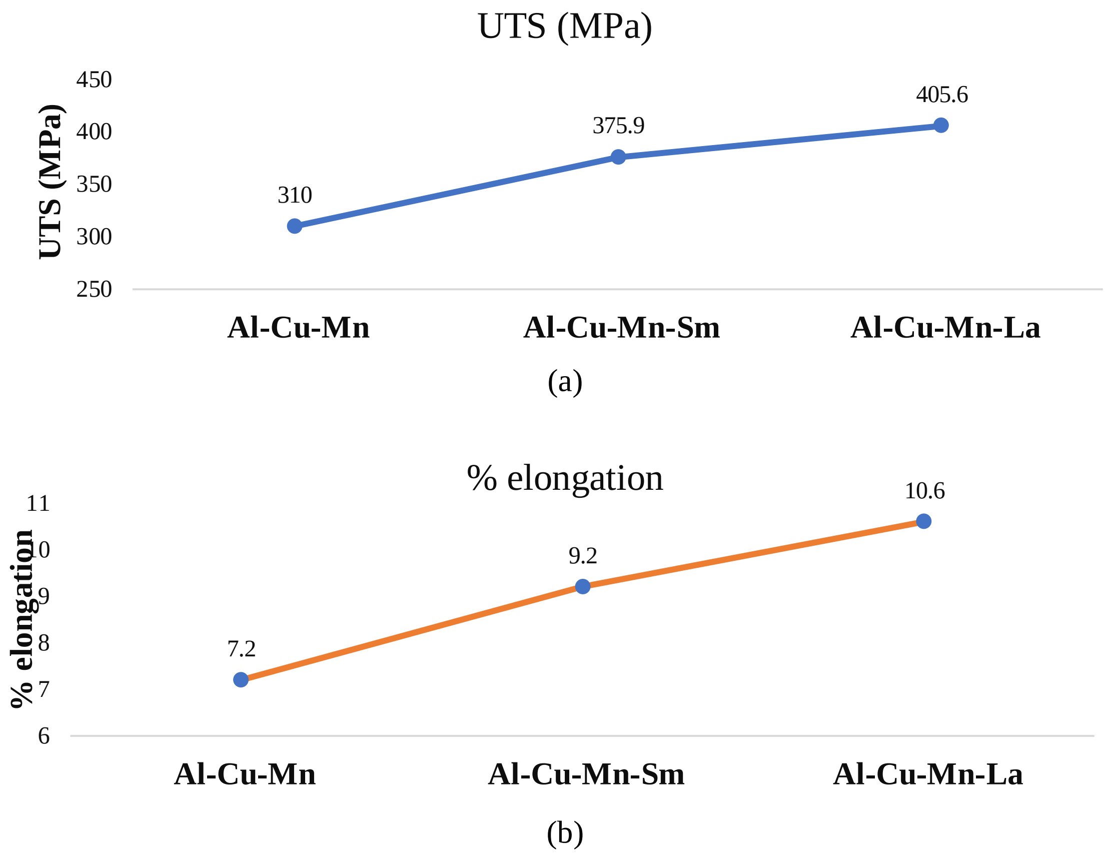
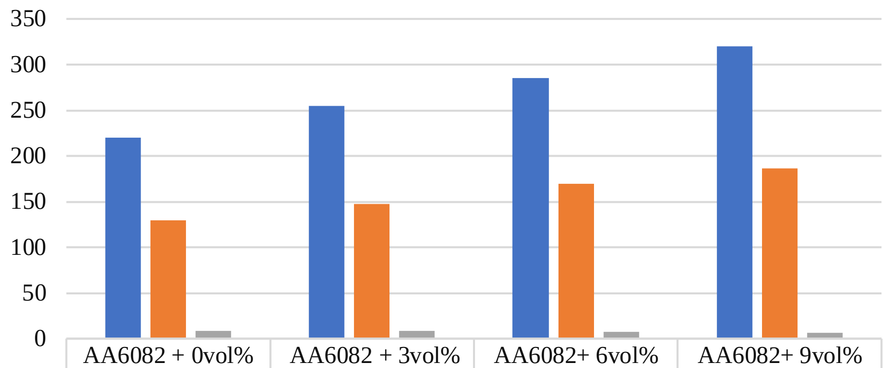


Fig. 6. Effect of La and Sm additions on (a) UTS and (b) %elongation of Al-Cu-Mn (based on data of [48])

Furthermore, the effect of Y_2O_3 at concentrations of 3, 6, and 9 vol.% on AA6082 aluminium alloy was explored by J. Ramesh Kumar et al. In accordance with ASTME8M-04, the samples were prepared using a method known as friction stir processing (FSP). As can be seen in Fig. 7, the 9 vol.% Y_2O_3 specimen exhibits a considerable increase in UTS (45.45 %), YS (43.17 %), and %elongation (33.33 %) [53]. Along a similar line, T. Satish Kumar et al., using FSP, developed a hybrid composite material constituted of AA6082 and graphite (4 vol.%) doped with Y_2O_3 at different compositions of 2, 4, and 6 %. The 6Y_2O_3 + 4Gr composite had a UTS of 300 MPa and a YS of 120 MPa [54].



	AA6082 + 0vol% Y2O3	AA6082 + 3vol% Y2O3	AA6082+ 6vol% Y2O3	AA6082+ 9vol% Y2O3
UTS (MPa)	220	255	285	320
YS (MPa)	130	147	170	186
%elongation	9	8	7	6

UTS (MPa) YS (MPa) %elongation

Fig. 7. Variation in UTS, YS and %elongation w.r.t Y_2O_3 vol% in AA6082 (based on data of [53])

To better understand the role that shape and size of reinforcement play, Tilak C. Joshi et al. compared the impact of micron-sized and nano-sized reinforcement particles of yttria on the mechanical behaviour of AA7075. Micron-sized (4 μm) and nano-sized (10 nm) yttria (0.1, 0.5, 1, and 3 vol.%) were incorporated into the aluminium alloy AA7075 using the powder metallurgy technique, which was then followed by a forging process. With 0.5 vol.% nano-yttria, the maximum tensile strength was 554 MPa, while with 5 vol.% micron-yttria, it was 247 MPa. Grain refinement due to better dispersion of nano-sized yttria led to the enhancement in mechanical characteristics of the composite [55]. In another study, V.K. Sharma et al. investigated the composite having aluminium alloy (Al-6063) as matrix and SiC and RE mixture of cerium oxide and lanthanum oxide i.e., (CeO_2 + La_2O_3) as reinforced with weightage of 3, 6, 9 wt.% and 1, 2, 3 wt.% respectively. Al-6063 alloy has been measured to have a tensile strength of 22 MPa. Incorporating RE at different concentrations significantly enhanced ultimate tensile strength (UTS) and elongation. The composites with 3wt% SiC showed an increase in ultimate tensile strength from 28 to 70 MPa and elongation from 0.24 to 0.62 % upon adding 1 % cerium and lanthanum combination. As shown in Fig. 8, the ultimate tensile strength of composites comprised of 6wt% and 9wt% SiC increased from 51 to 91 MPa and from 60 to 78 MPa, respectively, when the amount of RE was increased from 2 to 3 wt.% [56].

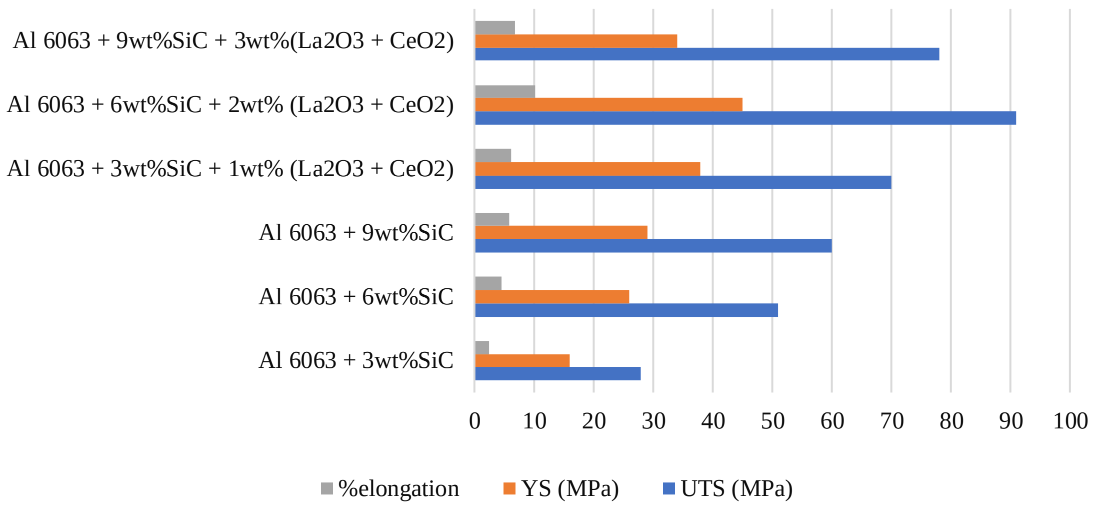


Fig. 8. Effect of RE mixture (CeO_2 + La_2O_3) on Al6063 composite (based on data of [56])

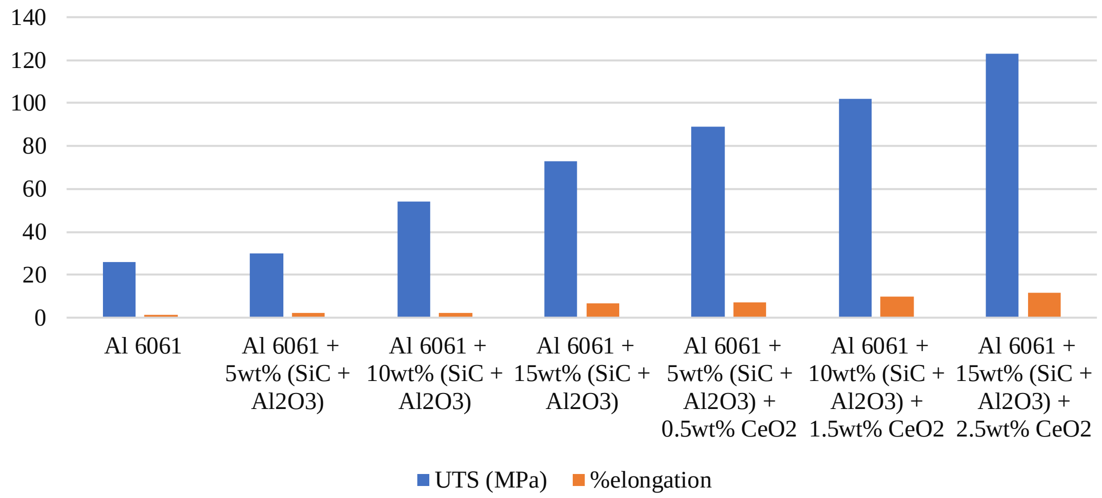


Fig. 9. Tensile strength of Al6061 as affected by (Al_2O_3 + SiC) mixture and CeO_2 (based on data of [57])

In a follow-up study, Vipin Kumar Sharma et al. examined how adding the rare earth metal cerium oxide affected a hybrid composite's mechanical and metallurgical properties. Stir casting was utilised to process the hybrid composites Al6061/(Al_2O_3 + SiC) and Al6061/(Al_2O_3 + SiC)/CeO_2. CeO_2 weight concentrations were 0.5, 1.5, and 2.5 %, while (Al_2O_3 + SiC) mixtures ranged from 5 to 15% by weight. From the base alloy's 26 MPa, the UTS increased to 30 MPa, 54 MPa, and 73 MPa after incorporating 5, 10, and 15 wt.% of (SiC + Al_2O_3). In the range of 30 to 89 MPa, the UTS increased for Al6061/5wt% (Al_2O_3 + SiC)/0.5wt%CeO_2, 54 to 102 MPa for Al6061/10wt% (Al_2O_3 + SiC)/1.5wt%CeO_2, and 73 to 123 MPa for Al6061/15wt% (Al_2O_3 + SiC)/2.5wt%CeO_2. Fig. 9 demonstrates that when compared to other materials, UTS is best for Al6061/15wt% (Al_2O_3 + SiC)/2.5wt% CeO_2. A higher elongation percentage was achieved after reinforcements were inserted [57].

In an extension of a similar kind of research, the A356.2 alloy was improved by Shaochen Zhang et al. by adding 0.1, 0.2, and 0.3 wt.% Yb and La, respectively. As shown in Fig. 10, the

UTS was raised to 279 MPa after T6 treatment, representing a rise of 28.2 % from the base alloy [58]. Based on the findings mentioned above, incorporating rare earth elements into the composite boosted tensile strength due to the following mechanisms: refining the Al matrix's grain, hindering crack propagation, and strengthening intermetallic bonds. However, after a specific fraction of reinforcement particles, some composites showed a modest decrease in the mechanical characteristics due to a higher degree of agglomeration of reinforced particles, resulting in weak intermetallic bonding.

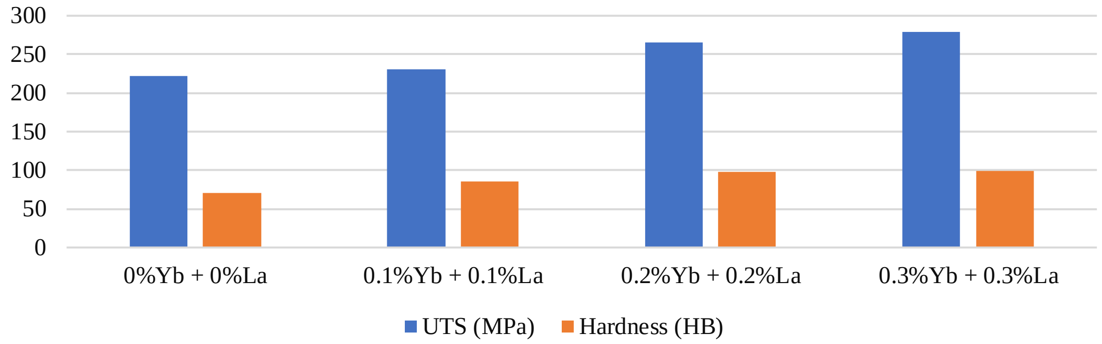


Fig. 10. Effect of (Yb + La) mixture on tensile strength and microhardness of A356.2 (based on data of [58])

Effect of REEs and REOs on the hardness of AMMCs. One of the essential characteristics of a material is its hardness, which is measured by how easily it can be dented or worn away by other means. Several studies comparing composite and base materials' hardness were presented.

As Hafeez Ahamed et al. reported, the microhardness increase for Al6063/1.5Al_2O_3 was 92 %, for Al6063/1.5Y_2O_3 was 108 %, and for Al6063/0.75Al_2O_3/0.75Y_2O_3 was 111 %, when each sample was doped volumetrically and prepared with PM. It could clearly be seen hybrid composite outperformed the other samples in terms of hardness [52]. Recent research published by J Ramesh Kumar et al. in advanced materials looked at how adding Y_2O_3 at 3%, 6 %, and 9 vol.% affects the mechanical and microstructural properties of FSP-processed AA6082 aluminium alloy. Increase in hardness from 88HV to 140HV when 9 vol.% Y_2O_3 was reinforced in AA6082 aluminium alloy [53].

A similar attempt was made by T Satish Kumar et al. (2019), who examined the hybrid composite of AA6028 and graphite (4 vol.%) doped with Y_2O_3 at 2, 4, and 6 % by volume and synthesized by FSP. The microhardness of the hybrid composite (6Y_2O_3 + 4Gr) was increased up to 132 HV from the base alloy (88 HV) [54]. In another evaluation, Shaochen Zhang et al. added Yb and La with 0.1, 0.2, and 0.3 % of each in A356.2 alloy. After T_6 treatment, the microhardness was increased to 99.2HB, which is increased by 47.3 % from the base alloy, as shown in Fig. 10 [58]. Regarding the advancement in AMMCs, Sharma et al. developed some quite intriguing outcomes associated with mechanical characteristics. They fabricated AMMCs containing Al6063, SiC (3 wt.%, 6 wt.%, and 9 wt.%), and RE mixture of cerium oxide and lanthanum oxide i.e., (CeO_2 + La_2O_3) (1 wt.%, 2 wt.%, and 3 wt.%) using the stir casting technique. Microhardness increased with the addition of reinforcements when 3 wt.%, 6 wt.%, and 9 wt.% of SiC were reinforced. After transforming from a ductile alloy to a brittle one, the microhardness increased from 46 VHN (base alloy Al6063) to 68.95, 76.04, and 106.46 VHN. With 1, 2, or 3 weight percent of (CeO_2 + La_2O_3) added to the prepared composites; the hardness increased to 108.6, 114.24, and 85.80 VHN, respectively. The maximum value for hardness was obtained in the case of 2 wt.% RE [59]. On a similar note, composites of Al6061 with (Al_2O_3 + SiC) mixture (5, 10 , and 15 wt.%) and CeO_2 (0.5, 1.5, and 2.5 wt.%) were also prepared by V.K. Sharma et al. via a stir casting process. Fig. 11 displays that the microhardness of the sample treated with 2.5 wt.%CeO_2 reached a maximum of 92.8 VHN, a value 16.39 % higher than that of the base alloy (79.3 VHN) [60].

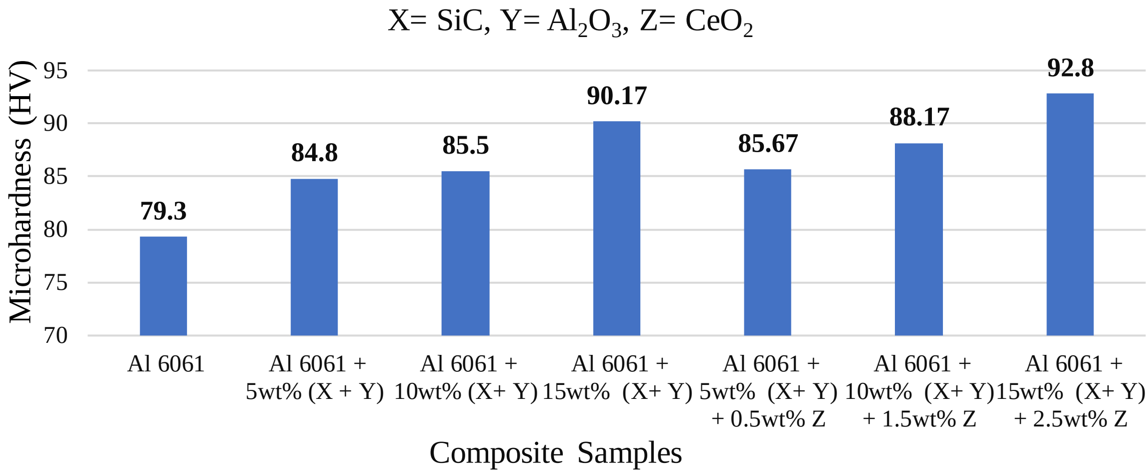


Fig. 11. Effect of (Al_2O_3 + SiC) and CeO_2 on microhardness of Al6061 (based on data of [60])

Tiachang Zhang et al. also investigated microhardness for composite, including commercial aluminium, incorporated by 1 wt.% of Yttria (Y_2O_3) and 1 wt.% of Yttrium (Y). They compared the characteristics of Al+1 wt.%Y_2O_3, Al+1 wt.%Y, Al6061, and casted aluminium. Composites made of 1 wt.%Y_2O_3 and 1wt% Y had hardness values of 66.2 and 66.5 HV, respectively. As a result of yttrium's higher oxygen affinity, oxides are formed at 1wt%Y, making the values nearly identical. The highest microhardness was showed by Al6061, i.e., 95.4 HV [61]. In the perpetuation of the same, Neeraj Kumar Bhoi et al. (2021) reported a considerable increment in microhardness from 36 to 58HV when aluminium was doped with 5wt% yttria, as shown in Fig. 12. The composite was prepared with ball milling followed by compaction and microwave hybrid sintering at 635°C [62]. Ravi Butola et al. fabricated aluminium metal matrix composites using the stir casting method; Al6063 alloy reinforced with 2 and 4 wt.% of yttrium oxide, respectively. Due to efficient load transmission and the obstruction of the movement of dislocations by hard ceramic particles of yttria, the microhardness of Al/2Y_2O_3 and Al/4Y_2O_3 was increased by 4.83 and 8.06 %, respectively [63].

In another study, Hafeez Ahamed and V. Senthilkumar worked on the aluminium hybrid nanocomposite, which included Al6063 incorporated with nano-sized Al_2O_3 and Y_2O_3 powder in a certain volumetric fraction. All Al6063, Al6063/1.5Al_2O_3, Al6063/1.5Y_2O_3, and Al6063/0.75Al_2O_3/0.75Y_2O_3 micro-crystalline (MC) and ultrafine-grained (UFG) samples were ball milled for 0h and 40h in advance of being compacted and sintered. To compare, the microhardness of UFG nanocomposites 1.5Al_2O_3, 1.5Y_2O_3, and 0.75Al_2O_3/0.75Y_2O_3 increased by 2.29, 2.39, and 2.54 times, respectively from the MC nanocomposites (milled for 0 h). The improved performance of the hybrid nanocomposite Al6063/0.75Al_2O_3/0.75Y_2O_3 was attributed to the smaller particle size of the nano-particles and the fact that they were embedded in a softer matrix [64].

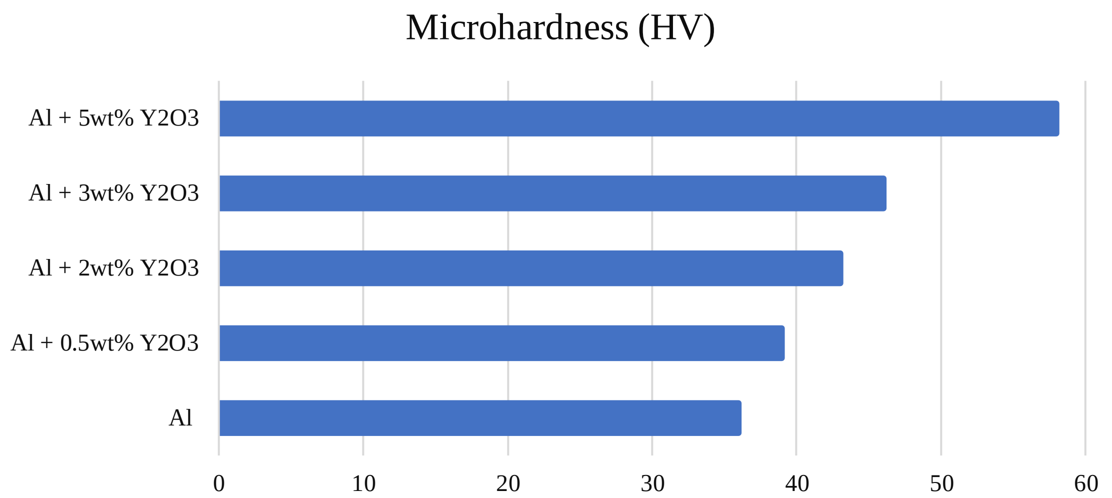


Fig. 12. Effect of wt% of Yttrium oxide on the hardness of aluminium alloy AA2024 (based on data of [62])

The mechanical properties of the hybrid composite AA2024/TiB_2 + Y_2O_3(YO) were studied by Semegn Cheneke et al. Stir rheocasting was used to produce a variety of samples with a constant 2 wt.% of TiB_2 and 0, 0.5, 1 and 1.5 wt.% of Y_2O_3. The microhardness of 2TiB_2/0.5YO, 2TiB_2/1YO, and 2TiB_2/1.5YO increased by 23, 24, and 25 %, respectively, as depicted in Fig. 13 [65].

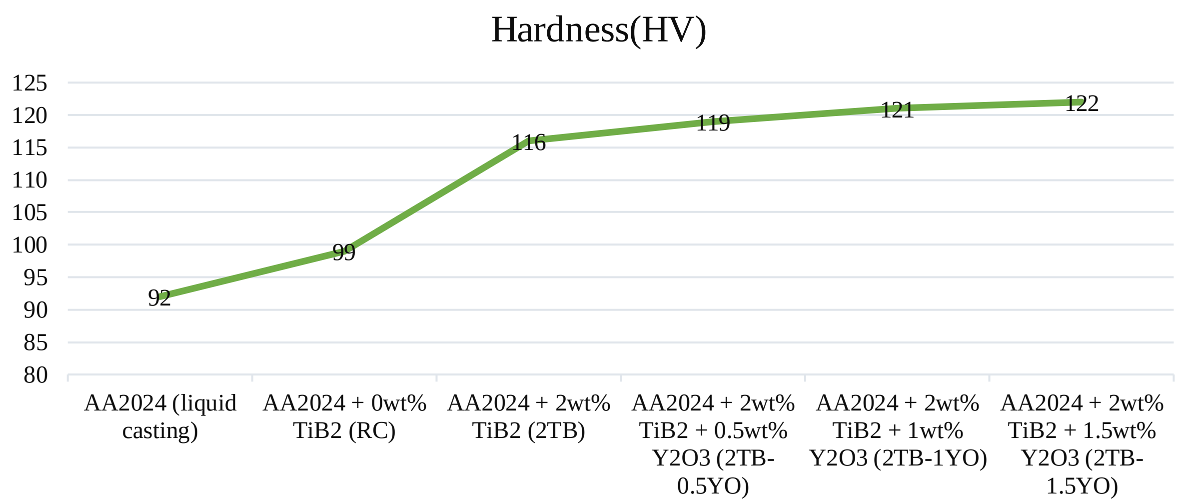


Fig. 13. Aluminium alloy AA2024 hardness as a function of wt% TiB_2 and Yttrium oxide (based on data of [65])

In addition, Al-ZnO-Y_2O_3 hybrid composites were explored by Neeraj Kumar Bhoi et al. Al, ZnO, and Y_2O_3 powders were combined and then sintered in a hybrid microwave to create the composite samples. Mechanical testing was performed on three samples (Al, Al/2ZnO/0.5Y_2O_3, and Al/2ZnO/2Y_2O_3). There was a 36 % increase in microhardness when comparing Al to the Al/2ZnO/2Y_2O_3 composition (Fig. 14) [66]. To investigate the effect of ball-milling time on composite performance, Prashanth et al. prepared a composite (AA7017 and 10wt%Y_2O_3) by high-energy ball milling for different amounts of time (zero, five, ten, fifteen, and twenty hours) before subjecting it to a hot pressing. Reports indicated that mechanical properties improve, attributed to an ultrafine grain structure achieved after 20 hours of milling. As can be seen in Fig. 15, the maximum hardness was reached after 20 hours of milling, i.e., 260VHN [67].

Hardness in Al-composites is affected by the grain structures and the level of reinforcement particle dispersion in the aluminium matrix. As the composite's foreign particles aggregate, the material's hardness decreases.

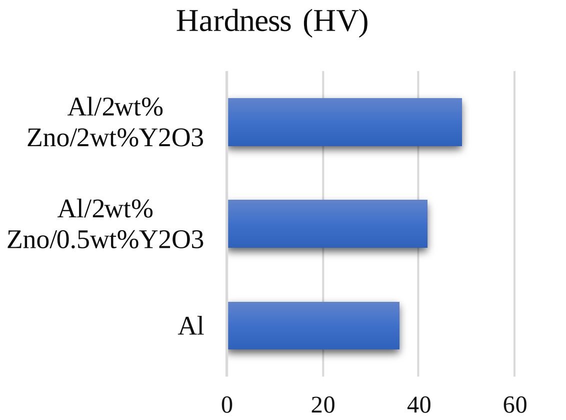


Fig. 14. Effect of wt% of Yttrium oxide and ZnO on the hardness of aluminium (based on data of [66])

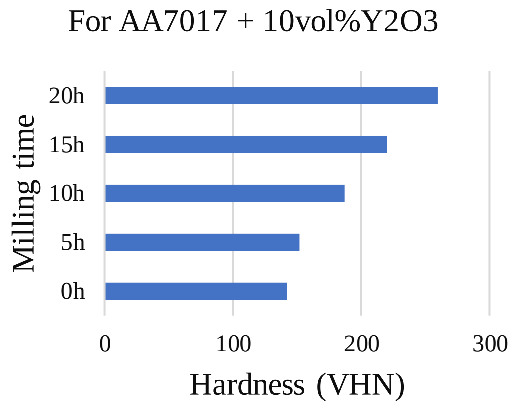


Fig. 15. Milling time's influence on AA7017 + 10vol% Y_2O_3 hardness (based on data of [67])

Effect of REEs and REOs on Microstructural properties of AMMCs

The micro-scale distribution of reinforcement particles and the degree of grain refinement determine the final composite's properties. The microstructure can be analysed using a number of methods, including scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD). Regarding the microstructure of composites, both the reinforcement percentage and the fabrication method are important considerations.

In the same trend, Neeraj Kumar Bhoi et al. examined the microstructure of a composite made of aluminium and yttria (0 to 5wt%). The composite was ball milled, compacted, and sintered in a hybrid microwave oven at 635 °C. Al (JCPDS-04-087) and Y_2O_3 (JCPDS-86-1326) peak heights were found to be consistent with the corresponding values from the standard diffraction data. Intermetallic compounds $Al_5O_{12}Y_3$ and Al_3Y have also been detected in X-ray diffraction, which helped in the enhancement of the physical properties of the composite. The uniform distribution of Y_2O_3 particles in the Al-5wt% has been found with the help of FESEM technique. The small agglomeration of Y_2O_3 particles has been detected due to mismatched density and thermal expansion coefficient. The degree of despersion of the Y_2O_3 nanoparticles throughout the Al matrix has been identified by using TEM. As a result of the intermetallic compound formation and the even distribution of doped particles throughout the Al-5wt% sample, the microhardness rose 1.62 times, nano-hardness reached 2.43 times and elastic modulus went 1.8 times of the material [62].

The behaviour of Al2024 reinforced with varying weight percentages of Y_2O_3 between 0 and 20 % was described by Mohanad Lateef Hamada et al. Incorporating up to 10 wt.% Y_2O_3 improved microhardness, tensile strength, and wear rate. Once this ratio was exceeded, composites' strength began to decline due to Y_2O_3 agglomeration. Agglomerated particles of Y_2O_3 weaken the internal structure of the composite. As a result, internal deformation and dislocations occur in the internal structure of the composite. The dislocations and deformation create voids in the internal structure, which results in increased porosity [68].

Along the same line, W.B. Bouaeshi et al. doped the yttrium oxide on aluminium metal's surface to enhance surface properties. Microstructure analysis of yttria-Al samples confirmed the absence of Y_2O_3 particles and suggesting that yttria particles may have melted or decomposed as a result of the high temperature experienced during arc melting (3700 °C), which was higher than the melting point of yttria (2430 °C). As per the Energy Dispersive Spectroscopy (EDS) analysis, oxygen was not detected in the Y_2O_3-added samples. Since there was an imperceptible amount of oxygen in the samples, it can be concluded that the oxygen released from Y_2O_3 was able to escape the samples during melting. Due to the melting of each sample four times, the chances of oxygen being released from the sample increased significantly. With the help of XRD technique, the samples has confirmed the existence of a new phase, Al_3Y. As a result of the Al_3Y phase formation and microstructure modification, the Al-20 wt.% Y_2O_3 sample exhibited improved hardness, enhanced polarisation behaviour, and wear resistance [69].

Guangzhu Bai et al. made Mg_2Si/Al composites using ultrasonic stir casting with different powers (50, 100, 150, and 200 W), with Al-20%Si and Al-50%La serving as the master alloys. The absence of lanthanum (La) caused the Mg_2Si primary particles to be of an irregular shape and distributed unevenly. La's incorporation resulted in a more uniform distribution of primary Mg_2Si particles and a refinement of their average particle size to 42 nm. Processing of sample (Mg_2Si/Al-0.4wt%La) at 150W was found to be optimal for microstructural and intermetallic bond modifications, especially $Al_{11}La_3$ [70].

Furthermore, Using A356 aluminium alloy as-received and milled form, E. Aguirre-De la Torre et al. doped the ACL (Al-6Ce-3La) alloy. The milling was performed for 5h and 10h. The ACL master alloy's La/Ce phase was successfully incorporated after 10 hours of milling, resulting in finer fragmentation. Adding 0.2wt% ACL with a 9.0wt% La/Ce content improved the A356's mechanical performance. Milling ACL resulted in finer grains, a higher degree of homogeneity in the distribution of La/Ce particles, and the formation of intermetallic compounds like $AlLa_4$, $CeAlO_3$, and $Al_{11}Ce_3$. These factors contributed to the improved performance of the resulting samples [71].

Hafeez Ahamed et al. performed a similar experiment, blending Al6063 with 1.3vol%Al_2O_3, 1.3 vol%Y_2O_3, and 0.65vol%Al_2O_3/0.65vol%Y_2O_3, and then analysing the composites for changes in morphology and particle size. In contrast to the 1.3Y_2O_3 system, the 1.3Al_2O_3 system generated more refined and smaller particles due to the spherical shape of Al_2O_3 hard ceramic particles. The average particle size was significantly reduced and particle distribution was made more homogenous after adding 1.3Y_2O_3 and 0.65Al_2O_3/0.65Y_2O_3. It was also concluded that the grain refinement and lattice strain increased up to 20 h milling time; afterwards, these remained constant. In addition, it was determined that the development of nanocomposites with high-energy ball milling led to microstructure refinement and randomly oriented interfacial boundaries [72].

Furthermore, Zhi-Qiang Yu et al. examined the nature of interfacial bonding for the modified reinforcement of sub-micron alumina coated with yttrium oxide in the Al-Mg-Si alloy at different age hardening at 130, 160, and 190 °C. The samples were prepared through the squeeze casting process. The new phase Y_2Al was attributed to a reaction between Y_2O_3 and the Al-matrix at the interface. After the formation of the new phase Y_2Al, thermal stresses between the modified particles and matrix increased, leading to the appearance of some dislocations in the matrix. Hardness values for aged modified composites are consistently higher than those for aged non-modified composites. This occurred because Y_2Al surrounded the grains, which boosted quenching vacancy saturation and favoured the zone nucleation of the grain particles [51].

Similar research was conducted by V.K. Sharma et al., who looked at composites of Al-6061 containing CeO_2 (0.5, 1.5, 2.5 wt.%) and SiC/Al_2O_3 (5, 10, 15 wt.%) and synthesised via the stir casting route. The dendritic growth in composite and the effective incorporation of SiC/Al_2O_3 particles have been depicted with the help of SEM technique. Decrease in the grain size has been observed with the incorporation of CeO_2 into the Al-matrix. On the other hand, some of the cerium oxide particles aggregated and clustered together, negatively affecting the mechanical properties. By using XRD analysis, it has been verified that α-Al, Al_4Ce, Al_3Ce, and Al_8Mg_5 phases were present in an Al-matrix. Better performance was observed in these samples compared to others, which was attributed to the successful incorporation of CeO_2 in the matrix, as evidenced by the presence of phases such as Al_4Ce and Al_3Ce [73].

Similarly, Vipin Kumar Sharma et al. also researched the influence of 1, 2, and 3 wt.% REP (CeO_2 + La_2O_3) on Al-6063/SiC (3, 6, and 9 wt.%) hybrid composites fabricated via a stir-casting route. REP mixture acted as a grain refiner and reduced the agglomeration of particles, leading to better performance of the hybrid composites. Still, some clustering of CeO_2 and La_2O_3 was noticed, which declined the performance of the composites. After testing, the failure samples showed grooves, pin holes, and micro-cracking due to the agglomeration and uneven distribution of reinforcement particles in some regions [74]. Xu Wang et al. reinforced neodymium (Nd) in the Gr/Al-17Mg matrix with different quantities of 0.2, 0.5, and 2 %. The phases at the interface, such as Al_3Mg_2 and $Al_{11}Nd_3$, were observed with the help of TEM and XRD. The addition of Nd significantly reduced the bending strength of Gr/Al composites from 1463 MPa (Gr/Al-17Mg) to 791 MPa (Gr/Al-17Mg-2Nd). The formation of the Al_3C, Al_3Mg_2, and $Al_{11}Nd_3$ phases, as well as the transition layer, increases the interfacial bonding strength, which reduces the amount of pulled-out single fibres and bundles [75].

The mechanical properties of a composite are profoundly affected by factors such as the grains' shape and size, the dispersion of reinforcement particles, and the emergence of new phases. However, the mechanical properties suffer, when there is an agglomeration of particles in the matrix. Fig. 16 depicts the overall impact of rare earth elements and their oxides on the properties of AMMCs.

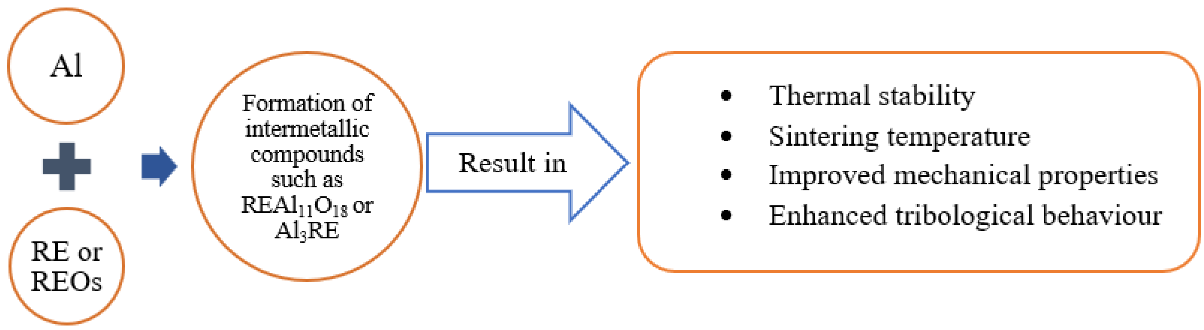


Fig. 16. Effect of RE incorporation in the aluminium matrix

Conclusions

The aerospace and automotive industries and the military have a high demand for aluminium metal matrix composites. Rare earth elements and rare earth oxides have been the main focus of this review due to their ability to improve tensile strength, hardness, and microstructural properties. In this section, we will go over a few of the most important results:

1. As a result of accessibility and ease of use, powder metallurgy and stir casting are the most reliable methods for processing aluminium metal matrix composites.
2. Including a slight amount of rare earth elements or oxides in an aluminium matrix significantly improved the material's mechanical and microstructural qualities.

3. The composite's microstructure is determined by the reinforcement type, shape and size, and input parameters used during fabrication. The homogenous dispersion of reinforcement particles achieves a better mechanical and tribological performance.
4. Because of variations in density and thermal expansion coefficients between the matrix and the reinforcement, the aggregates of incorporated particles can form. Due to this, the tribological and mechanical behaviour of the composite gets irregular. Agglomeration precluded the metal matrix from bonding to the reinforced particles and reducing mechanical properties. Selecting the most suitable fabrication approach, volume/weight percentage of reinforcement particles, and optimised input parameters will reduce the agglomeration or clustering degree of reinforced particles.
5. The defects such as pin holes, grooves, and micro-holes are observed during microstructural investigation of failed samples of AMMCs. These defects arise due to either improper handling during fabrication or due to the aggregation of reinforced particles.
6. Ultrafine grain structure and better mechanical strength can be attained when the fabricated composite is processed under secondary methods like forging, extrusion, heat treatments, etc.
7. Combining rare earth elements (REEs) with ceramic reinforcement (Al_2O_3, SiC, TiB_2, etc.) in an aluminium metal matrix led to a notable enhancement in mechanical and tribological properties.
8. Hardness, tensile strength, and elongation showed the increment range of 46-260 VHN, 26-562 MPa and 0.5 to 33.33 % when rare earth elements were used as a reinforced particle in the aluminium alloy matrix.

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