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Technology Overview of Al-TiO_2 Metal Matrix Composites

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The aim of this comprehensive literature review conducted on titanium dioxide (TiO_2) aluminum metal matrix composites (ALMMCs) is to explore their properties and potential applications, focusing on various aluminum alloy series, including 1xxx, 2xxx, and 6xxx. While there was a limited amount of literature found when compared to other reinforcement materials such as titanium diboride and silicon carbide, TiO_2-ALMMCs were found to offer numerous advantages like improved mechanical properties, enhancing the specific strength. These results imply a promising use in areas such as automotive and aerospace vehicles and defense platforms, where size, weight, and power are paramount metrics toward high-performance, next-generation defense systems. Methodologies for producing TiO_2-ALMMCs are few, with most research focused on stir-casting and powder metallurgy methods. These methods are discussed in detail in terms of both procedure and their respective advantages and disadvantages. The limited, existing research underscores the need for further investigations to fully unlock the potential of TiO_2-ALMMCs and pave the way for innovative and sustainable solutions in advanced materials. As the research in this domain progresses, TiO_2-ALMMCs hold significant promise in transforming the materials landscape and opening new vistas for lightweight and high-performance materials.

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Abstract

The aim of this comprehensive literature review conducted on titanium dioxide (TiO_2) aluminum metal matrix composites (ALMMCs) is to explore their properties and potential applications, focusing on various aluminum alloy series, including 1xxx, 2xxx, and 6xxx. While there was a limited amount of literature found when compared to other reinforcement materials such as titanium diboride and silicon carbide, TiO_2-ALMMCs were found to offer numerous advantages like improved mechanical properties, enhancing the specific strength. These results imply a promising use in areas such as automotive and aerospace vehicles and defense platforms, where size, weight, and power are paramount metrics toward high-performance, next-generation defense systems. Methodologies for producing TiO_2-ALMMCs are few, with most research focused on stir-casting and powder metallurgy methods. These methods are discussed in detail in terms of both procedure and their respective advantages and disadvantages. The limited, existing research underscores the need for further investigations to fully unlock the potential of TiO_2-ALMMCs and pave the way for innovative and sustainable solutions in advanced materials. As the research in this domain progresses, TiO_2-ALMMCs hold significant promise in transforming the materials landscape and opening new vistas for lightweight and high-performance materials.

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1.0 TI Request

1.1 Inquiry

What research is available regarding aluminum titanium dioxide (Al-TiO_2)?

1.2 Description

Areas of interest include both metal matrix composites (MMCs) and coatings. Research interests include manufacturing processes, material properties, materials testing, and applications.

2.0 TI Response

MMCs have gained significant attention in recent years due to their unique combination of mechanical, thermal, and physical properties. The motivation behind utilizing MMCs, particularly aluminum metal matrix composites (ALMMCs), stems from the need to enhance the mechanical properties while maintaining or reducing weight. ALMMCs offer improved strength, stiffness, and wear resistance compared to unreinforced aluminum (Al) alloys, making them desirable for a wide range of applications across industries.

MMCs consist of a matrix phase, typically a metal, and a reinforcement phase, which can be in the form of particles, fibers, or whiskers. In ALMMCs, the matrix phase is Al, renowned for its low density and good corrosion resistance. The reinforcement phase, on the other hand, aims to augment the mechanical and physical properties of the composite. An example is where the addition of silicon carbide (SiC) whiskers increased the creep resistance of 6061 Al alloy [1]. In addition to SiC, ALMMCs can include particles, fibers, or whiskers of alumina, boron carbide, graphene, and carbon nanotubes. These reinforcement particles are known for their high strength, hardness, and thermal stability, thereby significantly improving the overall performance of the composite material.

Titanium dioxide (TiO_2) can also provide similar benefits as the other reinforcement phases such as wettability, wear resistance, thermochemical stability at high temperatures, and mechanical properties. However, TiO_2 also accomplishes these at a much more economical price due to its abundance in nature in the rutile phase. Yet, intrigue in TiO_2 ALMMCs has just recently become of interest to investigators. This report discusses the manufacturing methods employed in the manufacture of these particular ALMMCs, their properties and methods by which they were measured, and applications of ALMMCs. It should be noted that the latter aspect is presented with a more generalized view, as searches did not reveal any public data where TiO_2-specific ALMMCs are in service.

2.1 Production Methods of TiO_2-ALMMCs

Several methods exist as means to produce ALMMCs in general. These include stir casting, powder metallurgy (P/M), spray casting, and in situ synthesis. However, the literature found on the production of TiO_2-ALMMCs is limited to stir casting and P/M. Notwithstanding that there are nuanced variations of these techniques, each has their own advantages and disadvantages. Thus, for each process provided, the general overview of the method is given, along with a discussion of unique variations.

2.1.1 Stir-Casting Methods

Of the two processes, stir casting is the more widely used to produce TiO_2-ALMMCs. A diagram of the general process is shown in Figure 1. Initially, the matrix alloy (Al in this case) is melted in a crucible within a resistive or induction furnace. This is followed by the steady incorporation of the reinforcement particles directly into a molten Al alloy, usually poured from an adjacent hopper. After complete charging of the reinforcement TiO_2 phase, the composite melt is stirred, either by mechanical agitation or electromagnetic induction, to achieve uniform distribution of the reinforcement phase. After sufficient homogenization, the contents are poured into a mold, by either removing from the furnace to a separate location or by tapping the bottom of the crucible to pour into the mold below. The solidified composite is then subjected to postprocessing steps such as heat treatment, machining, and surface finishing, as needed.

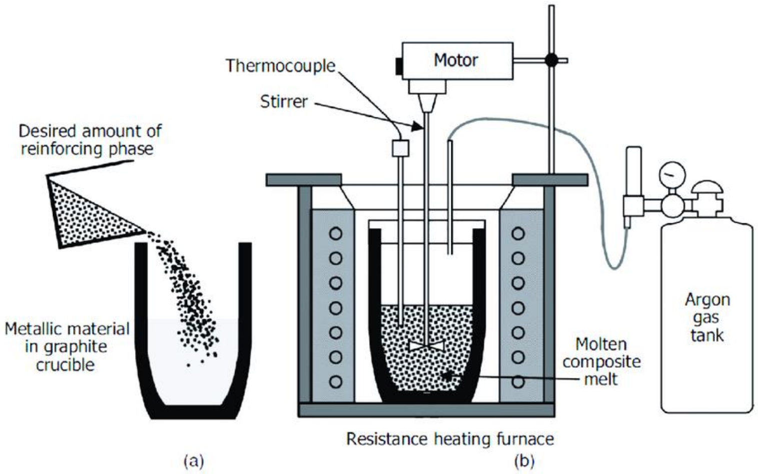

Figure 1. Schematic Sketch of Stir-Casting Process for Producing MMCs [2].

The main advantage of stir casting lies in its cost. No specialized furnaces are needed for this process, and graphite impellers are both affordable and commonly used within Al foundries already. The primary capital expenditure in refitting a foundry for TiO_2-ALMMCs is the hopper and the process equipment associated with charging control. The process is also versatile and scalable. It is versatile in the sense that the current pattern- and mold-making equipment is already available and suitable for fabricating molds with complex geometries. It is scalable in the sense that the size of the casting is restrained only by the volume of the furnace and corresponding molds. Also, the addition of the reinforcement phase acts as a grain refiner for the Al matrix due to the TiO_2 particles acting as increased nucleation sites. This is no surprise, as titanium diboride (TiB_2) has been used industrially as a grain refiner for decades [3]. The smaller grain size takes advantage of the Hall-Petch effect [4] correlating smaller grain size with strengthening.

That said, there are also some drawbacks. The first are particle settling and agglomeration. Depending on the magnitude of the density difference, there is a tendency for heavier reinforcement particles to settle to the bottom of the melt if the stirring forces are insufficiently high. On the other hand, excessive stirring speed will guide the particles toward the crucible wall and vortices at the centerline oxidizing the Al matrix phase. Thus, stirring control is critical.

Like all reinforcement phases, another disadvantage is the tendency of the TiO_2 particles to agglomerate with themselves within the melt. This is usually the case when the TiO_2 is used in higher concentrations, where the collision probability between TiO_2 particles is higher. It is exacerbated when moisture exists within the pores of the powder grains, increasing the surface tension/contact angle between the Al melt and the particles and increasing their affinity for agglomeration due to zero contact angle existing between like particles.

Mitigation strategies to these risks exist. The first is the use of commercial computational fluid dynamics software packages such as Ansys Fluent or COMSOL. This should give an acceptable range of stirring speeds, which will prevent both settling on the lower bound and excessive migration to the crucible. Second is the preventing of Al oxidation by using a flux gas such as argon (Ar) or carbon dioxide. The third is the preheating of the powder and ultrasonic or Ar degassing—the former drives adsorbed moisture from the pores, and the latter removes any remaining adsorbed air, improving wettability. Adding a trace amount of magnesium (Mg) to the melt further improved TiO_2-Al wettability [5].

The final mitigation step for settling and agglomeration is semisolid processing, a variation of the stir-casting process [5–8] that was used in the majority of cases. In this process, the Al is initially heated to a completely molten state (i.e., above the liquidus temperature). The melt is then cooled, after which the reinforcement phase is charged, whether all at once [5–7] or in stages, as with Khalko, Chevuri, and Dagarapu [8]. The increased viscosity of the semisolid state lowers the Stokes number of the particle, meaning the particle will want to follow the flow streamlines rather than settle. Furthermore, the presence of solid matrix particles within the flow impedes the ability of the TiO_2 particles from interacting with one another, reducing the potential for agglomeration.

2.1.2 P/M Methods

The P/M route involves the consolidation of Al alloy powders with reinforcement particles through processes such as powder mixing, compaction, and sintering. The steps for this process as represented in Figure 2 and may be generally described as follows. First, Al alloy powders and reinforcement particles are separately prepared. The powders are typically obtained through atomization or mechanical alloying, while the reinforcement particles can be manufactured using techniques like ball milling or chemical-vapor deposition. After this, the Al alloy and reinforcement-phase powders are blended using techniques such as mechanical mixing/alloying or ball milling. This ensures a uniform distribution of the reinforcement particles throughout the matrix phase while further refining particle size for better packing fraction. The particles are then placed into a die and compacted using either cold or hot pressing to form a “green” compact. The final density and shape fidelity depend on the compaction pressure and temperature. After this, the powder is sintered to densify the part. For ALMMCs, this is done in a controlled atmosphere or vacuum furnace to prevent oxidation. The final composite part is then subjected to postprocessing as necessary.

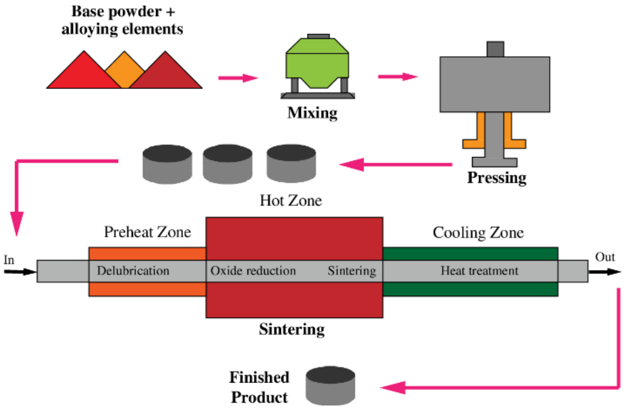

Figure 2. Schematic Sketch of Essential P/M Process Steps [9].

As with stir casting, P/M methods have their own advantages and disadvantages. The primary advantage is P/M allows for excellent control over the dispersion of the reinforcement phase throughout the Al matrix. The use of pre-alloyed or premixed powders ensures a uniform distribution of reinforcement through the ALMMC, resulting in a homogeneous structure. Of the articles reviewed for this activity, agglomeration phenomena were not excessively observed in optical or scanning electron microscope (SEM) micrographs. Also, due to the powder nature of the precursors, the P/M method enables the achievement of higher fractions of the reinforcement phase in ALMMCs, as stir casting is limited due to viscosity considerations during mixing. P/M also gives greater flexibility to the user to tailor the microstructure, which is controlled by green compaction force, sintering temperature, and sintering time. Due to the use of controlled atmospheres, the P/M process also minimizes oxidation of the matrix metal compared to the risk of air entrainment in the downsprue during the melting, stirring, and casting process. Finally, the pressed and sintered part is near-net shape, reducing the need for intensive machining and material waste.

Nonetheless, P/M may come with some additional costs when compared to a refit for stir casting. These costs would be initially manifested in the purchase of capital equipment such as powder blenders, compactors, and controlled atmosphere furnaces. These costs scale as the parts move into more of a mass production environment and are higher than those for stir casting. The other limitation of P/M is the component size. As it becomes more difficult to uniformly compact the powder mixture into a green part and densify it during sintering, the P/M method is more suited to small- to medium-sized components.

2.2 Experimental Methods for Property Measurements

In the articles reviewed for this report, the respective investigators each performed unique combinations of tests to measure the properties of the material, including tensile and compressive tests, wear resistance, hardness testing (both micro and macro), and metallography. Likewise, the parameters for these tests were not readily apparent, but it is taken in good faith that the tests were performed according to a standard operating procedure defined in standards for the respective measurements. As such, a list of ASTM International standards that should be used when performing investigations is presented. These standards ensure consistency and accuracy in test methods across different laboratories and industries. Table 1 lists commonly used ASTM standards for measuring properties of ALMMCs. Many of these are common, and older standards may be gleaned from the internet as portable document formats, better known as PDFs.

Table 1. Overview of ASTM Standards for Tests Observed in Review Articles

Test	ASTM Standard
Tensile Properties (elastic modulus, yield strength, ultimate tensile strength, elongation)	ASTM E8/E8M [10]
Compressive Properties (modulus, compressive strength, yield stress)	ASTM E9 [11] ASTM C39 [12]
Wear Properties (wear volume, wear rate, coefficient of friction, wear particle analysis)	ASTM G99 [13]
Vickers Hardness (microhardness, diamond indenter)	ASTM E92 [14]
Brinell Hardness (hardened steel ball indenter)	ASTM E10 [15]
Rockwell Hardness (variable indenters, loads)	ASTM E18 [16]

2.3 Properties of TiO_2-ALMMCs

This section focuses on exploring the properties of TiO_2-ALMMCs. These composites represent an intriguing avenue in the pursuit of advanced materials with enhanced mechanical and functional characteristics. In light of the wide array of methods and techniques employed for their synthesis, this analysis categorizes the investigations based on matrix-phase alloy classification, aiming to provide a comprehensive overview of their properties. While other materials such as TiB_2 and SiC have garnered significant attention as reinforcement phases in ALMMCs, the exploration of TiO_2-reinforced composites has been comparatively limited. This section delves into the existing body of research, highlighting the distinctive characteristics of TiO_2-ALMMCs and their potential implications for various engineering applications. By shedding light on the properties and current research landscape, this examination contributes to a deeper understanding of TiO_2 as a reinforcement phase in ALMMCs and paves the way for further advancements in the field of composite materials.

2.3.1 Commercially Pure Al (1xxx Series)

It is intuitively best to open with discussion of TiO_2-ALMMCs using commercially pure Al (i.e., 1xxx series) as the matrix material. The reason is twofold. First, the processing is relatively straightforward, as there is no need to incorporate the alloying elements during melting or powder preparation (e.g., mechanical alloying). Second, the results presented for pure Al provide a clearer picture of the effects of the reinforcement particles only, excluding the well-known effects of solid solution and precipitation hardening from the alloy.

One of the earlier, more fundamental investigations was by Ravichandran and Dineshkumar [6]. While they referred to the production method as the “liquid powder metallurgy” route, the experimental details revealed that the technique was essentially that of semisolid stir casting, as the pure Al was melted first in the graphite crucible. After reduction in temperature to the semisolid state, only two compositions were produced: (1) the pure Al to serve as a baseline and (2) another casting with 5 wt% TiO_2. Furthermore, the testing was limited to just Rockwell B hardness (100-kgf load with 1/16-in ball) and tensile testing. Results showed that the addition of the TiO_2 led to a 12% increase in hardness (from 24.5 HRB for the pure Al baseline to 27.5 HRB with 5 wt% added) and an approximate 10% increase in ultimate tensile strength (110 MPa to 121 MPa).

Ravichandran, Meignanamoorthy, and Dineshkumar [17] likewise followed up with a P/M version of their earlier investigation, expanding the range of investigated compositions from 0–10 wt% TiO_2 in 2.5-wt% increments. The powder sizes for the Al and TiO_2 phases were 300 µm and 10 µm, respectively, and billets were compacted with a high carbon steel die at 400 kN. Graphite was used as a lubricant on the dies to prevent adhesion of Al particles to the die walls. The billets were then fired at 550 °C, followed by hot extrusion and machining to make the ASTM E8 [10] cylindrical specimens. Vickers microhardness testing was performed in this case instead of Rockwell B. Results showed widely varying results in yield strength, tensile strength, and microhardness. Inspection of the micrographs showed severe agglomeration within the investigators' samples at higher concentrations, allowing for deformation around the harder TiO_2 particles. This is likely due to the large disparity between the matrix- and reinforcement-phase particles, as smaller particles can agglomerate within the voids of the larger matrix particles. Furthermore, the investigators used a large ratio of powder-to-ball-milling media (10:1), which lessens the effectiveness of the process. Notwithstanding, the positive trend at low concentrations, where the particles appear well dispersed, reinforces the notion of the strengthening effect of the TiO_2 phase.

Paul and Islam [18] had much better success with the P/M method, milling instead with a 2:1 ratio of powder-to-milling media, ensuring the powders had strong interaction with the milling balls. Compositions ranged from 0–12 wt% TiO_2 in 4-wt% increments. The experimental procedure for compaction was similar, with 250-MPa pressure for 5 minutes on a 50-mm^2 x 50-mm^2 die. Delubrication was also performed at 250 °C for 30 minutes before ramping to 450 °C for 4 hours. Brinell hardness (4.2-kN load) was performed by the investigators, along with compressive testing (ASTM C39 [12]). Results were more in line with expectations, as there was a monotonic increase in the hardness and compressive strength of the ALMMCs. Note that the compressive strength of pure Al is in relatively good agreement with reference values found through an internet search. This indicates uniform distribution of the TiO_2 reinforcement phase, as confirmed by their SEM micrographs.

2.3.2 Al-Copper (CU) Alloys (2xxx Series)

The 2xxx series Al alloys hold a position of great importance due to their exceptional strength-to-weight ratio and excellent mechanical properties. Primarily composed of Cu as the major alloying element, with small additions of other elements such as Mg, these alloys are renowned for their outstanding structural integrity and fatigue resistance. As a result, 2xxx series alloys have found widespread applications in critical industries, most notably in the aerospace sector, where lightweight yet robust materials are of paramount importance for aircraft components and structural elements. The high strength and fatigue resistance of 2xxx series alloys make them well suited for critical aerospace components such as wing structures, fuselage panels, and landing-gear components.

Additionally, the 2xxx series alloys demonstrate impressive machinability and are amenable to various fabrication processes, allowing for the creation of intricate and complex components with ease. Their exceptional combination of mechanical properties has extended their utility to other sectors, including sporting goods, automotive parts, and military equipment. In applications where high strength and weight reduction are crucial, the 2xxx series alloys provide viable solutions that translate into improved fuel efficiency, increased payload capacity, and enhanced performance.

This report presents the comprehensive results of two articles from the literature review on TiO_2-ALMMCs, where 2xxx series or Al-Cu alloys are the matrix phase. Both have been recently published: (1) Prosvirakov and Bazlov [19] in 2022 and (2) Khalko, Chevuri, and Lingadurai [8] in 2023.

On the P/M front, Prosvirakov and Bazlov [19] studied the effect of mechanical alloying and P/M parameters for Al-5%Cu. While this is usually a cast instead of a wrought alloy, this matrix-phase composition falls within the range for 2014 or 2022 wrought Al alloy for reference. The Al and Cu powders were alloyed together with 5 wt% TiO_2. As an alternative for comparison, a control batch with a processing control agent (PCA) was used, having the composition Al-5TiO_2-2PCA. The constituent powder compositions were ball milled for 10 hours and then hot pressed at 400 °C.

As expected, Prosvirakov and Bazlov [19] found that the addition of the Cu particles induced precipitation hardening like in their unreinforced counterparts. Annealing temperature was then studied. It was found that the Vickers microhardness was essentially steady compared to room temperature up to 300 °C, after which there was a precipitous drop. Examination of the differential scanning calorimetry curves showed this to be a result of grain growth, which lowers mechanical strength and resistance to plastic deformation.

Prosvirakov and Bazlov [19] then measured mechanical properties at elevated temperatures via a compression test at 300 °C. The ultimate tensile strength (UTS) values were read from the stress-strain curves for this report and are presented in Table 2 (additional process information is presented in parentheses). As expected from the hardness data, it is seen that annealing for any length of time leads to the degradation in mechanical properties due to grain growth. Most interestingly, however, it was found that the Al-Cu alloy had lower strength than the one with only the PCA. However, Prosvirakov and Bazlov conjectured that the stearic acid prevented the onset of particle welding during the sintering/hot pressing procedure. Here the coating would have to be burned off or evaporated to remove the barrier to the welding phenomenon. Moreover, the slower joining kinetics here simultaneously imply that there would be less grain growth within the heating window. While these results leave open questions and are thus not wholly comprehensive, they do suggest that stearic acid and other carboxylic acid ligands do enable finer-tuned sintering kinetics control.

Table 2. Al-Cu and Baseline Al-TiO_2-ALMMCS Mechanical Properties at 300 °C [19]

Specimen	UTS (MPa)
Al-5TiO_2-2PCA (as made)	255
Al-5TiO_2-2PCA (annealed 400 °C, 5 hours)	225
Al-5TiO_2-5Cu (as made)	150
Al-5TiO_2-5Cu (solutionized 540 °C, 10 hours, quenched, aged 180 °C, 8 hours)	70

Note: Values were read from the stress-strain curve in Prosvirakov and Bazlov's article [19] and are thus approximate.

Khalko, Chevuri, and Lingadurai [8] performed perhaps the most thorough investigation on TiO_2-ALMMCs to date, examining the influence of 1–4 wt% TiO_2 additions to 2014 Al alloy via stir casting. Understanding the challenges of particle settling and general concentration in stagnation zones along the periphery, the investigators performed semisolid processing. Alternatively, the investigators added the particles in four separate stages compared to all other stir-casting experiments adding them in a single step. The TiO_2 particles were preheated to 300 °C to drive off moisture, and initial Al matrix ingots were completely melted before addition (liquidus of 2014 Al is 652 °C). Four cycles then commenced where particles were added and the melt was cooled to 600 °C. After homogenization, the alloy was again reheated above liquidus and a second batch was added before being cooled to semisolid state. When all additions were complete, the crucible was then removed and quenched with cold water, solidifying the metal inside.

Khalko, Chevuri, and Lingadurai [8] found that the incremental addition method yielded higher relative densities than those typically found for stir casting (94–97%). This is on par with those fabricated via P/M. Micrographs also showed good dispersion of the TiO_2 particles, where the slow stirring and Ar degassing steps encouraged gas desorption from the TiO_2 pores, which would otherwise tend to carry the particles to the surface. After confirmation of the stability of TiO_2 within the MMC using x-ray diffraction, Vickers microhardness showed a 74% increase for 4% TiO_2 vs. the matrix phase alone (91 VH vs. 53 VH, respectively).

In addition to the Hall-Petch strengthening effect due to grain refinement, Khalko, Chevuri, and Lingadurai [8] also identified strengthening by the reinforcement particles due to the Orowan mechanism. In this mechanism, the particles act as pinning sites for dislocations, making it harder for slip to occur. Consequently, the addition of 4% TiO_2 increased the UTS by approximately 41% (328 MPa vs. 232 MPa) and the yield strength by 34% (312 MPa vs. 230 MPa) compared to the baseline 2014 Al values.

2.3.3 Al-Mg-Silicon (Si) Alloys (6xxx Series)

This subsection delves into the realm of 6xxx series Al. The 6xxx series alloys are Al-Mg-Si based, offering a remarkable balance of mechanical properties, formability, and corrosion resistance. Due to their exceptional strength-to-weight ratio and excellent weldability, these alloys have become a preferred choice in the manufacturing of lightweight yet robust components for the automotive, aerospace, marine, and architectural sectors.

The significance of the 6xxx series alloys lies in their ability to withstand demanding environments while maintaining structural integrity. Their corrosion resistance makes them well suited for applications exposed to harsh weather conditions or corrosive substances, such as marine components, architectural structures, and transportation vehicles. Additionally, the 6xxx series alloys exhibit good formability and can be easily extruded, making them ideal to produce intricate profiles and shapes used in architectural facades, window frames, and structural parts.

Two articles were found regarding TiO_2-ALMMCs from 6xxx series Al. The earliest was by Kataiah and Girish [5] in 2010, which examined the addition of TiO_2 to 6061 Al for pharmaceutical and medical uses such as oxygen tanks or other pressure vessels, electrical fittings, and valves. After melting at 700 °C, a coated stir rod was used to generate a vortex and TiO_2 preheated to 200 °C was added to the melt. A small quantity of additional Mg was added to improve wettability of the TiO_2. After stirring and degassing with dinitrogen, the alloy was cast into permanent molds. ASTM testing of mechanical properties was then performed on the specimens.

A summary of the results is shown in Figure 3. As shown, the addition of small amounts of TiO_2 in terms of weight percent have a strong effect on the mechanical properties. Note that the percentage increases in UTS and torsional strength are analogous to those from 2xxx series studies. However, there is a plateau that occurs for strength and hardness, as eventual agglomeration and extremely short distances between pinning sites do not act as effective barriers to dislocation motion.

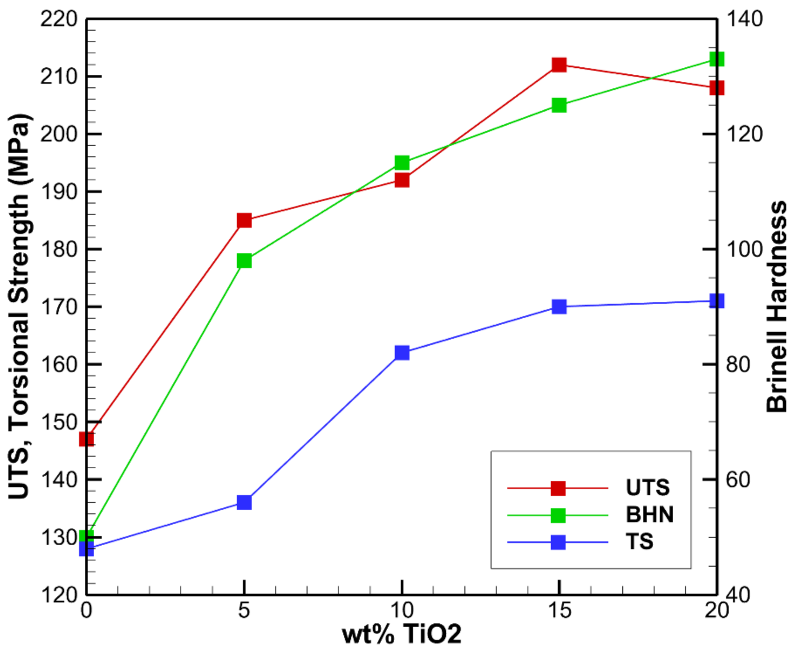

Figure 3. Effect of TiO_2 Additions to Mechanical Properties for 6061 Al [5].

More recently, Yoganandam, Raja, and Lingadurai [7] performed a similar investigation for 6082 Al. This was done using the compocasting method, whereby the stir casting is done completely in the semisolid state, with additions again being done in one step like the other stir-casting methodologies. TiO_2 compositions of 0–9% were studied in 3% increments by weight. After polishing and etching with Keller's Reagent, the microstructure showed severe agglomeration of the TiO_2 at 6% and 9%. These agglomerations were located near the eutectic portion of the grain boundaries, suggesting that the particles were "pushed" by the solidification of the solid phase until isothermal solidification at the eutectic point. However, the grain refinement effect tended to keep the agglomerate size low, as the grains between which the eutectic phase existed were very small. As a result of the agglomeration, mechanical properties were not profoundly increased, with UTS rising from 175 MPa for baseline 6082 Al to 205 MPa at 9 wt% TiO_2 loading. However, the addition of TiO_2 did provide an increase in hardness, increasing nearly 50% over the range of compositions investigated.

2.4 Conclusions

In conclusion, the investigation of TiO_2-ALMMCs presents a promising frontier in the quest for advanced materials with enhanced mechanical properties and broader applications. Throughout the literature review encompassing 1xxx, 2xxx, and 6xxx series Al alloys, it becomes evident that TiO_2 as a reinforcement phase in ALMMCs remains relatively unexplored compared to other materials like TiB_2 and SiC. However, the limited body of research shows encouraging results, indicating that TiO_2-ALMMCs hold tremendous potential for various engineering sectors.

The successful incorporation of TiO_2 particles into Al alloys offers opportunities to tailor the properties of ALMMCs, such as strength, hardness, wear resistance, and thermal stability. The lightweight nature of both Al and TiO_2 makes these composites particularly attractive for applications where weight reduction and structural integrity are paramount, including aerospace, automotive, and sporting-goods industries.

Venturing into a new era of materials research, the comprehensive understanding gained from this literature review lays a solid foundation for future investigations into TiO_2-ALMMCs. By bridging the gap in knowledge and expanding the understanding of the effects of TiO_2 addition to various Al alloys, the doors to innovative and sustainable solutions are opened. With continued research and advancements, TiO_2-ALMMCs have the potential to revolutionize the materials landscape, forging a path toward high-performance, lightweight materials that redefine engineering possibilities. As such, further research in this field holds significant promise in unlocking the full potential of TiO_2-ALMMCs and elevating the realm of composite materials to new heights.

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