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Enhancements in Titanium Matrix Composites: A Multifaceted Exploration of Various Structural Ceramics Reinforcement

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Abstract

This research study delves into the comprehensive exploration of Titanium Matrix Composites (TMCs) reinforced with Silicon Carbide (SiC), Alumina (Al_2O_3), and Boron Nitride (BN). The investigation is structured into three key phases, each addressing essential aspects of TMCs: Phase 1 involves materials and manufacturing, where TMC coupons were fabricated through the stir casting technique with varying compositions of aluminum and silicon carbide. Phase 2 focuses on characterization and defect detection, employing scanning electron microscopy, Rockwell hardness tests, and tensile strength tests to identify various defect types within the TMCs. The study emphasizes the importance of controlling factors such as ceramic particle size, distribution, particle-matrix interface strength, and consolidation porosity to produce high-quality TMCs tailored for applications across industries, including aerospace, automotive, biomedical, and electronics. TMCs reinforced with SiC demonstrate superior mechanical properties, while Al_2O_3 and BN-reinforced TMCs offer cost-effective alternatives. The research also details the manufacturing process and testing methodologies, providing valuable insights into the behavior of defects and temperature variations in TMCs over time. This study contributes to advancing the development and application of TMCs in various industries.

Keywords: Titanium Matrix Composites, Structural Ceramics, Stir Casting, Characterization, Non-Destructive Testing

1. Introduction

Manufacturing processes that utilize the least amount of material are gaining popularity as a means to enhance technological processes and material processing, in order to maintain competitiveness in modern industries. Enhancing the overall mechanical properties, specifically by increasing the durability of materials to reduce their spatial requirements in structures, is indeed the most efficient approach to achieve this goal [1-3]. This pathway aligns with contemporary environmental considerations. The transportation sector is actively seeking novel materials to fabricate vehicles that are lighter in weight, with the aim of mitigating fuel consumption and minimizing carbon dioxide emissions [4,5]. Light alloys have surpassed traditional steel building methods in popularity and now contribute significantly to the revenue of the manufacturing sector [6-8]. When comparing them to steel, the utilization of aluminum alloys leads to a substantial reduction in density, specifically by 33%. Similarly, the use of magnesium alloys results in an even greater decrease in density, amounting to 77% [9,10]. Magnesium alloys are renowned for their exceptional vibration damping properties, as evidenced by numerous studies [11-14]. Additionally, other alloys may possess fascinating and complementary mechanical properties. Although aluminum alloys have a higher density compared to magnesium alloys, they are still relatively straightforward to process. In order to prevent dangerous exothermic reactions during the processing of magnesium alloys, it is necessary to use a protective atmosphere containing toxic SF6 [15,16] and apply specific coatings to prevent rapid oxidation during casting processes [17,18]. Additionally, it is worth noting that magnesium alloys have lower melting points compared to steel. The mechanical and physical properties of aluminum alloys can be modified through specific processing techniques, such as precipitation/work hardening and forming/machining [19-21]. The alloying process involves the use of master alloys and soluble elements.

Currently, there are three techniques available for processing Metal Matrix Composites (MMCs), which vary depending on the condition of the matrix when the particles are introduced. The substances can exist in three states: solid (i), semi-solid (ii), and liquid (iii) [22]. For solid and semi-solid routes, powder metallurgy and sintering are commonly employed. These methods facilitate the bonding of reinforcements through a well-defined interaction of temperature and pressure. However, the practical implementation of these methods on an industrial scale is hindered by limitations in component volume and shape. The fabrication methods of liquid-based metal matrix composites (MMCs), such as casting, still possess significant potential for further development and innovation, making them highly attractive. Aluminum-based metal matrix composites (MMCs) are highly efficient in enhancing electrical conductivity, heat conduction, tribological performance, and overall load-bearing capacity [23]. Nevertheless, the liquid MMC processing method has its drawbacks. For instance, the porosity can be enhanced due to the transportation of gas in the interface layer or the formation of pores caused by thermal expansion gradients between the matrix and reinforcement materials. Another aspect to take into account is the phenomenon of particle agglomeration, which refers to the formation of clusters of particles, as well as the uneven distribution of reinforcement [24]. Insufficient melt-reinforcement wetting, which refers to the lack of effective bonding between the melt and the particles due to surface tension and contact angle, often causes problems with particle distribution and porosity [25]. Although numerous researchers have suggested various pre-processing techniques, such as ball milling, heat treatment, particle oxidization, coating, and composite powders, there is currently no conclusive documentation on the optimal approach to combining these methods. Stir casting is a widely used technique in liquid metal matrix composite (MMC) processes for evenly distributing reinforcement particles [26-28]. Stirring serves the purpose of dispersing the material and also has positive effects on wetting. However, the extent of these effects depends on various factors such as the temperature cycles of the melt, stirring speeds and durations, blade size and angle, as well as the volume fractions of additives and wetting agents. In a recent study, the authors have shown that the use of ultrasonic cavitation-induced streaming in Al-Si melts can effectively generate a distribution of microparticles and improve wettability [29,30]. In this study, we examine different methods of producing liquid metal matrix composites (MMC) and evaluate their respective advantages, focusing on the most commonly used techniques involving an Al-Si matrix. The casting process optics elucidates and delineates the experimental procedures and methodologies employed in the production of low-cost Metal Matrix Composites (MMCs). This review will examine the interaction between melt treatment and particles in pairs to ascertain the mechanical properties of the end product. The discussion encompasses the dispersive and deagglomerate capabilities of melt processing techniques, as well as the examination of the wettability between the matrix and reinforcement materials, and the microstructural consequences resulting from pre-processing techniques.

2. Fabrication and Characterization of Titanium Matrix Composites Reinforced with Structural Ceramics

The research was conducted in three phases. In the first phase, metal matrix composite coupons of silicon carbide-reinforced Ti/SiC were created using stir casting, resulting in three sets (A, B, C) with varying aluminium and silicon carbide compositions. In the second phase, defects in these composite specimens were examined using scanning electron microscopy, Rockwell hardness, and UTM tensile strength tests. The third phase involved detecting defects through liquid penetrant, radiography, and ultrasonic tests, while also comparing non-destructive testing methods such as active pulsed infrared thermography. The article further explores various reinforced titanium matrix composites (TMCs), highlighting SiC-reinforced TMCs as having the highest mechanical properties, while Alumina and Boron Nitride-reinforced TMCs offer cost-effective options for different industrial applications. Each TMC consists of a titanium matrix, 10% ceramic particles, a 10-micron particle size, and is stir-cast with magnesium as a wettability agent. Volume Fraction of Titanium Matrix Composites (TMCs) Reinforced with Various Structural Ceramics has been shown in table 1.

To create the titanium matrix composite (TMC), a series of steps are followed. First, the titanium powder and ceramic particles are thoroughly cleaned with a mild detergent and water, followed by drying in an oven at 100°C for one hour. Next, the cleaned materials are mixed in the desired proportions. The mixed powder is then placed in a die, with the interior of the die coated with a mold release agent. The die is positioned in a stir-casting furnace and heated to the titanium's melting temperature. During this process, the molten titanium and ceramic particles are vigorously stirred to ensure even distribution. Subsequently, the molten mixture is poured into the die and allowed to solidify. Once solidified, the TMC is removed from the die. To prepare it for metallographic analysis, the TMC is then ground and polished. These steps are crucial in the production and analysis of titanium matrix composites.

Table 1. Volume Fraction of Titanium Matrix Composites (TMCs) Reinforced with Various Structural Ceramics

Property	**TMC Reinforced with Silicon Carbide (SiC)**	**TMC Reinforced with Alumina (Al2O3)**	**TMC Reinforced with Boron Nitride (BN)**
Tensile strength	500-700 MPa	450-650 MPa	400-600 MPa
Young's modulus	100-120 GPa	90-110 GPa	80-100 GPa
Hardness	300-400 HV	250-350 HV	200-300 HV
Wear resistance	Excellent	Good	Good
Oxidation resistance	Good	Fair	Good
Cost	High	Medium	High
Volume fraction	10%	10%	10%
Matrix	Titanium	Titanium	Titanium
Reinforcement	Silicon Carbide (SiC)	Alumina (Al2O3)	Boron Nitride (BN)
Particle Size	10 µm	10 µm	10 µm
Process	Stir casting	Stir casting	Stir casting
Wettability Agent	Magnesium (Mg)	Magnesium (Mg)	Magnesium (Mg)
Stirring Speed rate	500 rpm	500 rpm	500 rpm

2.1. Stir casting technique

Stir casting is essential for experimental titanium matrix composites (TMCs). SiC, alumina, and boron nitride can reinforce TMCs. To ensure safety and efficiency, this process requires a stir casting furnace, graphite stirrer, pyrometer, tongs, safety glasses, and gloves. The sample preparation process is meticulous. The titanium powder and ceramic particles are dried at 100 degrees Celsius for an hour after washing and rinsing with a gentle detergent. This starts the process. The powders are carefully mixed according to the formula. A mould releasing agent is sprayed into the die after it has been heated to 200–300 degrees Celsius. After mixing, the powder is gently deposited into the die. After heating to 1700–1800 degrees Celsius, the die is placed in the stir casting furnace shown in figure 1. After melting the titanium powder, the ceramic particles are added and the molten mixture is vigorously stirred for 10–15 minutes. After the liquid composite solidifies in the die, the thermoplastic moulding compound (TMC) is removed.

Figure 1. Experimental setup of stir casting Process

Ceramic-reinforced titanium matrix composites (TMCs) are crucial in aerospace, automotive, biomedical, and electronics industries due to their high strength, stiffness, and wear resistance. The stir casting method for TMC production is well-established and requires several steps. After washing the titanium powder and ceramic particles with a mild detergent, they are dried in an oven at 100°C for an hour to make TMC. The desired TMC properties determine the titanium powder-ceramic particle ratio, with ceramic particle volume percentage being a key factor. Warming the TMC die to 200-300°C and coating it with a mold release agent prevents pores in the composite. The die is heated in a stir casting furnace to titanium's melting point of 1700-1800°C after adding the powder mixture. The ceramic particles are evenly distributed in the molten slurry by vigorous stirring for 10-15 minutes. After the mixture cools and solidifies in the die, the TMC is carefully removed. Tensile tests measure strength and Young's modulus, hardness tests evaluate indentation resistance, and wear resistance tests, usually using a pin-on-disc test, evaluate the TMC's suitability for specific applications. To meet the strict requirements of demanding industries, TMCs must carefully control ceramic particle size and distribution, particle-matrix interface strength, and consolidation porosity. High-quality TMCs with the right properties for their applications can be made by carefully managing these parameters.

(a) (b) (c)

Figure 2. (a) Titanium Matrix Composites (TMCs) Reinforced with Silicon Carbide (SiC), (b) Titanium Matrix Composites (TMCs) Reinforced with Alumina (Al_2O_3), (c) Titanium Matrix Composites (TMCs) with Boron Nitride (BN)

Titanium matrix composites (TMCs) are a class of materials that combine the high strength and stiffness of titanium with the enhanced properties of reinforcing materials, such as silicon carbide (SiC), alumina (Al_2O_3), and boron nitride (BN) shown in figure 2. TMCs are manufactured using a variety of methods, including stir casting, powder metallurgy, and infiltration. To manufacture TMCs using stir casting, the reinforcing material is added to molten titanium and mixed vigorously to ensure uniform dispersion. The molten mixture is then poured into a mold and allowed to solidify. TMCs manufactured using powder metallurgy involve mixing the titanium and reinforcing powders and then compacting the mixture into a preform. The preform is then sintered at high temperature to produce a dense TMC. Infiltration involves impregnating a porous titanium preform with a molten reinforcing material. The properties of TMCs are influenced by a variety of factors, including the type and amount of reinforcing material, the manufacturing process, and the post-processing treatment. TMCs reinforced with SiC, Al_2O_3, and BN typically exhibit improved strength, stiffness, wear resistance, and thermal conductivity compared to unreinforced titanium. In aerospace applications, TMCs are used to manufacture components such as compressor blades, turbine disks, and landing gear. In automotive applications, TMCs are used to manufacture components such as brake discs, pistons, and connecting rods. In biomedical engineering, TMCs are used to manufacture components such as artificial joints and dental implants.

- Weight ratio - 80% TITANIUM reinforced with 19 % SiC and 1% Mg metal matrix composite A set specimen: This TMC is manufactured using stir casting. It is characterized by its high strength, stiffness, and wear resistance. It is used in a variety of aerospace and automotive applications.
- Weight Ratio - 75% titanium reinforced with 24% Alumina (Al_2O_3) and 1% Mg metal matrix composite coupons B set specimens: This TMC is also manufactured using stir casting. It exhibits improved strength, stiffness, and wear resistance compared to unreinforced titanium. It is used in a variety of applications, including aerospace, automotive, and biomedical engineering.
- Weight Ratio - 75% titanium reinforced with 24% Boron Nitride (BN) and 1% Mg metal C set specimens: This TMC is manufactured using stir casting. It is characterized by its lightweight, oxidation resistance, and thermal conductivity. It is used in a variety of applications, including automotive, aerospace, and biomedical engineering.

The two-step casting method using a green sand mould is shown in figure 3. Part (b) shows the Al/SiC slurry being poured into the ready-made green sand mould, whereas Part (a) shows the creation of the green sand mould. Ti/SiC metal matrix Specimen has been shown in figure 4.

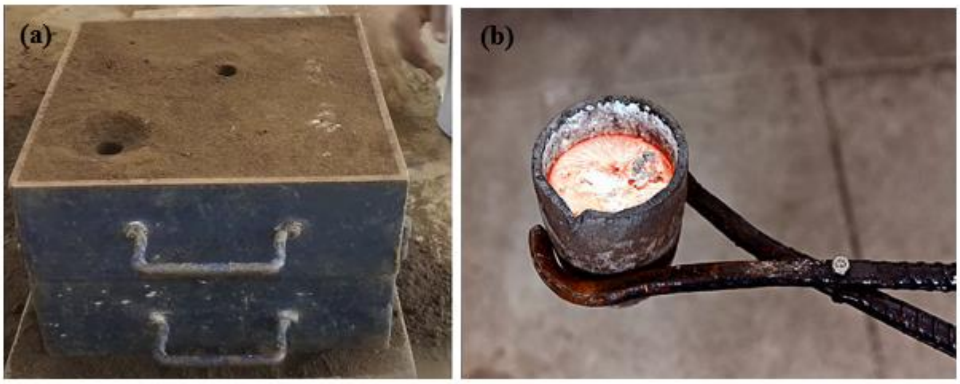

Figure 3. a) green sand mould preparation (b) Pouring of Al/SiC slurry in green sand mould

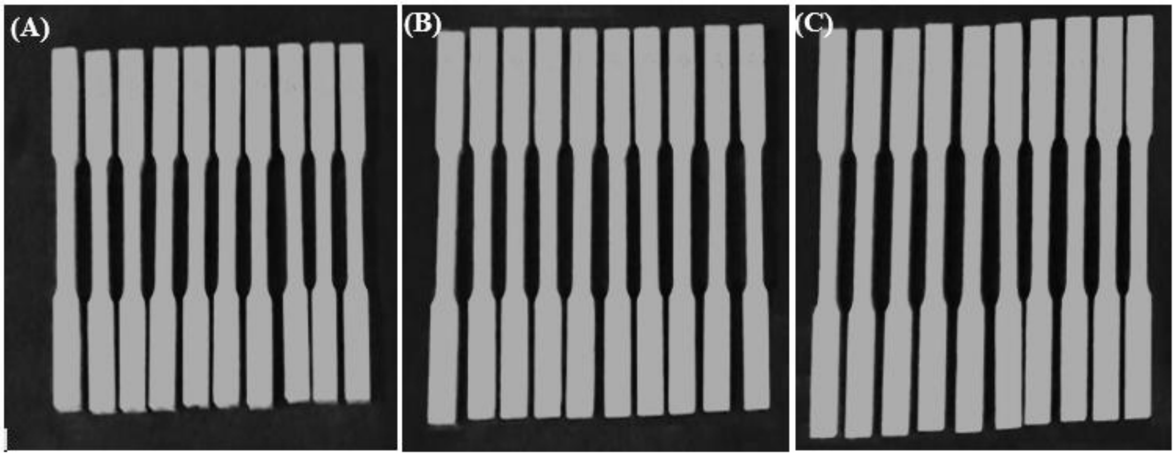

Figure 4. Ti/SiC metal matrix Specimen

3. Ti/SiC MMC CHARACTERIZATION

3.1. Scanning Electron Microscope Imaging Test (SEM)

A three-dimensional micro-level image of the materials was observed using a scanning electron microscope (SEM). The three-dimensional image was studied using magnification, extra high tension, and working distance variations. By focusing a beam of high-energy electrons on the surface of solid specimens, secondary electrons were created. A detector made of positively charged electrons collected these secondary electrons. PCED generated a micro-scale, three-dimensional image of the model at the end of the process, which could be used to learn more about the surface's chemical makeup and physical properties.

3.1.1. SEM imaging on defect surface of small sample

The defects in the specimen were analyzed by inducing blowhole effect on the 10 specimens out of 30. In the 3D SEM images of A set, among 9 specimens. The defect types were shrinkage (A1), porosity (A2), hot tear (A2), blow hole (A3). The table provides information on various SEM (Scanning Electron Microscope) samples. The samples are categorized into three groups: A, B, and C. Each sample is associated with a unique report number and characterized by its signal type (SE1), an extra high tension (EHT) of 20 kV, different zoom resolutions ranging from 10 µm to 300 µm, working distances from 1 mm to 13.5 mm, and magnifications from 2.00KX to 500X. The data demonstrates the range of imaging conditions for these SEM samples, offering options for different applications and magnification needs, with group A having higher zoom resolution and group C having the highest magnification.

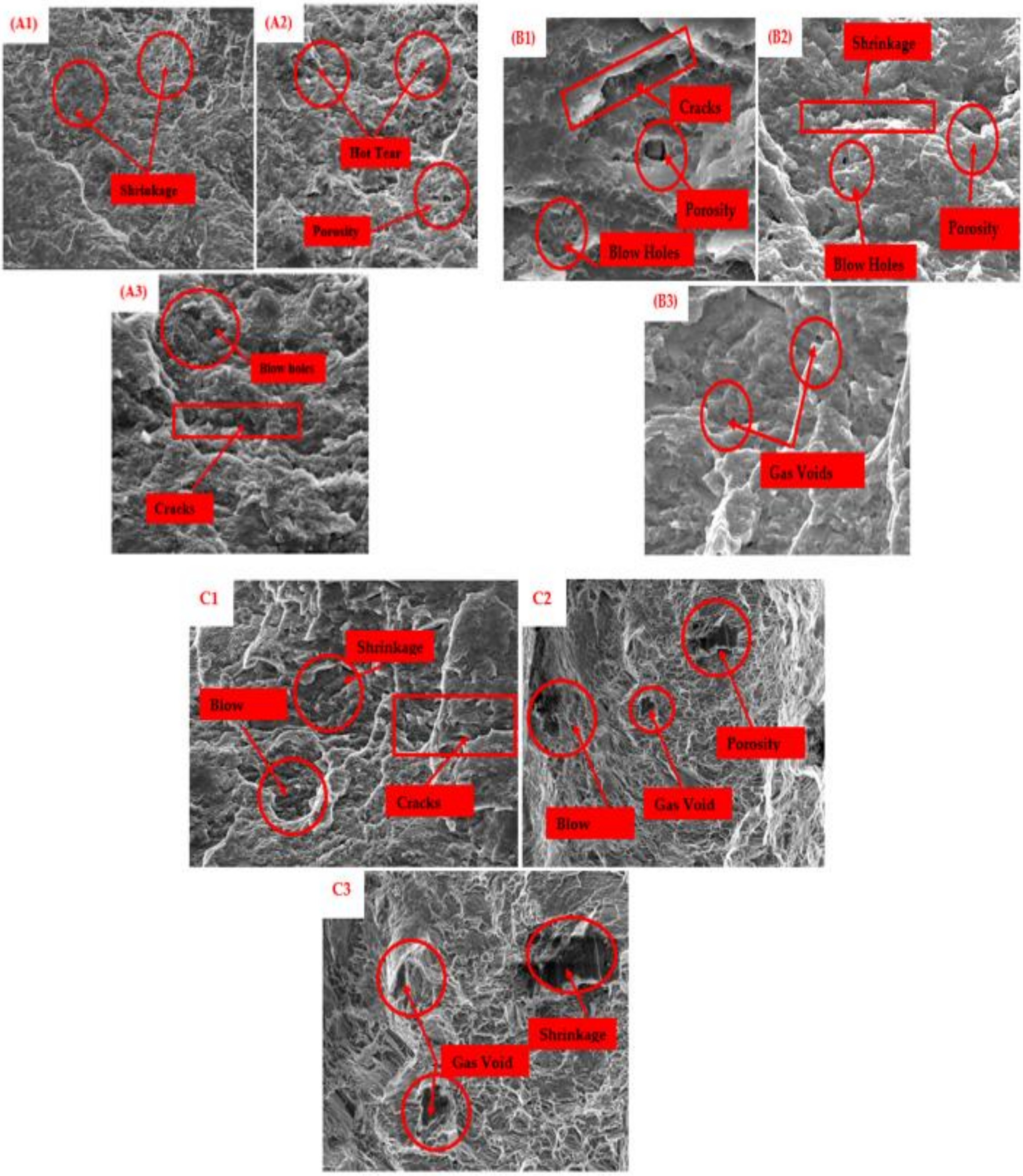

Figure 5. (A1, A2, A3) 3D SEM images of A set with the defect types; (B1, B2, B3) 3D SEM images of B set with the defect types; (C1, C2, C3) 3D SEM images of C set with the defect types.

All ten specimens examined in the 3D SEM images of the B set were discovered to have defects. The flaws identified were blowholes (B1, B2, B3) and porosity (B2). Due to the presence of a blow hole in the cut specimen, it was anticipated that all specimens in set B would exhibit imperfections. All ten specimens in the C set were found to have flawed 3D SEM images. The defects observed were porosity (C2), gas void (C2, C3), crack (C1), blow hole (C1, C2), and shrinkage (C1). Figure 5 illustrates three-dimensional scanning electron micrographs of specimens A, B, and C, each labeled with distinct types of defects: A1, A2, A3 for specimen A, B1, B2, B3 for specimen B, and C1, C2, C3 for specimen C. Initially, Scanning Electron Microscopy (SEM) was employed to verify the existence of flaws in the surplus of each sample by examining small sections that were cut.

3.2. Hardness testing (HT)

The term "hardness" referred to a material's resistance to localized plastic deformation. The hardness of the material, which is a mechanical characteristic that represents resistance to scratching, can be used to derive a qualitative measurement of its tensile strength. The toughness was assessed using the following three criteria: A measurement of the material's abrasion resistance, b) elastic hardness, and c) resistance to penetrating forces. A hardness test determines how resistant a material's surface is to being pierced by an object of comparable or greater hardness. The Rockwell hardness scale is based on the fundamental idea that "hardness varies inversely to depth of penetration." The scale's underlying logic was as follows. The table presents hardness values (measured in HV, Vickers hardness) for three different compositions of titanium matrix composites (TMCs). These compositions are identified as B1 (75% Ti + 24% Al_2O_3 + 1% Mg), C1 (75% Ti + 24% BN + 1% Mg), and A1 (80% Ti + 19% SiC + 1% Mg). For each composition, hardness measurements were taken across nine different samples. The hardness values for B1 ranged from 315 HV to 324 HV, with an average hardness of approximately 319 HV. The hardness values for C1 ranged from 295 HV to 304 HV, with an average hardness of about 299 HV. Finally, the hardness values for A1 ranged from 345 HV to 354 HV, with an average hardness of approximately 349 HV shown in figure 6. The data shows that composition A1 (80% Ti + 19% SiC + 1% Mg) exhibited the highest average hardness values, indicating strong resistance to indentation. Composition B1 (75% Ti + 24% Al_2O_3 + 1% Mg) showed intermediate hardness, while composition C1 (75% Ti + 24% BN + 1% Mg) had the lowest average hardness, suggesting it may be less resistant to indentation. These hardness measurements are critical in assessing the mechanical properties and suitability of these TMC compositions for specific applications, with higher hardness generally indicating greater resistance to wear and deformation. As a result, the higher the hardness, the shallower the penetration, and vice versa. The experimental setup that was used to measure the Rockwell hardness test of the titanium silicon carbide specimen.

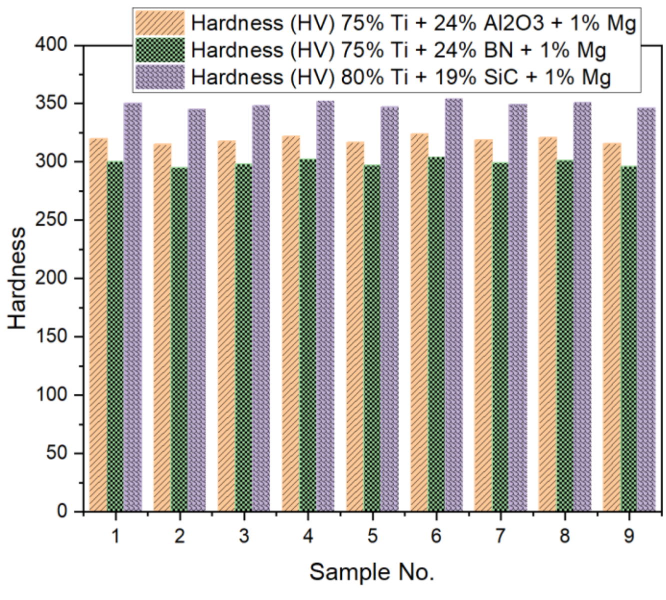

Figure 6. Rockwell hardness test of the titanium silicon carbide specimen

3.3. Mechanical properties Tensile strength, Yield strength, Elongation

The first set of TMCs, labeled A1 through A9, contains 80% titanium, 19% silicon carbide (SiC), and 1% magnesium (Mg). These composites exhibit consistent trends in tensile strength, yield strength, and elongation, with an average tensile strength of approximately 549 MPa, yield strength of around 449 MPa, and an average elongation of 10.3%. The second set of TMCs labeled B1 through B9, consists of 75% titanium, 24% aluminum oxide (Al_2O_3), and 1% magnesium (Mg). These TMCs show a similar trend with an average tensile strength of approximately 450 MPa, yield strength of around 350 MPa, and an average elongation of 8.3%. The third set, C1 through C8, comprises TMCs with 75% titanium, 24% boron nitride (BN), and 1% magnesium (Mg). These composites display the lowest mechanical properties among the three sets, with an average tensile strength of about 397 MPa, yield strength of roughly 297 MPa, and an average elongation of 6.1%. The figure 7 (a, b, c) provides a comprehensive dataset on the mechanical properties of different titanium matrix composites (TMCs) with varying compositions. The data illustrates that TMCs with higher silicon carbide content (A1-A9) exhibit the highest mechanical properties, including tensile and yield strength, along with greater elongation. TMCs with aluminum oxide (B1-B9) fall in the mid-range, while those with boron nitride (C1-C9) have the lowest mechanical performance. These variations in properties can influence the choice of TMC composition for specific applications, depending on the desired balance between strength and ductility.

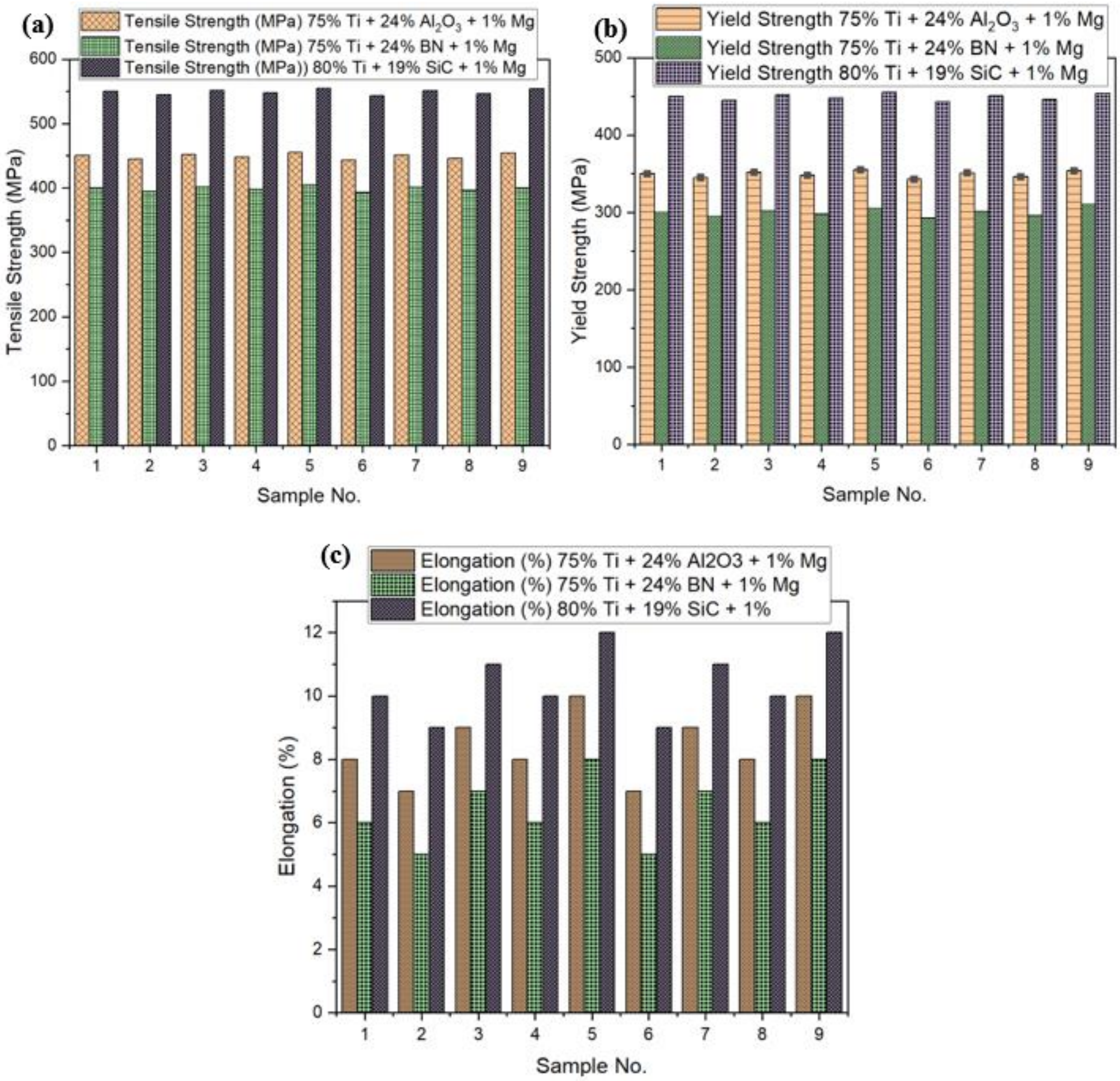

Figure 7. Mechanical Properties of Titanium Matrix Composites (TMCs) with Different Compositions (a) tensile strength (b) yield strength, (c) elongation

4. Maximum temperature difference vs defect depth in the defect area and maximum temperature difference in the non-defect area

The first set of TMCs, labeled A1 through A9, contains 80% titanium, 19% silicon carbide (SiC), and 1% magnesium (Mg). These composites exhibit consistent trends in tensile strength, yield strength, and elongation, with an average tensile strength of approximately 549 MPa, yield strength of around 449 MPa, and an average elongation of 10.3%. The second set of TMCs, labeled B1 through B9, consists of 75% titanium, 24% aluminum oxide (Al_2O_3), and 1% magnesium (Mg). These TMCs show a similar trend with an average tensile strength of approximately 450 MPa, yield strength of around 350 MPa, and an average elongation of 8.3%. The third set, C1 through C8, comprises TMCs with 75% titanium, 24% boron nitride (BN), and 1% magnesium (Mg). The figure 8 (a, b, c) provides a comprehensive dataset on the mechanical properties of different titanium matrix composites (TMCs) with varying compositions. These composites display the lowest mechanical properties among the three sets, with an average tensile strength of about 397 MPa, yield strength of roughly 297 MPa, and an average elongation of 6.1%. The data illustrates that TMCs with higher silicon carbide content (A1-A9) exhibit the highest mechanical properties, including tensile and yield strength, along with greater elongation. TMCs with aluminum oxide (B1-B9) fall in the mid-range, while those with boron nitride (C1-C8) have the lowest mechanical performance. These variations in properties can influence the choice of TMC composition for specific applications, depending on the desired balance between strength and ductility.

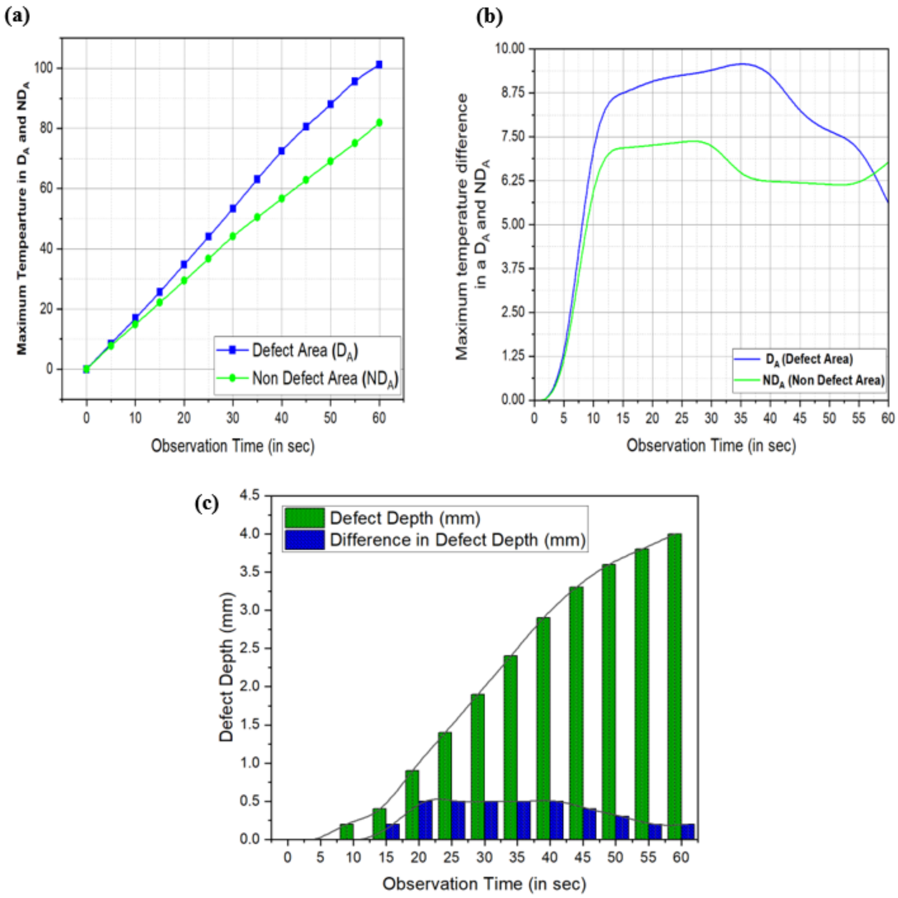

Figure 8. (a) Maximum Temperature in the Defect Area vs. Defect Depth, (b) (Maximum Temperature Difference in the Non-Defect Area, (c) defect depth

The maximum temperature difference in both defect and non-defect areas as a function of defect depth, observed over different time intervals. The table reveals that as the observation time increases from 0 to 60 seconds, the maximum temperature in the defect area experiences a gradual rise, reaching 101.18°C after 60 seconds. The maximum temperature difference in the defect area also increases from 0°C at the start to 9.37°C after 30 seconds, then tapers off to 5.60°C at 60 seconds. The defect depth in the defect area gradually deepens from 0 mm to 4.0 mm during the 60-second observation period. In contrast, the non-defect area shows different trends. The maximum temperature in the non-defect area increases from 0°C at the beginning to 81.88°C after 60 seconds. The maximum temperature difference in the non-defect area starts at 0°C and steadily climbs to 6.78°C after 60 seconds. Longer observation times lead to higher temperatures in both defect and non-defect areas, deeper defects, and increased temperature differences. This data is valuable for understanding the behavior of defects and temperature differences in different areas over time, which can be essential for various applications, such as non-destructive testing and quality control.

Conclusion

This research study provides a comprehensive exploration of Titanium Matrix Composites (TMCs) reinforced with Silicon Carbide (SiC), Alumina (Al_2O_3), and Boron Nitride (BN) with a focus on materials and manufacturing, characterization, and defect detection. The study emphasizes ceramic particle size, distribution, particle-matrix interface strength, and consolidation porosity to make high-quality TMCs for aerospace, automotive, biomedical, and electronics applications. The study began with stir casting TMC coupons with different aluminum and silicon carbide compositions. Different compositions of TMCs A, B, and C were used. For industrial applications, Al_2O_3 and BN TMCs are cheaper, but SiC ones have better mechanical properties. SEM detected specimen shrinkage, porosity, hot tear, and blow hole defects. SEM generated three-dimensional micro-level chemical and physical surface images. Rockwell hardness tests assessed localized plastic deformation resistance to determine tensile strength. The data revealed that SiC-reinforced TMCs exhibited the highest average hardness, indicating strong resistance to indentation. Tensile testing further highlighted the mechanical properties of the TMCs, with TMCs containing higher SiC content exhibiting the highest tensile strength and yield strength. The study also investigated temperature variations in defect and non-defect areas over time. Longer observation times led to higher temperatures in both areas, deeper defects, and increased temperature differences. In conclusion, this research contributes to the advancement of Titanium Matrix Composites in various industries by providing a detailed understanding of their manufacturing, characterization, defect detection, and mechanical properties. The study offers insights into tailoring TMC compositions for specific applications and ensuring high-quality production.

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