Mechanical, Thermal and Microstructural Characterization of Ti-SiC Metal Matrix Composites with Varying SiC Content using Powder Metallurgy.

Prof K.A. Shaikh[2], Dr B.K. Sonage[1], Prof S.S. Kale[2], Dr A.S. Kashid[2]

1. Professor in Mechanical Engineering Department at NKOCET Solapur

2 Assistant Professor in Mechanical Engineering Department at NKOCET Solapur

Abstract

These Ti MMCs reinforced with SiC have a high strength-to-weight ratio, high thermal stability, corrosion resistance, and are in great demand in the aerospace, automotive, and defence fields. This paper presents the mechanical, thermal, and microstructural characterization of Ti MMCs reinforced with different SiC contents, namely: 1.5%, 2.5%, 3.5%, and 4.5%. An analysis has been conducted into the effect of SiC content on hardness, tensile strength, fracture toughness, thermal conductivity, and microstructure of composites. According to the findings, Mechanical properties increased with an increase in SiC up to 3.5% followed by further increments of SiC, resulting in particle agglomeration with slight property degradation. Microstructural analysis reveals uniform dispersion of SiC at low concentrations and aggregation at higher SiC content. Such microstructural features could be optimized for Ti-SiC MMCs toward high-performance applications.

Keywords

Titanium Matrix Composites (Ti MMCs), Silicon Carbide (SiC), Reinforcement, Mechanical Properties, Microstructure, Thermal Conductivity

1. Introduction

Titanium and its alloys have impressive strength-to-weight ratio, corrosion resistance, and high-temperature performance. However, they are not without shortcomings in terms of wear resistance, stiffness, and thermal conductivity (Budinski, 1991; Kutas & Misra, 1992). To eliminate these disadvantages, the reinforcement of titanium with ceramic particles, in particular SiC, has been a subject of great interest (Poletti et al., 2008). SiC provides high hardness, low density, and excellent thermal stability, which has made it the most widely used reinforcement material for Ti MMCs (Oh et al., 2003).

In this study, the influence of different SiC contents on the mechanical, thermal, and microstructural properties of Ti MMCs was examined. Characterization was given more importance in characterizing the influence of SiC content on hardness, tensile strength, fracture toughness, and thermal conductivity.

2. Materials and Methods

2.1 Materials

In order to fabricate the composites, commercially pure titanium (Grade 2) as a matrix, which has an approximate composition that includes 99.2% titanium, 0.05% carbon, 0.1% nitrogen, 0.25% oxygen, and 0.1% iron; and silicon carbide (SiC) particles approximately 10 µm in diameter as the reinforcements. The utilized four different vol% SiC concentrations were as follows: 1.5%, 2.5%, 3.5%, and 4.5%.

Composition and 5mm balls placed in jar

Compression testing machine

Specimen after sintering

2.2 Fabrication of Ti-SiC MMCs

The composites were prepared using the powder metallurgy route. Initially, a planetary ball mill at 300 rpm for 6 hours was used to get uniform dispersion of the reinforcement after mixing titanium powder with SiC particles. Thereafter, the powders were cold-pressed into cylindrical molds at a pressure of 350 MPa followed by sintering in a vacuum furnace at 1100°C for 2 hours for full densification and homogenous composite formation.

2.3 Characterization Techniques

The following characterization techniques were utilized to assess the properties of Ti-SiC MMCs:

•Microstructural Analysis: The microstructure has been assessed by Scanning Electron Microscopy (SEM) and optical microscopy. An Energy-Dispersive X-ray Spectroscopy was carried out in order to evaluate the distribution of SiC particles within the titanium matrix.

•Hardness Testing: Vickers hardness has been measured at the cross-section of the composites, under a 1 kg load, for 15 seconds.

•Tensile Testing: The tensile strength and elongation at room temperature were tested on the Instron 5569 universal testing machine with a crosshead speed of 1 mm/min.

•Fracture Toughness: The SENB method was employed for the determination of fracture toughness by strictly following all the procedures mentioned in the ASTM E399 standards.

•Thermal Conductivity: The thermal conductivity was determined using the laser flash technique from 25°C to 500°C by employing the LFA 467 HyperFlash.

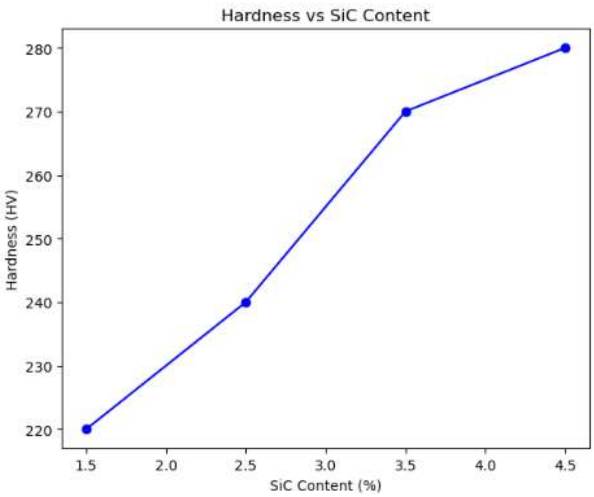
3. Results and Discussion

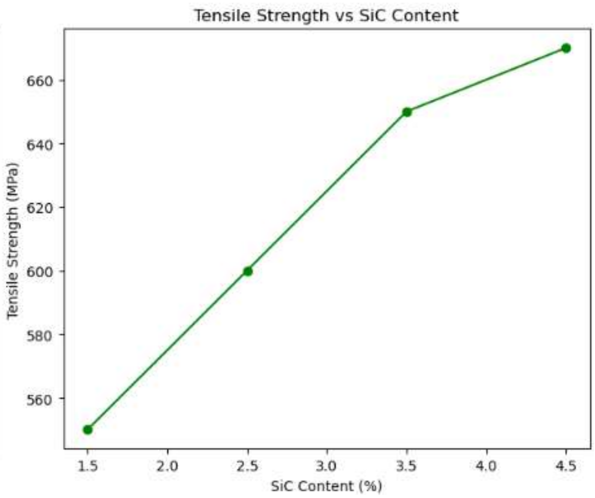
3.1 Microstructure of Ti-SiC MMCs

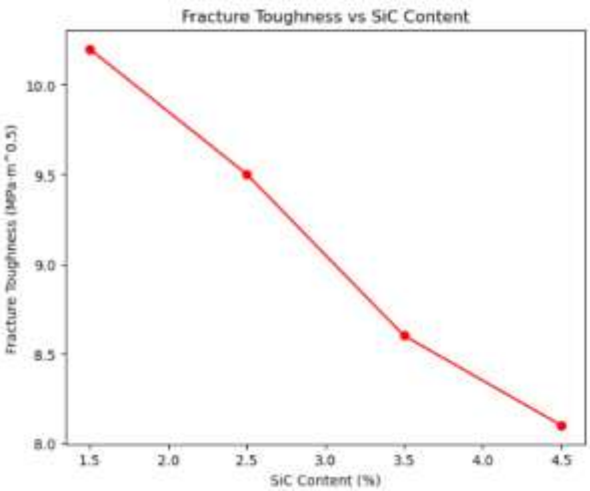
At the lower SiC concentrations of 1.5% and 2.5%, the SiC particles were uniformly distributed in the microstructure within the titanium matrix. Higher percentages of SiC (3.5% and 4.5%) promoted agglomeration, leading to localized clustering of these particles. Agglomeration may be detrimental to the mechanical properties of the composite. Though that was the case, the strength of the titanium matrix and the SiC particle interface was sound, which reveals good bonding of the matrix to the reinforcement. Figure 1 shows the microstructure of Ti-2.5%SiC composite wherein the SiC particles are very well dispersed throughout the titanium matrix with no detectable porosities or other defects, inferring effective sintering.

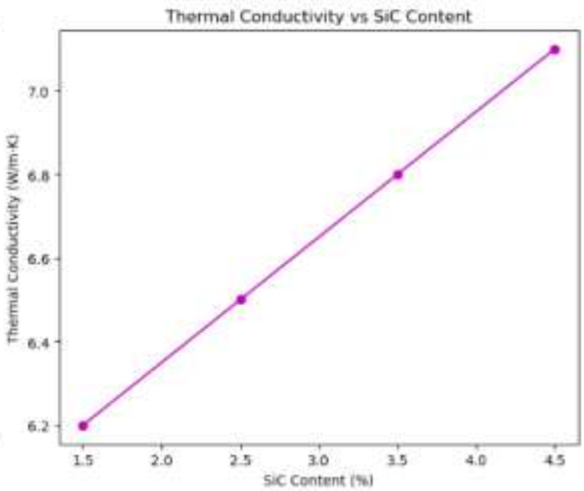
3.2 Hardness

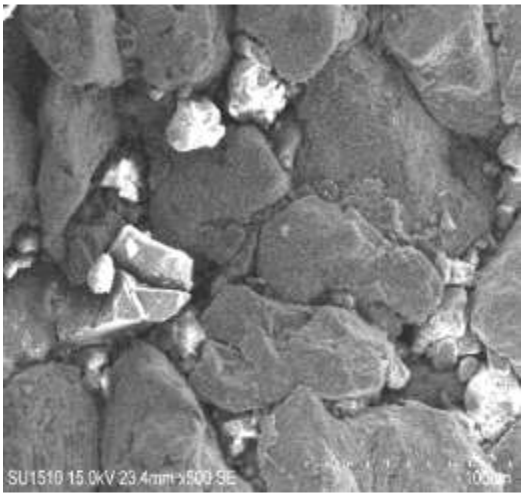
The hardness of the Ti-SiC MMCs increased with the addition of SiC content, as anticipated because of the inherent hardness of SiC. The Vickers hardness values for the composites with 1.5%, 2.5%, 3.5%, and 4.5% SiC content were found to be 220, 240, 270, and 280 HV, respectively. This increase in hardness can be explained by the SiC particles as an obstacle to impede dislocation motion, hence increasing the material's ability to resist indentation.



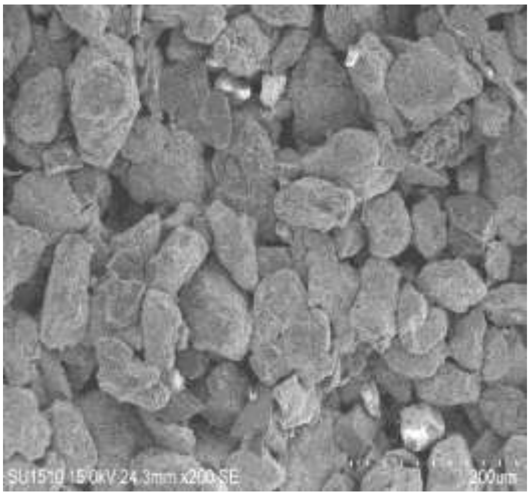








Ti 90%+Al 6%+V 4%+SiC 1.5%



Ti 90%+Al 6%+V 4%+SiC 3%

3.3 Tensile Strength

The tensile test revealed that UTS rose with a gradual increase in the SiC reinforcement. The composites of Ti-1.5%SiC, Ti-2.5%SiC, Ti-3.5%SiC, and Ti-4.5%SiC composites had their UTS at 550 MPa, 600 MPa, 650 MPa, and 670 MPa, respectively. A significant increase was seen in the value of UTS up to 3.5% SiC reinforcement.

At 4.5% SiC, there was a slight decrease in tensile strength. This could be due to agglomeration of SiC particles that could cause stress concentration in the composite matrix.

3.4 Fracture Toughness

The fracture toughness of the composites decreased with an increase in SiC content. The values for fracture toughness of the composites with 1.5%, 2.5%, 3.5%, and 4.5% SiC were 10.2 MPa·m^0.5, 9.5 MPa·m^0.5, 8.6 MPa·m^0.5, and 8.1 MPa·m^0.5, respectively. The reason for the reduction in fracture toughness is the increased brittleness due to hard, brittle SiC particles that act as stress concentrators, thus promoting crack propagation.

3.5 Thermal Conductivity

There was a slight increase with an increase in SiC content in the measurements of thermal conductivity. The thermal conductivity of Ti-SiC composites is 6.2 W/m·K for Ti-1.5%SiC, 6.5 W/m·K for Ti-2.5%SiC, 6.8 W/m·K for Ti-3.5%SiC, and 7.1 W/m·K for Ti-4.5%SiC. This is due to the fact that the particles of SiC have relatively high thermal conductivity and enhance heat transfer within the composite. However, it was modest since the inherent thermal conductivity of the titanium matrix was low.

4. Conclusion

Mechanical properties such as hardness, tensile strength, and thermal conductivity of titanium improve remarkably with the addition of SiC particles. Optimum overall performance is obtained at a content of 3.5% SiC, which provides maximum tensile strength without compromising the fracture toughness to be in a balanced condition. Particle agglomeration up to a content of 4.5% is detrimental to mechanical performance.

Next, future research aimed at optimizing properties of Ti-SiC composites for high-performance applications should focus their efforts on the dispersion of SiC particles and how to prevent agglomeration through more advanced processing methods. Techniques involving in-situ fabrication or improved powder mixing strategies can help further enhance the performance of such composites.

References

1. Poletti C, Balog M, Schubert T, Liedtke V, Edtmaier C. "Production of titanium matrix composites reinforced with SiC particles." *Composite Science and Technology*. 2008;68(9): 2171-2177.
2. Budinski KG. "Tribological properties of Titanium alloys." *Wear.* 1991;151: 203-217.
3. Kutas FM, Misra MS. "Friction and wear of Titanium alloys." *ASM Handbook*. 1992;18: 778-784.
4. Alman DE, Hawk JA, Simmons JS. "Abrasive wear behavior or P/M titanium metal- matrix composites." *Advances in Powder Metallurgy and Particulate Materials*. 1997;7: 3-18.

5. Ashish Srivastava, Kadir Aajij Shaikh, Satish Bopanna ”Microstructural characterization of SiC reinforced Ti–6Al–4V metal matrix composites fabricated through powder metallurgy route.”, Materials Physics and Mechanics. 2023;51(3): 29-37.

6. Oh JC, Yun E, Golkovski MG, Lee S. “Improvement of hardness and wear resistance in SiC/Ti-6Al-4V surface composites fabricated by high-energy electron beam irradiation.” *Material Science and Engineering A*. 2003;351(1-2): 98-108.

7. Kadiraajij shaikh, Satish babu boppana,vijee kumar and Samuel Dayanand,”Production and characterization of titanium based metal matrix composites: a review”, journal of mines, metals & fuels, Vol.69, No.12A, December, 2021.

8. Wang P, Nian G, Qu S, Shan Y, Huang L, Peng HX. “Numerical study on Mechanical properties of discontinuously reinforced titanium matrix composite with network reinforcement architecture.” *International Journal of Applied Mechanics*. 2017;9(5): 1750073.

9. Kim YJ, Chung H, Kang SJ. “Processing and mechanical properties of Ti-6Al-4V/TiC in situ composite fabricated by gas-solid reaction.” *Material Science and Engineering A*. 2002;333(1-2): 343-350.

10. Cui ZD, Zhu SL, Man HC, Yang XJ. “Microstructure and wear performance of gradient Ti/TiN metal matrix composite coating synthesized using gas nitriding technology.” *Surface and Coatings Technology*. 2005;190(2-3): 309-313

11. Selamat MS, Watson LM, Baker TN. “XRD and XPS studies on surface MMC layer of SiC reinforced Ti-6Al-4V alloy.” *Journal of Materials Processing Technology*. 2003;142(3): 725-737.

12. Godfrey TMT, Goodwin PS, Ward-Close CM. “Production of titanium particulate metal matrix composite by mechanical milling.” *Material Science and Technology*. 2000;16(7-8): 753-758.

13. Lu H, Zhang D, Gabbitas B, Yang F and Matthews S. “Synthesis of a TiBw/Ti6Al4V composite by powder compact extrusion using a blended powder mixture.” *Journal of Alloys and Compounds*. 2014;606: 262-268.

14. Kondoh K, Threrujirapapong T, lmai H, Umeda J, Fugetsu B. “Characteristics of powder metallurgy pure titanium matrix composite reinforced with multi-wall carbon nanotubes.” *Composites Science and Technology*. 2009;69(7-8): 1077-1081.

15. Liu Y, Chen LF, Tang HP, Liu CT, Liu B, Huang BY. “Design of powder metallurgy titanium alloys and composites.” *Material Science and Engineering A*. 2006;418(1-2): 25-35.

16. Kim IY, Choi BJ, Kim YJ, Lee YZ. “Friction and wear behavior of titanium matrix (TiB+ TiC) Composites.” *Wear*. 2011; 271(9-10): 1962-1965.

17. Alman DE, Hawk JA. “The abrasive wear of sintered titanium matrix- ceramic particle reinforced composites.” *Wear*. 1999:225-229: 629-639.

18. Ravindran P, Manisekar K, Rathika P, Narayanasamy P. “Tribological properties of powder metallurgy-Processed aluminium self-lubricating hybrid composites with SiC additions.” *Materials & Design. 2013;45: 561-570.*

19. Kobayashi M, Funami K, Suzuki S, Ouchi C. “Manufacturing process and mechanical properties of fine TiB dispersed Ti-6Al-4V alloy composites obtained by reactive sintering.” *Material Science and Engineering A*. 1998;243(1-2): 279-284.

20. Poletti C, Holtl G. “Mechanical properties of particle reinforced titanium and titanium alloys”, *Kovove Materials*. 2010;48(2): 87-95.

21. Sabry, I, Ghafaar MA, Mourad, AHI, Idrisi AH. “Stir casted SiC-Gr/Al6061 hybrid composite tribological and mechanical properties.” *SN Appl. Sci. 2020;2: 943.*

22. Siva Surya M, Prasanthi G. “Physical and mechanical characterisation of Al7075/SiC functionally graded materials fabricated by powder metallurgy route.” *Advances in Materials and Processing Technologies*. 2020;8(1): 1007-1022.

23. Gotman E, Gutmanas Y, Mogilevsky P. “Interaction between SiC and Ti powder.” *Journal of Material Research*. 1993;8(10): 2725-2733.

24. Sivakumar G, Ananthi V, Ramanathan S. “Production and mechanical properties of nano SiC particle reinforced Ti-6Al-4V matrix composite.” *Transaction of Non-ferrous metal society of China. 2017;27(1): 82-90.*

25. Tripathi H, Bharti A, Saxena KK, Kumar N. “Improvement in mechanical properties of structural AZ91 magnesium alloy processed by friction stir processing.” *Advances in Materials and Processing Technologies*. 2020;8(3). 1543-1556.