Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Investigation on Water Erosion Behavior of Ti-based Metal Matrix Composite: Experimental Approach

Dipak Kale[1], Rachayya Arakerimath[2], Khizar Ahmed Pathan[3], Sher Afghan Khan[4,*]

1 Department of Mechanical Engineering, G H Raisoni College of Engineering & Management, SPPU, Pune-412207, India
2 Department of Mechanical Engineering, Rajarshi Shahu College of Engineering, SPPU, Pune-412207, India
3 Department of Mechanical Engineering, CSMSS Chh. Shahu College of Engineering, Kanchan wadi, Aurangabad-431011, India
4 Mechanical and Aerospace Engineering Department, Faculty of Engineering, International Islamic University, Kuala Lumpur, 53100, Malaysia

ARTICLE INFO

Article history:
Received 14 June 2024
Received in revised form 21 September 2024
Accepted 30 September 2024
Available online 20 October 2024

Keywords:
Metal matrix composites; water droplet erosion; titanium; turbine blades

ABSTRACT

Wet steam flow produces big water droplets in the low-pressure zone of a steam turbine blade. These droplets clash with subsequent blades, resulting in a strong impact that is evident as erosion. Titanium and its alloys are valuable for technical applications such as turbine blades because of their low density, high strength, and exceptional corrosion resistance. The boron carbide(B4C) has a high hardness but a low strength; therefore, it's exciting to investigate water erosion of Ti/ B4C and SiC combination. The effect of 1 wt% B4C and 1, 3, 5, and 7 wt% SiC particles on water droplet erosion of Ti composite was studied using the SPS method for 5 minutes at 1200 °C temperature and 50 MPa pressure. The L9 orthogonal array with four levels of parameters of the Taguchi method is used to conduct the experiments. By measuring the weight of the specimen at interval time, the erosion behavior with time is obtained with different nozzle diameters. The effect of material and experimental parameters on erosion resistance is studied, and an empirical relation is developed.

1. Introduction

Water droplet erosion is the gradual loss of original material brought about by fast-moving water droplets or jets repeatedly striking a solid surface. Droplet impact erosion is a well-known phenomenon that occurs in the low-pressure stages of steam turbines and indirectly impacts the steam turbines' lifespan and efficiency [1-5]. In addition, water droplet erosion (WDE) has been observed in other machines like wind turbine blades, blades of gas turbines, aircraft outer parts, etc [6-8]. Ahmad *et al.,* [9] used the wear test setup to examine five distinct materials' water droplet impact on wear performance. They examined the effects of impact angle, droplet impact velocity, surface sawtooth formation, and material damage degree on liquid impingement erosion. The erosion resistance of the laser-hardened X5CrNiCuNb 16-4 was the best, while Ti6Al4V outperformed all other tested high-yield strength blade steels in the impact velocity range. Numerous studies that

* *Corresponding author.*
E-mail address: sakhan@iium.edu.my

https://doi.org/10.37934/arfmts.122.2.7182

have been conducted to link a material's WDE resistance with a set of macroscopic mechanical properties have revealed that a material's hardness, resilience, toughness, tensile strength, elasticity, and strain energy all have a major impact on its capacity to tolerate water droplet erosion [9,10]. It was shown that improving the hardness of the surface while preserving the homogeneous microstructure was a useful strategy for mitigating erosion-damaging occurrences and improving erosion performances [11]. Kamkar *et al.,* [12] investigated the WDE in Ti-6Al-4V and revealed the damage propagation mechanism in the early stages of water erosion. Ahmad *et al.,* [13] developed an empirical model to predict water droplet erosion in low-pressure steam turbine blades. The hardness-induced elastic resilience represents the material erosion strength, and it depends on parameters like yield strength, modulus of elasticity, and hardness value, as shown in Eq. (1).

$$Ur = \frac{{\sigma_y}^2}{2E} = \frac{{H_v}^2}{18E} \tag{1}$$

where Ur is the elastic resilience, σ_y yield strength, E modulus of elasticity, and H_v is the Vickers surface hardness value. Fujisawa *et al.,* [14] investigated the influence of material hardness on water droplet erosion ra, revealed that erosion decreases with increased hardness value, and developed an empirical model. A water droplet erosion model developed by Lee *et al.,* [15] is shown in Eq. (2).

$$E = k\left(\frac{m}{m_{ref}}\right)\left(\frac{V}{V_{ref}}\right)^{\alpha}\left(\frac{d}{d_{ref}}\right)^{\beta} 10^{\gamma Hv} \tag{2}$$

where m mass flow rate, V velocity, d droplet diameter, and α, β, γ are the constants.

The high strength-to-density ratio, high stiffness and strength, good wear resistance, and low thermal coefficient of expansion of titanium matrix composite make it popular; nevertheless, its low hardness and erosion value limit its applications [16-20]. The Ti-based composite with different reinforcing is considered to get around these restrictions. Han *et al.,* [21] manufactured (TiB+TiC)/Ti composite using Ti and B4C powder and stated that the 1wt% B4C addition gives higher elastic modulus, yield strength, and ultimate tensile strength. Mixing and B4C powder generates the TiB and TiC [22]. Namini *et al.,* [16] sintered the Ti with various wt% of B4C at 1200 oC and 50 MPa. They reveal that the ultimate tensile strength and elongation at room temperature is best for 0.24wt% B4C and the worst for 1.94wt% B4C. Also, they have demonstrated that more B4C is added to increase microhardness. Ti is reinforced with SiC particles to generate the Ti-SiC composite, and both wear resistance and hardness have improved in the composite [23]. The B4C-SiC composite made using spark plasma sintering shows an increase in SiC % and a decrease in density.

Moreover, the Vickers hardness value rises as the SiC % does [24]. Ti's wear resistance performance and microhardness SiC are reasonable compared to only Ti because of the formation of TiC component [25]. The impact of high velocity is correlated with material stiffness, and in the case of Ti, it is amplified by the presence of SiC-reinforcing particles [26]. There is no gain in hardness or strength when more SiC particles are added because they create a brittle interface [27].

Hence, The B4C particles give high hardness, yield strength, tensile strength, and elastic modulus, and the SiC reinforcement improves the wear resistance. The WDE depends on velocity, pressure, impact angle, and mass flow rate. This work aims to investigate the effect of water droplets and develop the WDE empirical model for the Ti matrix with reinforcement of B4C and varying wt% of SiC particles by considering various experimental parameters. Furthermore, the scanning electron microscopy and powder metallurgical process study are also presented, highlighting the development of new materials that will be helpful for the material research world.

Some studies have studied related topics using computational simulations and experimental methods. Shaikh *et al.,* [28,29] investigated the performance of catalytic converters, highlighting flow regularity and pressure drop minimization. Using numerical simulations, Pathan *et al.,* [30] and Shaikh *et al.,* [31] optimized nozzle designs for weight reduction and studied surface pressure distributions over wedges at high Mach numbers. Shamitha *et al.,* [32,33] contributed to understanding the surface pressure characteristics of wedges in supersonic and hypersonic flows, applying numerical techniques and design experiments (DOE).

Furthermore, using CFD analysis, Pathan *et al.,* [34-40] explored various aspects of suddenly expanded flows, including base pressure variations and thrust optimization. Their studies provided critical insights into fluid dynamics and geometric optimization in high-speed flow regimes.

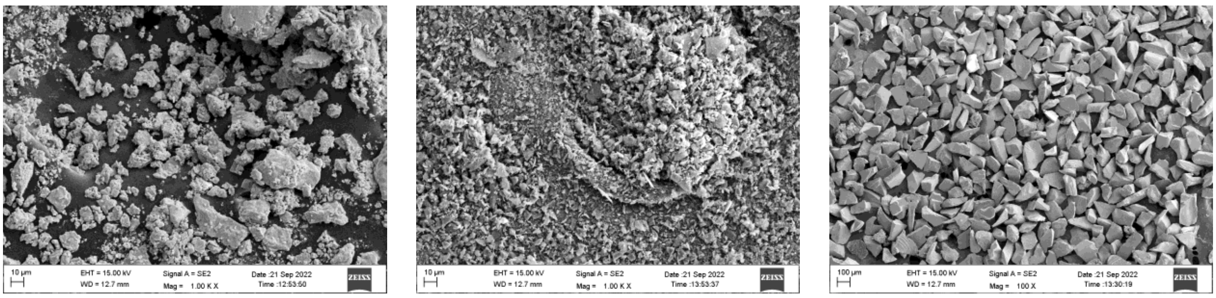
Moreover, Jain *et al.,* [41] investigated the influence of plate-fin heat sink orientation under natural convection, combining experimental and numerical approaches to enhance thermal performance. Khan *et al.,* [42,43] optimized two-dimensional wedge flow fields at supersonic Mach numbers, focusing on aerodynamic efficiency and optimization strategies.

These collective studies contribute significantly to understanding fluid dynamics, structural optimization, and aerodynamic performance across various applications. By leveraging these insights, the current study aims to explore experimental methodologies to characterize erosion resistance in Ti-based MMCs, thereby enhancing their durability and performance in practical environments.

2. Experimental

2.1 Materials

In this work, B4C and SiC particles were introduced as reinforced particles, and Ti powder was utilized as the matrix material. The Ti powder and B4C & SiC powder are supplied by NANOSHEL Punjab India and Universal Scientific Solutions (Alfa Aesar) Uttarakhand India, respectively. The high purity titanium micro powder with 99% purity, 40-50 micron approximate particle size, 47.86 g/mol molecular weight, and 4.54g/cm3 density, and B4C & SiC with 10 -15 micron, 120-150 micron respectively were used. The SEM images of Ti, B4C, and SiC powder are shown in Figure 1.



(a) (b) (c)

Fig. 1. SEM micrograph for (a)Ti, (b) B4C, and (c) SiC powder as received

The Retsch planetary ball milling machine is used to blend the powder. It has a 200 rpm milling speed, a 9:1 ball-to-powder ratio, room temperature, and a 2-hour milling duration. The milling medium consists of tungsten carbide spherical balls with a 10 mm diameter and a stainless steel vial. The mixed powder is pressed at 50MPa pressure inside the vacuum chamber for 5 minutes at a 1200^0 C temperature and 100 ^{0}C /min heating rate. The graphite dies used had an outer diameter and length of 30 mm and an inner diameter of 15.5 mm. A graphite sheet is positioned between the powder and the mold to aid in demolding. The specimen is prepared with different combinations of SiC particles, as shown in Table 1.

Table 1
Composition of the powder mixture

Composition	Designation
Ti	S1
Ti + B4C (1%)	S2
Ti + B4C (1%) + SiC (1%)	S3
Ti + B4C (1%) + SiC (3%)	S4
Ti + B4C (1%) + SiC (5%)	S5
Ti + B4C (1%) + SiC (7%)	S6

The specimen is cooled at atmospheric temperature. The sample specimen is shown in Figure 2.

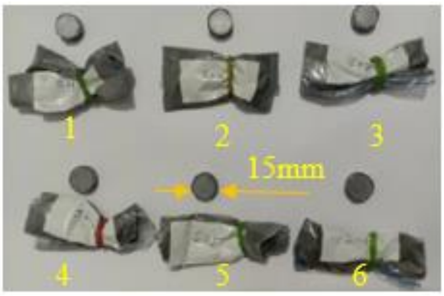
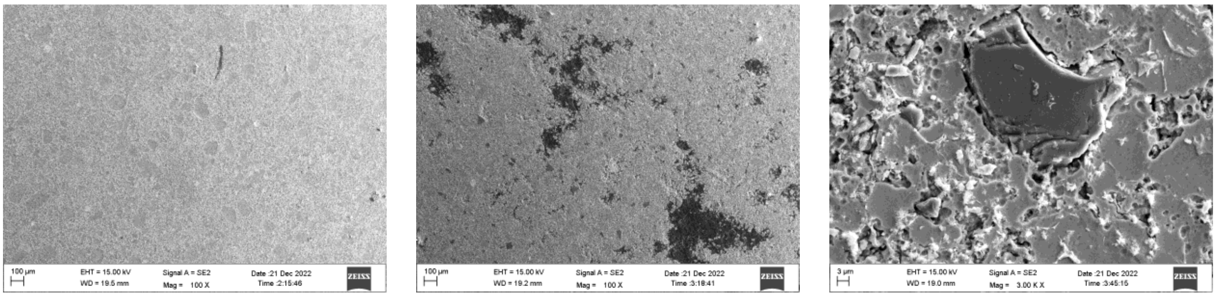


Fig. 2. Specimen prepared using SPS

Figure 3 shows the microstructure of the polished and etched surfaces of specimens S2, S4, and S5, a, b, and c, respectively. In the S4 sample, black patches are observed due to the aggregation of B4C and SiC powder particles. The SEM image of the S5 sample indicates the gap between the particles, which shows imperfect bonding, which leads to low mechanical strength and erosion resistance properties.

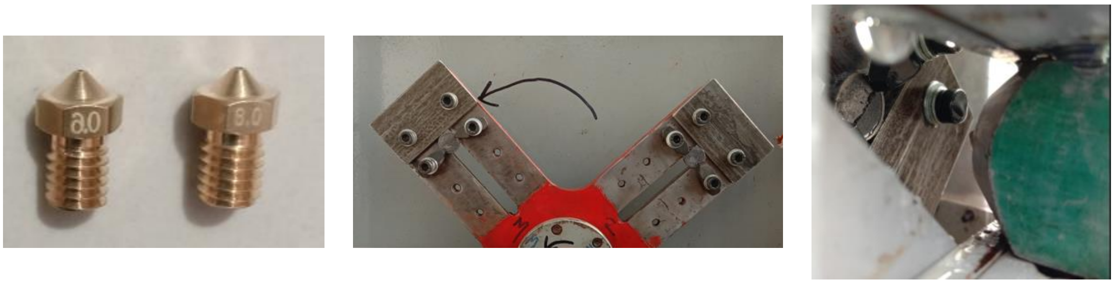

(a) (b) (c)
Fig. 3. SEM images of S2,S4 and S5 samples

2.2 Experimental Setup

The water droplet erosion test rig is designed to perform research experiments on water droplet erosion for different materials, especially blade-related ones. The test rig simulates a high-speed rotating turbine blade. Most of the experiment platform comprises a three-phase variable speed motor, a speed controller, an experimental chamber, a high-pressure water pump, and a nozzle assembly. The testing facility includes a chamber with a round disc with four arms and testing specimens fixed on the periphery. The actual test rig is shown in Figure 4. The rig is made up of a main frame that supports the high-speed three-phase motor, speed controller, and test chamber. The water container, jet assembly, and high-pressure pump are maintained separately from the main frame structure for portability.

Fig. 4. Experimental test rig

The speed regulator controls the three-phase motor, coupled to the spinning arms via the coupling and shaft. The motor speed ranges from 1500 to 3000 revolutions per minute. The maximum working pressure for the pump can reach 200 bar ~ 240 bar. Because of the measurable and adjustable nature of the water pressure, the jet velocity may accurately mirror the real-world velocity of wet steam droplets. The four rotating arms are configured to insert the specimen at various radial distances. An essential component of the throttle nozzle is its diameter, which needs to be adjustable or exchangeable. Figure 5(a) displays the throttle nozzles with different diameters.



(a) (b) (c)

Fig. 5. Nozzle and Specimen arrangement

As illustrated in Figure 5(c), the jet injector is attached to the test chamber shell, and the nozzle extending into the chamber cover inside confronts the specimen surfaces. The machine must be stopped throughout the experiment, and the specimen surface must be examined regularly. The front side of the test chamber is made of acrylic materials, which allows for a clear view of the specimen status. A precision balance with a 0.01 mg accuracy was used to measure the weight lost following a specific test duration. The length of the test was considered to cause significant impingement erosion. Table 1 gives the material samples tested for erosion.

2.3 Experimental Test Conditions

During the test, a well-known and proven Taguchi technique-based design of the experiment tool was implemented to develop a practical approach and simulate the effect of multiple process parameters of the erosion process. Experiments were performed using the four-factor, four-level Taguchi method to elaborate on the influence of individual parameters. The experiment parameters are shown in Table 2.

Table 2
Experiment test condition

Exp.No	Nozzle dia(mm)	Pressure(bar)	Angle(°C)	Speed(rpm)
1	0.4	140	60	1800
2	0.4	160	70	2000
3	0.4	180	80	2200
4	0.4	200	90	2400
5	0.6	140	70	2000
6	0.6	160	60	2400
7	0.6	180	90	1800
8	0.6	200	80	2000
9	0.8	140	80	2400
10	0.8	160	90	2200
11	0.8	180	60	2000
12	0.8	200	70	1800
13	1	140	90	2000
14	1	160	80	1800
15	1	180	70	2400
16	1	200	60	2200

3. Results and Discussion

In the current research study, Experiments are carried out to investigate the effect of water erosion on Ti-based metal matrix composites with varied amounts of SiC and B4C reinforcement. On a test rig, water erosion is performed on six different types of Ti metal matrix composite specimens created from powdered metallurgical processes for 180 min. Some sample erosion observation patterns of specimens are shown in Figure 6. The test condition is shown in Table 2 and Table 3. Figure 6 and Figure 7 to Figure 9 show the performance for test case 1 and test case 2 conditions, respectively. It is well known that properties of materials such as hardness, tensile strength, binding energy, and modulus of resilience play a critical role in determining erosion.

Table 3
Test Conditions 1

Test No	Nozzle dia (mm)	Angle of Impact	Disc speed (rpm)	Pressure (bar)
Test 1	0.8	90^0	2400	200
Test 2	0.6	90^0	2400	200

Fig. 6. Erosion in specimen S1-S4

Figure 7 shows the erosion resistance compared to the hardness value. In this research, erosion resistance is considered reciprocal to erosion mass. The erosion resistance for specimen 6 is higher than all other specimens. For S4 and S6, due to improper binding between reinforcement grains, the hardness value seems to have declined, irrespective of the high hardness of reinforcement, and the result shows poor erosion resistance. Figure 8 shows the erosion concerning surface hardness value. The regression equation is shown in Eq. (3) with an R2 value of 0.73.

$$Er = -0.0001Hv + 0.0921 \quad (3)$$

It is observed that erosion in specimens 6 and 3 is lower than in other specimens. The erosion resistance per unit hardness value representation is enclosed in Figure 7. The erosion resistance per unit hardness value is high for the S3 specimen, as shown in Figure.7. Compared to it, specimen 6 has an even higher percentage of SiC reinforcement with good hardness and erosion resistance properties. The erosion in specimen 1 is higher than in other specimens, as shown in Figure 8. for test condition 2. The empirical model considering experimental parameters is developed using regression analysis as given in Eq. (4). Eq. (5) provides the water with erosion with consideration of material properties and experimental properties.

$$E_e = a + \alpha_e N_d + \beta_e P + \gamma_e A + \delta_e V \quad (4)$$

$$E_{em} = b + \alpha_{em} N_d + \beta_{em} P + \gamma_{em} A + \delta_{em} V + c_{em} H_v + c_1 E - c_2 H_v \quad (5)$$

where E_e =erosion(g), N_d =nozzle diameter(mm), A =Angle of impact, V =Speed of specimen(rpm). α_e, β_e, γ_e, δ_e, α_{em}, β_{em}, γ_{em}, δ_{em} are the constants, and their values are shown in Table 4.

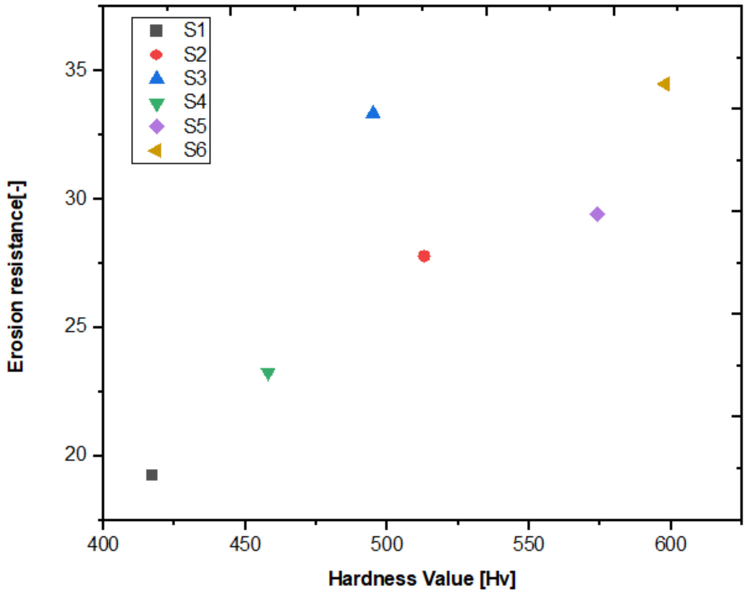


Fig. 7. Erosion resistance in test 1 condition

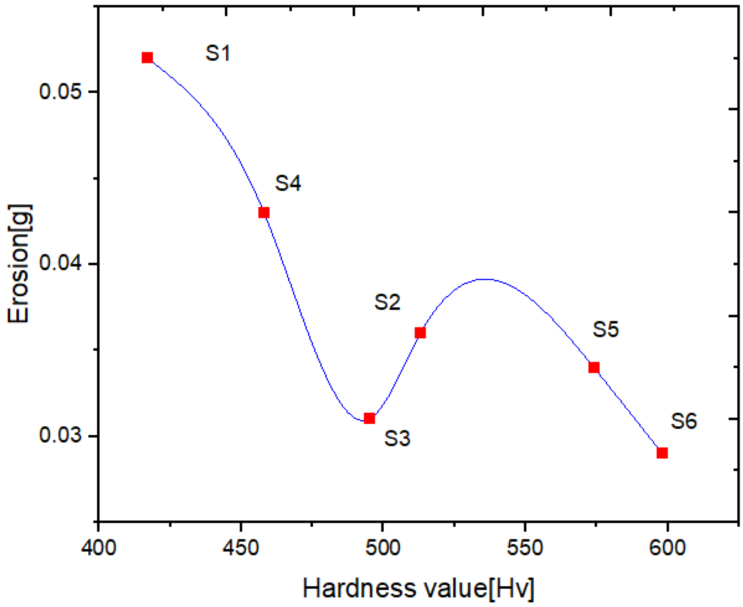


Fig. 8. Erosion in test 1 condition

Table 4
Erosion constants

Constant	Values
α_e	1.307E-2
β_e	6.53749E-05
γ_e	1.4527E-4
δ_e	5.44791E-06
α_{em}	9.3458E-3
β_{em}	4.672916E-05
γ_{em}	1.0384E-4
δ_{em}	3.894090E-06
a	1.174000E-09
b	2.674000E-02
c_1	2.271630E-04
c_2	1.106035E-04

It is seen from Figure 10 that excellent erosion resistance is given by specimen 6, followed by specimens 3 and 5. The resistance increased from specimen 1 to 3 and then decreased for 4. It is seen from Figure 8 and Figure 9 that excellent performance is given by the S3 specimen, which contains 1wt% of silicon carbide and boron carbide, followed by the S1 and S2 specimens. Adding 1wt% B4C in Ti enhanced the mechanical properties of the composite, and the addition of SiC improved the wear properties [21,23]. Due to this, the S3 specimen gives excellent results compared to other specimens. The SiC and B4C have an exceptional characteristic of absorbing impact energy. It is seen that Ti performance is improved by adding SiC and B4C with proper percentages.

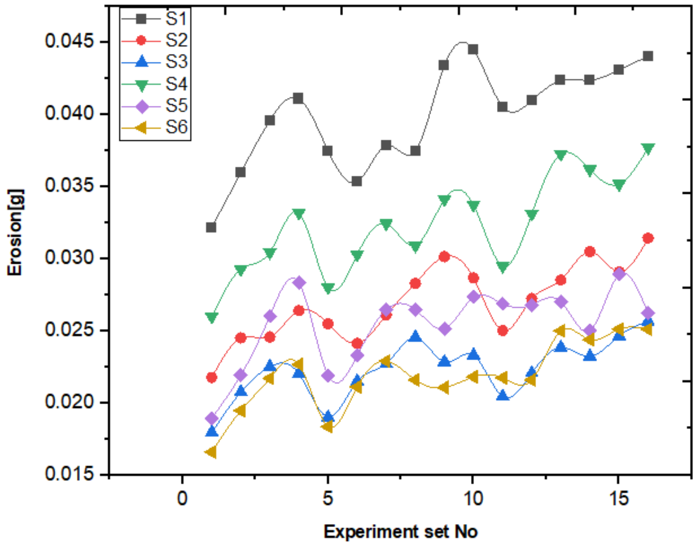


Fig. 9. Erosion in specimen S1-S6 for test condition 2

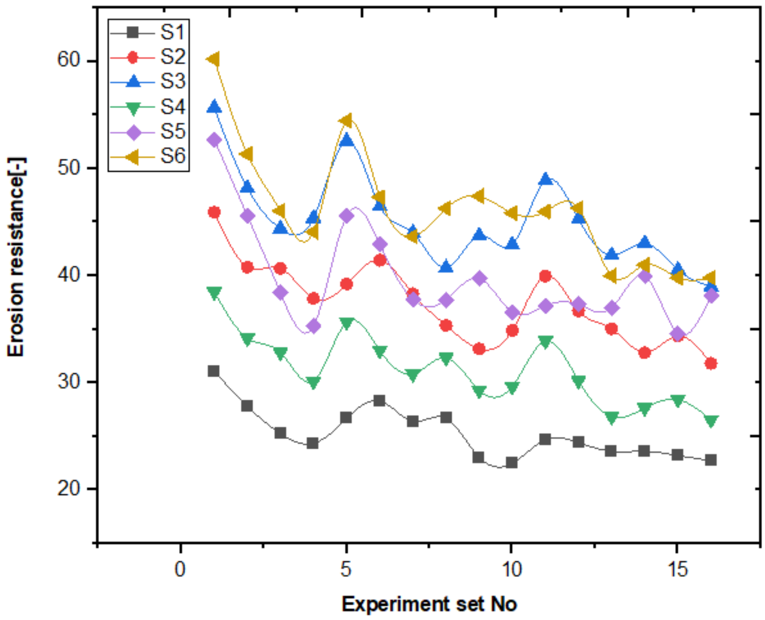


Fig. 10. Erosion resistance in specimen S1-S6 for test condition 2

4. Conclusions

The Ti- B4C-SiC metal matrix composite uses 1% B4C and 1%, 3%, 5%, and 7% SiC reinforcements using the spark plasma sintering powder metallurgical technique. They experimented with Ti metal matrix composites using a rotating specimen water erosion setup using the Taguchi method. An empirical model based on various parameters has been developed. The main conclusions are summarized below.

- (i) The water erosion testing is performed on six types of specimens for 180 min using Taguchi's L9 orthogonal array with 4-factor levels, and results are analyzed in detail.
- (ii) With increasing the percentage of SiC, agglomeration occurs, and the gap is produced between the grains. This causes the higher erosion per unit hardness in samples 5 and 6 compared to specimen 3.
- (iii) The erosion in specimen 1 is 44.23 times and 48.28 times more than in specimens 3 & 5, respectively.
- (iv) It is observed that, due to the addition of reinforcement materials, the water Erosion resistance in specimens 3 and 6 is improved compared to other specimens.

Acknowledgment
The use of the SPS facility at IIT Kanpur, procured with partial funding from the Department of Science and Technology, Government of India, and CARE funding from IIT Kanpur, is gratefully acknowledged.

References

[1] Mahdipoor, M. S., F. Tarasi, C. Moreau, A. Dolatabadi, and M. Medraj. "HVOF sprayed coatings of nano-agglomerated tungsten-carbide/cobalt powders for water droplet erosion application." *Wear* 330 (2015): 338-347. https://doi.org/10.1016/j.wear.2015.02.034

[2] Ziegler, D., M. Puccinelli, B. Bergallo, and A. Picasso. "Investigation of turbine blade failure in a thermal power plant." *Case Studies in Engineering Failure Analysis* 1, no. 3 (2013): 192-199. https://doi.org/10.1016/j.csefa.2013.07.002

[3] Rajendra, Kale Dipak, and Rachayya Arakerimath. "Analysis of Steam Turbine Blade Failure Causes." In *ICRRM 2019-System Reliability, Quality Control, Safety, Maintenance and Management: Applications to Civil, Mechanical and Chemical Engineering*, pp. 46-52. Springer Singapore, 2020. https://doi.org/10.1007/978-981-13-8507-0_8

[4] Kirols, H. S., D. Kevorkov, A. Uihlein, and M. Medraj. "The effect of initial surface roughness on water droplet erosion behaviour." *Wear* 342 (2015): 198-209. https://doi.org/10.1016/j.wear.2015.08.019

[5] Kirols, H. S., M. S. Mahdipoor, D. Kevorkov, A. Uihlein, and M. Medraj. "Energy based approach for understanding water droplet erosion." *Materials & Design* 104 (2016): 76-86. https://doi.org/10.1016/j.matdes.2016.04.089

[6] Chen, Junlei, Jihui Wang, and Aiqing Ni. "A review on rain erosion protection of wind turbine blades." *Journal of Coatings Technology and Research* 16 (2019): 15-24. https://doi.org/10.1007/s11998-018-0134-8

[7] Zhang, Shizhong, Kim Dam-Johansen, Sten Nørkjær, Pablo L. Bernad Jr, and Søren Kiil. "Erosion of wind turbine blade coatings-design and analysis of jet-based laboratory equipment for performance evaluation." *Progress in Organic Coatings* 78 (2015): 103-115. https://doi.org/10.1016/j.porgcoat.2014.09.016

[8] Burson-Thomas, Charles B., Richard Wellman, Terry J. Harvey, and Robert J. K. Wood. "Water droplet erosion of aeroengine fan blades: The importance of form." *Wear* 426 (2019): 507-517. https://doi.org/10.1016/j.wear.2018.12.030

[9] Ahmad, M., M. Casey, and N. Sürken. "Experimental assessment of droplet impact erosion resistance of steam turbine blade materials." *Wear* 267, no. 9-10 (2009): 1605-1618. https://doi.org/10.1016/j.wear.2009.06.012

[10] Mann, B. S. "Water droplet and cavitation erosion behavior of laser-treated stainless steel and titanium alloy: their similarities." *Journal of Materials Engineering and Performance* 22 (2013): 3647-3656. https://doi.org/10.1007/s11665-013-0660-6

[11] Mahdipoor, M. S., D. Kevorkov, P. Jedrzejowski, and M. Medraj. "Water droplet erosion behaviour of gas nitrided Ti6Al4V." *Surface and Coatings Technology* 292 (2016): 78-89. https://doi.org/10.1016/j.surfcoat.2016.03.032

[12] Kamkar, N., F. Bridier, P. Jedrzejowski, and Philippe Bocher. "Water droplet impact erosion damage initiation in forged Ti-6Al-4V." *Wear* 322 (2015): 192-202. https://doi.org/10.1016/j.wear.2014.10.020

[13] Ahmad, M., M. Schatz, and M. V. Casey. "An empirical approach to predict droplet impact erosion in low-pressure stages of steam turbines." *Wear* 402 (2018): 57-63. https://doi.org/10.1016/j.wear.2018.02.004
[14] Fujisawa, Nobuyuki, Takayuki Yamagata, Shotaro Takano, Kengo Saito, Ryo Morita, Kazutoshi Fujiwara, and Fumio Inada. "The influence of material hardness on liquid droplet impingement erosion." *Nuclear Engineering and Design* 288 (2015): 27-34. https://doi.org/10.1016/j.nucengdes.2015.03.016
[15] Lee, Byeong- Eun, Kap- Jong Riu, Se- Hyun Shin, and Soon- Bum Kwon. "Development of a water droplet erosion model for large steam turbine blades." *KSME International Journal* 17 (2003): 114-121. https://doi.org/10.1007/BF02984292
[16] Namini, Abbas Sabahi, Seyed Ali Delbari, Behzad Nayebi, Mehdi Shahedi Asl, and Soroush Parvizi. "Effect of B4C content on sintering behavior, microstructure and mechanical properties of Ti-based composites fabricated via spark plasma sintering." *Materials Chemistry and Physics* 251 (2020): 123087. https://doi.org/10.1016/j.matchemphys.2020.123087
[17] Zhang, Faming, Juan Wang, Tengfei Liu, and Caiyun Shang. "Enhanced mechanical properties of few-layer graphene reinforced titanium alloy matrix nanocomposites with a network architecture." *Materials & Design* 186 (2020): 108330. https://doi.org/10.1016/j.matdes.2019.108330
[18] Fan, Kuowei, Faming Zhang, Caiyun Shang, Farhad Saba, and Jin Yu. "Mechanical properties and strengthening mechanisms of titanium matrix nanocomposites reinforced with onion-like carbons." *Composites Part A: Applied Science and Manufacturing* 132 (2020): 105834. https://doi.org/10.1016/j.compositesa.2020.105834
[19] Attar, Hooyar, Shima Ehtemam-Haghighi, Damon Kent, and Matthew S. Dargusch. "Recent developments and opportunities in additive manufacturing of titanium-based matrix composites: A review." *International Journal of Machine Tools and Manufacture* 133 (2018): 85-102. https://doi.org/10.1016/j.ijmachtools.2018.06.003
[20] Lu, Jinwen, Longlong Dong, Yue Liu, Yongqing Fu, Wei Zhang, Yu Du, Yusheng Zhang, and Yongqing Zhao. "Simultaneously enhancing the strength and ductility in titanium matrix composites via discontinuous network structure." *Composites Part A: Applied Science and Manufacturing* 136 (2020): 105971. https://doi.org/10.1016/j.compositesa.2020.105971
[21] Han, Changjun, Rita Babicheva, Jasper Dong Qiu Chua, Upadrasta Ramamurty, Shu Beng Tor, Chen-Nan Sun, and Kun Zhou. "Microstructure and mechanical properties of (TiB+ TiC)/Ti composites fabricated in situ via selective laser melting of Ti and B4C powders." *Additive Manufacturing* 36 (2020): 101466. https://doi.org/10.1016/j.addma.2020.101466
[22] Nartu, Mohan Sai Kiran Kumar Yadav, Srinivas A. Mantri, Mangesh V. Pantawane, Yee-Hsien Ho, Brandon McWilliams, Kyu Cho, Narendra B. Dahotre, and Rajarshi Banerjee. "In situ reactions during direct laser deposition of Ti-B4C composites." *Scripta Materialia* 183 (2020): 28-32. https://doi.org/10.1016/j.scriptamat.2020.03.021
[23] Das, Mitun, Vamsi Krishna Balla, Debabrata Basu, Susmita Bose, and Amit Bandyopadhyay. "Laser processing of SiC-particle-reinforced coating on titanium." *Scripta Materialia* 63, no. 4 (2010): 438-441. https://doi.org/10.1016/j.scriptamat.2010.04.044
[24] Sahin, Filiz Cinar, Burcu Apak, Ipek Akin, Halide E. Kanbur, Didem H. Genckan, Ahmet Turan, Gultekin Goller, and Onuralp Yucel. "Spark plasma sintering of B4C-SiC composites." *Solid State Sciences* 14, no. 11-12 (2012): 1660-1663. https://doi.org/10.1016/j.solidstatesciences.2012.05.037
[25] Lin, Yuan-Ching, and Yu-Chi Lin. "Microstructure and tribological performance of Ti-6Al-4V cladding with SiC powder." *Surface and Coatings Technology* 205, no. 23-24 (2011): 5400-5405. https://doi.org/10.1016/j.surfcoat.2011.06.001
[26] Shojaei, Pouya, Mohamed Trabia, Brendan O'Toole, Richard Jennings, Xing Zhang, and Yiliang Liao. "Enhancing hypervelocity impact resistance of titanium substrate using Ti/SiC Metal Matrix Nanocomposite coating." *Composites Part B: Engineering* 194 (2020): 108068. https://doi.org/10.1016/j.compositesb.2020.108068
[27] Sivakumar, G., V. Ananthi, and S. Ramanathan. "Production and mechanical properties of nano SiC particle reinforced Ti-6Al-4V matrix composite." *Transactions of Nonferrous Metals Society of China* 27, no. 1 (2017): 82-90. https://doi.org/10.1016/S1003-6326(17)60009-8
[28] Shaikh, Sohel Khalil, Khizar Ahmed Pathan, Zakir Ilahi Chaudhary, B. G. Marlpalle, and Sher Afghan Khan. "An investigation of three-way catalytic converter for various inlet cone angles using CFD." *CFD Letters* 12, no. 9 (2020): 76-90. https://doi.org/10.37934/cfdl.12.9.7690
[29] Shaikh, Sohel Khalil, Khizar Ahmed Pathan, Zakir Ilahi Chaudhary, and Sher Afghan Khan. "CFD analysis of an automobile catalytic converter to obtain flow uniformity and to minimize pressure drop across the monolith." *CFD Letters* 12, no. 9 (2020): 116-128. https://doi.org/10.37934/cfdl.12.9.11612
[30] Pathan, Khizar Ahmed, Zakir Ilahi Chaudhary, Ajaj Rashid Attar, Sher Afghan Khan, and Ambareen Khan. "Optimization of Nozzle Design for Weight Reduction using Variable Wall Thickness." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 112, no. 2 (2023): 86-101. https://doi.org/10.37934/arfmts.112.2.86101

[31] Shaikh, Javed Shoukat, Khizar Ahmed Pathan, Krishna Kumar, and Sher Afghan Khan. "Effectiveness of Cone Angle on Surface Pressure Distribution along Slant Length of a Cone at Hypersonic Mach Numbers." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 104, no. 1 (2023): 185-203. https://doi.org/10.37934/arfmts.104.1.185203

[32] Shamitha, Shamitha, Asha Crasta, Khizer Ahmed Pathan, and Sher Afghan Khan. "Numerical simulation of surface pressure of a wedge at supersonic Mach numbers and application of design of experiments." *Journal of Advanced Research in Applied Mechanics* 101, no. 1 (2023): 1-18. https://doi.org/10.37934/aram.101.1.118

[33] Shamitha, Shamitha, Asha Crasta, Khizar Ahmed Pathan, and Sher Afghan Khan. "Analytical and Numerical Simulation of Surface Pressure of an Oscillating Wedge at Hypersonic Mach Numbers and Application of Taguchi's Method." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 30, no. 1 (2023): 15-30. https://doi.org/10.37934/araset.30.1.1530

[34] Pathan, Khizar A., Sher A. Khan, N. A. Shaikh, Arsalan A. Pathan, and Shahnawaz A. Khan. "An investigation of boattail helmet to reduce drag." *Advances in Aircraft and Spacecraft Science* 8, no. 3 (2021): 239.

[35] Pathan, Khizar, Prakash Dabeer, and Sher Khan. "An investigation of effect of control jets location and blowing pressure ratio to control base pressure in suddenly expanded flows." *Journal of Thermal Engineering* 6, no. 2 (2019): 15-23. https://doi.org/10.18186/thermal.726106

[36] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Effect of nozzle pressure ratio and control jets location to control base pressure in suddenly expanded flows." *Journal of Applied Fluid Mechanics* 12, no. 4 (2019): 1127-1135. https://doi.org/10.29252/jafm.12.04.29495

[37] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Optimization of area ratio and thrust in suddenly expanded flow at supersonic Mach numbers." *Case Studies in Thermal Engineering* 12 (2018): 696-700. https://doi.org/10.1016/j.csite.2018.09.006

[38] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Investigation of base pressure variations in internal and external suddenly expanded flows using CFD analysis." *CFD Letters* 11, no. 4 (2019): 32-40.

[39] Pathan, Khizar Ahmed, Syed Ashfaq, Prakash S. Dabeer, and Sher Afgan Khan. "Analysis of Parameters Affecting Thrust and Base Pressure in Suddenly Expanded Flow from Nozzle." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 64, no. 1 (2019): 1-18.

[40] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Influence of expansion level on base pressure and reattachment length." *CFD Letters* 11, no. 5 (2019): 22-36.

[41] Jain, Yogeshkumar, Vijay Kurkute, Sagar Mane Deshmukh, Khizar Ahmed Pathan, Ajaj Rashid Attar, and Sher Afghan Khan. "The Influence of Plate Fin Heat Sink Orientation under Natural Convection on Thermal Performance: An Experimental and Numerical Study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 114, no. 2 (2024): 118-129. https://doi.org/10.37934/arfmts.114.2.118129

[42] Khan, Sher Afghan, M. A. Fatepurwala, K. N. Pathan, P. S. Dabeer, and Maughal Ahmed Ali Baig. "CFD analysis of human powered submarine to minimize drag." *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* 8, no. 3 (2018): 1057-1066. https://doi.org/10.24247/ijmperdjun2018111

[43] Khan, Sher Afghan, Abdul Aabid, Imran Mokashi, Abdulrahman Abdullah Al-Robaian, and Ali Sulaiman Alsagri. "Optimization of two-dimensional wedge flow field at supersonic Mach number." *CFD Letters* 11, no. 5 (2019): 80-97.