

Mechanical and wear optimization investigation of Titanium alloy nanocomposites made with selective laser melting process

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ABSTRACT

Titanium alloys are utilized in many fields of science, engineering, and technology because of their superior mechanical and tribological properties. The investigation goal is to develop an innovative composite for use in the automobile industry by applying additive processes such as selective laser melting and reinforcing titanium alloy with bio-silica. Bio-Silica (BS) nanoparticles are extracted using agricultural waste of *Calotropis gigantea* as reinforcement. The Industrial Grade Titanium (IGT) alloy nanocomposites are employed for making alloys with bio-silica nanoparticles reinforcement of 0, 5, 10, and 15%. The IGT/BS nanocomposites mechanical properties, such as microhardness, tensile (ultimate and yield) strength, and compressive strength, were investigated. According to the investigation's outcomes, 15wt.%IGT/BS nanocomposites had better mechanical characteristics. L9 Taguchi's orthogonal array is utilized to illustrate the wear trials. ANOVA is used to optimize outcomes. The ANOVA was utilized to determine the ideal process parameters that would result in the lowest possible wear rate and coefficient of friction (COF). The findings indicated that the applied load of 30 N, sliding velocity of 4 m/s, and sliding distance of 2000 m may achieve the lowest wear. According to an ANOVA, load is the most significant factor (30%) influencing wear.

Keywords: Titanium alloy; Selective laser melting; Wear; ANOVA; Bio-silica.

1. INTRODUCTION

Lightweight applications were needed by the automobile sector to increase overall system performance. Mechanical and tribological characteristics, including creep, fatigue, hardness, density, strength, stiffness, wear resistance, and thermal conductivity, all improve system efficiency and performance for the automobile sector [1]. Composite materials are claimed to produce good mechanical and tribological characteristics in a variety of engineering, science, and technology fields, including automotive, aerospace, biomedical and instruments, civil structures, defence, electrical and electronics equipment, food technology equipment, marine applications, sports goods, and transportation [2]. The metal matrix composites were able to achieve improved mechanical, physical, chemical, and tribological properties by the utilization of many matrix components, such as copper, titanium, magnesium, aluminium, and steel [3]. Excellent mechanical and tribological qualities were also attained by titanium and its alloy, which found usage in a variety of productions, including sports goods, automotive, aerospace, marine, defence, biomedical, and power plants [4]. In metal matrix composites, reinforcing is essential for improving tribological and mechanical properties such as creep, fatigue, hardness, density, strength, stiffness, wear resistance, and thermal conductivity [5]. For the purpose of enhancing mechanical, physical, chemical, and tribological properties, commonly used ceramic type reinforcements include Alumina (Al_2O_3), Silicon Carbide (SiC), Titanium Carbide (TiC), Titanium Boride (TiB_2), Zirconium Oxide (ZrO_2), Boron Carbide (B_4C), Aluminum Nitride (AlN), Silicon Nitride (Si_3N_4), Magnesium Oxide (MgO), Titanium Nitride (TiN), Zirconium Carbide (ZrC), and Tungsten Carbide (WC) [6].

For this investigation, the matrix material of choice was Industrial Grade Titanium (IGT), which is renowned for its remarkable strength-to-weight ratio, corrosion resistance, and biocompatibility. Among the industries that commonly employ IGT are automotive, aerospace and aviation, chemical processing, marine applications, energy, medical and dental, sports equipment, architecture, and electronics. In titanium alloys with high temperature stages, silicon in the form of silicide is an important content and improves the strength, creep resistance, and oxidation resistance [7]. The addition of nanoscale silicon and silicide to titanium alloy (Ti-4Al-4Mo-4Sn) improved the composites' high strength, yield strength, bonding between the titanium alloy and reinforcement, and reduced ductility when they were produced using a powder metallurgy method [8]. SiCf/SiC reinforcement was added to the titanium-silicon alloy (Ti16Si84) for making composites, which demonstrated enhanced wettability and corrosion resistance [9]. Ti6Al4V matrix composites enhanced with SiC were solidified by pulsed electric current sintering (PECS). One of the consequences of the composites was the strengthening, enhanced hardness, and greater flexural strength achieved by adding SiC particles to the titanium matrix [10]. Three different categories of industrial debris with high concentrations of Si, Ti, and Fe. Minimizing resource depletion, protecting the ecosystem, and promoting sustainability growth in industry all depend on their recovery [11]. (TiC + Ti_3Si_3)/Ti layered composites with graphene oxide and silicon powder added have shown improved yield strength, ultimate tensile strength, and strengthening of the grain boundary [12]. Reaction-bonded silicon carbide (RBSC) requires a high-strength joining in order to be used in the semiconductor industry [13]. The aerospace material titanium grade 5 alloy was coated with silicon aluminium mixed with multi wall carbon nanotubes utilizing a thermal spray technique to increase its physical, mechanical and tribological properties [14]. It is unique to reinforce pottery elements through nanoscale magnitudes on titanium alloys, boosting their hardness and resistance to wear. Conversely, a decrease in particle size also contributes to the reinforced materials' increased ductility, strength, and resistance to creep [15].

Microcrystalline silicon is a particle that is amorphous. In comparison to diamond, silicon exhibits softness, low melting, and chemical reactivity due to its lower bonding energy in its crystalline state. Machining apparatus, engines, cylinder heads, dynamo and transformer plates, and their decomposition are all made with silicon [16]. SiC/C nanocomposite material is produced from Si-containing biomass using a novel two-step process. Husks from rice, oats, and oats were selected as waste from agriculture because they have a high silicon concentration in the mineral component. Consequently, the discovered method enables us to transform waste from agriculture into high-tech, valuable goods in the form of materials that are electrocatalytically active [17]. The traditional restrictions in its synthesis process had been disrupted by the flaring out of silica nanoparticles from agricultural wastes. Rice husk, maize cob, sugarcane bagasse, palm ash, coconut fibre, bamboo leaves, tapioca, and other silica-rich effluvia were acknowledged as cost-effective precursors to activate silica nanoparticles [18].

Dental implants are surgically placed in the oral cavity to progress an capability to wad food. Crowns and other prosthetic teeth, bridges, and dentures are supported by them. Composites of silicate and bio-silica are used to make pharmacological prostheses [19]. The purpose of the bio-silica, which was made from Bermuda grass, is to enhance the mechanical and wear properties of the silver-grey magnesium. The excellent mechanical and tribological properties of the magnesium reinforced with bio-silica composite, produced using the stirring moulding technique, were attributed to improved bonding between the composite's components [20]. An aluminium/rice husk ash hybrid metal composite's composition diminished as the number of small concentrations of reinforcement elements augmented [21].

Numerous methods, including casting, additive manufacturing, spray casting, metallurgical route, and physical vapor deposition, are utilized to create metal matrix composites. Among all the production processes, stir forming is the most hands-on and cost-effective way to produce metal composites [22]. Nonetheless, conventional techniques of preparation such as the powder metallurgy route and the casting process show significant problems, including reactive surfaces that are harsh and restricted wettability between the matrix and reinforcements. As such, the metal matrix composites made using these techniques have unsatisfactory and uneven characteristics. SLM overcame the challenges by suitably altering the process parameters, enabling the creation of MMCs with directionally generated unique structures in detail [23]. Metal composites are treated using an additive manufacturing technique called selective laser melting (SLM). The benefit is the quick creation of intricate geometric patterns on objects. The shipbuilding, automotive, aerospace, and aviation industries have all lately seen a significant increase in the usage of flexible laser technology for additive manufacturing [24].

Calotropis gigantea is often considered a weed due to its large-scale cultivation for agricultural purposes, despite the fact that it grows wild along roadsides. The majority of creatures of all kinds do not consider it to be a suitable or safe diet. Calotropis gigantea is poisonous, so it's not a good idea to feed it to a lot of animals or birds of prey as an overall feed for animals. Agricultural waste of Calotropis gigantea may be utilized in many ways for metal applications, mainly because it can be employed as a potential strengthening component and

in ecologically conscious production methods. This is why waste from agriculture from *Calotropis gigantea* is used to create bio-silica nano reinforcement. According to earlier studies, bio-silica can provide efficient nano reinforcements that facilitate the production of metal matrix composites with better mechanical and tribological qualities at a lower weight and expense. The best way to get rid of *Calotropis gigantea* plant residue environmentally is to use the plant's leftovers to make bio-silica reinforcements. One extremely environmentally friendly method of eliminating *Calotropis gigantea* residue from leftover material from plants is to use bio-silica as nano reinforcement. Industrial Grade Titanium nanopowders (IGT)/bio-silica composite can be used in the aerospace, aero-structural, automotive, defence, energy storage, and medical instrument industries to make industrial tooling, mould making, robotics, manufacturing equipment, oil and gas valves, pumps, wellhead components, pipes, and chemical Heat exchangers, reactors, and process equipment. When lightweight components with outstanding hardness and strength are required, advantages over traditional production include weight savings, customization, easier assembly, quicker prototyping, and improved lifespan costs. The *Calotropis gigantea* plant is used to create the bio-silica that is added to a matrix of Industrial Grade Titanium nanopowders (IGT) to create this unique composite. This study examines the tribological parameters (wear, CoF) and mechanical parameters (microhardness, compressive strength, and tensile strength) of a special blend of bio-silica and Industrial Grade Titanium nanopowders (IGT) made by selective laser melting. The purpose of the investigation is to optimize the wear resistance parameters for the least amount of wear rate and coefficient of friction.

2. EXPERIMENTAL AND TESTING METHODS

In this current investigation, the Industrial Grade Titanium nanopowders (IGT) are added with bio-silica (0, 5, 10 and 15 wt.%) and the nanocomposites are prepared by selective laser melting. The bio-silica reinforcement is extracted from using agricultural waste of *Calotropis gigantea*. The process of bio-silica preparation is explained in Figure 1. *Calotropis gigantea* was harvested from Avinashi areas and used to prepare the bio-silica. Enormous quantities of *Calotropis gigantea* are accessible at Avinashi village inside the settlement area.

Calotropis gigantea dried in the sun for four days. The dried *Calotropis gigantea* lawn plants were put in an iron drum and sent separately to burn completely. The burning procedure resulted in the production of ash. After being sun-dried, utilizing a cylindrical roller grinder, the *Calotropis gigantea* ash is crushed to a smooth ingredient. It cooled for eight and a half hours before being removed from the drum. Lowering the temperature of carbonization was especially important to improve this technology's ecological attributes without sacrificing its suitability to be used in the purifying process. After purification, follow the phases of the processing of bio-silica as shown in Figure 2, and the produced high purity bio-silica. The detailed process for making Bio-silica (BS) nano reinforcement extract from *Calotropis gigantea* Ash (CGA) is depicted in the figure. The CGA blend with In a suitable container, dissolve 3.5 NaOH in distilled water to create an alkaline solution. After that, stir the mixture constantly while heating it for two hours to a temperature of around 150°C. Proceed to the following step of filtering and washing the mixture to remove the solid residue from the liquid after the alkaline treatment. Use distilled water to completely wash away any excess NaOH and other contaminants from the solid residue. The filtrate produced by the precipitation of silica method contains sodium silicate, which is dissolved



Figure 1: Synthesis of bio-silica nano reinforcing particles derived from *Calotropis*.

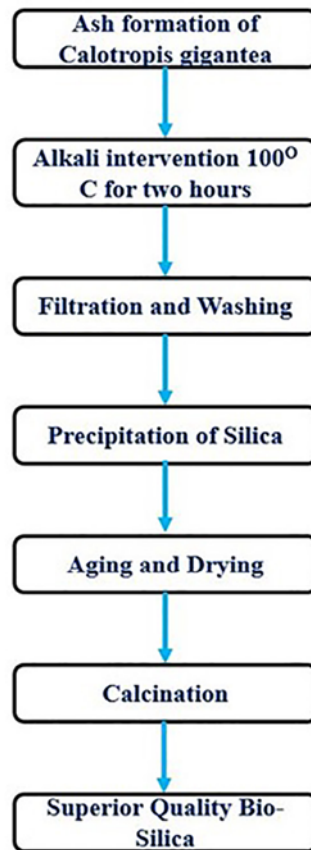


Figure 2: The phases of the processing of bio-silica.

silica. Using an HCL acid to bring the solution's pH down to about 7 can cause silica to precipitate out of it as a gel. For aging and drying, the following step. To enhance the silica gel's qualities, let it sit for a few hours. Use distilled water to wash the gel in order to get rid of any leftover contaminants. The silica gel should be dried entirely in an oven at 130°C. To get pure bio-silica, calcine the dried silica gel in an incinerator at a heating of around 800°C. This phase guarantees the elimination of any leftover organic contaminants and enhances the bio-silica's purity.

The IGT/BS nanocomposite had been formed by layer-by-layer fabrication using selective laser melting (SLM). The SLM process with nanocomposite production was explained in Figure 3. IGT/BS nanocomposite produced in compliance with Table 1. The preparation of the tensile test specimens can be observed in Figure 4. A popular advanced additive manufacturing method for creating intricate, high-performance parts is selective laser melting (SLM). Customization and design freedom, material efficiency, precise control, material versatility, enhanced mechanical properties, and cost-effectiveness for complex batches are some of the benefits of using SLM for experimentation, particularly when working with materials like titanium alloy nanocomposites [25].

Vickers microhardness tester was used to assess the microhardness of the IGT/BS nanocomposite. The ASTM E8-M04 micro hardness test was performed on four specimens. The computerized UTM was used to perform the tensile test. The ASTM E-8 standard was followed in the preparation of the test specimens. The specimens were produced in compliance with ASTM E-9 guidelines, as well as the compressive test was performed through a computerized UTM.

The pin-on-disc apparatus provided by DUCOM was utilized to conduct dry sliding wear testing on an alternative specimen. The ASTM G99 guidelines was adhered to, and grade H11 tool steel was used for the disc material in the pin on disc wear test apparatus. The hardness rating of the disc is 500 HB. This alloy can experience deep hardening by air quenching. This alloy's low carbon content and hardness make it appropriate for highly stressed structural components in the aircraft industry. The specimen was whipped next to the opposite face of a rotating disk that had a 60 mm wear track. Using a deadweight loading method, the specimen was loaded next to the disk. The wear test was conducted at sliding velocities of 2, 4, and 6 m/s and below the

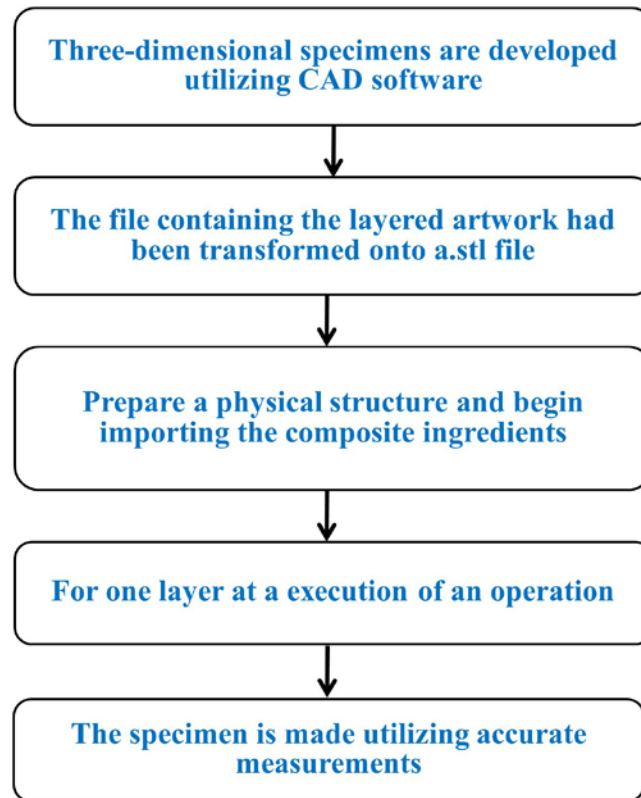


Figure 3: The SLM procedure flow diagram for the preparation of IGT alloy and IGT/BS nanocomposite.

Table 1: Contents of the produced IGT/BS nanocomposite.

SPECIMEN NO.	MATRIX (IN %)	REINFORCEMENT (IN %)
T1	100	0
T2	95	5
T3	90	10
T4	85	15



Figure 4: The tensile specimen of IGT alloy and IGT/BS nanocomposites.

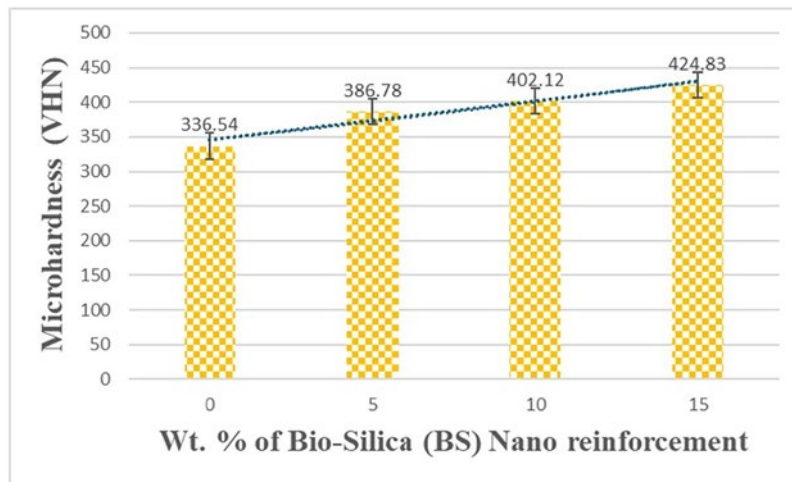


Figure 5: The microhardness of IGT and IGT/BS nanocomposite (in different wt. %).

standard loads of 10 N, 20 N, and 30 N. As shown below, wear tests were carried out over a total sliding distance of 2000 m (constant) in parallel environments. An IGT/BS nanocomposite specimen's wear worn surface analyses were performed utilizing field emission scanning electron microscopy (FESEM). ASTM E3-11 rules are followed in the production of the specimens. Taguchi's approach is a strong optimization strategy that focuses on reducing variance caused by uncontrolled elements in order to improve the quality of processes and products. It use orthogonal arrays and a design of experiments (DOE) methodology to methodically investigate how various factors affect performance. One statistical technique for determining and measuring each factor's and their interactions' contributions to overall performance is ANOVA [26]. The main input parameters for this approach are load, sliding velocity, and sliding distance, and The experiment is conducted with a L9 orthogonal array.

3. RESULTS AND DISCUSSION

3.1. Impact of Bio-Silica (BS) reinforcement on mechanical properties

The impact of bio-silica nano reinforcing particles on the microhardness of IGT alloy, IGT/BS nanocomposites at 5, 10, and 15 wt. % is shown in the Figure 5. The microhardness values of the IGT alloy and IGT/BS nanocomposites are 336.54 VHN, 386.78 VHN, 402.12 VHN, and 424.83, respectively. The increase in hardness seen in IGT/BS nanocomposites was due to producing dislocation brought on by the variation in laser heat expansion between IGT alloy and BS nano reinforcement. Meanwhile, the microhardness flinches to grow with the addition of 5, 10, and 15 weight percent of BS nano reinforcement. When compared to base alloy, there was a 26.23% improvement in microhardness and excellent bonding among the BS reinforcement with IGT matrix after the addition of BS particles to the IGT matrix. For previous investigation, titanium matrix composites (Ti6Al4V)/(TiB + TiC) and discovered that the addition of reinforcements enhances the material's microhardness [27]. Furthermore, compared to 20 wt.% SiCp, 15 wt.% SiCp generates an α -phase of titanium, enhancing the hardness. Furthermore, when SiCp weight percentage increases, fractures emerge due to a reduction in attraction and becoming interconnected [28]. TiC reinforcement was included in an alloy constructed from titanium (Ti-13Nb-13Zr) to develop an in-situ laser composite material were examined. In contrast to composites employing WC reinforcement particles, the outcomes demonstrated the composites' enhanced microhardness and wear resistance [29]. When high entropy alloy particles are added to the titanium alloy matrix at the sintering temperature, the hardness of the titanium matrix rises while the hardness of the high-entropy alloy particles falls [30]. For the similar studies that were conducted some of the reinforcement added to the matrix, due to the agglomeration of reinforcement, it can obviously be identified the microhardness values dropped and the failure occurred. When Al_2O_3 was added to the Al-Fe-Si Alloy Matrix in varying ratios, the hardness value decreased by 12 wt. % [31]. The investigation discovered that attaining desired mechanical characteristics depends critically on the ideal content of reinforcements. SiC presence increases hardness, but too much of it can cause agglomeration, increase porosity, and reduce hardness [32]. In contrast to the Mg-SiC composite without Ti, the hardness of the composite dropped when Ti was added [33].

Figure 6 illustrates the impact of bio-silica nano reinforcing particles on the yield and ultimate strengths of IGT alloy and IGT/BS nanocomposites at 5, 10, and 15 wt.%. The addition of BS nano reinforcing particles



Figure 6: The IGT and IGT/BS nanocomposites ultimate tensile and yield strengths.

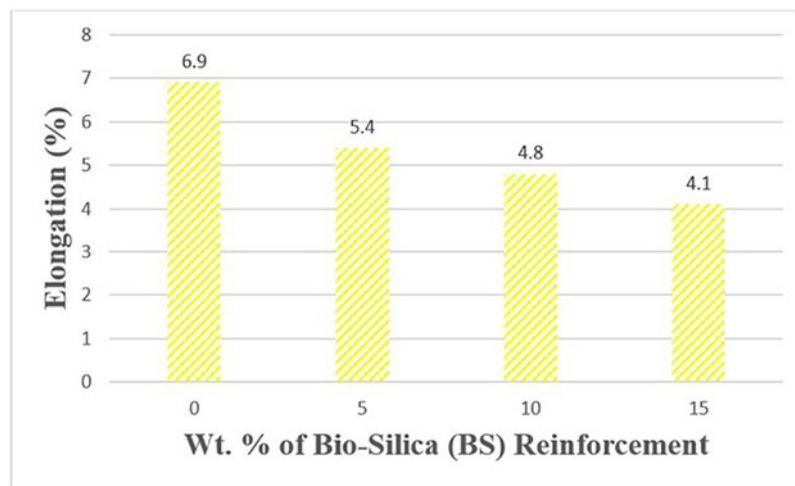


Figure 7: The elongation (%) of IGT and IGT/BS nanocomposite.

steadily increases the ultimate and yield strength of IGT alloys and IGT/BS nanocomposites. In contrast to the IGT matrix alloy, the IGT/BS nanocomposite's ultimate strength and yield strength are enhanced by 39.49% and 58.26%, respectively. The highest values of these strengths are 484.24 and 292.47, respectively. The % elongation of the IGT alloy and IGT/BS nanocomposites was shown in Figure 7, with the corresponding values being 6.9, 5.4, 4.8, and 4.1. The addition of BS nano reinforcing particles increases ultimate and yield strength relative to the base IGT alloy matrix without significantly lowering the nanocomposites percentage of elongation to failure. This is demonstrated by the IGT/BS nanocomposites higher ultimate and yield strength values than those of the IGT alloy base matrix.

In comparable research, stir casting was used for making SG-Mg-10% Si/bio-silica composites, which outperformed the basic matrix of silver-grey magnesium alloy in terms of tensile strength. A cutting-edge bio-silica substance made from wheat husks for high-tech silica-based applications [20]. The multilayer composite Ti 6Al 4 V/Cp Ti alloy was created by laser energy deposition, and the outcomes demonstrated improved homogeneity, tensile strength, ductility, and impact strength of the composites [34]. *Prosopis juliflora* was the source of the silicon dioxide, which was added to the magnesium alloy matrix to improve tribological and mechanical characteristics [35]. The formation of structural composites based on natural fiber for use in hybrid energy storage systems. Tensile, flexural, and impact strength were improved when natural fibers were added to epoxy resin and hardener, according to their research [36]. Biosilica's incorporation into the matrix by electroless Ni-P coating may improve the material's hardness, wear and strength. The SEM surface morphology showed that the composite surface exhibited strong Ni-P deposition [37]. The study found adding filler made of

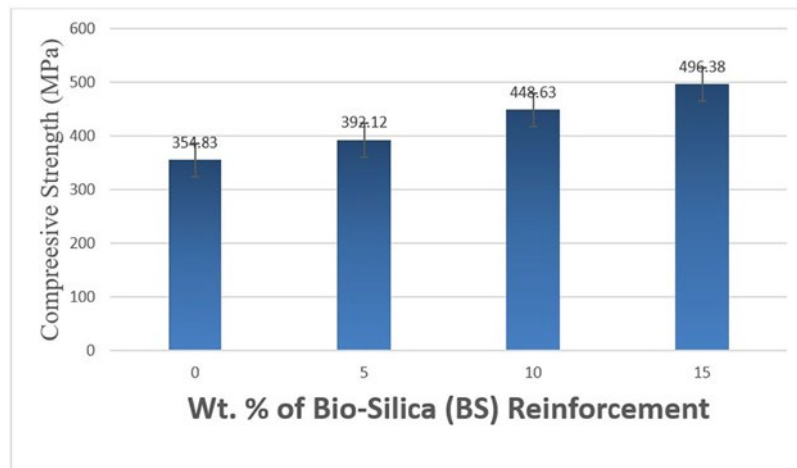


Figure 8: The compressive strength of IGT and IGT/BS nanocomposite (in different wt. %).

biosilica enhanced the density and the amount of moisture of the bio-foam when compared to bio-foam without filler. However, the strength and durability of the bio-foam combination increased once coconut oil was added. The compressive and tensile strengths of the bio-foam were higher when coconut oil was added than when it wasn't [38]. Biosilica-reinforced composites offer remarkable tensile strengths. The composite that contained 20wt.% biosilica was composed of 36.15% increase in tensile strength [20].

The representation illustrates the impact of bio-silica nano reinforcing particles on the compressive strengths of IGT alloy and IGT/BS nanocomposites (5, 10, and 15 wt%) as shown in Figure 8. Compressive strength values prominence from 354.83 MPa to 496.38 MPa progressively as a result of the addition of bio-silica nano reinforcing particles. The IGT alloy has a higher compressive strength of 39.9% when compared to IGT/BS nanocomposites, making it appropriate for use in the automotive, aerospace, defense, and medical industries [39]. The compression characteristics of titanium alloy Ti6Al4V/hydroxyapatite composites were enhanced in a prior study by the functioning evaluated structure and selective laser melting [40]. For reinforcement, titanium and nickel microparticles were introduced using the powder metallurgy approach to the AZ91D matrix. It has been determined that the addition of titanium to hybrid composites increased the hybrid materials' yield strength, compressive strength, and ductility by around 29%, 80%, and 30%, respectively [41]. In a different investigation, Ti64-HA composites with 5% HA were made effectively; nonetheless, their compressive strength was noticeably lower than that of Ti64 [42]. Aluminium alloy 2024 hybrid composites with many SiC and red-mud reinforcements have been designed in order for improving the blended composites strength in compression [43]. ZGŁOBICKA *et al.* [44] developed the magnesium matrix reinforced with biosilica filler. Improved microhardness, strength, reduced compressive strain, and modifications to thermo-elastic properties including coefficient of thermal expansion and conductivity were among the outcomes. The compressive strength and corrosion resistance of graphene nanosheet-based composites based on AZ61 and AZ91 were enhanced by the use of liquid phase exfoliation procedures [45].

3.2. Wear and frictional analysis for IGT/BS nanocomposite

The wear rate of the IGT base alloy matrix and the IGT/BS nanocomposite varies with respect to sliding distance at various composite locations, as shown in Figure 9. For a typical wear graph (0, 5, 10, and 15 weight percent), four specimens are used, with the sliding distance varying from 500 to 2000 meters. The bio-silica nano reinforcing particle approach enhances the wear rate of the IGT alloy to the utmost. IGT/BS nanocomposite wear rates then decrease. The wear resistance of IGT/BS nanocomposites is clearly increased when compared to the IGT base alloy matrix, as demonstrated by the impact of bio-silica nano reinforcing particles. The graph indicates that the maximum wear rate utilized to generate IGT alloy is $570 \times 10^{-3} \text{ mm}^3/\text{m}$, and the values for applied stress, sliding distance, and velocity range from 10 N to 30 N, 500 m to 2000 m, and 2 m/s to 6 m/s. The minimum wear rate showed in IGT/15 wt.% of BS as $148 \times 10^{-3} \text{ mm}^3/\text{m}$.

In a similar work, NAIDU *et al.* [46] synthesized a hybrid composite by selective laser melting an aluminum-silica alloy matrix reinforced with graphene and bio-silica. The reinforcements were made of rye grass and leftover coconut shell, which were used to make graphene and biosilica. The effects of bio-silica and graphene on the hybrid composites' wear, tensile strength, and hardness were studied and contrasted with the

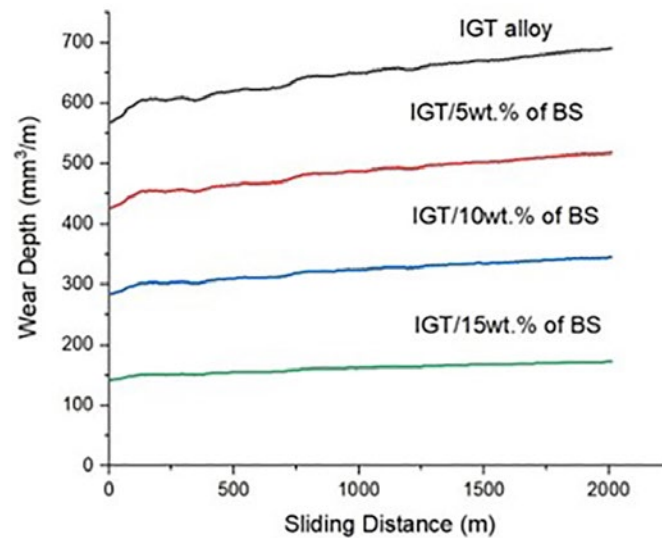


Figure 9: The wear depth of IGT and IGT/BS nanocomposite.

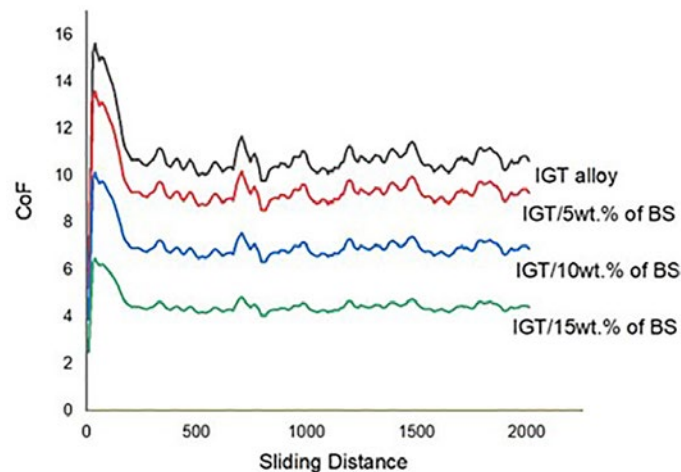


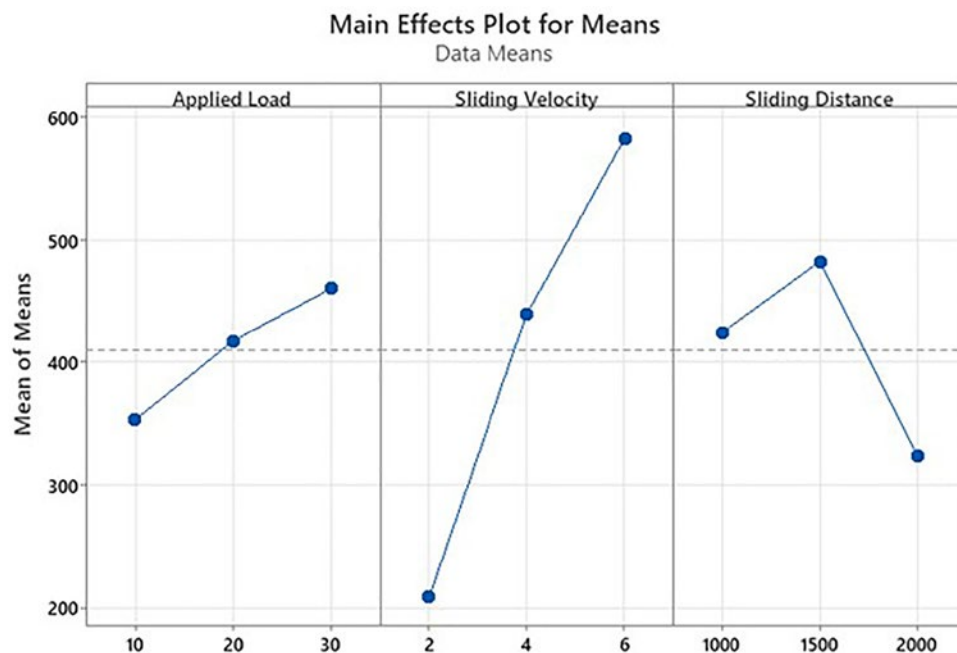
Figure 10: The CoF of IGT and IGT/BS nanocomposite.

fundamental matrix alloy. The composites had been developed by JIA *et al.* [20] employing the stir casting method, a magnesium matrix alloy supplemented with bio-silica, and enhanced mechanical and tribological results. VENKATESH *et al.* [47] developed hybrid composites by employing the squeeze casting process and adding boron carbide and groundnut shell ash to an aluminum matrix. Utilizing sustainable agricultural waste, groundnut shell ash reinforcement is made. Improved density, hardness, tensile strength, and impact strength are the outcomes of the study. A silicon-containing magnesium alloy was employed to increase wear resistance [48]. The system's total efficiency is increased by the superior qualities for biosilica, including robust excessive maximum strength of tensile, outstanding resistance to oxidation, photoconductivity and lower wear rate [49].

At different nanocomposite sites, as seen in Figure 10, the Coefficient of Friction (CoF) of the IGT/BS nanocomposite and the IGT base alloy matrix changes with respect to sliding distance. IGT/BS nanocomposites and IGT alloy matrix have average CoF of 4.42, 9.28, 6.9, and 10.65, respectively. When related to the IGT alloy matrix, the wear resistance and CoF of IGT/BS metal nanocomposites are improved by 28.51% and 14.09%, respectively. Comparable research revealed that enhanced tensile characteristics, a particular wear resistance, hardness of the surface, and coefficient of friction were the outcomes of an in situ method to assess biosilica's reinforcing applying a Al-TiB₂ [50]. The introduction of FMH biosilica particles resulted in

Table 2: Wear and CoF experimental data of IGT alloy and IGT/BS nanocomposite.

APPLIED LOAD (N)	SLIDING VELOCITY (m/s)	SLIDING DISTANCE (m)	WEAR $\times 10^{-3}$ (mm ³ /m)	COF
10	2	2000	151.17	62.3
10	4	2000	454.59	56.7
10	6	2000	453.51	58.79
20	2	2000	302.34	64.32
20	4	2000	345.3	54.21
20	6	2000	604.68	57.25
30	2	2000	172.65	52.36
30	4	2000	517.95	59.85
30	6	2000	690.6	53.54

**Figure 11:** ANOVA- main effects plot for means of wear parameters.

the lowest specific wear rate and CoF. In order to enhance the biosilica, the scientists added coconut rachilla and millet finger husk [51].

3.3. Wear and coefficient of friction of IGT/BS nanocomposites: analysis of variance (ANOVA)

The wear and Coefficient of Friction (CoF) study is conducted in this part to identify the most advantageous parameters for achieving wear and CoF of the IGT/BS nanocomposite through the application of the analysis of variance (ANOVA) approach. Trials were conducted in accordance with orthogonal array L9 according to plan, and Table 2 contains the experimental data.

Depending on the maximum mean values that were observable for separate limits, the ideal parameter was selected in the response table. Based on Figures 11 and 12, the best parameters for increased wear resistance were selected from the most prominent points as A1-B1-C3 and A3-B3-C2, or 20 N of applied load, 4 m/s of disc velocity, and 2000 m of sliding distance. Sliding velocity was the most wear-inducing parameter, tracked by distance and load, according to the rank in Table 3 and Table 4 and Figures 11 and 12. The significant influence of the factors was determined using an ANOVA with a 96% confidence level. The ANOVA statistical tool is

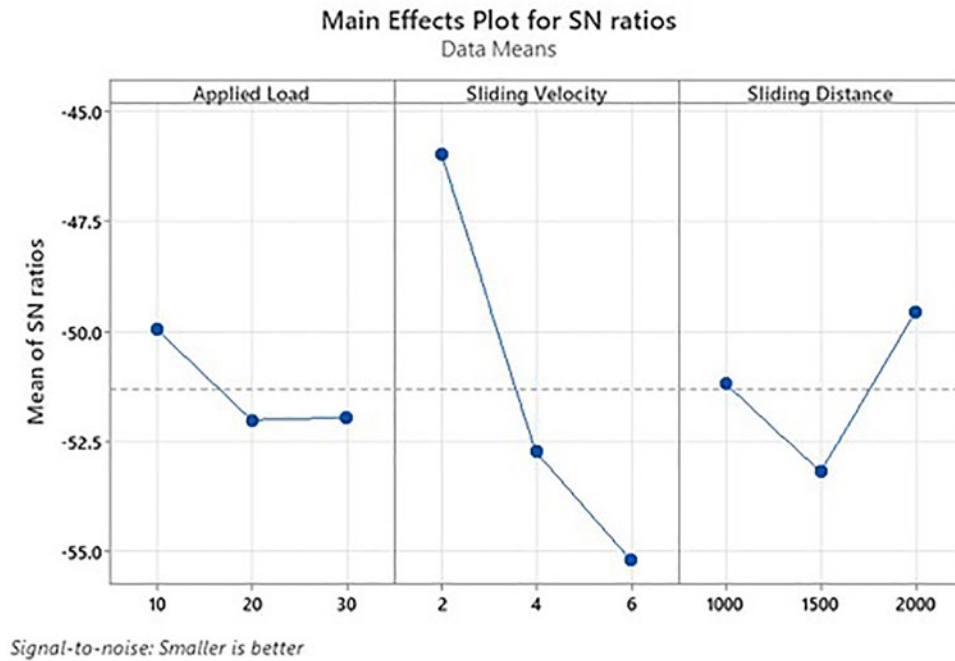


Figure 12: ANOVA- main effects plot for SN ratios of wear parameters.

Table 3: Response table for signal to noise ratios (smaller is better).

LEVEL	APPLIED LOAD	SLIDING VELOCITY	SLIDING DISTANCE
1	-49.96	-45.98	-51.17
2	-52.00	-52.73	-53.18
3	-51.94	-55.18	-49.55
Delta	2.04	9.20	3.64
Rank	3	1	2

Table 4: Response table for means.

LEVEL	APPLIED LOAD	SLIDING VELOCITY	SLIDING DISTANCE
1	353.1	208.7	424.6
2	417.4	439.3	482.5
3	460.4	582.9	323.8
Delta	107.3	374.2	158.7
Rank	3	1	2

Table 5: Analysis of variance (ANOVA).

SOURCE	DF	ADJ SS	ADJ MS	F-VALUE	P-VALUE
Applied Load	1	17273	17273	3.01	0.143
Sliding Velocity	1	210050	210050	36.57	0.002
Sliding Distance	1	15235	15235	2.65	0.164
Error	5	28717	5743		
Total	8	271275			

applied to determine the percentage effect of specific wear characteristics on response values [26]. ANOVA has been conducted, and the results are shown in Table 5. Results from related investigations indicated that lower SR and greater MRR were attained. The most important process parameters for MRR were Ton and WF, while the least important process variables for surface roughness included pulse on time and pulse off time [52]. The

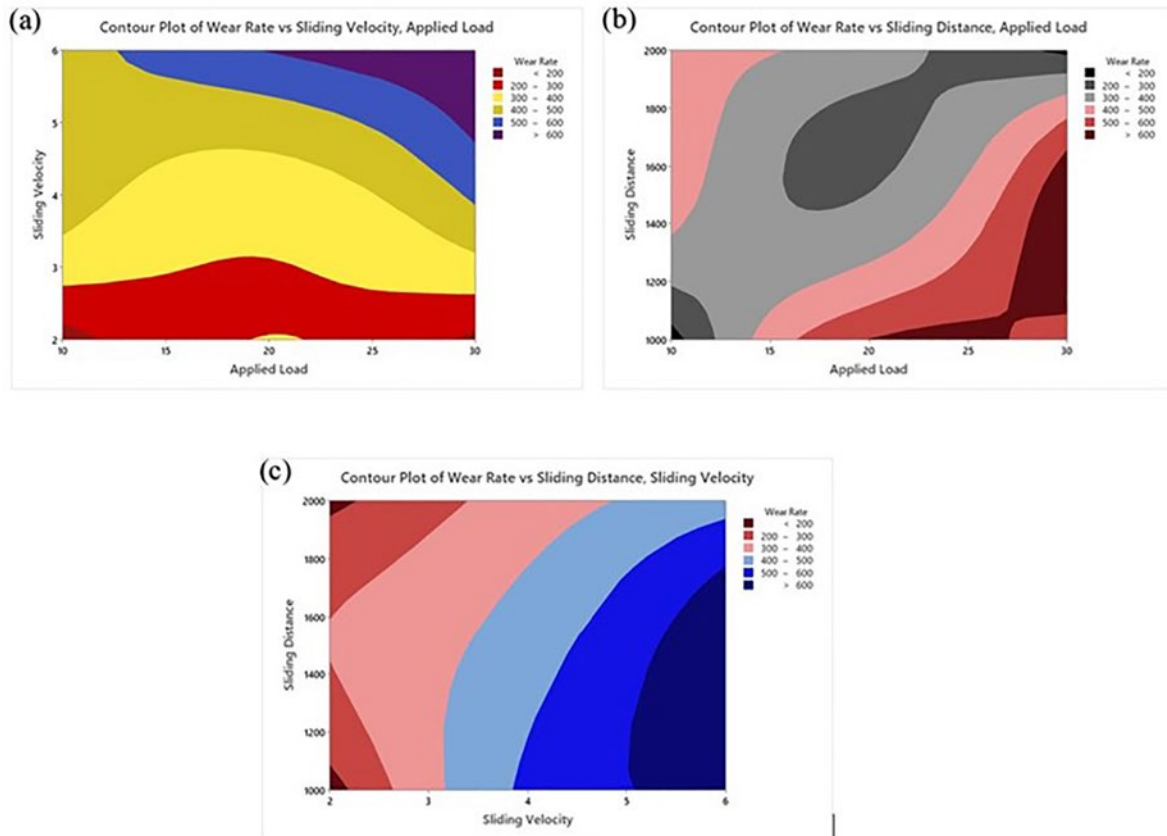


Figure 13: Wear rate dependent on sliding velocity, sliding distance, and applied. Load in IGT/BS nanocomposites contour plot.

results of the ANOVA show that temperature, load, and sliding distance all affect wear. When compared to sliding distance and weight, temperature has the biggest impact [53].

3.4. IGT/BS nanocomposites contour plot analysis for wear analysis

The wear contrary to applied load (10 to 30 N), sliding velocity (2 to 6 m/s), and sliding distance (2000 m constant) contour plots in Figure 13(a–c) help illustrate the primary progression limit for the lowest wear rate. Figure 13(a) displays the outline conspiracy for the wear in relation to sliding velocity and applied load.

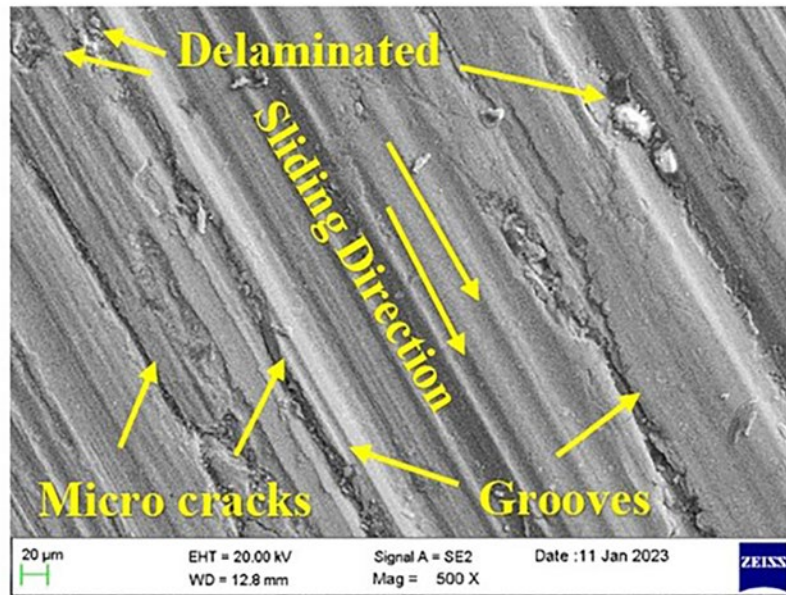
This indicates that the applied load (about 10 to 12 N range) and wear rate ($<200 \times 10^{-3} \text{mm}^3/\text{m}$) were both at a minimal. The velocity was also reduced (2 m/s). The wear rate steadily rises as the load and sliding distance are grew. The contour plot for sliding distance and applied load for response wear rate are shown in Figure 9(b). As can be seen in Fig. 13(b), under nominal load (13 N) and sliding distance (about 1100 m), the wear rate was lower ($200 \times 10^{-3} \text{mm}^3/\text{m}$) than it was with higher applied load and sliding velocity. It additionally demonstrates that wear increased with weight, regardless of sliding distance. Plotting the retort wear rate against distance and velocity is shown in Figure 13(c). It clear that reduced disc velocity and sliding distance result in less wear ($<200 \times 10^{-3} \text{mm}^3/\text{m}$). Even yet, there is less contact time between the pin and the disc. Furthermore, it is mentioned that raising the disc velocity led to the observation of greater wear ($>600 \times 10^{-3} \text{mm}^3/\text{m}$). ANOVA was employed from the similat investigations, and the low F value demonstrated the hypothesis's adequacy. The optimum wear rate based on load and time was achieved by reducing the wear rate [54]. ANOVA analysis indicates that load has a strong important role in every sample category. Sliding distance is the subsequent most important element, according to the vacuum aided resin transfer molding and resin transfer molding interaction plot and ANOVA, while the sliding velocity of hand layup specimens has a secondary impact on the wear rate [55].

3.5. Confirmation test

The improvement in grade from the original setting to the projected parameter value was finally verified by confirmation tests. The trials were carried out, and Table 6 contains the results. Using ANOVA, the expected parameter was determined to be 172.65×10^{-3} and improved by 30%, from the initial parameter setting to the anticipated parameter value.

Table 6: Confirmation test.

	OPENING PARAMETERS	PROPHESED	OPTIMAL PARAMETERS
Applied Load	30	30	30
Sliding velocity	6	4	4
Sliding distance	2000	2000	2000
Wear	690.6×10^{-3}	172.65×10^{-3}	172.65×10^{-3}
Wear Resistance Enhancement	172.65×10^{-3}		

**Figure 14:** Worn surface analysis of 15 wt.% of IGT/BS nanocomposite.

3.6. Worn surface analysis of IGT/BS nanocomposite

Figure 14 displays a FESEM examination demonstrating the wear worn surface track observed on the 15 wt.% IGT/BS nanocomposite under applied loads varying from 30 N, sliding velocity 6 m/s, and constant sliding distance 2000 m. The FESEM image clearly displays microcracks, grooves, delaminated and worn debris. The development of a tiny layer that prevents the specimen from interacting directly with the revolving steel disc surface is what caused the worn surface of the IGT/BS nanocomposite to become less accurate. The reinforcement and matrix have a robust and evenly distributed bonding structure throughout the matrix. The A significant role of the reduced wear behaviour of the 15 wt.% IGT/BS nanocomposite can be attributed to the bio-silica reinforcing. The 15 wt.% of IGT/BS nanocomposite pin started to move across the counterface disc as the load was applied, and wear debris accumulated, as seen in Fig. 14. The grooves were created by ploughing motion, and these wear remnants function as a third body abrasion. Substantial wear debris develops at higher loads as a result of dry sliding among metal contacts, which encourages massive deformation of plastic and removes an important quantity of material from the nanocomposite surface. Studies that correspond show that the strengthening element were isolated homogeneously through the metal composite. The strengthening elements gathering was inattentive after the metal composites. Consequently, inside the different base alloy matrixes, the laser melting process aids in attaining a homogeneous dispersal of strengthening elements [56]. SEM micrographs were used in similar tests to confirm the interface relationship among the biosilica fragments and the matrix of SG-MgSi alloy [20]. FESEM analysis was used to identify tiny cracks, shallow and broad channels, molten debris, flakes, and delamination in wear detritus. According to this research, the reinforced material and matrix have an effective bonding arrangement that is evenly dispersed across the matrix [41].

4. CONCLUSION

This work The influence of adding bio-silica (BS) nano-reinforcing particles to the IGT alloy on the resultant IGT/BS nanocomposites' microhardness, ultimate tensile and yield strength, compressive strength, and wear properties remained inspected in this work. The following is a summary of the major findings:

- The IGT/BS nanocomposite comprising IGT alloy and addition with bio-silica (0, 5, 10, and 15 wt.%) is formed satisfactorily utilizing selective laser melting.
- The results of the Vickers hardness test, which has been employed to assess micro hardness, were 336.54 VHN, 386.78 VHN, 402.12 VHN, and 424.83 VHN. Over the basic matrix of the IGT alloy, this suggested a 26.23% increase in microhardness.
- By evaluating the tensile strength, the ultimate, yield, and % of elongation were ascertained. At 484.24 MPa and 292.47 MPa, respectively, the T4 specimen had the maximum confirmed standards for ultimate and yield strength. At 4.1, the specimen exhibited the least amount of elongation.
- At specimen T4 (15 wt. % of IGT/BS nanocomposite), the highest compressive strength value is recorded as 496.38 MPa.
- In wear analysis, the sliding velocity and applied load parameters are utilized to compute the wear rate based on the sliding distance (2000 m, constant). The IGT/BS nanocomposite minimum and maximum wear rates are $570 \times 10^{-3} \text{ mm}^3/\text{m}$ and $148 \times 10^{-3} \text{ mm}^3/\text{m}$.
- The IGT/BS nanocomposites wear behaviour was examined using ANOVA, and the ideal parameters for increased resistance to wear and least possible coefficient of friction were found to be 30 N load, 4 m/s velocity, and 2000 m distance. The findings after ANOVA showed a 30% improvement over the original setting condition.
- FESEM study to identify grooves, microcracks, delaminated, and worn debris was performed. There is a strong and uniform bonding structure between the reinforcement and matrix throughout the matrix. The bio-silica reinforcing has a major role to play in the 15 wt.% of IGT/BS nanocomposites decreased wear behaviour setting condition.
- This study helps to provide high-performance materials that are appropriate for challenging uses such as the aerospace, biomedical, automotive, energy sector, tooling, and industrial machinery by improving the mechanical and wear characteristics.

5. BIBLIOGRAPHY

- [1] ARUN, K., JASMIN, N.M., KAMESH, V., *et al.*, “Applications of artificial neural network simulation for prediction of wear rate and coefficient of friction titanium matrix composites”, *Materials Research*, v. 26, pp. 1–12, 2023. doi: <http://doi.org/10.1590/1980-5373-mr-2022-0306>.
- [2] JIAO, Y., HUANG, L., GENG, L., “Progress on discontinuously reinforced titanium matrix composites”, *Journal of Alloys and Compounds*, v. 767, pp. 1196–1215, 2018. doi: <http://doi.org/10.1016/j.jallcom.2018.07.100>.
- [3] PALANIVEL, R., DINAHARAN, I., LAUBSCHER, R.F., “Application of an artificial neural network model to predict the ultimate tensile strength of friction welded titanium tubes”, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, v. 41, n. 2, pp. 1–13, 2019. doi: <http://doi.org/10.1007/s40430-019-1613-2>.
- [4] MUTUK, T., GÜRBÜZ, M., MUTUK, H., “Prediction of wear properties of graphene-Si₃N₄ reinforced titanium hybrid composites by artificial neural network”, *Materials Research Express*, v. 7, n. 8, pp. 1–10, 2020. doi: <http://doi.org/10.1088/2053-1591/abaac8>.
- [5] ALI, M.H., ANSARI, M.N.M., KHIDHIR, B.A., *et al.*, “Simulation machining of titanium alloy (Ti-6Al-4V) based on the finite element modeling”, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, v. 36, n. 2, pp. 315–324, 2014. doi: <http://doi.org/10.1007/s40430-013-0084-0>.
- [6] SOUNDARARAJAN, R., RAMESH, A., SIVASANKARAN, S., *et al.*, “Modeling and analysis of mechanical properties of aluminium alloy (A413) reinforced with boron carbide (B₄C) processed through squeeze casting process using artificial neural network model and statistical technique”, *Materials Today: Proceedings*, v. 4, n. 2, pp. 2008–2030, 2017. doi: <http://doi.org/10.1016/j.matpr.2017.02.047>.

- [7] ERTUAN, Z., SHICHEN, S., YU, Z., “Recent advances in silicon containing high temperature titanium alloys”, *Journal of Materials Research and Technology*, v. 14, pp. 3029–3042, 2021. doi: <http://doi.org/10.1016/j.jmrt.2021.08.117>.
- [8] BOWEN, Z., XIAOGANG, W., DELIANG, Z., “Effect of silicon addition on microstructure and mechanical properties of a high strength Ti-4Al-4Mo-4Sn alloy prepared by powder metallurgy”, *Journal of Alloys and Compounds*, v. 893, pp. 162267, 2022. doi: <http://doi.org/10.1016/j.jallcom.2021.162267>.
- [9] XIAOYU, X.I.A., JUANLI, D.E.N.G., SIJIE, K.O.U., *et al.*, “Microstructure and properties of pressure-less joining of SiCf/SiC composites by Ti-Si alloys”, *Ceramics International*, v. 48, n. 15, pp. 22387–22400, 2022. doi: <http://doi.org/10.1016/j.ceramint.2022.04.245>.
- [10] ROMINIYI, A.L., MASHININI, P.M., ROMINIYI, O.L., “Microstructure, phase evolution and mechanical properties of nickel-silicon carbide reinforced Ti6Al4V alloy processed by pulsed electric current sintering”, *Ceramics International*, v. 50, n. 18, pp. 33926–33936, 2024. doi: <http://doi.org/10.1016/j.ceramint.2024.06.212>.
- [11] GU, H., WU, J., WEI, K., *et al.*, “Synergetic recovery of Ti and Fe from Ti-bearing blast furnace slag and red mud by diamond wire saw silicon waste”, *Process Safety and Environmental Protection*, v. 190, pp. 1301–1310, 2024. doi: <http://doi.org/10.1016/j.psep.2024.08.004>.
- [12] LEI, C., PAN, Y., KUANG, F., *et al.*, “A novel configuration design of strong and ductile (TiC + Ti₃Si₃)/Ti laminated composites”, *Materials Science and Engineering A*, v. 892, pp. 145961, 2024. doi: <http://doi.org/10.1016/j.msea.2023.145961>.
- [13] ZHAO, Z., LIU, Y., ZHOU, B., *et al.*, “Wettability and joining of reaction-bonded silicon carbide (RBSC) by Ti-Si eutectic alloy”, *Ceramics International*, v. 50, n. 12, pp. 21184–21192, 2024. doi: <http://doi.org/10.1016/j.ceramint.2024.03.227>.
- [14] SRINIVASAN, R., KAMARAJ, M., RAJEEV, D., *et al.*, “Plasma spray coating of aluminum-silicon-MWCNT blends on titanium grade 5 alloy substrate for enhanced wear and corrosion resistance”, *Silicon*, v. 14, n. 14, pp. 8629–8641, 2022. doi: <http://doi.org/10.1007/s12633-022-01657-z>.
- [15] FALODUN, O.E., OBADELE, B.A., OKE, S.R., *et al.*, “Titanium-based matrix composites reinforced with particulate, microstructure, and mechanical properties using spark plasma sintering technique: a review”, *International Journal of Advanced Manufacturing Technology*, v. 102, n. 5–8, pp. 1689–1701, 2019. doi: <http://doi.org/10.1007/s00170-018-03281-x>.
- [16] BARROSO, G., LI, Q., BORDIA, R.K., *et al.*, “Polymeric and ceramic silicon-based coatings - a review”, *Journal of Materials Chemistry. A, Materials for Energy and Sustainability*, v. 7, n. 5, pp. 1936–1963, 2019. doi: <http://doi.org/10.1039/C8TA09054H>.
- [17] NIKITIN, D.S., SHANENKOV, I.I., YELETSKY, P.M., *et al.*, “Agricultural waste derived silicon carbide composite nanopowders as efficient coelectrocatalysts for water splitting”, *Journal of Cleaner Production*, v. 442, pp. 140890, 2024. doi: <http://doi.org/10.1016/j.jclepro.2024.140890>.
- [18] AASHIKHA SHANI, R.S., JEICE, A.R., “Introspect of prying out silica from agricultural wastes by various methods and incorporating them in distinct uses”, *Biomass Conversion and Biorefinery*, 2024. doi: <http://doi.org/10.1007/s13399-024-05360-4>.
- [19] NATRAYAN, L., DEVARAJAN, Y., “Catalytic activities of oxidation on hydrazine and azo-dye of nano palladium particles synthesis from bio-waste Cinnamomum camphora leaf extract”, *Biomass Conversion and Biorefinery*, v. 13, n. 16, pp. 15135–15148, 2023. doi: <http://doi.org/10.1007/s13399-023-04388-2>.
- [20] JIA, X., MADHU, S., NAVEEN, S., *et al.*, “Utilization of biosilica from Bermuda grass ash on silver-grey magnesium: influence of biosilica on its mechanical and tribological properties”, *Biomass Conversion and Biorefinery*, v. 14, n. 18, pp. 23015–23030, 2024. doi: <http://doi.org/10.1007/s13399-023-04502-4>.
- [21] PRASAD, D.S., SHOBA, C., RAMANAIAH, N., “Investigations on mechanical properties of aluminium hybrid composites”, *Journal of Materials Research and Technology*, v. 3, n. 1, pp. 79–85, 2014. doi: <http://doi.org/10.1016/j.jmrt.2013.11.002>.
- [22] HAN, X., YANG, L., ZHAO, N., *et al.*, “Copper-coated graphene nanoplatelets-reinforced Al-Si alloy matrix composites fabricated by stir casting method”, *Acta Metallurgica Sinica*, v. 34, n. 1, pp. 111–124, 2021. doi: <http://doi.org/10.1007/s40195-020-01112-1>.
- [23] ZHANG, S., CHEN, Z., WEI, P., *et al.*, “Wear properties of graphene/zirconia biphasic nano-reinforced aluminium matrix composites prepared by SLM”, *Materials Today. Communications*, v. 30, pp. 103009, 2022. doi: <http://doi.org/10.1016/j.mtcomm.2021.103009>.

- [24] ZHANG, P., TAN, J., TIAN, Y., *et al.*, “Research progress on selective laser melting (SLM) of bulk metallic glasses (BMGs): a review”, *International Journal of Advanced Manufacturing Technology*, v. 118, n. 7–8, pp. 2017–2057, 2022. doi: <http://doi.org/10.1007/s00170-021-07990-8>.
- [25] ZOU, T., MEI, S., CHEN, M., *et al.*, “Influence of SiC content on microstructure and mechanical properties of SiCp/AlSi7Mg composites fabricated by selective laser melting”, *Journal of Materials Engineering and Performance*, v. 32, n. 1, pp. 296–304, 2023. doi: <http://doi.org/10.1007/s11665-022-07079-7>.
- [26] NAIDU, S., VELLINGIRI, S., CHINNASAMY, S.M., *et al.*, “Optimization of tribological behavior of Aluminium (A356) composites using TGRA technique”, *Matéria (Rio de Janeiro)*, v. 29, n. 3, pp. e20240129, 2024. doi: <http://doi.org/10.1590/1517-7076-rmat-2024-0129>.
- [27] DONG, G., GUO, Z., DAI, Y., *et al.*, “Experimental study of surface residual stress and hardness of TiBw mesh reinforced titanium matrix composites in rotary ultrasonic grinding”, *International Journal of Advanced Manufacturing Technology*, v. 133, n. 9–10, pp. 4807–4821, 2024. doi: <http://doi.org/10.1007/s00170-024-13938-5>.
- [28] HEGDE, A., NAYAK, R., BOLAR, G., *et al.*, “Comprehensive investigation of hardness, wear and frictional force in powder metallurgy engineered Ti-6Al-4V-SiCp metal matrix composites”, *J. Compos. Sci.*, v. 8, n. 2, pp. 39, 2024. doi: <http://doi.org/10.3390/jcs8020039>.
- [29] BERA, T., MANNA, I., MAJUMDAR, J.D., “Titanium carbide (TiC) dispersed surface on titanium based alloy (Ti-13Nb-13Zr) by in-situ laser composite surfacing and its wear performance”, *Journal of Materials Processing Technology*, v. 328, pp. 118394, 2024. doi: <http://doi.org/10.1016/j.jmatprotec.2024.118394>.
- [30] YUAN, Z., WANG, K., LI, S., *et al.*, “Effect of sintering temperature on the properties of titanium matrix composites reinforced with Al_{0.5}CoCrFeNi high-entropy alloy particles”, *Materials Science and Engineering A*, v. 911, pp. 146920, 2024. doi: <http://doi.org/10.1016/j.msea.2024.146920>.
- [31] SAKTHIVELU, S., SETHUSUNDARAM, P.P., RAVICHANDRAN, M., *et al.*, “Experimental investigation and analysis of properties and dry sliding wear behavior of Al-Fe-Si alloy matrix composites”, *Silicon*, v. 13, n. 4, pp. 1285–1294, 2021. doi: <http://doi.org/10.1007/s12633-020-00662-4>.
- [32] AHMADIAN, H., ZHOU, T., ALANSARI, A., *et al.*, “Microstructure, mechanical properties and wear behavior of Mg matrix composites reinforced with Ti and nano SiC particles”, *Journal of Materials Research and Technology*, v. 31, pp. 4088–4103, 2024. doi: <http://doi.org/10.1016/j.jmrt.2024.07.125>.
- [33] SINHA, S., REDDY, S., GUPTA, M., “Scratch hardness and mechanical property correlation for Mg/SiC and Mg/SiC/Ti metal-matrix composites”, *Tribology International*, v. 39, n. 2, pp. 184–189, 2006. doi: <http://doi.org/10.1016/j.triboint.2005.04.017>.
- [34] GUSHCHINA, M.O., KUZMINOVA, Y.O., DUBININ, O.N., *et al.*, “Multilayer composite Ti-6Al-4V/Cp-Ti alloy produced by laser direct energy deposition”, *International Journal of Advanced Manufacturing Technology*, v. 124, n. 3–4, pp. 907–918, 2023. doi: <http://doi.org/10.1007/s00170-022-10521-8>.
- [35] ARUNDEEP, M., SURESH, V., SRINIVASNAIK, M., *et al.*, “Effect of nanoparticles reinforcement of Silicon dioxide derived from prosopis juliflora on Silver-Grey Magnesium nanocomposite: utilization of silicon dioxide mechanical and tribological properties”, *Materials Research Express*, v. 11, n. 10, pp. 106502, 2024. doi: <http://doi.org/10.1088/2053-1591/ad7dd6>.
- [36] PANCHAL, R.N., SOLLAPUR, S.B., SURYATAL, B.K., *et al.*, “Investigating the mechanical aspects of natural fiber-based structural composite for hybrid energy storage applications”, *Journal of The Institution of Engineers (India): Series D*, 2024. doi: <http://doi.org/10.1007/s40033-024-00681-0>.
- [37] ANAND, S.H., VENKATESHWARAN, N., “Effect of heat treatment and biosilica on mechanical, wear, and fatigue behavior of Al-TiB₂ in situ metal matrix composite”, *Biomass Conversion and Biorefinery*, v. 13, n. 3, pp. 2163–2175, 2023. doi: <http://doi.org/10.1007/s13399-021-01402-3>.
- [38] RAJA, T., DEVARAJAN, Y., “Effective utilization of fibre extracted from the waste neem tree twigs—a step towards sustainable practices”, *Biomass Conversion and Biorefinery*, v. 14, n. 17, pp. 21049–21057, 2024. doi: <http://doi.org/10.1007/s13399-023-04133-9>.
- [39] DEY, D., BHOWMIK, A., BISWAS, A., “A grey-fuzzy based multi response optimisation study on the friction and wear characteristics of titanium diboride reinforced aluminium matrix composite”, *Proceedings of the Institution of Mechanical Engineers. Part B, Journal of Engineering Manufacture*, v. 234, n. 15, pp. 2227–2239, 2023. doi: <http://doi.org/10.1177/09544054221147973>.

- [40] LIN, Y., BALBAA, M., ZENG, W., *et al.*, “Osteogenic properties of titanium alloy Ti6Al4V-hydroxyapatite composites fabricated by selective laser melting”, *Journal of Materials Engineering and Performance*, v. 33, n. 18, pp. 9664–9675, 2023. doi: <http://doi.org/10.1007/s11665-023-08632-8>.
- [41] KELEN, F., “Fabrication, microstructure and mechanical properties of novel titanium and nickel micro-particulates reinforced AZ91D magnesium alloy metal matrix hybrid composites”, *Journal of Alloys and Compounds*, v. 968, pp. 171999, 2023. doi: <http://doi.org/10.1016/j.jallcom.2023.171999>.
- [42] TERRAZAS, C.A., MURR, L.E., BERMUDEZ, D., *et al.*, “Microstructure and mechanical properties of Ti-6Al 4V-5% hydroxyapatite composite fabricated using electron beam powder bed fusion”, *Journal of Materials Science and Technology*, v. 35, n. 2, pp. 309–321, 2019. doi: <http://doi.org/10.1016/j.jmst.2018.10.025>.
- [43] SINGH, J., CHAUHAN, A., “Fabrication characteristics and tensile strength of novel Al2024/SiC/red mud composites processed via stir casting route”, *Transactions of Nonferrous Metals Society of China*, v. 27, n. 12, pp. 2573–2586, 2017. doi: [http://doi.org/10.1016/S1003-6326\(17\)60285-1](http://doi.org/10.1016/S1003-6326(17)60285-1).
- [44] ZGŁOBICKA, I.B., DOBKOWSKA, A., ZIELIŃSKA, A., *et al.*, “In-depth analysis of the influence of bio-silica filler (*Didymosphenia geminata* frustules) on the properties of Mg matrix composites”, *Journal of Magnesium and Alloys*, v. 11, n. 8, pp. 2853–2871, 2023. doi: <http://doi.org/10.1016/j.jma.2023.08.001>.
- [45] ZHU, J., QI, J., GUAN, D., *et al.*, “Tribological behaviour of self-lubricating Mg matrix composites reinforced with silicon carbide and tungsten disulfide”, *Tribology International*, v. 146, pp. 106253, 2020. doi: <http://doi.org/10.1016/j.triboint.2020.106253>.
- [46] NAIDU, S., VELLINGIRI, S., SHANKAR, E., *et al.*, “Effect of graphene and bio silica extract from waste coconut shell and rye grass: aluminum silicon alloy hybrid composites for energy storage applications”, *Biomass Conversion and Biorefinery*, 2024.
- [47] VENKATESH, L., ARJUNAN, T.V., RAVIKUMAR, K., “Microstructural characteristics and mechanical behaviour of aluminium hybrid composites reinforced with groundnut shell ash and B₄C”, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, v. 41, n. 7, pp. 295, 2019. doi: <http://doi.org/10.1007/s40430-019-1800-1>.
- [48] KAVIMANI, V., PRAKASH, K.S., STARVIN, M.S., *et al.*, “Tribo-surface characteristics and wear behaviour of SiC@ r-GO/Mg composite worn under varying control factor”, *Silicon*, v. 12, n. 1, pp. 29–39, 2020. doi: <http://doi.org/10.1007/s12633-019-0095-2>.
- [49] ELSAYED, H., REBESAN, P., CROVACE, M.C., *et al.*, “Biosilicate scaffolds produced by 3D printing and direct foaming using preceramic polymers”, *Journal of the American Ceramic Society*, v. 102, n. 3, pp. 1010–1020, 2019. doi: <http://doi.org/10.1111/jace.15948>.
- [50] HANISH ANAND, S., VENKATESHWARAN, N., SAI PRASANNA KUMAR, J.V., *et al.*, “Optimization of aging, coating temperature and reinforcement ratio on biosilica toughened in-situ Al-TiB₂ metal matrix composite: a taguchi grey relational approach”, *Silicon*, v. 14, n. 8, pp. 4337–4347, 2022. doi: <http://doi.org/10.1007/s12633-021-01232-y>.
- [51] SIVAMURUGAN, P., SELVAM, R., PANDIAN, M., *et al.*, “Extraction of novel biosilica from finger millet husk and its coconut rachilla reinforced epoxy biocomposite: mechanical, thermal, and hydro phobic behaviour”, *Biomass Conversion and Biorefinery*, v. 14, n. 13, pp. 14251–14259, 2024. doi: <http://doi.org/10.1007/s13399-022-03342-y>.
- [52] DHILIP, J.D.J., GANESAN, K.P., SIVALINGAM, V., “Machinability studies and optimization of process parameters in wire electrical discharge machining of aluminum hybrid composites by the VIKOR”, *Journal of Materials Engineering and Performance*, v. 33, n. 11, pp. 5547–5562, 2024. doi: <http://doi.org/10.1007/s11665-023-08323-4>.
- [53] KUMAR, K., DABADE, B.M., WANKHADE, L.N., *et al.*, “Experimental investigation on tribological performance and development of wear prediction equation of aluminium composite at elevated temperatures”, *Int J Interact Des Manuf*, v. 18, n. 4, pp. 1979–1987, 2024. doi: <http://doi.org/10.1007/s12008-022-00911-3>.
- [54] KUMAR, T.S., RAGHU, R., THANKACHAN, T., *et al.*, “Mechanical property analysis and dry sand three-body abrasive wear behaviour of AZ31/ZrO₂ composites produced by stir casting”, *Scientific Reports*, v. 14, n. 1, pp. 1543, 2024. doi: <http://doi.org/10.1038/s41598-024-52100-9>. PubMed PMID: 38233510.

- [55] BHARAT, N., BOSE, P.S.C., “Wear performance analysis and optimization of process parameters of novel AA7178/nTiO₂ using ANN-GRA method”, *Proceedings of the Institution of Mechanical Engineers. Part E, Journal of Process Mechanical Engineering*, v. 238, n. 3, pp. 1409–1419, Jun. 2024. doi: <http://doi.org/10.1177/09544089231156074>.
- [56] WEI, K., WANG, Z., ZENG, X., “Preliminary investigation on selective laser melting of Ti-5Al-2.5Sn Ti alloy: from single tracks to bulk 3D components”, *Journal of Materials Processing Technology*, v. 244, pp. 73–85, 2017. doi: <http://doi.org/10.1016/j.jmatprotec.2017.01.032>.