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Original Research Article

From Machining Waste to Advanced Implants: Recycled Ti/GO Composite with Improved Mechanical Properties for Orthopedic Applications

Ramezanali Mahdavinejad [a, *], Sayyed Hossein Hosseininasab [b], Sayyed Mohammadreza Sedehi [c]

[a] *Professor, School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran.*
[b] *MSc student, School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran.*
[c] *PhD student, School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran.*

* Corresponding Author Email: Mahdavin@ut.ac.ir (R. Mahdavinejad) URL: https://www.acerp.ir/article_247744.html

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A B S T R A C T

This study introduces a novel strategy for recycling titanium machining chips through powder metallurgy combined with graphene oxide (GO) nanoparticles, enabling the fabrication of biocompatible implants with enhanced mechanical strength and resistance properties. The process involves converting machining chips into powder using ball mill grinding, followed by the fabrication of recycled samples through spark plasma sintering (SPS). Furthermore, the investigation explores the fabrication of a composite by combining recycled titanium powder with 0.2% graphene oxide (GO) nanoparticles. In this research, three distinct samples are examined: pure titanium, recycled titanium, and a titanium/graphene oxide composite. Characterization of the samples is accomplished using scanning electron microscopy (SEM), light microscopy, and X-ray diffraction (XRD). In addition, the properties, including hardness, wear resistance, and corrosion resistance, are investigated. The hardness test revealed that pure titanium had the lowest hardness, at 322 HV. The recycled sample exhibited a 17% increase, reaching 378 HV, while the composite sample exhibited a 25% increase, reaching 402 HV. The wear resistance test showed that the pure titanium specimen, recycled titanium sample, and composite sample had mass losses of 17.98, 11.77, and 0.86 mg, respectively. The corrosion test results indicated that pure titanium had a corrosion rate of 0.0022 mm/year, while the recycled titanium sample had a corrosion rate of 0.00156 mm/year. The composite specimen had the lowest corrosion rate, at 0.00012 mm/year. The findings indicate that this recycling process not only facilitates the reuse of industrial waste but also, by enhancing mechanical and resistance properties, constitutes an effective step toward the development of high-performance medical implants.

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1. INTRODUCTION

The raw materials used in the fabrication of orthopedic implants significantly impact their performance and durability. Titanium and its alloys are widely recognized as essential materials in medical implants due to their exceptional mechanical strength, corrosion resistance, and favorable biocompatibility (Hamza et al., 2025; Kohal & Dennison, 2020; Nikam et al., 2025). However, challenges concerning properties such as the modulus of elasticity and wear resistance have underscored the importance of enhancing these materials (Alfaer et al., 2025; Ganko et al., 2025). On the other hand, the utilization of industrial waste, such as titanium chips, as

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a raw material has been demonstrated to reduce production costs while enhancing environmental sustainability (Abogunrin-Olafisoye & Adeyi, 2025; Alavizadeh et al., 2025; Chen et al., 2025). The fabrication of high-quality orthopedic implants requires adherence to precise engineering and medical standards. In this field, prominent manufacturers aim to enhance the mechanical properties and biocompatibility of their products through the utilization of advanced technologies and composite materials (Cong & Zhang, 2025; Nsanzumuhire et al., 2025). In this regard, the incorporation of reinforcing nanomaterials, such as graphene oxide, into the titanium matrix has the potential to result in several advantageous outcomes, including enhanced strength, reduced weight, and improved cellular behavior (Aminnezhad et al., 2025; Nsanzumuhire et al., 2025; Vasudev et al., 2025). The Spark Plasma Sintering (SPS) method is a novel technological process that facilitates the fabrication of materials with high density and a uniform microstructure in a relatively brief timeframe and at moderate temperatures (Strakošová et al., 2025). This method is particularly well suited for titanium-based composites reinforced with nanomaterials such as graphene oxide, as it prevents the growth of undesirable grains and ensures a uniform distribution of the reinforcing phase (Sedehi et al., 2021). Studies have demonstrated that the Ti/GO composites produced by this method exhibit high compressive strength, a customized elastic modulus, and improved biocompatibility, making them an ideal option for orthopedic applications (Sedehi et al., 2025).

Unlike prior studies, which primarily concentrated on raw materials (Lee et al., 2025; Liang et al., 2025) or focused on producing ultrafine-grained (UFG) titanium through severe plastic deformation (SPD) techniques (Mahmoodian et al., 2019), this work introduces a sustainable route by recycling industrial Ti machining chips and reinforcing them with GO via SPS. SPD-based approaches and surface modification methods (Khorasani & Faraji, 2025; Reshadi et al., 2020) have shown improvements in surface topography, hardness, and osseointegration but typically require virgin Ti feedstock and additional processing steps. This method addresses environmental and economic concerns by valorizing machining waste (Pallewatta et al., 2023), while achieving grain refinement and GO dispersion in a single SPS cycle. This integrated recycling-reinforcement strategy enhances hardness, wear resistance, and corrosion resistance relative to conventionally processed nanostructured Ti. The distinct integration of circular economy principles, enhanced mechanical properties, and favorable biological performance positions this technological innovation as a significant advancement in the development of next-generation implants.

2. MATERIALS AND METHODS

Initially, the chips are collected from the turning process of a titanium bar. The chemical composition of the titanium bar is shown in Table 1.

Titanium chips, used as the raw material, are produced through a closed-loop machining cycle under common industrial machining conditions listed in Table 2 to reflect typical part manufacturing practices. These chips are converted into powder using a mechanical ball mill. Oxidation caused by heat generated during milling can affect the mechanical properties. To prevent this, the operation is conducted in an argon atmosphere. Ball milling is performed for 3 h using stainless steel cups and zirconia balls at a ball-to-powder weight ratio of 10:1.

The distribution of the composite's composition is a critical factor, with a balanced and uniform distribution resulting in enhanced properties. To accomplish this, the following steps must be considered in the powder metallurgy pathway: a) GO is added to pure ethanol at a weight percentage of 0.2% and dispersed ultrasonically at 25 °C until a stable, homogeneous dark suspension is obtained, indicating full dispersion of GO within the solvent (Sedehi et al., 2021). b) Titanium powder is dispersed in ethanol using a mechanical agitator at 25°C, and then both suspensions are combined and mixed for 30 minutes until a homogeneous suspension is obtained. c) The mixed suspension is completely dried in a vacuum furnace at a temperature of 70°C for 18 hours. d) To ensure a uniform composition during the fabrication of the composite sample, the resulting powder is blended in a ball mill for four hours under an argon protective atmosphere at a speed of 400 rpm with a powder-to-ball ratio of 1:10. The balls utilized in this study are composed of zirconia to avoid contaminating the powder mixture (Tanaka et al., 2022), a critical concern in biomedical applications such as dental and bone implants.

TABLE 1. Specifications of the titanium used for machining

element	Si	C	N	O	Fe	Ti
Weight Percentage	0.02	0.02	0.03	0.27	0.05	99.61

TABLE 2. machining process variable

Parameter	**Value**
Feed rate (mm/s)	0.7
cutting depth (mm)	0.5
Tool tip radius (mm)	0.1
Spindle speed (rpm)	1356
Cooling	---

To compact the powder and produce test samples using the SPS method, a graphite mold with an inner diameter of 50 mm is utilized, and a 0.5 mm-thick graphite foil sheet is placed between the mold and the powder to prevent excessive carbon infiltration, which can cause material brittleness and disrupt cellular interaction with the body (Petersen, 2016; Walunj et al., 2024). The process is executed at a heating rate of 50°C/min, a holding time of 6 minutes, and low and high pulse frequencies of 40 and 200 s^{-1}, respectively, with the pressure and temperature maintained at 45 MPa and 850°C. Each mechanical, wear, and corrosion experiment was performed under identical testing conditions, and the reported values represent the average of repeated measurements. Experimental repeatability was verified through consistent testing procedures, and the obtained results were comparatively analyzed to evaluate the influence of the processing parameters on material performance.

3. Results and discussion

The three titanium samples investigated in this study are presented in Fig. 1. Sample a consisted of commercially pure cast titanium, exhibiting the microstructural characteristics and mechanical behavior typically associated with conventional casting processes. Sample b was fabricated from recycled titanium powder obtained through the recovery and processing of machining chips, offering a sustainable and cost-effective route for material production. Sample c was produced by reinforcing the recycled titanium powder with graphene oxide (GO), a nanostructured material known for its outstanding mechanical strength and load-transfer capability.

The incorporation of GO and the refinement of the microstructure are expected to enhance resistance to localized plastic deformation, improve wear performance, and increase the overall load-bearing capacity of the material. Since hardness is closely related to resistance to deformation, improvements in hardness and wear resistance can be considered indicative of enhanced tensile and compressive strength. Furthermore, microstructural modifications such as grain refinement and homogeneous reinforcement distribution can influence both the mechanical performance and electrochemical behavior of titanium-based materials, thereby affecting their corrosion resistance and long-term durability. The reinforcing efficiency of graphene oxide is generally dependent on its dispersion within the titanium matrix. According to previous studies, a more homogeneous distribution enhances interfacial bonding and facilitates effective load transfer, whereas GO agglomeration may reduce the reinforcing efficiency by acting as a stress concentration site. Therefore, careful control of powder processing and mixing conditions is considered an important factor in achieving the desired mechanical and corrosion performance of Ti/GO composites.

3.1. Microstructure Analysis by Optical Microscopy and SEM

Specimens are sectioned from the central region of the sintered disks, perpendicular to the pressing direction, to minimize edge effects and ensure a representative microstructure. The selected areas are located at least 5 mm away from the sample surface to avoid microstructural variations or temperature gradients during SPS processing. Key properties, including strength, corrosion resistance, and biocompatibility, are closely associated with the microstructure, particularly grain size (Langdon, 2007). The machining process induces substantial deformation in chips due to elevated strain rates and low temperatures, resulting in grain refinement (Taherkhani et al., 2024). As indicated in Fig. 1, grain size measurements revealed that sample b exhibited an average grain size of 19.54 µm, whereas the addition of GO in sample c reduced the average grain size to 15.21 µm. This grain refinement can be attributed to the role of GO in pinning grain boundaries and inhibiting excessive grain growth. The presence of continuous graphene layers at the grain boundaries creates a physical barrier similar to the Zener pinning mechanism. This effectively suppresses grain boundary migration, especially in the direction parallel to the graphene sheets (Lee et al., 2018; Liu et al., 2016). As a result, the structure exhibits finer grains compared to the graphene-free sample. Grain size is critical for biomedical applications, especially implants. Fine-grained structures have been demonstrated to enhance hardness, corrosion resistance, and interaction with body tissues (Wang et al., 2024). Furthermore, surfaces with smaller grains offer better protein adsorption and cell adhesion (Misra et al., 2013). SEM images demonstrated the presence of the TiC phase in the recycled titanium specimen b, resulting from carbon penetration from the graphite mold. In the composite sample c, most GO sheets were firmly attached to the titanium particles, indicating a uniform distribution. This homogeneous dispersion of GO within the titanium matrix suggests consistent mechanical properties throughout the sample.

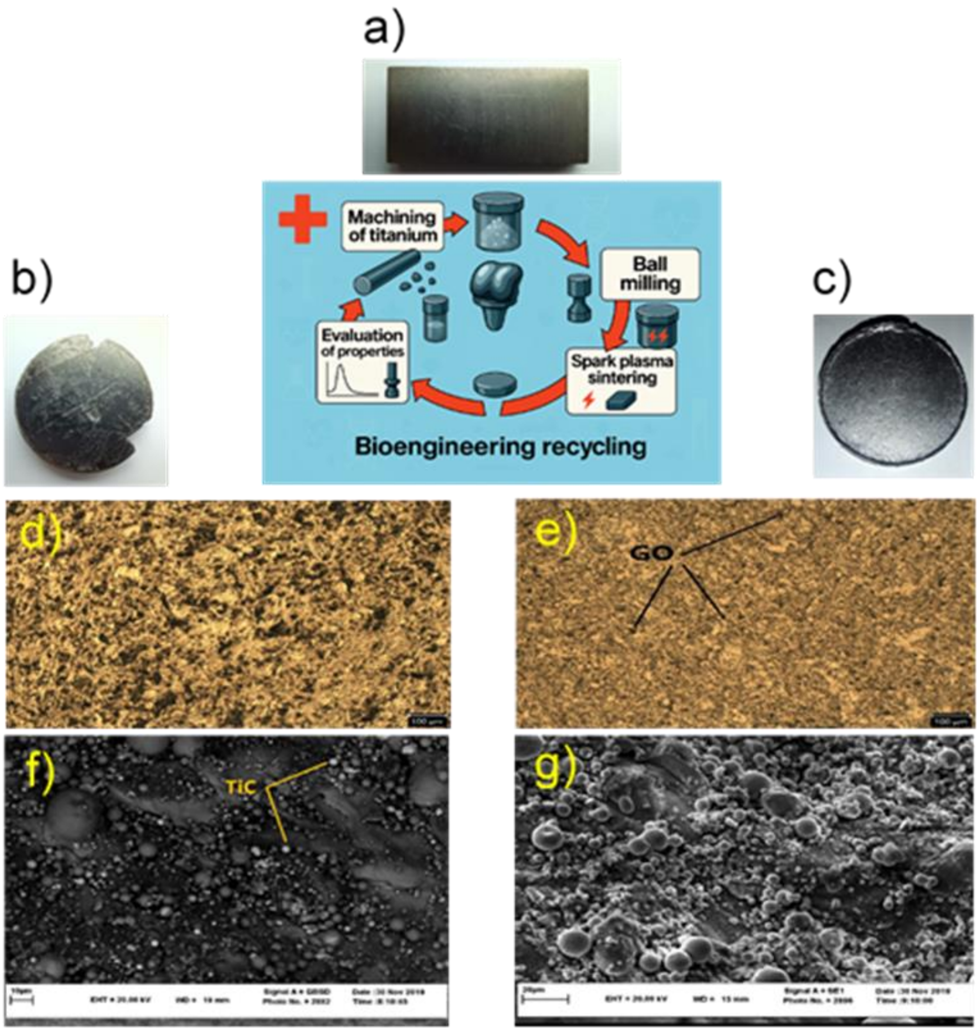

Figure 1. Schematic and experimental procedure: (a) pure Ti sheet, (b) recycled Ti sample, (c) recycled Ti/GO sample. Metallographic microstructure: (d) recycled Ti, (e) recycled Ti/GO. SEM images: (f) recycled Ti, (g) recycled Ti/GO

3.2. XRD

Initially, XRD analysis, presented in Fig. 2, was performed on the obtained powder to ensure the absence of impurities or titanium oxide. The diffraction peaks corresponded precisely to titanium, confirming the purity of the powder. To evaluate phase transformations during the SPS process, an additional XRD analysis was performed on the consolidated samples.

XRD analysis revealed Ti and TiC as the predominant phases in the samples. Peaks corresponding to pure titanium were designated as the baseline, with the most intense peak at 40° consistently observed across all samples. A weak peak at 12.5°, corresponding to GO, was unique to the composite sample. The prominent TiC peak at 78° emerged during the SPS process as a result of the use of a graphite mold and subsequent carbon diffusion. In the recycled titanium sample, this diffusion occurred in a controlled manner due to the presence of graphite foil. Research has demonstrated that the formation of this phase at the surface can significantly enhance mechanical properties, such as microhardness and wear resistance, leading to an increase in the lifespan of the implant (Chen et al., 2021). The presence of oxygen functional groups on GO promotes its uniform dispersion within the Ti matrix, increasing the effective interfacial contact area (Wei, Liu, Gao, et al., 2021). This chemical bonding significantly enhances load transfer efficiency (Wei, Liu, Gao, et al., 2021). GO sheets act as barriers to dislocation motion, activating the Orowan strengthening mechanism and increasing dislocation density (Wang et al., 2018). In addition, GO located at grain boundaries exerts a pinning effect, suppressing grain growth and stabilizing a refined microstructure (Chen et al., 2024). The combined action of dispersion strengthening, effective load transfer, Orowan strengthening, and grain growth inhibition leads to simultaneous improvements in the strength, hardness, and mechanical stability of the composite (Wei, Liu, Gao, et al., 2021).

In previous studies, GO coatings have been identified as a potential solution for enhancing the quality of bone-implant interfaces. The microstructures created and the chemical properties of GO coatings on titanium implant surfaces have the potential to induce cell adhesion, proliferation, osteogenic differentiation, and osseointegration, which may result in a variety of biomedical applications in the fields of dental and orthopedic implantology (Kwak et al., 2022). In this case, the GO is uniformly dispersed throughout the material.

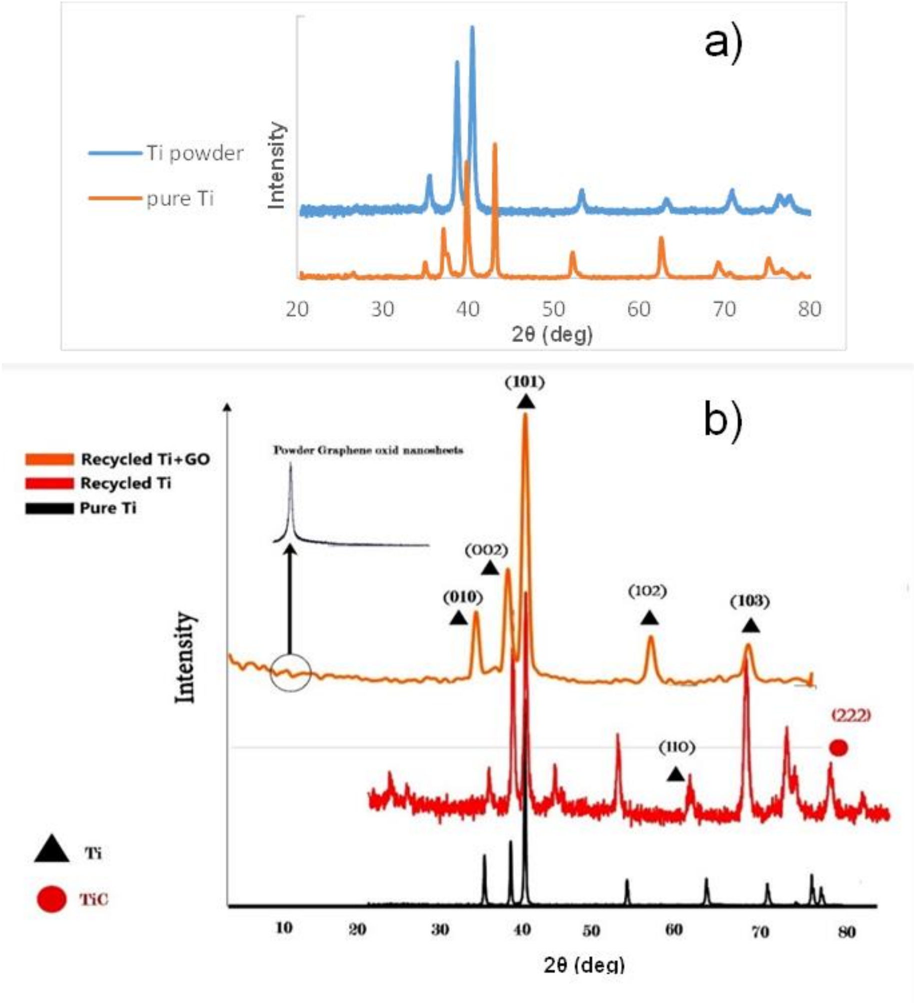

Figure 2. XRD micrographs of a) Powder obtained from chips and b) samples

3.3 hardness

Increasing implant hardness improves wear resistance and longevity (Wu et al., 2023), but excessive stiffness can reduce physiological loading on the surrounding bone, causing stress shielding and impairing remodeling in accordance with Wolff's law (Pivonka et al., 2017). Bone healing relies on optimal mechanical stimuli; thus, hardness gains must be balanced with an elastic modulus that supports healthy load transfer and bone regeneration. Although the present study did not directly measure the elastic modulus of the processed products, the observed grain refinement and homogeneous microstructure obtained through SPS, as well as the incorporation of GO, are expected to influence stiffness (Sedehi et al., 2021). Prior studies have reported that nanostructuring and reinforcement with carbon-based phases can reduce the effective modulus of titanium while maintaining strength (Ammisetti et al., 2024), thereby improving load transfer and minimizing stress shielding. According to Fig. 3, the Vickers hardness test was performed with a load of 30 kgf and a dwell time of 10 s.

The hardness of the commercially pure titanium sample was found to be 322 HV, while the recycled titanium sample synthesized using the SPS method exhibited a hardness of 378 HV, representing a 17% increase. In a previous study, a hardness of 325 HV was achieved for titanium fabricated from atomized powder using SPS (Chaudhari & Bauri, 2014). The results of the present study demonstrate that powder obtained from recycled titanium chips can enhance the hardness of the material compared to atomized powder (Sabour et al., 2024; Taherkhani et al., 2024). Furthermore, the SPS method gives rise to a structure characterized by enhanced density and finer grains. The addition of graphene oxide to recycled titanium powder in the composite sample increased the hardness to 402 HV, representing a 25% increase relative to commercially pure titanium. The enhanced hardness of Ti/GO composites stems from multiple synergistic mechanisms.

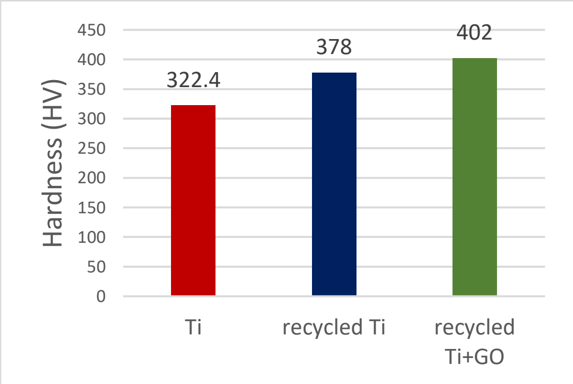

Figure 3. Vickers hardness test results of pure Ti sheet, Recycled Ti, and Ti/RGO composite

GO sheets obstruct dislocation motion and induce grain refinement through their pinning effect, thereby strengthening the matrix through the Hall-Petch relationship. Efficient load transfer from the titanium matrix to the stiff GO layers further improves resistance to indentation. Together, these mechanisms markedly increase material hardness, a critical property in biomedical applications, particularly for orthopedic and dental implants.

Higher hardness provides enhanced resistance to applied stresses, thereby preventing fracture and deformation of the implant. This, in turn, directly affects the lifespan of the implant (Wu et al., 2023). This characteristic has been shown to reduce wear, maintain structural integrity, and stabilize prosthetic connections (Saha & Roy, 2022). Conversely, the mechanical stability derived from appropriate hardness creates favorable conditions for bone formation and bone-implant integration (Sanati et al., 2025).

3.4. Wear resistance

The test results, based on weight-loss measurements conducted over three intervals, with a total sliding distance of 250 m, are presented in Table 3.

Testing was performed using the ball-on-disk method with a 52100 steel ball of 6 mm diameter. Weight-loss values reflected the extent of wear under an applied load of 5 kgf, a disk rotation speed of 150 rpm, and a linear speed of 8 cm/s. The findings shown in Fig. 4 provide clear insight into the wear behavior of the samples.

TABLE 3. wear rate of samples

sample	Wear rate (mm)			
	first 83meter	second 83meter	third 83meter	total
pure Ti	5.5	5.85	6.63	17.98
Recycled Ti	4.4	3.74	3.63	11.77
Recycled Ti+GO	0.48	0.25	0.13	0.86

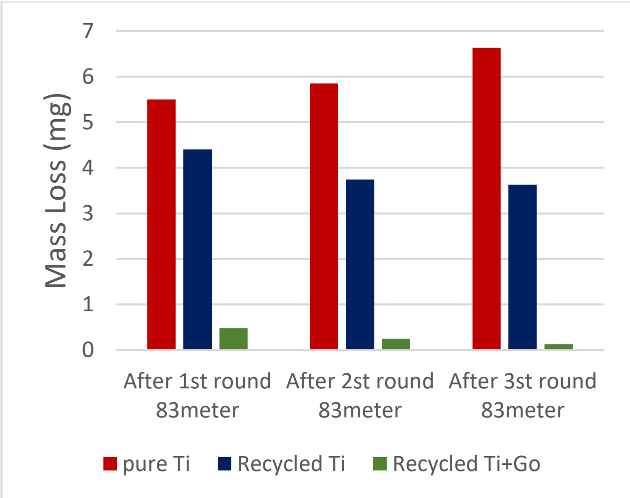

Figure 4. Comparison of wear Values of Samples

In the pure titanium sample, mass loss increased progressively at each stage, with a total loss of 17.98 mg. By contrast, the specimen fabricated from recycled titanium chips demonstrated superior wear resistance, with a mass loss of 11.77 mg, corresponding to a 52% improvement over cast titanium. The recycling process, followed by SPS, produced a dense, homogeneous microstructure with finer grains, reducing surface friction and thereby enhancing wear resistance. Additional strengthening of the chips during machining further contributed to this improvement. These findings indicate that recycling can enhance the mechanical performance of titanium, particularly its wear resistance. Unlike the pure titanium sample, the recycled specimen exhibited a consistent decrease in wear rate across successive test stages. The reduction of wear in implants is a crucial objective, as it can contribute to the increased lifespan and efficiency of the implants (Skjöldebrand et al., 2022). Implant wear can result in adverse effects such as inflammation of surrounding tissues, infection, and even implant failure (Hodges et al., 2021).

In the composite sample, the incorporation of GO into recycled titanium powder resulted in a substantial enhancement of wear resistance. GO, with its nanoscale structure, functions as an exceptional reinforcing agent. The graphene nanoparticles are dispersed within the titanium matrix, forming a reinforcing network that reduces friction and enhances wear resistance. The inherent lubricating properties of graphene can also act as a protective layer, preventing surface scratching. Xuyang Liu et al. (Wei, Liu, Zheng, et al., 2021) also conducted a study on the wear resistance of a Ti/GO composite, which demonstrated that, with an increase in graphene content and sintering temperature, the friction coefficient decreased and the wear resistance increased. The mass loss of the worn material in this specimen was 0.86 mg, exhibiting wear resistance approximately 21 times greater than that of commercially pure titanium.

These materials show promising potential for applications such as dental implants and orthodontics, where high durability and biological compatibility are essential. The primary reason for revision surgery of metal or ceramic hip joint components is implant loosening. In such cases, the primary causative factor is widely considered to be the presence of wear debris generated from the articulating surfaces (Matharu et al., 2016). Therefore, various surface treatments are employed to enhance the wear resistance of implants. Nevertheless, the adhesion of implant coatings remains a primary concern, as inadequate adhesion can result in coating detachment and excessive wear (Skjöldebrand et al., 2022). Unlike conventional coatings that often suffer from poor adhesion, the recycling-reinforcement approach used here avoids this limitation and offers two advantages: reduced production costs and alignment with sustainable medicine.

3.5. Corrosion

Despite the fact that metallic biomedical implants are typically employed for bone tissue regeneration and repair, the need for innovative technologies arises from the sensitivity of medical applications and the imperative to prevent any potential adverse reactions (Kalali et al., 2025). This necessity is driven by the objective of enhancing implant-to-bone integration and inhibiting infection through the mitigation of corrosion and excessive stress (Thakur et al., 2022).

The polarization corrosion test was conducted under ambient conditions at a temperature of 25°C in a solution containing 3.5% NaCl. To quantify corrosion, the Tafel slopes in the linear region of the polarization curves, shown in Fig. 5, were plotted, and the polarization parameter was calculated based on the Stern-Geary equation given below (Aljohani et al., 2021):

$$R_P = \frac{b_a b_c}{2.303(b_a + b_c) i_{corr}} \quad (1)$$

$$i_{corr} = \frac{E_{corr}}{R_P} \quad (2)$$

$$E_{corr} = \frac{b_a b_c}{2.303(b_a + b_c)} \quad (3)$$

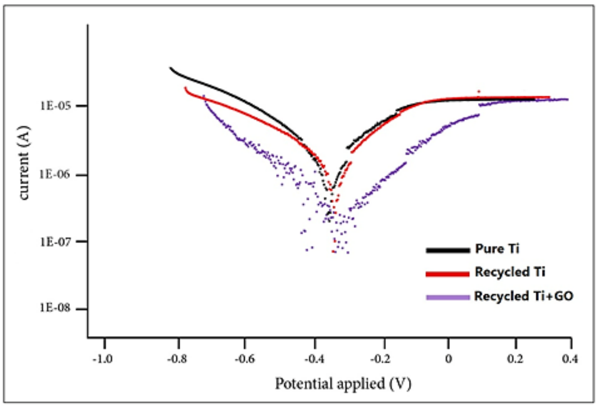

Figure 5. polarization curves of pure Ti, recycled Ti, and recycled Ti/GO in 3.5% NaCl solution at room temperature. The x-axis represents the applied potential (V), and the y-axis shows the measured current (A) on a logarithmic scale

In these equations, R_P represents the linear polarization resistance (LPR), b_a and b_c denote the slopes of the anodic and cathodic Tafel curves, respectively. The corrosion current density, i_{corr}, and the corrosion potential, E_{corr}, are also incorporated into the equation. A comparison of these parameters and the corrosion rates of the fabricated samples with those of the pure cast sample is presented in Table 4.

The manufacturing process for the recycled sample resulted in a 31% reduction in corrosion current compared to the commercially cast sample. This value decreased by a factor of 18 in the composite sample.

The corrosion rate of pure titanium was found to be 0.0022 *mm/year*. A comparative analysis of the corrosion results for the recycled titanium sample revealed a higher degree of corrosion resistance, with a corrosion rate of 0.00156 *mm/year*. The application of SPS effectively prevented the penetration of corrosive agents into the material (Nokhrin et al., 2021). In the third specimen, the incorporation of GO into the recycled titanium powder resulted in a substantial enhancement in corrosion resistance, with a corrosion rate of 0.00012 mm/year. The nanoscale properties of GO enable the formation of a protective layer, thereby preventing corrosive agents from contacting the titanium surface. Previous studies have demonstrated that incorporating GO into titanium oxide during the anodizing process enhances corrosion resistance by forming a protective surface layer (Aljohani et al., 2021).

TABLE 4. Values Calculated in Corrosion Test

Parameter	Ti	Recycled Ti	Ti+GO
E_{corr} (V)	-0.37	-0.353	-0.40
I_{corr} (A)	3.024×10^{-7}	2.076×10^{-7}	1.64×10^{-8}
b_a (V/dec)	0.15	0.124	0.17
b_c (V/dec)	0.166	0.169	0.13
R_p (Ohm)	1.14×10^{5}	1.5×10^{5}	2×10^{6}
Corrosion rate (mm/year)	0.0022	0.00156	0.00012

The incorporation of this nanomaterial into recycled titanium powder yields a composite material with remarkably high corrosion resistance, enabling its effective performance in corrosive environments. The improvement in corrosion resistance observed in the recycled samples can be attributed to microstructural modifications and enhanced surface characteristics resulting from the spark plasma sintering process. This technique promotes grain refinement and a more uniform distribution of reinforcements within the metallic matrix, which facilitates the formation of a more stable and homogeneous passive oxide layer on the surface (Zhang et al., 2024). In addition, the formation of secondary phases such as TiC, arising from interfacial reactions, contributes to increased surface hardness and a reduction in the number of active sites for corrosion initiation (Zhou et al., 2021). The presence of graphene oxide also plays a significant role by acting as a physical barrier against the penetration of corrosive ions, thereby lowering the corrosion rate. The selection of appropriate materials for implants can minimize corrosion and extend their lifespan (Naghdbishi et al., 2025), particularly in the field of dental implants, where corrosion is a significant concern that can compromise durability and performance. Despite advances in preventing the corrosion of dental implants, the mechanisms of metal ion release and their role in the pathogenesis of peri-implant disease remain to be fully elucidated. This underscores the urgent need for further research into the etiopathogenesis of corrosion products and the development of effective preventive strategies to limit surface degradation (Nagay et al., 2022).

The recycling of titanium, combined with the incorporation of graphene oxide due to its remarkable corrosion resistance, has emerged as a promising approach. This method has been identified as one of the most effective solutions for environments characterized by corrosive conditions and high sensitivity. In the corrosive environment of the body and saliva, this function helps ensure that the release of titanium ions, which can contribute to soft-tissue inflammation and allergic reactions, is minimized. Alterations in grain size can modify both surface and bulk characteristics, thereby influencing the electrochemical response and corrosion resistance (Savaedi et al., 2022).

4. Conclusion

This research, with a specific focus on medical needs and implant applications, highlights the recyclability of machined titanium chips as a sustainable feedstock for advanced composites with enhanced mechanical and biological performance. In this study, the chips were converted into powder suitable for powder metallurgy processes. The samples were synthesized through Spark Plasma Sintering at a temperature of 850 °C, a pressure of 45 MPa, and a holding time of 6 minutes. The present study systematically investigated the impact of using recycled powder in conjunction with 0.2% GO on the structural and mechanical properties of the samples. Although the developed recycled Ti/GO composite exhibited significant improvements in mechanical properties, wear resistance, and corrosion performance, these findings primarily demonstrate its potential for orthopedic implant applications. Further investigations, including comprehensive in vitro biocompatibility assessments, long-term biological evaluations, and in vivo studies, are required before considering clinical translation and practical biomedical implementation.

The following key results were obtained:

1. Recycled titanium retained its properties and performed better than standard pure titanium. Furthermore, the addition of graphene oxide nanoparticles improved the material properties, which is vital for medical applications such as dental and orthopedic implants.
2. The SPS process facilitates rapid production, high density, and superior microstructure control, thereby enabling the precise and customized design of implants and surgical instruments.
3. The hardness test demonstrated that pure titanium exhibited the lowest hardness, at 322 HV. The recycled sample exhibited a 17% increase in hardness, reaching 378 HV, while the composite sample demonstrated a 25% increase in hardness, reaching 402 HV. This increase in hardness is a key indicator of implant durability.
4. Wear resistance increased significantly. The pure sample exhibited the lowest wear resistance, with a mass loss of 17.98 mg, while the recycled sample, with a mass loss of 11.77 mg, demonstrated 52% greater wear resistance. The composite sample, with a mass loss of only 0.86 mg, exhibited wear resistance approximately 21 times greater than that of pure titanium.
5. The corrosion test results indicated that the corrosion rate of pure titanium was 0.0022 mm/year. The recycled titanium sample, with a corrosion rate of 0.00156 mm/year, exhibited 31% less corrosion than the initial sample. The composite specimen, with a corrosion rate of 0.00012 mm/year, exhibited the lowest corrosion rate, representing an approximately 18-fold

improvement in corrosion resistance relative to pure titanium. This is critical for ensuring the long-term stability of implants in the physiological environment.

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Conflict of interest

The authors declare no financial interests or personal relationships that could have influenced the findings presented in this study.

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NOMENCLATURE

GO	Graphene Oxide
HV	Vickers Hardness
LPR	Linear Polarization Resistance
NaCl	Sodium Chloride
SEM	Scanning Electron Microscopy
SPD	Severe Plastic Deformation
SPS	Spark Plasma Sintering
Ti	Titanium
TiC	Titanium Carbide
UFG	Ultrafine-Grained
XRD	X-ray Diffraction

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