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Effect of the Si Content on the Dry and Wet Sliding Wear Behavior of the Developed Ti-15Mo-(0-2) Si Alloys for Biomedical Applications

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Abstract: The durability of a metallic biomaterial to withstand weight loss is a key factor in determining its service life and performance. Therefore, it is essential to create biomaterials with high wear resistance to ensure the biomaterial has a long service life. Thus, this study aims to explore the dry and wet sliding wear characteristics of the developed Ti-15Mo-xSi as-cast alloys (where x equals 0, 0.5, 1, 1.5, and 2 wt.%) in order to assess the impact of the Si addition on the microstructure, mechanical properties, and wear resistance and to consider them for biomedical applications. The wear experiments were conducted using a pin-on-desk wear testing machine at a load of 20 N and a sliding distance of 1000 m with and without applying simulated body fluid (SBF). Different techniques were utilized in the evaluation of the developed Ti-15Mo-xSi alloys. The results showed that significant grain refining was attained with the Si addition. The hardness, compressive strength, and wear resistance of the Ti-15Mo-xSi as-cast alloys increased with the increase in Si content. The Ti-15Mo-2Si as-cast alloy exhibited the highest dry and wet wear resistance of all the Ti-15Mo-xSi alloys. The worn surfaces were investigated, the roughness and main features were reported, and the wear mechanisms were also discussed.

Keywords: Ti alloys; mechanical properties; dry wear; wet wear; simulated body fluid; Si addition; hardness; compressive strength; wear mechanisms; roughness; worn surface

Citation: El-Sayed Seleman, M.M.; Ataya, S.; Aly, H.A.; Haldar, B.; Alsaleh, N.A.; Ahmed, M.M.Z.; Bakkar, A.; Ibrahim, K.M. Effect of the Si Content on the Dry and Wet Sliding Wear Behavior of the Developed Ti-15Mo-(0-2) Si Alloys for Biomedical Applications. *Metals* **2023**, *13*, 1861. https://doi.org/10.3390/met13111861

Academic Editor: Jürgen Eckert

Received: 26 September 2023
Revised: 1 November 2023
Accepted: 2 November 2023
Published: 8 November 2023

1. Introduction

With the current technological progress, the use of metal-based materials in prosthetic parts has increased due to urgent human needs. Dental roots, orthopedic fixation, joint replacements, and stents are all examples of different alloys utilized to provide internal support and replace biological tissue. The alloys that are primarily used in biomedical applications are Co alloys [1], stainless steels [2,3], and Ti alloys [4,5]. Biomaterials must meet a range of characteristics, including exceptional corrosion resistance, sufficient strength, effective bioadhesion, optimal biocompatibility, appropriate biofunctionality, and high wear resistance [6]. It has been reported that wear [7,8] and corrosion [9,10] are the main causes of implant failure.

Due to their outstanding strength-to-weight ratio, toughness, and corrosion resistance, commercially pure Ti and Ti-based alloys are currently widely used in biomedical and

engineering applications instead of traditional alloys [11–13]. They are considered a popular choice for the replacement of synovial joints such as the hip, shoulder, and knee in biomedical applications. However, there remain several unresolved issues pertaining to the utilization of Ti-based alloys as materials for implants [14–16]. The two factors under research consideration are the biocompatibility of the Ti alloy composition and the elastic modulus [17]. Although Ti-6Al-4V and Ti-5Al-2.5 Fe alloys have been widely employed in orthopedic implantation due to their good biocompatibility, mechanical properties, and favorable corrosion resistance [4,18,19], the long-term performance of these alloys has raised some concerns as a result of the release of Al, Fe, and V. Recently, Fe, Al, and V have been recognized as higher cytotoxic elements [20]. As a result, various biomaterials that are free of these hazardous components have been researched for their potential use as implant materials [10,21]. In addition, the comparatively high stiffness of Ti alloys in comparison to neighboring bone can cause stress-shielding issues and implant loosening. The elastic modulus of natural bone ranges between 20 and 40 GPa [20,22]. Consequently, an alloy with a low elastic modulus is ideal for replacing hard tissue instruments. It was reported that alloying elements such as Mo, Zr, Nb, and Ta are recommended to reduce the elastic modulus of Ti alloys while keeping their strength. In addition, these elements are nontoxic, making them suitable for use in implantology [23]. One of the important alloying elements that has recently been introduced into Ti alloys is Si, which improves the castability and acts as a β-phase stabilizer when added in the range from 0.5 to 2 wt.% to the Ti15Mo alloy system [23]. Ti undergoes an allotropic transformation, as a result of this structural change, Ti alloys are classified into three types: α-phase alloys, (α + β)-phase alloys, and β-phase alloys, depending on the addition of α and/or β alloying stabilizers. Oliveira et al. [24] studied the phase compositions of TiMo alloy systems with the addition of Mo from 4 to 20 wt.%. They reported that, for the alloy containing 10% Mo, a significant retention of the β-phase was seen; however, at higher Mo additions (15% and 20%), retention of the β-phase was only detected. The β-alloy type of Ti alloys is recommended over the α + β alloy type due to the possibility of governing the fabricating parameters to achieve specific results like a low modulus of elasticity, a high corrosion resistance, and enhanced tissue response [24,25]. In addition to biocompatibility and reaching the β-phase alloy for the new design of titanium-based alloys, it is important to keep in mind that pure Ti has a low wear resistance, which limits its usage in implants that come into contact with their own or neighboring bone. In fact, the wear behavior of Ti-based alloys is considered to be a crucial factor in their suitability for biomedical applications [26,27]. This is due to the fact that the generation of wear debris during the movement of artificial joints significantly contributes to the occurrence of aseptic loosening (mechanical loss results in the failure of the fixation of a prosthetic alloy component in the absence of infection) [28,29]. Pure or commercial Ti alloys have often been observed to exhibit limited resistance to sliding wear and limitations in high-stress applications because of their difficulty in polishing, low strength, and poor wear resistance [30,31]. This is primarily attributed to their inadequate ability to withstand plastic shearing and the insufficient protection provided by surface oxides. In previous works [6,29], wear debris created by long-term use in a human body was found to enhance osteolytic mediators, leading to aseptic loosening of prostheses.

Furthermore, numerous harmful reactions may occur as a result of the accumulation of wear debris in tissue [2,7,32]. As a result, it is essential to develop and produce biomaterials with high wear resistance to guarantee a long lifespan with high performance.

Based on the available data derived from a comprehensive review of the available literature, a few works have been conducted on the Ti-Mo alloy systems, and most of them were focused on studying the effect of adding the molybdenum percentage on phase transformation [21], thermal expansion under various heating rates [33], electrochemical corrosion behavior [24], microstructure and some mechanical properties of a specific alloy composition [34], or even wear behavior in the dry state [35]. It is evident that no systematic study has been conducted to investigate the impact of adding silicon up to 2 wt.% and Mo up to 15 wt.% on the dry and wet wear properties of Ti alloy. Hence, the novelty of

the current work is to explore the impact of the addition of Si on the dry and wet sliding wear characteristics of the developed Ti-15 Mo alloys. In addition, this aim is extended to address the current state of knowledge of the phase composition, microstructure grain size, hardness, compressive strength, worn surface roughness, and wear mechanisms. Figure 1 summarizes the work plan for the current study.

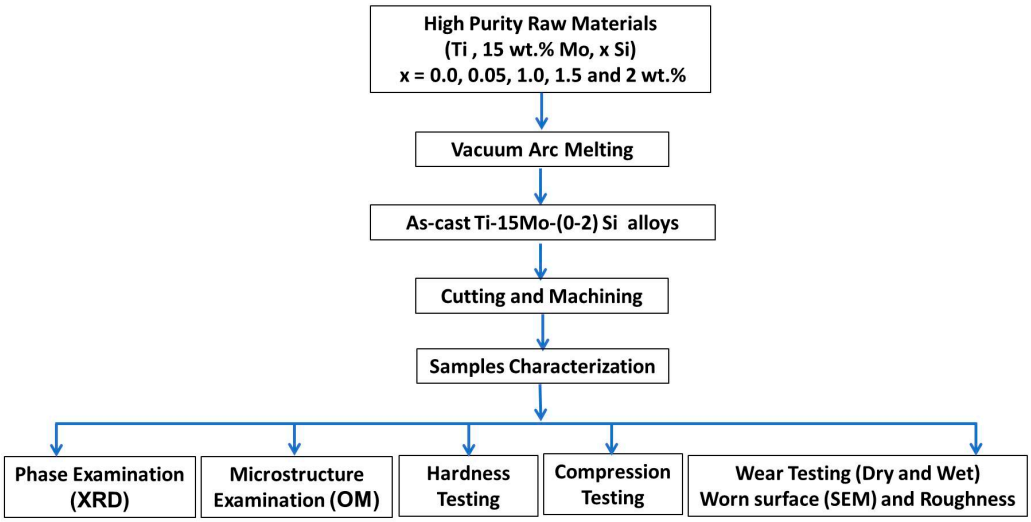

Figure 1. The flow chart summarizes the work plan of the processing and characterization for the developed Ti-15Mo-x Si alloys.

2. Materials and Methods

Ti-15 wt.% Mo-(0-2) wt.% Si alloys were produced from high purity as-received metallic materials of Ti, Mo, and Si supplied by the Nilaco Corporation, Japan. According to the supplier, the purity is not less than 99.96 for each supplied metal. These developed Ti alloys were produced by melting in a vacuum arc remelting (VAR) furnace (ARCAST 800A, USA model) under a controlled high purity argon atmosphere with a special magnetic stirring process to achieve high composition homogeneity. The melted alloys were finally cast utilizing an advanced water-cooled system.

The produced materials were machined in square and cylindrical samples for the different materials' characterizations. For microstructure investigation, the machined samples were ground up with 2400 grit SiC papers, then polished utilizing micro-diamond suspensions, followed by polishing using a nano silica suspension to achieve a mirror surface finish. Then, they were investigated using an Olympus optical microscope (OM) (BX41M-LED, Tokyo, Japan). The X-ray diffractometer (X'PERTPRO. A PANLYTICAL instrument, Malvern, UK) was used to identify the formed phases in the produced Ti alloys with the working conditions of a Cu-Kα target with secondary monochromatic at 45 kV and 40 mA. The investigation was performed at a step size of 0.04° in the range 2θ: 20–80°. The hardness test was carried out using a universal hardness testing machine, model NEMESIS 9104, INNOVATEST, Maastricht, Netherlands. The Vickers hardness measurements were performed using an applied load of 20 N with a holding time of 10 s. The compression test was conducted using a 30-ton Universal testing machine (WDW-300, Jinan Precision Testing Equipment Co., Ltd., Jinan, China) at room temperature and at a constant loading rate of 0.1 mm/min. The machined cylindrical samples were prepared according to ASTM E9. The dry and wet wear tests for the machined samples (5 mm diameter and 40 height mm) were performed using a pin-on-disk wear testing machine (Mode T-01 M, ITeE-PIB, Radom, Poland). The wear test conditions were an applied load of 20 N and a sliding distance of 1000 m at both dry and wet conditions. The wet medium was simulated body fluid (SBF). The SBF is a commonly used solution that simulates the chemical composition of human body fluid. To ensure the accuracy of the results for each test, at least three samples were tested, and the average results were calculated. After the wear tests, the worn surfaces

were examined using a scanning electron microscope (SEM) (FE-SEM, ZEISS Sigma 300 VP, Oberkochen, Germany).

3. Results and Discussion

3.1. XRD Analysis and Microstructure Evaluation

The suggested Ti-15 wt.% Mo-xSi alloy systems (where x equals 0.0, 0.5, 0.1, 1.5, and 2.0 wt.%) were melted in a vacuum arc remelting furnace using a water-cooled copper hearth, applying a special stirring system to attain complete homogeneity. This was followed by a fast cooling, which helps to obtain solid-state phase transformations and promotes the formation of the β-Ti phase. XRD analysis was carried out to identify the present phases in the produced Ti-15Mo-xSi alloys, as shown in Figure 2. The XRD patterns for all samples exhibited the same behavior, with the peak positions and intensities of the β-phase, as well as the absence of α-phase or any intermetallics, indicating the designed weight ratios of 15Mo and xSi alloying elements are very effective in stabilizing the β-phase of the quenched Ti alloys at room temperature [33]. This result also corresponded with the findings of other researchers, who found that only the β-phase was present in the Ti base alloys at 15 wt.% additions of β-phase stabilizing elements [34,36,37].

The mechanical properties and biomedical applications of the Ti base alloys are influenced by their microstructure features, including the presence of different phases, grain size, and the distribution of alloying elements [38]. All the as-cast Ti-15Mo-(0-2)Si alloy microstructures were investigated, and the representative OM-images of the Ti-15Mo master alloy, Ti-15Mo-1Si, and Ti-15Mo-2Si are presented in Figure 3a–c, respectively. It can be observed that large equiaxed grains of β-Ti were formed in the master alloy with a grain size range from 105 to 800 μm, as shown in Figure 3d. The average grain size attained a value of 497.5 ± 39 μm. With the addition of 1 wt.% Si, the Ti-15Mo-1Si showed a lower grain size range from 50 to 680 μm (Figure 3e) compared to the Ti-15Mo ally. The average grain size attained a value of 292.1 ± 31 μm. In the case of adding 2 wt.% Si, the grain size range of Ti-15Mo-2Si reached values from 44 to 280 μm (Figure 3f), and the average grain size was 105.3 ± 12 μm.

Figure 4 presents the trend of grain size refining with the increase in the Si addition to the master alloy Ti15Mo. It can be noted that the grain size of the Ti-15Mo decreases with the increase in the Si content from 0.05 to 2.0 wt.%, and the grain size reduction is sensitive to any weight addition of Si. Thus, it can be said that Si can play a significant role in the grain refining of beta titanium (β-Ti) alloys. This grain refining may be due to Si acting as a pinning agent, impeding the growth of the β-Ti grains during the solidification process at rapid cooling. The presence of Si in the alloy can hinder the movement of grain boundaries and suppress grain growth, resulting in finer grains in the final microstructure. These results are consistent with prior works [39], which revealed that increased Si content in the Ti base alloys resulted in the formation of finer grains and more subgrains. The effectiveness of the Si addition on the grain refinement of Ti alloys depends on its concentration, processing conditions, cooling rate, and the presence of other alloying elements [34].

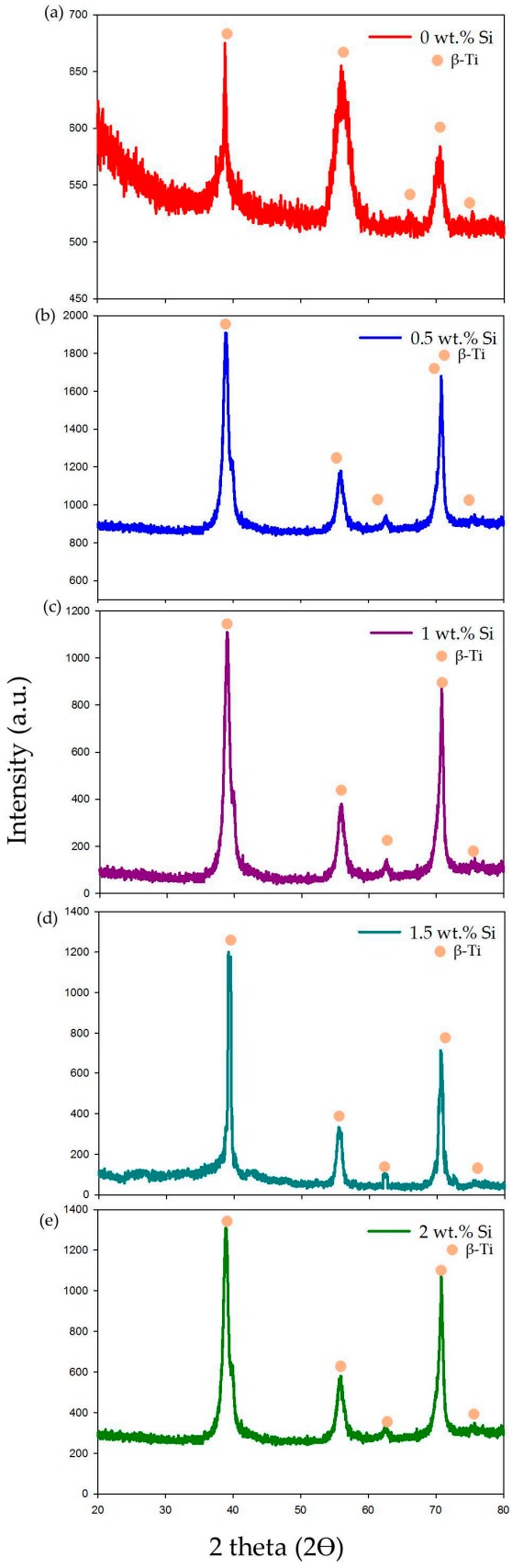

Figure 2. XRD patterns of the Ti15Mo as-cast alloys with Si additions of (**a**) 0.0 wt.%, (**b**) 0.5 wt.%, (**c**) 1.0 wt.%, (**d**) 1.5 wt.%, and (**e**) 2.0 wt.%.

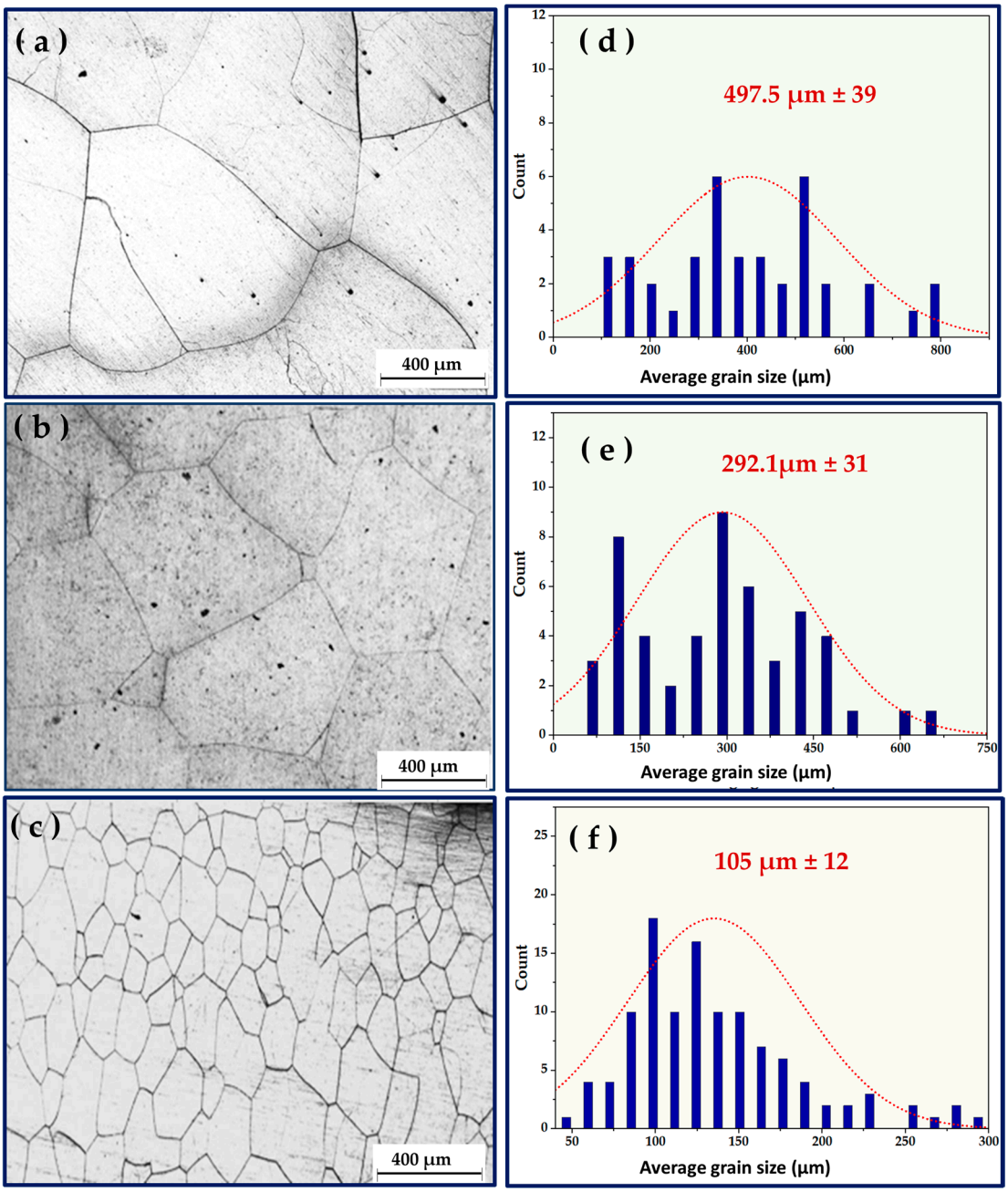

Figure 3. OM microstructure images of (**a**) Ti15Mo, (**b**) Ti15Mo-1Si, and (**c**) Ti15Mo-2Si cast alloys and their related grain size histograms in (**d**–**f**), respectively.

3.2. Hardness and Compressive Strength

Hardness is a property related to the material's ability to resist penetration or scratching; it is a localized plastic deformation. Compressive strength refers to a material's ability to withstand a uniform compressive load without failure, it is an indicator of the material's ability to resist bulk deformation under mechanical stress. Both properties are important for Ti alloys that are candidates for biomedical applications [38]. Figures 5 and 6 illustrates the average values of the hardness and compressive strength–strain curves of the Ti15Mo-(0-2)Si as-cast alloys as a function of Si content, respectively. It can be seen that both the hardness and compressive strength increase with the increase in the Si addition in the range from 0.0 to 2.0 wt.%. In the case of the hardness measurements, as plotted in Figure 5, the average values of hardness increase gradually from 340 ± 3.6 to 437 ± 7.2 HV with the increase in the Si content from 0.0 to 2.0 wt.%, respectively, in the produced Ti alloys. The

hardness increment percentage of the Ti15Mo-2Si alloy is 30.10% higher than that of the Ti15Mo master alloy (without Si content).

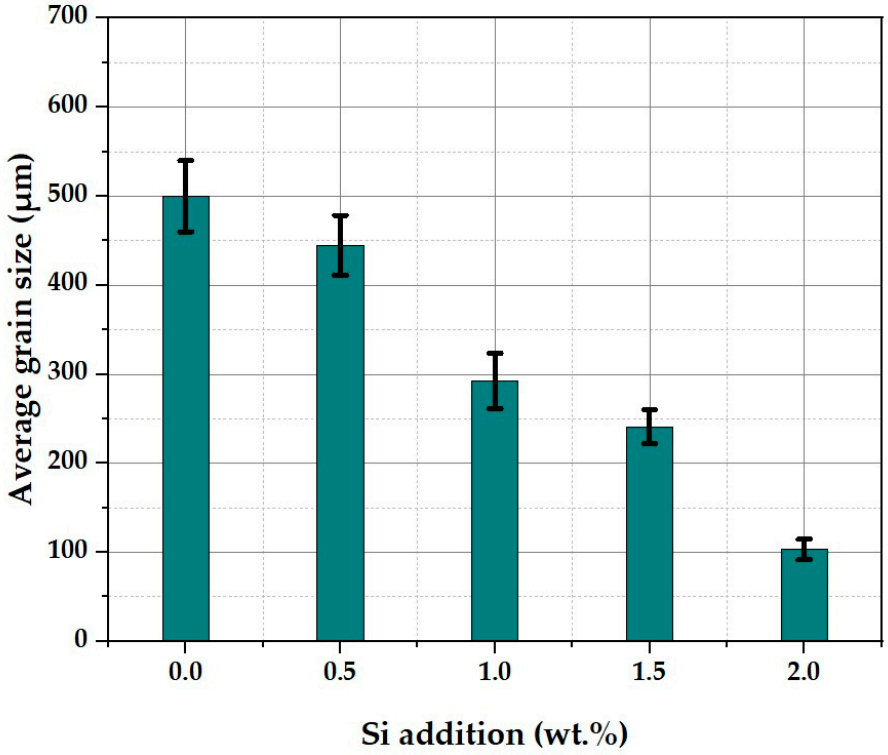

Figure 4. The average grain size of the Ti15Mo-XSi cast alloys versus the Si content.

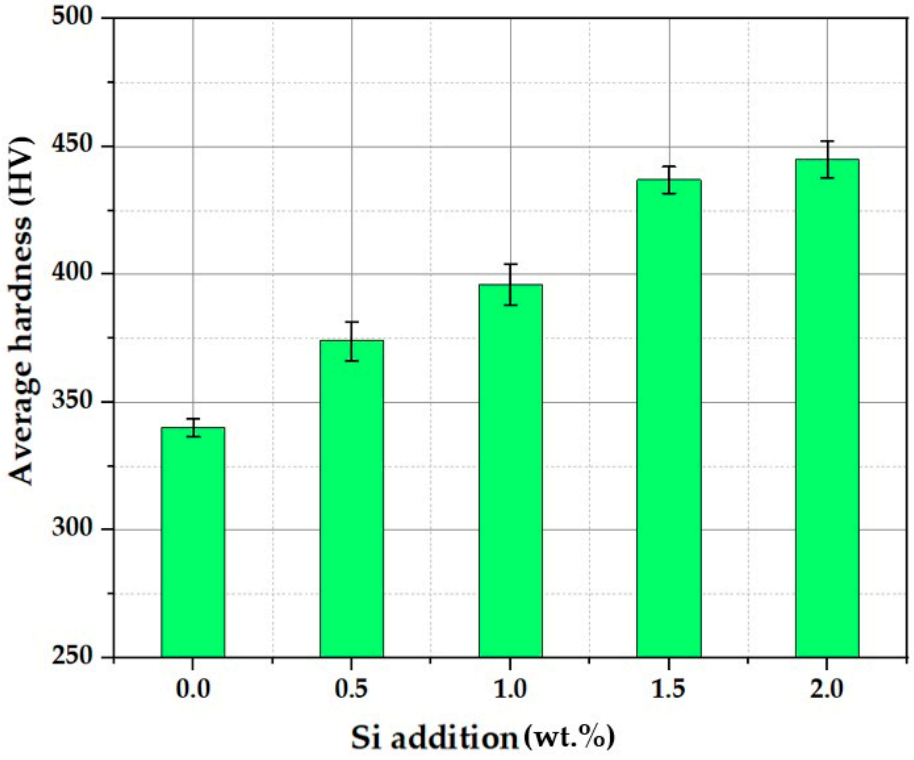

Figure 5. The average hardness values of the Ti15Mo-XSi cast alloys as a function of Si addition from 0.0 to 2.0 wt.%.

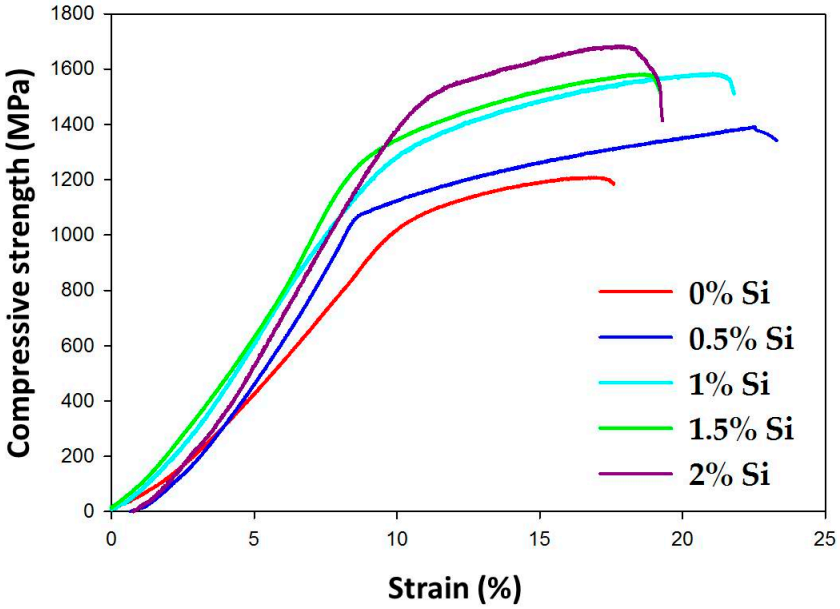

Figure 6. The compression strength–strain curves of the Ti15Mo-XSi cast alloys as a function of the Si content from 0.0 to 2.0 wt.%.

In general, the addition of Si enhances both the compressive strength and ductility of the Ti15Mo-xSi alloys over the Ti15Mo base alloy, as shown in Figure 6. Table 1 represents the average compressive strength at different Si contents for the Ti15Mo-xSi. It can be noted that the compressive strength of the Ti15Mo-2Si specimen showed the highest compressive strength behavior, while the Ti15Mo alloy specimen showed the lowest compressive strength value during the compression test, as shown in Table 1. The percentage of the strength enhancement of the Ti15Mo-2Si alloy reaches a value of 16.64% over the alloy without Si content (the Ti-15Mo alloy).

Table 1. The average compressive strength at different Si contents from 0.0 to 2.0 wt.% for the Ti15Mo-xSi alloys.

Si Content (wt.%)	0	0.5	1	1.5	2
Compressive strength (MPa)	1442 ± 22.3	1570 ± 20.1	1585 ± 25.2	1634 ± 13.1	1682 ± 33.9

In Ti-alloys, strength can be influenced by factors such as alloy composition, processing methods, heat treatments, and the presence of various strengthening mechanisms like solid solution strengthening, precipitation hardening, and grain refinement [40]. Si can play a significant role in the grain refining of β-Ti alloys, which can lead to improved mechanical properties according to the Hall–Petch equation [41,42]. Grain size plays a significant role in both hardness and compressive strength. In general, finer grain sizes tend to result in higher hardness and compressive strength. This is because a finer grain structure enhances the effectiveness of grain boundaries as barriers to dislocation movement, leading to increased strength [43].

Additionally, smaller grains can hinder the propagation of cracks and improve the material's resistance to deformation and failure under compression [44]. Thus, the as-cast alloy containing 2 wt.% Si addition shows the highest compressive strength value of 1682 MPa among all the processed alloys in the current study. It should be noted that the relationship between compressive strength and hardness in Ti alloys is generally positive, although there is no direct correlation. Ti alloys with higher hardness values tend to exhibit higher compressive strengths. This is because factors that contribute to increased hardness, such as solid solution strengthening, precipitation strengthening, and grain refinement, also tend to enhance the overall strength of the material. However, it is important to consider

that other factors, such as the presence of brittle phases or flaws, can influence the material's compressive strength independently of hardness [45].

3.3. Wear Characterization in Dry and Wet Conditions

Wear is a common cause of component failure and can lead to increased maintenance costs and system downtime. By studying wear in both dry and wet environments, researchers can gain insights into the wear patterns, rates, and failure modes of materials. This information can be used to develop a new antiwear material, predict component lifetimes, and implement preventive measures to minimize wear-related failures in biomedical applications [46]. Furthermore, understanding dominant wear mechanisms in tribological experiments helps researchers identify the factors influencing wear resistance, develop mitigation strategies, and improve the design and performance of Ti alloys for various and specific biomedical applications [7,32].

In the current work, the five developed Ti-15Mo-xSi alloys were subjected to wear tests using a pin-on-desk testing machine at a constant wear load of 20 N and a constant sliding distance of 1000 m in dry and wet conditions. The liquid medium was SBF, and the gained data were plotted as the weight loss and wear resistance in Figure 7a,b, respectively. It can be noted that for the weight loss in both dry and wet wear conditions (Figure 7a), the average weight loss of Ti15Mo base alloy decreased from 0.1164 g $\pm$ 0.0026 to attain 0.0193 g $\pm$ 0.0022 in the case of the dry wear condition and from 0.0895 g $\pm$ 0.0020 to reach 0.0077 g $\pm$ 0.0017 in the case of the wet wear condition with the increase in Si content from 0.0 to 2.0 wt.%, respectively, indicating a significant improvement in the dry and wet wear resistance with the increase in the Si addition. It is also observed that the weight loss values of Ti-15Mo-xSi specimens subjected to wet wear testing were lower than those tested under dry wear in the presence of SBF wet conditions.

Depending on the collected data from the dry and wet wear testing parameters and the measured density of the developed Ti-15Mo-xSi alloys, the wear behavior is plotted as the wear resistance versus the wt.% of Si content as shown in Figure 7b. It can be noted that the addition of Si from 0.05 to 2.0 wt.% improves the wear resistance (Figure 7b) and decreases the coefficient of friction (Table 2) in both the dry and wet conditions. Furthermore, the wet wear tested specimens of the developed Ti alloys gives a higher wear resistance than that tested in the dry condition in the presence of SBF. It can be concluded that the wear resistance of Ti15Mo alloys is influenced by the wear test medium. In biomedical applications, Ti alloys are often used in load-bearing implants such as orthopedic implants (e.g., hip and knee replacements) and also dental implants. The wear test medium used to simulate the physiological environment in these cases can significantly impact the wear test results [35].

To understand the wear mechanisms of the current developed Ti-15Mo-xSi alloys, the worn surfaces were examined by SEM. Figures 8 and 9 represent the SEM images of the worn surfaces of the Ti-15Mo-xSi alloys after dry and wet wear testing at a wear load of 20 N and a sliding distance of 1000 m, respectively. In both cases, the same features of worn surfaces can be noted with different degrees and more effects on the dry surface. Thus, it can be said that a 20 N wear load is sufficient for surface damage in Ti-15Mo-xSi alloys. The worn surface of the Ti15Mo base alloy shows clear damage in the form of continuous scratches. The parallel wear tracks indicate plastic deformation by the harder counterface of the wear machine disk. Therefore, the width of the deep scratches decreases with the increasing Si content in the tested alloys. For the Ti15Mo alloy, deep wear tracks, severe plastic deformation, and large wear debris are the main features in both the dry (Figure 8a) and wet (Figure 9a) test conditions. Similar worn surface features are noted when the alloy contains 0.5 wt.% Si on the worn surfaces of the dry (Figure 8b) and wet (Figure 9b) testing at the same wear testing parameters. Besides, microcracks and cavities are noted. This difference comes from the fact that the wear track in some places becomes shallow, indicating the improvement in the hardness and strength with the addition of 0.5 wt.% Si to the Ti15Mo master alloy. With the increasing Si content to 1.0 wt.% (Figures 8c and 9c),

1.5 wt.% (Figures 8c and 9c), and 2 wt.% (Figures 8e and 9e) in the produced Ti15 Mo alloy, the formed debris and the detached or attached deformed layers decrease, indicating the impact of the Si addition on the alloy wear resistance.

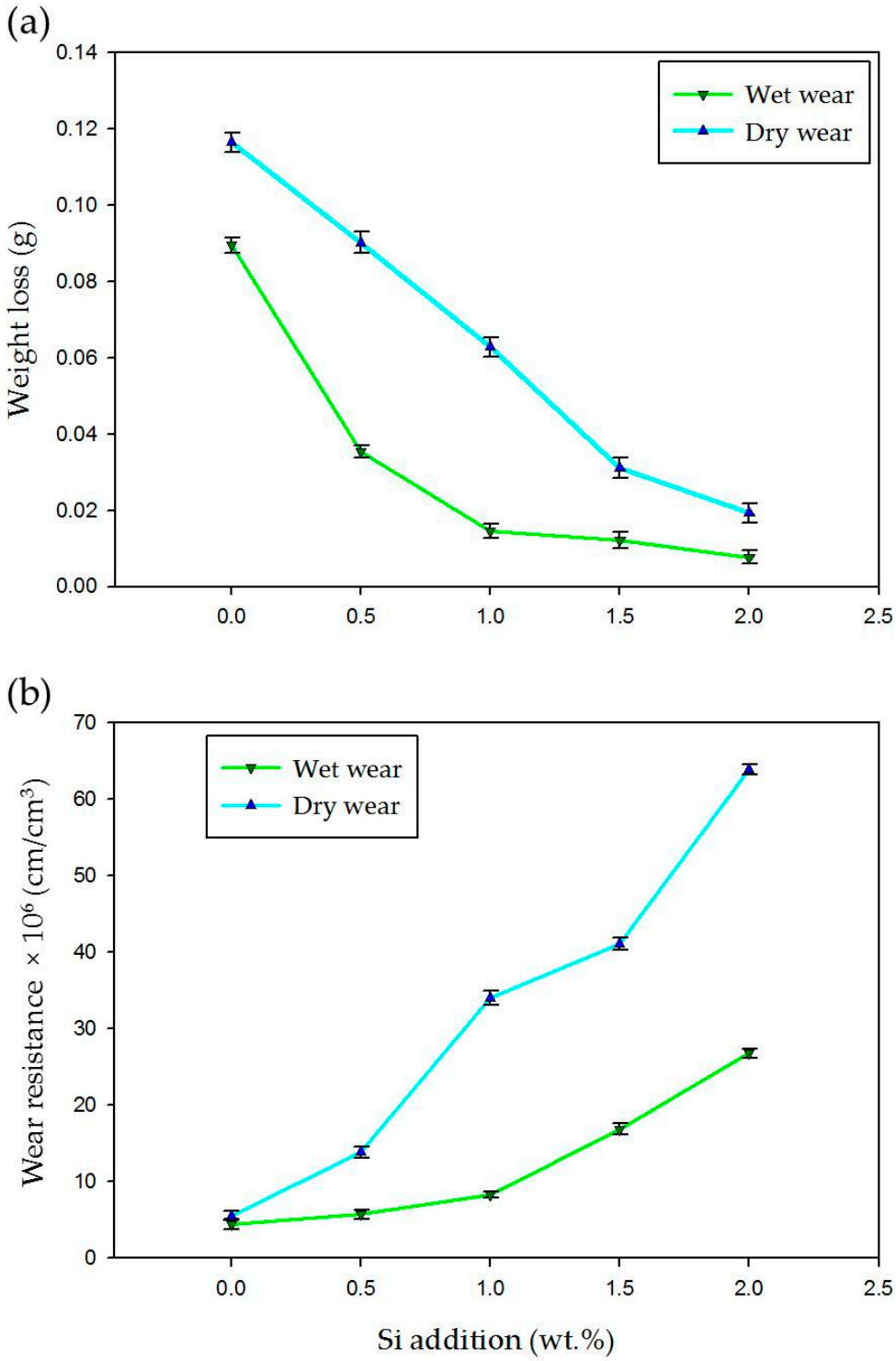

Figure 7. (**a**) weight loss and (**b**) wear resistance of the Ti-15Mo-xSi alloys against different Si additions ranging from 0 to 2 wt.% after dry and wet wear testing at a wear load of 20 N and a sliding distance of 1000 m.

Table 2. The average values of the coefficient of friction (COF) for the dry and wet wear conditions of the Ti15Mo-(0-2)Si alloys tested at a wear load of 20 N and a sliding distance of 1000 m.

Si Content (wt.%)	0	0.5	1	1.5	2
COF (dry wear)	0.680 ± 0.030	0.630 ± 0.020	0.550 ± 0.0320	0.510 ± 0.015	0.400 ± 0.018
COF (wet wear)	0.700 ± 0.031	0.670 ± 0.025	0.600 ± 0.032	0.530 ± 0.020	0.470 ± 0.030

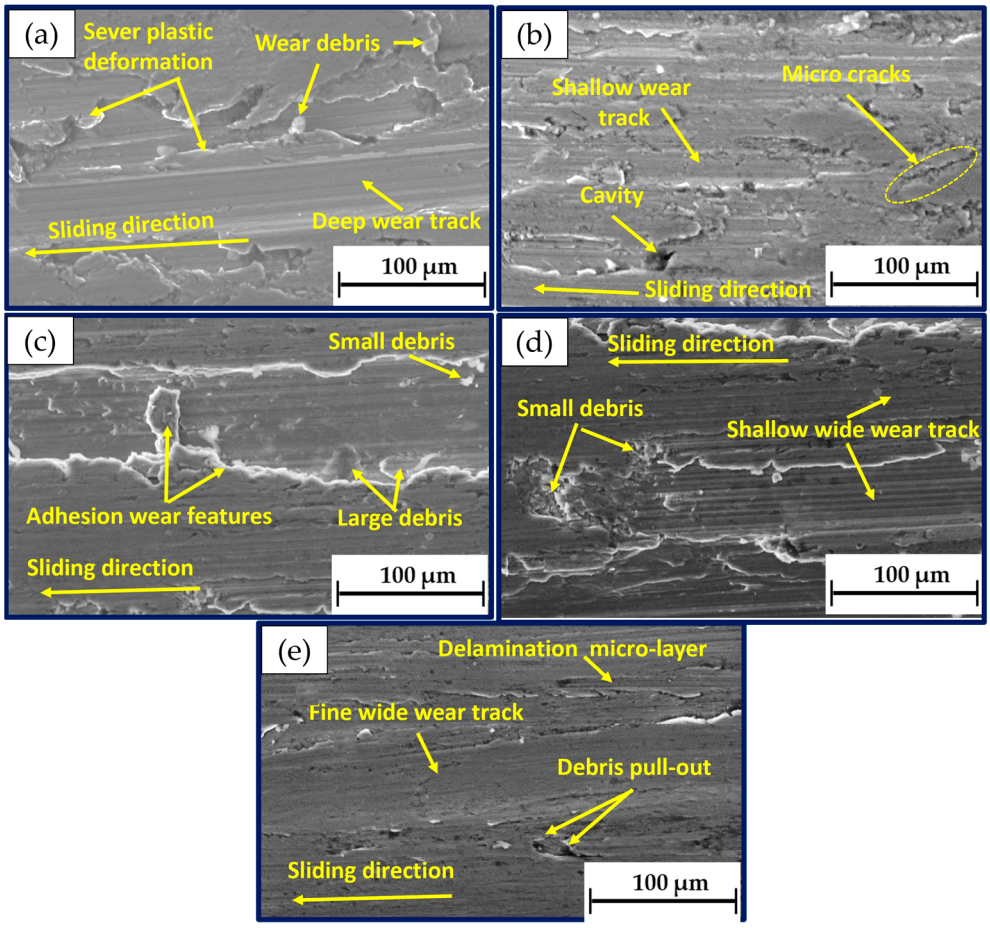

Figure 8. SEM images of the worn surfaces of Ti-15Mo-xSi alloys after dry wear testing at a wear load of 20 N and a sliding distance of 1000 m, where (**a**) Ti-15Mo master alloy, (**b**) Ti-15Mo-0.5Si, (**c**) Ti-15Mo-1.0Si, (**d**) Ti-15Mo-1.5Si, and (**e**) Ti-15Mo-2.0Si.

Two wear mechanisms are responsible for the lower resistance in the dry wear condition compared to the wet wear condition: first, adhesive wear occurs when two contacting surfaces experience applied wear loading and subsequent shearing forces. In the case of the Ti15Mo-xSi alloys, adhesive wear can lead to material transfer, surface deformation, and the formation of wear debris. The size of the wear debris depends on the accumulated heat and the amount of plastic deformation during the dry wear condition [47–49]. This wear mechanism is dominant in the dry wear condition. Second, abrasive wear involves the removal of material due to the presence of asperities or small debris in the sliding interface. Abrasive wear can result in surface roughening, scratching, and material loss. These two mechanisms are also detected in the SBF wet wear test condition as shown in Figure 9 with different worn surface features. The presence of SBF dissipates the frictional heat and reduces the direct friction between the rubbing surfaces resulting in a lower wear loss [2].

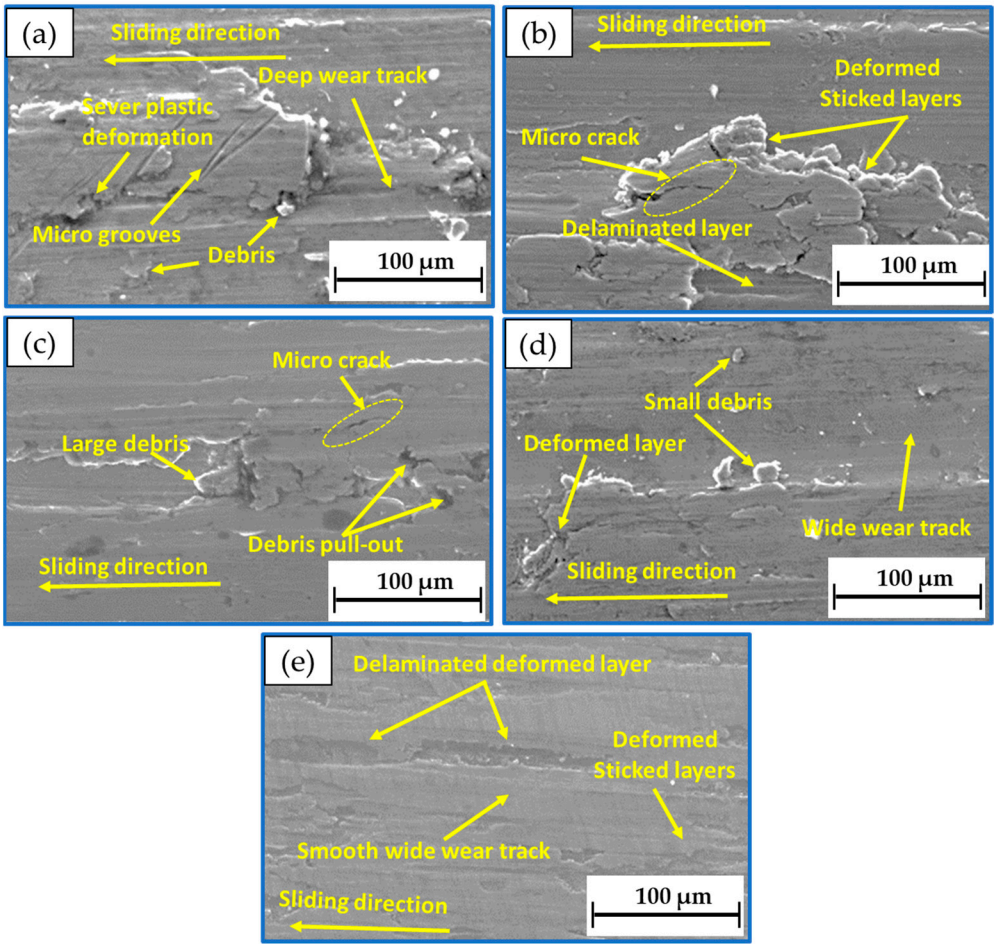

Figure 9. SEM images of the worn surfaces of Ti-15Mo-xSi alloys after wet wear testing at a wear load of 20 N and a sliding distance of 1000 m, where (**a**) Ti-15Mo master alloy, (**b**) Ti-15Mo-0.5Si, (**c**) Ti-15Mo-1.0Si, (**d**) Ti-15Mo-1.5Si, and (**e**) Ti-15Mo-2.0Si.

The surface roughness of the wear-tested Ti alloys can vary based on a number of variables, including alloy composition, processing methods, surface treatment, and wear conditions [50]. Figures 10 and 11 show the wear roughness graphs in terms of the wear depth versus the lateral position of the worn surfaces of the Ti-15Mo-xSi alloys after dry and wet wear testing at 20 N and 1000 m, respectively. It can be seen that the representative surface roughness of all the wear-tested specimens shows different roughness patterns related to the main worn surface features given in SEM images in Figures 8 and 9 for the dry and wet wear conditions, respectively. It can be noted that the roughness decreases with the increasing Si content in the range from 0.0 to 2.0 wt.% to the master alloy Ti-15Mo for the tested specimens in dry and wet conditions. Furthermore, the roughness of the worn surfaces after wet wear testing in the presence of SBF shows lower roughness values than those given by the worn surfaces of the specimens tested under the dry condition, as illustrated in Figure 12a,b, respectively. These results are consistent with the results obtained for the microstructure features, hardness, and compressive strength of the as-cast Ti alloys having different Si content.

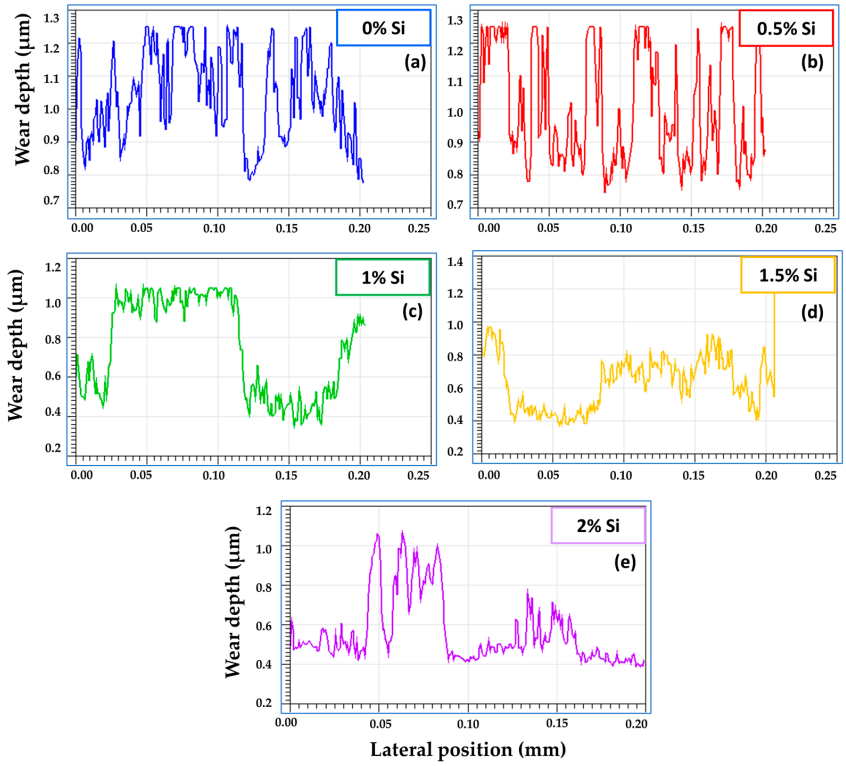

Figure 10. Wear depth graphs of the worn surfaces of the produced Ti-15Mo-xSi alloys after dry wear testing at 20 N and 1000 m for the (**a**) Ti-15Mo master alloy, (**b**) Ti-15Mo-0.5Si, (**c**) Ti-15Mo-1.0Si, (**d**) Ti-15Mo-1.5Si, and (**e**) Ti-15Mo-2.0Si.

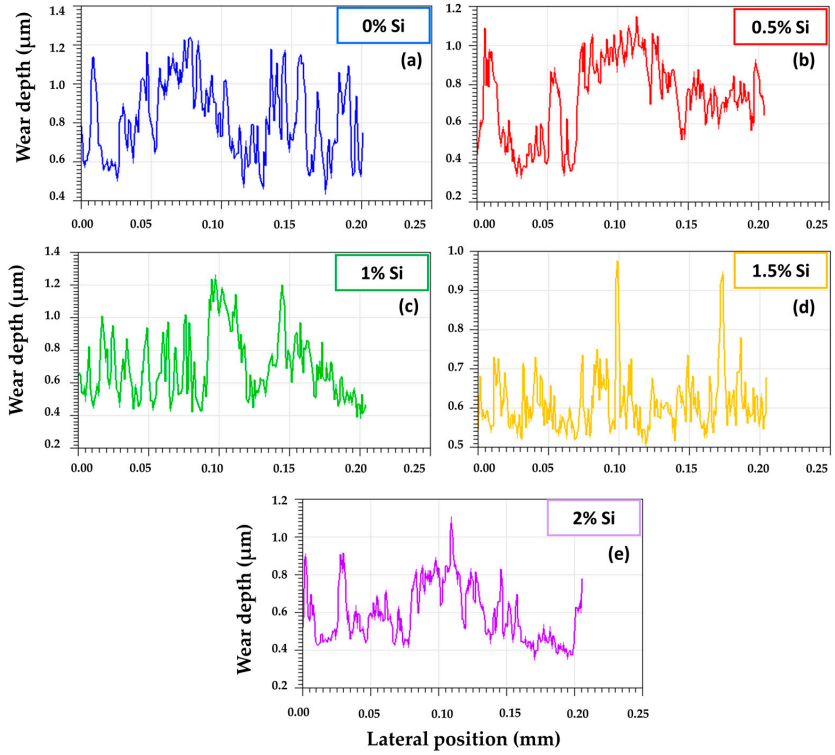

Figure 11. Wear depth graphs of the worn surfaces of the produced Ti-15Mo-xSi alloys after wet wear testing at 20 N and 1000 m for the (**a**) Ti-15Mo master alloy, (**b**) Ti-15Mo-0.5Si, (**c**) Ti-15Mo-1.0Si, (**d**) Ti-15Mo-1.5Si, and (**e**) Ti-15Mo-2.0Si.

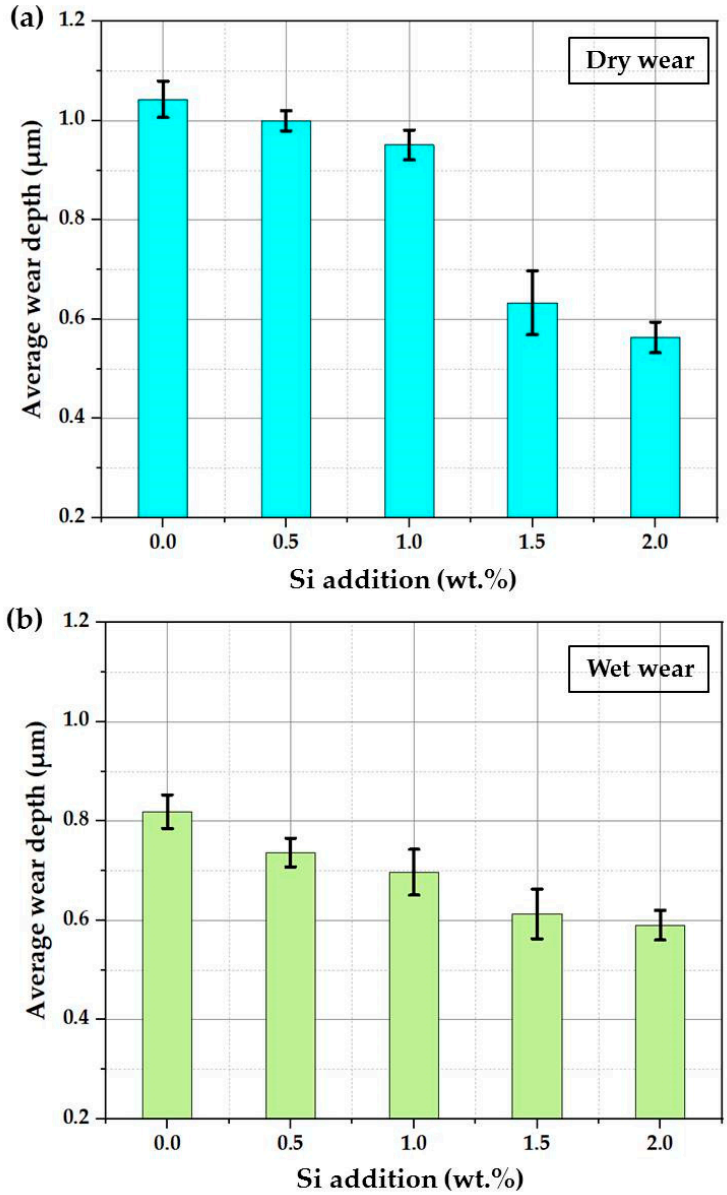

Figure 12. Average wear depth as a function of the Si content of the worn surfaces of the produced Ti-15Mo-(0-2) Si alloys after (**a**) dry wear and (**b**) wet wear testing at 20 N and 1000 m.

Regarding the roughness of the wear surfaces of Ti alloys having different composition, Ti base alloys have varying microstructures and mechanical properties, which can influence the wear behavior and surface roughness. For example, commercially pure titanium (CP-Ti) tends to exhibit higher wear rates and surface roughness compared to alloyed titanium grades like Ti-6Al-4V due to the differences in hardness and wear resistance [51]. The processing methods used to manufacture Ti components can affect the surface roughness of wear surfaces [51,52]. Surface treatments can be applied to titanium alloys to modify their surface properties and enhance the wear resistance and reduce the surface roughness [53]. The type and severity of wear conditions experienced by Ti alloys can influence the resulting surface roughness. Factors such as the load, sliding speed, contact pressure, abrasive particles, and lubrication significantly affect the wear process and can impact the roughness of the wear surface. The wear mechanisms involved in Ti alloys, such as the adhesive wear, abrasive wear, or fretting wear, can influence the surface roughness [54]. Different wear mechanisms can lead to distinct surface damage patterns, including material removal and microcracking, which can affect the final roughness [55]. It is important to note that achieving a specific surface roughness in Ti alloys for wear applications often

involves a balance between wear resistance, mechanical properties in terms of hardness and compressive strength, and manufacturing considerations.

4. Conclusions

The dry and wet sliding wear behavior of different Ti-15 wt.% Mo base alloys containing various silicon contents (0, 0.5, 1, 1.5, and 2 wt.%) was investigated in order to evaluate the impact of both the Si and Mo β-stabilizing elements in Ti wear resistance to consider them for biomedical applications.

1. The addition of alloying elements like Mo and Si influences both the microstructure and the mechanical properties of the Ti-Mo-Si alloys. These elements can form solid solutions with titanium and alter the phase transformation behavior, microstructure, mechanical strength in terms of the hardness, compressive strength, and wear resistance of the alloy.
2. Significant grain refining was attained with the Si addition. The reduction in grain size of the Ti15Mo base alloy reached 10.25, 41.82, 51.5, and 78.8% with the addition of 0.5, 1.0, 1.5, and 2.0 wt.% Si, respectively.
3. The average values of the hardness of Ti-15Mo-(0-2) Si increased from 340 ± 3.6 to 437 ± 7.2 HV, and the compressive strength increased from 1442 ± 22.3 to 1682 ± 33.9 MPa by increasing the Si addition in the range from 0.05 to 2.0 wt.%, respectively.
4. The weight loss values of the Ti-15Mo-(0-2) Si specimens subjected to wet wear testing were lower than those tested under dry wear in the presence of the SBF wet conditions at the applied parameters of a wear load of 20 N and a sliding distance of 1000 m. The weight loss decreased with the increase in the Si content.
5. The worn surface roughness in terms of the average wear depth of the Ti-15Mo-xSi alloys decreased from 1.043 to 0.5637 μm for the dry test specimens and from 0.819 to 0.5902 μm for the wet test specimens with the increase in the Si content from 0.0 wt.% to 2 wt.%, respectively.

Author Contributions: Conceptualization, M.M.E.-S.S., M.M.Z.A. and S.A.; methodology, K.M.I., M.M.E.-S.S. and H.A.A.; software B.H., N.A.A. and S.A.; validation, N.A.A., A.B. and M.M.E.-S.S.; formal analysis, H.A.A., A.B. and M.M.Z.A.; investigation, H.A.A. and A.B.; resources, H.A.A. and A.B.; data curation, K.M.I.; writing—original draft preparation, M.M.E.-S.S. and H.A.A.; writing—review and editing, M.M.E.-S.S., M.M.Z.A. and S.A.; visualization K.M.I., M.M.E.-S.S. and S.A.; supervision B.H., M.M.E.-S.S. and M.M.Z.A.; project administration, B.H., N.A.A. and S.A.; funding acquisition B.H. and N.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-RG23023).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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