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Influence of Microstructural Features on Wear Resistance of Biomedical Titanium Materials

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***Abstract*—**The field of biomedical materials plays an imperative requisite and a critical role in manufacturing a variety of biological artificial replacements in a modern world. Recently, titanium (Ti) materials are being used as biomaterials because of their superior corrosion resistance and tremendous specific strength, free- allergic problems and the greatest biocompatibility compared to other competing biomaterials such as stainless steel, Co-Cr alloys, ceramics, polymers, and composite materials. However, regardless of these excellent performance properties, Implantable Ti materials have poor shear strength and wear resistance which limited their applications as biomaterials. Even though the wear properties of Ti alloys has revealed some improvements, the crucial effectiveness of biomedical Ti alloys as wear components requires a comprehensive deep understanding of the wear reasons, mechanisms, and techniques that can be used to improve wear behavior. This review examines current information on the effect of thermal and thermomechanical processing of implantable Ti materials on the long-term prosthetic requirement which related with wear behavior. This paper focuses mainly on the evolution, evaluation and development of effective microstructural features that can improve wear properties of bio grade Ti materials using thermal and thermomechanical treatments.

***Keywords*—**Wear Resistance, Heat Treatment, Thermomechanical Processing, Biomedical Titanium Materials.

I. Introduction

THE wide use of Ti materials for biomedical applications is constantly growing due to their specialized properties such as high specific strength, good mechanical properties, low elastic modulus, superior corrosion resistance, and higher biocompatibility compared with the other conventionally used metallic biomaterials [1]. These outstanding properties were a motivating force for the early offering of (α) cpTi and (α + β) Ti-6A1-4V alloys as well as for the more recent development of recent Ti-alloy compositions of α, α+ β, β and metastable β Ti alloys. One of the main concerns for further development of Ti alloys for biomedical applications is undoubtedly its fretting and sliding wear resistance, when they are subjected to action of sliding and rubbing contact of articulating surfaces during their service in the body [2]. Generally, wear property can be defined as damage to a solid surface, involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances. Recently main concern, for further development of biometallic implant materials, is, among others, stress transmission between hard tissue and biometallic components which are in contact since further bone degradation and bone adsorption should be avoided [3]-[4]. Namely, great difference between bone and biometallic implant materials rigidity and other mechanical and tribological characteristics may lead to further bone loss and degradation.

Fretting and sliding wear conditions lead to damage and then fracture of the passive oxide film [5]-[8] which could be disrupted at very low shear stresses [9]. Unfortunately, Ti is an extremely reactive metal and has a reputation for poor tribological properties [10], [11] and inferior performance when compared with another implantable materials like Co–Cr alloys. In general, the wear and corrosion failures are the main reasons of degradation [12] and great difference of tribocharacteristcs between bone and implant must be limited to increase the service life of the surgical implants and to avoid bone degradation and adsorption [4]. The poor tribological properties of Ti alloys, attributed to their low resistance to plastic shearing and low mechanical stability of the passive surface oxide layer, are significant clinical problems [13]-[18] which may lead to the premature removal of the prostheses. Because of titanium's tendency to gall and seize, a piece of bone rubs against the implant, or two parts of a total joint replacement rub against one another, localized stresses at the contact regions will cause heavy damage on their surfaces that will consume the Ti material gradually [13], [19]-[21] and thereby the wear debris will be generated which often found into the implant surrounding tissues [1], [13] as shown in Fig. 1. Their accumulation may cause allergy and toxic reactions on local tissue [22]-[23] and causes an adverse cellular reactions [24], leading to negative healthy situations such as inflammation, release of damaging enzymes, infection, restricted action, pain in the body and even implant loosening due to osteolysis. Therefore, it is of great interest to enhance the surface friction and wear resistance of orthopaedic Ti alloys inside the human body that will increase the longevity of total joint components.

Much research efforts have been devoted to study and improve the performance in terms of the wear behavior of the biomedical Ti alloys. Various Proper surface modification techniques, such as ion implantation, TiN coating, thermal oxidation, composition adjustment and selection of appropriate thermal and thermomechanical processing procedures have thus been proposed to improve the wear resistance by changing the nature of the surface. [25]-[27]. It is well known that the tribological property of Ti alloys, is

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highly dependent on its microstructural characteristics.

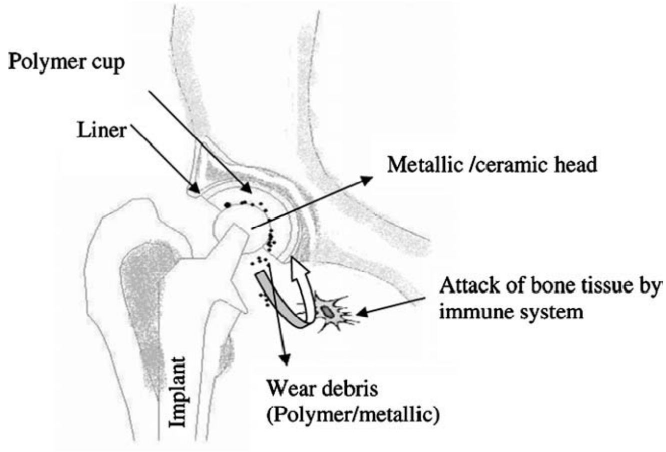

Fig. 1 Wear of total joint replacements

Extensive studies have been made on the wear behavior of bio Ti alloys in both dry and wet conditions to investigate the effect of thermal and thermomechanical treatments on it. The importance of the subject, increasing research interest and huge unexplored potential is the driving force behind this literature review. The present review study has been done with a view to provide the researchers in the field to have a bird's eye view on the hotspots on research in the thermal/thermo-mechanical processing and also to provide a clear correlation between microstructural features and tribological properties of biomedical Ti alloys.

II. Principle of Thermal and Thermomechanical Processing

Heat treatment is generally defined as any one of a number of controlled heating and cooling operations used to bring about a desired change in various properties of a metal. Its purpose is to improve the structural and physical properties for some particular use or for future work on the metal. The microstructure has a substantial effect on the properties of Ti alloys and of all metals in general. The microstructure of Ti alloys usually are varied and controlled or manipulated in a degree of freedom by thermal or processing followed by heat treatment (TMT), which can perturb or alter the transformation mechanisms. Also, the alloy class and type controls the nature and degree of microstructure obtained [28]. The chemical composition is the major factor on which affects the response of Ti alloys to heat treatments and depending on that the properties and volume fraction of the main phases, α and β are determined. Due to the α/β transformation in the alloy, a variety of microstructures and property combinations can be achieved through TMT, which permits the adaptation of properties to specific applications [29] with high strength/weight rates [30]. TMTs generate different microstructures as a complex sequence of solution-heat-treatment, plastic deformation (by rolling or forging, extrusion or spinning etc.), recrystallization, aging and annealing. The relationship between all parameters mentioned above as schematically outlined in Fig. 2 [30]. The amount of plastic deformation, strain rate and temperature are critical factors of TMT, as well as working methods [31].

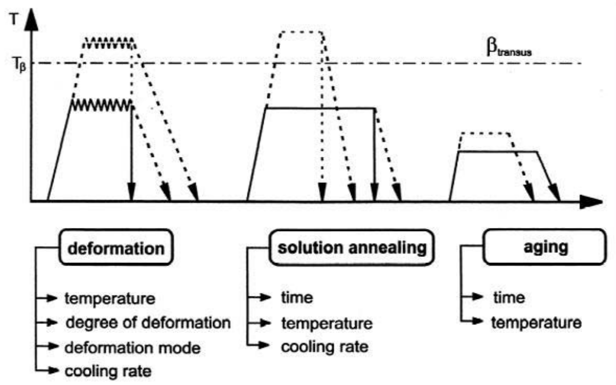

Fig. 2 Thermo-mechanical treatments of Ti alloys

It is widely understood that the better performance of biomedical Ti alloys can be achieved through microstructure control. The marriage of microstructure to Ti properties is the end goal of all research in structural materials. As a result, microstructure (type of phases, grain size and shape, morphology, and distribution of main phase α and β colonies) plays a very important role in the wear properties of biomedical Ti alloys.

III. Biomedical Titanium Framework

Structural Ti alloys may be classified as Alpha (α), near-α, Alpha-Beta (α-β), metastable β, and stable β depending upon the microstructure at room temperature. In this regard, alloying elements for Ti fall into three categories: (1) α-stabilizers, such as Al, O, N, C; (2) β-stabilizers, such as V, Nb, Ta, Mo (isomorphous), Fe, W, Cr, Ni, Si, Co, Mn, H (eutectoid); (3) neutrals, such as Zr and Sn. [32]. The α and near-α Ti alloys exhibit superior corrosion resistance but have limited low temperature strength. In contrast, the α + β alloys exhibit higher strength due to the presence of both the α and β phases. The β alloys also offer the unique characteristic of low elastic modulus and superior corrosion resistance [33]-[34]. Earlier systems of Ti in medical, surgical, and dental devices were based on commercial pure Ti (cpTi) and most popular used Ti-6Al-4V alloy. As a result of the truth that releasing small amounts of vanadium and aluminum in the human body induces possible cytotoxic effect and neurological disorders, respectively [35]-[38] led to develop Ti-6Al-7Nb [36], Ti-Zr based and Ti-Sn based alloys [39]. New systems of non-toxic elements β-type Ti alloys have been developed recently such as: Ti-Nb system, Ti-Nb-Mo system, Ti-Nb-Pd system, Ti-Nb-Zr system, Ti-Nb-Sn system, Ti-Nb-Zr-Sn system, Ti-Nb-Zr-Fe system, Ti-Nb-Ta system, Ti-Nb-Ta-Zr system, Ti-Ta system, Ti-Mo system, Ti-Mo-Zr system, Ti-Mo-Zr-Fe system, Ti-Fe-Ta system, Ti-Fe-Ta-Zr system, Ti-Cr-Nb system, Ti-Cr-Mn-Sn system alloys [40]-[54] and another systems are still developing.

IV. Effect of Thermal and Thermomechanical Processing on Wear Behavior of Bio Grade Titanium Materials

TLM alloy (Ti–Zr–Sn–Mo–Nb) consists of nontoxic elements has been designed in order to develop higher performance β type biomedical Ti alloys with lower modulus of elasticity, higher strength and wear resistance, excellent plasticity, and lower cost. YU Zhen-tao et al. [55] have investigated the effect of heat treatments on the microstructure and phase constitution and then sliding wear behavior of Ti-3Zr-2Sn-3Mo-15Nb (TLM) alloy as compare with annealed Ti-6Al-4V and aged Ti-13Nb-13Zr. Different microstructures have been shown that the specimens cooled from α+β dual phase region are mainly composed of β phase, primary α phase, and a little needle-like α″ martensite phase, while the specimen cooled from β single phase region is mainly composed of predominate metastable β phase and α phase. They have found that the coefficient of friction of TLM alloy treated at 680°C, 1h, AC + 510°C, 6 h, AC is smaller than that of others and even better than of annealed Ti-6Al-4V and aged Ti-13Nb-13Zr, thereby TLM alloy has a better wear resistance.

Since β Ti alloys have superior resistance to wear and abrasion, as well as excellent biocompatibility and other properties [56], they became raw material to scientific researches in recent years. Thus, several studies have been found on the influence of microstructure features on wear behavior and its effect on the performance of biomedical Ti materials. Majumdar et al. [57] investigated the sliding wear behavior of the Ti-13Nb-13Zr alloy hot worked and heat treated under different conditions to produce a variety of microstructures which consisted of acicular and globular α, β and martensite. Higher wear rate was found in case dry condition, when the sample deformed by hot rolling above β transus temperature and then solution treated at 800 ◦C followed by water quenching and aging, because of the presence of acicular α. The investigation revealed that faster cooling after solution treatment resulted in higher wear rate in Hank’s solution and bovine serum. Moreover, it was found that the finer microstructure and the presence of elongated a accelerate ‘corrosion-wear’. According to Cvijovic´-Alagic´ et al.[58] the influence of diverse heat treatments on microstructural and tribological characteristics of Ti-6Al-4V ELI (mass%) alloy have been studied. It has been done two solution treatments to evaluate the microstructure of Ti-6Al-4V ELI alloy with the heat treatment conditions. The solution treatment above the β transus and subsequent water quenching resulted in martensitic structure, while this alloy solution treated below the β transus and water quenched exhibited primary α and untransformed β microstructure. The β solution treatment increased its hardness markedly. In addition, the appreciable change in microstructure and hardness appeared as a result of diverse solution treatment temperatures affected the wear resistance of this Ti alloy. Namely, increase in the solution treatment temperature improved its wear resistance in simulated body fluids. However, the wear rate was greater for (α+β) solution treated alloy than for β solution treated alloy. Also, Cvijovic´-Alagic´ et al. [59] have studied Ti-13Nb-13Zr alloy by applying 25 % cold rolling after solution treatment at 900°C for 30 min and compare it with different microstructures of Ti-6Al-4V ELI. They have found that the wear resistance of the Ti-6Al-4V ELI alloy in Ringer’s solution (simulated body fluid) is better than that of the Ti-13Nb-13Zr alloy irrespective of microstructure, and the highest wear loss is achieved in the Ti-13Nb-13Zr alloy. Amongst applied heat treatments, the lowest wear loss is obtained for the Ti-6Al-4V ELI alloy ST above β transus temperature and subsequent water quenching, due to the formation of a hard martensitic microstructure (higher hardness). Whilst increase in the solution treatment temperature improves its wear resistance substantially, the variation of the wear loss with cooling rates is not significant.

Recently, ultrafine-grained (UFG) structures with submicrometre or nanometre grain sizes have been developed broadly by using severe plastic deformation (SPD). It was found from extensive investigations that UFG materials have superior properties than their coarse-grained structure. Good wear resistance as well as a combination of high strength with good ductility at room temperature is important properties can be produced by SPD. Currently, equal-channel angular pressing (ECAP) is a group of metalworking techniques and the most developed SPD processing technique [60]. The technique is a feasible forming process to extrude metals by use of particularly designed channel dies without substantially changing the geometry by imposing SPD as shown in Fig. 3 [61].

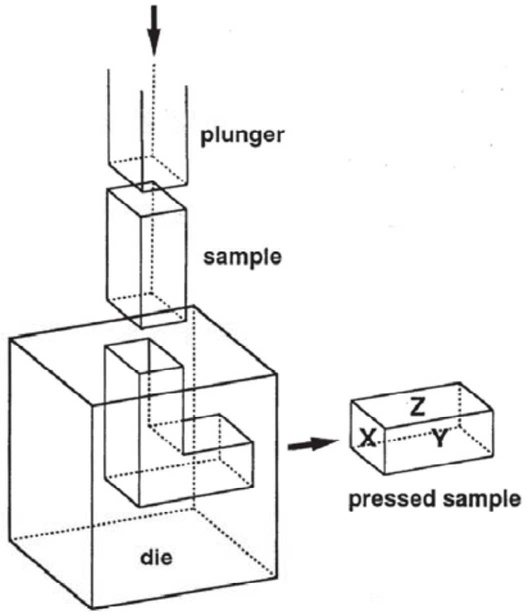

Fig. 3 A schematic illustration of the equal channel angular pressing

To a large extent, ECAP technique depends on the imposing very high shear deformations on the metal under superimposed hydrostatic pressure. Lots of studies have been focused on Ti materials and most of them proved enhanced wear resistance by ECAP. La P. et al. [62] have investigated the tribological behavior of commercial pure (CP) Ti processed by ECAP under dry sliding using varying loads and speeds. They have found that the wear rate of the UFG Ti was about 30% lower than of the coarse grained annealed Ti.

V. Conclusion

Amongst biometallic materials, titanium materials are the most appropriate for use in biomedical application especially for artificial joint replacements, e.g. hip, knee or shoulder joints, due to their superior performance. Despite its ever increasing application, the potential of titanium alloys still remains under exploited in this vital field. The literature reveals that serious attempts from researchers have been made towards understanding the technology- structure-property relation to uncover the new facets of titanium and its unique characteristics that will improve function and lifetime of an implant in the human body. The wear behavior of titanium materials has significant effects on the serviceability and durability of their performance. It follows that the wear behavior must be taken into account as an important property in the design of titanium devices and components. Generally, titanium is an extremely reactive metal and has a poor reputation in the tribological field. Therefore, improving the wear characteristics of biomedical components is a major problem of scientists, engineers, and researchers in the field of biomedical engineering. The effect of thermal and thermomechanical processing on the evaluation of microstructures features of titanium materials and thus on their wear resistance has taken any attention in this review. Therefore, the purpose of the present paper is to evaluate the wear behavior of titanium materials with changing various varieties of phase fractions, their morphologies, and precipitations in the microstructure by applying thermal and thermomechanical processing.

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