



Effect of surface and bulk plastic deformations on the corrosion resistance and corrosion fatigue performance of AISI 316L

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ABSTRACT

This study reports on the electrochemical characteristics and corrosion fatigue performance of plastically deformed AISI 316L. Bulk deformation was processed through rotary swaging (RS) and surface deformation was induced through shot peening (SP). Moreover, hydroxyapatite coating (HA) was applied to the bulk- and surface-deformed materials to improve their corrosion resistance. Ringer's solution was used as an electrolyte for the corrosion and corrosion fatigue tests. The results showed marked improvement of the fatigue life, of rotary swaged and shot peened materials, tested in air and Ringer solution. In terms of the corrosion behavior, the rotary swaged (RS) material improved the corrosion resistance compared to the as-received material, while the shot peening (SP) led to lower corrosion resistance. Application of hydroxyapatite coating (HA) led not only to marked corrosion resistance but also to further improvement of the fatigue life.

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1. Introduction

Austenitic stainless steel, especially medical grade AISI 316L, is widely utilized as an implant material to make devices like artificial joints, bone plates, stents and hip prosthesis. AISI 316L has good mechanical properties, high corrosion resistance and relatively low cost compared with other metallic biomaterials [1–3]. The shape of hip prosthesis is complex. It consists of a femoral head and a stem, which serve in load bearing, wear and fatigue resistance [4–6]. Numerous studies have reported on the problems of fatigue fracture and wear of the femoral head surface [5–7], mechanical strength [4–8] and the stability of the stem of a hip prosthesis [9].

Previous works stated that the femoral head and the stem of a hip prosthesis suffer from fatigue fracture, wear, mechanical strength, and stability of the stem of a hip prosthesis [5–9]. Fig. 1 illustrates some examples of the fatigue fracture of implant devices such as hip prosthesis and mechanical heart valve. The surface sub-structure of biomaterials is a key factor to understand the mechanisms of fatigue failure [7]. Fig. 2 shows a schematic cross-section of a deformed metallic biomaterial surrounded by a physiological environment. Teoh [7] documented that the sub-structure is composed of three distinct layers: molecular absorbed layer, passive oxide film and deformed layer. Cyclic loading leads to the generation of wear debris (contact body). The molecular absorbed layer consists of growing tissue (cells) in contact with the

physiological environment and the passive layer on the surface of the metallic implant. The combined influence of corrosion and cyclic loading is known to affect the mechanical properties of metallic alloys. The cracks frequently initiate from corrosion-induced surface defects. Crack initiation mechanisms include competition between pit growth and short crack growth [1], preferential dissolution of plastically deformed material [2], local rupture of the passive film by persistent slip bands (PSB) [3] and hydrogen embrittlement in the cathodic domain and deformation/corrosion synergy effects [10–12]. Crack initiation accelerates the failure of the implant by fatigue. Among the various types of fractures, fatigue fracture is identified as a crucial problem associated with implant loosening. Fatigue characteristics are closely related with the microstructures. The microstructures in metallic structural biomaterials change according to the employed processing method.

Generally, mechanical strength is related to the ability of metals to deform plastically. Plastic deformation processes belong to the top down approach and are capable of leading to substantial grain refinement so that the grains can be reduced to the sub-micrometer or even the nanometer range.

Ultra fine grains metals and alloys are expected to have high strength as a result of structural refinement, according to the Hall–Petch relationship, where the yield stress varies with the reciprocal of the square root of the grain size. On the other hand, ultra fine grain materials have limited ductility due to susceptibility to deformation localization. The grain refinement can produce through equal channel angular pressing (ECAP) [13] or rotary swaging (RS) which is a hammer forging process for the reduction of cross-section of solids, tubes and

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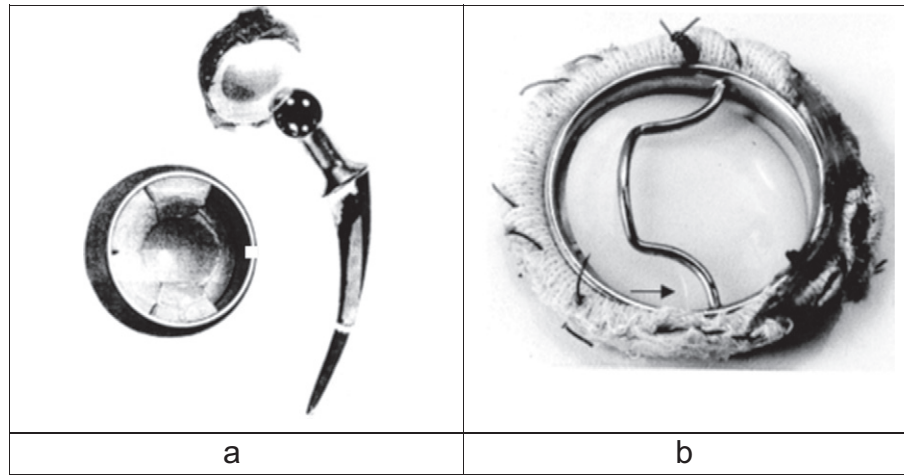


Fig. 1. Some examples of fatigue failure of medical devices [7]: (a) hip prosthesis; and (b) explanted disc mechanical heart valve.

wires. Some of the advantages of rotary swaging include short cycle times, good surface finishes and tight size tolerances [14]. This grain refinement can lead to drastic increases in yield stress, tensile strength and high cycle fatigue (HCF) strength.

In addition to the strength, the stem of a hip prosthesis must be stable after being implanted. The stem must integrate with the surrounding host tissue without loosening to support its load bearing function [9]. Shot peening (SP) is widely applied as a surface treatment to improve the integration quality of biomaterials with the host tissue [15–19]. In principle, the treatment is implemented to generate a rough surface to which specific proteins can adhere well and subsequently initiate bone tissue development on the implant surface [20,21]. Moreover, it is well known that shot peening (SP) is able to increase the fatigue strength and endurance of metallic components [22]. The positive effect of shot peening on the fatigue properties is generally related to its ability to introduce a compressive residual stress in the surface layer of the material and to the surface work hardening caused by the not uniform plastic deformation caused by the multiple impacts of the shot flow [23].

The success of implants in the human body depends on many factors such as biocompatibility and biofunctionality in the environment wherein the implants are placed. Hydroxyapatite (HA) coatings are commonly used to coat acetabular components, knee prosthesis, pin/screw components and dental implants [24]. HA coatings are also

widely employed to enhance the osseointegration of orthopedic and dental implants [25], and used to improve corrosion resistance by forming a barrier against the penetration of metal ions from the substrate [26,27].

In this study, a combination of bulk and surface plastic deformations was developed through rotary swaging and shot peening (SP) on the AISI 316L stainless steel. The effects of these treatments on corrosion fatigue, microhardness, surface microstructure, surface roughness and corrosion resistance of the stainless steel are investigated. Hydroxyapatite coating (HA) was applied on the deformed and the shot peened materials to enhance their corrosion resistance and biocompatibility.

2. Experimental work

Cylindrical rod of AISI 316L stainless steel with a diameter of 25 mm was used in this study. The chemical composition of AISI 316L is (wt.%): 0.03 C, 24.30 Cr, 11.96 Ni, 1.75 Mo, 1.24 Mn, 0.44 Si, 0.86 Cu, and balanced Fe. The rod was hot swaged at 800 °C using a rotary swaging (RS) machine down to 11 mm diameter. Simple disk specimens were cut from the as-received rod (AR) and rotary swaged material (RS). Part of the AR samples was subjected to shot peening (SP). Shot peening was performed using Injektoranlage — model 1000 shot peening machine. SP was done using ceramic balls of Z850, which consist of SiO₂, ZrO₂ and Al₂O₃, at various Almen intensities of 0.17, 0.24 and

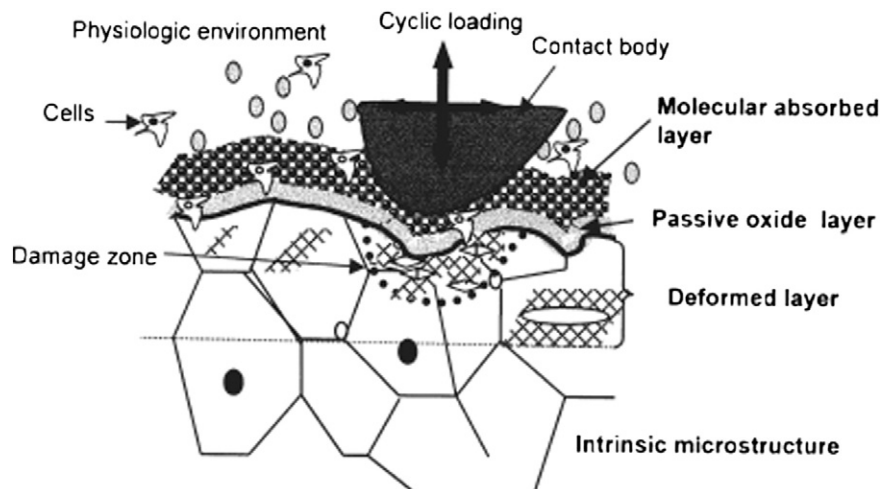


Fig. 2. Schematic representation of the substructure of a metallic biomaterial [7].

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