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Improving the fatigue behavior of dental implants through processing commercial purity titanium by equal-channel angular pressing

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ABSTRACT

An investigation was conducted to evaluate the feasibility of using commercial purity (CP) titanium of grade 1 for dental implants after processing by equal-channel angular pressing (ECAP). The material was processed by ECAP for 4 passes at room temperature. Dental implants were machined from the unprocessed material and the material processed by ECAP and their mechanical properties were evaluated in tensile and compression testing and in fatigue using the conditions specified in the ISO 14801 standard for dental implants. The results show processing by ECAP increases the yield stress and the ultimate tensile stress but reduces the strain hardening rate and hence the overall elongation to failure. Although processing by ECAP increases the fatigue life using cyclic bending loads, a comparison with published data suggests the fatigue behavior CP Ti of grade 1 is slightly less satisfactory than for commercial implants fabricated from higher grade titanium alloys.

1. Introduction

Severe plastic deformation (SPD) techniques are widely used to strain-harden and refine the grain structure of metallic materials [1,2]. In practice, these processes provide the capability of hardening pure metals while avoiding the addition of solutes as in solid solution hardening or second phases as in precipitation hardening. This is particularly important when processing a biomaterial such as titanium, which is widely used for orthopedic and dental implants [3,4], because the solute atoms and precipitates may easily compromise the biocompatibility.

Among the various SPD techniques that are now available [5], including equal-channel angular pressing (ECAP) [6] and high-pressure torsion (HPT) [7], processing by ECAP has to date received the most attention and use. This is because processing by ECAP involves repetitively pressing a short bar or rod through a die constrained within a channel that is bent through a sharp angle and this processing method is relatively easy to perform in any mechanical testing laboratory. However, there is an inherent difficulty associated with the processing of commercial purity (CP) titanium because it was shown in early experiments that the material exhibits segmented flow when processed at room temperature and at a high pressing speed of 25 mm/s [8]. For this reason, the early reports on processing of CP-Ti by ECAP described investigations in which the processing was performed at temperatures of 623 K or higher [9–11] and it was also reported that the ultimate tensile strength of the material may be further improved by subsequently introducing room temperature deformation [9].

The problem of the occurrence of segmentation in ECAP processing is a well-established phenomenon which is especially prevalent when the material has a low strain rate sensitivity [12]. Calculations using finite element modeling, considering ECAP dies with 90°, 110° and 135° between channels, showed that alloys prone to segmentation, the so-called difficult-to-work alloys, may be processed more easily if the channel angle within the ECAP die is increased to a higher value instead of using the conventional angle of 90° [13]. Accordingly, later experiments showed that CP-Ti may be successfully processed through one pass at room temperature (RT) by using a die with a channel angle of 120° and a relatively low ram speed of 0.5 mm s^{-1} [14] and subsequently it was reported that titanium may be processed at room temperature using a 120° die and a faster ram speed of 2 mm s^{-1} to give a grain

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size of ~200 nm after 8 passes [15]. There are also some reports on the processing of CP-Ti at room temperature using an ECAP die with an angle of 135° [16,17] and there is a very recent report of room temperature processing using a special composite lubricant with a 90° die at a speed of 3.5 mm s^{-1} where a grain size of ~150 nm was produced after 4 passes [18]. This latter result is identical to the grain size reported in CP-Ti when processing by HPT at room temperature for 10 turns [19]. All of these results confirm that additional cold deformation is not a necessary prerequisite for achieving strength enhancement in CP-Ti after ECAP since a high strength may be introduced directly using room temperature processing.

The improved mechanical properties attained in CP-Ti permit the use of this material as a structural biomaterial in dental implants. Thus, an early paper reported the production of dental implants from CP-Ti processed by ECAP with a subsequent thermal mechanical treatment [20]. Also CP Ti exhibits excellent biocompatibility after processing by ECAP by comparison with its coarse-grained counterpart [21–23] and, in addition, it has been shown that titanium processed by ECAP has an increased fatigue life and fatigue limit under constant load testing [24].

It is important in practice to recognize that conventional mechanical testing is not adequate for providing comprehensive information on the mechanical response of dental implants under loading. This is because dental implants are subjected to multiple loading conditions and also to stress concentration factors. A specific standard for testing dental implants was implemented by the International Organization of Standardization and this standard, designated ISO 14801, incorporates the inclined loading and bone resorption that occurs during the fatigue life of real dental implants. Recently, a report compared the mechanical response of dental implants made from metallic and ceramic materials and showed that changing the angle of loading, and considering the bone resorption, significantly affected the response of these implants [25]. Specifically, the ceramic implant exhibited a better response for parallel loading and without bone resorption but the metallic implant exhibited a better response when inclined loading and bone resorption were also considered [25]. Taking these difficulties into consideration, the present investigation was initiated in order to use the testing conditions mandated by the ISO14801 standard and to directly evaluate and compare the fatigue behavior of dental implants fabricated from conventional CP-Ti of grade 1 both without any SPD processing and after processing by 4 passes of ECAP at room temperature.

2. Experimental material and procedures

The material used in the present experiments was a CP-Ti of grade 1 with a composition, in wt%, of 0.100% O, 0.001% H, 0.010% N, 0.007% C and 0.030% Fe. The material was received in a hot-rolled and annealed condition with an initial average grain size of ~23 μm. Billets were machined parallel to the rolling direction with lengths of 70 mm and cross sections of 15 × 15 mm^2.

Some of these billets were processed by 4 passes of ECAP at room temperature using a die with an angle between the two parts of the channel of 120° and an outer arc of curvature of 20°. It can be shown that this geometry leads to an imposed strain of ~0.6 on each pass through the ECAP die [26]. All billets were processed using route B_C in which the billets are rotated by 90° in the same sense after each pass through the die [27]. Further details on the ECAP processing were given in an earlier report [15].

Samples for tensile and compression testing were machined from the initial unprocessed material and from the material processed by ECAP through 4 passes. The loading direction was parallel to the pressing direction for the ECAP samples and parallel to the rolling direction for the unprocessed samples. For tensile testing, the specimens had gauge lengths of 25 mm and cross-sectional areas of 3.0 × 1.4 mm^2. For compression testing, the specimens had lengths of 9 mm and cross-sectional areas of 6.0 × 6.0 mm^2. All tests were conducted at room temperature using an Instron universal testing machine having a maximum load capacity of 100 kN and equipped with an optical extensometer. Marks were placed within the gauge lengths of the samples prior to testing and the displacements between these marks were tracked during testing and converted directly to strain. Direct measurements of the minimum cross-sections were recorded after the initiation of necking and these measurements were used to determine the true stress and true strain at all stages of the tensile deformation.

Representative dental implants were machined from the unprocessed material and from the material processed by ECAP. These implants had lengths of 14 mm and the external diameters of the threaded ends were 3.75 mm. The implants are illustrated in Fig. 1. Fatigue testing was conducted specifically to follow the requirements of the ISO 14801 standard. Thus, the implants were mounted in a supporting structure at an angle of 60° with the horizontal such that the crest of the implant was maintained at a distance of 3 mm from the support surface in order to simulate the bone resorption effect. This configuration is illustrated schematically in Fig. 2. The abutments were attached to the implants with a torque of 35 N cm. A crown was machined from steel with a hemispherical shape at the most distant point having a radius of 4 mm. The crown length was such that the distance between the simulated bone level and the center of the hemisphere was equal to 11 mm. An alternating load was then applied vertically through the center of the hemisphere on the crown as required for fatigue testing under the ISO 14801 standard. The load was adjusted to vary following a sinusoidal pattern such that the minimum load corresponded to 10% of the maximum load. The frequency for application of the load was 10 Hz.

Fig. 1. Dental implants used in the experiments. Left: implants machined from the as-received material. Right: implants machined from the material processed by ECAP.