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Bulk nanostructured metals for advanced medical implants and devices

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Abstract. Nanostructured metals (Ti and Ti alloys, stainless steels, Mg alloys) with enhanced static and fatigue strengths are promising materials for medical implants [1]. The use of severe plastic deformation (SPD) methods leads to significant strengthening of the metallic materials due to their nanostructuring when the formation of ultrafine grains is combined with the formation of nanostructural features – nano-phased precipitations, grain boundary segregations, nano-twins, etc. [2]. In the present article the recent developments from author and his colleagues on continuous SPD processing, i.e. equal channel angular pressing (ECAP)-Conform techniques, for producing nanostructured CP titanium are considered. The use of nanoTi rods with enhanced strength and fatigue life has enabled the fabrication of implants with improved design for dentistry and orthopedics. Furthermore, surface modification of nanoTi through chemical etching and bioactive coatings allows for considerable improvement of its biomedical properties. As a result of conducted studies, miniaturized dental implants and nanoTi plates with reduced thickness and enhanced osseointegration were manufactured and successfully tested in clinical trials.

1. Introduction

Presently, over 70% of implant devices are made of the metallic materials and many of metal and metals alloys that are used in the medical field include titanium and its alloys, stainless steels, Co-Cr alloys, Mg alloys and some other [3,4]. Research and developments of new types of implants with increased safety and efficiency are closely related to improving the mechanical properties of the materials, such as strength, plasticity and durability, no less than the functional ones – corrosion, toxicity level, osseointegration [4-6]. As is known, traditionally the properties of metals and alloys are improved through optimization of their chemical composition with application of plastic deformation and heat treatment.

In the last decade the nanostructuring of metals by SPD aimed at enhancing their properties has become also a developed area of modern materials science and engineering [2]. With regard to medical applications, the creation of nanostructures in metals and alloys by SPD processing can improve both mechanical and biomedical properties. This paper describes the results of our recent investigations relating to titanium and its alloys that are the most extensively used to fabricate medical implants and other items. The examples demonstrate that nanostructured metals with advanced properties offer opportunities to create a new generation of medical devices with improved design and functionality [7-9].

2. Experimental procedures

Rods of Grade 4 commercially pure (CP) titanium 12-mm in diameter, meeting all the specifications of the ASTM F67 standard for medical implants, were used in the study reported herein. The material impurity data was as following (in at.%) 0.197 C, 0.50 Fe, 1.035 O, 0.024 N, 0.094 H and the average grain size of the titanium rods in as-received condition equalled to ~25 µm. The rods were nanostructured via ECAP-C and drawing. The former processing technique is a comparatively recent modification of the standard ECAP method [10-12]. In the course of this process, a work-piece is forced through an ECAP die in a manner analogous to the Conform process, however in this case an upgraded ECAP design is applied for nanostructured materials to be produced with repeat-passes.

As-received Grade 4 Ti rods were subjected to ECAP-C in a die-set with a 120° intersection angle Φ through the B_c route. Subsequent drawing was carried out to a reduction ratio of 85%. The deformation temperature was equal to 200 °C. The processing details are presented in Refs. [11, 12]. The final processed rods had a length of 3 m with the diameter from 3 to 6 mm.

The microstructure was analysed by means of optical as well as transmission electron microscopy (TEM) in a JEOL JEM 2100 TEM with acceleration voltage 200 kV.

The cylinder-shaped samples (3 samples per each processing term as in table 1), 3 mm in diameter and of 15 mm gauge length were tensile-tested at room temperature in an INSTRON-type device with a primary strain rate of 10^{-3} s^{-1}. The tensile axis was parallel to the rod axis. Stress-controlled fatigue tests at ambient temperature were carried out to characterize the behaviour of nanostructured (NS) and conventional coarse grain (CG) CP titanium at a load ratio of R ($\sigma_{min}/\sigma_{max}$) = -1. Rotational bending testing with a frequency of 50 Hz was performed.

Surfaces of mechanically-polished CG and NS samples of Grade 4 Ti were acid-etched in 30% HNO_3 + 3% HF+H_2O for 20 minutes. Surface topography was examined with a LSM-5-Exciter laser scanning microscope (LSM). Surface profiles were analysed to determine the surface roughness parameter R_a and the size of etching dimples.

3. Results and discussions

3.1. Grain refinement and mechanical properties

The processing resulted in a large reduction in grain size, from the 25 µm equiaxed grain structure of the initial titanium rods to 150 nm after combined ECAP-C and drawing processing, as shown in figure 1. The selected area electron diffraction pattern, figure 1(c), further suggests that the ultrafine grains contained predominantly high-angle grain boundaries with increased grain-to-grain internal stresses [11, 12].

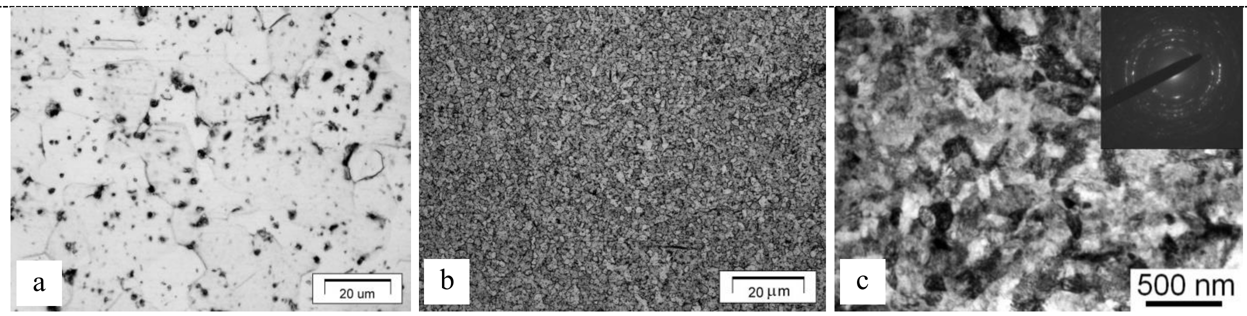

Figure 1. Microstructure of Grade 4 CP Ti: a) the initial coarse-grained rod; b, c) after ECAP+drawing (optical and TEM pictures)

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The important thing was to produce homogeneous ultrafine-grained structure along the entire three-meter rod lengths to enable economical pilot production of implants and provide sufficient material for thorough testing of the mechanical and bio-medical properties of the nanostructured titanium. As is seen in table 1, the strength characteristics of nano Ti are very high and even considerably excel over the properties of two-phase Ti alloy. At the same time, as was demonstrated in recent studies [13], the nature of such high strength originates from several hardening mechanisms when dislocation and substructure hardening is introduced alongside with grain boundary hardening dealing with ultrafine grains and also the segregation of impurities at grain boundaries is possible.

Table 1. Mechanical properties of conventionally processed and nanostructured Grade 4 Ti produced by ECAP-C and drawing. Data on Ti-6Al-4V ELI alloy are presented to compare.

Processing/ treatment terms	UTS, MPa	YS, MPa	Elongation, %	Reduction of area, %	Fatigue strength at 10^7 cycles
Conventional Ti (as-received)	700±9	530±20	25±2	52	340
nano-Grade 4	1330±12	1267±23	11±1	48	620
Annealed Ti-6Al-4V ELI	940±10	840±18	16±1	45	530

3.2. Design of miniaturized implants

The simple rules can be used when it comes to redesigning the devices in terms of the influence of changing materials, such as replacing CG Ti by nanostructured CP Ti [9]. Fatigue performance must be retained with thorough account for the possibility of changing the device cross-sectional dimensions. The data on fatigue properties of nano Ti and initial Ti (see Table 1) [7] were used to calculate the design of dental implant with the diameter 2.4 and 2.0 mm (figure 2a) produced by the company "Timplant" s.r.o., Czech Republic [14,15] and nanoTi mini-plates (figure 2b) from the company «Conmet», Moscow (www.conmet.ru/e_main.html). The implants were tested to demonstrate exceptionally high properties [7].

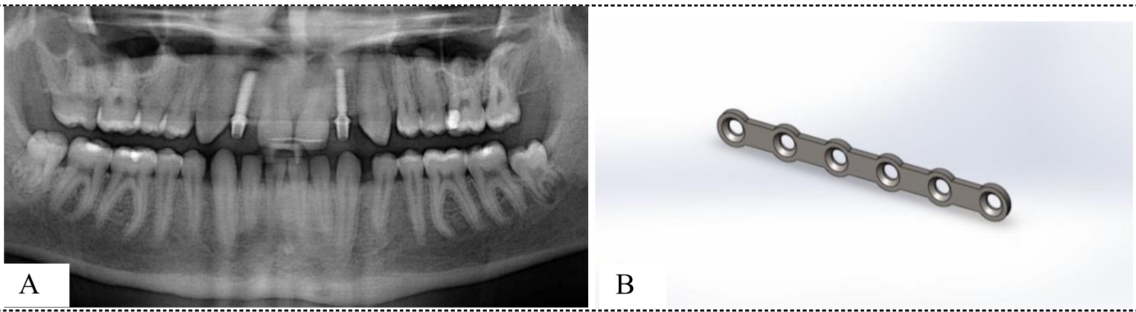

Figure 2. Nanoimplant of 2.0 mm diameter (www.timplant.cz/en/) from NS Grade 4 Ti in a panoramic X-ray radiograph after surgery (A) and the image of a miniplate with six holes made from NS Grade 4 Ti (B).

3.3. Surface modification of nano Ti implants

Surface properties are an important aspect of an implant design to ensure effective osseointegration. Pure Ti has very low bioactivity (i.e. bioinert material) and it does not bond directly to the human bone [6]. Extensive studies have shown that grain refinement down to the nanoscale in CP Ti can stimulate various bone-forming cell types to adhere and proliferate with increased efficiency [7,8,16-18]. Additional surface modification can further improve bioactivity of implants made from nano Ti. Two main approaches of surface modifications are studied in our works: chemical etching and deposition of bioactive coatings [7, 18-24].

The topography of etched surfaces is strongly determined by etching solution and etching time. Different solutions, such as acidic (H_2SO_4/H_2O_2) or basic (NH_4OH/H_2O_2) Piranha solutions can be used for etching of CP Ti [24] resulting in different surface topographies. Manipulation with etching time can substantially modify the surface topography and this effect is more pronounced in the nano Ti, as it has been very recently demonstrated in figure 3 [24].

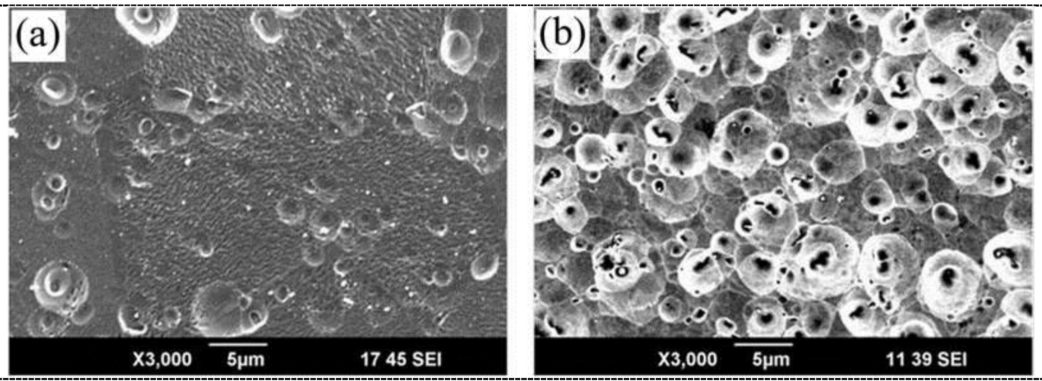

Figure 3. Surface of CG and NS samples of Grade 4 Ti after mechanical polishing and etching in the mixture of acids 30% HNO_3 + 3% HF+H_2O for 20 minutes: (a) CG Ti surface; (b) nano-Ti surface. SEM images.

Biocompatible coatings can also essentially facilitate integration of the nano Ti implants into a human bone [22, 23]. Presently, the research into synthesis of biocompatible coatings integrating the inorganic (Ca-, P- containing phases) and organic (biologically active and bioinert molecules) components on titanium implants appears to be topical state of the art [25, 26].

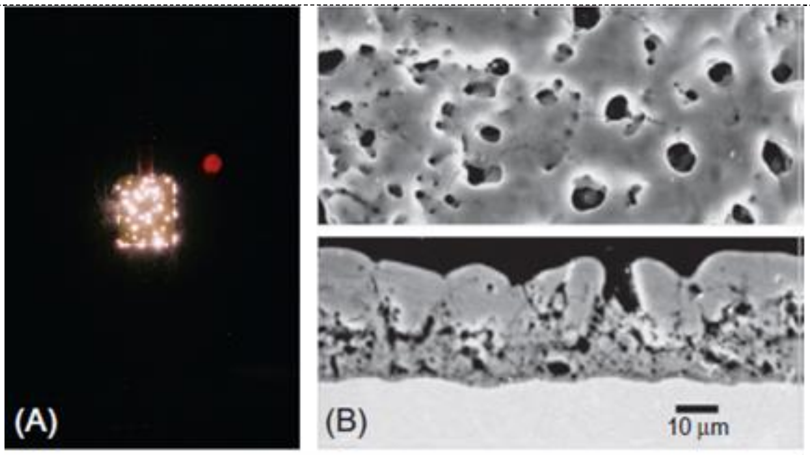

Figure 4. Photographs of microdischarges on the sample surface during PEO process (a); SEM image of PEO Ca-, P- containing coating on titanium, top view (above) and cross-section (below) (b) [28, 31].

During the last decade, significant attention is attracted to Ca-, P- containing coatings obtained by the method of plasma electrolytic oxidation (PEO) [20, 27, 28]. PEO process is an expansion of the traditional anodizing into the high voltages up to 600 V; these voltages promote microdischarges within the coating (figure 4); this results in its resoldifying and intensive growth [28, 29]. This method is applicable to both CG and UFG titanium [20, 30]. The coatings obtained by this method contain stable titania (rutile and anatase) tightly attached to the surface because of the process mechanism including electrochemical oxidation and numerous melting and crystallizing events at the microdischarge sites. This coating formation mechanism helps to develop coatings with regulated porosity, with the pore size from 0.1 to 10 μm [31]. This coating morphology provides gradual change of the elasticity modulus from the metallic implant to the bone; this enhances their biomechanical compatibility. High surface area of the PEO coating promotes osteoblast attachment on the implant surface. Applying varying pulse polarity during PEO and introduction of bioactive particles into the electrolyte helps to incorporate the anions and cations of the electrolyte into the coating; this provides Ca-, P- containing bioactive crystalline phases within the coating: hydroxyapatite, tricalciumphosphate, tetracalciumphosphate, perovskite [31]. Adhesion of the PEO coatings is higher than of the other coating types.

4. Summary and conclusions

Thus, nanostructured Grade 4 titanium appears to be the material with a very high potential for medical applications as its elements have no harmful effects on humans. It should be noted that nanostructured CP Ti also imparts good machinability. Additional research on nanostructured Ti and some of its alloys is foreseen to even further increase ultimate strength and yield strength as well as to develop a way to reduce the effective modulus of elasticity that could come close to the modulus of elasticity of jaw-bone [1, 7].

The recent results have shown also that ECAP-C with subsequent drawing provides new opportunities in the development of nanostructured Ti, providing the ability to enhance the strength uniformly in long-length rods that can be machined into dental implants and other devices for medical applications. Nanostructuring of CP Ti by SPD processing produces a material with mechanical properties superior to those of Ti-6Al-4V. The application of nano-Ti in maxillofacial surgery can be promising for producing miniature implant designs, in particular plates that will endure the same loads as the conventional items.

Chemical etching and deposition of bioactive coatings can be utilized for surface modification in nanostructured Ti. Nanostructured CP Ti with modified surfaces can show improved functional properties such as improved surface bioactivity and reduced Ti ion release into human body. This makes nanostructured Ti an attractive material for manufacturing implants. The first clinical studies have shown a significance of these research results [14, 32, 33].

A number of biomedical researches have been already made to date, which shows that further biological studies are still needed. This applies also to other nanostructured metals (β-Ti alloys, stainless steel, Co-Cr alloys, magnesium alloys etc.), which are now actively developing for biomedical applications [1].

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