



Interface and in bulk residual stress analysis in biomedical systems by non-destructive techniques



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ARTICLE INFO

Available online 14 February 2012

Keywords:

Residual stress
Diffraction
Non-destructive techniques
Bioceramic
Interface

ABSTRACT

Bioceramic coatings on metallic implants are proposed to be a solution for combining the mechanical properties of the metal with the necessarily bioactive character of the ceramic layer, leading to a better integration of the entire implant.

Residual strains, developed in a metal/ceramic system due to the processing route, were experimentally measured using non-destructive methods. In this work a specimen of an implant constituted by two biomedical ceramic/metal parts: (i) titanium dental like-implants and (ii) porcelain crown are presented. In particular the stress distributions are reported in: (i) a 50 µm hydroxyapatite coating deposited by plasma-spray technique on titanium alloy as well as (ii) a multilayer consisting of 1.8 mm glassy-ceramic and 0.35 mm opaque ceramic Porcelain-Fused to Metal on a 1.6 mm palladium substrate.

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1. Introduction

Coatings are used in many biomedical applications to reduce corrosion and wear. To understand the dependencies on the process and to have the chance to influence them the knowledge of their residual stress (RS) state becomes a necessity. This knowledge helps to improve the properties of ceramic/metal systems and therewith gives a chance to enhance their lifetime. The control of the RS in the coating and in the substrate obtained during the manufacturing of process is extremely delicate as they are not only a result of the fabrication of the substrate but also of the process of the coating deposition. The RS is present in both, the substrate and the coating. Indeed as reported in [1,2], the RS is essentially induced in the ceramic coating and in the metal substrate once deposited; they are caused by the differences in the thermal properties between them as well as owing to the complicated solidification process within the coating. In order to investigate the stress state and stress distribution in the coatings and in the substrate, the residual stresses can be studied by diffraction techniques.

Stress/strain analysis using diffraction techniques, such as classical X-ray and neutron diffraction or synchrotron radiation, are widely applied for non-destructive testing. Diffraction techniques are the most powerful tools available to study the three dimensional state of structures at the atomic scale (Fig. 1).

The interplanar distance d_{hkl} (where hkl are the Miller indices of the investigated lattice planes) can be evaluated by using the Bragg law:

$$\lambda = 2d_{hkl}\sin\theta. \quad (1)$$

The corresponding lattice strain is defined as:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_0}{d_0} \quad (2)$$

where d_0 is the hkl -interplanar distance in a stress-free material.

From Eq. (2) the RS (σ) can be calculated using the Hooke's law [3].

In practice, the technique consists of precisely measuring the angular position of the Bragg peak for the stress-free and stressed material (Fig. 1). From the observed shift one can obtain the value of the lattice strain and by knowing the elastic constants of the medium, the value of the lattice stress is obtained [4]. One can note that the direction of the measured strain is normal to the diffracting planes and is given by the $\mathbf{Q}$ vector in Fig. 1.

A complete dental implant consists of three parts, as sketched in Fig. 2: the implant (1), a titanium screw which replaces the root and part of a missing natural tooth. It is placed in the bone allowing to bond with the bone and serve as an anchor for the tooth to be replaced; the abutment (2), which serves as a connector between the implant and the crown; and the crown itself (3), which is fabricated by a dental laboratory, placed by a restorative dentist and attached to the abutment.

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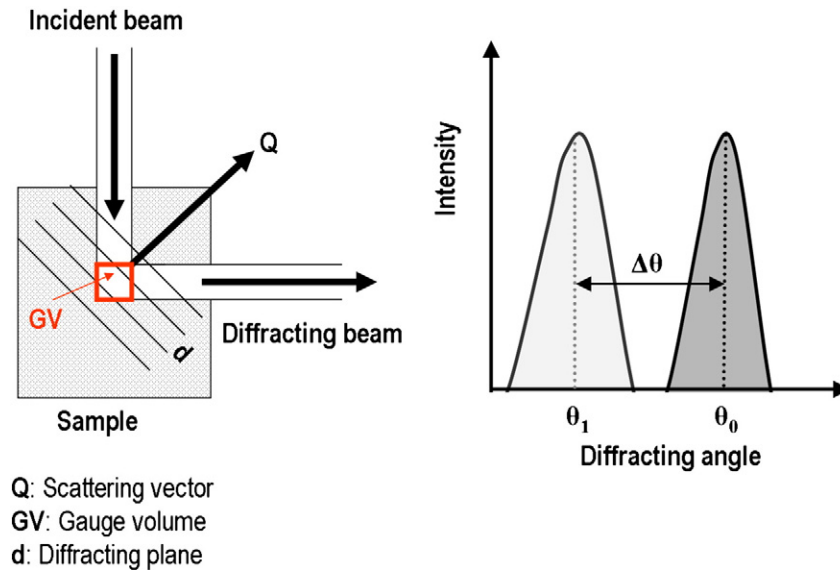


Fig. 1. Geometrical configuration of the measurement and shift of the measuring the angular position of the Bragg peak, corresponding to the presence of strain.

Titanium materials (commercially pure titanium, ASTM Grades 1 to 4, or Ti-based alloys, e.g. Ti–6Al–4 V) are considered to be the most biologically compatible materials to vital tissue. Their importance in the implant dentistry is related to their low elastic modulus, being half as high as the ones of Co–Cr alloys and their high yield points which are equal to that ones of carbon steel. However, Ti alloys are not bioactive such as bone-substitute implant materials. This results in only mechanical bonding rather than direct chemical bonding between the titanium implant material and the host bone tissue [5]. This can be improved by the deposition of bioceramic active films on the metallic surface. The plasma spray technique (PS) is a commonly and commercially used technique for the coating of hip implants with such films, for example hydroxyapatite (HA, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$), on a base substrate of titanium or its alloys. HA is a bioactive material with a high biocompatibility [6] and achieves bone mineralization directly on the implant surface, improving the bone growth and penetration of the cells as well as giving better direct contact between the tissue and the implant surface [7]. In accordance with various in-vitro and in-vivo tests, HA implant coatings have shown an improved bone apposition in comparison with the uncoated ones in the first weeks after operation [8]. Even though

the PS technique to deposit HA offers a very good biocompatibility, it exhibits a disadvantage concerning its long-term stability of the implant and, therefore, its lifetime.

For the crown coating the Porcelain-Fused to Metal (PFM) technique seems to be the most favourable one in terms of mechanical properties, bio-corrosion resistance, coating-substrate bonding strength and process feasibility in dental application [9]. The PFM technique is used for the deposition of dentin-like porcelain on precious metals. For a successful process, the materials to be coupled are selected in relation to their physical propriety and their biocompatibility. The Coefficient of Thermal Expansion (CTE) of the porcelain should be correctly matched with that one of the alloy and the melting range of the alloy must be raised adequately above the fusion temperature of the porcelain for enamelling. For these reasons special dental alloys with high palladium content are employed for the PFM technique. Palladium has a melting point of about 1828 K and its thermal expansion is too low to be used with most of the commercial porcelains. So, for dentistry applications Pd-based (usually 75–78 wt.%) ternary alloy systems (e.g. Pd–Ag–Sn or Pd–Cu–Ga) were developed to overcome this problem. To meet the porcelain–metal compatibility, the content of palladium is modified by adding silver to raise the CTE while tin and gallium to strengthen the palladium. Due to its inertness in aggressive environments, as well as optical properties, thermal expansion, strength, good wear resistance, and hardness porcelain based on potassium feldspar, such as leucite (KAlSi_2O_6), is largely used in restorative dentistry [10,11]. The leucite crystals serve to increase the thermal expansion of the porcelain, bringing it closer to that one of the metal substrate.

In this paper two examples for the application of biomedical coatings are given:

- (i) dental like implant, composed of a 50 μm HA thick coating on Ti–6Al–4 V [12], processed by PS technique, and
- (ii) samples of porcelain made by glass ceramic (GC) and opaque ceramic (OC) layers, coated on a Pd–Ag–Sn substrate [13] by PFM technique.

The aim of this paper is to investigate the RS introduced on these systems during processing by using the classical X-ray (XRD), neutron diffraction (ND) and the high-energy synchrotron X-ray diffraction in energy dispersive method (HESXRD).

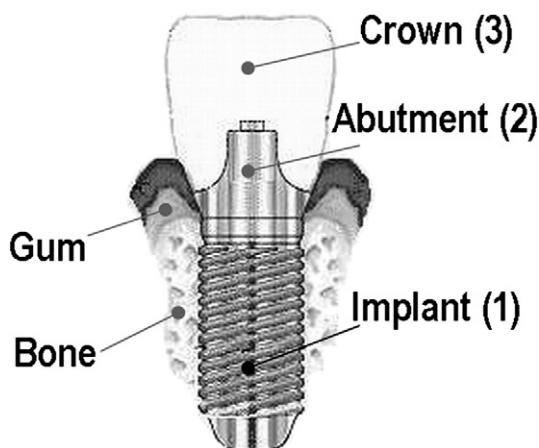


Fig. 2. A dental implant is built up by a titanium screw (1), being connected to the crown (3) using an abutment (2).

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