Thermal properties of a Ti-6Al-4V alloy used as dental implant material

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A titan grade 5 material for dental implants behavior was analyzed by thermal point of view. Heating on 23 to 150 °C temperature range the material Ti6Al4V exhibit a proper manifestation through reduce thermal conductivity, small dilatation or depth penetration. The thermal properties were analyzed by differential dilatometry and thermal conductivity at room temperature and under heating process during time as well. The results are comparing with properties of other dental materials like enamel, dentin, amalgam, gold, porcelain, glass, pmma polymer or ZnPO4.

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1. Introduction

Over the last decades titanium based implants have become more and more important in all areas of modern medicine. First of all the used materials have to be biocompatible defined as the ''ability of a material to perform with an appropriate host response in a specific application" [1] and there are always some sort of interaction between the physiological environment and the foreign body – the response being strongly influenced by the surface properties of the implant material. Long-term success of an implant requires the formation of a functional interface that supposes to be maintained between the physiological environment and the implant.

Therefore, not only the material has to sustain the conditions in the body but also, and first of all, the physiological environment must tolerate the implant material and structure in an adequate way. Commercially pure titanium and its titanium– aluminum–vanadium alloy Ti6Al4V, titan grade 5, have been used as implants due to their excellent biocompatibility and ability to allow bone-implant integration. Ti6Al4V has been also used preferentially in orthopedic- prosthetic replacement due to its added mechanical strength, while commercial pure Ti has been employed for some dental implants [2]. Titanium forms a biocompatible surface oxide layer capable of interacting with surrounding biological fluids and cells when implanted in situ [3, 4]. This layer, composed primarily of TiO_2, is found superficially on both commercial pure Ti and Ti6Al4V metals [5].

Generally, the thermal properties of implants and implant materials are characterized under strongly simplified heating and environmental conditions. Thermal fatigue loading and the resulting microstructural changes on the implant surface may strongly affect the interface to the living tissue.

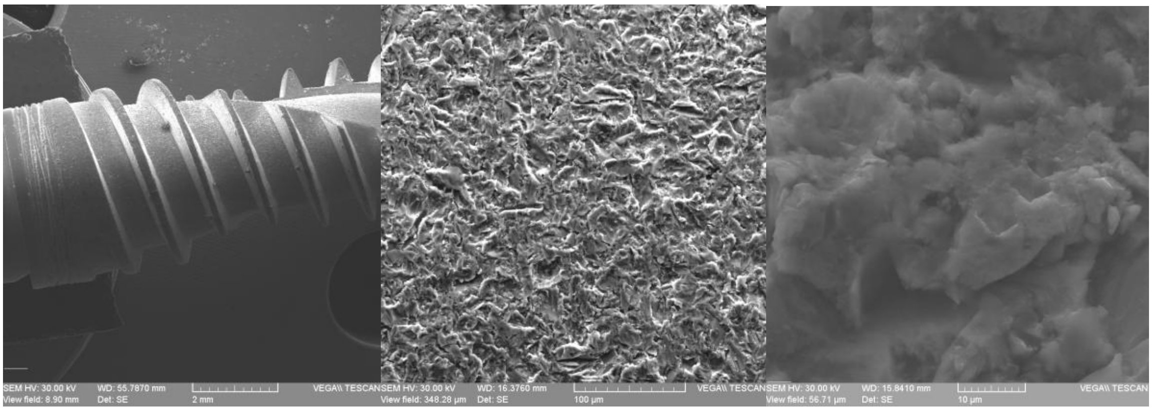
A multiplicity of implant surface forms exist, engineered with mechanical features that physically interlock the implant with bone. Various strategies have been utilized to improve bone integration of titanium-based implants. However, the effects of chemical modifications [6-8] of the surface oxide of Ti-alloys on their physical, chemical and biological properties have not been extensively studied. The objective of this investigation was to examine the effects of different heating rates apply on Ti6Al4V and to analyze the material thermal conductivity property.

In this paper some thermal characteristics of Ti6Al4V dental alloy are presented and comment to establish thermal behavior of these materials used in medical applications.

2. Experimental procedures

Thermal analyses of a Ti6Al4V alloy were carried out by dilatometry (using Linseis 75 type equipment) and thermal conductivity at room temperature (with TCi device and typical test preparation [9, 10]) point of view using differential equipments. Chemical composition of the titanium based alloy was obtained on a mass spectrometer Foundry Master showing a Titan 5 type composition [11]. The test temperatures were from room to 150 °C concerning calorimetry and dilatometry properties and at room temperature for thermal conductivity. Samples of 46 mm length and 5 mm diameter were used for dilatometry tests, in thermal conductivity case samples of 50 mm diameter and 10 mm height also in round shape were used. For differential calorimeter experiment sample of 25 mg was used from the same bar material.

Samples were obtain from A.B. Dental Devices' implants, made of the titanium alloy Ti-6Al-4V ELI, in accordance with ASTM F136-02 [12]. In Fig. 1a) general view of a dental implant is presented with details of geometrical shape and physical dimensions as thread pitch, thread dimension characteristics that influence the implant evolution in time. In Fig. 1b) and c) the implant surface is analyzed by scanning electrons microscopy at different amplification scales, 100 and respectively 10 µm showing TiO_2 specific microstructures [13]. In this study thermal properties of Ti6Al4V alloy, propose for dental applications, are analyzed in a room to 150 °C temperature range.



a) b) c)

Fig. 1. SEM micrographs of a dental implant made from Ti6Al4V alloy a) general view, b) microstructure of surface at 500 x power amplification and c) detail of surface at 2000 x image amplification.

3. Experimental results

Dilatometry tests shows a different behavior of Ti6Al4V dental material at heat modifications by heating rate modifications, in this case 2 and 5 k/min as is graphically represented in Fig. 2. Following the results represented in Fig. 2 can be observe a loop difference in 60 to 105 °C temperature range in 2K/min case, the superior represented line, marking an increase of material dilatation in a reduce temperature case impact with the implant material similar in opposed to shape memory alloys behavior at temperature exchange in martensitic transformations range [14, 15].

In this study case of thermal interesting behavior of Ti6Al4V was obtained a dilatation of 7.4 µm in heating regime of material with 5 K/min and 14.48 µm, almost double, for 2 K/min heating regime. At a maximum temperature of 150 °C the material dilatation measure 17.26 µm in 5 K/min heating case and 22.33 µm in 2K/min case presenting a smaller deployment in faster heating case.

The material behavior as environment temperature modification influence was analyzed by collaboration of the medium temperature and sample temperature evaluation in time, property connected straight to thermal conductivity properties of the material.

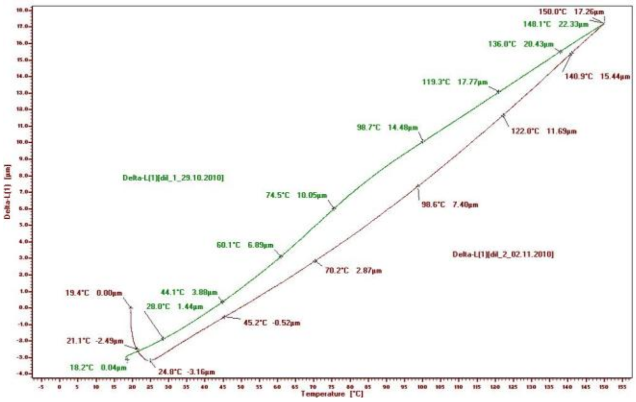
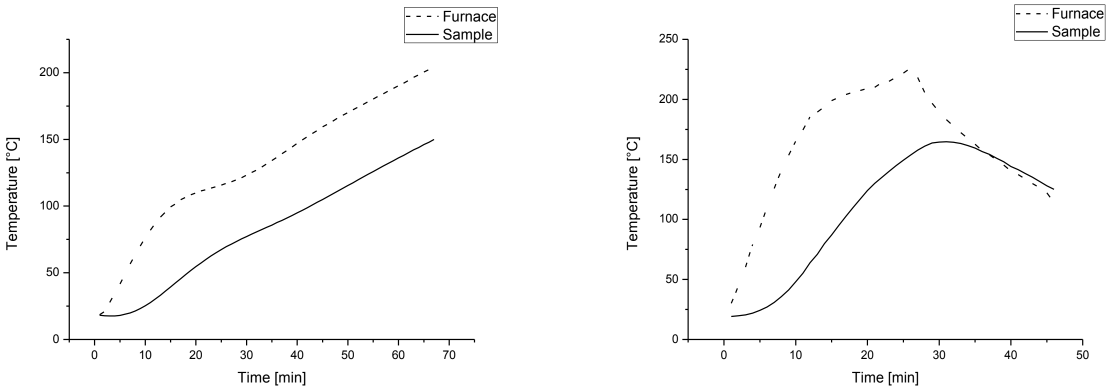


Fig. 2. Thermal behavior of a Ti6Al4V dental alloy at different heating rates respectively 2 and 5 K/min.

Starting from the same environment temperature, from variations of temperature with time presented in Fig. 3, the material behavior at heating can be appreciate that Ti6Al4V is a low thermal conductive material kipping a 50 °C degrees difference between furnace and sample temperature. Using a higher heating rate, 5K/min, and a loop on 50 to 105 °C range is observe for both thermal conditions. The low thermal conductivity is observed on cooling branch as well for the second regime, in Fig. 3 b).



a) b)

Fig. 3. Furnace and sample temperature behavior during a heating cycle for dilatometry test a) heating rate of 2K/min and b) heating rate of 5K/min.

Thermal conductivity tests of dental material based on titanium were obtained at room temperature in conditions presented in Table 1. Ten tests were carried out to determine the thermal conductivity and other thermal properties of the investigated alloy. Most important properties concerning a thermal behavior of a material like thermal conductivity, effusivity, diffusivity, heat capacity, depth penetration and R value (thermal resistance) are given also for ten tests and as average in Table 2. Comparing with other metallic materials, Ti6Al4V alloy, have a reduce thermal conductivity with a value ranged of 6.516347 W/(m K) (Table 2) much smaller than steel or cobalt based materials and them alloys conductivity [10] but bigger than cements, epoxy, resigns or polymers [16]. Concerning other dental materials like enamel with 0.9, dentin with 0.6, amalgam with 23, gold with 300, porcelain with 1.0, glass with 0.6 to 1.4, PMMA (Poly(methyl metacrylate) acid) with 0.2 to 0.3 and ZnPO4 with 1.2, Ti6Al4V have a medium experimental value of thermal conductivity.

Thermal resistance (R-value) present a very small value of 2.15043 × 10^{-6} m^2K/W comparing to other materials like dental cements based on CoCr, glass, foams or polymers [16].

Table 1. Thermal conductivity of Ti6Al4V alloy results obtained on TCi equipment.

Nr. crt	Sensor	V0 (mV)	VMax (mV)	DeltaV (mV)	Ambient (°C)	T0 (°C)	DeltaT (°C)
1	TC92	2741.007	2744.543	3.535986	22.13577	20.60594	0.377501
2	TC92	2740.391	2744.001	3.610611	22.13577	20.54014	0.385468
3	TC92	2738.951	2742.547	3.595591	22.13577	20.38643	0.383864
4	TC92	2740.034	2743.647	3.613949	22.13577	20.50201	0.385823
5	TC92	2739.559	2743.181	3.621578	22.13577	20.45136	0.386639
6	TC92	2738.907	2742.509	3.602266	22.13577	20.38172	0.384577
7	TC92	2739.69	2743.318	3.627539	22.13577	20.46536	0.387275
8	TC92	2738.997	2742.603	3.606081	22.13577	20.39129	0.384984
9	TC92	2738.534	2742.134	3.599405	22.13577	20.34196	0.38427
10	TC92	2739.683	2743.299	3.615379	22.13577	20.4646	0.385976
Average	**TC92**	**2739.575**	**2743.178**	**3.602839**	**22.13577**	**20.45308**	**0.384638**

Penetration depth measures the distance or thickness of thermal energy propagating into the surface through conduction. In most heat transfer textbooks and literatures, penetration depth is only dealt with qualitatively for the simple surface boundary condition- a prescribed surface temperature (i.e. boundary condition of first kind). In this study, the concept of penetration depth is presented by TCi software point of view as a medium value of 6.716426mm lower than the value registered on a aluminum alloy type 6061 of 37.1 mm or even of a stainless steel 304L with a value of 8.9 mm [17].

Thermal diffusivity with a range value of 0.509512 x10^{-6} m^2/s has an eight times smaller value comparing with a 304A stainless steel thermal diffusivity of 4.2 × 10^{-6} m^2/s or three times smaller than a quartz material with 1.4x10^{-6} value [17], materials also used in corrosion resistance fields. Comparing with values obtained for other dental materials the Ti6Al4V thermal diffusivity has a medium value near to enamel material characterized by a 0.5 values or porcelain 0.4 and ZnPO4 with 0.3, bigger than dentin and PMMA and much smaller than gold, amalgam or glass [16].

Table 2. Thermal properties of Ti6Al4V dental alloy at room temperature.

Nr. crt	Effusivity (Ws½/m²K) $x10^{-3}$	Thermal conductivity k (W/mK)	Diffusivity (m²/s)$x10^{-12}$	Heat Capacity (J/kgK) $x10^{6}$	Depth Penetration (m) x 10^{-6}	R-Value ((m²K)/W)	1/m
1	4756.934	6.840227	483629.9	0.0022	6543.858	2.10219E-06	183.1499
2	4636.99	6.475201	512821.1	0.002023	6738.453	2.15657E-06	178.64
3	4631.187	6.457651	514322.3	0.002014	6748.309	2.15927E-06	178.4226
4	4637.739	6.477464	512628.3	0.002024	6737.187	2.15622E-06	178.668
5	4644.989	6.499405	510766.3	0.002034	6724.94	2.15286E-06	178.9398
6	4643.066	6.493584	511258.9	0.002032	6728.182	2.15375E-06	178.8677
7	4642.693	6.492456	511354.4	0.002031	6728.81	2.15392E-06	178.8537
8	4651.271	6.518424	509164.3	0.002044	6714.385	2.14995E-06	179.1753
9	4630.446	6.455412	514514.5	0.002013	6749.57	2.15962E-06	178.3949
10	4629.863	6.453650	514665.9	0.002012	6750.563	2.15989E-06	178.373
Average	**4650.518**	**6.516347**	**509512.6**	**0.002043**	**6716.426**	**2.15043E-06**	**179.1485**

The heat capacity is typically for titanium alloys having a reduce thermal conductivity with a value averaged of 2.043 J g^{-1} K^{-1} higher than chrome, copper, tin, tungsten or other dental materials like enamel with 0.75, dentin – 1.26, amalgam – 0.210, gold – 0.126, porcelain – 1.1, glass – 0.8, PMMA 1.46 or ZnPO4 with 0.5 J g^{-1} K^{-1} [16].

4. Conclusions

Thermal behavior of dental material based on titan was analyzed in 23 to 150 °C temperature range. Dilatometry present a reduce dilatation until 150 °C evidencing a loop in 50 to 105°C range. The material behavior, as heat conductivity, under constant heating was analyzed registering a similar loop in thermal transfer from the environment to material in the same temperature range. The material present a poor thermal conductivity comparing with other metallic alloys used in dentistry but bigger than cements, rubbers, polymers or epoxy materials. A comparison with other dental materials (enamel, dentin, amalgam, porcelain, glass, PMMA or ZnPO4) thermal properties is also realized.

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