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Development of Functionally Graded Implant Materials in Commercial Use

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ABSTRACT

Total hip replacements (THR) and total knee replacements (TKR) are the most frequently performed surgeries in the world. Some problems appeared after implantation was solved step by step in terms of prophylaxis against infection and thrombosis, but there are some major problems remain to be solved. In total hip replacement, the femoral stem is still under many investigations performed by lots of researchers. The researchers have investigated the ways of producing a femoral stem in order to improve the corrosion resistance and the mechanical properties. For instance, one of the main problems in this area is related to the resorption of the bone due to the high value of Young's modulus of metallic part of the implant. Therefore, when the femoral stem is located in the bone, the stresses are concentrated on the down part of the implant which mainly causes pain for the patient. Another problem is related to the metallic ion releasing which causes inflammatory reaction for the body. After the implantation, the fixation of the implant inside the bone tissue is the main important issue, thus the femoral stem material needs to be biocompatible and needs to have suitable conditions for growing the bone tissue. There are several materials such as stainless steel, titanium and its alloys, cobalt-chromium based alloys suitable for producing femoral stem. Cobalt-chromium based alloys are strong, hard and also have good corrosion resistant. These alloys are used in a variety of joint replacement implants that require a long service life. Although, Co-Cr based alloys show a good background, there is still has some problems to be solved like lack of bioactivity, metallic ion releasing, aseptic loosening and high value of Young's modulus.
Keywords: Total hip replacements, CoCrMo-based implant materials,

INTRODUCTION AND MOTIVATION

In order to solve the issues, an important amount of researchers focused their attention on studying and evaluating the metal materials coated with different layers of biocompatible materials for improving the surface properties of the femoral stem. However, there are still some problems such as coating failure of the substrate due to the poor adhesion of the coating the bulk material. Bone cement is also utilized for fixing the stem in the bone and to solve the Young's modulus mismatch between bone and the metallic implant. However the main disadvantage of cemented implant fixation is related to the cracks or infections that can be occur in the joint after implantation.

We hypothesized that a gradient structure both in terms of porosity and chemical composition (from CoCrMo core to hydroxyapatite (HAP) rich surface) can be applied to CoCrMo-based implant materials in order to eliminate the mismatch of the Young's modulus between bone and metallic implant. Furthermore, this structure with porosity gradient prepares a suitable place for growing bone tissue that will increase the osseointegration. On the other hand, by creating a HAP-rich surface, which is known as an excellent support for bone restoration, the biocompatibility of the CoCrMo implant material can be increased in large extend. HAP is commonly used as a filler to replace amputated bone in order to promote the bone ingrowth into the implant. In this work CoCrMo will be used as a base material for creating a FGM, due to its good mechanical properties and good wear resistance. On the other hand, HAP-rich surface may also be helpful for decreasing the metallic ion releasing by decreasing the contact of metallic implant and bone.

In order to produce final FGM based on CoCrMo alloy, the investigations will be carried out on the homogeneous layers that will allow for evaluating the properties of different layer and understanding the percentage of material that will be used for producing each layer. The collected information about the results of each tested layer will allow designing the final FGM structure, which will be characterized and tested as well.

OBJECTIVES

The present work aims at developing a CoCrMo/HAP FGM material for femoral stem in order to improve the properties for the widely concerned issues, namely: i) Young's modulus mismatches between bone and the metallic implant, ii) metallic ion releasing, and iii) lack of bioactivity and osseointegration. For this purpose the following sub-objectives needed to be accomplished:

1. Producing different homogenous layers using various percentages of CoCrMo, HAP and ß-TCP in order to decrease the Young's modulus layer by layer and the final surface to consist from a porous structure and a lower Young's modulus values close to the bone. In order to create a porous surface, β-TCP will be used as a space holder, and after processing, β-TCP will be dissolved in body fluid. The porous HAP-rich surface will increase the bioactivity and osseointegration, allowing the bone tissue to grow in the pores, for having a stable fixation. It is also aimed at reducing metallic ion releasing by using HAP-rich surface via reducing the metallic area contacted with bone.
2. After producing different homogeneous layers, the properties will be evaluated in order to understand the behavior of each layer by changing the percentages of the materials.
3. Ultimately, FGM will be designed and produced utilizing the properties obtained from the homogenous layers which have been characterized before. The FGM structure will be characterized by a decrease of percentage of CoCrMo and increase of HAP and porosity from the core of implant till the surface. Therefore after implantation, HAP-rich andporous surface will be in contact with the bone.
4. After producing, the FGM samples, microstructural, chemical, and physical characterization studies will be performed in order to obtain the hardness and Young modulus, chemical composition, and porosity profiles.

STATE OF THE ART

Implant material-Biomaterial

A Statistical review from 2009 till 2010 shows an income of more than $200 billion on medical device companies around the world [1]. Many studies were performed on biomaterials for explaining and improving the required characteristics for a good function of an implant device.

Mechanical strength, biocompatibility and corrosion resistant are some of the most important issues.

The most common implant material is considered as titanium and its alloys which demonstrate a good biocompatibility as compared to the other implant materials [2]. Corrosion resistance to biological fluids makes titanium and its alloys the most popular and the most consumed biomaterial [3, 4]. The formation of the stable oxide film on the metal surface protects the bulk material from physiological environments [5, 6]. CoCrMo alloys are currently the one of the most used materials for metal-on-metal implant bearings. These alloys have a superior combination of properties including fracture toughness, ductility, biocompatibility, strength, and corrosion resistance. The femoral heads of hip joint are made from CoCrMo alloys which replace the stainless steel that have a poor corrosion resistance and titanium alloys for its poor wear resistance [7].

In order to improve the properties of biomaterials, the researchers are performing investigations for solving the most important problems, which are showed in Table 1.

Table 1 most important problems related to the implant material.

Metallic ion releasing
Osteolysis and aseptic loosing
Lack of bioresorbability
Mismatch of the young's modulus between bone and metallic implant material

All the problems shown above are related to the implant metal surface where needs to be focused to the researchers' attention. Therefore, many efforts have been made to improve the surface properties of the implant materials. A major problem still remains is lack of bioresorbability and aseptic loosening. To avoid the loosening of the implant especially for more active patients, it is required more reliable, resistant and stable interface between bone and implant [8]. Osteolysis is one of the major causes that can lead to loosening of the implant due to increased wear rates [9, 10, 11 and 12]. Some studies showed that the areas, where osteolysis was detected, exhibit a bigger concentration of debris particles than the areas with nonosteolysis region of the loosen implant [11, 13].

In order to improve the properties, the surface of the implant is modified by coatings [14- 18]. The process can lead to coating failure of the substrate due to poor adhesion of the coating to the bulk material [19]. It is well known that titanium and its alloys show a good biocompatibility and good corrosion resistance due to the oxide film that is forming instantaneously on the surface [20]. On the other hand, the release of the metallic ions is still a problem for the replaced joint [21]. It is known that proteins, cells, inorganic ions, which are in composition of the body fluid, can accelerate the rate of corrosion as well as releasing metal ions. Also, a big amount of ion release is taking place when the mechanical damage (sliding and fretting wear) occurs on the metal surface and the regeneration of the oxide layer take some time [22]. The advantage of a good corrosion resistance and biocompatibility of titanium and its alloys is disrupted by poor wear resistance. Thus many researchers are focused on CoCrMo alloy materials, because of their excellent mechanical properties with higher wear resistance together with good corrosion resistance.

Another important issue for the implant materials is the mismatch of mechanical properties between the bone and the biomaterial chosen for joint replacement. This problem can lead to lack of osseointegration between the implanted material and bone. First approach in order to overcome this problem is using bone cement to fix the hip prosthesis. The other approach avoids the use of cement and relies on the porous nature of the hip implant to encourage the body to hold it firm. The main disadvantage of cemented implant fixation is related to the cracks or by the attack of inflammatory process in the joint [23]. A solution of all these problems could be the using of Functionally Graded Material (FGM) which is characterized by variation of the properties in a certain pattern to match the biomechanical properties that are required at different areas in the hosting bone [24].

For a healthy bone when the stresses are applied to the top of the femur, the stresses are transmitted through the cortical bone (Fig. 1). Comparing with the femoral implant after applying the stresses to the top of the femur, since the Young's modulus of implant is higher than that of the bone, stresses are transmitted down to the stem of the implant and hence less stresses are carried by some certain part of the bone that is resulted to resorption. The main transmissions of the stresses are located in down part of the stem, which causes pain for patients [25].

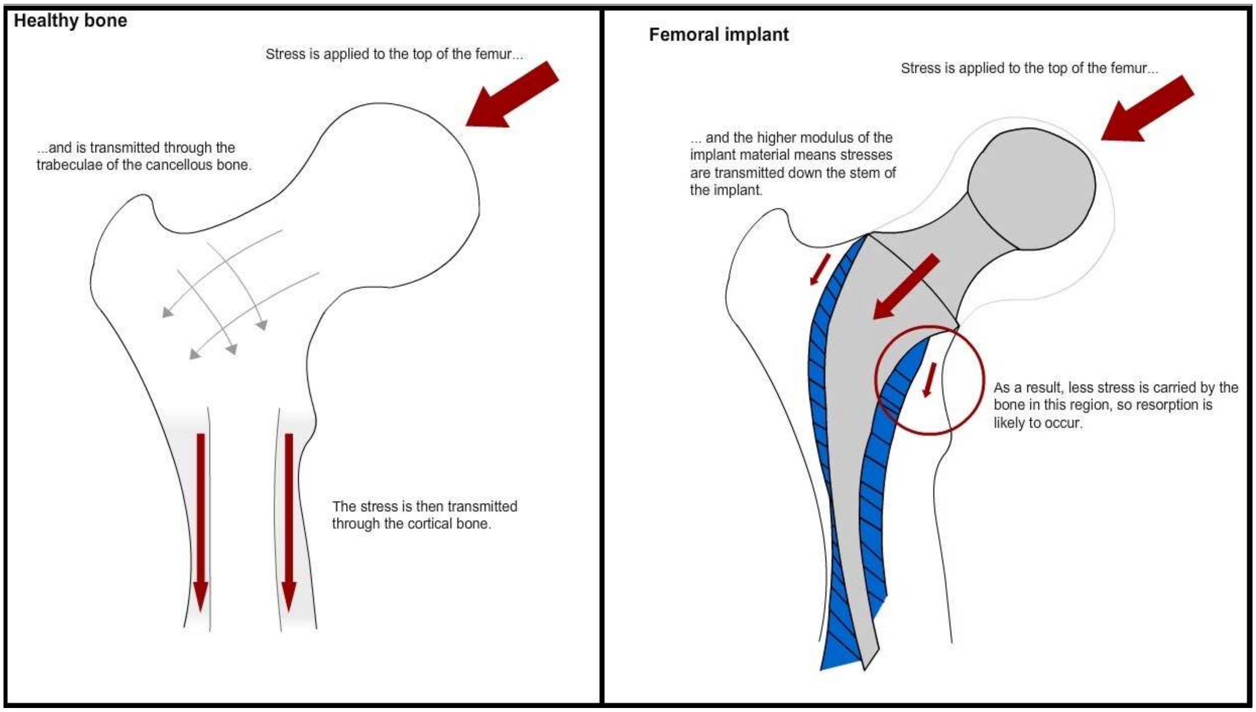

Figure 1 healthy bone and femoral implant after applying stress [25].

Functionally graded Biomaterial

The notion of FGM was mentioned for the first time in 1984, in Japan within a space plane project. The propose of the project was to create a combination of materials which surface could resist a temperature of 2000K and a gradient temperature of 1000K in a 10 mm thickness. FGM could be applied to a large area of industries such as automotive, space, naval and also medicine. The concept is to make a composite material by varying the microstructure from one material to another material with a specific gradient. This enables the material to have the best of both materials. If it is for thermal, or corrosive resistance or malleability and toughness both strengths of the material may be used to avoid corrosion, fatigue, fracture and stress corrosion cracking [26]. These materials could be useful in many applications that require gradient properties along a specific part [27]. Various approaches based on the bulk (particulate processing), perform processing, layer processing and melt processing are used to fabricate the FGMs.

An essential challenge in materials science is attributed to development of new biomaterials for medical industry. The living tissue is a complex system, made up of cells separated by non-living material, which can be characterized as a gradual functionality. As human bone is a living tissue with gradient features, from a dense, strong external structure (the cortical bone) to a porous internal one (the cancellous bone). Material science is open to the new approaches of manufacturing devices used for bone replacement, as implants. This structure optimizes the material's response to an external loading. Thus the optimized structure for an artificial implant should show a similar gradation [28]. An important technology used for improving and lengthening the life cycle of the material is coating. However, the singular stress induced by the discontinuous character of the coating substrate may contribute to cracks, which can lead to spallation. Due to the big difference of the thermal expansion coefficients between the bulk material and coating, the residual stresses are very high especially when the material is operated in a high-temperature environment. The concept of the FGM has been introduced to eliminate singular stresses, relax residual stresses, and enhance bonding strength [29, 30].

Functionally graded implant needs to fulfill all the properties such as biocompatibility, strength and corrosion resistance [31]. HAP has bioactive properties for new bone formation. HAP is the main component of hard tissue such as bone and teeth [32–34]. Many researchers have investigated mismatch of Young's modulus between metal part and bone. M. Thieme*et. all* [35] carried out an investigation which had result in the fact that a suitable adaption between Young's modulus of the material and elastic properties of bone can obstruct the stress shielding effects and improve long-term performance of the implant-bone system. Stress shielding refers to the reduction in bone density (osteopenia) as a result of removal of normal stress from the bone by an implant (for instance, the femoral component of a hip prosthesis). This is due to Wolff's law; a bone in a healthy person or animal will remodel in response to the loads it is placed under. Therefore, if the loading on a bone decreases, the bone will become less dense and weaker because there is no stimulus for continued remodeling that is required to maintain bone mass. A porous structure is a suitable solution for bone resorption. According to the earlier findings based on animal implantation studies with porous model specimens, optimal dimension of the porous structure has to be 100±400 µm till 0.2±0.5 mm [36-38].

In literature, there are several studies related to titanium-based FGMs. R. Roop Kumar *et al.* [39] performed some studies for producing functionally graded bioactive coating onto Ti by mixing HAP powder with Titanium oxide in different weight percentages. The authors produced a coating layer having a thickness about 230 µm. Another study performed by K.A. Khoretet*. al.* [40] showed the effect of using plasma spray process for producing functionally graded HAP/Ti–6Al–4V coatings. The Young's modulus and fracture toughness results showed highly anisotropic elastic behavior with relatively higher E and K_{IC} (fracture toughness) values parallel to the coating surface due to the intrinsic lamellar structure of the plasma sprayed coatings. Chenglin Chu *et al.* [41] investigated HAP-Ti/Ti/HAP-Ti symmetrical FGM. Optimized distribution function of components of this FGM based on the classical lamination theory and thermo-elastic mechanics was derived to eliminate the demand toward micro-cracking in earlier samples. R. Roop Kumar *et al.* [42] investigated the functionally graded coating of HAP-Ti composites. The authors reported that HAP/Ti is a suitable composite biomaterial with good biocompatibility and high mechanical properties. On the other hand Chenglin Chu *et al.* [43], studied HAP/Ti asymmetrical functionally graded biomaterial, and reported that thermal expansion coefficients of HAP/Ti composites increase with the rise of testing temperature or the content of HAP ceramic. Hot pressing has been used for fabricating HAP/Ti asymmetrical FGM with the optimum graded composition. The same research team [44] developed a functionally graded biomaterial in a HAP–Ti system by an optimized powder metallurgical process. It has been shown that HAP–Ti FGM is a promising biomaterial for being use for hard tissue replacement implants from mechanical properties point of view.

There are very limited studies available on Co-based FGM materials and Co-based coatings. F. Watari *et al.* [45] investigated the tissue reaction to the gradient structure of Ti/HAP and Ti/Co FGM implants. The authors concluded that the change of Co concentration can affect the tissue response of the material used for implantation. Another study realized by B. Henriques *et. al.* [46] conducted a study which is a comprehensive one in the field of dental restoration was to compare the shear bond strength between conventional porcelain fused to the metal and new functionally graded dental restoration after thermal-mechanical cycling. The authors concluded the metal ceramic shear bond strength values of the new functionally graded restorations

(FGMR) were significantly higher than those of conventional porcelain fused to metal restoration (PFM) irrespective of the fatigue testing conditions. On the other hand, some researchers were focused on investigating the FGM coatings on different implant materials. For instance, B. Vamsi Krishna *et al.* performed studies on functionally graded Co–Cr–Mo coating on Ti–6Al–4V alloy structures. The researchers showed that by the addition of Co–Cr–Mo alloy onto the surface of Ti–6Al–4V alloy, the surface hardness increased significantly without any intermetallic phases in the transition region [47].

Powder Metallurgy (PM) is the process that includes three basic steps; the material powder is mixed fallowed by a compaction of the powder materials into a desired shape or form (compacting) using pressure and then sintering at a specific temperature. This procedure is a vital one in this process. Within the sintering process, the particles are welded together and substantially compacted, leading to enhance strength of the dense material. Occasionally, the sintering process is done in a protective atmosphere or vacuum and the temperature does not reach the melting point [48].

The main advantages of Powder Metallurgy technique are shown in Figure 2 [49].

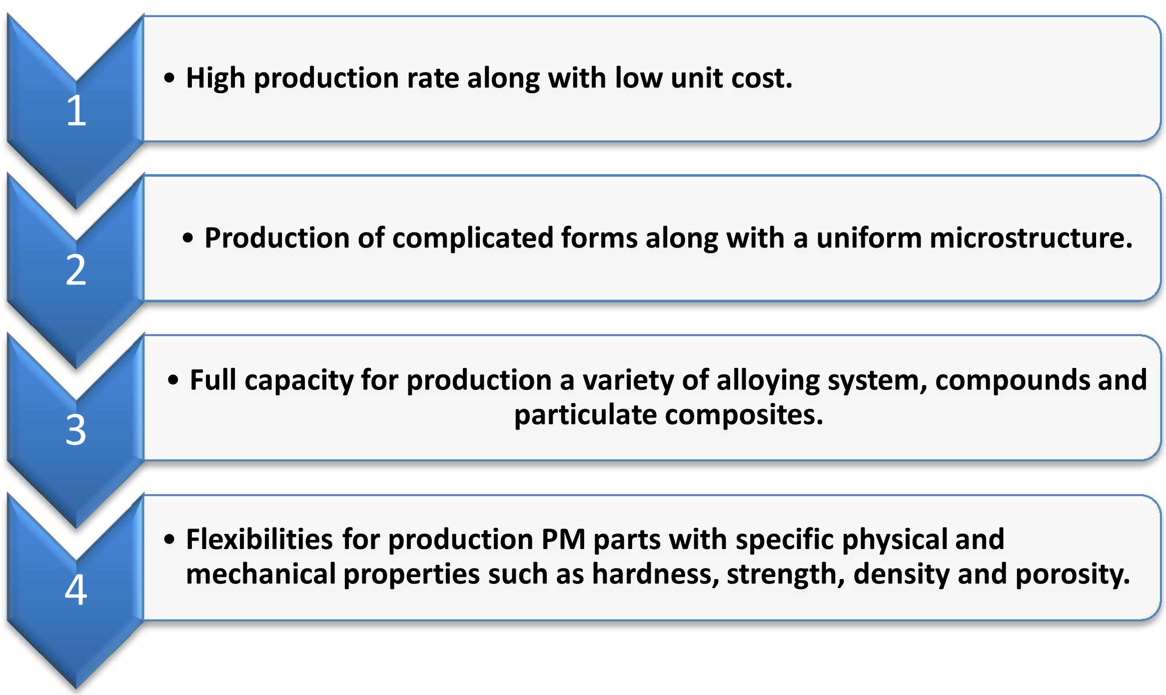

Figure 2 the main advantages of powder metallurgy technique

Hot pressing is a high pressure process for forming of a powder compact at an enough high temperature for inducing sintering process. This will be obtained by the simultaneous application of heat and pressure. In most of the cases a graphite mould is used for loose or pre-compacted powders because graphite mould allows induction or resistance heating up to temperatures of typically 2400 °C. By this mold pressures can be applied up to 50 MPa [50]. Sintering induced contacting particles to bond together at higher temperatures. It can occur at temperatures below the melting point by solid-state atomic transport events, but in some cases involving the formation of liquid phase. Inherently, sintering is due to the motion of atoms that occurs at high temperatures and the reduction in the surface energy associated with small particles. Powder fabrication is largely related to putting energy into the material to create surface area or surface energy. Now in sintering, that energy is eliminated. Surface energy per unit volume depends on inverse of the particle size [51].

Hot pressing process has also been used by researchers. It was mentioned that there are some advantages and disadvantages on the process [52]:

- Short synthesis time.
- Good surface finish.
- Low pressure.
- Simple procedure and high purity in the final product.
- Hard materials used to make components that are difficult to machine can be readily made.
- Suited for moderate to high volume component production.
- Parts with controlled porosity can be made.
- Less strong parts than wrought ones.
- Less well known process.

Similar to every project, there are some advantages and disadvantages. When comparing the advantages and disadvantages, one can demonstrate the feasibility of the project with the advantages which can be depicted as follows:

The aim is to produce a femoral stem with excellent corrosion resistance together with good wear resistance. It is expected to have good mechanical properties such as high value of fatigue strength to have a long life and biocompatible for body tissue as well.

One of the disadvantages as showed in figure 3 is the surgical technique that is related to porous structure femoral stem which is difficult for implantation and fitting the hip prosthesis. Another disadvantage is the recovery time which is slow after hip replacement surgery and it cannot take the weight of the body straight away. The replacement hip can still loosen over time if a good connection is not made between the hip prosthesis and the internal surface of the femur [53].

Advantage

- **To have corrosion resistance and wear resistance**
- **To have Good mechanical properties**

Disadvantage

- **The surgical technique is more difficult.**
- **Recovery time is slower after uncemented hip replacement**

Figure 3 Advantages and disadvantages of the proposed work

DESCRIPTION OF THE TASKS

Task 1 Bibliographical research

A bibliographical research will be a continuous task throughout the work in order to follow the state of the art and to adapt some revisions when it is needed. Information obtained will enable the candidate to acquire a deeper and comprehensive knowledge on those topics. The main part of this task is carried out during the first 3 months of research program but it will continue for the rest of the time.

Task 2 Producing of homogenous layer

The aim this task is to produce homogenous layer with different percentage of ß-TCP and HAP added to the CoCrMo alloy in order to solve the problems as explained in state of the art. In this section hot pressing process will be used for processing homogenous layers.

By the end of this task, those issues will be defined:

- Optimal percentage of additive materials will be determined.
- Open gradient porous structure will be obtained.

Task 3 Mechanical and microstructural characterization of homogenous layer

Mechanical and microstructural characterization will be performed on the as-produced homogenous composites. By the end of this task, those issues will be defined:

- Optimum mechanical properties will be defined.

- Microstructural properties will be obtained.

Task 4 Producing of functionally graded materials

This task is one of the ambitious and one of the main goals of this project. Production of functionally graded material (FGM) is one of the most difficult processes that scientists are researching on it. For this purpose hot pressing process will be used to produce FGM. The results of Task 3 will be used for choosing the optimal percentage of the material of each layer in order to produce FGM structure.

By the end of this task, those issues will be completed:

- CoCrMo- HAP FGMs will be produced together with a porosity gradient.

Task 5 Mechanical and microstructure characterization of functionally graded materials

After production, FGMs will be tasted in terms of mechanical and microstructural characterization.

By the end of this task, this issue will be defined:

- Hardness and Young modulus profiles.
- Chemical composition profiles.
- Porosity profiles.

RESEARCH METHODOLOGIES

Production of homogeneous layers

At the beginning of the experimental studies, the powders will be characterized in order to observe the microstructure, chemical composition and particle size distribution. After powder characterization, the homogenous layers will be produced. The main materials are CoCrMo alloy with different percentage of addition materials such as HAP and ß-TCP. For producing these layers, hot pressing process in vacuum condition will be used. Prior to processing, the metal and additional powder will be mixed in ball mixer to create homogenous distribution. Hot pressed CoCrMo substrates will be obtained by pressing the metal powders in a graphite die at various parameters of sintering time, temperature and pressure. The graphite die is painted with zirconium in order to avoid carbon diffusion to metal substrates. After, the mixed powder is placed in the mold the hot pressing process will take place with the fixed sintering time, temperature and pressure. The temperature will be increased constantly till the fixed sintering temperature which will be kept for fixed sintering time. After the sintering the samples will be cooled down to the room temperature in the vacuum chamber. This process will be used for producing different homogenous layers and eventually, the percentage of CoCrMo is reduced and percentage of HAP will be increased layer by layer.

Mechanical and microstructural characterization of homogenous layer

After producing homogeneous layers (which are described in Task 2) the characterization of the material will be divided in two parts, which will contained a part of Mechanical characterization of the samples and the second tribological part. For mechanical characterization several types of tests will be done.

Sintered materials will be subjected to three point bending tests by following the ISO standards. The fracture surfaces obtained from the three point bending tests will be investigated by SEM in order to understand the fracture characteristics of the homogenous layers. Furthermore, Micro and nano indentation tests will be performed in order to obtain the hardness. Axial compression or DMA test will be used to measure the Young's Modulus. In order to measure the porosity of samples the polishing procedure will be used for achieving mirror surface condition. Using an optical microscope in order to get images, the porosity will be calculated after analyzing the images by the software.

The human body is usually subjected to movements. The replacement part of the bone like a hip or knee implants are subjected to fatigue during physical motion of body. Thus, fatigue test also will be performed in order to determine the behavior of materials under fluctuating loads. Mechanical cycling of the specimens will simulate the mechanical forces in human body.

Dry sliding test will be performed for evaluating the wear mechanism by determining wear process. For this test parameters like load, speed, frequency and time need to be specified. The registered of coefficient of friction after dry sliding test can be obtained from the software.

It is important to know that implant materials are in contact with body fluid. Thus, the synergy action of the wear and corrosion processes (tribocorrosion) becomes important. Therefore, Tribocorrosion test will be performed in order to understand the interaction between the material surfaces in a corrosive environment where material has a relative displacement. Tribocorrosion involves wear and corrosion that can minimize the system performance or even lead to a system failure. In a hip joint, there are many possibilities for tribocorrosion events at the implant surface. Next to articulation between the femoral head and acetabulum, micro-movement between the femoral stem and cortical bone can occur. The tribocorrosion test will be performed with pin on flat reciprocating movement system equipped with a potentiometer which will registered the electrochemical parameters. Electrochemical techniques used for studying tribocorrosion process allow controlling test condition during sliding and quantifying the relation between a corrosion and wear volume.

The second goal of this task is to produce gradient porous layer. Porous structure is very important for solving the mismatch of Young's modulus between the metallic part of implant and bone. A good approach about this problem can be achieved by making gradient porous layer by using ß-TCP. This stage involves the production of porous layer of CoCrMo by adding ß-TCP during the hot press process and then put the samples in a proper solution to dissolve ß-TCP and get gradient porous structure. For this purpose first it needs to make porous ß-TCP structure then use it for making CoCrMo by using hot pressing process.

Production of functionally graded material

Following the characterization of the homogenous layers produced (Tasks 2, and 3) the FGM structure will be achieved as presented in figure 2.

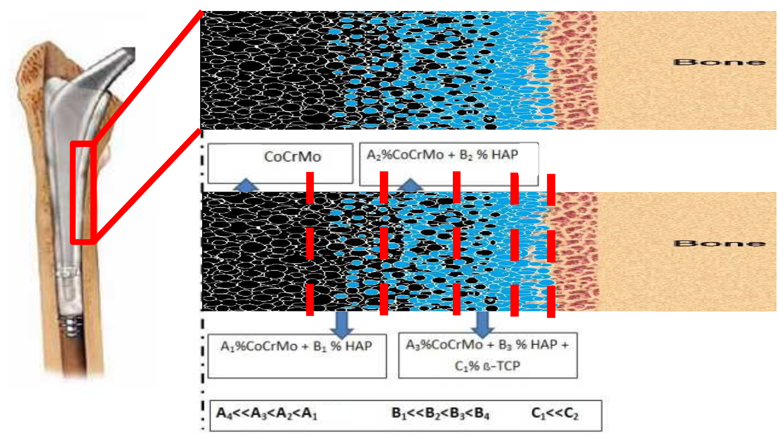

Figure 2 FGM implant with porous surface

Different techniques will be studied in order to build the gradient structure:

1. Deposition of layers of powder mixtures with stepwise changes in the mixture

The gradient form is achieved by the deposition of powder layers with changing compositions in the compacting die [54- 59]. Discrete changes, limited number of layers (up to 10 in laboratory scale, but not more than two or three in potential fabrication), limited thickness of individual layers (normally not less than 1 mm), limited size of the part (<100 cm^2) due the limits of compaction forces, discontinuous manufacturing with low productivity are disadvantages of this process. However this method enables effective laboratory studies of functionally graded systems.

2. Wet powder spraying

A thin powder layer can be achieved by an air brush system only if the powder suspension is suitable for deposition [60]. By including a mixing system and controlled feeding of two or more suspensions graded powder layers can be deposited on a flat, curved or rotating substrate [61, 62].

Simultaneous drying allows building up parts reaching millimeter thickness with only small variations from layer to layer. The size of the sprayed droplets is controlling the minimum thickness of the layers that could be less than 50 µm [63].

3. Slurry dipping

If a porous body is sequentially dipped into slurries with varying powder characteristics, liquid drag into pores by capillary forces leaves surface layers with a stepped gradient behind [64-66].

Mechanical and microstructural characterization of functionally graded materials

The produced material will be tested with several types of experiments to evaluate the properties. The FGM samples will be characterized in terms of hardness and Young's modulus profiles by Nano indentation, chemical composition profiles by EDS and porosity profiles by image analysis tools. The effect of the curvature and possible layer orientations also can be considered for further investigation as it has been reported to have a significant role in stress concentration [67-68]. Damage material due to external forces are investigated in [69-70]

CHORONOGRAM

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