The place of metal foams in biomaterial applications

Nuray Beköz Üllen* *(ORCID:https://orcid.org/0000-0003-2705-2559)*
Gizem Karabulut *(ORCID:https://orcid.org/0000-0003-0930-5380)*

Istanbul University-Cerrahpaşa, Faculty of Engineering, Department of Metallurgy Engineering, İstanbul, Turkey

*Corresponding author e-mail: nbekoz@istanbul.edu.tr

Abstract

Today, metal foams are preferred in many structural or functional applications in different sectors such as transportation and construction, biomaterials and military materials, thanks to their rigidity, lightness and strength properties. The pore structure of the metal foams can be open, closed or mixed. In the open pore structure, the pores are in contact with each other and the environment in which they are located and they are permeable. In the closed pore structure, the pores are isolated from the environment and from each other. In the mixed pore structure, two pore structures are together. The materials that are intended to be used in the body as biomaterials must have some properties. First of all, it should be biocompatible with its living tissue (it should not be toxic, not cause allergies and not contain carcinogenic components). Then there should be mechanical and physical properties such as adequate strength, elastic modulus, toughness, fatigue strength abrasion resistance and low density. In order to increase the biocompatibility and to have a long lifetime, the biomaterial should have an open porous structure that does not prevent the circulation of blood and body fluids, without preventing the development of living tissue. Considering these desired properties, metal foams have significant potential for biomaterial applications. Metals such as titanium and its alloys, magnesium, tantalum are porously produced and used as biomaterials. Metallic foam shows brittle behavior under the effect of tensile stress. Thanks to its highly porous structure, its energy absorption capacity is high under compression stress. In this review, metal foams used as biomaterials, where are they used and the importance of applications, are discussed in the light of the researches.
Keywords: metal foams, biomaterials, biocompatibility

INTRODUCTION

Nowadays, metallic foams have commercially attracted the attention of many industries. They are preferred in many fields such as automotive, aviation and medical applications thanks to their properties which it has. Although the meaning of "foam" is original sense as gas in the liquid, the structure obtained by dispersing the gas also in the solid is called foam. Metallic foam generally means solid foam (Banhart, 2001). The production method of metallic foams can be selected according to the type of metal, that the foam will be produced (Al, Fe, Mg, Cu, Ni etc.) and the properties of the foam (porosity, pore type, density, etc.) (Beköz, 2011). Depending on the shape, distribution and connection of the pores, their properties vary and they have a wide range of uses (Mutlu, 2011). Porous metals are divided into three as closed, open and mixed porous according to the connections of the pores. This is the parameter that basically separates the areas of usage. Since foams with closed pore structure have better mechanical properties, they are used in structural, impact and sound insulation applications. Open porous foams are used in filters, catalyst carriers and biomedical applications due to their permeability properties (Beköz, 2011). In recent years, metallic foams made of different metals have been used in different parts of the body. Metallic open porous foam structures have a significant potential in biomedical applications, especially since they show a similar structure to the tissue of the bone (Matassi et al., 2013). In this review, the reason for the importance of metallic foam structures in biomedical applications, the implants and their usage areas are mentioned.

IDEAL BIOMATERIAL AND ADEQUACY OF METALLIC FOAMS

In order for a material to be used as a biomaterial, it should have basic properties (Mutlu, 2011). In this section, these features and the compatibility of metallic foams with these features are mentioned.

Biocompatibilty

The biomaterial that was used can react in to four different ways with living tissue; toxic, bioinert, bioactive and biodegradable. When the implant material is placed in the body, the body tissue either completely rejects the implant or keeps it in place with some complications. The goal for an ideal implementation; is to implant the material into the body without any complications or bad effects (Cömert, 2005). Metals such as Ni, Al and V exhibit toxic behavior. Ti, Stainless Steel (316L, 17-4 PH) and Co-Cr alloys exhibit bioinert behavior, while metals such as Mg and Zn exhibit biodegradable behavior. The used metal should not react with the tissue, bone or body fluids. It should not form toxic substances, not cause allergy, not contain carcinogenic substances and not release metallic ions (Cömert, 2005). The foams produced from Ti, SS, Co-Cr alloys and Mg used in biomaterial applications exhibit compatible behavior with the body (Mutlu, 2011). In addition, the porous structure of metallic foams has a structure similar to that of the bone, so that it can transmit body fluids increases adhesion to the tissue where the implant is located (Nouri, 2017).SEM images of cancellous bone and open-cell metallic foam structure are given in Figure 1.

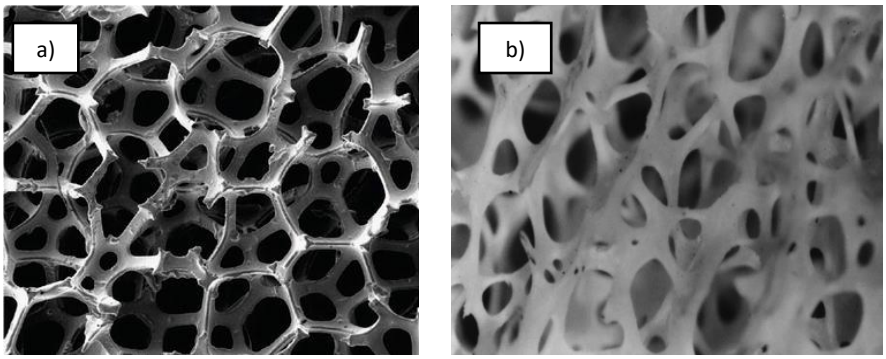

Figure 1. SEM images a) open porous metallic foam (Alhusseny et al., 2017) b) cancellous bone (Wu et al., 2014)

In Figure 2, bone structure and schematic representation of osseointegration of bone and foam are given. Bone has two different structures, cortical (compact) and cancellous (porous). Cortical bone generally has 5-10% and cancellous bone has %75-95 porosity (Mutlu, 2011).The term osseointegration firstly used by Professor Branemark. It is defined as the formation of a structural and functional bond between bone and implant (Cranin and Lemons, 2004).

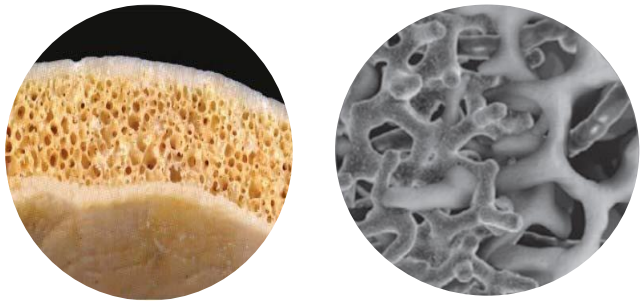

Figure 2. Bone structure (Kayacan et al., 2016) and osseointegration of bone and foam (Nouri, 2017)

Mechanical Properties

It is desired that the mechanical properties (strength, hardness, elastic modulus, toughness, wear resistance etc.) of the material to be used as a biomaterial are compatible with the properties of the bone. In order to choose the appropriate material, firstly it is necessary to know the properties of the bone. The elasticity modulus of the cortical bone is in the range of 15-20 GPa and the compression yield strength is in the range of 30-150 MPa. The elasticity modulus of the cancellous bone is in the range of 0.09-2 GPa and the compression yield strength is in the range of 10-70 MPa (Mutlu, 2011; Matsushita et al., 2017). The incompatibility of the mechanical properties of the implant and bone causes the formation of stress shielding effect. With the incompatibility of the mechanical properties, the implant will carry the load, in this case, stress shielding occurs and the load no transmitted to the bone and it weaken over time (Joshi et al., 2000). In order to reduce or

prevent the occurrence stress shielding effect, materials should be selected close to the bone structure. For example, while the elastic modulus of the dense form of Ti metal, which is frequently preferred in bone implant applications, is 100 GPa, it is advantageous to reduce the porous form of 45-50% to the range of 5-10 GPa (Matsushita et al., 2017). In addition, the porosity can be changed to adjust the mechanical properties and thanks to this, metallic foams are advantageous for biomedical applications.

Physical and Chemical Properties

Properties of biomaterials such as weight, porosity and pore size are important physical properties. If the implant material used is heavy, it will disturb the host. Therefore titanium implants are preferred over heavy implants such as platinum, which were previously used. Porous materials' being lightweight construction and energy absorption properties would be advantageous in this respect. At the same time, the porous structure provides transportation of nutrients and tissue ingrowth, thereby ensuring osseintegration and long-life (Karageorgiou and Kaplan, 2005). In order to facilitate bone tissue regeneration, interconnected structure of pores, pore size and shapes, and porosity factors are important. Xue et al. reported that the porous size of the porous structures intended to be used as biomaterials should be at least 200 μm. If it is smaller, the cells block the pores and cannot pass (Xue et al., 2007). In addition, high pore sizes also negatively affect mechanical properties, but porosity is a more important parameter affecting mechanical property (Mutlu, 2011). With increasing porosity, the permeability amount increases, but the elastic modulus decreases (Wu et al., 2014). The porous structure of metallic foams and the pore size, porosity and open or closed pore shapes can be adjusted in production methods and that provides advantage to metallic foams in biomedical applications. In addition to these properties, the properties of porous metals such as corrosion resistance, heat transfer, and electrochemical activity are better than their dense ones. Because foams' specific surface areas are more than dense metals (Qin et al., 2015).

Reproducibly

The used material must be sterilized and reproducible in accordance with international standards. The pores can be obtained by coating or at the production stage. In addition, production costs must be reasonable. Implantation should be simple, precise and reproducible (Matassi et al., 2013).

METAL FOAMS IN BIOMEDICAL APPLICATIONS

As mentioned in the previous sections, metallic foams have many advantages in biomedical applications. In this section, metals such as stainless steel, titanium which are frequently used in the applications, their usage areas and their advantages/disadvantages are mentioned.

Stainless steel

Stainless steels are one of the first bioinert metals used in orthopedic implant applications. Stainless steels mainly contain iron, carbon, nickel and chromium, sometimes using additives such as molybdenum improves their properties. Generally preferred stainless steel is 316L. Compared to other used metals, stainless steels show lower strength, higher corrosion resistance and hardness. However, 316L provides corrosion resistance it relies on passivation with the thin layer of oxide. Increased porosity increases the corrosion resistance of 316L. The distribution of pores and surface geometries are important parameters. Since the open pore structure facilitates the transfer of oxygen, it allows the formation of a passive layer. Their high hardness makes Titanium and its alloys more advantageous in applications (Mariotto et al., 2011; Matassi et al., 2013).

Magnesium

Magnesium is an important material in biomedical applications for bone. It is essential for human nutrition and bone health. Its biodegradability and compatibility of its mechanical properties with bone structure provides advantages for biomaterial applications. Thanks to its biodegradability, it will heal the tissue after it is placed and then it will be absorbed or expelled from body. Thus, no secondary operation is required. In addition, low temperature required for the preparation of porous magnesium and less use of spacing agents required are other advantages. However, porous magnesium is not preferred much because of its corrosion resistance inadequate in vitro, multiple phases in its structure and insufficient porosity (Zhuang et al., 2008; Zhou et al., 2017; Qin et al., 2015).

Co-Cr alloys

CoCr alloys are preferred metals as implants thanks to their inertness and wear resistance. It is preferred in applications such as acetabular cup, femoral stems or total knee arthroplasty components that require abrasion resistance. However, when tissue ingrowth is examined, a small fibrous ingrowth is observed. This may prevent long-lasting application. In addition, CoCr based alloys contain high amounts of Ni. This can cause allergies. Instead of Ni, alloys containing Mo should be preferred (Cömert, 2005; Matassi et al., 2013).

Tantalum

Tantalum is a new remarkable biomaterial compared to other metals. Thanks to its biocompatibility and suitable biomechanical properties, it has potential in biomedical applications. It is preferred because it has high friction resistance, low elastic modulus and can be produced as highly porous (George and Nair, 2018). Studies have shown that despite its high porous structure, it is resistant to physiological loads and can support bone ingrowth even under these conditions. In addition, it is more resistant to corrosion than titanium, which is more often preferred in biomedical applications. However, the production cost is higher. In-vitro studies, better extracellular matrix formation and advanced cell adherence and growth in tantalum were observed (Matassi et al., 2013).Nowadays, it is used in many orthopedic applications such as total hip (acetabular component) and knee implants (patellar component), foot and ankle surgery and spine fusion implant etc. (Matassi et al., 2013; George and Nair, 2018). Despite its superior advantages, it has very high melting temperature (2996 ^{o}C) and high affinity to oxygen; these are limiting its production and methods to be used (Qin et al., 2015).In total hip arthroplasty (THA) operations, the life of the implant depends on many factors such as design and production process, surface structure and bone integration features. Tantalum is ideal for this application and tantalum acetabular components can be found in three forms: a monoblock acetabular component with direct compression molded polyethylene, a monoblock acetabular cup with peripheral screw fixation, and a modular acetabular component coated with porous tantalum framework (George and Nair, 2018). Figure 3, Shows the porous tantalum monoblock acetabular component for use in total hip implants. Osteonecrosis of the hip occurs when there is a blood flow problem in the head of the femoral bone. Since sufficient nourishment does not occur, the head of bone cannot be fed and dies and collapses over time. As a result, the articular cartilage covering the hip bones also collapses, leading to disabling arthritis (Foran and Miller, 2018). Figure 4 shows tantalum implant commonly used to prevent the early stages of this disease. It is thought that porous tantalum improves transportation of nutrient thanks to its close to bone mechanical properties and porous structure and also supports bone formation (George and Nair, 2018).



Figure 3. Tantalum monoblock acetabulum (George and Nair, 2018)



Figure 4. Osteonecrosis implant (George and Nair, 2018)

Porous tantalum is also preferred in cervical and lumbar spine surgeries. Previous research has shown that the use of porous Ta in implant applications for the spine provides advantages in many aspects (George and Nair, 2018; Levine et al., 2006). The implants used in spine applications are shown in Figure 5.



Figure 5. Spine arthrodesis implants (George and Nair, 2018)

In addition, porous tantalum is also used in total knee arthroplasty. Currently, the parts used in this application are parts such as a monoblock tibial component, patella button. Thanks to the properties and advantages of tantalum mentioned in other applications, it also has a potential in this operation (George and Nair, 2018, Levine et al. 2006).



Figure 6. Monoblock tibia, revision TKA augments, and salvage patella button (George and Nair, 2018)

It is clear that tantalum has an important place in bone implant applications thanks to its properties. However, it seems necessary to do more studies and improve its properties such as adhesion properties and lifetime of implant (George and Nair, 2018).

Titanium and its alloys

Porous titanium is a material that is frequently used in biomaterial applications and it is achieved successful results. It is preferred due to its high chemical stability and mechanical properties. They are preferred because of their high chemical stability, mechanical properties, good biological compatibility with living tissue and their elastic modulus suitable with bone tissue (Matsushita et al., 2017; Xue et al., 2007). Although titanium foams are currently preferred as dental implants, they are used in total knee, hip and shoulder arthroplasty implants (Matassi et al., 2013). Figure 7 shows the femural and tibial components used in total knee surgery.

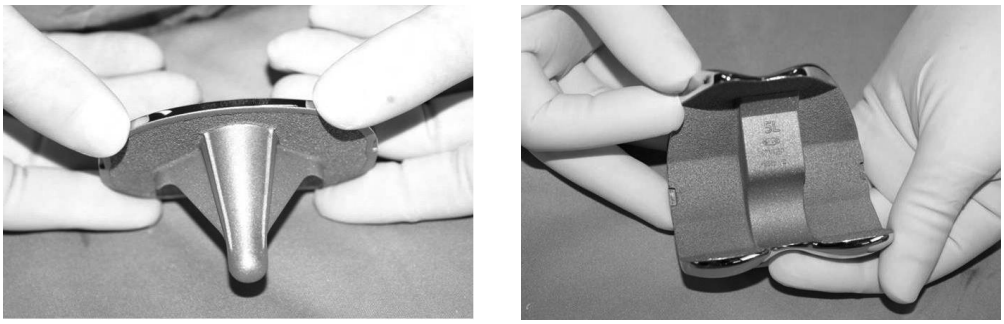

Figure 7. Porous titanium components; Tibial (left) and Femural (right) (Matassi et al., 2013)

Figure 8 shows the biofoam cancellous titanium developed by Wright Medical Technology. This component is used for treatment of the adult flatfoot deformity.

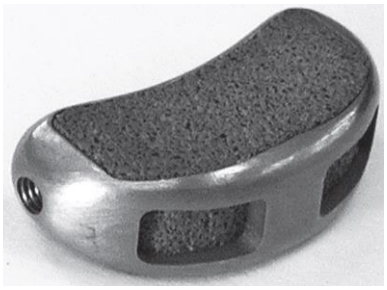

Figure 8. Porous titanium component used in treatment of the flatfoot deformity (Tucker,2010)

Figure 9 shows the bioactive titanium foam used for spinal interbody fusion. The component consists of titanium foam that produced with powder metallurgy technique placed in a dense frame.

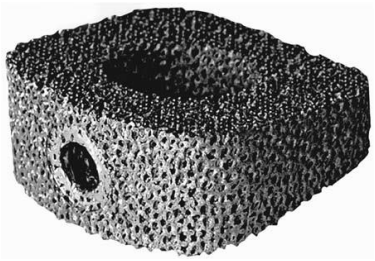

Figure 9. Titanium foam used for lumbar interbody fusion (Matsushita et al., 2017)

Thanks to the good osseointegration shown by metallic foams, one of the area is in dental implants where the most important potential. Figure 9 shows the implant developed by Zimmer Dental Inc. Thanks to the integration of the porous part of the implant with the mandible; the implant inserted in the place of the missing tooth gives better results (Nouri, 2017).

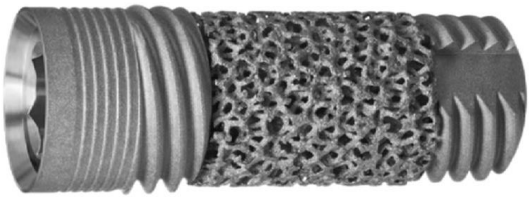

Figure 10. Dental implant developed by Zimmer Dental Inc. (Nouri, 2018)

CONCLUSION

Metallic foams are used in many areas and have significant potential in many areas thanks to their improvable properties. One of the most important areas of use is biomedical, thanks to the similarity of the pore structure to the structure of the cancellous bone. Many metals have been tested for use in this field from past to present. In this review the compatibility of the properties of metallic foams in bioimplant applications, the types of metallic foam used in the applications and the areas of use are mentioned. Especially tantalum and titanium foams have an important place in applications. However, it creates problems because its pore structure causes a decrease in corrosion resistance and causes ion release. For this reason, it is preferred as coating or regionally instead of completely porous structure. It is seen that the use of metallic foams will increase and become

indispensable in the field of biomaterials with the development of production methods and increasing the strength of the parts.

REFERENCES

Alhusseny ANM, Nasser A, Al-zurfi NMJ 2017. High-Porosity Metal Foams: Potentials, Applications, and Formulations, Porosity - Process, Technologies and Applications, IntechOpen, pp. 181-200.

Banhart J 2001. Manufacture, characterisation and application of cellular metals and metal foams, Progress in Materials Science, 46: 559–632.

Beköz N 2011. Microstructural and mechanical properties of iron based foamed metals obtained by powder metallurgy method, Doctoral Thesis, Istanbul University.

Cömert I 2005. Using powder metallurgy process on applications of the biomaterials, Master's Thesis, Yıldız Technical University.

George N, Nair AB 2018. Porous tantalum: A new biomaterial in orthopedic surgery, Fundamental Biomaterials: Metals, 243-268.

Foran JRH, Miller MD 2018. Osteonecrosis of the Hip, Available at: https://orthoinfo.aaos.org/en/diseases--conditions/osteonecrosis-of-the-hip, [18.08.2020]

Joshi MG, Advani SG, Miller F, Santare MH 2000. Analysis of a femoral hip prosthesis designed to reduce stress shielding, Journal of Biomechanics, 33(12), 1655-1662.

Karageorgiou V, Kaplan D 2005. Porosity of 3D biomaterial scaffolds and osteogenesis. Biomaterials, 26: 5474–5491.

Kayacan MC, Delikanlı YE, Duman B, Özsoy K 2018. Examining of mechanical properties of transitive (variable) porous specimens produced by SLS using ti6Al4v alloy powder, Journal of the Faculty of Engineering and Architecture of Gazi University, 33(1):127-143.

Levine BR, Sporer S, Poggie RA, Valle CJD, Jacobs JJ 2006. Experimental and clinical performance of porous tantalum in orthopedic surgery, Biomaterials 27, 4671–4681.

Matassi F, Botti A, Sirleo L, Carulli C, Innocenti M 2013. Porous metal for orthopedics implants, Clinical Cases in Mineral and Bone Metabolism, 10(2): 111-115.

Matsushita T, Fujibayashi S, Kokubo T 2017. Titanium foam for bone tissue engineering, Metallic Foam Bone Processing, Modification and Characterization and Properties, 111-130.

Mutlu İ 2011. Microstructural and mechanical properties of porous martensitic stainless steel obtained by powder metallurgy method, Doctoral Thesis, Istanbul University.

Nouri A 2017. Titanium foam scaffolds for dental applications, Metallic Foam Bone Processing, Modification and Characterization and Properties, 131-160.

Tucker DJ 2010. Lateral Column Lengthening in Adult Flatfoot Surgery Using a Titanium Metal Foam Wedge Implant, Techniques in Foot & Ankle Surgery, 9(4), 205-210.

Qin J, Chen Q, Yang C, Huang Y 2016. Research process on property and application of metal porous materials, Journal of Alloys and Compounds, 654, 39-44.

Wen CE, Mabuchi M, Yamada T, Shimojima K, Chino Y, Asahina T 2001. Processing of biocompatible porous Ti and Mg, Scripta Materialia 45:1147-1153.

Wu S, Liu X, Yeung KWK, Liu C, Yang X 2014. Biomimetic porous scaffolds for bone tissue engineering, Materials Science and Engineering R 80:1–36.

Xue W, Krishna BV, Bandyopadhyay A, Bose S 2007. Processing and biocompatibility evaluation of laser processed porous titanium, Acta Biomaterialia 3: 1007–1018.

Zhuang H, Han Y, Feng A 2008. Preparation, mechanical properties and in vitro biodegradation of porous magnesium scaffolds, Materials Science and Engineering: C, 28(8), 1462-1466.