Fabrication and surface modification of porous titanium alloy scaffolds for biomedical applications

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ABSTRACT

In recent years the development of porous metal materials for metal implants can be described in terms of considerable to breakthrough, and our experiment used the TiMo alloy which have very biological activity and low elastic modulus as a starting blueprint and used the method of the removing space holder to make porous TiMo scaffolds. Because the ammonium bicarbonate (NH4HCO3) has a characteristics witch is low melting point so it's easily to removal at low temperature, as a result of selecting it as the pore-forming agent. At experimental begining, we try to ball milling Ti and Mo element powders to get homogeneous, and after ball milling to t9, we observed the powders which have homogeneous by the backscattered electrons microscopy, so used this group to make the TiMo porous scaffold, but the results show that the compressive strength is extremely vulnerable due to the titanium metal powder ball milled at atmospheric environment has a oxidation of 45 wt%, which led it can't has a well sinterability, so follow-up of this trial will be non-ball milling Ti and Mo powders to made porous scaffold by the blended elemental method. In this experiment, we used different amount of pore-forming agent to make porous scaffolds which were 40, 50, 60, 70 and 80 vol%, as we know, the compressive strength will be declining with increasing porosity, so coordinate the results of the compressive strength, we choosed the dosage of 60% of the porous TiMo scaffolds for the follow-up application of surface modification, because it's compressive strength was 127 MPa and elastic modulus was 4.21 GPa, which were fitted to applied for cortical bone implant materials. In order to investigate the impact of holes for the apatite formation, so we used a solid TiMo as a control group. After the surface modification (alkali and alkaline treatment) , we found that the sample surface had a network structure conformation. After analysis by high resolution X-ray diffraction (high resolution X-ray diffractometer, HR-XRD), it had showed a sodium titanate hydrogel layer(Na2Ti6O13), and the results of soaking in the simulated body fluids (simulated body fluid, SBF) 14 days, it had showed the alkali and alkaline treatment of the porous TiMo had been covered with apatite inside the holes, but the size of the apatite of alkali treatment had large more. Until 21 days, no matters the porous inside and outside that the apatite were be covered, but the solids were still had no good result. And we didn't find the apatite formation on the porous TiMo which were no any treatments after 21 days.

Keywords : Powder metallurgy、Porous titanium、Mechanical properties、Surface modification、Simulated body fluid (SBF)

Table of Contents

REFERENCES

[1]Inglis A.E.,“ Advances in implant arthroplasty in the upper extremity, circa1988 ”, Clinical and Experimental Rheumatology 7:141-144, 1989.

[2]Paul R.,“ Alkaline aqueous electrolyte cell for biomedical application ”, Journal of the Electrochemical Society 127:1667-1678, 1980.

[3]Dressman H.,“ Uber knochenplombierun ”, Beitr Klin Chir 9: 804-810, 1892.

[4]Albee F.H. and Morrison H.,“ Studies in Bone Growth: Triple Calcium Phosphate As A Stimulus To Osteogenesis ”, Annals of Surgery 71: 32-39, 1920.

[5]Vincenzini P.,“ Ceramics in sub-stitutive and reconstructive surgery ”, Elsevier Science Publishers B.V., 1991.

[6]Katthagen B.D.,“ Bone regeneration with bone substitutes ”, Springer-Verlag, Berlin, 1987.

[7]Wroblewski B.M.,“ 15-21 year results of the charnley low friction arthroplasty ”, Clin. Orthop 211: 30-35, 1986.

[8]Steflik D.E., McKinney R.V., Sisk A.L., Koth D.L., Singh B.B. and Parr G.R.,“ Ultrastructural investigations of the bone and fibrous connective tissue interface with endosteal dental implants ”, Scanning microscopy 4: 1039-1047, 1990.

[9]Bothe R.T., Beaton L.E. and Davenport H.A.,“ Reaction of bone to multiple metallic implants ”, Surg GynecoL Obstet 17:598-602, 1940.

[10]Leventhal G.S.,“ Titanium, a metal for surgery ”, Journal of Bone and Joint Surgery 33: 473-474, 1951.

[11]Steinemann S.G.,“ Titanium alloys as metallic biomaterials ”, Titanium Science and Technology 2, pp. 1327-1334, 1984.

[12]Slanina P., Frech W., Bernhardson A., Cedergren A. and Mattsson P.,“ Influence of dietary factors on aluminum adsorption and retention in brain and bone of rat ”, Aeta YharmacoL Toxicol 56: 331-336, 1985.

[13]Van Der Voet G.B., Marani E., Tio S. and De Wolff F.A.,“ Aluminum neurotoxicity, Histo and Cyto-Chemist W as a Tool in Environmental Toxicology ”, Fisher, Stuttgart, pp. 235-242, 1991.

[14]Wang K.,“ The use of titanium for medical applications in the USA ”, Materials Science and Engineering A 213: 134-7, 1996.

[15]Park, J.B., Hetherington V.J., Park, S.H., Carnett, J.A., Patterson, B.A., Bratkiewicz, L. and Kessler, D.A.,“ Effects of Fibrin Sealant on the Fixation of Porous Titanium and Pyrolytic Carbon Implants ”, Journal of Foot Surgery 28: 145-150, 1989.

[16]Park J.B., Lakes R.S.,“ Biomaterials an Introduction 2nded ”. Plenum Press, New York, pp. 2-3, 1992.

[17]Dunand D.C.,“ Processing of titanium foams ”, Advanced Engineering Materials 6: 369-76, 2004.

[18]Ryan G., Pandit A. and Apatsidis D.P.,“ Fabrication methods of porous metals for use in orthopaedic applications ”, Biomaterials 27:

2651-70, 2006.
[19]Sumner D.R. and Galante J.O.,“ Determinants of stress shielding: design versus materials versus interface ”, Clin Orthop and Relat Research 274: 202-12, 1992.
[20]Takao T., Hiroshi K., Akihiro F., Akinori S., Hiroshi K., and Toshitaka N.,“ Exposure of macrophage-like cells to titanium particles does not affect bone resorption, but inhibits bone formation ”, Journal of Orthopaedic Science 4: 32-8, 1999.
[21]Oh I. and Harris W.H.“ Proximal strain distribution in the loaded femur. An in vitro comparison of the distributions in the intact femur and after insertion of different hip-replacement femoral components ”, The Journal of Bone and Joint Surgery 60: 1 75-85, 1978.
[22]林殿傑，“鑄造鈦-鉭-鐵及鈦-鉭-鉻合金性質研究”，國立成功大學材料科學及工程學系博士論文，2002。
[23]Buly R.L.,“ Titanium wear debris in failed cemented total hip arthroplasty ”, Journal of Arthroplasty 7: 315-323, 1992.
[24]Lucas L.C., Lemons J.E. and Buchanan R.A.,“ Biocompatibility evaluations of Fe, Co and Ti base alloys ”, Transactions of the Annual Meeting of the Society for Biomaterials in Conjunction with the Interna 6: 65-69, 1983.
[25]Fukui H., Wei Y. and Morita A.,“ Study of biocompatible and high melting point Ti-Ta-Nb ternary alloys:development of a non-contaminating melting process ”, International Journal of Materials and Product Technology 16: 461-467, 2001.
[26]Ito A., Okazaki Y. and Tateishi T.,“ In vitro biocompatibility,mechanical properties, and corrosion resistance of Ti-Zr-Nb Ta-Pd and Ti-Sn-Nb-Ta-Pd alloys ”, Journal of Biomedical Materials Research 29: 893-899, 1995.
[27]Okazaki Y., Rao S., and Ho Y.,“ Corrosion resistance,mechanical properties, corrosion fatigue strength and cytocompatibility of new Ti alloys without AI and V ”, Biomaterials 19: 1197-1215, 1998.
[28]Ho W.F., Ju C.P. amd Lin J.H.,“ Structure and properties of cast binary Ti-Mo alloys ”, Biomaterials 20: 2115-2122, 1999.
[29]陳建清，“探討多國籍企業子公司策略角色之演變與發展-以粉末冶金超硬合金泰登公司為例”，國立中央大學企業管理研究所，2003。
[30]Tih W.H. and Wang C.T.,“ Tungsten: Source ”, Metallurgy Properties and Applications Plenum Press, New York, pp. 335-338, 358-362, 1979.
[31]Lenel, F.V.,“ Powder Metallurgy Principal and Application ”, Metal Powder Industries Federation, New Jersey, pp. 337-348, 1980.
[32]劉文海，“鋁基複合材料於活塞之應用動向”，金屬中心ITIS 計畫，2008。
[33]Price P.E. and Kohler S.P.,“ Hot isostatic pressing of metal powders ”, American Society for Testing of Materials, Ohio, pp. 419-443, 1988.
[34]Schubert Th., Trindade B., Wei?慊 arber T. and Kieback B.,“ Interfacial design of Cu-based composites prepared by powder metallurgy for heat sink applications ”, Materials Science and Engineering A 475: 39-44, 2008.
[35]Froes F.H. and Smngeresky J.E.,“ Proceedings of TMS-ALME Symposium ”, Las Vegas, p. 175, 1980.
[36]Weimer G.A.,“ Core crushing: a problem in big bearing design ”, Iron Age 221: 70-71, 1978.
[37]Narasimhan K.S.,“ Sintering of powder mixtures and the growth of ferrous powder metallurgy ”, Materials Chemistry and Physics 67: 56-65, 2001.
[38]Abbasi C.V., Madaah H.H.R. and Nofar M.,“ Micro structural features and mechanical properties of Al – Al3Ti composite fabricated by in – situ powder metallurgy route ”, Journal of Alloys and Compounds 473: 127-132, 2009.
[39]Froes F.H., Eylon D.,“ Powder metallurgy of titanium alloys ”, International Materials Reviews 35, pp. 161-182, 1990.
[40]Abkowitz S. and Weithraum P.,“ Trimming the cost of MMCs ”, Advanced Materials and Processes 136, pp. 31-34, 1989.
[41]Saito T. and Furuta T.,“ Proceedings of 1993 Powder Metal World Conference ”, JPMA-JSPM, pp. 606-609, 1993.
[42]Scott Weil K., Nyberg E. and Simmons K.,“ A new binder for powder injection molding titanium and other reactive metals ”, Journal of Materials Processing Technology 176: 205-209, 2006.
[43]Rak Z.S. and Walter J.,“ Porous titanium foil by tape casting technique ”, Journal of Materials Processing Technology 175:358-363, 2006.
[44]Hanson A.D., Runkle J.C., Widmer R. and Hebeissen J.C.,“ Titanium near net shapes from elemental powder blends ”, International Journal of Powder Metallurgy 26: 157-164, 1990.
[45]Froes F.H.,“ Producing titanium aerospace components from powder using laser forming ”, Journal of the Minerals Metals and Materials Society 52: 28-30, 2000.
[46]Froes F.H. and Eylon D.,“ Titanium Powder Metallurgy-A Review ”, Titanium Net Shape Technologies, pp. 1-20, 1984.
[47]Coolidge W.D.,“ Production of refractory conductors ”, U.S. Patent No. 41913, 1908.
[48]陳克紹，“粉末冶金概論”，全華科技圖書股份有限公司，台灣，1985。
[49]Froes F.H., Suryanarayana C., Krishnamurthy S. and Kim Y.W.,“ Development of light alloys by rapid solidification processing ”, International Journal of Powder Metallurgy 26: 117, 1990.
[50]Liu Y., Chen L.F., Tang H.P., Liu C.T., Liu B. and Huang B.Y.,“ Design of powder metallurgy titanium alloys and composites ”, Materials Science and Engineering A 418: 25-35, 2006.
[51]Park J., Toaz M.W., Ro D.H. and Aqua E.N.,“ Blended Elemental Powder Metallurgy of Titanium Alloys ”, Titanium Net Shape Technologies, p. 95, 1984.
[52]Tamirisakandala S., Bhat R.B., Ravi V.A. and Miracle D.B.,“ Powder metallurgy Ti-6Al-4V-xB alloys: Processing, microstructure, and

properties ”, Journal of the Minerals, Metals and Materials Society 56: 60-63, 2004.
[53]Benjamin J.S.,“ Mechanical alloying ”, Scientific American 234: 40-57, 1976.
[54]Koch C.C., Cavin O.B., McKamey C.G. and Scarbrough J.O.,“ Preparation of amorphous Ni60Nb40 by mechanical alloying ”, Applied Physics Letters 43, p. 1017, 1983.
[55]Suryanarayana C. and Froes F.H.,“ Mechanical Alloying of Titanium-Base Alloys ”, Advanced Materials 5: 96-106, 1993.
[56]Wen C.E., Yamada Y. and Hodgson P.D.,“ Fabrication of novel TiZr alloy foams for biomedical applications ”, Materials Science and Engineering C 26: 1439-1444, 2006.
[57]Wen C.E., Kobayashi K., Sugiyama A., Nishio T. and Matsumoto A.,“ Synthesis of nanocrystallite by mechanical alloying and in situ observation of their combustion phase transformation in Al3Ti ”, Journal of Materials Science 35: 2099-2105, 2000.
[58]張尚偉，以機械合金法合成鐵鈮非晶質合金粉末之研究，私立逢甲大學材料科學學系，2000。
[59]蘇英源，“ 粉末冶金學 ”，全華科技圖書股份有限公司，台灣，2001。
[60]ASM Handbook,“ Properties and Selection: Nonferrous Alloys and Special-Purpose Materials ”, The Materials Information Society, USA, p. 586-657, 1990.
[61]Ouchi C., Iizumi H. and Mitao S.,“ Effects of ultra-high purification and addition of interstitial elements on properties of pure titanium and titanium alloy ”, Materials Science and Engineering A 243: 186-195, 1998.
[62]Haman J.D., Boulware A.A., Lucas L.C., Crawmer D.E. and Therm J.,“ High-velocity oxyfuel thermal spray coatings for biomedical applications ”, Journal of Thermal Spray Technology 4:179-184, 1995.
[63]Haman J.D., Chittur K.K., Crawmer D.E., Lucas L.C. and Biomed J.,“ Analytical and mechanical testing of high velocity oxy-fuel thermal sprayed and plasma sprayed calcium phosphate coatings ”, Journal of Biomedical Materials Research Part B: Applied Biomaterials 48: 856-860, 1999.
[64]Bowers K.T., Keller J.C., Randolph B.A., Wick D.G. and Michaels C.M.,“ Optimization of surface micromorphology from enhanced osteoblast response in vitro ”, Int J Oral Maxillofac Implants 7: 302-10, 1992.
[65]Groessner-Schereider B. and Tuan R.S.,“ Enhanced extracellular matrix production and mineralization by osteoblasts cultured on titanium surfaces in vitro ”, Journal of Cell Science 101: 209-17, 1992.
[66]Schwartz Z. and Boyan B.D.,“ Underlaying mechanisms at the bone biomaterial interface ”, Journal of Cellular Biochemistry 56: 340-7, 1994.
[67]Boyan B.D., Hummert T.W., Kieswetter K., Schraub D., Dean D.D. and Schwartz Z.,“ Effect of titanium surface characteristics on chondrocytes and osteoblasts in vitro ”, Cell Mater 5: 323-35, 1995.
[68]Martin J.Y., Schwartz Z., Hummert T.W., Schraub D.M., Simpson J., Lankford J., Dean D.D., Cochran D.L. and Boyan B.D.,“ Effect of titanium surface roughness on proliferation, differentiation and protein synthesis of human osteoblast-like cells (MG63) ”, Journal of Biomedial Materials Research 29: 389-401, 1995.
[69]Ong J.L., Prince C.W., Raikar G.N. and Lucas L.C.,“ Effect of surface topography of titanium on surface chemistry and cellular response ”, Implant Dent 5: 83-8, 1996.
[70]Deligianni D.D., Katsal N., Ladas S., Sotiropoulou D., Amedee J. and Missirlis Y.F.,“ Effect of surface roughness of the titanium alloy Ti – 6Al – 4V on human bone marrow cell response and on protein adsorption ”, Biomaterials 22: 1241 – 51, 2001.
[71]Schwartz Z., Lohmann C.H., Sisk M., Cochran D.L., Sylvia V.L., Simpson J., Dean D.D. and Boyan B.D.,“ Local factor production by MG63 ostoblast-like cells in response to surface roughness and 1,25-(OH)2D3 is mediated via protein kinase C- and protein kinase A-dependent pathways ”, Biomaterials 22: 731-41, 2001.
[72]Eylon D., Fujishiro S., and T. Kishi, Proceedings of Fifth International Symposium on Metallurgy and Technology of Practical Titanium Alloys, Tokyo, pp. 29-36, 1993.
[73]Maeda T., Onodera H., Watakabe S., Nakajima H., Ohyama H., Fuji H., Takahashi K., Fujishiro S., Eylon D. and Kishi T., Proceedings of Fifth International Symposium on Metallurgy and Technology of Practical Titanium Alloys, Tokyo, pp. 53-61, 1993.
[74]Haanappel V.A.C., Pe ’ rez P. and Stroosnijder M.F.,“ The effect of niobium on the oxidation behaviour of titanium in N2:20% O2 atmospheres ”, Materials Science and Engineering A 284: 26-137, 2000.
[75]Hanrahan R.J. and Butt D.P.,“ The Effects of Nitrogen on the Kinetics and Mechanisms of Oxidation of Titanium-Tantalum Alloys ”, Oxidation of Metals 48, pp. 41-58, 1997.
[76]Chaze A.M., Coddet C. and Be ’ ranger G.,“ Influence de l'aluminium sur la tenue ? l'oxydation du titane entre 550 et 750 ° C ”, Journal of the Less Common Metals 83: 49-70, 1982.
[77]Chaze A.M. and Coddet C.,“ Influence of silicon on the oxidation of titanium between 550 and 700 ° C ”, Oxidation of Metals 27: 1-20, 1987.
[78]Chaze A.M. and Coddet C.,“ Influence of chromium on the oxidation of titanium between 550 ° and 700 ° C ”, Oxidation of Metals 21: 205-231, 1984.
[79]Li Y.H., Chen R.B., Qi G.x., Wang Z.T. and Deng Z.Y.,“ Powder sintering of porous Ti – 15Mo alloy from TiH2 and Mo powders ”,

Journal of Alloys and Compounds 485: 215-218, 2009.
[80]Kaneko Y., Ameyama K. and Sakaguchi S.,“ Application of injection molding to Ti – 5 wt.% Co and Ti – 6 wt.% Al – 4 wt.% V mixed powders ”, Journal of the Japan Society of Powder and Powder Metallurgy 37: 591-598, 1990.
[81]Ciomek M.A., US Patent 5,064,463, 1991.
[82]Levenfeld B., Varez A. and Torralba J.M.,“ Effect of residual carbon on the sintering process of M2 high speed steel parts obtained by a modified metal injection molding process ”, Metallurgical and Materials Transactions A 33: 1843-1851, 2002.
[83]Grohowski J.A., Sherman B., Starus J.T., Lawcock R. and Wright M.,“ Advances in powder metallurgy and particulate materials ”, Metal Powder Industries Federation, Princeton, NJ, p.8, 273, 2003.
[84]Nyberg E.N., Simmons K.L. and Weil K.S.,“ Feedstock composition and method of using same for powder metallurgy forming of reactive metals ”, US Patent Pending 10/796,424, 2004.
[85]Weil K.S., Nyberg E., Simmons K.,“ A new binder for powder injection molding titanium and other reactive metals ”, Journal of Materials Processing Technology 176: 205-209, 2006.
[86]Kim J.C., Ryu S.S., Lee H. and Moon I.H.,“ Metal Injection Molding of Nanostructured W-Cu Composite Powder ”, International journal of powder metallurgy 35, p.47-55, 1999.
[87]Hwang K.S. and Tsou T.H.,“ Thermal Debinding of Powder Injection Molded Parts:Observations and Mechanisms ”, Metallurgical Transactions A 23, pp. 2775-2782, 1992.
[88]Zu Y.S. and Lin S.T.,“ Optimizing the Mechanical Properties of Injection Molded W-4.9%Ni-2.1%Fe in Debinding ”, Journal of Materials Processing Technology 71, pp. 337-342, 1997.
[89]Finn C.W.P.,“ Vacuum Binder Removal and Collection ”, International Journal of Powder Metallurgy 27, pp. 127-132, 1991.
[90]鄭文堡,“ 金屬粉末射出成型二維毛細吸附脫脂及飽和度之研究 ”, 國立中央大學機械工程研究所, 2002。
[91]Stoch A., Jastrzebski W., Brozek A., Stoch J., Szaraniec J., Trybalska B. and Kmita G.,“ FTIR absorption-reflection study of biomimetic growth of phosphates on titanium implants ”, Journal of Molecular Structure 555, pp. 375-382, 2002.
[92]Williams J.M. and Buchanan R.A.,“ Ion implantation of surgical Ti-6AI 4V ”, Materials Science and Engineering 69: 237-246, 1985.
[93]Dobbs H.S. and Scales J.T.,“ Behavior of commercially pure titanium and Ti-318 (Ti-6A1-4V) in orthopeadic implants ”, ASTM Special Technical Publication, 173-186, 1983.
[94]Ho W.F., Ju C.P. and Lin J.H.,“ Structure and properties of cast binary Ti-Mo alloys ”, Biomaterials 20: 2115-22, 1999.
[95]Moyen B.J., Lahey P.J., Weinberg E.H. and Harris W.H.,“ Effects on intact femora of dogs of the application and removal of metal plates ”, A metabolic and structural study comparing stiffer and more flexible plates. The Journal of Bone and Joint Surgery A 60:940-7, 1978.
[96]Uhthoff H.K. and Finnegan M.,“ The effects of metal plates on posttraumatic remodelling and bone mass ”, The Journal of Bone and Joint Surgery B 65: 66-71, 1983.
[97]Aydogmus T.L., Bor S.,“ Processing of porous TiNi alloys using magnesium as space holder ”, Journal of Alloys and Compounds 478: 705-710, 2009.
[98]金屬工業研究發展中心-www.mirdc.org.tw [99]Meneghini R.M., Ford K.S., McCollough C.H., Hanssen A.D., and Lewallen D.G.,“ Bone Remodeling Around Porous Metal Cementless Acetabular Components ”, The Journal of Arthroplasty, 2009.
[100]Werner S., Huck O., Frisch B., Vautier D., Elkaim R., Voegel J.C., Brunel G. and Tenenbaum H.“ The effect of microstructured surfaces and laminin-derived peptide coatings on soft tissue interactions with titanium dental implants ”, Biomaterials 30: 2291-2301, 2009.
[101]Shishkovsky I.,“ Stress – strain analysis of porous scaffolds made from titanium alloys synthesized via SLS method ”, Applied Surface Science 255: 9902-9905, 2009.
[102]Zheng Y., Yuan Q. and Yu H.,“ Synthesis of nanocrystalline Ti(C,N) powders by mechanical alloying and influence of alloying elements on the reaction ”, International Journal of Refractory Metals and Hard Materials 27: 121-125, 2009.
[103]Zheng Y., Yuan Q. and Yu H.,“ Mechanism of synthesizing nanocrystalline TiC in different milling atmospheres ”, International Journal of Refractory Metals and Hard Materials 27: 696-700, 2009.
[104]Wang H.T., Liu X.Q. and Chen F.L.,“ Kinetics and mechanism of a sintering process for macroporous alumina ceramics by extrusion ”, Journal of the American Ceramic Society 81: 781-4, 1998.
[105]Mao X., Wang S. and Shimai S.,“ Porous Ceramics with tri-modal pores prepared by foaming and starch consolidation ”, Ceramics Internation 34: 107-112, 2008.
[106]Yang H.S., Zhu Y.C., Li M.Q. and Lu Y.,“ Current situation and development of porous ceramic material ”, Journal of Jiamusi University 23: 1-88, 2005.
[107]Zhu X., Jiang D. and Tan S.,“ Preparation of silscon carbide reticulated porous ceramics ”, Materials Science and Engineering A 323: 232-238, 2002.
[108]Carpenter G.J.C., Wronski Z.S., Phaneuf M.W.,“ TEM study of nanopores and the embrittlent of CVD nickel foam ”, Materials Science and Technology 20: 1421-1426, 2004.
[109]Hollandera D.A., Walter M.V., Wirtz T., Sellei R., Bernhard S.R., Paar O. and Erli H.J.,“ Structural, mechanical and in vitro

characterization of individually structured Ti – 6Al – 4V produced by direct laser forming ” , Biomaterials 27: 955-963, 2006.
[110]Pattanayak D.K., Matsushita T., Doi K., Takadama H., Nakamura T. and Kokubo T., “ Effects of oxygen content of porous titanium metal on its apatite-forming ability and compressive strength ” , Materials Science and Engineering C 29: 1974-1978, 2009.
[111]Hong T.F., Guo A.Z.X. and Yang A.R., “ Fabrication of porous titanium scaffold materials by a fugitive filler method ” , Journal of Materials Science: Materials in Medicine 19: 3489-3495, 2008.
[112]Vasconcellos L.M.R., Oliveira M.V., M.L. Alencastro, Vasconcellos L.G.O., Carvalho Y.R. and Cairoc C.A.A., “ Porous Titanium Scaffolds Produced by Powder Metallurgy for Biomedical Applications ” , Materials Research 11: 275-280, 2008.
[113]Wen C.E., Chen X.B., Li Y.C., Plessis J.D. and Hodgson P.D., “ Influence of calcium ion deposition on apatite-inducing ability of porous titanium for biomedical applications ” , Acta Biomaterialia 5: 1808-1820, 2009.
[114]Otsuki B., Takemoto M., Fujibayashi S, Neo M., Kokubo T. and Nakamura T., “ Pore throat size and connectivity determine bone and tissue ingrowth into porous implants: Three-dimensional micro-CT based structural analyses of porous bioactive titanium implants ” , Biomaterials 27: 5892-5900, 2006.
[115]Zhang X.P., Li D.S., Zhang Y.P. and Eggeler G., “ High porosity and high-strength porous NiTi shape memory alloys with controllable pore characteristics ” , Journal of Alloys and Compounds 470: L1-L5, 2009.
[116]Zhang X.P., Zhang Y.P., Li D.S., “ Gradient porosity and large pore size NiTi shape memory alloys ” , Scripta Materialia 57:1020-1023, 2007.
[117]Wen C.E., Xiong J.Y., Li Y.C., Wang X.J. and Hodgson P.D., “ Titanium – nickel shape memory alloy foams for bone tissue engineering ” , Journal of the Mechanical Behavior of Biomedical Materials 269-273, 2008.
[118]Wen C.E., Xiong J.Y., Li Y.C., Wang X.J. and Hodgson P.D., “ Mechanical properties and bioactive surface modification via alkali-heat treatment of a porous Ti – 18Nb – 4Sn alloy for biomedical applications ” , Acta Biomaterialia 4: 1963-1968, 2008.
[119]Wen C.E., Wang X.J., Li Y.C., Xiong J.Y. and Hodgson P.D., “ Porous TiNbZr alloy scaffolds for biomedical applications ” , Acta Biomaterialia 5: 3616-3624, 2009.
[120]Stuppd S.I., Sargeant T.D., Guler M.O., Oppenheimer S.M., Mata A., Satcher R.L. and Dunand D.C., “ Hybrid bone implants: Self-assembly of peptide amphiphile nanofibers within porous titanium ” , Biomaterials 29: 161-171, 2008.
[121]Wang Y., Shen Y., Wang Z., Yang J., Liu N. and Huang W., “ Development of highly porous titanium scaffolds by selective laser melting ” , Materials Letters 64: 674-676, 2010.
[122]Walter M., Hollander D.A., Wirtz T., Sellei R., Bernhard S.R., Paar O., Erli H.J., “ Structural, mechanical and in vitro characterization of individually structured Ti-6Al-4V produced by direct laser forming ” , Biomaterials 27: 955-963, 2006.
[123]Koh Y.H., Lee J.H. and Kim H.E., “ Highly porous titanium (Ti) scaffolds with bioactive microporous hydroxyapatite/TiO2 hybrid coating layer ” , Materials Letters 63: 1995-1998, 2009.
[124]Weng J., Zhao J. and Lu X., “ Macroporous Ti-based composite scaffold prepared by polymer impregnating method with calcium phosphate coatings ” , Materials Letters 62: 2921-2924, 2008.
[125]Starly B., Parthasarathy J., Raman S. and Christensen A., “ Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM) ” , Journal of the Mechanical Behavior of Biomedical Materials 3: 249-259, 2010.
[126]Wen C.E., Mabuchi M., Yamada Y., Shimojima K., Chino Y. and Asahina T., “ Processing of biocompatible porous Ti and Mg ” , Scripta Materialia 45: 1147-53, 2001.
[127]Takemoto M., Fujibayashi S., Otsuki B., Matsushita T., Kokubo T. and Nakamura T., “ 3-D anallysis of pore structure of porous biomaterials using micro focus X-ray computed tomography ” , Bioceramics 18: 1095-8, 2006.
[128]Zhang X.P., Li D.S., Zhang Y.P., Ma X., “ Space-holder engineered porous NiTi shape memory alloys with improved pore characteristics and mechanical properties ” , Journal of Alloys and Compounds 474: L1-L5, 2009.
[129]Tzenov N.V. and Barsoum M.W., “ Synthesis and characterization of Ti3AlC2 ” , Journal of the American Ceramic Society 83: 825-832, 2000.
[130]Wang X.H. and Zhou Y.C., “ Microstructure and properties of Ti3AlC2 prepared by the solid – liquid reaction synthesis and simultaneous in-situ hot pressing process ” , Acta Mater 50: 3141-3149, 2002.
[131]Zhou A., Wang C. and Huang Y., “ A possible mechanism on synthesis of Ti3AlC2 ” , Materials Science and Engineering A 352: 333-339, 2003.
[132]Ge Z., Chen K., Guo J. and Zhou H., “ Combustion synthesis of ternary carbide Ti3AlC2 in Ti – Al – C system ” , The Journal of the European Ceramic Society 23: 567-574, 2003.
[133]Lopacinski M., Puszynski J. and Lis J., “ Synthesis of ternary titanium aluminum carbides using self-propagating high-temperature synthesis technique ” , Journal of the American Ceramic Society 84: 3051-3053, 2001.
[134]Wen C.E., Yamada Y. and Hodgson P.D., “ FABRICATION OF NOVEL METAL ALLOY FOAMS FOR BIOMEDICAL APPLICATIONS ” , National Institute of Advanced Industrial Science and Technology (AIST), Nagoya, 463-8560, 2005.
[135]Wen C.E., Wang X.J., Li Y.C., Xiong J.Y. and Hodgson P.D., “ Porous TiNbZr alloy scaffolds for biomedical applications ” , Acta

Biomaterialia 5: 3616-3624, 2009.
[136]Wen C.E., Xiong J.Y., Li Y.C., Wang X.J. and Hodgson P.D., " Mechanical properties and bioactive surface modification via alkali-heat treatment of a porous Ti – 18Nb – 4Sn alloy for biomedical applications " , Acta Biomaterialia 4: 1963-1968, 2008.
[137]Cameron J.R., Skofronick J.G. and Grant R.M., " Physics of the Body. 2nd ed. Madison " , Medical Physics Publishing: 182, 1999.
[138]Martin R.B., Burr D.B. and Sharkey N.A., " Skeletal tissue mechanics " , New York: Springer, pp. 127-141, 1998.
[139]Wen C.E., Chen X.B., Li Y.C. and Hodgson P.D., " Microstructures and bond strengths of the calcium phosphate coatings formed on titanium from different simulated body fluids " , Materials Science and Engineering C 29: 165-171, 2009.
[140]Gibson L.J., " The mechanical behaviour of cancellous bone " , Journal of Biomechanics 18: 317-328, 1985.
[141]Wen C.E., Chen X.B., Li Y.C. and Hodgson P.D., " The importance of particle size in porous titanium and nonporous counterparts for surface energy and its impact on apatite formation " , Acta Biomaterialia 5: 2290-2302, 2009.
[142]Wen C.E, " Synthesis of Ti-Sn-Nb alloy by powder metallurgy " , Materials Science and Engineering A 485: 562-570, 2008.
[143]Zhou J.B. and Rao K.P., " Structure and morphology evolution during mechanical alloying of Ti – Al – Si powder systems " , Journal of Alloys and Compounds 384: 125-130, 2004.
[144]Lu L. and Lai M.O., " Mechanical Alloying " , Kluwer Academic Publishers, Boston, MA, 1998.
[145]Kokubo T. and Takadama H., " How useful is SBF in predicting in vivo bone bioactivity? " , Biomaterials 27: 2907-2915, 2006.
[146]Zhang Y., Wei X.Y., Mao C.H., Li T.F., Yuan P. and Du J., " Preparation and pumping characteristics of Ti – 7.5 wt.%Mo getter " , Journal of Alloys and Compounds 485: 200-203, 2009.
[147]Wisutmethangoona S., Denmud N. and Sikong L., " Characteristics and compressive properties of porous NiTi alloy synthesized by SHS technique " , Materials Science and Engineering A 515: 93-97, 2009.
[148]Masaki U., Kim H.M., Tadashi K., Shunsuke F. and Takashi N., " Effect of Water Treatment on the Apatite-Forming Ability of NaOH-Treated Titanium Metal " , Journal of Biomedical Materials Research Part B 63, pp. 522-530, 2002.
[149]Kokubo T., Miyaji F., Kim H.M. and Nakamura T., " Spontaneous formation of bonelike apatite layer on chemically treated titanium metals " , Journal of the American Ceramic Society 79: 1127-1129, 1996.
[150]Kim H.M., Miyaji F., Kokubo T. and Nakamura T., " Apatite-forming ability of alkali-treated Ti metal in body environment " . Journal of the ceramic Society of Japan 105: 111-116, 1997.
[151]Wen C.E., Xiong J.Y., Li Y.C., Wang X.J. and Hodgson P., " Mechanical properties and bioactive surface modification via alkali-heat treatment of a porous Ti – 18Nb – 4Sn alloy for biomedical applications " , Acta Biomaterialia 4: 1963-1968, 2008.