Effect of ball milling on properties of porous titanium alloy for biomedical applications

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ABSTRACT

The most commonly used porous metal material in studies of recent years refers to titanium and its alloys, because titanium and its alloys have excellent biocompatibility, biological activity, and lower elastic modulus. As a result, titanium and its alloys have been widely used in biomedical materials. The purpose of the experiment is to achieve an amorphous alloy powder between pure elements Ti and Mo powders within the TiMo alloy system through mechanical alloying (MA). Ammonium bicarbonate (NH4HCO3) was used as the pore-forming agent for this study, and the reason being ammonium bicarbonate is characterized by its low melting point, which makes removal easier. The milling time of the experiment was set respectively as 3, 15, and 30, which were represented as BM3, BM15, and BM30 respectively. Back electron microscope showed that powder did not reach homogenization after treatment in BM3, and homogenization was only reached after BM15 and BM30 treatment. Ball-milled alloy powder was then used for making porous TiMo scaffold. It then underwent vacuum sintering in a vacuum heat treatment furnace at a vacuum of D1 Pa, sintering temperature of up to A1 °C that last for B1, B2, B3 and B4 hours. In the XRD phase analysis, the porous TiMo alloy showed no sign of any pure element of titanium and molybdenum after different sintering stage. During this time it would also produce a new alloy phase β-(Ti, Mo). In terms of compressive strength, porous TiMo scaffolds of B1, B2, B3 and B4 hours were already produced under different holding temperatures. The results showed that an increase of sintering time can help to improve the compressive strength of porous TiMo scaffold. In working with the compressive strength results, the experiment then selected the alloy powder of BM15 and the porous samples sintered for B1 hours as the follow-up study on surface modification. Therefore, the group conditions of compressive strength and elastic modulus were 25.02 MPa, and 1.72 GPa respectively, very suitable for the application as an implant material for cancellous bones. Also in the pore size distribution, the majority of them are 100-200 μm for porous samples of different milling time and different sintering stages; but after BM30 treatment, the powder particle size distribution tends to be more uniform, leading to the existence of gaps between powders after compression molding, which in turn affects the pore size differences. Therefore, we can clearly see a visibly increased number of above 400 μm aperture in BM30 treated porous samples. After surface modification (alkali treatment and alkali water treatment) of porous samples, it was found that a mesh-like porous structure will form on specimen surface, which was identified as Na2Ti6O13 (sodium titanate hydrogel) using HR-XRD analysis. Through FE-SEM observations, it was found that alkaline water treatment produces mesh of smaller pore size than the alkali treatment. However, in order to observe the effects of pores on formation of apatite, solid specimens were used as control group. Thereafter, both solid and porous specimens were soaked in simulated body fluid (SBF). The results showed that apatite has already begun to form inside the pores in porous specimens with alkali and alkali water treatments after SBF-14 days of immersion. In the follow-up observation of 21 days immersion, it was found that on porous specimens with alkali and alkali water treatments, both inside and outside the pores was covered in apatite, although no noticeable results were seen for the solid part. But the follow-up EDS analysis revealed extremely high content of Ca and P in both alkaline and alkaline water treatments. This result showed that porous TiMo scaffolding has a better bioactivity after surface modification in terms of porous implant material.

Keywords : mechanical alloying、porous titanium alloy、porous metal materials、powder metallurgy、mechanical properties、surface modification、biocompatibility、biological activity

Table of Contents

REFERENCES

[1]Helmus MN, Tweden K, Materials selection Encyclopedic Handbook of Biomaterials and Bioengineering. Part A: Materials 1(1):27-59, 1995.
[2]Suchanek W, Yoshimura M, Processing and properties of hydroxyapatite-based biomaterials for use as hard tissue replacement implants. Journal of Materials Research 13:94-117, 1998.
[3]Ratner B.D., Hoffman A.S, Schoen F.J. and Lemons J.E., in: Biomaterials Science: An Introduction to Materials in Medicine, AcademicPress, London, p.37, 1996.
[4]Wang K, The use of titanium for medical applications in the USA. Materials Science and Engineering A 213:134-137, 2006.
[5]Yamamuro M, Igarashi H, Katayama Y, Tsuganezawa T, Terashi A, Owan C, Three-Dimensional Anisotropy Contrast (3DAC) Magnetic Resonance Imaging of the HumanBrain: Application to Assess Wallerian Degeneration. Internal Medicine 37:662-668, 1998.
[6]Hierholzer S, Hierholzer G, Sauer KH, Paterson RS, Increased corrosion of stainless steel implants in infected plated fractures. Archives of Orthopaedic and Trauma Surgery 102(3):198-200, 1984.
[7]Rae T, The action of cobalt, nickel and chromium on phagocytosis and bacterial killing by human polymorphonuclear leucocytes; its relevance to infection after total joint arthroplasty. Biomaterials 4(3):175-180, 1983.
[8]Andriano KP, Tabata Y, Ikada Y. Heller J, In vitro and in vivo comparison of bulk and surface hydrolysis in absorbable polymer scaffolds for tissue engineering. Journal of Biomedial Materials Research 48(5):602-612, 1999.
[9]Steflik DE, McKinney RV, Sisk AL, Parr GR, Koth DL, Scanning electron microscopic studies of the oral tissue responses to dental implants.

Department of Oral Pathology, Medical College of Georgia School of Dentistry 4(4):1021-1037, 1990.
[10]王盈錦, 林峰輝, 胡孝光 等編著, 生物醫學材料, 國立編譯館, 1992.
[11]Collings EW, In vitro apatite formation on chemically treated (P/M) Ti-13Nb-13Zr. Dental Materials 24(1):50-56, 1984.
[12]Liu X, Chu PK, Ding C, Surface modification of titanium, titanium alloys, and related materials for biomedical applications. Materials Science and Engineering Reports 47:49-121, 2004.
[13]Okazaki Y, Ito Y, Kyo K, Corrosion resistance and corrosion fatigue strength of new titanium alloys for medical implants without V and Al. Materials Science and Engineering 213:138-147, 1996.
[14]Kawahara H, Cytotoxicity of implantable metals and alloy. Bulletin of the Japan Institute of Metals 31:1033-1039, 1992.
[15]Zhentao Y, Lian Z, Influence of martensitic transformation on mechanical compatibility of biomedical type titanium alloy TLM. Materials Science and Engineering A 438-440:391-394, 2006.
[16]Okazaki Y, Ito Y, Ito A, Tateishi T, New titanium alloys to be considered for medical implants. In: Brown SA, Lemons JE, editors. Medical applications of titanium and its alloys: The Material and Biological Issues. West Conshohocken, PA:ASTM, pp.45-59, 1996.
[17]Nouri A, Chen XB, Hodgson PD, Wen CE, Preparation and characterisation of new titanium based alloys for orthopaedic and dental applications. Advances in Materials Research 15-17:71-76, 2007.
[18]Pypen CMJM, Dessein K, Helsen JA, Gomes M, Leenders H, Bruijn JD, Comparison of the cytotoxicity of molybdenum as powder and as alloying element in a niobium – molybdenum alloy. Journal of Materials Science Materials in Medicine 9:761-765, 1998.
[19]Kujala S, Ryhanen J, Danilov A, Tuukkanen J, Effect of porosity on the osteointegration and bone ingrowth of a weight-bearing nickel-titanium bone graft substitute. Biomaterials 24:4691-4697, 2003.
[20]Yang SF, Leong KF, Du ZH, Chua CK, The design of scaffolds for use in tissue engineering. Part 1. Traditional factors. Tissue Engineering 7:679-690, 2001.
[21]Gomes ME, Ribeiro AS, Malafaya PB, Reis RL, Cunha AM, A new approach based on injection moulding to produce biodegradable starch-based polymeric scaffolds: morphology, mechanical and degradation behaviour. Biomaterials 22:883-889, 2001.
[22]Wen CE, Yamada Y, Shimojima K, Chino Y, Asahina T, Mabuchi M, Processing and mechanical properties of autogenous titanium implant materials. Journal of Materials Science Materials in Medicine 13: 397-401, 2002.
[23]Fujibayashi S, Neo M, Kim H, Kokubo T, Nakamura T, Osteoinduction of porous bioactive titanium metal. Biomaterials 25:443-450, 2004.
[24]Wen CE, Mabuchi M, Yamada Y, Shimojima K, Chino Y, Asahina T, Processing of biocompatible porous Ti and Mg. Scripta Materialia 45:1147-1153, 2001.
[25]Wen CE, Yamada Y, Shimojima K, Chino Y, Hosokawa H, Mabuchi M, Novel titanium foam for bone tissue engineering. Journal of Materials Research 10:2633-2639, 2002.
[26]Wen CE, Yamada Y, Shimojima K, Chino Y, Hosokawa H, Mabuchi M, Compressibility of porous magnesium foam: dependency on porosity and pore size. Materials Letters 58:357-360, 2004.
[27]Livingston TL, Bioactive foam for bone tissue engineering: An in vivo study. University of Pennsylvania 1999.
[28]Hing K.A., Best S.M. and Bonefield W., " Characterization of porous hydroxyapatite ", Journal of Materials Science Materials in Medicine 10(3):135-145, 1999.
[29]De Oliverira JF, De Aguiar PF, Rossi AM, Soares GA, Effect of process parameters on the characteristics of porous calcium phosphate ceramics for bone tissue scaffolds. International Social Artificial Organs 27:406-411, 2003.
[30]Vamsi Krishna B, Bose S, Bandyopadhyay A, Low stiffness porous Ti structures for load-bearing implants. Acta Biomaterialia 3:997-1006, 2007.
[31]Plenk H, Prosthesis-Bone Interface. Journal Biomedical Materials Research (Applied Biomaterials) 43:350-355, 1998.
[32]Clemow AJT, Weinstein AM, Klawitter JJ, Koeneman J, Anderson J, Interface mechanics of porous titanium implants. Journal of Biomedial Materials Research 15:73-82, 1981.
[33]Evans FG, The mechanical properties of bone. Artificial Limbs 13:37-48, 1969.
[34]Wang XH, Zhou YC, Microstructure and properties of Ti3AlC2 prepared by the solid – liquid reaction synthesis and simultaneous in-situ hot pressing process. Acta Materialia 50:3141-3149, 2002.
[35]Gibson LJ, The Mechanical Behaviour of Cancellous Bone. Journal of Biomechanics 18:317-328, 1985.
[36]Ontanon M, Aparicio C, Ginebra MP, Planell J, in: M. Elices (Ed.), Structural Biological Materials. Design and Structure-Property Relationships, Pergamon Press, Oxford, pp.31-72, 2000.
[37]Takemoto M, Fujibayashi S, Neo M, Suzuki J, Kokubo T, Nakamura T, Mechanical properties and osteoconductivity of porous bioactive titanium. Biomaterials 26: 6014-6023, 2005.
[38]Cameron JR, Skofronick JG, Grant RM, Physics of the body. 2nd ed. Madison, WIMadison (WI): Medical Physics; 1999.
[39]Martin RB, Burr DB, Sharkey NA, Skeletal tissue mechanics. New York: Springer; 1998.
[40]Yang R, Guo ZX, Hong TF, Fabrication of porous titanium scaffold materials by a fugitive filler method. Journal of Materials Science Materials in Medicine 19:3489-3495, 2008.

[41]Biswas A, Porous NiTi by thermal explosion mode of SHS: processing, mechanism and generation of single phase microstructure. Acta Materialia 53:1415-1425, 2005.
[42]Li YH, Rong LJ, Li YY, Pore characteristics of porous NiTi alloy fabricated by combustion synthesis. Journal of Alloys and Compounds 325:259-262, 2001.
[43]Wen CE, Yamada Y, Hodgson PD, Fabrication of novel metal alloy foams for biomedical applications. Materials Forum Volume 29:274-278, 2005.
[44]Wang X, Li Y, Xiong J, Hodgson PD, Wen C, Porous TiNbZr alloy scaffolds for biomedical applications. Acta Biomaterialia 5:3616-3624, 2009.
[45]Wen CE, Xiong JY, Li YC, Wang XJ, Hodgson PD, Mechanical properties and bioactive surface modification via alkali-heat treatment of a porous Ti-18Nb-4Sn alloy for biomedical applications. Acta Biomaterialia 4:1963-8, 2008.
[46]Xiong JY, Li YC, Wang XJ, Hodgson PD, Wen CE, Titanium-nickel shape memory alloy foams for bone tissue engineering. Journal of the Mechanical Behavior of Biomedical Materials 1(3) 269-273, 2008.
[47]Li YH, Rong LJ, Li YY, Compressive property of porous NiTi alloy synthesized by combustion synthesis. Journal of Alloys and Compounds 345:271-274, 2002.
[48]Li YH, Chen RB, Qi GX, Wang ZT, Deng ZY, Powder sintering of porous Ti-15Mo alloy from TiH2 and Mo powders. Journal of Alloys and Compounds 485:215-218, 2009.
[49]Nouri A, Hodgson PD, Wen CE, Effect of Process Control Agent on the Porous Structure and Mechanical Properties of a Biomedical Ti-Sn-Nb Alloy Produced by Powder Metallurgy. Acta Biomaterialia 6:1630-1639, 2010.
[50]Wen CE, Yamada Y, Shimojima K, Sakaguchi Y, Chino Y, Hosokawa H, Novel titanium foam for bone tissue engineering. Journal of Materials Research 17:2633-2639, 2002.
[51]M?剕ller FA, Bottino MC, M?剕ller L, Henriques VAR, Lohbauere U, Bressiani AHA, Bressiani JC, In vitro apatite formation on chemically treated (P/M) Ti-13Nb-13Zr, Dental Materials 24: 50-56, 2008.
[52]Zhu SL, Yang XJ, Fu DH, Zhang LY, Li CY, Cui ZD, Stress-strain behavior of porous NiTi alloys prepared by powders sintering. Materials Science and Engineering A 408:264-268, 2005.
[53]Li BY, Rong LJ, Li YY, The influence of addition of TiH2 in elemental powder sintering porous Ni-Ti alloys. Materials Science and Engineering A 281:169-175, 2000.
[54]L?厎jering G, Williams JC, Titanium. Berlin:Springer-Verlag 2003.
[55]Park JB, Lakes RS, Biomaterials: An introduction. New York: Plenum press, 1994.
[56]Wang XJ, Li YC, Hodgson PD, Wen CE, Nano-and macro-scale characterisation of the mechanical properties of bovine bone. Materials Forum 31:156-159, 2007.
[57]Heinl P, M?剕ller L, K?宁ner C, Singer RF, M?剕ller FA, Cellular Ti-6Al-4V structures with interconnected macro porosity for bone implants fabricated by selective electron beam melting. Acta Biomaterials 4: 1536-1544, 2008.
[58]Lopez-Heredia MA, Sohier J, Gaillard C, Quillard S, Dorget M, Layrolle P, Rapid prototyped porous titanium coated with calcium phosphate as a scaffold for bone tissue engineering. Biomaterials 29:2608-2615, 2008.
[59]Ishizaki K, Komarneni S, Nanko M, Porous Materials: Process Technology and Applications. Materials Technology Series Kluwer Academic Publishers pp.56-65, 1998.
[60]Oh IK, Nomura N, Masahashi N, Hanada S, Mechanical properties of porous titanium compacts prepared by powder sintering. Scripta Materialia 49:1197-1202, 2003.
[61]Taddei BE, Henriques VAR, Silva CRM, Properties of Porous Ti-35Nb-7Zr-5Ta Processed by the Spacer Method for Use in Biomedical Applications. Materials Science Forum Vol 591-593, pp.224-234, 2008.
[62]Dunand DC, Processing of Titanium Foams. Advanced Engineering Materials 6(6):369-376, 2004.
[63]Li Y.H., Rao G.B., Rong L.J., Li Y.Y. and Ke W., " Effect of pores on corrosion characteristics of porous NiTi alloy in simulated body fluid ", Materials Science and Engineering A 363:356-359, 2003.
[64]Li H, Yuan B, Gao Y, Chung CY, Zhu M, High-porosity NiTi superelastic alloys fabricated by low-pressure sintering using titanium hydride as pore-forming agent. Journal of Materials Science 44:875-881, 2009.
[65]Steinemann SG, Evaluation of Biomaterials, edited by Winter GD, Leray JL, Groot de K (Wiley, New York) pp.1-3310, 1980.
[66]Okazaki Y, Rao S, Ito Y, Tateishi T, Corrosion resistance, mechanical properties and cytocompatibility of new Ti alloys without Al and V. Biomaterials 19:1197-1215, 1998.
[67]Niinomi M, Fatigue performance and cyto-toxicity of lowrigidity titanium alloy Ti-29Nb-13Ta-4.6Zr. Biomaterials 24:2673-2683, 2003.
[68]Kasuga T, Nonami M, Niinomi M, Hattori T, Bioactive calcium phosphate invert glass-ceramic coating on β-type Ti-29Nb-13Ta-4.6Zr alloy. Biomaterials 24:283-290, 2003.
[69]Okazaki Y, Effect of friction on anodic polarization properties of metallic biomaterials. Biomaterials 23:2071-2077, 2002.
[70]Inoue A, Stabilization of metallic supercooled liquid and bulk amorphous alloys. Acta Materialia 48:279-306, 2000.

[71]Ma E, Amorphization in mechanically driven material systems. Scripta Materialia 49:941-946, 2003.
[72]Li JP, De Wijn JR, Van Blitterswijk CA, De Groot K, Porous Ti-6Al-4V scaffold directly fabricating by rapid prototyping: preparation and in vitro experiment. Biomaterials 27: 1223-1235, 2006.
[73]Li JP, Li SH, Van Blitterswijk CA, De Groot K, A novel porous Ti-6Al-4V: characterization and cell attachment. Journal of Biomedial Materials Research A73:223-233, 2005.
[74]Hollander DA, Von Walter M, Wirtz T, Sellei R, Schmidt-Rohlfing B, Paar O, Structural, mechanical and in vitro characterization of individually structured Ti-6Al-4V produced by direct laser forming. Biomaterials 27: 955-963, 2006.
[75]Davidson JA, Mishra AK, Kovacs P, Poggie RA, New surface hardened low-modulus corrosion-resistant Ti-13Nb-13Zr alloy for total hip arthroplasty. Bio-Medical Materials and Engineering 4:231-243, 1994.
[76]Geetha M, Mudali UK, Gogia AK, Asokamani R, Raj B, Influence of microstructure and alloying elements on corrosion behavior of Ti-13Nb-13Zr alloy. Corrosion Science 46: 877-892, 2004.
[77]Semiatin S.L., Seetharaman V. and Weiss I., “ The thermomechanical processing of alpha/beta titanium alloys ”, JOM Journal of the Minerals, Metals and Materials Society 49:33-39, 1997.
[78]Okazaki Y, Nishimura E, Nakada E, Kobayashi K, Surface analysis of Ti-15Zr-4Nb-4Ta alloy after implantation in rat tibia. Biomaterials 22:599-607, 2001.
[79]Kuroda D, Niinomi M, Morinaga M, Kato Y, Yashiro T, Design and mechanical properties of new β type titanium alloys for implant materials. Materials Science and Engineering A 243:244-249, 1998.
[80]Berthon G, Aluminium speciation in relation to aluminium bioavailability metabolism and toxicity, Coordination Chemistry Reviews 228:319-341, 2002.
[81]Yu SY, Scully JR, Corrosion and passivity of Ti-13Nb-13Zr in comparison to other biomedical implant alloys. Corrosion 53:965-976, 1997.
[82]Matsuno H, Yokohama A, Watari F, Uo M, Kawasaki T, Biocompatibility and osteogenesis of refractory metal implants, titanium, hafnium, niobium, tantalum and rhenium. Biomaterials 22:1253-1262, 2001.
[83]Lipscomb I.P. and Nokes L.D.M., “ The Application of Shape Memory Alloys in Medicine ”, Mechanical Engineering Publications Suffolk UK p.154, 1996.
[84]Hosoda H, Hunada S, Inoue K, Fukui T, Mishina Y, Suzuki T, Martensite transformation temperatures and mechanical properties of ternary NiTi alloys with offstoichiometric compositions. Intermetallics 6:291-301, 1998.
[85]Chen MF, Yang XJ, Hu RX, Cui ZD, Man HC, Bioactive NiTi shape memory alloy used as bone bonding implants. Materials Science and Engineering C 24:497-502, 2004.
[86]Gjunter VE, in: Delay Law and New Class of Materials and Implants in Medicine, STT, Northampton, p.11, 2000.
[87]Itin VI, Gjunter VE, Shabalovskaya SA, Sachdeva RLC, Mechanical properties and shape memory of porous nitinol. Materials Characterization 32:179-187, 1994.
[88]Li BY, Rong LJ, Li YY, Gjunter VE, Electric resistance phenomena in porous Ni-Ti shape-memory alloys produced by SHS. Scripta Materialia 44:823-827, 2001.
[89]Ayers RA, Simske SJ, Bateman TA, Petkus A, Sachdeva RLC, Gjunter VE, Effect of nitinol implant porosity on cranial bone ingrowth and apposition after 6 weeks. Journal of Biomedial Materials Research 45(1):42-47, 1999.
[90]Li BY, Rong LJ, Li YY, Gjunter VE, Synthesis of porous Ni-Ti shape-memory alloys by self-propagating high-temperature synthesis: reaction mechanism and anisotropy in pore structure. Acta Materialia 48:3895-3904, 2000.
[91]Chu CL, Chung CY, Lin PH, Wang SD, Fabrication of porous NiTi shape memory alloy for hard tissue implants by combustion synthesis. Materials Science and Engineering A 366:114-119, 2004.
[92]DC Lagoudas, EL Vandygriff, Processing and characterization of NiTi porous SMA by elevated pressure sintering. Journal of Intelligent Material Systems and Structures 13:837-850, 2002.
[93]Yuan B, Chung CY, Zhu M, Microstructure and martensitic transformation behavior of porous Ni-Ti shape memory alloy prepared by hot isostatic pressing processing. Materials Science and Engineering A 382:181-187, 2004.
[94]Zhu SL, Yang XJ, Hu F, Deng SH, Cui ZD, Processing of porous TiNi shape memory alloy from elemental powders by Ar-sintering. Materials Letters 58:2369-2373, 2004.
[95]Zhao Y, Taya M, Kang Y, Kawasaki A, Compression behavior of porous NiTi shape memory alloy. Acta Materialia 53:337-343, 2005.
[96]Elema H, De Groot JH, Nijenhuis AJ, Pennings AJ, Veth RPH, Klompmaker J, Jansen HWB, Use of porous biodegradable polymer implants in meniscus reconstruction. Science 268: 1082-1088, 1990.
[97]Klompmaker J, Jansen HWB, Veth RPH, Nielsen HKL, De Groot JH, Pennings AJ, Porous implants for knee joint meniscus reconstruction: a preliminary study on the role of pore sizes in ingrowth and differentiation of fibrocartilage. Clinical Mat 14:1-11, 1993.
[98]McNeese MD, Lagoudas DC, Pollock TC, Processing of TiNi from elemental powders by hot isostatic pressing. Materials Science and Engineering A 280:334-348, 2000.
[99]Bram M, Ahmad-Khanlou A, Heckmann A, Fuchs B, Buchkremer HP, St?労er D, Powder metallurgical fabrication processes for NiTi shape

memory alloy parts. Materials Science and Engineering A 337:254-263, 2002.
[100]Shih CC, Lin SJ, Chen YL, Su YY, Lai ST, Wu GJ, Kwok CF, Chung KH, The cytotoxicity of corrosion products of nitinol stent wire on cultured smooth muscle cells. Journal of Biomedial Materials Research 52:395-403, 2000.
[101]Wataha JC, O ’ Dell NL, Singh BB, Ghazi M, Whitford GM, Lockwood PE, Relating nickelinduced tissue inflammation to nickel release in vivo. Journal of Biomedial Materials Research Part B Applied Biomaterials 58:537-544, 2001.
[102]Otsuka K, Wayman CM, Shape Memory Materials. Cambridge University Press, Cambridge 13:1-14, 1998.
[103]Baure G, Jardine AP, Modifying the mechanical properties of porous equiatomic nitinol for osteoimplants. In: Proc. Int. Conf. on Shape Memory and Superelastic Technologies. Kurhaus, BadenBaden, Germany, pp. 475-482, 2004.
[104]Yamamuro T, Patterns of osteogenesis in relation to various biomaterials. Journal Japanese of Society Biomaterials 7:19-23, 1989.
[105]Chu CL, Chung CY, Zhou J, Pu YP, Lin PH, Fabrication and characteristics of bioactive sodium titanate/titania graded film on NiTi shape memory alloy. Journal of Biomedial Materials Research A75:595-602, 2005.
[106]Gu YW, Li H, Tay BY, Lim CS, Yong MS, Khor KA, In vitro bioactivity and osteoblast response of porous NiTi synthesized by SHS using nanocrystalline NiTi reaction agent. Journal of Biomedial Materials Research A78:316-323, 2006.
[107]Prymak O, Bogdanski D, K?雍ler M, Esenwein SA, Muhr G, Beckmann F, Morphological characterization and in vitro biocompatibility of a porous nickel-titanium alloy. Biomaterials 26:5801-5807, 2005.
[108]Gibson LJ, Ashby MF, Cellular Solids. Structure and Properties, second edition, Cambridge University Press Cambridge, New York 1997.
[109]Ho WF, Ju CP, Lin JHC, Structure and properties of cast binary Ti-Mo alloys. Biomaterials 20:2115-2122, 1999.
[110]Rao S, Okazaki Y, Tateishi T, Cytocompatibility of New Ti Alloy without Al and V by Evaluating the Relative Growth Ratios of Fiblroblasts L929 and Osteoblasts MC3T3-E1 cells. Materials Science and Engineering C4:311-314, 1997.
[111]Helsen JA, Breme HJ, Metals as Biomaterials. Wiley, Baffins Lane, Chichester, England p.522, 1998.
[112]Moyen BJ, Lahey Jr P.J., Weinberg EH, Harris WH, 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. Journal of Bone and Joint Surgery American 60:940-947, 1978.
[113]Vehof, Johan WM, Paul HM Spauwen, John A Jansen, Bone formation in calcium-phosphate-coated titanium mesh. Biomaterials 21:2003-2009, 2000.
[114]Slenes K, Ackerman WC, Brotzman RW, Stoltzfux J, Gunaji M, Surf Coat Technol 68-69:pp.51-57, 1994.
[115]Lemons JE, Biomaterials biomechanics tissue healing and immediate-function dental implants. Joumal of Oral Implantology 30:318-324, 2004.
[116]Ducheyne P, van Raemdonck W, Heughbaert JC, Heughbaert M, Structural analysis of hydroxyapatite coatings on titanium. Biomaterials 7:97-103, 1986.
[117]Kim HM, Kokubo T, Fujibayashi S, Nishiguchi S, Nakamura T, Bioactive macroporous titanium surface layer on titanium substrate. Journal of Biomedial Materials Research 52:553-557, 2000.
[118]Ishizawa H, Ogino M, Formation and characterization of anodic titanium oxide films containing Ca and P. Journal of Biomedial Materials Research 29:65-72, 1995.
[119]Zhu XL, Kim KH, Jeong YS, Anodic oxide films containing Ca and P of titanium biomaterial. Biomaterials 22:2199-2206, 2001.
[120]Han Y, Hong SH, Xu K, Structure and in vitro bioactivity of titania-based films by micro-arc oxidation. Surface and Coatings Technology 168:249-258, 2003.
[121]Song WH, Jun YK, Han Y, Hong SH, Biomimetic apatite coatings on micro-arc oxidized titania. Biomaterials 25: 3341-3349, 2004.
[122]Suryanarayana C, Mechanical Alloying and Milling. Progress in Materials Science 46:1-184, 2001.
[123]L? L, Lai MO, Mechanical Alloying. Boston: Kluwer Academic Publishers, 154:361-370, 1998.
[124]Soni PR, Mechanical alloying: fundamentals and applications. Cambridge: International Science Publishing, 1999.
[125]Suryanarayana C, Froes FH, Mechanical Alloying of Titanium-Base Alloys. Advanced Materials 5:96-106, 1993.
[126]Henriques VAR, Bellinati CE, Silva CRM, Production of Ti-6% Al-7% Nb alloy by powder metallurgy (P/M). Journal of Materials Processing Technology 118: 212-215, 2001.
[127]Taddei EB, Henriques VAR, Silva CRM, Cairo CAA, Production of new titanium alloy for orthopedic implants. Materials Science and Engineering C 24:683-687, 2004.
[128]Gilman PS, Benjamin JS, Mechanical alloying. Annual Review of Materials Science 13:279-300, 1983.
[129]Tsuruga E, Takita H, Itoh H, Kuboki Y, Pore Size of Porous Hydroxyapatite as the Cell-Substratum Controls BMP-Induced. Journal of Biochemistry 121:317-324, 1997.
[130]Sikavitsas VI, Temenoff JS, Mikos AG, Biomaterials and bone mechanotransduction. Biomaterials 22:2581-2593, 2001.
[131]Athanasiou K, Agrawal C, Barber F, Burkhart S, Orthopaedic applications for PLA-PGA biodegradable polymers. Arthroscopy 14:726-737, 1998.
[132]Gogolewski S, Bioresorbable polymers in trauma and bone surgery. Injury 31:28-32, 2000.
[133]Murphy WL, Kohn DH, Mooney DJ, Growth of continuous bonelike mineral within porous poly(lactide-co-glycolide) scaffolds in vitro.

Journal of Biomedial Materials Research 50:50-58, 2000.
[134]Dong J, Kojima H, Uemura T, Kikuchi M, Tateishi T, Tanaka J, In vivo evaluation of a novel porous hydroxyapatite to sustain osteogenesis of transplanted bone marrow-derived osteoblastic cells. Journal of Biomedial Materials Research 57:208-216, 2001.
[135]Rezwan K, Chen QZ, Blaker JJ, Boccaccini AR, Biodegradable and bioactive porous polymer/inorganic composite scaffolds for bone tissue engineering. Biomaterials 27:3413-3431, 2006.
[136]Hing KA, Best SM, Tanner KE, Bonfield W, Revell PA, Mediation of bone ingrowth in porous hydroxyapatite bone graft substitutes. Journal of Biomedial Materials Research 68A:187-200, 2004.
[137]De Long WG, Einhorn TA, Koval K, McKee M, Smith W, Sanders R, Bone grafts and bone graft substitutes in orthopaedic trauma surgery. Joumal of Bone and Joint Surgery 89:649-658, 2007.
[138]Yoshikawa H, Myoui A, Bone tissue engineering with porous hydroxyapatite ceramics. Joumal of Artificial Organs 8:131-136, 2005.
[139]Bertheville B, Porous single-phase NiTi processed under Ca reducing vapor for use as a bone graft substitute. Biomaterials 27:1246-1250, 2006.
[140]Uchida M, Kim HM, Miyaji F, Kokubo T, Nakamura T, Apatite formation on zirconium metal treated with aqueous NaOH. Biomaterials 23:313-317, 2002.
[141]Kokubo T, Kim HM, Kawashita M, Novel bioactive materials with different mechanical properties. Biomaterials 24:2161-2175, 2003.
[142]Kokubo T, Apatite formation on surfaces of ceramics, metals and polymers in body environment. Acta Materialia 46:2519-2527, 1998.
[143]Otsuki B, Takemoto M, Fujibayashi S, Neo M, Kokubo T, 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.
[144]Han Y, Cui K, Sun J, Microstructure and apatite-forming ability of the MAO-treated porous titanium. Surface & Coatings Technology 202:4248-4256, 2008.
[145]Lin J.H, Chang CH, Chen YS, Lin GT, Formation of bone-like apatite on titanium filament by a simulated body fluid inducing process. Surface & Coatings Technology 200:3665-3669, 2006.
[146]Kokubo T, Takadama H, How useful is SBF in predicting in vivo bone bioactivity. Biomaterials 27:2907-2915, 2006.
[147]Wen C, Hodgson PD, Nouri A, Chen X, Li Y, Yamada Y, Synthesis of Ti-Sn-Nb alloy by powder metallurgy. Materials Science and Engineering A 485:562-570, 2008.
[148]German RM, Particle packing characteristics. NJ: Metal Powder Industries Federation 404-407, 1989.
[149]Martin CL, Bouvard D, Isostatic compaction of bimodal powder mixtures and composites. Intemational Joumal of Mechanical Sciences 24:907-927, 2004.
[150]McGeary RK, Mechanical packing of spherical particles. Journal of the American Ceramic Society 44:513-522, 1961.
[151]Zhang Y, Wei XY, Mao CH, Li TF, Yuan P, Du J, Preparation and pumping characteristics of Ti-7.5 wt.%Mo getter. Journal of Alloys and Compounds 485:200-203, 2009.
[152]Takashi N, Tomiharu M, Kenji D, Hiroaki T, Pattanayak DK, Tadashi K, 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.