合金元素添加對生醫用鑄造三元鈦合金的結構及性質之影響研究

潘昌宏、何文福

E-mail: 9708021@mail.dyu.edu.tw

摘 要

在本研究中，將探討TZX、TCX及TCFX之相/晶體構造、微結構、機械性質及研削性，並與商業純鈦做比較，期望能開發出適合作為牙科應用之鈦合金。 TZX合金方面：實驗結果與對照組c.p. Ti做為比較。結果顯示，TZ合金添加少量的合金元素可以改善相/晶體結構、微結構、機械性質及研削性。雖然所有合金的研削量需用研削速度來加以控制，但是合金元素Nb、Mo、Cr及Fe在研削條件下明顯提升研削比。TZM合金與c.p. Ti做比較，微硬度增加(63 %)、彎曲強度(40 %)、彈性模數(30 %)及彈性回復角(180 %)，也發現有良好的研削性質。TZM合金，如果滿足牙科鑄造條件下，可用於牙科修復材使用。 TCX合金方面：TC及TCX合金之彎曲強度均遠高於c.p. Ti，特別是TCN有最高之彎曲強度。三元合金的彎曲彈性模數均較c.p. Ti及TC合金高，其中以TCZ合金具有最高之彎曲彈性模數。此外，TC及TCX合金也具有較c.p. Ti更為良好之彈性回復能力。因此，本研究探討之TC與TCX合金具有良好的機械性質，且其β相的結構也可使合金具有較好的加工性，相信在牙科鑄造用合金上將具有不錯的應用潛力。 TCFX合金方面：實驗結果顯示，只有TCF5與TCF6展現出延性特徵。TCF5與TCF6未含有ω相，彈性模數遠低於含有ω相的TC1與TCFX。TCF5擁有最高抗彎強度/彈性模數比值25.1，高於商業純鈦(c.p. Ti) 195 %與TC1合金132 %。此外，TCF6也具有高比值24.6，遠高於c.p. Ti 189 %與TC1合金128 %。此外，彈性回復能力TCF5 (31.5 °)和TCF6 (29.6 °)合金均高於c.p. Ti (2.7 °)，分別高達1067 %和996 %。從微結構發現，TCF5與TCF6涵蓋了許多滑移線。以目前尋求更好的植入材，低彈性模數、延性特徵、良好的彈性回復能力及適當的高強度或(高強度/彈性模數比值) β相TCF5與TCF6合金將會是最好的選擇。研削結果顯示，TCFX合金微結構與Fe有關。當Fe含量超過0.5%時，等軸β相完全保留下來，TC1、TCF2、TCF3及TCF4合金發現含有ω相。TCF3與TCF4合金含有大量ω相和極高的微硬度。TC1及TCFX合金顯示研削量與微硬度有相同趨勢。TC1、TCF2、TCF3及TCF4合金，尤其在500、750及1000 m/min時，研削量表現最佳。而且研削量比例隨著研削速率到1000 m/min為最高，到1200 m/min隨之減少。這項研究結果發現添加Fe可以增加鈦合金硬度及改善研削性。

關鍵詞 : 鈦合金 ; 牙科合金 ; 結構 ; 機械性質 ; ω相 ; 研削性 ; 加工性 ; 鈦合金 ; 研削性 ; 微結構 ; 研削量

目錄

參考文獻

[1] Horlington M. Biomaterials: present and future. Materials World. 1995. p. 332-333.

[2] Hench LL. Biomaterials: a forecast for the future. Biomaterials. 1998;19:1419-1423.
[3] Clemson Advisory Board for Biomaterials Definition of the word biomaterial Thc 6th Annnal Intermalionel Biomaterial Symposium 1974. p. 20-24.
[4] Wesolowski SA, Dennis C. Fundamentals of Vascular Grafting. New York: McGraw-Hill publication, 1963.
[5] Paul R. Alkaline aqueous electrolyte cell for biomedical application. J Electrochem Soc 1980;127(8):1667-1678.
[6] Browning E. Toxicity of Industrial Metals. 2nd ed. Butterworths. Lodon, 1969.
[7] 島村 昭治, 未來?拓?先端材料, 工業調查?, 1989; pp. 186-190.
[8] Hierholzer S, Hierholzer G, Sauer KH, Paterson RS. Increased corrosion of stainless steel implants in infected plated fractures. Arch Orthop Trauma Surg 1984;102(3):198-200.
[9] 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 1983;4(3):175-180.
[10] Chang CK, Wu JS, Mao DL, Ding CX. Mechanical and histological evaluations of hydroxyapatite-coated and noncoated Ti6Al4V implants in tibia bone. J Biomed Mater Res 2001;56(1):17-23.
[11] Heughebaert M, LeGeros RZ, Gineste M. Physicochemical characterization of deposits associated with HA ceramics implanted in nonosseous sites. J Biomed Mater Res 1988;22(3):257-268.
[12] Ripamonti U. Osteoinduction in porous hydroxyapatite implanted in heterotopic sites of different animal models. Biomaterials 1996;17(1):31-35.
[13] Magan A, Ripamonti U. Geometry of porous hydroxyapatite implants influences osteogenesis in baboons (Papio ursinus). J Craniofac Surg 1996;7(1):71-78.
[14] Goh JCH. Biomechanics and advances in total joint replacement design. Proc the 3rd World Congress of Biomechanics (WCB ’ 98) 1998;4:182-347.
[15] Schmalzried TP, Callaghan JJ. Current concepts review: wear in total hip and knee replacements. J Bone Joint Surg B 1999;81:115-136.
[16] Hall SJ. Basic Biomechanics: the biomechanics of human bone growth and development. Mosby-Year Book: St Louis. 1995;4:86-109.
[17] Chen WP, Liu PH, Liao JD. Modular Finite Element Mesh Generation and Contact Stress Analysis of Total Hip Replacement. Chinese J Mechanics 1998;14: 51-60.
[18] 王盈錦, 林峰輝, 胡孝光 等編著, 生物醫學材料, 國立編譯館, 1992.
[19] Hayasahi K. Biodegradation of implant materials. JSME Int J 1987;30:(268) 1517-1525.
[20] Chiba A, Sakakura S, Kobayashi K, Kusayanagi K. Dissolution amounts of nickel, chromium and iron from SUS 304, 316 and 444 stainless steels in sodium chloride solutions. J Mater Sci 1997;32:1995-2000.
[21] [23]Noort RVan. Titanium: the implant of today. J Mater Sci Mater Med 1987;22: 3801-3811.
[22] Williams DF. Biocompatibility of Clinical implant materials. v2. CRC press. Inc. Boca Raton. Florida, 1981. p. 112.
[23] Branemark PI, Hansson BO, Adell R, Breine U, Lindstrom J, Hallen O, Ohman A. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. Scand J Plast Reconstr Surg Suppl 1977;16:1-132.
[24] Branemark KP, Hansson B, Adell R. Intraosseous anchorage dental prostheses: I experimental studies. Scand J Plast Reconstr Surg Suppl 1977;16:1-4.
[25] Kokubo T, Nakamura T, Miyaji F. Bioceramics 9: Proceedings of the 9th International Symposium on Ceramics in Medicine. Otsu Japart, 1996. p.11.
[26] Kathy W. The use of titanium for medical application in USA. Mater Sci and Eng A 1996;123:134-137.
[27] Abkowitz S. The emergence of the titanium industry and the development of the Ti-6Al-4V alloy: collections and recollections. TMS. Warendale. PA: USA, 2000. p. 42.
[28] Moffat DL, Larbalestier DC. The competition between Martensite and Omega in Quenched Ti-Nb Alloys. Metall Trans A 1988;19(7):1677-1686.
[29] Williams JC. High performance materials development in the 21st century trends and direction. Mater Sci for vols 2004;449-452:7-12.
[30] Covington LC, Schutz RW. Corrosion resistance of titanium. Metals Handbook. 9th. ASM publications. Ohio, 3:413-415, 1979.
[31] Donachie MJ. Titanium and titanium alloys source book. Metals Park. OH: The American Society for Metals. 1982. p.10-19.
[32] 賴耿陽, 金屬鈦, 復漢出版社, 1990, p.1-60.
[33] Brobst DA , Pratt WP. United states mineral resources: U.S. geological survey professional paper. No: 820, 1973. p. 662.
[34] Donachie jr MJ. Titanium atechnical guide. ASM International. Metal Park: Oh44073, 1988. p.14.
[35] Ogden HR. Rare Metals Handbook. in: Clifford AH editors, Rinhdd Publishing Corporation. Chapman & Hall Ltd. Lndon. 1961.p.559-579.
[36] Collings EW. The physical metallurgy of titanium alloys. in: Gegel HL editors. ASM Series in Metal Processing. Edward Amold publications. Cleveland. Metals Park:OH, 1984. p.66-478.
[37] Burgers WG. On the process of transition of the cubic-body-centered modification into the hexagonal-close-packed modification of zirconium. Physica 1934;1:561-586.

[38] 丹尼．爾漢克爾, 工程材料.美商麥格羅．希爾出版社, 2002, p. 161-163.
[39] Kahles JF, Field M, Eylon D, Froes FH. Machining of titanium alloys. J Met 1985;37(4):27-35.
[40] Blenkinsop PA. High temperature titanium alloys. IMI Titanium Limited. Birmingham. England, 1986. p.189-198.
[41] Machado AR, Wallbank J. Machining of titanium and its alloys - a review. Proc Inst Mech Eng B 1990;204(1):53-60.
[42] Borradaile JB, Jeal RH. Mechanical properties of titanium alloys. Warrendale: Metallurgical society of AIME, 1980. p.1-3.
[43] 金重勳, 工程材料, 復文出版社, 1996, p. 389.
[44] Leyens C, Peters M. Titanium and Titanium Alloys: Fundamentals and Applications. John Wiley & Son Inc, 2003.
[45] Murray JL. Phase Diagrams of Binary Titanium Alloys. ASM International. Metal Park:OH, 1987. p.68-340.
[46] Margolin H, Rozenberg L. Titanium ' 80 Science and Technology. Proceeding of the 4th International Conference on Titanium. 1980.
[47] Lee CM, Ju CP, Chern Lin JH. Structure-property relationship of cast Ti-Nb alloys. J Oral Rehabil 2002;29:314-322.
[48] Hall GS, Seagle SR, Bomberger HB. Improvement in High Temperature Tensile and Creep Properties of Titanium Alloy. Titan Sci and Tec 1973;4:2141-2150.
[49] Bania PJ, Hall JA. Titanium Science and Technology. Deutsche Gesellschaft fur Metallkunde. Oberursel. Germany,1985.
[50] Louzguine DV, Kato H, Inoue A. High strength and ductile binary Ti-Fe composite alloy. J Alloy Comp 2004;384(1-2):L1-L3.
[51] Louzguine DV, Kato H, Inoue A. High-strength hypereutectic Ti-Fe-Co bulk alloy with good ductility. Philos mag lett 2004;84(6):359-364.
[52] Louzguine DV, Louzguina LV, Kato H. Investigation of Ti-Fe-Co bulk alloys with high strength and enhanced ductility. Acta Mater 2005;53:2009-2017.
[53] 機械工程手冊編輯委員會, 金屬材料, 五南圖書出版, 台北, 台灣p.647.
[54] Long M, Rack HJ. Titanium alloys in total joint replacement-a materials science perspective. Biomaterials 1998;19:1621-1639.
[55] Taylor JC, Hondrum SO, Prasad A, Brodersen CA. Effects of joint configuration for the arc welding of cast Ti-6Al-4V alloy rods in argon. J Prosthet Dent 1998;79(3):291-297.
[56] Berg E, Wagner WC, Davik G., Dootz ER. Mechanical properties of laser-welded cast and wrought titanium. J Prosthet Dent 1995;74(3):250-257.
[57] Yoshinari M, Ozeki K, Sumii T. Properties of hydroxyapatite-coated Ti-6Al-4V alloy produced by the ion-plating method. Bull Tokyo Dent Coll 1991;32:147 – 156.
[58] Nakajima H, Okabe T. Titanium in dentistry: development and research in the USA. Dent Mater J 1996;15:77-90.
[59] Niinomi M. Mechanical properties of biomedical titanium alloys. Mater Sci Eng A 1998;243:231-236.
[60] Wang K. The use of titanium for medical applications in the USA. Mater Sci Engng A 1996;213:134-137.
[61] Steinemann SG, Perren SM. Titanium alloys as metallic biomaterials. in: Lutjering G, Zwicker U, Bunk W, editors. Titanium Science and Technology DGM 1985. p.1327-1334.
[62] Laing PG, Ferguson Jr AB, Hodge ES. Tissue reaction in rabbit muscle exposed to metallic implants. J Biomed Mater Res 1967;1:135-149.
[63] Buly RL, Huo MH, Salvati E. Titanium wear debris in failed cemented total hip arthroplasty. An analysis of 71 cases. J Arthroplasty 1992;7-3:315-323.
[64] Zwicker R, Buehler K, Mueller R. Mechanical properties and tissue reactions of a titanium alloy for implant material. Titanium ' 80:Science and technology In: Kimura H, Izumi O, editors. Proceedings of the Fourth International Conference on Titanium. Kyoto. Japan. The Met. Coc. AIME. 1980. p.505-514.
[65] Semlitsch M, Staub F, Weber H. Titanium-aluminium-niobium alloy, development for biocompatible, high strength surgical implants. Biomed Tech 1985;30:334-339.
[66] Okazaki Y, Ito Y, Kyo K, Tateishi T. Corrosion resistance and corrosion fatigue strength of new titanium alloys for medical implants without V and Al. Mat Sci Engng A 1996;213:138-147.
[67] Song Y, Xu DS, Yang R, Li D, Wu WT, Guo ZX. Theoreticla study of the effects of alooying elements on the strength and modulus of β-type bio-titanium alloys. Mater Sci Eng A 1999;260:269-274.
[68] Gibeling JC, Shelton DR, Malik CL. Application of fracture mechanics to the study of crack propagation in bone. In: Rack H, Lesuer D, Taleff E, editors. Editeds Structural Biomaterials for the 21st Century, TMS. Warrendale. Pennsylvania:U.S.A., 2001. p. 239-254.
[69] Wang K, Gustavson L, Dumbleton J. Low modulus, high strength, biocompatible titanium alloy for medical implants. In: Titanium ' 92 Science and Technology. Warrendale: The Minerals, Metals & Materials Society. 1993;2697-2704.
[70] Wang KK, Gustavson LJ, Dumbleton JH. Microstructure and properties of a new beta titanium alloy, Ti-12Mo-6Zr-2Fe developed for surgical implants. In: Brown SA, Lemons JE, editors. Medical applications of titanium and its alloys: the material and biological issues. ASTM STP vol. 1272. ASTM. West Conshohocken, 1996. p. 49-60.
[71] Robare EW, Bugle CM, Davidson JA, Daigle KP. Development of processing methods for Ti-13Nb-13Zr. In: Weiss I, Srinivasan R, Bania PJ, Eylon D, Semiatin SL, editors. Advances in the Technology of Titanium Alloy Processing. The Minerals. Metals and Materials Society, 1997. p.283-291.
[72] Davidson JA, Mishra AK, Kovacs P, Poggie RA. New surface-hardened, low-modulus, corrosion-resistant Ti-13Nb-13Zr alloy for total hip

arthroplasty. Biomed Mater Eng 1994;4(3):231-243.
[73] Okazaki Y, Rao S, Ito Y, Tateishi T. Corrosion resistance, mechanical properties, corrosion fatigue strength and cytocompatibility of new Ti alloys without Al and V. 1998;19(13):1197-1215.
[74] Ito A, Okazaki Y, Tateishi T, Ito Y. In vitro biocompatibility, mechanical properties, and corrosion resistance of Ti-Zr-Nb-Ta-Pd and Ti-Sn-Nb-Ta-Pd alloys. J Biomed Mater Res 1995;29(7):893-899.
[75] Niinomi M. Fatigue performance and cyto-toxicity of low rigidity titanium alloy, Ti-29Nb-13Ta-4.6Zr. Biomaterials 2003;24(16):2673-2683.
[76] Lavos-Valereto C, Wolynec S, Deboni MCZ, Konig Jr B. In vitro and in vivo biocompatibility testing of Ti-6Al-7Nb alloy with and without plasma-sprayed. J Biomed Mater Res 2001;58(6): 727-733.
[77] Been J, Faller K. Using Ti-5111 for marine fastener applications. J O M 1999;51:21-24.
[78] Gorynin IV. Titanium alloys for marine application. Mater Sci Eng A 1999;263:112-116.
[79] Kim SW, Oh S, You CK, Ahn MW, Kim KH, Kang IK, Lee JH, Kim S. Preliminary radiological in vivo study of calcium metaphosphate coated Ti-alloy implants. Key Eng Mater 2004;254-256:881-886.
[80] Ratner BD. A perspective on titanium biocompatibility. In: Brunette DM, Tengvall P, Textor M, Thomsen P, Editors, Titanium in medicine. Springer-Verlag. Berlin. Heidelberg, 2001. p.1-12.
[81] Shira C, Froes FH. Titanium golf clubs. MRS. Bulletin. 1998;23(3):42-46.
[82] Sjogren G, Andersson M, Bergman M. Laser welding of titanium in dentistry. Acta Odontol Scand 1988;46:247-253.
[83] Berg E, Davik G, Hegdahl T, Gjerdet NR. Hardness, strength, and ductility of prefabricated titanium rods used in the manufacture of spark erosion crowns. J Prosthet Dent 1996;75:419-425.
[84] 金聖泰, 小田豐, 住井俊夫, 齒科???鑄造?????評價?關??研究, 齒科學報, 1994;94:845-857.
[85] Sunnerkrantz PA, Syverud M, Hero H. Effect of casting atmosphere on the quality of Ti-crowns. Scand J Dent Res 1990;98:268-272.
[86] Zinelis S. Effect of pressure of helium, argon, krypton, and xenon on the porosity, microstructure, and mechanical properties of commercially pure titanium castings. J Prosthet Dent 2000;84(5):575-582.
[87] Miyakawa O, Watanabe K, Okawa S, Nakano S, Kobayashi M, Shiokawa N. Layered structure of cast titanium surface. Dent Mater J 1989;8(2):175-185.
[88] Takahashi J, Kimura H, Lautenschlager EP, Chern Lin JH, Moser JB, Greener EH. Casting pure titanium into commercial phosphate-bonded SiO2 investment molds. J Dent Res 1990;69:1800-1805.
[89] Oda Y, Kudoh Y, Kawada E, Yoshinari M, Hasegawa K. Surface reaction between titanium castings and investments. Bull Tokyo Dent Coll 1996;37(3):129-136.
[90] Wang RR, Welsch GE, Castro-Cedeno M. Interfacial reactions of cast titanium with mold materials. Int J Prosthodont 1998;11(1):33-43.
[91] Ida K, Togaya T, Tsutsumi S, Takeuchi M. Effect of magnesia investments in the dental casting of pure titanium or titanium alloys. Dent Mater J 1982;1(1):8-21.
[92] 佟天夫, 熔模鑄造工藝, 機械工業出版社, 1991, p. 335-42.
[93] Molchanova EK. Phase Diagrams of Titanium Alloys. Israel Program for Scientific Translations. Jerusalem, 1965. p.154.
[94] Kuroda D, Niinomi M, Morinaga M, Kato Y, Yashiro T. Design and mechanical properties of new β type titanium alloys for implant materials. Mat Sci Eng A 1998;243:244-249.
[95] Morinaga M, Yukawa N, Maya T. Theoretical design of titanium alloys. In: Lacombe P, editors. Sixth World Conference of Titanium. France. Societe Francaise de Metallurgie. 1988. p.1601-1606.
[96] 劉瑛, 鄧波, 應用d 電子合金設計理論優化GH907 合金組織及持久性能, 材料工程, 1997;7:23-29.
[97] Mackenzie JK, Bowles JS. The crystallography of martensite transformations. Acta Metall 1954;2:138.
[98] Ankem S, Seagle SR. Heat treatment of Metastable Beta Titanium Alloys. Beta Titanium Alloys in the 1980’s. in: Boyer RR, Rosenberg HW, editors. The Metallurgical society of AIME. 1984.
[99] Mantani Y, Tajima M. Phase transformation of quenched α″martensite by aging in Ti-Nb alloys. Mater Sci Eng A 2006;438-440:315-319.
[100] Kobayashi S, Nakai K, Ohmori Y. Analysis of phase transformation in a Ti-10 mass% Zr alloy by hot stage optical microscopy. Mater Trans 2001;42(11):2398-2405.
[101] Ohmori Y, Ogo T, Nakai K, Kobayashi S. Effects of ω-phase on β to α, α″ transformations in a metastable β titanium alloy. Mater Sci Eng A 2001;312:182-188.
[102] Beneteaua A, Weisbeckera P, Geandierb G, Aeby-Gautiera E, Appolairea B. Austenitization and precipitate dissolution in high nitrogen steels: an in situ high temperature X-ray synchrotron diffraction analysis using the Rietveld method. Mater Sci Eng A 2005;393(1-2):63-70.
[103] Bowen AW. Omega Phase Formation in Metastable Beta-Titanium Alloys. Beta Titanium Alloys in the 1980's 1983;2:85-103.
[104] Yamada K, Ogawa A, Ouchi C, Eylon D. Effect of Al on omega phase transformation behavior in Ti-8 V-5 Fe-(1-3) Al alloy. Mater Trans 1996;37(4):855-859.
[105] Sikka SK, Vohra YK, Chidambaram R. Omega phase in materials. Prog Mater Sci 1982;27:245-310.
[106] Ahmed TA, Long M, Silverstri J, Ruiz C, Rack HJ. A new low modulus biocompatible titanium alloy. Titanium 95': Sci. Technol, 1996.

p.1760-1767.
[107] 李夫舍茨, 金屬與合金的物理性能, 北京:冶金工業出版社, 1959.
[108] Saito T, Furuta T, Hwang JH, Kuramoto S, Nishino K. Multifunctional Alloys Obtained via a Dislocation-Free Plastic Deformation Mechanism. Science 2004;300:464-467.
[109] Brown ARG, Clark D, Eastabrook J. The Titanium-Niobium System. Nature 1964;201:914-915.
[110] Song Y, Yang R, Li D, Hu Z, Guo Z. Calculation of bulk modulus of titanium alloys by first principles electronic structure theory. J Computer-Aided Materials Design 1999;6:355-362.
[111] Silver FH. Biomaterials, Medical Devices and Tissue Engineering: An Integrated Approach. Boston: Chapman & Hall Press:London, 1994. p.15.
[112] Steinemann SG. Surgical implant and alloy for use in making an implant. US Patent No. 4040129. 1977.
[113] Kawhara K. Cytotoxicity of implantable metals and alloys. Bull Jpn Inst Met 1992;31:1033-1039.
[114] 岡崎義光, 生体材料???????合金開?, 輕金屬, 1999;49(12):613-620.
[115] 桜井 弘, 金屬?人体???必要?, 講談社?一????, 1996.
[116] 寺岡久之, 森井??, 小林 純, ?養?食糧, 34:221, 1981.
[117] 陳威凱, 牙科用鈦-鋯合金之微結構及性質研究, 大葉大學, 2007.
[118] 姜宗佑, 生醫用鈦-鉻二元合金之結構及性質探討, 大葉大學, 2007.
[119] Vander Voort G F. Metallography principles and practice. McGraw-Hill: U.S.A. 1984. p.449.
[120] Hilliard JE. Estimating grain size by the intercept method. Met Prog 1964;84:99-102.
[121] Guha A. Metals handbook. 9th ed. v8. In: Boy HE, Gall TL, editors. American Society for Metals Metals Park.1985. p.133-136.
[122] Ho WF, Ju CP, Chern Lin JH. Structure and properties of cast binary Ti-Mo alloys. Biomaterials 1999;20:2115-2122.
[123] Ohkubo C, Watanabe I, Ford JP, Nakajima H, Hosoi T, Okabe T. The machinability of cast titanium and Ti-6Al-4V alloy. Biomaterials 2000;21(4):421-428.
[124] Takahashi M, Kikuchi M, Okuno O. Mechanical properties and grindability of experimental Ti-Au alloys. Dent Mater J 2004;23(2):203-210.
[125] Ohkubo C, Hosoi T, Ford JP, Watanabe I. Effect of surface reaction layer on grindability of cast titanium alloys. Dent Mater 2006;22(3):268-274.
[126] Kikuchi M, Takahashi M, Sato H, Okuno O, Nunn ME, Okabe T. Grindability of cast Ti-Hf alloys. J Biomed Mater Res B Appl Biomater 2006;77(1):34-38.
[127] Margolin H, Nielsen JP. Titanium Metalllurgy. in:Modern Marerials. Advances in Development and Application. In: Hausner HH, editors. Vol 2, New York:Academic Press, 1960. p.225-325.
[128] Collings EW. Materials Properties Handbook: Titanium Alloys. In: Boyer R, Welsch G, Collings EW, editors. ASM International. Materials Park:OH, 1994. p.1053.
[129] Kobayashi E, Matsumoto S, Doi H, Yoneyama T, Hamanaka H. Mechanical properties of the binary titanium-zirconium alloys and their potential for biomedical materials. J Biomed Mater Res 1995;29:943-950.
[130] Takahashi M, Kikuchi M, Takada Y. Grindability and microstructures of experimental Ti-Zr alloys. J J Dent Mater 2006;25(5):327.
[131] Bagariaskii IA, Nosova GI, Tagunova TV. Factors in the formation of metastable phase in titanium-base alloys. Sov Phys Dokl (Engl Transl) 1959;30:1014-1018.
[132] Combe EC. Notes on dental materials, Churchill Livingstone. New York, 1977. p.64.
[133] Davis R, Flower HM, West DRF. Martensitic transformations in Ti-Mo alloys. J mater sci 2004;14(3)712-722.
[134] Williams JC. Titanium Science and Technology; Proceeding, Metallurgical Society of AIME, Plenum Press:New York, 1973. p.1433.
[135] 簡仁德, 楊子毅, 張柳春, 材料科學與工程, 學銘圖書有限公司, 1996, p. 255-260.
[136] Bobyn JD, Mortimer ES, Glassman AH, Engh CA, Miller J, Brooks C. Producing and avoiding stress shielding: laboratory and clinical observation of noncemented total hip arthroplasty. Clin Orthop 1992;274:79-96.
[137] Ammen CW. The Metalcaster ' s Bible. McGraw Hill PA U.S.A. 1980.
[138] Kikuchi M, Takahashi M, Okabe T, Okuno O. Grindability of dental cast Ti-Ag and Ti-Cu alloys. Dent Mater J 2003;22(2):191-205.
[139] Takeyama H, Murata R. Temperature dependence of tool wear. J Jpn Soc Preci Eng 1961;27(1):33-38. (in Japanese) [140] Narutaki N, Murakoshi A. Study on machining of titanium alloys. Annals CIRP 1983;321:65-69.
[141] Chandler H.E. Machining of reactive metals. Metals Handbook 9th ed., v16 Machining. ASM Int. Metals Park: OH 1989. p. 844-846.
[142] Kikuchi M, Takahashi M, Okuno O. Mechanical properties and grindability of dental cast Ti-Nb alloys. Dent Mater J 2003;22(3):328-42.
[143] Porter LF, Rosenthal PC. Factors affecting fluidity of cast irons. Trans AFS 1952;60:725-739.
[144] Cheng WW, Ju CP, Chern Lin JH. Structure castability and mechanical properties of commercially pure and alloyed titanium cast in graphite mould. J Oral Rehabil 2003;30:1-13.
[145] Koike M, ltoh M, Okuno O, Kimura K, Takeda O, Okabe TH, Okabe T. Evaluation of Ti-Cr-Cu alloys for dental applications. J Mater Eng Perform 2005;14(6):778-783.

[146] William DC. Materials science and engineering: an introduction. John Wiley & Sons New York, 2003.
[147] Silcock JM. An x-ray examination of the ω phase in TiV, TiMo and TiCr alloys. Acta Metall 1958;6:481-493.
[148] Pack HJ, Kalish D, Fike KD. Stability of as-quenched beta-IIItitanium alloys. Mater Sci Eng 1970;6:181-198.
[149] Ohmori Y, Natsui H, Nakai K, Ohtsubo H. Effects of ω phase formation on decomposition of α"/β duplex phase structure in a metastable β Ti alloy. Mater Trans JIM 1998;39(1):40-48.
[150] Ageev NV, Karpinskii OG, Petrova LA. Stability of the β-solid solution of titanium-chromium alloys. Zh Neorg Khim 1976;6. (in Russian)
[151] Saha RJ, Handy TK, Misra RDK, Jacob KT. On the evaluation of stability of rare earth oxides as face coats for investment casting of titanium. Metall Trans B 1990;21(3):559-566.
[152] Frueh C, Poirier DR, Maguire MC. The effect of sicilica-containing binders on the titanium/face coat reaction. Metall Mater Trans B 1997;28:919-926.
[153] Suzuki K, Nishikawa K, Watakabe S. Stability of yttria for titanium alloy precision casting mold. Mater Trans JIM 1997;38(1):54-62.
[154] Saha RL, Misra RDK. Formation of low-melting eutectic at the metal-mould interface during titanium casting in zircon sand moulds. J Mater Sci Lett 1991;10:1318-1319.
[155] Williams JC, Hickman BS, Marcus HK. The effect of omega phase on the mechanical properties of titanium alloys. Metall Trans 1971;2:1913-1919.
[156] Kikuchi M, Takada Y, Kiyosue S, Yoda M, Woldu M, Cai Z, Okuno O, Okabe T. Mechanical properties and microstructures of cast Ti-Cu alloys. Dent Mater 2003;19:174-181.
[157] William DC. Materials science and engineering: an integrated approach. John Wiley & Sons, New York, 2003. p. 255-256.
[158] Lammie GA, Laird WRE. Osborne & Lammie's partial dentures. London: Blackwell Scientific. 5th ed. 1986. p. 190-192.
[159] Kikuchi M, Takada Y, Kiyosue S, Yoda M, Woldu M, Cai Z, Okuno O, Okabe T. Grindability of cast Ti-Cu alloys. Dent Mater 2003;19(5):375-381.