The Study of Structure and Properties of Binary Ti-Cr Alloys for Biomedical Applications

姜宗祐、何文福 ; 許學全

E-mail: 9608326@mail.dyu.edu.tw

ABSTRACT

The purpose of this study is to investigate the structure, mechanical properties and grindability of a series of binary Ti-Cr alloys with Cr contents ranging from TiC1-TiC5 wt% were investigated, with the aim of developing a dental titanium alloy. In addition, this study was also to evaluate the bond strength of experimental binary Ti-Cr alloys to dental porcelain. Through SEM with energy-dispersive spectrometry (EDS), the bonding interface between metal and porcelain substrates after the bending test was also observed. In addition, the CTE values of the Ti-Cr alloys and c.p. Ti was also evaluated. Experimental results indicated that the structure of Ti-Cr alloys is sensitive to the Cr content. The cast c.p. Ti has a hexagonal α phase. With TiC1, metastable β phase starts to be retained. With Cr contents higher than TiC2, the equi-axed β phase is almost entirely retained. In addition, athermal ω phase was found in the TiC1 and TiC2 alloys. The largest quantity of ω phase and highest microhardness were found in TiC2 alloy. The grinding rate of the Ti-Cr alloys showed a similar tendency with the microhardness. The TiC2 alloy exhibited the best grindability, especially at 1000 m/min, which presumably due to the brittle nature of the alloy containing the ω phase in the β matrix. The bending strength of the TiC3 alloy was about 1.8 times greater than for c.p. Ti. TiC2 alloy had relatively higher bending strength almost near the TiC3 alloy. This is believed to be a result of the strengthening effect of ω phase. From SEM fractographs, the TiC2 alloy was featured by coarse cleavage facets in the fracture surface together with some terrace-type morphology. The TiC3 exhibited ductile properties, but not for alloys with other compositions. In addition, the elastic recovery capability of TiC3 alloy was greater than that of c.p. Ti by as much as 460%. From the unpolished optical micrographs, the surfaces of TiC3 alloys were covered with large amounts of slip bands. It showed that the deformation of TiC3 alloy was dominated by slip of dislocations. By judging from the results of mechanical properties and deformation behavior, TiC3 is considered to be the most expected alloy for prosthetic dental applications if other properties necessary for dental casting are obtained. The bond strengths of all the Ti-Cr alloys were higher than that of c.p. Ti. Except TiC1 and TiC2 alloys, the bond strengths of all the other Ti-Cr alloys exceeded the lower limit value in the ISO 9693 standard for the 3-point bending test (25 MPa). On the other hand, c.p. Ti surface after debonding exhibited the least amount of retained porcelain on the metal surface, and mainly adhesive bond failure. However, more traces of retained porcelain were observed on specimens that contained higher alloying elements, such as TiC4 and TiC5 alloys, attesting to a better mechanical performance. In addition, the CTE of the Ti-Cr alloys ranged from 10.0×10-6/oC (TiC2) to 11.8×10-6/oC (TiC5), and were higher than that for c.p. Ti (10.1×10-6/oC). The TiC5 alloy had significantly higher bond strength than the other Ti-Cr alloys and c.p. Ti. It was concluded that the difference in the CTE between TiC5 alloy and Duceratin porcelain is less than 1×10-6/oC, ratifying the data obtained by bond strength testing.

Keywords : Titanium alloy ; Structure ; Mechanical property ; ω phase ; Grindability ; Bong strength ; Thermal expansion coefficient

Table of Contents

REFERENCES

[1] Inglis A.E.,“ Advances in implant arthroplasty in the upper extremity, circa 1988 ”, Clinical & Experimental Rheumatology, 7(3):141-144, 1989.

[2] Ravaglioli A. and Krajewski A.,“ Bioceramics materials ”, Properties, Applications. Chapman and Hall, pp. 81-99, 1992.

[3] Rateitschak K.H. and Wolf H.F.,“ Color atlas dental medicine ”, Thieme Medical Publishers, pp. 11-24, 1995.

[4] Block M.S., Kent J.N. and Guerra L,S.,“ Implants in dentistry ”, Philadelphia: Saunders, pp. 45-62, 1997.

[5] Park J.B. and Lakes R.S.,“ Biomaterials: an introduction ”, Plenum Press, 2nd ed., New York, 1992.

[6] Okazaki Y., Ito Y., Kyo K. and andtateishi T.,“ Corrosion resistance and corrosion fatigue strength of new titanium alloys for medical implants without V and Al ”, Mater. Sci. Eng., v213, pp. 138-147, 1996.

[7] Okazaki Y., Rao S., Ito Y., and Tateishi T.,“ Corrosion resistance, mechanical properties, corrosion fatique strength and cytocompatibility of new Ti alloys without Al and V ”, Biomaterials, 19:1197-1215, 1998.

[8] Hench L.L. and Ethridge E.C.,“ Biomaterials - an Interfacial approach, ” Acdamic Press, New York, pp. 18-21, 1982.

[9] Hench L.L.,“ Bioceramics: from concept to clinic ”, J. Am. Ceram. Soc., 74(17):1487-1510, 1991.

[10] Doremus R.H.,“ Review bioceramics ”, J. Mater. Sci., 27(3):287-297, 1992.

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

[12] 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(4):1039-1047, 1990.

[13] Williams D.F.,“ Biocomatibility of Clinical implant materials ”, v2, CRC press, Inc. Boca Raton, Florida, pp. 112, 1981.

[14] Mckellop H.A. and Rostlund T.V.,“ The wear behavior of ion-implanted Ti-6Al-4V against UHMW polyethylene ”, J. Biomed. Mater. Res., 24:1413-1425, 1990.

[15] Combe E.C., Trevor Burke F.J. and Douglas W.H.,“ Dental biomaterials ”, Boston: Kluwer Academic Publishers, pp. 476, 1999.

[16] Moffat D.L. and Larbalestier D.C.,“ The competition between Martensite and Omega in Quenched Ti-Nb. Alloys, ” Metall. Trans., A19(7):1677-1686, 1988.

[17] Covington L.C.,“ Corrosion resistance of titanium ”, Metals Handbook, 9th, ASM publications, Ohio, 3:413-415, 1979.

[18] Donachie M.J.,“ Titanium and titanium alloys source book ”, Metals Park, OH: The American Society for Metals, pp. 10-19, 1982.

[19] 草道英武,“ 金????????用 ”, 日刊工業新聞社, 東京, 日本, 1983.

[20] Brobst D.A. and Pratt W.P.,“ United states mineral resources: U.S. geological survey professional paper ”, No: 820, pp. 662, 1973.

[21] 蔡幸甫,“ 鈦及鈦合金工業之應用及現況 ”, 工業材料, 145期, pp. 68-70, 1999, [22] Collings E.W.,“ The physical metallurgy of titanium alloys ”, Metals Park, OH: The American Society for Metals, pp. 3-5, 1984.

[23] Burgers W.G., " On the process of transition of the cubic-body-centered modification into the hexagonalclose-packed modification of zirconium " , Physica, 1:561-586, 1934.
[24] Kahles J.F., Field M., Eylon D. and Froes F.H., " Machining of titanium alloys " , J. Met., 37(4):27-35, 1985.
[25] Blenkinsop P.A., " High temperature titanium alloys " , IMI Titanium Limited, Birmingham, England, pp. 189-198, 1986.
[26] Machado A.R. and Wallbank J., " Machining of titanium and its alloys - a review " , Proc. Inst. Mech. Eng. B, 204(1):53-60, 1990.
[27] Borradaile J.B. and Jeal R.H., " Mechanical properties of titanium alloys " , Warrendale: Metallurgical society of AIME, vols. 1-3, 1980.
[28] Blenkinsop P.A., " IMI Titanium, Commercially pure titanium " , Kynoch Press, Birmingham, England, 1978.
[29] Brick R.M., Pense A.W. and Gorden R.B., " Structure and properties of engineering materials " , McGraw Hill, New York, pp. 234-253, 1997.
[30] Frost P.D., Parris W.M., Hirsch L.L., Doig J.R. and Schwartz C.M., " Isothermal transformation of titanium-chromium alloys " , Trans. ASM, 46:231-256, 1953-1954.
[31] Lin W., Spalt H. and Batterman B.W., " Study of the ω phase in Zr-Nb alloys by Mossbauer and x-ray diffuse scattering " , Physical Review B (Solid State), v13, pp. 5158-5169, 1976.
[32] Silock J.M., Davies M.H. and Hardy H.K., " Monography and report series No. 18 " , Inst. Of Metals, London, pp. 93, 1956.
[33] Blackburn M.J. and Williams J.C., " Phase transformation in Ti-Mo and Ti-V alloys " , Trans. Metall. Soc. AIME, 242:2461-2469, 1968.
[34] Sikka S.K., Vohra Y.K. and Chidambaram R., " Omega phase in material " , Progr. Mater. Sci., 27:245-310, 1982.
[35] Silcock J.M., " An x-ray examination of the ω phase in TiV, TiMo and TiCr alloys " , Acta. Metall., 6:481-493, 1958.
[36] Pack H.J., Kalish D. and Fike K.D., " Stability of as-quenched beta-Ⅲtitanium alloys " , Mater. Sci. Eng., 6:181-198, 1970.
[37] Ohmori Y., Natsui H., Nakai K. and Ohtsubo H., " Effects of ω phase formation on decomposition of α"/β duplex phase structure in a metastable β Ti alloy " , Mater. Trans. JIM, 39(1):40-48, 1998.
[38] Bagariaskii I.A., Nosova G.I. and Tagunova T.V., " Factors in the formation of metastable phase in titanium-based alloys " , Sov. Phys. Dokl., 3:1014-1018, 1959.
[39] Hickman B.S., " Omega phase precipitation in alloys of titanium the transition metals " , Trains. AIME, 45:1329-1335, 1969.
[40] Kawhara K., " Cytotoxicity of implantable metals and alloys " , Bull. Jpn. Inst. Met., 31:1033-1039, 1992.
[41] Steinemann S.G., " Surgical implant and alloy for use in making an implant " , US Patent No, 4040129, 1977.
[42] Murray J.L., " Phase diagrams of binary titanium alloys " , v15, ASM International, Metals Park, Ohio, 1987.
[43] Duwez P. and Taylor J.L., " A partial titanium-chromium phase diagram and the crystal structure of TiCr2 " , Trans. ASM, 44:495-513, 1952.
[44] Thyne van R.J., Kessler H.D. and Hanse M., " The system titanium-chromium and titanium-lron " , Trans. ASM, 44:974-989, 1952.
[45] Takemoto S., Hattori M., Yoshinari M., Kawada E., Asami K. and Oda Y., " Corrosion behavior and surface characterization of Ti-20Cr alloy in a Solution confining fluoride " , Dent. Mater. J., 23(3):379-386, 2004.
[46] Pourbaix M., " Electrochemical corrosion of metakkic biomaterials " , Biomaterials, 4:122-134, 1984.
[47] Richard V.N, " Introduction to dental materials " , Publisher: Mosby, 2nd ed., 2002.
[48] Craig R.G., " Restorative dental materials " , Mosby-Year Book, Inc., 9th ed., 1993.
[49] Anusavice K.J., " Dental ceramics " , Philips ' Science of Dental Materials, 10th ed., pp. 583-618, 1996.
[50] Zinelis S., Tsetsekou A. and Papadopoulos T. " Thermal expansion and microstructural analysis of experimental metal-ceramic titanium alloys " , J. Prosth. Dent., 90(4):332-338, 2003.
[51] Christensen G.J., " The use of porcelain-fused-to-metal restorations in current dental practice: a survey " , J. Prosth. Dent., 56(1): 1-3, 1986.
[52] Robert G., " Dental materials: Properties and manipulation " , Philadelphia: Hanley and Belfus, 8th ed., 2003.
[53] Mclean J.W., " Evolution of dental ceramics in the twentieth century " , J. Prosth. Dent., 85(1):61-66. 2001.
[54] Ozcan M., " Fracture reasons in ceramic-fuses-to-metal restorations " , J. Oral. Rehabil, 30(3):265-269, 2003.
[55] Kononen M. and Kivilahti J., " Fusing of dental ceramics to titanium " , J. Dent. Res., 80(3):848-854, 2001.
[56] Yilmaz H. and Dincer C., " Comparison of the bond compatibility of titanium and an NiCr alloy to dental porcelain " , J. Dent., 27(3):215-222, 1999.
[57] Kimura H., Horning C.J. and Okazak M.I., " Oxidation effect on porcelain-titanium interface reaction and bond strength " , Dent. Mater. J., 9:91-99, 1990.
[58] Akagi K., Okamoto Y., Matsuura T. and Horibe, T. " Properties of test metal ceramic titanium alloys " , J. Prosth. Dent., 68, 462-467, 1992.
[59] Asgar K. and Peyton F.A., " Effect of microstructure on the physical properties of cobalt-base alloys " , J. Dent. Res., 40:63-72, 1961.
[60] Allan F.C. and Asgar K., " Reaction of cobalt-chromium casting alloy with investment " , J. Dent. Res., 45:1516-1528, 1966.
[61] Geurtsen W., " Biocompatibility of dental casting alloys " , Crit. Rev. Oral. Biol. Med., 13(1):71-84, 2002.
[62] Fenton A.H. and Jeffrey J.D., " Allergy to a partial denture casting: case report " , J. Can. Dent. Assoc., 44(10):466-468, 1978.
[63] Jones T.K., Hansen C.A., Singer M.T. and Kessler M.P., " Dental implications of nickel hypersensitivity " , J. Prosth. Dent., 56(4):507-509, 1986.

[64] Kononen M. and Kivilahti J.,“ Bonding of low-fusing dental porcelain to commercially pure titanium ”, J. Biomed. Mater. Res., 28(9):1027-1035, 1994.
[65] Zitter H.,“ Corrosion behavior and biocompatibility of titanium alloys for implants ”, Werkstoffe and Corrosion, 39(12):574-582, 1988.
[66] Anusavice K.J.,“ Science of dental materials ”, Philadelphia: WB Saunders Co., 10th ed., 1996.
[67] Bagby M., Marshall S.J. and Marshall G.W.,“ Metal ceramic compatibility: A review of the literature ”, J. Prosth. Dent., 63(1):21-25, 1990.
[68] Kautz K.,“ Further data on enamel adherence ”, J. Am. Ceram. Soc., 19(4):19-93, 1936.
[69] Mackert J.R., Parry E.E., Hashinger D.T. and Fairhurst C.W.,“ Measurement of oxide adherence to PFM alloys ”, J. Dent. Res., 63:1335-1340, 1984.
[70] Mackert J.R., Ringle R.D., Parry E.E., Evans A.L. and Fairhurst C.W.,“ The relationship between oxide adherence and porcelain-metal bonding ”, J. Dent. Res., 67:474-478, 1988.
[71] Ibrahim AI Hussanini. and Khalid A. Al Wazzan.,“ Effect of surface treatment on bond strength of low-fusing porcelain to commercially pure titanium ”, J. Prosth. Dent., 94:305-356, 2005.
[72] O ’ Brien W.J. and Ryge G.,“ Relation between molecular force calculation and observed strengths of enamel-metal interfaces ”, J. Am. Ceram. Soc., 47(1):5-8, 1964.
[73] Lin Z. and Welsch G.E.,“ Effects of oxygen and heat treatment on the mechanical properties of alpha and beta titanium alloys ”, Metal. Trans. A, 19(5):527-542, 1988.
[74] Adachi M., Mackert J.R., Parry E.E. and Fairhurst C.W.,“ Oxide adherence and porcelain bonding to titanium and Ti-6Al-4V alloy ”, J. Dent. Res., 69(6):1230-1235, 1990.
[75] Kofstad P., Hauffe K. and Kjollesdal H.,“ Investigation on the oxidation mechanism of titanium ”, Acta. Chem. Scand., 12(2):239, 1958.
[76] Cai Z., Bunce N., Nunn M.E. and Okabe T.,“ Porcelain adherence to dental cast CP titanium: Effects of surface modifications ”, Biomaterials, 22(9):979-986, 2001.
[77] De?rand T. and Hero H,“ Bond strength of porcelain on cast vs. wrought titanium ”, Scand. J. Dent. Res., 100(3):184-188, 1992.
[78] Tesch U., Sandig S.C. and Mann E.,“ Metallische werkstoffe in der zahnarztlichen prothetik Ein Symposium in Erfurt ”, Die Quintessenz, 44:373-380, 1993.
[79] Yoda M., Konno T., Takada Y., Iijima K., Griggs J., Okuno O., Kimura K. and Okabe T.,“ Bond strength of binary titanium alloys to porcelain ”, Biomaterials, 22:1675-1681, 2001.
[80] Giordano R.A.,“ Dental ceramic restorative systems ”, Compend. Contin. Educ. Dent., 17(8):779-86, 1996.
[81] Reyes M.J.D., Oshida Y., Andres C.J., Barco T., Hovijitra S. and Brown D.,“ Titanium-porcelain system. Part III: Effects of surface modification on bond strengths ”, Biomed. Mater. Eng., 11(2):117-136, 2001.
[82] Fung L.W.,“ A study on bond strength of fired porcelain on nitrided-pure titanium (Thesis) ”, Indiana University School of Dentistry. Indianapolis, 1994.
[83] 菊地聖史, 奥野攻,“ ?科用快削???合金?開? ”, 第19回日本歯科??????術講演?, 10月, 福島, 日本, p. 8-13, 2006.
[84] Takeyama H. and Murata R.,“ Study on machinability of pure titanium ”, J. Jpn. Soc. Preci. Eng., 28(6):331-337, 1962. (in Japanese) [85] Metals handbook desk edition. Metals Park. OH: American Society for Metals. p. 1-24, 1984.
[86] 竹山秀彦,“ 切削加工 ”, 丸善株式?社, 東京, 日本, 1997.
[87] 李鈞澤,“ 切削刀具學 ”, 文京圖書, 台北, 台灣, pp. 130, 1995.
[88] Donachie M.J.,“ Titanium: A technical guide ”, ASM. pp. 79-84, 2000.
[89] Ida K., Togaya T., Tsutsumi S. and Takeuchi M.,“ Effect of magnesia investments in the dental casting of pure titanium and titanium alloys ”, Dent. Mater. J. 1(1):8-21, 1982.
[90] Taira M., Moser J.B. and Greener E.H.,“ Studies of Ti alloys for dental castings ”, Dent. Mater., 5(1):45-50, 1989.
[91] ?????協?,“ ????加工技術 ”, 日刊工業, pp. 19-68, 1992.
[92] 狩野勝田,“ 機械?工具 ”, 11月, pp. 97-104, 1999.
[93] 狩野勝田,“ 機械?工具 ”, 12月, pp. 89-96, 1999.
[94] Ezugwu E.O. and Wang Z.M.,“ Titanium alloys and their machinability - A review ”, J. Mater. Proc. Tech., 68(3):262-274, 1997.
[95] Takeyama H. and Murata R.,“ Temperature dependence of tool wear ”, J. Jpn. Soc. Preci. Eng., 27(1):33-38, 1961. (in Japanese) [96] Araki T. and Yamamoto S.,“ Nansaku zairyo to hisakusei ”, Kikai Gijutsu, 21(8):22-27, 1973. (in Japanese) [97] Kikuchi M., Takahashi M., Okabe T. and Okuno O.,“ Grindability of dental cast Ti-Ag and Ti-Cu alloys ”, Dent. Mater. J., 22(2):191-205, 2003.
[98] 木村篤良, 中村貞行,“ 日本金????報 ”, 27:397-399, 1988.
[99] Takahashi M., Kikuchi M., Takada Y. and Okuno O.,“ Mechanical properties and microstructures of dental cast Ti-Ag and Ti-Cu alloys ”, Dent. Mater. J., 21(3):270-280, 2002.
[100] Takada Y., Nakajima H., Okuno O. and Okabe T.,“ Microstructure and corrosion behavior of binary titanium alloys ”, Dent. Mater. J., 20(1):34-52, 2001.
[101] Miyawaki H., Taira M., Wakasa K. and Yamaki M.,“ Dental high-speed cutting of four cast alloys ”, J. Oral. Rehabil., 20(6):653-661,

1993.
[102] Komatsu S. and Ikeda M., “ Thermal conductivity and electrical resistivity of titanium and its alloys ” , Titanium Japan, 46(4):1-4, 1998.
[103] Baker H., “ Properties of pure metals-Silver ” , Metals Handbook 9th ed, v2 Properties and selection: Nonferrous alloys and pure metals, ASM Int, Metals Park, OH, 794-796, 1997.
[104] Okabe T., Ohkubo C., Watanabe I., Okuno O. and Takada Y., “ The present status of dental titanium casting ” , J. Metals., 50:24-29, 1998.
[105] Ohkubo C., Watanabe I., Ford J.P., Nakajima H., Hosoi T. and Okabe T., “ Machinability of cast Ti and Ti-6Al-4V alloy ” , J. Dent. Res., 77:165, 1998.
[106] Watanabe I., Ohkubo C., Ford J.P., Atsuta M. and Okabe T., “ Cutting efficiency of air-turbine burs on cast titanium and dental casting alloys ” , Dent. Mater., 16:420-425, 2000.
[107] Koike M., ltoh M., Okuno O., Kimura K., Takeda O., Okabe T.H. and Okabe T., “ Evaluation of Ti-Cr-Cu alloys for dental applications ” , J. Mater. Eng. Perform., 14(6):778-783, 2005.
[108] Kikuchi M., Takahashi M. and Okuno O., “ Mechanical properties and grindability of dental cast Ti-Nb alloys ” , Dent. Mater. J., 22(3):328-342, 2003.
[109] Koike M., Ohkubo C., Sato H., Fujii H. and Okabe T., “ Evaluation of cast Ti-Fe-O-N alloys for dental applications ” , Mater. Sci. Eng., 25(3):349-356, 2005.
[110] Okabe T., Kikuchi M., Ohkubo C., Koike M., Okuno O. and Oda Y, “ Cost-Affordable titanium symposium dedicated to professor harvey flower ” . TMS, Warrendale, PA, 177, 2004.
[111] ANSI/ADA Specification No: 14. “ Dental base metal casting alloys ” , American Dental Association, Chicago, 1982.
[112] Vander Voort G.F., “ Metallography principles and practice ” , McGraw-Hill, U.S.A., pp. 449, 1984.
[113] American Society of Testing and Materials. “ Annual book of ASTM standards ” , Section 3:03.01, E112-96, Philadelphia, PA, 1998.
[114] Guha A. “ Metals handbook ” , 9th ed., v8. edited by Boy H.E. and Gall T.L., American Society for Metals, Metals Park, pp. 133-136, 1985.
[115] Ho W.F., Ju C.P. and Chern Lin J.H., “ Structure and properties of cast binary Ti-Mo alloys ” , Biomaterials, 20:2115-2122, 1999.
[116] Prosbter L., Maiwald U. and Weber H., “ Three-point bending strength of ceramics fused to cast titanium ” , Eur. J. Oral. Sci., 104(3):313-319, 1996.
[117] Ohkubo C., Watanabe I., Ford J.P., Nakajima H., Hosoi T. and Okabe T., “ The machinability of cast titanium and Ti-6Al-4V alloy ” , Biomaterials, 21(4):421-428, 2000.
[118] Watanabe I., Kiyosue S., Ohkubo C., Aoki T. and Okabe T, “ Machinability of cast commercial titanium alloys ” , J. Biomed. Mater. Res., A63(6):760-764, 2002.
[119] Kikuchi M., Takada Y., Kiyosue S., Yoda M., Woldu M., Cai Z., Okuno O. and Okabe T., “ Grindability of cast Ti-Cu alloys ” , Dent. Mater., 19(5):375-381, 2003.
[120] Takahashi M., Kikuchi M. and Okuno O., “ Mechanical properties and grindability of experimental Ti-Au alloys ” , Dent. Mater. J., 23(2):203-210, 2004.
[121] Ohkubo C., Hosoi T., Ford J.P. and Watanabe I., “ Effect of surface reaction layer on grindability of cast titanium alloys ” , Dent. Mater., 22(3):268-274, 2006.
[122] Kikuchi M., Takahashi M., Sato H., Okuno O., Nunn M.E. and Okabe T., “ Grindability of cast Ti-Hf alloys ” , J. Biomed. Mater. Res. B. Appl. Biomater., 77(1):34-38, 2006.
[123] Porter L.F. and Rosenthal P.C., “ Factors affecting fluidity of cast irons ” , Trans AFS, 60:725-739, 1952.
[124] Ragone D.V., Adams C.M. and Taylor H.F., “ A new method for determining the effect of solidification range on fluidity ” , Trans AFS, 64:653-657, 1956.
[125] Campbell J., “ Review of fluidity concepts in casting ” , Cast Metals, 7(4):227-237, 1994.
[126] Niesse J.E., Flemings M.C. and Taylor H.F., “ Application of theory in understanding fluidity of metals ” , Trans AFS, 67:685-796, 1959.
[127] Cheng W.W., Ju C.P. and Chern Lin J.H., “ Structure castability and mechanical properties of commercially pure and alloyed titanium cast in graphite mould ” , J. Oral. Rehabil., 30:1-13, 2003.
[128] William D.C., “ Materials science and engineering: an introduction ” , John Wiley & Sons, New York, 2003.
[129] Ageev N.V., Karpinskii O.G. and Petrova L.A., “ Stability of the β-solid solution of titanium-chromium alloys ” , Zh. Neorg. Khim., 6, 1976. (in Russian) [130] Williams J.C., “ Critical review: Kinetics and phase transformations ” , Titanium Science and Technology, Plenum Press, New York, pp. 1445, 1450, 1462, 1973.
[131] William D.C., “ Materials science and engineering: an integrated approach ” , John Wiley & Sons, New York, pp. 255-256, 2003.
[132] Saha R.J., Handy T.K., Misra R.D.K. and Jacob K.T., “ On the evaluation of stability of rare earth oxides as face coats for investment casting of titanium ” , Metall. Trans. B, 21(3):559-566, 1990.
[133] Frueh C., Poirier D.R. and Maguire M.C., “ The effect of sicilica-containing binders on the titanium/face coat reaction ” , Metallurgical

and Materials Transactions B, 28:919-926, 1997.
[134] Suzuki K., Nishikawa K. and Watakabe S., “ Stability of yttria for titanium alloy precision casting mold ” , Mater. Trans. JIM, 38(1):54-62, 1997.
[135] Saha R.L. and Misra R.D.K., “ Formation of low-melting eutectic at the metal-mould interface during titanium casting in zircon sand moulds ” , J. Mater. Sci. Lett., 10:1318-1319, 1991.
[136] Bagariaskii I.A., Nosova G.I. and Tagunova T.V., “ Factors in the formation of metastable phase in titanium-base alloys ” , Sov. Phys. Dokl., 30:1014-1018, 1959.
[137] Combe E.C., “ Notes of dental materials ” , Churchill Livingston, Edinburgh, 6th ed., 64, 1992.
[138] Williams J.C., Hickman B.S. and Marcus H.K., “ The effect of omega phase on the mechanical properties of titanium alloys ” , Metall. Trans., 2:1913-1919, 1971.
[139] Lin D.J., Chern Lin J.H. and Ju C.P., “ Structure and properties of Ti-7.5Mo-xFe alloys ” , Biomaterials, 23:1723-1730, 2002.
[140] Benes F., “ Effect of antimony and tin on temper brittleness of Cr-V steel, (Vliv antimonu a cinu na popousteci krehkost) ” , Hutn Listy, 26(9):639-646, 1971.
[141] Kikuchi M., Takada Y., Kiyosue S., Yoda M., Woldu M., Cai Z., Okuno O. and Okabe T., “ Mechanical properties and microstructures of cast Ti-Cu alloys ” , Dent. Mater., 19:174-181, 2003.
[142] Lammie G.A. and Laird W.R.E., “ Osborne & Lammie ’ s partial dentures ” , London: Blackwell Scientific, 5th ed., pp. 190-192, 1986.
[143] Bobyn J.D., Mortimer E.S., Glassman A.H., Engh C.A., Miller J. and Brooks C., “ Producing and avoiding stress shielding: laboratory and clinical observation of noncemented total hip arthroplasty ” , Clin. Orthop., 274:79-96, 1992.
[144] Kuroda D., Niinomi M., Morinaga M., Kato Y. and Yashiro T., “ Design and mechanical properties of new β type titanium alloys for implant materials ” , Mater. Sci. Eng. A, 243(1-2):244-249, 1998.
[145] Niinomi M., “ Mechanical properties of biomedical titanium alloys ” , Mater. Sci. Eng. A, 243(1-2):231-236, 1998.
[146] Wang K., “ The use of titanium for medical applications in the U.S.A. ” , Mater. Sci. Eng. A, 213(1-2):134-137, 1996.
[147] Blackman R.B., “ Evaluation of the dimensional changes and surface roughness of gold crowns cast with rapidly prepared phosphate-bonded investment: a pilot study ” , J. Prosth. Dent., 82(2):187-193, 2000.
[148] Garbelini W.J., Henriques G.E.P., Troia M., Mesquita M.F. and Dezan C.C., “ Evaluation of low-fusing ceramic system combined with titanium grades Ⅱ and V by bending test and scanning electron microscopy ” , J. Appl. Oral. Sci., 11(4):354-60, 2003.
[149] ISO 9693: 1999(E), “ Metal-ceramic dental restorative systems ” , 2nd ed., Switzerland, International Organization for Standardization, 1999.
[150] Johnson T., Noort R.V. and Stokes C.W. “ Surface analysis of porcelain fused to metal systems ” , Dent. Mater., 22(4):330-337, 206.
[151] Kurisaki Y. and Nagayama K., “ Influence of metal elements in Pd alloys on the bonding to porcelain ” , Shika Zairyo Kikai, 9:11-29, 1990. (English abstract) [152] Papadopoulos T., Tsetsekou A. and Eliades G., “ Effect of aluminium oxide sandblasting on cast commercially pure titanium surfaces ” , Eur. J. Prosthodont Restor Dent., 7:15-21, 1999.
[153] Tro?ia Jr. M.G., Henriques G.E.P., No?bilo M.A.A. and Mesquita M.F., “ The effect of thermal cycling on the bond strength of low-fusing porcelain to commercially pure titanium and titanium-aluminium-vanadium alloy ” , Dent. Mater., 19(8):790-796, 2003.
[154] O ’ Brien W.J., “ Cohesive plateau theory of porcelain-alloy bonding. Conference Proceedings ” , University of Southern California. Dental Porcelain-State of the Art, 1977.
[155] Boning K. and Walter M., “ Ceramo-metallic bond of cast titanium ” , Dtsch Zahnarztl Z, 46:750-753, 1991.
[156] Wagner W.C., Asgar K., Bigelow W.C. and Flinn A., “ Effect of interfacial variables on metal-porcelain bonding ” , J. Biomed. Mater. Res., 27:531-537, 1993.
[157] Wu Y., Moser J.B., Jameson L.M. and Malone W.F.P., “ The effect of oxidation heat treatment on porcelain bond strength in selected base metal alloys ” , J. Prosth. Dent., 66:439-44, 1991.
[158] Narayanan G.H., Luhman T.S., Archbold T.F., Taggart R. and Polonis D.H., “ A phase separation reaction in a binary titanium-chromium alloy ” , Metallography, 4:343-358, 1971.
[159] Chandrasekaran V., Taggart R. and Polonis D.H., “ Decomposition processes prior to detection of the ω phase in aged Ti-Cr alloys ” , Metallography, 6(4):313-322, 1973.
[160] Weast, R.C., “ Handbook of chemistry and physics ” , CRC Press Inc., 63rd edn, Florida., pp. D-191, 1982.
[161] Togaya T., Suzuki M., Tsutsumi S. and Ida K., “ An application of pure titanium to the metal porcelain system ” , Dent. Mater. J., 2(2):210-219, 1983.
[162] Kimura H., Horng C.J., Okazaki M. and Takahashi J., “ Thermal compatibility of titanium-porcelain system ” , Journal of the Osaka University Dental School, 30:43-52, 1990.
[163] Hautaniemi J.A. and Hero H., “ Effect of crystalline leucite on porcelain bonding on titanium ” , J. Am. Ceram. Soc., 74:1449-1451, 1991.
[164] Boyer, H.E. and Gall, T.L., “ Metals Handbook Desk edn ” , American Society for Metals, Ohio., pp. 1-48, 1995.
[165] Boyer R., Welsch G. and Collings E.W., “ Materials properties handbook: titanium alloys ” , 1st edn ASM International, Ohio. pp. 221,

1994.
[166] Anusavice K.J.. “ Phillip's Science of Dental Materials ”, Saunders Company, Philadelphia, 10th edn, pp. 45-493, 1996.
[167] Fairhurst C.W., Anusavice K.J., Hashinger D.T., Ringle R.D. and Twiggs S.W., “ Thermal expansion of dental alloys and porcelain ”, J. Biomed. Mater. Res., 14:435-436, 1980.
[168] Nielsen J.P. and Tuccillo J.T., “ Calculation of interfacial stress in dental porcelain bonded to gold alloy substrate ”, J. Dent. Res., 51:1043-1047, 1972.
[169] Ammen C.W., “ The Metalcaster ’ s Bible ”, McGraw Hill, PA, U.S.A., 1980.
[170] Ashiura Y. and Motonishi S., “ Machining, fabrication technique of titanium ”, Japan Titanium Society, Tokyo, pp. 19-50, 1992. (in Japan)
[171] Miyakawa O., “ Reactivity of titanium with abrasive materials and its polishing ”, J. Jpn. Prosthodont Soc., 42(4):540-546, 1998. (in Japan)
[172] Narutaki N. and Murakoshi A., “ Study on machining of titanium alloys ”, Annals CIRP, 321:65-69, 1983.
[173] Chandler H.E., “ Machining of reactive metals ”, Metals Handbook 9th ed., v16 Machining, ASM Int., Metals Park, OH, pp. 844-846, 1989.
[174] 洪良德, “ 切削刀具學 ”, 全華科技圖書, 台北, 台灣, pp. 60-63, 1992.
[175] 徐明堅, “ 最新切削加工技術 ”, 復漢出版社, 台南, 台灣, pp. 179-182, 1992.
[176] Dahn C.J., “ Explosivity and pyrophoricity of metal powders ”, Metals Handbook 9th ed., v7 Powder Metallurgy, ASM Int., Metals Park, OH, pp. 194-200, 1989.