Effect of sintering temperature on the microstructure and mechanical properties of the Ti-2.5Zr alloy

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Abstract
Zirconium effectively became an emerging alloying element used for titanium in order to improve its mechanical properties by Ti grains refinement and solid solution strengthening effects. As a result, Ti-Zr alloy enhances its industrial applications. In this study the titanium powders were sintered after the addition of 2.5 wt% of Zr using Spark Plasma Sintering (SPS) technology. The original pre-mixed powder consists of pure Ti and ZrH2 particles. An applied pressure of 40 MPa and a short sintering time of 5 min were fixed in all experiments under a vacuum of 1 Pascal. EDS, XRD and XPS analysis showed that Zr dispersion as solid solution through α-Ti was homogenized for sintered samples at 1000 °C and 1200 °C while the agglomeration of ZrH2 was detected in the sample sintered at 800 °C. These agglomerated particles reduced the average Zr content through titanium matrix compared to an average of 2.3 to 2.7 wt% for samples sintered at 1000 °C and 1200 °C. The hardness increases with the increase in the sintering temperature. However, since the sample sintered at 1200 °C showed an excessive grain growth that reduced its strength, it was found that 1000 °C sintering temperature can be an optimum temperature for this process.

1. Introduction

Titanium has high specific strength, good ductility, high corrosion resistance and biocompatibility. These excellent properties made titanium and its alloys a replacement of steels in many industrial applications [1–3]. Strengthening of commercially pure titanium by alloying elements such as aluminium, vanadium, molybdenum, and zirconium resulted in widening the scope of its applications. In addition, it was reported that ubiquitous elements like hydrogen, oxygen and nitrogen form interstitial solid solutions that would improve both strength and ductility if proper compositions and uniform distributions were acquired [4–8]. Recent research studies showed that Zr as a substitutional element in the α-Ti beside its biocompatibility enhances the mechanical properties of commercially pure titanium [9–11]. Some researchers focused on the effect of Zr on the application of Ti-Zr in dental implants that require sufficient metallic biomaterial to reduce the component size [12, 13]. Other studies focused on the effect of the Zr solutes on the microstructure and mechanical properties of the Ti-Zr alloy. For example, Ti-10% Zr was introduced as a spectacle frame to replace Ni based alloy due to its high strength and biocompatibility [14]. However, from the scientific literature it was noticed that alloying titanium by zirconium although resulted in improving strength and hardness, it was reported that the more Zr addition the less elongation and ductility we achieve for the Ti-Zr alloy. The presence of interstitial atoms such as N and O further increase the strength on the expense of ductility [15]. Therefore, it is desirable to fabricate a Ti-Zr alloy with low zirconium content in order to increase the strength and preserve the ductility of the titanium alloy at the same time. In this study, Spark Plasma Sintering technology (SPS) was applied to fabricate Ti with 2.5% Zr at various temperatures in order to investigate the effects on the microstructure and
mechanical properties. SPS is a widely used technique for powder sintering for both conductive and non-conductive materials \cite{16,17}. SPS has the advantages of performing rapid sintering at lower temperatures compared to hot pressing. This is due to the plasma created among powders allowing high heating rate and resulting in a homogenous bulk with minimum grain growth \cite{18}. As for titanium sintering in particular, there are successful research studies reported on SPS of titanium \cite{19–21}.

2. Experimental procedure

2.1. Sample preparation and sintering

Pure Titanium powder (purity 99.9\%, Average Particle Size 25 μm) and ZrH₂ powder (purity 99.5\%, Average Particle Size 1.05–5.05 μm) purchased from Nanografi Inc. These powders were used as initial precursor materials for the experiments. Figure 1. Shows SEM images of the powders. The two powders were first mixed using a mortar and pestle for ∼45 min. Then, the mixture was placed in a planetary ball mill (Fritsch Pulverisette 7) for 8 h at a speed of 300 rpm using stainless steel balls and agate chamber. The balls-to-powder weight ratio was 8:1.

Spark Plasma Sintering machine (SPS-210Sx from SUGA Co., Ltd, Japan) was used to sinter the samples. Each sample’s weight was adjusted to 1.1 g in order to get similar thicknesses while using a graphite die of 10 mm thickness. The powder was introduced inside the die and the chamber was evacuated till vacuum level reaches 1 pascal. Applied load of 40 MPa (3.2 kN) and a holding time of 5 min were set for each experiment. Sets of densified samples were produced at 600, 800, 1000 and 1200 °C to investigate the effect of sintering temperature. Furthermore, one extra set of samples was produced at 800 °C in 30 min sintering time.

2.2. Microstructure and mechanical evaluation

The sintered samples were separated into two sets for each condition. One set of the sintered samples was dedicated for compression test and Carbon Hydrogen Nitrogen (CHN) gas analysis. The other set of the samples was mounted in Bakelite powder (Buehler, Lake Bluff, IL, USA) then grinded using SiC paper in water to 1000 grid. The samples were then polished on fine clothes using Al₂O₃ dispersed particles gradually from 6 μm particle size till 0.5 μm size to reach mirror like surfaces. For microstructure observation and elemental analysis, A JSM-7600F field emission scanning electron microscope—FESEM- (SEM, Joel, Tokyo, Japan) was used. The samples’ surfaces were further analyzed by x-ray Photoelectron Spectroscopy (XPS), model number (JPS-9030) manufactured by JOEL company, Japan. Samples were etched for 60 s by Ar gas to remove surface contamination inside Ultra High Vacuum Chamber (UHV) of about 10⁻⁹ Torr. X-Ray Diffraction (Bruker D-8 Advance, USA) was used to identify the phases present in the sintered samples. In order to observe the grains of the sintered samples, an Olympus Optical Microscope was used. Prior to the use of optical microscope, the samples were etched by Kroll’s reagent (92 ml distilled water, 6 ml Nitric Acid, 2 ml Hydrofluoric Acid). Kroll’s reagent is used for titanium and its alloys that can reveal grains and grain boundaries when proper etching time is applied \cite{22–25}. Perkin-Elmer 2400 Series II, CHNS Analyzer was used to measure the weight percentages of N, O and H. The CHNS analyser work on the principle of Dumas Method which involves a complete and instantaneous oxidation of the sample by flash combustion. ZHVµ micro Vickers hardness tester from Zwick Roell using a load of 300 gf was applied to measure the hardness of the samples. An average of six indentations per each sample were calculated and reported. The compression test was done using computer control electronic universal Testing Machine (INSTRON 5984) using cross head speed of 0.5 mm min⁻¹ and strain rate of 2.5 × 10⁻³ s⁻¹ to evaluate the maximum compression strength of the samples.

Figure 1. SEM images of the as-received powders (a) Ti, (b) ZrH₂.
3. Results and discussion

3.1. Microstructure observations by optical and electron microscopes

Figure 2 shows the SEM image of the mixed powders before sintering where reduction of the particle sizes and agglomeration can be observed. Figure 3 shows low magnification SEM micrograph of the samples sintered at 800, 1000 and 1200 °C. The surface texture looks similar but the sample sintered at 800 °C reveals more pores and clear dispersoid spots which could indicate the presence of a different phase which differ from the base alloy. For this reason, high magnification backscattered SEM were taken for the samples with EDS spot analysis. SEM and EDS spot analysis of the dispersoids in the samples were performed. Figure 4 shows the SEM and EDS analysis for the sample sintered at 800 °C while figure 5 shows the SEM and EDS analysis for the sample sintered at 1200 °C. The dispersoid was identified by EDS spot analysis and found that it contains about 99.04% Zr with less than 1% Ti in weight %, which suggests that these regions might be an agglomeration of Zr based material (likely to be ZrH2). Note that EDS is not typically able to identify Hydrogen atoms. In contrast with figure 2, no dispersoids appeared in the samples sintered at 1000 and 1200 °C. Note that figures 2 and 3 show the SEM
backscattered images, whose contrast variation depends on the atomic number Z. The spot analysis of different regions for the sample sintered at 1200 °C found an average composition of Zr of about 2.5% throughout the sample area. This can be seen in figure 3. The EDS analysis showed the dispersoids appeared in 800 °C were different in composition compared to the dispersoids seen in higher temperature sintered samples, which have remarkably less contrast variation. The EDS spot analysis suggested that at 1000 and 1200 °C no Zr-based materials were agglomerated in the samples.

The average quantities of Zr in the sintered titanium (outside the dispersoid regions) were measured by EDS spot analysis and found that the 1000 °C and 1200 °C have an average of 2.3 to 2.5 wt% where the 800 °C sample has an average of 1 to 2 wt% of Zr. Further metallographic investigation using optical microscope after etching the samples was performed. Figure 6 shows optical micrograph of three samples after etching them by Kroll’s reagent. The grains observed in the 800 °C sample are homogenously fine and equiaxed. On the other hand, with higher temperature sintering the grains tend to grow in inhomogeneous spatial direction and took a rode like shape. Similar kind of distorted grains shape of sintered titanium at temperature above 900 °C was previously reported. The microstructure evolution was linked to the α to β allotropic phase transformation which usually starts to occur at 882 °C for pure titanium. The β phase would enhance self-diffusion due to its lower Atomic Packing Factor (APF) compared to the α phase. The higher the rate of diffusion, the higher the rate of grain growth [26, 27]. Rod-like grain shape starts to appear in the sintered sample at 1000 °C where the sample sintered at 1200 °C showed similar feature with noticeable grain growth.

### 3.2. Compositional analysis

XRD analysis was performed for the three sintered samples and lattice constants were calculated. Figure 7 shows the XRD patterns for the sintered samples at various temperatures. The hcp α-titanium phase was detected in all samples as the major phase. Weak Zr peak was also detected confirming the results obtained by EDS analysis. The peak at ~54 can be attributed to β phase according to literature [27, 28]. ZrH₂ and TiH₂ phases were observed for the sample sintered at 800 °C. These two phases were not detected for samples sintered at 1000 °C and 1200 °C suggesting a significant reduction of Hydrogen (dehydration) for these two samples. For the sake of investigating the relation between sintering temperature and the dehydration, a narrow scan XRD in the angle range 2θ between 50° and 65° were taken for the samples since this range has the significant XRD peaks of the ZrH₂ and TiH₂ phases [15]. Furthermore, additional sintered sample at 600 °C was made along with another sample made at 800 °C but with sintering time of 30 min. The objective was to investigate if more sintering
(holding) time at 800 °C might improve dehydration. Narrow scan XRD patterns of the samples sintered at 600, 800, 1000 and 1200 °C for 5 min along with the pattern of the sample sintered at 800 °C for 30 min are shown in figure 8. It was clear that the sample sintered at 800 °C would contain ZrH₂ and TiH₂ even with longer sintering
time. The two phases also appeared as expected for the sample sintered at 600 °C where no indication of these phases for samples sintered at 1000 °C and 1200 °C which support the results obtained by EDS analysis. The β titanium phase appeared more clearly in the samples sintered at 1200 °C.

Table 1 shows the lattice constants of the HCP titanium at different sintering temperatures. The a lattice constant was calculated using the Ti (100) peak located at ∼35°–35.4°. The c lattice constant was calculated using the Ti (002) peak located at ∼38°–38.6°. The calculated values agree with the values reported in the literature [29]. Calculated lattice constant shows that the α titanium which has HCP crystal structure was expanded as a result of the formation of Ti-Zr solid solution. Since the atomic weight of Zr is 91.2 u and has higher atomic size compared to Ti which has atomic weight of 47.8 u, the crystal is expected to expand as a result of substitutional solid solution. This was clearly shown in table 1 for the sample sintered at 800 °C compared to the pure Ti powder. On the other hand, the lattice constants seemed to shrink as a function of sintering time, although the distribution of Zr atoms was observed by EDS to be more homogenous when sintering temperature increase. This is well established phenomenon that relate diffusivity to temperature according to Arrhenius equation [30, 31]. In order to further investigate the reason behind the decrease of the lattice constants with increasing sintering temperature, elemental analysis using CHN analyser was performed to investigate the quantities of the elements in the samples. Although the sintering was done in vacuum of about 1 Pascal, the mixing process prior to sintering was done in air, allowing oxygen and nitrogen to be diffused into the powders. Table 2 shows the weight percentages of hydrogen, oxygen and nitrogen for the three sintered samples. The high percentage of hydrogen (0.29%) in the sample sintered at 800 °C gave extra confirmation of the presence of ZrH2 and TiH2 in this particular sample.

![Narrow XRD patterns of the sintered samples.](image)

**Table 1.** Calculated lattice constants of the HCP titanium at different sintering temperatures.

| Sintered temp. | a (Å)    | c (Å)   | c/a     |
|---------------|----------|---------|---------|
| 800 °C        | 2.9589   | 4.7190  | 1.5948  |
| 1000 °C       | 2.9258   | 4.6661  | 1.5948  |
| 1200 °C       | 2.9258   | 4.6614  | 1.5932  |
| Ti powder (ref) | 2.9390   | 4.6972  | 1.5983  |

**Table 2.** Elemental analyses of H, O and N present at the sintered samples.

| Sintered temp. | Weight | Hydrogen | Oxygen | Nitrogen |
|---------------|--------|----------|--------|----------|
| 800 °C        | 1.820 g| 0.29%    | 2.32   | 0.13%    |
| 1000 °C       | 2.010 g| 0.07%    | 0.56   | 0.11%    |
| 1200 °C       | 2.380 g| 0.02%    | 0.16   | 0.09%    |
It can be seen on the other hand that there is a reduction of these elements with respect to sintering temperature. These atoms which have much less atomic sizes compared to titanium atoms can be present in the interstitial sites of the lattice, causing strain fields and therefore increasing lattice constant \[32\]. This can explain the fact that the sample sintered at 800 °C has the most expanded lattice site since it has more O and N. With increasing sintering temperature, the interstitial atoms were observed to be decreasing and therefore the lattice constant increased due to the loss of these interstitial atoms.

XPS narrow scan analysis of the Zr regions were performed as seen in figures 6 and 7. Zr3d \[5/2\] is located at its metallic position for both 1000 °C and 1200 °C samples at 178.6 eV. For the 800 °C sample, it is shifted by \(\sim 0.5–0.6\) eV to 179.2 eV, which strongly suggests a Zr-H bond. Zr3p region is more motivating but with a weak signal. The Zr3p3/2 peak looked composed of two peaks: one with lower-energy peak at \(\sim 329.5\) eV that corresponds to the metallic Zr and another one with higher energy that possibly corresponding to Zr-H. Interestingly, the contribution of the metallic peak increases with temperature. A similar behaviour, with careful looking, might also be concluded for the Zr3d5/2 and Zr3d3/2 peaks shown in figures 9 and 10. Figure 11 shows the narrow scan XPS of Ti2p. The energy shifts between the samples were small (maximum of 0.2 eV). Ti2p3/2 was used as a reference for the energy axis at 454.0 eV. TiH2 if present should appear as a small shoulder on the Ti2p3/2 peak \[33\]. However, the small quantity of H we have in our samples might be a reason that the peak was not detected by XPS beside its narrow energy shift.

![Figure 9. XPS peaks of Zr3d for the Ti-2.5% Zr sintered at 800, 1000 and 1200 °C.](image)

![Figure 10. XPS peaks of Zr3p for the Ti-2.5% Zr sintered at 800, 1000 and 1200 °C.](image)
3.3. Microhardness and compression test evaluation

The measured hardness values of the samples were shown in figure 12. Hardness increased from 409 to 430 as the temperature increased from 800 to 1000 °C. However, the increase in hardness was smaller (430 to 436) as the temperature increased from 1000 to 1200 °C. The increase in hardness can be related to the fact that higher sintering temperature induces higher diffusion rate in the milled powder causes more necking in the powder to be formed during sintering and higher relative density to be achieved. Therefore, it enhances the overall structural integrity of the sintered components \[4, 27, 28\]. It should be noted that the hardness tests for the 800 °C sample was taken from the base material (not focusing on the dispersoids regions). This explanation agrees with EDS analysis which showed average quantities of 2.3 to 2.5 wt% of Zr for the samples sintered at 1000 and 1200 °C where a significant smaller quantity (1.2 wt%) of Zr was present in the sample sintered at 800 °C. The increase in hardness as a result of Zr addition to titanium agree with the works reported by Gulsory and El Kadiri \[34, 35\]. Both reported increasing hardness and tensile strength even though their system has 4%–5% Fe that usually impose ductility behavior of titanium by stabilizing the β phase.

Figure 13 shows the compression strength of the sintered samples. The 800 °C sample has the highest compression strength, most likely because the ZrH\(_2\) hard particles are present in the samples as dispersoids. These ZrH\(_2\) dispersoids might work as hard particles to block dislocations movement which are responsible for materials failure. The strength decreases from 1262 MPa to 1064 MPa for the samples sintered at 1000 °C and 1200 °C respectively. Both samples have comparable homogenous solution of Zr and N, O contents. However, the decrease of strength for the 1200 °C sample could be attributed to the grain growth presented in figure 4. The larger the grains, the weaker the material according to Hall-Petch relationship \[2\]. Furthermore, the stress-strain
behavior of the compression tests for the sintered samples was presented in figure 14. The graphs showed ductile behavior before fracture and this can be comparable to pure titanium stress-strain curve [36]. In the literature, alloying Ti with higher percentages of Zr usually reduced the ductility even if additional alloying elements such as Fe was added [15, 34, 35] which make a small percentage of Zr attractive to increase strength and hardness and preserve the ductility. The mechanical measurements presented here by hardness and compression tests suggest that the sintering of Ti-2.5%Zr at 1000 °C has the optimum condition compared to others. Sintering at 1000 °C allows for homogenous solid solution of Zr in titanium, removing hydrogen and therefore prevents the formation of ZrH2 and TiH2. Furthermore, no significant grain growth appeared at this sintering temperature.

4. Conclusions

Titanium with 2.5 wt% Zr were successfully sintered by SPS for 5 min at different sintering (holding) temperatures. Three sintering temperatures of the Ti-2.5Zr alloy were investigated thoroughly by SEM, OM, XRD and XPS. The samples sintered at 800 °C contain agglomerated ZrH2 and TiH2 phase where no ZrH2 or TiH2 phases were detected in the samples sintered at 1000 °C and 1200 °C implying a more homogenous dispersion of Zr through titanium for higher temperature sintering samples. The removal of hydrogen was not possible at sintering temperature of 800 °C even with 30 min sintering time. The hardness of the sintered samples increases with the increase of sintering temperature. On the other hand, the compression strength was decreasing. The reduction in compression strength of the sintered sample done at 1200 °C was attributed to the excessive grain growth. It was concluded that for this small percentage of Zr as a substitutional solute of

Figure 13. Compression test profile of the sintered samples.

Figure 14. Stress-strain curve of the compression test for sintered samples at 800, 1000 and 1200 C.
titanium, it is recommended to use 1000 °C as an optimum sintering temperature since the produced sample will have balance of good hardness, high compression strength with little grain growth. Moreover, the precipitation of ZrH₂ and TiH₂ will not occur due to the dehydration at this specific temperature.

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References

[1] Leyessa C 2002 Titanium and Titanium Alloys: Fundamentals and Applications (Hoboken, NJ, USA: Wiley) (https://onlinelibrary.wiley.com/doi/10.1002/532602119)
[2] Zhang L-C and Chen L-Y 2019 A review on biomedical titanium alloys: recent progress and prospect Adv. Eng. Mater. 21 1801215
[3] Boyer R R 1995 Titanium for aerospace: rationale and applications Adv. Perform. Mater. 2 349–68
[4] Sun B, Li S, Imai H, Mimoto T, Umeda J and Kondoh K 2013 Fabrication of high-strength Ti materials by in-process solid solution strengthening of oxygen via P/M methods Mater. Sci. Eng. A 563 95–100
[5] Kamiyama K, Kariya S, Fukuo M, Umeda J and Kondoh K 2020 Ductility improvement mechanism of Ti-6Al-4V/γO sintered Material, Mater. Trans. 61 430–7
[6] Shen J, Chen B, Umeda J and Kondoh K 2018 Microstructure and mechanical properties of CP-Ti fabricated via powder metallurgy with non-uniformly dispersed impurity solutes Mater. Sci. Eng. A 716 1–10
[7] Issariyapat A, Visuttipituk P, Song T, Umeda J, Qian M and Kondoh K 2020 Strength–ductility improvement of extruded Ti–N materials using pure Ti powder with high nitrogen solution Mater. Sci. Eng. A 779 131936
[8] Ye X, Imai H, Shen JH, Chen B, Han GQ, Umeda J, Takahashi M and Kondoh K 2017 Strengthening-toughening mechanism study of powder metallurgy Ti-Si alloy by interrupted in situ tensile tests J. Alloy. Compd. 694 381–93
[9] Steinemann S G 1980 Corrosion of surgical implant in vivo and in vitro tests Evaluation of Biomaterials ed G D Winter et al (New York: Wiley) pp 164–7
[10] Gerber H and Perren S M 1980 Evaluation of tissue compatibility of in vitro cultures of embryonic bone Evaluation of Biomaterials ed G D Winter et al (New York: Wiley) pp 307–14
[11] Williams D F and Williams R L 2004 Degradative effects of the biological environment on metals and ceramics Biomaterials Science: an Introduction to Materials in Medicine ed B D Ratner et al (Oxford: Elsevier Academic Press) pp 430–9
[12] Grandin H M, Berner S and Durst M 2012 A review of titanium zirconium (TiZr) alloys for use in endosseous dental implants Materials 5 1348–60
[13] Medvedev A E, Molotnikov A, Lapovok R, Zeller R, Berner S, Habersetzer P and Torre F D 2016 Microstructure and mechanical properties of Ti-15Zr alloy used as dental implant material J. Mech. Behav. Biomed. Mater. 62 384–98
[14] Nakasuji K and Okada M 1996 New high strength titanium alloy Ti-10%Zr for spectacle frames Mater. Sci. Eng. A 213 162–5
[15] Kondoh K, Fukuo M, Kariya S, Shiibara K, Li S, Alhazaa A and Umeda J 2021 Quantitative strengthening evaluation of powder metallurgy Ti-Zr binary alloys with high strength and ductility J. Alloys Compd. 852 169954
[16] Xie G 2013 Spark plasma sintering: a useful technique to develop large-sized bulk metallic glasses J. Powder Metall. Miner. 6 150–7
[17] Sahneh N, Hayat U and Hassan S F 2019 Recent advances and future prospects in spark plasma sintered alumina hybrid nanocomposites Nanomaterials 9 1607
[18] Diouf S and Molinari A 2012 Densification mechanisms in spark plasma sintering: effect of particle size and pressure Powder Technology 221 220–7
[19] Yang Y and Qian M 2015 Spark plasma sintering and hot pressing of titanium and titanium alloys Titanium Powder Metallurgy (Oxford, UK: Butterworth-Heinemann) pp 219–35
[20] Weston N et al 2013 Spark plasma sintering of commercial and development titanium alloy powders J. Mater. Sci. 50 4860–78
[21] Ayodele O O, Shongwe M B, Obadele B A and Olahambi P A 2019 Spark plasma sintering of titanium-based materials Spark Plasma Sintering of Materials: Advances in Processing and Applications 673–701 (https://biust.pure.elsevier.com/en/publications/spark-plasma-sintering-of-titanium-based-materials)
[22] Pederson1,2 R, Gaddam1 R and Aniti M-L 2012 Microstructure and mechanical behavior of cast Ti-6Al-4V with addition of boron Cent. Eur. J. Eng. 2 347–57
[23] Finlay W L, Resketo J and Vordahl M B 1950 Optical metallography of titanium Ind. Eng. Chem. 42 218–22
[24] Craver C B 1951 Differentiation of grain size and phases in titanium Metal Progress 59 371–3
[25] Tiley J et al 2004 Quantification of microstructural features in α/β/titanium alloys Mat. Sci. Eng. A-Struct. 372 191–8
[26] Zadra M, Casari F, Girardini L and Molinari A 2008 Microstructure and mechanical properties of cp-titanium produced by spark plasma sintering Powder Metall. 51 59–65
[27] Asl M S, Namini A S and Azadbeh M 2018 Effects of sintering temperature on microstructure and mechanical properties of spark plasma sintered titanium powder Mater. Chem. Phys. 203 266–73
[28] Henriques, Rodrigues S A and Azadbeh M 2018 Effects of sintering temperature on microstructure and mechanical properties of spark plasma sintered titanium powder Mater. Chem. Phys. 203 266–73
[29] Wood R M 1962 The lattice constants of high purity alpha titanium Proc. Phys. Soc. 80 783
[30] Perez R, Nakajima H and Dyment F 2003 Diffusion in α'/Ti and Zr Mater. Trans. 44 2–13
[31] Zhu L et al 2017 Measurement of interdiffusion and impurity diffusion coefficients in the bcc phase of the Ti–X (X = C, Hf, Mo, Nb, V, Zr) binary systems using diffusion multiples J. Mater. Sci. 52 3255–68
[32] Baril E, Lefebvre L P and Thomas Y 2011 Interstitial elements in titanium powder metallurgy: sources and control Powder Metall. 54 183–6
[33] Wang C, Zhang Y, Wei Y, Mei L, Xiao S and Chen Y 2016 XPS study of the deoxidization behavior of hydrogen in TiH2 powders Powder Technol. 302 423–5
[34] Gülsoy H O, Güney V, Baykara T and German R M 2012 Injection molding of mechanical alloyed Ti–Fe–Zr powder Mater. Trans. 53 1100–5
[35] El Kadiri H, Wang L, Gülsoy H O, Suri P, Park S J, Hammi Y and German R M 2009 Development of a Ti-based alloy: design and experiment JOM 61 60–6
[36] Chen1, a W, Yamamoto 2, b Y and Peter W H 2010 Investigation of pressing and sintering processes of CP-Ti powder made by Armstrong process Key Eng. Mater. 436 123–30