The Effect of Ta Content on Phase Constitution and Aging Behavior of Ti-Ta Binary Alloys *

Masahiko Ikeda¹, Shin-ya Komatsu¹ and Yuichiro Nakamura²

¹Department of Materials Science and Engineering, Faculty of Engineering, Kansai University, Suita 564-8680, Japan

²Graduate Student of Kansai University, Suita 564-8680, Japan

Using Ti-Ta alloy to which Ta was added systematically, *i.e.* Ti-5 mass% Ta, 10 mass% Ta, 20 mass% Ta, 30 mass% Ta, 40 mass% Ta and 50 mass% Ta alloys, the effect of Ta concentration on phase constitution in the solution treated and quenched state and aging behavior is studied by electrical resistivity and Vickers hardness measurements and X-ray diffractometry. All alloys were solution treated at 1173 K for 3.6 ks and then quenched into ice water (STQ). STQed specimens were isochronally heat treated from 323 to 1173 K. STQed specimens of Ti-50 mass% Ta alloy were isothermally aging at five different temperatures, 573 K, 623 K, 673 K, 723 K and 773 K. In the solution treated and quenched state, only reflections of hexagonal martensite, α' were observed by XRD in Ti-5Ta to 30Ta alloys, whereas only orthorhombic martensite, α'' , was identified by XRD in Ti-40Ta and 50Ta alloys. α'' in Ti-50Ta alloy is reversely transformed into β upon isochronal heat treatment: the starting temperature is situated at a temperature between 623 K and 673 K. Isothermal aging of this alloy shows that α'' directly decomposes to α and β phases without reverse transformation of α'' at 573 K and 623 K aging. On isothermal aging above 673 K, α'' reversely transforms into β and then isothermal ω phase precipitates in the reversed β .

(Received May 9, 2002; Accepted September 9, 2002)

Keywords: titanium-tantalum alloys, medical applications, orthorhombic martensite, athermal omega, isothermal omega phase, beta phase, electrical resistometry, X-ray diffractometry

1. Introduction

In some countries of Europe and Asia, especially Japan, the ratio of elders above 65 years old to total population is increasing.¹⁾ The major reason for this phenomenon is advance of medical technique and its equipment. For example, equipment for replacement of failed hard tissue, especially medical implants, has been significantly developed and making steady progress.²⁾ Representative of medical implants is artificial bone.³⁾

In generally, artificial bone parts consist with metals, ceramics and polymers.²⁾ The stem of artificial bone, which the part carries the main applied load of the human, is made of metallic materials, *i.e.* alloys, because alloys have higher strength and toughness than ceramics and polymers.³⁾

A typical metallic material for medical application is stainless steel, especially Fe-Cr-Ni austenitic systems because of excellent corrosion resistance.³⁾ However, nickel is one of a number of strongly toxic metallic elements to the human body.³⁾ Therefore, recently the trend is to reduce the use of Fe-Ni-Cr system stainless steels for the medical applications.³⁾

Many researchers actively investigate β Ti alloys⁴⁻⁶⁾ with low elastic modulus for medical implants using Nb, Ta, Zr Mo and Fe as alloying elements, *e.g.* artificial bone. For instance, Ti-35.3Nb-5.1Ta-7.1Zr β alloy⁴⁾ which is the first Ti-Nb-Ta-Zr alloy developed for medical applications and Ti-13Nb-13Zr near β alloy⁵⁾ were produced in the USA. These alloys have low elastic modulus and excellent mechanical properties, *i.e.* high yield and tensile strength and good fatigue strength in the annealed state. In Japan, Ti-29Nb-13Ta-4.6Zr alloy for medical implants was independently de-

veloped by Prof. Niinomi's group in Toyohashi University of Technology.⁶⁾ That alloy has a good balance between strength and ductility as well as lower elastic modulus.

There are many reports about Ti-Nb binary alloys, *e.g.* reports about superconductivity⁷⁾ and shape memory effect of the orthorhombic martensite.⁸⁾ Ti-Zr binary alloys exhibit complete mutual solubility in the α and β phase and Zr plays the role of a neutral element in titanium. Though alloy in this system are not heat-treatable, there are some reports about that system, *e.g.* martensite transformation.⁹⁾

There are some reports of Ti-5 mass% Ta alloy as a corrosion resistant alloy¹⁰⁾ and Ti-high concentration Ta alloy, *e.g.* Ti-60 mass% Ta alloy, for nuclear reactor¹¹⁾ or medical implant application,¹²⁾ recently. Though Ta is one of the important alloying elements for Ti, as a non-toxic β stabilizer,³⁾ the Ti-Ta alloy system has not been systematically and actively investigated. Therefore, studies for phase constitution in solution treated and quenched state and aging behavior should be undertaken.

In this study, Ti-Ta alloys to which Ta was added systematically were prepared. Using those alloys, the effect of Ta concentration on phase constitution in the solution treated and quenched state or after aging is investigated by electrical resistivity, Vickers hardness measurements and X-ray diffractometry.

2. Experimental Procedure

Ti-5 mass% Ta, 10 mass% Ta, 20 mass% Ta, 30 mass% Ta, 40 mass% Ta and 50 mass% Ta alloys were prepared in a laboratory-scale arc furnace under a high purity argon atmosphere from sponge Ti (99.8% + purity) and Ta powder (99.9%) as raw materials. Button shaped ingots were hot-forged and hot rolled to around 5 mm thick plates at about 1170 K. Table 1 shows alloy codes and chemical compo-

*This Paper was Presented at the Spring Meeting of the Japan Institute of Metals, held in Chiba, on March 30, 2001.

Table 1 Alloy code and chemical composition of Ti–Ta alloys used.

Alloy code	Ta (mass%)	O (mass%)
5Ta	5.3	0.05
10Ta	10.0	0.05
20Ta	19.4	0.07
30Ta	29.6	0.07
40Ta	39.5	0.09
50Ta	49.1	0.10

sitions of alloys used. Specimens were prepared from hot-rolled plates by cutting, grinding and polishing. After all specimens were encapsulated in quartz tubes under about 3 mPa of atmosphere, the specimens were solution-treated at 1173 K for 3.6 ks and then quenched into ice water through breaking the quartz tubes (STQ).

STQed specimens for isochronal treatment were isochronally heat-treated for 3.6 ks at temperature intervals of 50 K up to the solution treatment temperature. The purpose of the isochronal treatment is to estimate the phase transformation temperature during the heating process up to solution treatment temperature. Ti–50Ta alloy was isothermally aged at five different temperatures, *i.e.* 573 K, 623 K, 673 K, 723 K and 773 K.

In heat-treated specimens, electrical resistivity was measured at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}) and Vickers hardness, using 4.9N as applied load, was measured. Phase constitution of all heat-treated specimens was established by X-ray diffraction at room temperature (XRD). Microstructures of STQed specimens were observed by optical microscopy (OM) after mechanical polishing followed by etching with 5 pct HF, 25 pct HNO₃ and the balance H₂O.

3. Results and Discussion

3.1 Solution treated state

Figure 1 shows XRD profiles of STQed Ti–5Ta, 30Ta, 40Ta and 50Ta alloys. Hexagonal martensite, α' , was identified in Ti–5 and 30Ta alloys quenched from 1173 K. In Ti–40 and 50Ta alloys, orthorhombic martensite, α'' , was identified in STQed state. Optical microstructures of Ti–30Ta, 40Ta and 50Ta alloys quenched from 1173 K are shown in Fig. 2. Bywater and Christian¹³⁾ reported orthorhombic martensite was observed above 32 mass%Ta. Our results of XRD are consistent with their work. The Ti–30Ta alloy exhibited “acicular martensite” with relatively large sized plates. With increase Ta content, the martensite plate size is finer.

Figure 3 shows change in resistivity at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}), resistivity ratio (ρ_{LN}/ρ_{RT}) and Vickers hardness (HV) with increasing Ta content in STQed state. Resistivity, resistivity ratio and HV monotonously increase with increase in Ta content because of solid solution of Ta. No abrupt change between 30Ta having hexagonal martensite and 40Ta having orthorhombic martensite was observed on those curves. Negative temperature dependence of resistivity was also not apparent in all STQed alloys. Bagariatskii *et al.*¹⁴⁾ reported change in Vickers hardness with Ta content. In that report, hardness is higher than observed in the present results, *e.g.* 340HV in 25Ta alloy.¹⁴⁾

Fig. 1 Examples of X-ray diffraction (XRD) profiles of Ti–5Ta, 30Ta, 40Ta and 50Ta alloys in STQed state.

This higher value is due to a higher content of gas impurities, *e.g.* oxygen, because their alloys were prepared by powder-metallurgy method.¹⁴⁾ Bywater *et al.*¹⁵⁾ also reported, HV values of Ti–22 mass%Ta, 32 mass%Ta and 36 mass%Ta alloys, which were prepared using an argon arc furnace, of about 175, 178 and 175 in the STQed state, respectively. These HV values are constituent with present HV data, though the increase in HV with Ta content is not evident because of the narrow composition range between 22 and 36 mass%Ta which they studied.¹⁵⁾

3.2 Aging behavior

Figure 4 shows changes in resistivity, resistivity ratio and HV of Ti–5 to 50 mass%Ta alloys with an increase in isochronal treatment temperature. Table 2 shows summary of changes in X-ray profiles of Ti–5Ta to 50Ta alloys with increase in isochronal treatment temperature. In Ti–5 to 20 mass%Ta alloys having hexagonal martensite, no changes in these measurements were observed. When α precipitation occurs during the isochronal treatment in the Ti–5 to 20 mass%Ta alloys, resistivity decreases and HV increases. However, no change in resistivity and HV were observed, as mentioned above. Therefore, it is considered that the heat treatment time (3.6 ks) is too short for changes of the measurements to appear.

In Ti–30Ta alloy having α' martensite, both resistivity and resistivity ratio started to decrease from 723 K and reached a minimum value at 973 K. Then, the resistivity and its ratio increased with heat-treatment temperature. HV began to increase from 723 K. HV reached maximum at 923 K and then decrease with increase in the temperature. From XRD results

Fig. 2 Optical microstructures of of Ti-30Ta, 40Ta and 50Ta alloys in STQed state.

shown in the Table 2, decomposition of α' martensite to α and β phase causes decreases of resistivity and resistivity ratio and increase of HV. α'' martensite was observed in the Ti-30Ta alloy quenched from 973 K and 1023 K.

In Ti-40 mass%Ta having orthorhombic martensite, resistivity and resistivity ratio started to decrease from 673 K and reached a minimum at 873 K. HV began to increase from 723 K and reached a maximum at around 823 K at which minima of ρ and ρ_{LN}/ρ_{RT} were observed. From XRD results shown in the Table 2, the change in HV are due to decomposition of α'' to α and β phases.

In Ti-50Ta alloy, resistivity at LN (liquid nitrogen temperature) and resistivity ratio increased at 573 K and reached a maximum at 673 K. Above 673 K, resistivity at RT and LN and resistivity ratio decreased. Those values became minima at 873 K and then increased with temperature. HV also began to increase at 573 K and maximum value was observed at 723 K. Above 723 K, HV decreased with increase in temperature. Moreover, values of the decreasing HV curve of 50Ta are almost the same as those of 40Ta alloy between 823 K and 973 K. The reason ρ_{LN} and ρ_{LN}/ρ_{RT} increased

Fig. 3 Changes of electrical resistivity at room and liquid nitrogen temperatures (ρ_{RT} and ρ_{LN}), resistivity ratio (ρ_{LN}/ρ_{RT}) and Vickers hardness (HV, applied load; 4.9N) with increase in Ta content. Phase constitutions identified by XRD were indicated near plots of ρ_{RT} .

Table 2 Summary of phase constitutions of all isochronally heat-treated Ti-Ta alloys by XRD at RT, except for Ti-50Ta alloy heat treated at 323 K for 3.6 ks.

	5Ta	10Ta	20Ta	30Ta	40Ta	50Ta
STQ	α'	α'	α'	α'	α''	α''
323 K	α'	α'	α'	α'	α''	—
373 K	α'	α'	α'	α'	α''	α''
473 K	α'	α'	α'	α'	α''	α''
573 K	α'	α'	α'	α'	α''	α''
623 K	α'	α'	α'	α'	α''	α''
673 K	α'	α'	α'	α'	α''	$\alpha'' + \beta$
723 K	α'	α'	α'	α'	$\alpha + \beta$	$\beta + \omega$
773 K	α'	α'	α'	$\alpha + \beta$	$\alpha + \beta$	$\beta + \omega$
823 K	α'	α'	α'	$\alpha + \beta$	$\alpha + \beta$	$\alpha + \beta$
873 K	α'	α'	α'	$\alpha + \beta$	$\alpha + \beta$	$\alpha + \beta$
923 K	α'	α'	α'	$\alpha + \beta$	$\alpha'' + \beta$	α''
973 K	α'	α'	α'	$\alpha'' + \alpha'$	$\alpha'' + \beta$	α''
1023 K	α'	α'	α'	$\alpha'' + \alpha'$	α''	α''
1073 K	α'	α'	α'	α'	α''	α''
1123 K	α'	α'	α'	α'	α''	α''
1173 K	α'	α'	α'	α'	α''	α''

from 573 K is the reverse transformation of α'' to metastable β phase shown in XRD results (Fig. 5). Maximum value of HV, about 400HV, is higher than those of Ti-30Ta and 40Ta alloys. The extremely high HV is due to isothermal ω precipitation in Ti-50Ta alloy heat-treated up to 723 K, as shown in Fig. 5.

In Ti-35 mass%Nb alloy having α'' , it is already reported

Fig. 4 Changes in ρ_{RT} , ρ_{LN} , ρ_{LN}/ρ_{RT} and HV with increase in heat treatment temperature. In this study, isochronal heat treatment means isothermal heat treatment at intervals of 50 K up to 1173 K for 3.6 ks.

Fig. 5 Example of change in XRD profile of Ti-50Ta alloy with isochronal heat treatment.

that ρ_{LN} and resistivity ratio increased by reverse transformation from α'' into β .¹⁶⁾ The reason why the increment of ρ_{LN} is larger than that of ρ_{RT} , *i.e.* resistivity ratio increases by reverse transformation, is that reversely transformed metastable β phase has a negative temperature dependence of electrical resistivity.¹⁶⁾ It is expected that the starting temperature for reverse transformation of Ti-50Ta alloy will be located at a temperature between 623 K and 673 K.

Ti-50Ta alloy in which reverse transformation occurred was isothermally aged at five different temperatures within range between 573 K and 773 K. Figure 6 shows changes in ρ_{RT} , ρ_{LN} , ρ_{LN}/ρ_{RT} and Vickers hardness (HV) of Ti-50Ta alloy with aging time at various aging temperatures. Resistivity at LN and resistivity ratio started to increase from 30 ks on 573 K aging and 12 ks on 623 K aging, respectively. HV began to increase from 60 ks on 573 K aging and 12 ks on 623 K aging, respectively. Incubation period of HV was observed, *e.g.* up to 30 ks on 573 K aging. Only orthorhombic martensite, α'' was identified in Ti-50Ta alloy aged for times within the incubation period. At longer times, at which resistivity started to increase, *e.g.* 120 ks on 573 K aging, beta phase was identified by XRD as shown in Figs. 7 and 8, respectively.

R. Davis, H. M. Flower and D. R. F. West reported that decomposition of α'' martensite into Mo enriched α'' and Mo denuded α'' in Ti-8 mass%Mo alloy during aging at 723 K¹⁷⁾ and they also reported that the similar decomposition of α'' in

Fig. 6 Changes in ρ_{RT} , ρ_{LN} , ρ_{LN}/ρ_{RT} and HV of Ti-50Ta alloy with isothermal aging at five different temperatures, 573 K, 623 K, 673 K, 723 K and 773 K.

Fig. 7 Example of change in XRD profile of Ti-50Ta alloy with isothermal aging at 573 K.

Fig. 8 Example of change in XRD profile of Ti-50Ta alloy with isothermal aging at 623 K.

Ti-Nb alloys was observed.¹⁸⁾ Therefore, though alloying element between their works^{17,18)} and present work is different, as aging proceeds at 573 K and 623 K, it is considered that α'' decomposes into Ta enriched α'' and Ta denuded α'' and then Ta enriched α'' reversely transforms into β phase at the aging temperature. Furthermore, by quenching for measurements of resistivity, HV and XRD, it is also considered that the reversely transformed β phase retained to room temperature. However, no reflection of isothermal ω phase was identified in the specimen aged at further aging time, *i.e.* 600 ks on 573 K aging and 120 ks on 623 K aging.

On aging at 673 K, resistivity at LN and resistivity ratio abruptly increased at 0.3 ks and then increased further with aging. HV increased from 0.3 ks when the abrupt increase of ρ_{LN} and ρ_{LN}/ρ_{RT} appeared. Maximum HV was at 120 ks and then decreased with aging time. Figure 9 shows the change of X-ray diffraction profiles with increase in aging time. Reflections of β phase were identified at 0.3 ks and intensity of those reflections became stronger with aging time. Reflections of isothermal ω phase were first identified at 600 ks. However, that intensity is very weak.

H. M. Flower, R. Davis and D. R. F. West reported that from results of aging behavior of Ti-20 mass%Nb alloy on 673 K aging, complex structure could be produced when reversion of α'' into β and precipitation occurred on aging and partial transformation to martensite took place on cooling.¹⁸⁾ Therefore, though alloying element between their work¹⁸⁾ and

Fig. 9 Example of change in XRD profile of Ti-50Ta alloy with isothermal aging at 673 K.

Fig. 10 Example of change in XRD profile of Ti-50Ta alloy with isothermal aging at 723 K.

present work is different, it is considered that on aging at 673 K α'' reversely transformed into β at 673 K and then β decomposed to Ta enriched β and denuded Ta β phase during aging at 673 K for 0.3 ks. After aging for 0.3 ks, denuded β re-transformed into α'' while enriched β phase is retained to room temperature during quenching into ice water. Ta concentration difference between the enriched β and denuded β will be small because of short time aging, *i.e.* only 0.3 ks (5 min). Therefore, Ta enriched β phase is a metastable state, because resistivity at LN is larger than that at RT, *i.e.* volume fraction of athermal ω increases with decrease in temperature.¹⁹⁾ When stability of β phase increases, volume fraction of formed athermal ω decreases with decrease in temperature, *i.e.* temperature dependence of resistivity changes from negative to positive.¹⁹⁾ On further the aging, denuded β phase transforms into isothermal ω phase and finally α phase, while enriched β phase becomes stable β phase.

On aging at 723 K, resistivity at LN and resistivity ratio increased from 0.3 ks and the resistivity and resistivity ratio peaked at 1.2 ks. ρ_{LN} and the ratio then decreased with aging at 723 K. HV significantly increased from 0.6 ks and maximum HV was achieved at around 120 ks. Figure 10 shows examples of X-ray diffraction profiles of specimens aged for suitable aging times. Reflections of β phase were identified at 0.6 ks. Reflections of isothermal ω phase were

Fig. 11 Example of change in XRD profile of Ti-50Ta alloy with isothermal aging at 773 K.

Fig. 12 Isothermal transformation diagram of Ti-50Ta alloy. Open circle marks, ○ indicate aging time at which β phase was first identified by XRD. Solid circle marks, ● also indicate aging time at which isothermal ω phase was first identified by XRD.

first identified at 1.2 ks. At 300 ks, α phase appeared in X-ray diffraction profile. On aging at 773 K, resistivity at LN and resistivity ratio slightly increased to 0.6 ks aging and then decreased with increase in aging time. HV significantly increased from 0.6 ks and maximum value of HV reached at around 600 ks. Figure 11 shows changes of X-ray diffraction profiles on 773 K aging. Reflections of β phase appeared at 1.2 ks and isothermal ω phase was first identified at 3.0 ks.

The aging times at which β reflections were first identified on 723 K and 773 K aging, i.e. 0.6 ks and 1.2 ks, respectively, were longer than that on 673 K aging. Aging time at which reflections of isothermal ω phase were identified became shorter in order of 673 K and 723 K. However, aging time at which isothermal ω phase was detected by XRD on 773 K aging was longer than that on 723 K aging. It is considered that the volume fraction of isothermal ω phase in specimen aged at 773 K was much lower than that of specimen aged at 723 K and α precipitation was accelerated by 773 K aging.

Figure 12 shows isothermal transformation diagram of Ti-50Ta alloy expected from results of XRD and resistivity measurements. Plots indicate aging time at which β or isothermal ω phase was identified by XRD. The nose of transformation of α'' into β was located at around 673 K and that for isothermal ω precipitate is around 723 K. From this diagram, it is revealed that the reverse transformation of α'' into β occurred

by aging above a temperature between 623 K and 673 K in Ti-50 mass% Ta alloy.

4. Conclusions

Phase constitution and aging behavior in STQed Ti-Ta alloys were investigated through electrical resistivity, Vickers hardness measurements, X-ray diffraction and optical microscopic observation. Obtained results are as follows.

In the solution treated and quenched state, only reflections of hexagonal martensite, α' , were observed by XRD at room temperature in Ti-5Ta to 30Ta alloys, while only orthorhombic martensite, α'' , was identified by XRD at room temperature in Ti-40Ta and 50Ta alloy. Resistivity at RT and LN and HV increased with increase in Ta content. However, negative temperature dependence of resistivity was not apparent in all STQed alloys.

In Ti-5Ta to 20Ta alloys, no changes in resistivity and HV with isochronal treatment were observed. In 30Ta alloy, decrease of resistivity and increase of HV due to decomposition of α' into α and β were observed. In 40Ta alloy, decrease of resistivity and increase of HV due to decomposition of α'' into α and β were observed. In 50Ta alloys, significant increases of resistivity and resistivity ratio at LN due to reverse transformation of α'' into β appeared by isochronal treatment. It is considered that the starting temperature for reverse transformation of α'' into β is located at a temperature between 623 K and 673 K.

From results of resistivity, HV and XRD profile changed by isothermal aging in Ti-50Ta alloy, the aging time for which transformation of α'' into β was observed on 673 K aging was shorter than at other aging temperatures. Isothermal ω phase was detected in specimen aged at 673 K, 723 K and 773 K by XRD.

Acknowledgments

One of authors, M. IKEDA, specially thanks to Professor Harvey M. Flower of Imperial College for his useful advice and comments.

REFERENCES

- 1) *Hukushiyogu-seihinkaiatsu no shin-tenkai*, ed. by Tore Research center, (Tore research center, Ltd., Tokyo, 2000) pp. 5–8.
- 2) H. Kawahara and M. Nakamura: *Seitakei kara mita zairyou-soshiki kaimen no syo seishitsu*, Iyou zairyou no kagaku, ed. by Nihon kagaku-kai, (Gakkai syuppan senta, Tokyo, 1978) pp. 13–34.
- 3) M. Niinomi: *Metall. Mater. Trans. A* **33A** (2002) 477–486.
- 4) T. Ahmed, M. Long, J. Silvetri, C. Ruiz and H. J. Rack: *Titanium '95: Science and Technology*, ed. by P. A. Blenkinsop, W. J. Evans and H. M. Flower (The Institute of Materials, London, 1996) pp. 1760–1767.
- 5) A. K. Mishra, J. A. Davidson, P. Kovacs and R. A. Poggie: *Ti-13Nb-13Zr: A New Low Modulus, High Strength, Corrosion Resistance Near-Beta Alloy for Orthopedic Implants*, Beta Titanium Alloys in the 1990's, ed. by D. Eylon, R. R. Boyer and D. A. Koss (TMS, Warrendale, 1993) pp. 61–72.
- 6) K. Wang, L. Gustavson and J. Dumbleton: *The Characterization of Ti-12Mo-6Zr-2Fe A New Biocompatible Titanium Alloy Developed for Surgical Implant*, Beta Titanium Alloys in the 1990's, ed. by D. Eylon, R. R. Boyer and D. A. Koss (TMS, Warrendale, 1993) pp. 49–60.
- 7) E. W. Collings: *A Sourcebook of Titanium Alloy Superconductivity*, (Plenum Press, New York, 1983) pp. 213–298.
- 8) C. Baker: *Metal Science Journal* **5** (1971) 92–100.

- 9) S. Kobayashi, K. Nakai and Y. Ohmori: Abstracts of 128th Spring Meeting of The Japan Inst. of Metals (2001) pp. 130.
- 10) T. Yashiki and F. Kamikubo: *Corrosion Resistant Titanium Alloy and Surface Treatments for Titanium*, "R&D" Kobe Steel Engineering Reports **49** (1999) 43–48.
- 11) R. W. Margevicius and J. D. Cotton: Metall. Mater. Trans. A **29A** (1998) 139–147.
- 12) E. A. Trillo, H. M. Obispo, S. W. Stafford and L. E. Murr: *Electrochemical and Microstructural Analysis of Titanium–Tantalum Alloys for Metallic Implant Consideration*, Non-Aerospace Applications of Titanium, ed. by F. H. Froes, P. G. Allen and M. Niinomi (TMS, Warrendale, 1998) pp. 201–206.
- 13) K. A. Bywater and J. W. Christian: Philos. Mag. **25** (1972) 1249–1274.
- 14) Iu A. Bagariatskii, G. I. Nosova and T. V. Tagunova: Sov. Phys. Dokl. **3** (1959) 1014–1018.
- 15) K. A. Bywater and J. W. Christian: Philos. Mag. **25** (1972) 1275–1289.
- 16) M. Ikeda, S. Komatsu, T. Sugimoto and K. Kamei: J. Japan Inst. Metals **53** (1989) 664–671.
- 17) R. Davis, H. M. Flower and D. R. F. West: Acta Metall. **27** (1979) 1041–1052.
- 18) H. M. Flower, R. Davis and D. R. F. West: *Titanium and Titanium Alloys: Scientific and Technological Aspects*, ed. by J. C. Williams and A. F. Belov (Plenum Press, New York, 1982) pp. 1703–1715.
- 19) M. Ikeda, S. Komatsu, T. Sugimoto and K. Kamei: J. Japan Inst. Metals **54** (1990) 743–751.