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Relationships of strength to composition and phase constitution for three aged beta titanium alloys

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X-ray diffraction techniques were used to study properties of three beta titanium alloys in the alpha aged condition. The alloys studied were Beta III (Ti–11.5 Mo–6 Zr–4.5 Sn), Beta C (Ti–3 Al–8 V–6 Cr–4 Mo–4 Zr), and 8–8–2–3 (Ti–8 V–8 Mo–2 Fe–3 Al). The volume percentage of alpha phase present and the lattice parameters of both the alpha and beta structures were determined for different ageing treatments. Ultimate tensile strength is related to both alpha content and beta unit cell size in these alloys. However, at high strength levels, beta unit cell size is a more sensitive indicator of tensile strength than percentage of alpha phase. The effects of precipitation hardening mechanisms and alloy partitioning on strengthening are discussed.

1. Introduction

There is considerable interest in the so-called "beta" titanium alloys because of their high strength-to-weight ratio, fabricability, strength, good fracture toughness at high strength levels, and under some conditions, low stress corrosion cracking susceptibility. They have the further advantage of being readily heat-treatable over a broad range of strengths, even in heavy sections.

The objectives of the various beta titanium alloy development programmes have been: (a) to take advantage of the good plasticity characteristics of the beta (body-centred-cubic) structure, (b) to seek higher strength alloys by controlled metallurgical reactions, and (c) to develop alloys capable of uniform metallurgical reaction throughout thick sections.

The strength of beta titanium alloys is a result of solid-solution strengthening in the annealed or solution-treated condition and of both solid-solution strengthening and precipitation hardening mechanisms in the heat-treated (aged) condition. In beta titanium alloys, higher strengths are achieved by ageing heat-treatments following a solution-treatment. Ageing heat-treatments can result in the transformation of a portion of the metastable beta phase to omega, alpha, or in some cases, intermetallic compounds. Properties of the beta titanium alloys commercially available have been reviewed and summarized [1].

Previous measurements of alpha phase percentage in beta titanium alloys have been confined to Beta III titanium [2]. A comparison between those measurements and our results will be discussed later.

2. Experimental

2.1. Description of material

The three metastable beta titanium alloys investigated in this study were Ti–11.5 Mo–6 Zr–4.5 Sn (Beta III), Ti–3 Al–8 V–6 Cr–4 Mo–4 Zr (38–6–44 or Beta C), and Ti–8 Mo–8 V–2 Fe–3 Al (8–8–2–3). The heat numbers, forms, and solution-treatment conditions are given in Table I for each piece of material. Table II contains a detailed chemical analysis of the alloys used in this work as furnished by the manufacturers.

2.2. Sample preparation

Specimens, used in the X-ray diffraction analysis, were cut from the plates and the sheet bar product by sawing. The surfaces were then milled to remove any heat affected material. Finally, one face of each specimen was hand-ground and polished to provide a smooth, undisturbed surface.

The ageings were carried out primarily in a high vacuum furnace to minimize gaseous absorption. The furnace temperature was maintained constant

TABLE I Identification of test materials and pre-ageing heat-treatments

Material	Heat no.	Solution annealing treatment[a]	Supplier
Beta III Ti 5.1 cm plate	K-50401	732° C-1 h water quenched 816° C-1½ h air cooled[b]	Crucible, Inc
Beta III Ti 3.2 cm plate	99100	718° C-5 min water quenched	Crucible, Inc
38–6–44 Ti 3.2 cm plate	294465	926° C-½ h air cooled	RMI Company
8–8–2–3 Ti 7.6 cm sheet bar stock	K-4179	871° C-1 h water quenched	Titanium Metals Corp of America
8–8–2–3 Ti 2.5 cm plate	V-4734	788° C-½ h water quenched[c]	Titanium Metals Corp of America

[a] All solution annealing treatments were conducted in air.
[b] This heating was to flatten a warped plate in the forge press and followed the regular solution-treatment.
[c] This material was re-solution-treated after a malfunction of the furnace caused an improper ageing.

TABLE II Chemistry of the Beta titanium alloys

	Wt % constituents											
Material	Al	Mo	V	Cr	Fe	Sn	Zr	C	N	O	H	Ti
Beta III 5.1 cm plate		10.8			0.01	4.7	6.4	0.01	0.013	0.13	0.0099	Bal.
Beta III 3.2 cm plate	Not available											
38–6–44 3.2 cm plate	3.4	4.1	7.8	5.8	0.16		3.7	0.02	0.012	0.093	0.0023	Bal.
8–8–2–3 7.6 cm sheet bar stock	3.0	7.9	8.3		2.0			0.022	0.011	0.15	0.001	Bal.
8–8–2–3 2.5 cm plate	3.0	8.0	8.0		1.94			<0.05	0.011	0.117	<0.015	Bal.

by automatic controller to better than ± 3° C. All specimens aged in the vacuum furnace were then furnace cooled to room temperature. Some of the 8–8–2–3 titanium alloy specimens from the 2.54 cm plate were heated at different temperatures in an air furnace followed by water quenching. Specimens aged at 538° C for different time periods were also heated in this manner.

2.3. X-ray diffraction procedure

X-ray diffraction measurements were made using a General Electric XRD-5 diffractometer. A diffractometer trace at a scanning rate of 2° per minute was made on each specimen using nickel filtered copper radiation. A 3° medium resolution beam slit, 0.2° detector slit, and medium resolution (MR) detector Soller slit was used in the experiments. A pulse-height selector was used to minimize fluorescent radiation.

The direct comparison method [3] was used in determining the volume fractions of alpha and beta phase present. Owing to the preferred orientation and large grain size in the specimens, many sets of peaks were averaged in calculating the volume fractions of phases present in the aggregate. This averaging technique has been found to give more accurate results [4] compared to taking only one or two spectra into account.

The volume percentage of alpha in two phase titanium alloy containing alpha and beta is given by the expression

$$\text{vol \% alpha} = \frac{\left(\frac{R_\beta}{R_\alpha}\right) I_\alpha}{I_\beta + \left(\frac{R_\beta}{R_\alpha}\right) I_\alpha} \times 100, \quad (1)$$

where I_α and I_β are integrated X-ray intensities as measured for specific diffraction lines, R_β/R_α is the intensity factor ratio for the diffraction lines

measured. The ratio R_β/R_α was solved theoretically for two sets of peaks where R is defined in terms of the structure factor, multiplicity factor, volume of the unit cell, Lorentz Polarization factor and temperature factor*. Structure factors were calculated using atomic scattering factors from Cullity [3] and dispersion corrections from James [5].

Lattice parameters, a_0, of the beta unit cell, as well as, c and a of the alpha unit cell, were determined from the angular positions of the diffraction lines. The error found in determining, a_0, was ± 0.002 Å. The error in determining a, was ± 0.002 Å, while that in determining c was ± 0.003 Å.

3. Results

3.1. Effect of different ageing temperatures on percentage of alpha phase formed

The volume percentage of alpha phase measured at different ageing temperatures is shown in Fig. 1. The temperatures selected were those spanning the range of ageing heat-treatments recommended by the developers for strengthening by alpha phase formation. All specimens were aged for 8 h except for a 38–6–44 sample which was aged for 12 h at 510° C. The ageing time of 8 h is commonly used by the fabricators to obtain good mechanical properties in a reasonable time period. An increasing volume percentage of alpha phase is observed in all alloys for decreasing ageing temperatures. Higher percentages of alpha phase are found in Beta III titanium as compared to the alloys, Beta C (38–6–44) and 8–8–2–3 titanium. Beta C titanium and 8–8–2–3 titanium contain practically identical amounts of alpha for a given ageing temperature. It can also be noted that these alloys have the same nominal percentages of alpha (3% Al) and beta (18% total†) stabilizers present.

These results indicate a correspondence between tensile strengths and percentage of alpha phase in Beta III, 8–8–2–3 and 38–6–44 specimens aged at temperatures ranging from 482° C to 667° C. As shown in Fig. 2, an increase in tensile strength corresponds to an increase in the percentage of dispersed alpha phase present in all three beta titanium alloys measured. For specimens aged to high strength levels, 38–6–44 and 8–8–2–3 samples contain a smaller percentage of alpha phase for a given tensile strength. Also, at high strength levels, large changes in tensile strength are observed for only small percentage changes in alpha, particularly in 38–6–44 and 8–8–2–3 titanium. These results indicate that other factors play an important role in strengthening of these alloys at the high strength levels.

3.2. Effect of ageing time at 538° C on amount of alpha phase formed

The effect of ageing time on the formation of

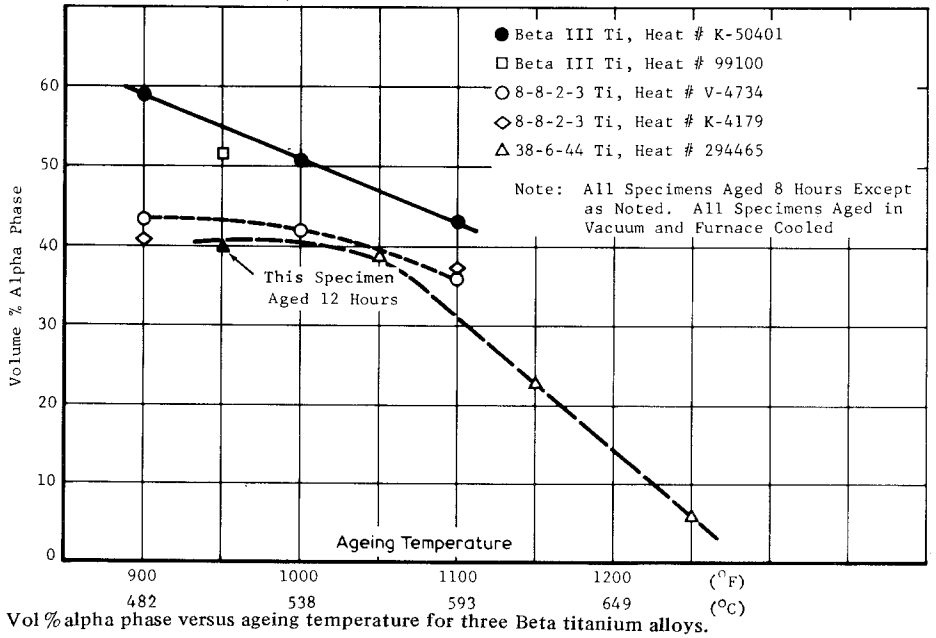

Figure 1 Vol % alpha phase versus ageing temperature for three Beta titanium alloys.

* See Equation 14.10 [2] p. 392.

† In 8–8–2–3, vanadium, molybdenum, and iron are all considered beta stabilizers. In Beta C, vanadium, chromium, molybdenum are beta stabilizers, while zirconium is considered neutral, strengthening both the alpha and beta phases.

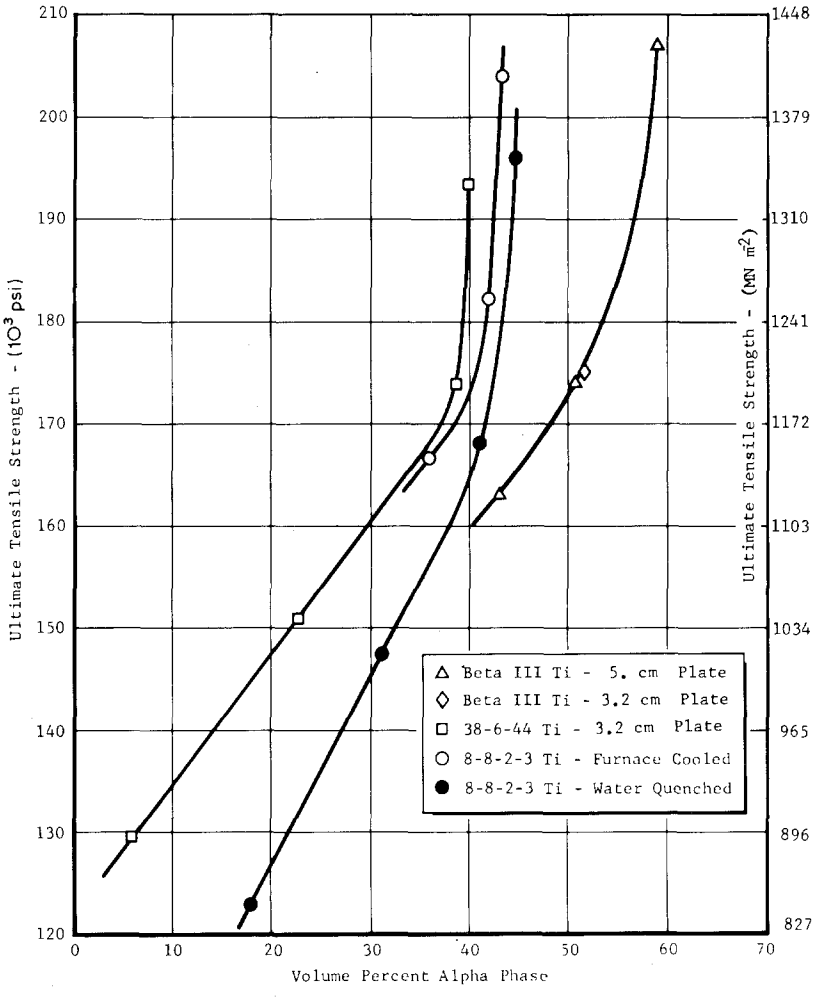

Figure 2 Tensile strength as a function of the percentage Alpha phase for three metastable Beta titanium alloys.

TABLE III Effect of ageing time on crystallographic structure for metastable Beta titanium alloys. Ageing temperature = 538° C

Material	Heat no.	Ageing time (h)	$a(\alpha)$ (Å)	$c(\alpha)$ (Å)	$a_0(\beta)$ (Å)	Vol % α phase
Beta III Ti	K-50401	2	2.969 ± 0.002	4.705 ± 0.003	3.277 ± 0.002	49.9
	K-50401	4	2.966	4.705	3.274	51.2
	K-50401	8	2.962	4.702	3.272	50.9
	K-50401	24	2.963	4.698	3.273	53.2
38–6–44 Ti	294465	2	2.938	4.684	3.220	33.2
	294465	8	2.937	4.682	3.218	37.9
	294465	24	2.937	4.684	3.216	40.9
8–8–2–3 Ti	V-4734	2	2.935	4.680	3.232	36.4
	V-4734	4	2.936	4.680	3.226	39.8
	V-4734	8	2.935	4.680	3.218	40.9
	V-4734	24	2.933	4.678	3.218	43.3

Note: All specimens were aged in an air furnace and cooled by water quenching.

alpha phase was determined in Beta III, 38–6–44, and 8–8–2–3 samples aged at 538° C. Ageing times of 2, 4, 8 and 24 h were used. As shown in Table III, the volume fraction of alpha phase becomes significantly larger with increased ageing time in 38–6–44 and 8–8–2–3, while a much

smaller change in percentage of alpha occurred with time in Beta III. Volume percentages of alpha phase have been measured in aged Beta III of similar chemical content by standard line intercept and point counting techniques using both optical and surface replica methods [2]. For samples aged at 593° C, very little change in percentage of alpha was found for samples aged at 100 h as compared to 8 h. For samples solution-treated at 704° C, then aged at 538° C for 100 h, 53% alpha was obtained which agrees quite well with 53.2% which was obtained for Beta III aged 24 h at 538° C in the present experiments. Also, Froes *et al.* [2] found 43% alpha present in Beta III after ageing at 593° C for 8 h. This is the same amount we found for the same ageing treatment.

No previous data are available on measurements of volume percentage of alpha phase contained in aged specimens of 38–6–44 and 8–8–2–3 titanium. However, limited data are available on the effects of ageing time on tensile strengths in these alloys. Results on 38–6–44 titanium [6], indicate that the ultimate tensile strength increases from 1255 MN m^{-2} for a 4-h ageing at 538° C to 1351 MN m^{-2} for 24-h aged material at 538° C. These results are consistent with the percentage of alpha phase increase with time observed in this study for 38–6–44.

3.3. Lattice parameter studies

Lattice parameter measurements on the size of the alpha and beta unit cells, as a function of ageing temperature, were made on Beta III, 38–6–44 and 8–8–2–3 titanium. Results are shown in Table IV. An increase in a_0 of the beta unit cell with increase in ageing temperature is found in all three alloys.

The tensile strengths in these alloys were found to be closely related to beta unit cell size (Fig. 3). As seen in Fig. 3, at higher strength levels, there is a significant change in beta phase unit cell size with strength. Beta unit cell sizes in 38–6–44 and 8–8–2–3 are practically identical for material aged to the same strength level.

The lattice parameter c of the alpha unit cell is enlarged with increase in ageing temperature. However, the increase is quite small in 38–6–44. The lattice parameter a of the alpha unit cell behaves differently in all three alloys as a function of ageing temperature. In Beta III titanium, a increases with increase in ageing temperature while in 38–6–44, a decreases. Very little change with ageing temperature is observed in 8–8–2–3. No definite trends can be established between alpha lattice parameters and mechanical properties. In 38–6–44 and 8–8–2–3, it is expected that in samples containing higher percentages of alpha,

TABLE IV Effect of ageing temperature on crystallographic structure for metastable Beta titanium alloys

Material	Heat no.	Ageing temperature (° C)	Cooling method	$a(\alpha)$ (Å)	$c(\alpha)$ (Å)	$a_0(\beta)$ (Å)
Beta III Ti	K-50401	482	FC	2.958 ± 0.002	4.696 ± 0.003	3.268 ± 0.002
	K-50401	538	FC	2.961	4.699	3.271
	K-50401	593	FC	2.968	4.717	3.278
	99100	510	FC	2.963	4.702	3.272
38–6–44 Ti	294465	510	FC	2.941	4.680	3.204
	294465	566	FC	2.948	4.680	3.218
	294465	621	FC	2.936	4.682	3.226
	294465	677	FC	2.920	4.684	3.229
8–8–2–3 Ti	K-4179	482	FC	2.932	4.663	3.207
	K-4179	593	FC	2.932	4.672	3.218
	V-4734	482	FC	2.933	4.666	3.211
	V-4734	538	FC	2.932	4.678	3.217
	V-4734	593	FC	2.932	4.678	3.220
	V-4734	482	WQ	2.932	4.666	3.210
	V-4734	538	WQ	2.932	4.678	3.218
	V-4734	593	WQ	2.929	4.678	3.223
	V-4734	649	WQ	2.929	4.684	3.234

Notes: All specimens were aged for 8 h.
FC = furnace cooled; WQ = water quenched.

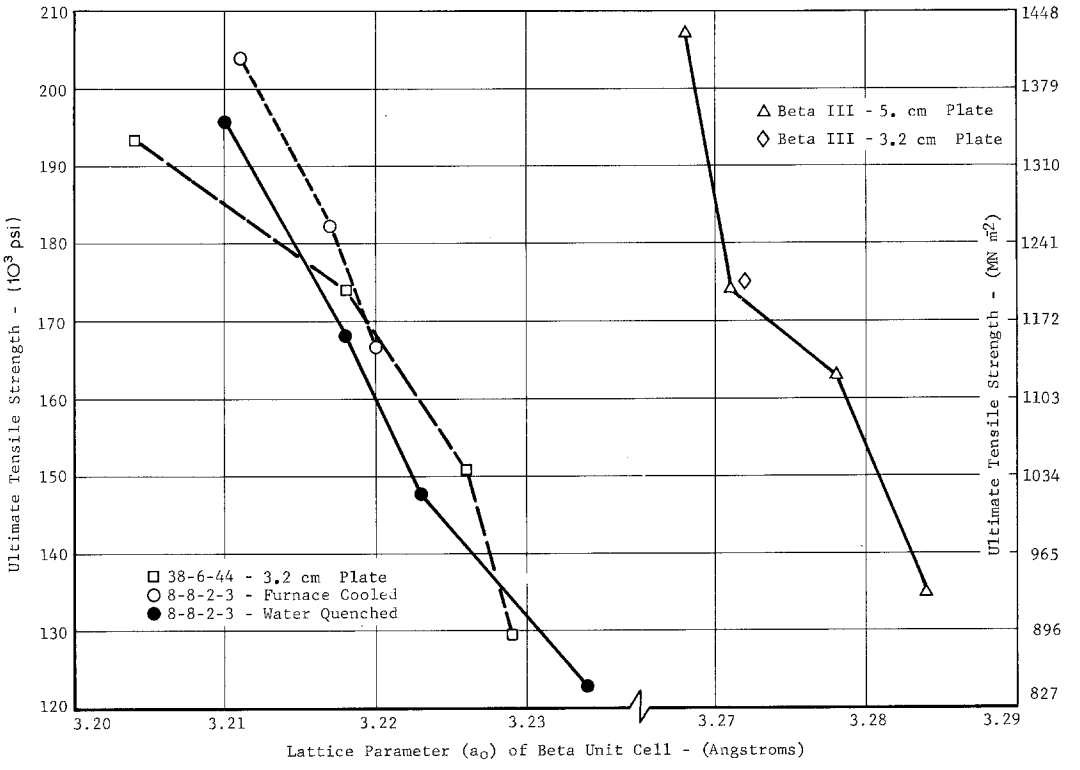

Figure 3 Tensile strength as a function of Beta unit cell size for three titanium alloys.

the alpha phase is rich in the alpha stabilizer, aluminium. Aluminium tends to increase the c/a ratio of the alpha unit cell by decreasing a without causing much change in c [7]. However, since the atomic radius of aluminium is nearly the same as that of titanium, changes in the lattice parameter are practically insensitive to small changes in aluminium. Therefore, changes in the lattice parameter c are apparently due to changing concentrations of iron, vanadium or molybdenum with increasing temperature. The 2.54 cm plate of 8–8–2–3, heated at 593° C in a high vacuum furnace, then furnace cooled, had a higher percentage of alpha phase as compared to the same material water quenched. These results are also reflected in the lower lattice constant, a_0, of the beta unit cell.

Lattice parameter measurements were made as a function of ageing time for Beta III, 38–6–44, and 8–8–2–3 samples aged at 538° C. These results were shown in Table III. A decrease in the lattice constant, a_0, of the beta unit cell was observed in all samples when the ageing time was increased from 2 to 8 h. This is consistent with the beta phase unit cell size decreasing with increasing volume of alpha phase. Very little change in a_0 was observed when the ageing time was increased from 8 to 24 h. The lattice parameters c and a of the alpha unit cell remain practically constant with changes in ageing time for 38–6–44 and 8–8–2–3. Decreases in both c and a are observed in Beta III with increases in ageing time.

4. Discussion

Since precipitation hardening mechanisms are influenced by the size, spacing and volume fraction of the precipitated phase, it is reasonable to expect the tensile strength to be closely related to the amount of alpha phase particles present in these alloys providing the size and spacing are not drastically different. This relationship appears to hold especially well for material heat-treated in the slightly overaged and overaged condition (538 to 677° C). However, in all three beta titanium alloys, aged at temperatures to give maximum strengthening, the alpha phase is more finely dispersed as compared to overaged material. Since the volume fraction changes in Beta C and 8–8–2–3 are small for changes in ageing temperature at the higher strength levels, it appears that the precipitation hardening mechanism is influenced more by the size of the alpha particles over this ageing interval

than by the total amount of alpha phase present.

Other studies have also shown that with increasing volume percentage of alpha phase, the beta-phase unit cell size decreased [2]. Thus, the correlation of tensile strength with beta unit cell size can be expected. However, for the higher strength alloys, the beta phase unit cell size is a more sensitive indicator of tensile strength than volume percentage of alpha, especially in 38–6–44 and 8–8–2–3. For instance, 8–8–2–3 samples aged at 482° C were considerably stronger than samples aged at 538° C, although only a small change was observed in volume content of alpha. Quite a large change in beta lattice parameter was observed. No correlations could be found between alpha lattice parameters and mechanical properties.

In Beta III titanium, this decrease in beta phase unit cell size at lower ageing temperatures was related to partitioning of molybdenum to the beta phase [2]. Although 38–6–44 and 8–8–2–3 contain smaller percentages of molybdenum, a similar type of partitioning would be expected to occur. In these alloys, it is postulated that the alpha phase would be relatively soft, since it contains little molybdenum; thus, the composition of the beta phase would be expected to exert a strong influence on the strength characteristics [8]. Our results relating the beta lattice parameter to tensile strength and finding no correlation between alpha lattice parameter and strength appear to confirm this postulate. The variation of lattice constants with ageing temperature emphasizes the importance of alloy partitioning on strengthening in these alloys.

5. Summary

X-ray diffraction studies have shown that in each of the three beta titanium alloys investigated, a correlation exists between the volume percent of alpha phase developed on ageing and the tensile strength. At the very highest strengths, however, the increase in alpha content is very small for large increases in strength.

The beta unit cell size decreases with increasing tensile strength and this correspondence remains tractable to the highest strengths attainable in the three beta titanium alloys. Phase composition and lattice parameters in 38–6–44 and 8–8–2–3 beta titanium alloys are very similar for nearly identical ageing heat-treatments. Formation of the alpha phase at 538° C is more sluggish in 38–6–44 and 8–8–2–3 as compared to Beta III titanium.

The relationship between strengthening in these alloys and beta unit cell size emphasizes the importance of alloy partitioning on strengthening.

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