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Modeling wear of cast Ti alloys

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Abstract

The wear behavior of Ti-based alloys was analyzed by considering the elastic–plastic fracture of individual alloys in response to the relevant contact stress field. Using the contact stresses as the process driving force, wear was computed as the wear rate or volume loss as a function of hardness and tensile ductility for Ti-based cast alloys containing an α , $\alpha+\beta$ or β microstructure with or without the intermetallic precipitates. Model predictions indicated that wear of Ti alloys increases with increasing hardness but with decreasing fracture toughness or tensile ductility. The theoretical results are compared with experimental data to elucidate the roles of microstructure in wear and contrasted against those in grindability.

Keywords

Dental alloys; Wear; Contact stress field; Structure–property relations

1. Introduction

Commercially pure (CP) titanium has been increasingly used for some dental appliances because of its excellent biocompatibility, corrosion resistance and light weight [1]. Through a considerable amount of research performed to solve casting problems, the quality of cast titanium prostheses has improved; however, there are still some obstacles to be overcome for the application of titanium to dentistry to be completely successful.

One of the disadvantages of titanium for structural applications is its poor tribological characteristics [2]. In their review of titanium alloys for orthopedic applications, Long and Rack [3] presented the complications of the wear phenomenon of titanium and indicated that overall alloy composition, which controls the surface oxide composition and subsurface deformation behavior, is a critical factor in titanium wear. A dentist observed the *in vivo* wear of cast CP Ti dental prostheses [4] and found that it underwent a greater amount of wear than conventional dental alloys. Shimura [5] reported that the greatest wear was found when the same grade of cast CP Ti teeth was used for both upper and lower teeth. Kawalec et al. [6] observed the most severe wear when pieces of wrought Ti–6Al–4V specimens fretted against themselves compared with a Co–Cr–Mn alloy. Despite the importance of wear resistance, detailed studies on the friction and wear performance of titanium alloys are sparse.

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In a recent in vitro wear study of three types of titanium alloys with α , $\alpha+\beta$ and β structures, the wear resistance was found to be sensitive to their microstructures [7]. The amounts of plastic deformation on the worn surfaces are different for Ti–15V–3Cr–3Sn–3Al (β -alloy), CP Ti (α -alloy) and Ti–6Al–4V ($\alpha+\beta$ -alloy). The experimental evidence appears to suggest that the higher ductility of the β Ti alloys contributed to the low wear resistance. Moreover, the microstructures of the worn surfaces of the titanium specimens showed clear evidence of increased plastic deformation with an increase in ductility [7]. In contrast, titanium alloys with Cu, which consist of the $\alpha + \text{Ti}_2\text{Cu}$ microstructure, have an increased wear resistance [8], while the ductility of Ti–Cu alloys decreased with Cu [9]. Thus, the higher ductility appeared to be a contributing factor to poor wear resistance. Therefore, without any obstacles (the eutectoid structure, multiphase structure, etc.) to the plastic deformation, the wear seemed to have advanced because of their easier slip processes [10].

While some understanding of the roles of microstructure in wear resistance has been established, there is still a lack of quantitative relations or micromechanical models for predicting the wear resistance in Ti alloys. The objective of this article is to highlight the developments of a micromechanical model for predicting the wear resistance in Ti alloys. To develop the wear model, the stress field associated with a flat wear pad on a flat surface is analyzed. The contact stress field is then utilized to define the onset of wear on the basis of a shear fracture criterion. The model is then applied to compute the wear behavior of Ti alloys in terms of tensile properties. The results of the proposed models are compared with experimental data to elucidate the effects of microstructure and the underlying fracture process on wear resistance in dental Ti alloys.

2. The wear model

This section summarizes the development of a model for treating wear in Ti alloys subjected to simulated chewing actions. Fig. 1 illustrates schematically an in vitro two-body wear tester that is commonly utilized to simulate the chewing actions and to measure abrasive wear in maxillary and mandibular teeth [7,8]. To simulate wear in the teeth, a cyclic compressive load is applied to the upper tooth while a cyclic load or displacement is simultaneously applied to the lower tooth, causing a sliding motion from cusp to cusp and from cusp to the tooth fosses. As the load is removed, the lower tooth returns to its original position. This entire sequence of motions constitutes one cycle. A total of 50,000 cycles is generally carried out for each set of teeth and the volume of material loss after 50,000 cycles is taken as a measure of the material's wear resistance.

The contact stress field of a flat pad on a flat surface substrate was utilized as the driving force for material removal by wear. The contact stress field formulated as part of a fretting–fatigue model described by Chan et al. [11] was utilized to compute the local stress distributions under a flat pad on a flat Ti substrate, as shown in Fig. 2(a). The normal load, P (per unit pad thickness in mm), was taken to be 122.4 N and the shear traction, Q , was 61.2 N. The ratio of P/Q was taken to be 0.5, which corresponds to the coefficient of friction for Ti. The magnitude of P was chosen arbitrarily since the stress results would eventually be normalized by P . Physical properties of a typical Ti alloy were used, including an elastic modulus, E , of 117.1 GPa, a Poisson ratio of 0.3 and a coefficient of friction of 0.5. The width, $2d$, of the contact zone was not known, but it could be computed by solving the overall force equilibrium equation (Eq. (4) in [11]) for the normal traction once the elastic properties and the pad geometry are specified. Three different flat pads with a flat region of width $2b$, of 1, 25.4 and 1016 μm , were used to compute the contact zone width $2d$, using the procedure described by Chan et al. [11]. This set of $2b$ values led to contact zone widths, $2d$, of 139, 155 and 1078 μm , respectively. Thus, the contact regions appeared to approach 138 μm as $2b$ became small.

The computed elastic stresses were utilized to construct stress contours under the grinding wheel or the flat pad for various contact zone widths. Results of the σ_{xy} and J_2 stress contours are shown in Fig. 2(b). The shear stress σ_{xy} and the J_2 values are highest within the contact zone under the grinding wheel. As shown in Fig. 2(b), both the shear and the deviatoric stresses decrease with increasing distance from the grinding surface. The deviatoric stresses are the driving force for plastic deformation.

The wear model was developed by considering the plastic deformation of asperities on the contact surfaces, shown schematically in Fig. 3(a), for a flat pad on a flat substrate with a hardness H . The applied load on the pad is P and the shear traction is Q . At the onset of gross slip, $Q = \mu P$, where μ is the coefficient of friction. The slip distance is denoted as s while the intense deformation layer under the pad is l_w (Fig. 3(b)). According to Archard's formulation [12], the wear rate is proportional to the total area of surface in contact and the contact pressure, σ , as given by [12,13]:

$$w \propto n\pi a^2 \left(\frac{\sigma}{H} \right) \quad (1)$$

where w is the wear rate per unit cycle, H is the hardness of the substrate, n is the number and a is the diameter of the asperities on the contact surfaces. The amount of wear, w , produced in a wear cycle is proportional to the wear depth, l_w , and the strain concentration at the roots of individual asperities, leading to

$$w = k_0 n\pi a^2 l_w \left(\frac{\gamma_p}{\Delta\gamma} \right) \left(\frac{\sigma}{H} \right) \quad (2)$$

where k_0 is a constant, γ_p is the plastic strain at the root of the asperities and $\Delta\gamma$ is the shear strain range applied on the asperities along the wear surface. The total area of asperities in contact of the pad is proportional to the ratio of P/H and is described by [13]

$$n\pi a^2 = a_o^2 \left(\frac{\sigma}{H} \right) \quad (3)$$

The shear strain range, $\Delta\gamma$, is given by

$$\Delta\gamma = \frac{\delta}{l_w} \quad (4)$$

as shown in Fig. 3(a). The slip distance at the onset of gross slip [14,15] is determined by the friction stress, which, in turn, depends on the coefficient of friction and the size of the asperities on the contact surfaces. On this basis, the slip distance s is assumed to be proportional to the radius a of individual asperities, leading to

$$\delta = \alpha a = \frac{\alpha a_o}{\sqrt{n\pi}} \left[\frac{\sigma}{H} \right]^{1/2} \quad (5)$$

and

$$\Delta\gamma = \frac{\alpha}{\sqrt{n\pi}} \left(\frac{a_o}{l_w} \right) \left[\frac{\sigma}{H} \right]^{1/2} \quad (6)$$

where α is a proportional constant. Combining Eqs. (2), (3) and (6) leads one to a wear rate of

$$w = \frac{2k_o \sqrt{n\pi} a_o j_o^2 \epsilon_p}{\alpha} \left[\frac{\sigma}{H} \right]^{3/2} \quad (7)$$

per unit wear cycle, where the shear strain ($\gamma_p = 2\epsilon_p$) is related to the plastic strain at fracture (i.e. tensile ductility). The total wear after N cycles is

$$W = wN = \frac{2k_o \sqrt{n\pi} a_o j_o^2 \epsilon_p}{\alpha} \left[\frac{\sigma}{H} \right]^{3/2} N \quad (8)$$

for a constant wear depth of l_w that does not vary with wear cycle. If the wear depth varies with wear cycle according to

$$l_w = l_o N^\lambda \quad (9)$$

where l_o is the initial wear depth and λ is an empirical constant, the total wear after N wear cycles is then given by

$$W = wN = \frac{2k_o \sqrt{n\pi} a_o j_o^2 \epsilon_p}{\alpha} N^{1+2\lambda} \left[\frac{\sigma}{H} \right]^{3/2} \quad (10)$$

after Eq. (9) is combined with Eq. (8). Eq. (10) can be simplified to

$$W = c_o \epsilon_p N^{1+2\lambda} \left[\frac{\sigma}{H} \right]^{3/2} \quad (11)$$

with

$$c_o = \frac{2k_o \sqrt{n\pi} a_o j_o^2}{\alpha} \quad (12)$$

where c_o is a constant that is related to the volume of asperity particles produced in a single wear cycle.

The relation described in Eq. (11) suggests that the volume loss by wear can be related to hardness (H) and tensile ductility (ϵ_p) of the pad/substrate system, as well as the contact pressure (σ). The validity of Eq. (11) for treating wear of Ti alloys was evaluated by plotting wear data [7,8,16,17] as a function of hardness (H), tensile ductility (ϵ_p) and the product of $\epsilon_p H^{-3/2}$, respectively. The results indicated that wear data of Ti alloys does not exhibit an obvious correlation with hardness. In contrast, wear data appeared to correlate linearly with tensile ductility or with $\epsilon_p H^{-3/2}$ for α -Ti precipitation-hardened β -Ti alloys and single-phase β -Ti alloys. The correlation coefficients (r^2) are presented in Table 1, which shows that wear data of α -Ti and precipitation-hardened β -Ti alloys correlate linearly with $\epsilon_p H^{-3/2}$. As summarized in Table 1, the correlation coefficients (r^2) are 0.967 and 0.998 for α -Ti and precipitation-hardened β -Ti alloys, respectively. The wear data for single-phase β -Ti alloys with the equiaxed microstructure exhibit a linear correlation and lie on a separate line with a higher slope than that of α -Ti and precipitation-hardened β -Ti alloys. The correlation coefficient (r^2) for the β -Ti alloys is 0.84. The wear data of α + β -Ti alloys exhibit considerably more scatter and the linear correlation is marginal, with a correlation coefficient of 0.56 only. Fitting Eq. (11) to the wear data in Fig. 4 provided the value of the slope, c_s , which is given in Table 1. According to Eq. (11), $c_s = c_o \sigma^{-3/2} N^{1+2\lambda}$. For all wear data shown in Fig. 4, the number of wear cycles, N , was 50,000. Previous work by Iijima et al. [16] indicated that wear of Ti-6Al-7Nb and CP Ti (Grades 2 and 3) increased linearly with the number of wear cycles. Thus, the value of λ

was taken to be zero for α -Ti and $\alpha+\beta$ -Ti alloys. Similarly, $\lambda = 0$ for two-phase β -Ti alloys since their wear response is similar to $\alpha+\beta$ -Ti alloys. Using $N = 50,000$ and $\lambda = 0$, the value of $c_0\sigma^{-3/2}$ was computed from the slope of the fitted lines for α -Ti, $\alpha+\beta$ -Ti and two-phase β -Ti alloys. As shown in Table 1, the $c_0\sigma^{-3/2}$ value is relatively constant, ranging from 0.0275 to 0.0374 for these three groups of Ti alloys. For β -Ti alloys, the value of $c_0\sigma^{-3/2}$ was taken to be identical to that for the two-phase β -Ti alloys. The value of λ was then computed from the slope using $c_0\sigma^{-3/2} = 0.0374$ and $N = 50,000$, leading to $\lambda = 0.051$, as shown in Table 1. The results in Table 1 and Fig. 4 suggest that there are fair to good correlations between wear and $\epsilon_p H^{-3/2}$ for α -, $\alpha+\beta$ - and β -Ti alloys. The theoretical and experimental results suggest that wear of Ti alloys can be improved by increasing the hardness (H) and by reducing the tensile ductility.

The relatively poor wear resistance observed in single-phase β -Ti alloys can be attributed to their lower hardness and high tensile ductility. In contrast, the improved wear resistance in α -Ti, $\alpha+\beta$ -Ti and precipitation-hardened β -Ti alloys may be attributed to a higher hardness and a lower ductility. Eutectoid precipitation, such as that in Ti–Cu alloys [7], increases hardness and reduces tensile ductility; both are expected to enhance wear resistance. In the precipitation-hardened β -Ti alloys, the higher Cu contents and the formation of eutectoid phases in Ti–13Cr–7Cu and Ti–13Cr–5Cu alloys results in a higher wear resistance compared with Ti–13Cr–3Cu because the larger amounts of hard TiCu₂ precipitates increase the hardness but reduce the tensile ductility in these alloys. The presence of a hardened α -case on α -Ti or $\alpha+\beta$ -Ti alloys is expected to provide enhanced wear resistance in Ti alloys. The presence of a hardened α -case reduces the fatigue strength and ductility [18]. In contrast, there are no statistical differences in biocompatibility [19] and electrochemical behavior [20] between cast Ti alloys with and without an α -case. In most cast dental prostheses, the surface layer is often removed with a solution containing HNO₃/HF. This treatment usually removes as much as 150 μm of the surface layer, depending on the immersion conditions. On the other hand, the thickness of the α -case varies in cast dental prostheses, depending on the metal composition and how fast the casting cools during solidification. On many dental appliances, the α -case is approximately 30–400 μm thick [21]. Although this layer is not desirable for fatigue strength and ductility, the appliances are used clinically with some α -case remaining on the surfaces. Under this circumstance, the wear resistance may benefit from the presence of the remaining α -case.

A correlation between wear data and microstructure indicates that the wear resistance in single-phase Ti–15V–3Cr–3Sn–3Al with an equiaxed β -grained microstructure (Fig. 5(a)) is lower than that in Ti–13Zr–13Nb with an acicular α' martensite microstructure (Fig. 5(b)). This finding suggests that the phase morphology of the microstructure may also be an important factor affecting the wear resistance in dental Ti alloys. The multiphase microstructures in α -Ti and $\alpha+\beta$ -Ti alloys and precipitation-hardened β -Ti alloys, and the acicular α' martensite microstructure in β -Ti alloy all exhibit closely spaced boundaries that can serve as dislocation barriers and impede slip across the boundaries. The increased resistance against plastic flow is thought to increase the local hardness and impede shear localization at the surface asperities, thereby improving the wear resistance.

3. Discussion

The proposed wear model shows good correlation with the wear data of α -Ti, single-phase and precipitation-hardened β -Ti alloys, and gives a correlation coefficient of r^2 in the range of 0.84–0.998. Although the correlation coefficient is only 0.57 for $\alpha+\beta$ -Ti alloys, the wear data of these Ti alloys are generally lower than those of α -Ti alloys, including CP Ti, and are similar to those of precipitation-hardened β -Ti alloys, with comparable tensile ductility and hardness values. Most of the scatter for the $\alpha+\beta$ -Ti alloys comes from Ti–5Al–1Fe, which exhibits a very low wear loss, and Ti–6Al–4V–5Cu, which exhibits a low tensile ductility because of Cu

addition and eutectoid phase formation. The larger scatter in the $\alpha+\beta$ -Ti alloys may be attributed to a wider range of microstructures that are feasible in this class of Ti alloys. Future work will be required to characterize the microstructural features, such as the prior β grain size, lamellar spacing and intermetallic phases, in greater detail in order to identify the cause of scatter in the wear data. Until the scatter can be reduced, the wear model should be used with caution for $\alpha+\beta$ -Ti alloys because of the low r^2 value.

As shown in Eqs. (11) and (12), the constants c_0 and λ are related to the slope in a plot of wear versus $\varepsilon_p H^{-3/2}$. In Table 1, the values of $c_0/\sigma^{3/2}$ are presented because only one set of maxillary and mandibular teeth geometry was used in the experiment and the complexity of teeth geometry precluded the determination of the contact stress on the teeth. For the same teeth geometry under the same conditions, the contact stress on the teeth can be assumed to be constant for all cases. On this basis, the c_0 values for all four types of Ti alloys are very similar, with α -Ti alloys showing the lowest c_0 value. The main difference among the four groups of Ti alloys lies in the λ value, which determines the variation of the wear with cycle. For α -Ti, $\alpha+\beta$ -Ti and precipitation-hardened β -Ti alloys, $\lambda = 0$ and the slope of the wear versus cycle is predicted to be linear. Such a linear relation has been reported by Iijima et al. [16] for Ti-6Al-7Nb. For single-phase β -Ti, the value of λ constant in Eq. (11) is 0.051, which implies that the wear of these alloys increases nonlinearly with increasing wear cycles. Such a wear behavior, which is different from those of α -Ti, $\alpha+\beta$ -Ti and precipitation-hardened β -Ti alloys, has not been investigated and needs to be examined in future work.

The clinical use of dental prostheses fabricated by casting CP Ti started mainly in Europe and Japan, with some such use in the USA, about 15 years ago. Through their 10-year clinical experience with cast titanium restorations and fixed and removable prostheses, clinicians [4, 5] discovered several practical problems, including the permanent deformation and fracture of titanium clasps, debonding of the denture base resin and discoloration of the titanium surface. Severe wear of cast CP Ti prosthetic teeth was frequently observed. One way to obtain improved mechanical properties and better wear resistance is to use titanium alloys. The findings of the current study offer guidelines for selecting Ti alloy castings with higher wear resistance than CP Ti castings for dental applications. Both the wear model and the experimental data indicate that α -Ti alloys with a higher hardness and lower tensile ductility would provide a higher wear resistance than CP Ti. Similarly, $\alpha+\beta$ -Ti alloys and precipitation-hardened β -Ti alloys can offer higher wear resistance than CP Ti, providing that their tensile ductility is lower and the hardness is higher compared with CP Ti. Furthermore, single-phase β -Ti alloys might not be suitable for dental applications where wear resistance is required because of a lower wear resistance that continues to degrade with wear cycles. These insights on wear performance cannot be attained without extensive wear testing but is readily obtained via the model developed in this study.

Good wear resistance of dental appliances is important for stable, long-term restorations of occlusion with acceptable occlusal function. Unbalanced occlusion results from the difference in the volume of wear between the right and left sides of dentition, which follows the displacement of the temporomandibular joint [5]. Okabe and coworkers [7,8,16,17] have tested various cast experimental and industrial titanium alloys in an effort to find titanium alloys that exhibit not only acceptable strength characteristics without sacrificing cytotoxicity and corrosion resistance, but also other properties, including wear. Ohkubo et al. [7] evaluated the in vitro two-body wear of cast specimens using a testing apparatus that simulated the chewing function (5 kgf for 60 cycles/min under water for up to 50,000 cycles) by sliding two cast titanium crowns of the same metal against one another. Wear is assessed as the volume loss after chewing.

Many factors influence the wear test results. Our previous in vitro experiments [7,17] investigated the wear behavior of pairs of teeth fabricated from the same types of metals abrading one another, which is limited to two-body wear. The assessment of wear testing of dental materials is not simple, no matter which in vitro or in vivo test protocol is used. Many types of investigations have been tried [22–24]. Nevertheless, we attempted to analyze our experimental data on the wear of various titanium alloys using a mechanics of materials approach in order to develop an understanding of the properties and microstructure relationships. The proposed model provides a means for comparing the wear results of various investigators for different materials, assuming that the contact stresses in the wear experiments are known or can be computed. In addition, the model allows estimation of the wear of a dental Ti alloy on the basis of tensile ductility and hardness data when the wear data is not available. Thus, the proposed model, even though it is relatively simple, can be quite useful in guiding the generation of the right types of wear data and in interpreting the wear data of Ti alloys generated by various investigators.

In a companion publication [25], we investigated the relationships between the microstructure, grindability and tensile ductility of Ti alloys. One of the key findings of this study is the identification of the subtle differences between the dependence of grindability and wear resistance on microstructure, tensile ductility, hardness and ultimate fracture strength. These differences are summarized in the schematics shown in Fig. 6(a) and (b) for grindability and wear resistance, respectively. As illustrated in Fig. 6(a), good grindability requires a low tensile ductility (or low fracture toughness) and low ultimate fracture strength. In comparison, good wear resistance is provided by a high hardness (or ultimate fracture strength) and a low ductility, as depicted in Fig. 6(b). Decreasing tensile ductility and increasing hardness would result in higher wear resistance. Since the process driving force for wear is shear localization and fracture, the plastic flow and fracture behaviors of both the matrix and the strengthening phases are important factors controlling the wear rate. As a result, wear resistance in Ti alloys depend on the presence of intermetallics and eutectoid phases as well as the grain morphology of the matrix phase in the microstructure. The current wear model, together with the previous grindability model [25], allows one to delineate these various, sometimes opposite, effects of the microstructure and to optimize both grindability and wear resistance in Ti alloys.

The reduction in enamel opposing another material such as metal is important for acceptable dental treatment. Although some reports are available [7], little is known about the wear of enamel opposing titanium crowns. Further studies on the wear of not only titanium but also the tooth structure itself are needed.

4. Summary

The wear resistance in Ti alloys has been modeled using the contact stress field as the process driving force. It has been demonstrated that wear resistance increases with decreasing tensile ductility and increasing hardness. The precipitation of hard eutectoid and intermetallic phases in the microstructure enhances wear resistance by reducing the tensile ductility and increasing hardness. Furthermore, the acicular α' martensite microstructure is more beneficial for wear resistance compared with the equiaxed β microstructure in single-phase β -Ti alloys. The wear data of α -Ti, α + β -Ti and precipitation-hardened β -Ti alloys are comparable and all exhibit higher wear resistance than the single-phase β -Ti alloys.

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Fig 1. Schematics of an in vitro two-body wear tester commonly utilized to simulate the chewing actions and to determine wear in maxillary and mandibular teeth that are subjected to a compressive load P and a cyclic tangential force ΔQ .

Fig 2.
 (a) Schematics of a flat pad with rounded edges and width $2b$ activity on a flat Ti substrate. The flat pad is subjected to a bearing load, P , a shear force, Q , and a contact zone, $2d$; (b) distribution of the deviatoric stress, $J_2^{1/2}$ and shear stress, σ_{xy} , at $x/d = 0$ in a normalized plot.

(a)

(b)

Fig 3.

Schematics (not drawn to scale) of the wear process by shear fracture of asperities on the contact surfaces: (a) intense localized shearing of asperities within a surface layer of depth l_w and (b) the attainment of a shear fracture strain at l_w .

Fig 4.

Linear correlation between wear data and $\epsilon_p H^{-3/2}$, where ϵ_p is the tensile elongation and H is the hardness. The single-phase β -Ti alloys exhibit an equiaxed grain structure (open squares). The β -Ti alloys represented by the filled squares have an equiaxed structure with eutectoid (TiCu_2) or intermetallic precipitates. The α -Ti alloys have a lamellar microstructure. The $\alpha + \beta$ -Ti alloys have a lamellar $\alpha + \beta$ microstructure, some of which also contain eutectoid or intermetallic phases.

(a)

(b)

Fig 5. Microstructures β -Ti alloys: (a) equiaxed microstructure in Ti-15V-3Cr-3Sn-3Al and (b) acicular microstructure Ti-13Zr-13Nb. The acicular α' martensite microstructure exhibits a higher wear resistance compared with the equiaxed microstructure.

(a)

(b)

Fig 6. Schematics illustrate the various routes of changing tensile ductility, ultimate tensile strength and hardness to improve grindability and wear resistance in dental Ti alloys.

Table 1

Correlation coefficients and wear constants for Ti alloys

Alloy	Microstructure	Slope (c_0), $\text{mm}^3 \text{MPa}^{-3/2}$	r^2	$c_0/\sigma^{3/2}$, $\text{mm}^3 (\text{MPa}^{3/2} \text{ cycle})^{-1}$	λ
α -Ti	lamellar	1374	0.967	0.0275	0
α + β -Ti	lamellar α + β	1867	0.56	0.0385	0
Two-phase β -Ti	β + eutectoid or intermetallics	1927	0.998	0.0374	0
Single-phase β -Ti	equiaxed β	5650	0.84	0.0374	0.051