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Fracture Toughness of Titanium Alloys

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Abstract:

The effects of microstructure, interstitial impurity content, and ambient temperature on the fracture toughness of titanium alloys were comprehensibly studied in relation to the tensile strength. The R curves of "microcracks" propagating from precrack tips before the onset of unstable fracture were accurately measured, and the crack initiation and propagation resistance characteristics were determined. It was found as a result that the difference of fracture toughness between titanium alloys can be explained by the difference of crack initiation and propagation resistance characteristics, irrespective of the alloy type or test temperature, and that the propagation characteristics of "microcracks" are an important factor governing fracture toughness, particularly at 0°C. On the basis of the study results, guidelines were set forth for improving the fracture toughness of titanium alloys for different alloy types and test temperatures.

1. Introduction

Many studies have been conducted on the fracture toughness, and much has been clarified about the fracture mechanisms, of titanium alloys. There still remain many unsolved problems, however, as summarized below.

(1) The K_{IC} value widely varies for the same titanium alloy at the same tensile strength[1].

(2) The K_{IC} value greatly changes with specimen geometry and increases with increasing specimen size[2].

(3) The K_{IC} value obtained by the acoustic emission method is nearly 20% lower than that obtained according to ASTM E 399[3].

(4) An acicular microstructure provides smaller tensile ductility but higher fracture toughness than an equiaxed microstructure does.

(5) Generally, the fracture toughness improves with coasening microstructure.

(6) When the specimen is held under a constant load at or below the K_{MAX} point, the crack may extend and result in unstable fracture (this phenomenan is called sustained load cracking)[4].

The problems (2), (4), and (5), in particular, contradict, the common knowledge about the fracture toughness of ferrous materials, and must be solved as soon as possible for practical purposes as well as for clarifying the fracture mechanism involved.

The authors have systematically worked to clarify the relationship between the fracture toughness, strength, and metallurgical factors of titanium alloys[5-9]. They previously pointed out [5,6] (1) that the fracture toughness of titanium alloys is critically influenced by the behavior of the main microcrack that initiates and propagates from the precrack tip prior to the onset of unstable fracture, and (2) that an accurate R curve of the microcrack must be obtained to examine the change of crack initiation and propagation resistance characteristics, so that the fracture mechanism at work can be clarifed

The present study selected several titanium alloys, changed their manufacturing conditions over a wide range, and investigated the resultant change in fracture toughness in relation to strength. The accurate R curve of the microcrack was prepared

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Table 1 Chemical compositions of experimental materials

Alloy (typ)	Al	V	Cr	Sn	Cu	Mo	O	N	C	Fe	H
Ti-5Al-2.5Sn(α)	5.02	—	—	2.94	0.046	—	0.17	0.006	0.005	0.34	0.0056
Ti-8Al-1Mo-1V	8.25	1.04	—	—	—	1.02	0.04	0.008	0.005	0.07	0.0051
(Near α)	8.13	1.02	—	—	—	1.04	0.12	0.006	0.006	0.08	0.0027
Ti-6Al-4V	6.59	4.13	—	—	—	—	0.05	0.010	0.010	0.07	0.0071
(α+β)	6.31	4.29	—	—	—	—	0.14	0.010	0.010	0.17	0.0082
Ti-6Al-6V-2Sn (α+β)	6.36	4.47	—	—	0.37	—	0.193	0.014	0.007	0.17	0.0029
Ti-10V-2Fe-3Al (Near β)	3.26	9.93	—	—	—	—	0.08	0.008	0.006	2.06	0.0022
Ti-15V-3Cr-3Sn-3Al	3.26	15.3	3.28	—	—	—	0.08	0.012	0.005	0.04	0.0080
(β)	2.91	15.7	3.40	—	—	—	0.17	0.014	0.006	0.06	0.0070

for each titanium alloy, and crack initiation and propagation resistance characteristics were clarified, in relation to microstructure, interstitial impurity content, and the fracture toughness value.

2. Experimental Materials and Methods

Six titanium alloys with different β phase stability were used. Their chemical compositions are given in **Table 1**. The near α alloy Ti-8Al-1Mo-1V, α + β alloy Ti-6Al-4V, and β alloy Ti-15V-3Cr-3Al-3Sn were studied each in two types of specimens with different oxygen content to examine the effect of impurities. Ti-6Al-4V were studied in two types of specimen: standard specimen and extra-low-interstitials (ELI) specimen. The hot working and heat treating conditions were widely changed for these three titanium alloys (see **Table 2**).

Each titanium alloy was hot rolled to a plate of about 15 mm in thickness and heat treated. Various test specimens were taken from the midthickness of the plate at right angles to the rolling direction. Three-point bend test specimens (B = 10 mm, W = 20 mm, span = 80 mm) were used in the fracture toughness test, where fatigue precracks were introduced. The test temperatures were 0°C and −196°C. Fracture toughness was evaluated by the critical crack tip opening displacement (δ_C)[10] and K_{IC} (or K_Q)[11]. The R curve of the microcrack was obtained by applying to the above-mentioned three-point bend test specimen a load lower than the maximum load, immediately unloading the specimen, and measuring the crack propagation Δa of the specimen. **Fig. 1** shows the relationship between the unloading point and the observed microcrack propagation on the COD curve (load-CTOD curve) of Ti-6Al-4V. The microcrack length was measured at three positions on the through-thickness section of the specimen under an optical microscope and averaged to obtain Δa. Furthermore, the CTOD value δ_R or J value J_R was obtained at each unloading point and used to develop the R curve. In this case, the precrack was machined (as a 0.01-mm slit) to clearly distinguish it from the extended crack. Microcrack initiation and propagation characteristics were evaluated by the CTOD value δ_i, δ_R at Δa = 0, and the slope of the R curve $d\delta_R/da$, respectively. The tensile test used round bar specimens with 6.25 mm diameter and GL = 25 mm and was conducted at 0°C and −196°C.

Table 2 Hot working and heat treating conditions for main titanium alloys

Alloy	Processing	Variables in heat treatment
Ti-8Al-1Mo-1V	α+β rolled β rolled	Annealing temperature Cooling rate
Ti-6Al-4V	α+β rolled β rolled	Annealing temperature Cooling rate STA condition
Ti-15V-3Cr-3Al-3Sn	β rolled	ST condition Aging temperature Aging time

STA: Solution treatment and aging

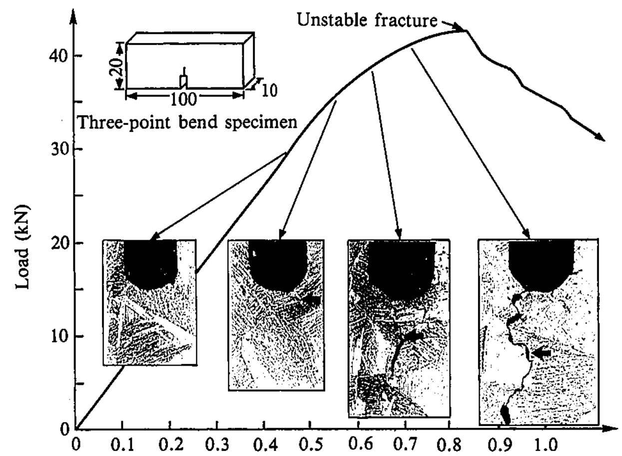

Fig. 1 Relationship between unloading position and crack propagation (Ti-6Al-4V, acicular microstructure, 0°C)

3. Experimental Results

Some of the relations between the 0.2% offset yield strength $\sigma_{0.2}$ and the fracture toughness δ_C at 0°C and −196°C are shown in **Figs. 2** to **4**, where "β treated" denotes a specimen worked or heat treated in the β region. The results of the near α alloy Ti-8Al-1Mo-1V, α + β alloy Ti-6Al-4V, and β alloy Ti-15V-3Cr-3Al-3Sn are given. These results and those of the other titanium alloys may be summarized as follows.

(1) Test temperature of 0°C

1) Each alloy type exhibits contradicting tendencies strength and fracture toughness. The strength dependence of fracture toughness is greater for the α alloy and the α + β alloy which have large amounts of the α phase than for the β alloy.
2) The acicular microstructure specimens of the α alloy, near α alloy, and α + β alloy exhibit higher fracture toughness than the equiaxed microstructure specimens, regardless of the tensile strength.
3) The β alloy and near β alloy exhibit roughly the same fracture toughness as the α + β alloy in the low-strength region, but higher fracture toughness than the α + β alloy when the 0.2% offset yield strength ($\sigma_{0.2}$) is 1,000 MPa or above.

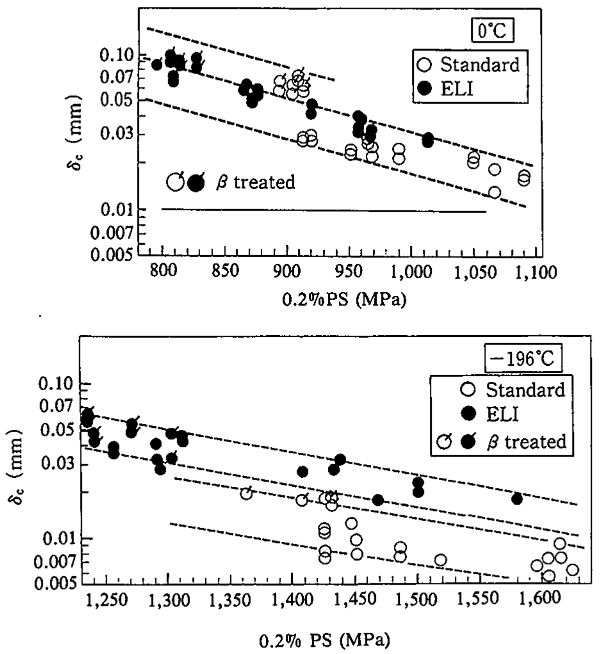

Fig. 2 Relationship between tensile strength and fracture toughness of Ti-6Al-4V (top: 0°C, bottom: −196°C)

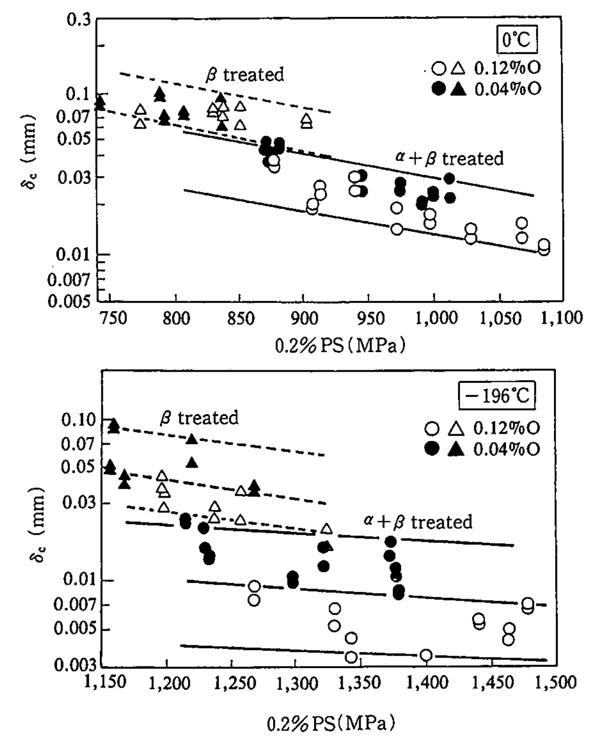

Fig. 3 Relationship between tensile strength and fracture toughness of Ti-8Al-1Mo-1V (top: 0°C, bottom: −196°C)

4) The strength being equal, the α alloy exhibits virtually the same fracture toughness as the α + β alloy, irrespective of the microstructure.
5) The effect of reducing the interstitial impurity content in improving the fracture toughness is slightly recognized in the equiaxed microstructure specimens of the α alloy and α + β alloy, but is hardly recognizable in the other titanium alloys.

(2) Test temperature of −196°C

1) Regardless of the type of titanium alloy, increasing the strength decreases fracture toughness, and the effect of the impurity content on fracture toughness is apparent. The specimens with low impurity content exhibit high fracture toughness, irrespective of strength.
2) The α + β alloy exhibits little difference of fracture toughness between the equiaxed microstructure specimens and acicular microstructure specimens, but the acicular microstructure specimens of the α alloy and the near α alloy still exhibit higher fracture toughness than the equiaxed microstructure specimens.
3) The β alloy exhibits lower fracture toughness than the α + β alloy when $\sigma_{0.2}$ is in the neighborhood of 1,500 MPa. When $\sigma_{0.2}$ is over 1,500 MPa, however, the alloy's fracture toughness decreases its strength dependence and exhibits a practically constant level.
4) The α alloy and near α alloy exhibit a slightly lower fracture toughness than the α + β alloy, regardless of strength.

In **Fig. 5**, the above-mentioned changes in the fracture toughness of different titanium alloys are schematically illustrated respectively for test temperatures of 0°C and −196°C.

Next, the R curves of microcracks were developed for each titanium alloy, and microstructure, interstitial impurity content and test temperature were investigated for their effects on the crack initiation δ_i and crack propagation resistance $d\delta_R/da$ properties obtained from R curves. Some of the test results are shown for Ti-6Al-4V, Ti-8Al-1Mo-1V, and Ti-15V-3Cr-3Al-3Sn

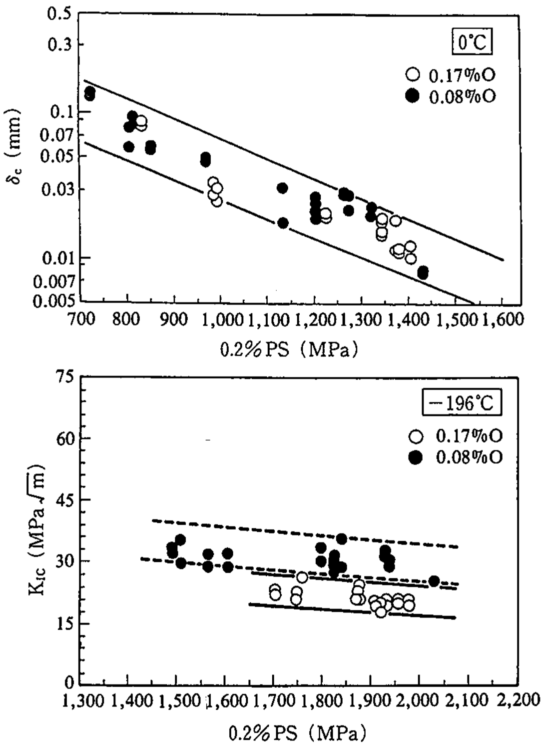

Fig. 4 Relationship between tensile strength and fracture toughness of Ti-15V-3Cr-3Al-3Sn (top: 0°C, bottom: −196°C)

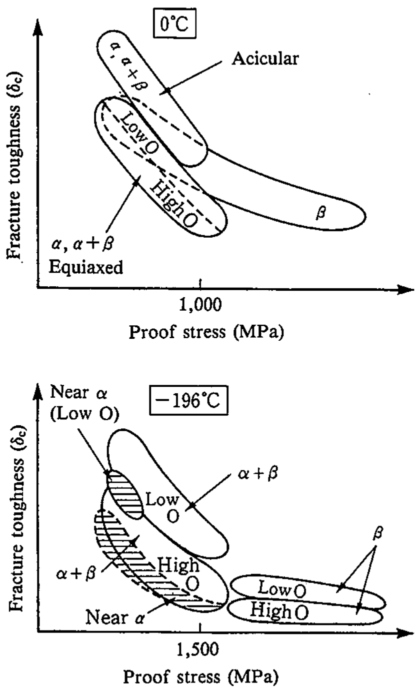

Fig. 5 Schematic diagrams summarizing relationship between tensile strength and fracture toughness (top: 0°C, bottom: −196°C)

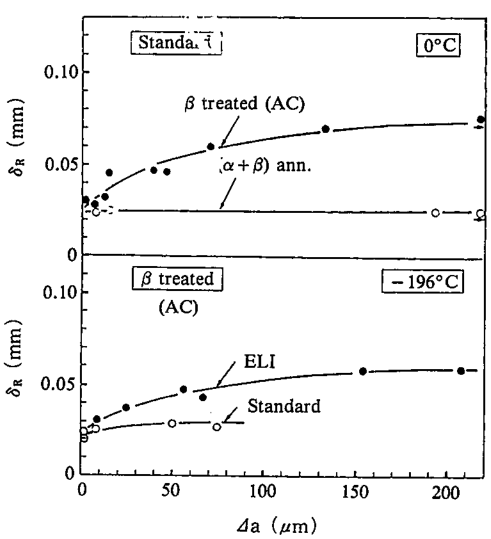

Fig. 6 R curve comparison of Ti-6Al-4V

Top: Equiaxed and acicular microstructure specimens (standard specimens, 0°C)
Bottom: Standard and ELI specimens (acicular microstructure specimens, −196°C)

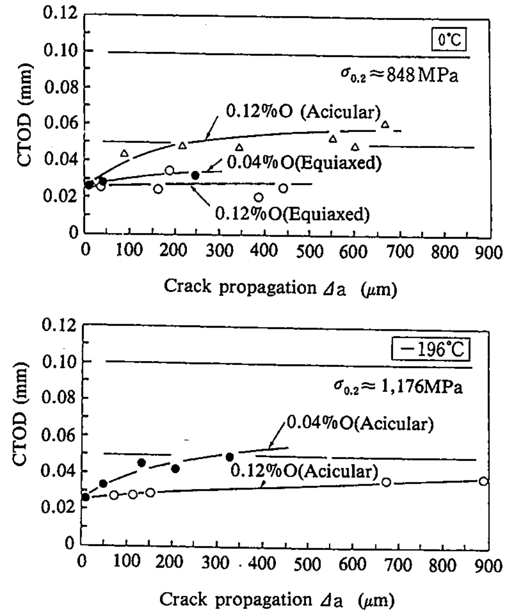

Fig. 7 R curve comparison of Ti-8Al-1Mo-1V (top: 0°C, bottom: −196°C)

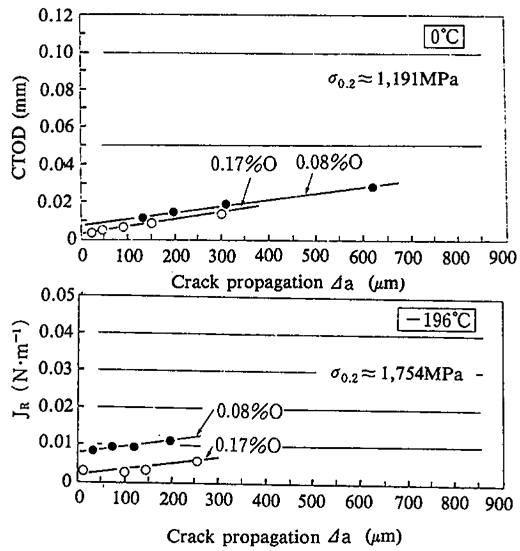

Fig. 8 Effect of oxygen content on R-curves of Ti-15V-3Cr-3Al-3Sn (top: 0°C, bottom: −196°C)

in **Figs. 6** through **8**, respectively. The acronym "AC" denotes air cooling after the solution treatment. Principal results, including those of the other titanium alloys, may be summarized as follows:

(1) Crack initiation

1) The crack initiation toughness δ_i of the near α alloy and $\alpha + \beta$ alloy is a practically constant 0.02 to 0.03 mm, irrespective of the strength, microstructure, or interstitial impurity content, and changes little as the test temperature decreases.

2) If there are fine precipitates (α, α_2), the crack initiation toughness δ_i sharply drops for each titanium alloy.

3) The crack initiation toughness δ_i of the β alloy increases with decreasing oxygen content at −196°C.

(2) Crack propagation resistance

1) The acicular microstructure specimens of the near α alloy and $\alpha + \beta$ alloy have higher crack propagation resistance $d\delta_R/da$ than the equiaxed microstructure specimens. At −196°C, the acicular and equiaxed microstructure specimens of the $\alpha + \beta$ alloy exhibit little difference in crack propagation resistance, but for the near α alloy, the acicular microstructure specimens still exhibit higher crack propagation resistance than the equiaxed microstructure

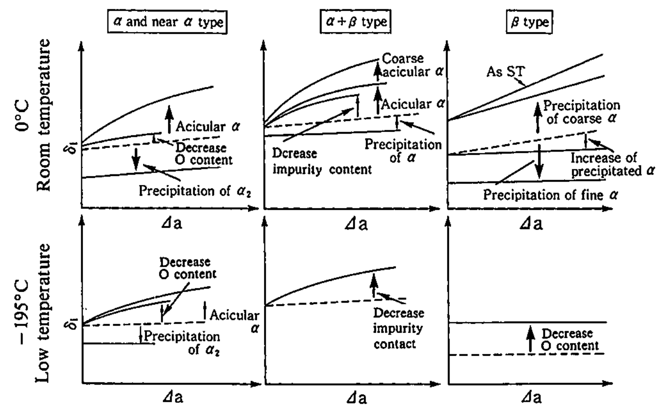

Fig. 9 Summary of microcrack R curves for titanium alloys (top: 0°C, bottom: −196°C, dotted line: R curve for standard specimen of each alloy type)

specimens.

2) The ELI specimens of the near α alloy and $\alpha + \beta$ alloy have higher crack propagation resistance than the standard specimens. This difference is particularly pronounced at −196°C.
3) For the β alloy, solution-treated (ST) specimens and coarse acicular microstructure specimens exhibit higher crack extension resistance.
4) In the near β alloy and β alloy, the crack propagation resistance sharply drops at −196°C, but this drop is small for the ELI specimens of the near α alloy and $\alpha + \beta$ alloy.

In **Fig. 9**, the above-mentioned changes in the R curves are summarized by alloy type and test temperature.

4. Discussion

As shown in **Figs. 2** to **4**, the fracture toughness of titanium alloys differs with microstructure, interstitial impurity content, and alloy type at the same strength level. These differences in fracture toughness have often been discussed by relating the fracture surface morphology and crack propagation path to microstructure, chemical composition and precipitates, and so on[12,13]. It seems irrational, however, to relate fracture toughness, a macroscopic material parameter, to such microscopic material parameters as microstructure and precipitates. As already described, the behavior of the microcrack propagating from the precrack tip is an important factor governing the fracture toughness of titanium alloys. The relationship of fracture toughness with the crack initiation and propagation resistance characteristics obtained from the R curve of the microcrack is studied here for each test temperature. When the test temperature was 0°C, the following differences in fracture toughness were observed between the titanium alloys studied:

(1) In the α alloy and $\alpha + \beta$ alloy, the acicular microstructure has higher fracture toughness than the equiaxed microstructure.
(2) When $\sigma_{0.2}$ is in the vicinity of 1,000 MPa, the β alloy has higher fracture toughness than the $\alpha + \beta$ alloy.
(3) In the near α alloy and $\alpha + \beta$ alloy, the ELI specimens have higher fracture toughness than the standard specimens.

These differences in fracture toughness are discussed in relation to the microcrack R curve changes shown in **Fig. 9**. The titanium alloys studied hardly differ from each other in microcrack initiation toughness, but are greatly different in crack propagation resistance.

Next, the difference of fracture toughness in titanium alloys at −196°C may be interpreted as follows:

(1) The low-impurity specimens of the near α alloy and $\alpha + \beta$ alloy have higher fracture toughness than the standard specimens.
(2) For the α alloy and near α alloy, acicular microstructure specimens have higher fracture toughness than equiaxed microstructure specimens.
(3) When $\sigma_{0.2}$ is in the vicinity of 1,500 MPa, the β alloy has lower fracture toughness than the $\alpha + \beta$ alloy.
(4) The low-impurity specimens of the β alloy have higher fracture toughness than the standard specimens.
(5) The α_2-precipitated specimens of the α alloy and near α alloy have lower fracture toughness than the standard specimens.

From the measured results of **Fig. 9**, it is confirmed that the differences in fracture toughness from (1) to (3) above are closely related to differences in the microcrack propagation resistance, and (4) and (5) are closely related to differences in the crack initiation toughness. The above relations of fracture toughness with microcrack initiation and propagation behaviors are summarized in **Table 3**.

From the above-mentioned study it was found that the fracture toughness of titanium alloys is largely governed by the initiation and propagation characteristics of the microcrack generated at the precrack tip before the onset of unsteady-state fracture, irrespective of the alloy type and test temperature, that the difference of fracture toughness between different titanium alloys at the same strength is strongly correlated with the difference of the microcrack initiation and propagation resistance, and that particularly at 0°C, the difference of fracture toughness between titanium alloys can be explained by the difference of microcrack propagation resistance depending on the microstructure and interstitial impurity content.

One of the future issues is to clarify the relationship of the microcrack initiation and propagation characteristics with the relevant microscopic metallurgical factors and to elucidate the micromechanism in the fracture of titanium alloy.

Next, how to improve the fracture toughness of titanium alloys is discussed on the basis of the above study results. As discussed above, the difference in the propagation resistance of microcracks generated from the precrack tip below the maximum load has large bearings on the difference of fracture toughness between titanium alloys. **Table 4** shows the ratio of crack initiation toughness δ_i to the fracture toughness δ_C of specimens with representative microstructures. In most cases, the δ_i/δ_C ratio is small, and $\Delta\delta$ ($= \delta_C - \delta_i$) during crack propagation accounts for about 70% or more of the fracture toughness δ_C. Improving the crack propagation resistance is thus considered helpful in enhancing the fracture toughness of titanium alloys. The δ_i/δ_C ratio sometimes exceeds 50% at −196°C, as shown for No. 4 and 11 in **Table 4**. In such a case, improving the crack initiation characteristics must also be considered.

In the α alloy and $\alpha + \beta$ alloy, the microcrack propagation resistance strongly influences the fracture toughness at both 0°C and −196°C. Formation of an acicular α microstructure is most effective in raising the crack propagation resistance. It is also effective to turn some of the microstructure into an acicular one

Table 3 Relationship of difference of fracture toughness with difference of microcrack initiation and propagation resistance characteristics

Testing temperature	Comparison of fracture toughness (at the same strength)	Comparison of microcrack behavior	
		Crack initiation δ_i	Crack propagation resistance $d\delta_R/da$
0°C	Equivaxed < Acicular (α, Near α, $\alpha+\beta$ type)	Equivalent	Equiaxed < Acicular
	$\alpha+\beta$ < Near β, β ($\sigma_{0.2}$ = 900 - 1,100MPa)	Nearly equivalent	$\alpha+\beta$ type < Near β, β type
	Standard < ELI (Near α, $\alpha+\beta$ type)	Equivalent	Standard < ELI
−196°C	Standard < ELI (Near α, $\alpha+\beta$ type)	Equivalent	Standard < ELI
	Equiaxed < Acicular (α, Near α type)	Equivalent	Equiaxed < Acicular
	Standard < Low O content (β type)	Standard < Low O content	Equivalent
	β type < $\alpha+\beta$ type ($\sigma_{0.2} \fallingdotseq$ 1,500MPa)	Nearly equivalent	β type < $\alpha+\beta$ type
	Standard < α_2-precipitated (α, Near α type)	Standard < α_2-precipitated	Equivalent

Table 4 Ratio of crack initiation characteristics δ_i to fracture toughness δ_c of titanium alloys

No.	Microstructure	Alloy	Feature	δ_c (mm)	δ_i (mm)	δ_i/δ_c (%)
1	α + retained β	Ti-5Al-2.5Sn	......	0.074	0.004	5
2		Ti-8Al-1Mo-1V	α_2	0.025	0.003	12
3	Equiaxed α + transformed β	Ti-6Al-4V	......	0.035	0.008	22
4			−196°C	0.011	0.088	73
5	Fine acicular α		Standard	0.075	0.012	16
6			ELI	0.092	0.012	13
7	Primary α + precipitated $\alpha+\beta$	Ti-10V-2Fe-3Al	......	0.016	0.003	19
8	β	Ti-15V-3Cr-3Al-3SN	As ST	0.136	0.030	22
9	β + fine α		High O	0.021	0.002	10
10			Low O	0.028	0.010	36
11			−196°C	0.0012	0.0007	58
12	β + coarse α		......	0.088	0.030	34

by changing the transformed β phase into an acicular structure and to bring the primary α phase close to the coarse acicular α phase by hot working, for example. It should be noted, however, that the formation of the acicular α microstructure may simultaneously reduce the strength of the α alloy and $\alpha + \beta$ alloy studied here. Reducing the oxygen content is effective in improving fracture toughness at −196°C, because it improves the crack propagation resistance, irrespective of the type of microstructure. Reducing the oxygen content is also effective in improving the fracture toughness of the equiaxed microstructure specimens at 0°C because it improves the crack propagation resistance as well. Suppressing the α_2 phase precipitation is little effective in improving the 0°C fracture toughness at the same strength. At the cryogenic temperature of −196°C where the fracture toughness is governed by the crack initiation toughness, suppression of α_2 phase precipitation is very effective in improving the fracture toughness. When the $\alpha + \beta$ alloy has a fine α phase precipitated by aging, the crack initiation toughness sometimes drops. At −196°C, in particular, the fracture toughness of the $\alpha + \beta$ alloy becomes lower than when there is no precipitated α phase.

When $\sigma_{0.2}$ of the β alloy and near β alloy is about 1,000 MPa, the crack propagation resistance practically controls the fracture toughness. When $\sigma_{0.2}$ is 1,200 MPa or more, the crack initiation toughness governs the fracture toughness. This emphasizes the importance of improving the crack propagation resistance in the low-strength region and the crack initiation toughness in the high-strength region. The crack initiation toughness can be effectively improved by controlling the formation of fine precipitates (for example, a fine α phase precipitated by low-temperature aging) and reducing the interstitial impurity content, the oxygen content in particular. Reducing the oxygen content is particularly effective in improving the crack initiation toughness at −196°C. The presence of a coarse α phase precipitated by overaging, for example, is effective in improving the crack propagation resistance. Reducing the oxygen content and coarsening the β grains are effective in improving the fracture toughness of specimens solution treated in the β region. In **Table 5**, the above guidelines are summarized according to the alloy type and test temperature.

Fracture toughness is closely related to tensile strength. In most cases, an improvement in the fracture toughness accompanies a reduction in the tensile strength. Measures for improving fracture

Table 5 Summary of guidelines for improving fracture toughness of titanium alloys

Alloy type	Room temperature		Cryogenic temperature (~ −196°C)	
	Crack initiation	Crack propagation resistance	Crack initiation	Crack propagation resistance
α, near α type	Suppression of α_2 precipitation	• Change from equiaxed α to acicular • Reduction of oxygen content • (Coarsening of grain size)	Suppression of α_2 precipitation	• Change from equiaxed α to acicular α • Reduction of oxygen content
α+β type	Suppression of the α precipitation	• Change from equiaxed α to acicular • Reduction of impurity content • Changing secondary α to lamellar α	Suppression of α precipitation	• Reduction of oxygen content
β type	Suppression of ω or fine α precipitation	• Coarsening secondary α or changing it to lamellar α • Reduction of oxygen content or coarsening of grain size (As solution treated)	• Reduction of oxygen content	

toughness with attendant reduction in the tensile strength are not practical. Study must be made to find out means of enhancing the fracture toughness of titanium alloys without sacrificing the tensile strength.

5. Conclusions

(1) The fracture toughness of α, α + β, and β titanium alloys generally decreases with increasing strength and varies with the microstructure, interstitial impurity content and service temperature, even at the same strength.

(2) The fracture toughness of titanium alloys is governed by the initiation and propagation resistance characteristics of the microcrack generated from the precrack tip before the maximum load, irrespective of the alloy type and test temperature.

(3) At 0°C, the difference of fracture toughness at the same strength comes from the difference of microcrack propagation resistance for each alloy type. At −196°C, the difference of fracture toughness at the same strength is due mainly to the difference of microcrack propagation resistance for the α and α + β alloys, and to the difference of crack initiation characteristics for the β alloy.

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