Influence of Metastable Beta on the Low Cycle Fatigue Behaviour of Ti–6.3Al–3.5Mo–1.9Zr–0.2Si Alloy

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ABSTRACT

The influence of metastable beta on low cycle fatigue (LCF) behaviour of the alloy Ti-6.3Al-3.5Mo-1.9Zr-0.23Si has been studied. Water quenching from within $\alpha+\beta$ field results in metastable beta. The presence of metastable beta leads to an increase in the work hardening rate with plastic strain under monotonic conditions and cyclic hardening and concomittant decrease in plastic strain with number of cycles under cyclic conditions. Twinning was seen to be the dominant mode of deformation in case of water quenched structures. These microstructures exhibit superior fatigue resistance as compared to furnace cooled and conventionally treated conditions. The observed improvement in fatigue resistance can be attributed to twinning as the dominant mode of deformation.

KEY WORDS

Low cycle fatigue, titanium alloy, metastable beta, fatigue life, cyclic hardening and cyclic softening.

INTRODUCTION

Attempts have been made in the recent past to impart fatigue resistance to $\alpha+\beta$ titanium alloys by incorporating metastable β through suitable heat treatments (Gilmore et al., 1985; Imam and Gilmore, 1983). Depending on the concentration of β stabilisers, the metastable β can undergo stress/strain induced transformation to orthorhombic martensite (Oka and Taniguchi, 1980; Williams, 1973) or omega (Hanada and Izumi, 1980). In the absence of phase transformation it can lead to twinning as the dominant mode of deformation (Chackraborty et al., 1978; Hanada and Izumi, 1987). Rapid cooling from within $\alpha+\beta$ region results in metastable β (Makhnev et al., 1982; Mukherjee et al., 1982), the presence of which has been found to improve fatigue life in Ti-6Al-4V alloy (Imam and Gilmore, 1983) and retard fatigue crack growth rate in CORONA 5 (Gilmore et al., 1985). The increased fatigue life in case of Ti-6Al-4V has been attributed to strain induced transformation of retained β. However, to the knowledge of authors no detailed studies exist in the literature on the influence of metastable β on the LCF behaviour of $\alpha+\beta$ titanium alloys. Here we report the results obtained on the influence of metastable β on the room temperature (25°C) LCF behaviour of the alloy Ti-6.3Al-3.5Mo-1.9Zr-0.23Si, commercially designated as VT9.

EXPERIMENTAL PROCEDURE

The alloy was received in the form of 100 x 100 mm square cross-section billet in the mill annealed condition. The alloy has the chemical composition, by wt. pct., 6.3Al, 3.5Mo, 1.9Zr, 0.23Si, 0.10Fe, 0.009C, 1370ppm O_2, 124ppm N_2, 60ppm H_2 and balance titanium. The billet was hot rolled at 960°C in the α+β region to 15mm thick plate. Heat treatment schedules employed are given in Table-1. To retain β in the metastable condition, a solutionising temperature of 875°C was chosen on the basis of the phase composition diagram developed by Makhnev et al. (1982) for the alloy under consideration. A recrystallization anneal of 960°C/2h was incorporated in case of WQ II treatment.

Table-1 : Heat Treatments Employed

Treatment	Designation
875°C/2h, FC	FC
875°C/2h, WQ	WQI
960°C/2h, FC → 875°C/1.5h, WQ	WQII

FC = Furnace Cooled, WQ = Water Quenched

Tensile tests were conducted using cylindrical specimens of 16mm gauge length and 4.5mm gauge diameter at a strain rate of $10^{-3}sec^{-1}$. Fully reversed, total strain controlled LCF tests were conducted at a constant frequency of 0.1 Hz on a closed loop servohydraulic Instron-8033 test system using Wood's metal grips. Efficiency button headed specimens of 15mm parallel length and 6.35mm gauge diameter were used. A dynamic extensometer of 10mm gauge length was used to monitor strain.

Thin foils were examined under a Phillips EM300 transmission electron microscope (TEM). The specimens intended to study deformation aspects were taken from sections close to the fractured surfaces. Ion beam thinning technique was employed to avoid reversion of strain induced martensite (Spurling et al., 1974). Polished and etched microstructures as well as fractured surfaces were examined under ISI 100A scanning electron microscope (SEM).

RESULTS AND DISCUSSION

Microstructure

The microstructures corresponding to the treatments FC, WQI and WQII are shown in Fig.1. Both FC and WQI treatments have resulted in elongated primary α phase due to lack of recrystallization (Figs.1a and 1b). Samples subjected to FC treatment possess primary α and widmanstatten α (Fig.1a). In case of WQI treatment the microstructure comprises primary α and retained β (Fig.1b). Presence of some secondary α is also evident. On the other hand, the microstructure of WQII treatment that incorporates a recrystallization anneal shows equiaxed primary α and retained β (Fig.1c). Bright field TEM micrograph of the alloy in WQII condition and the respective selected area diffraction (SAD) patterns are shown in Fig.2. Analysis of the SAD patterns in [$\bar{2}$110] zone axis of hexagonal phase and [11$\bar{1}$] zone

axis of cubic phase establishes that the structure comprises primary α and metastable β.

Tensile Properties

Tensile properties of the alloy in FC, WQI and WQII conditions are listed in Table-2. There exists considerable variation in 0.2% proof stress between FC, WQI and WQII conditions though the ultimate tensile strength remains unaffected. The alloy possesses maximum proof stress (834 MPa) in FC condition and minimum in the WQII (590 MPa) condition. The alloy in WQI condition shows an intermediate value of 740 MPa. This is consistent with the fact that water quenching from within α+β region, as in case of WQI and WQII conditions, results in retention of metastable β which has lower yield strength (D'yakova et al., 1976; Fopiano and Hickey, 1973; Gilmore et al., 1985; Luzhnikov et al., 1964; Makhnev et al., 1982). Higher strength in case of WQI condition as compared to WQII may be related to the unrecrystallized structure of WQI. Further, the presence of metastable β in WQI and WQII conditions has resulted in lowering of the Young's modulus (88 and 77 GPa respectively) as compared to the FC condition (122 GPa). Water quenched structures showed marginal improvement in ductility as compared to the FC condition (Table-2). Lowering of proof stress (0.2%) as well as Young's modulus and marginal improvement in ductility as a result of metastable β are in line with the reported observations on α+β titanium alloys (D'yakova et al., 1976; Fopiano and Hickey, 1973; Luzhnikov et al., 1964; Majahan and Margolin, 1982; Smelser et al., 1978).

Table-2 : Tensile Properties of the Alloy VT9 in FC, WQI and WQII Conditions

Treatment	0.2% Proof Stress, MPa	UTS MPa	Elongation %	Reduction in Area, %	Young's Modulus, GPa
FC	834	1040	15.3	38.2	122
WQI	740	1065	16.3	44.0	88
WQII	590	1069	16.5	49.2	77

Work hardening rate is presented as a function of plastic strain in Fig.3 for the three conditions. Work hardening rate initially decreases steeply in all the three cases. Following an initial drop, a rise in the work hardening rate is seen in case of WQI and WQII conditions. Work hardening rate attains a peak at plastic strains of 0.033 and 0.037 for WQI and WQII conditions respectively, beyond which in either case it decreases steeply with plastic strain. It is also evident that at all plastic strains water quenched microstructures work harden more than the furnace cooled condition. TEM observations have revealed {112} <111> twinning in metastable β. Increased work hardening rate associated with twinning is in line with that reported by Hanada and Izumi (1987).

Cyclic Stress Response

The cyclic stress response curves for the alloy in the three different conditions are shown in Fig.4. The alloy in FC condition exhibits cyclic softening till fracture (Fig.4a), whereas cyclic hardening is observed with WQII condition (Fig.4c). Further, cyclic softening is seen to be more pronounced than hardening. In case of the WQI condition, following an initial softening the alloy cyclically hardens till fracture (Fig.4b). In all the three conditions the cyclic stress never attains saturation.

The cyclic softening in case of FC condition (Fig.4a) may be attributed to the dislocation dynamics wherein an increase in mobile dislocation density is accompanied by a decrease of the flow stress (Theodorski and Koss, 1982; Wojcik and Koss, 1977). On the other hand, the cyclic hardening in WQII condition (Fig.4c) can be understood in terms of twinning as the dominant mode of plastic deformation. Large cyclic hardening is associated with twin interfaces acting as barriers to continued deformation and with lattice defects generated by the twinning mechanism (Chackraborty et al., 1978). Specimens corresponding to WQII treatment subjected to fatigue at low, intermediate and high strain amplitudes were examined under TEM. At all strain amplitudes {112} ⟨111⟩ twinning in metastable β and {10$\bar{1}$1} twinning in alpha has been observed (Fig.5).

Cyclic Strain Response

The cyclic plastic strain response curves corresponding to a total imposed strain amplitude of 1.5% for the alloy in the three different conditions are shown in Fig.6. In all the three cases plastic strain never attains a stable value. The plastic strain range ($\Delta\epsilon_p$) increases considerably with number of cycles in case of FC condition, which exhibits cyclic softening (Fig.6). On the other hand, in case of WQII condition, $\Delta\epsilon_p$ decreases gradually till fracture (Fig.6). Part of the plastic strain gets converted to elastic strain as a result of cyclic hardening associated with twinning. WQI condition exhibits a mixed behaviour. Following an initial increase, the plastic strain range decreases (Fig.6) as in the case of WQII condition.

Fatigue Life

Fatigue life variation in terms of reversals to failure ($2N_f$), where N_f is the number of cycles to fracture, with applied total strain amplitude ($\Delta\epsilon_t/2$) for FC, WQI and WQII conditions is shown in Fig.7. Among the three treatments studied, the alloy in WQII condition shows superior fatigue resistance at all strain levels. In the strain range under consideration, WQII condition has shown 2-5 times higher fatigue life than that of WQI condition and 4-8 times that of FC condition (Fig.7).

For the sake of comparison, a conventional treatment (designated as AC) was also studied. The treatment AC involves soaking for 1 hour at 960°C, followed by air cooling and stabilizing anneal at 530°C for 6 hours. Stabilizing anneal is intended to stress relieve and do not appreciably alter the microstructure, at least at optical level (Mukherjee, 1986). The microstructure consists of equiaxed primary alpha surrounded by secondary alpha laths (Mukherjee et al., 1982). The alloy in the AC condition possesses 949MPa proof stress (0.2%), 1088 MPa ultimate tensile strength, 18.5% elongation, 49% reduction in area and 120 GPa Young's modulus. LCF data corresponding to AC condition are included in Fig.7. It is evident from Fig.7 that water quenching significantly improves fatigue resistance as compared to the AC treatment. Fatigue lives are enhanced by 2-4 times.

Fractographic studies were conducted on the fractured LCF specimens. Irrespective of prior treatment, fractured surfaces are characterised by ductile dimpled features. A typical fractograph corresponding to WQII treatment is shown in Fig.8. Only in case of WQII condition, fatigue striations are seen at crack initiation sites (Fig.8b). Secondary cracks are also seen parallel to the striations.

The improvement in fatigue resistance observed in the present study as a result of metastable beta is in line with that reported in case of

Ti-6Al-4V alloy (Imam and Gilmore, 1983). However, TEM study in the present case has revealed twinning with no evidence to the occurrence of transformation of metastable β to martensite as reported in the case of Ti-6Al-4V (Imam and Gilmore, 1983). As a result of twinning, the alloy cyclically hardens and concomittantly part of the plastic strain gets converted to elastic strain during the course of cycling (Fig.6). For a given damage accumulation and thereby failure, it therefore needs a greater number of cycles than the situation where the plastic strain continuously increases upon cycling i.e., FC treatment. Further, in the presence of metastable beta, the alloy is seen to withstand large damage accumulation prior to failure. For example, at the total strain amplitude of 1.5%, the plastic strain accumulated in case of WQII condition (6.75) is seen to be more than twice that of FC condition (3.14). The damage accumulated was estimated as the area under plastic strain range vs number of cycles curve till fracture.

CONCLUSIONS

1. Water quenching from within alpha + beta region results in the retention of metastable beta.
2. Metastable β results in increase in monotonic work hardening rate with plastic strain.
3. The alloy in the water quenched condition exhibits cyclic hardening whereas the same in furnace cooled condition undergoes softening till fracture.
4. Water quenching leads to significant improvement in strain controlled low cycle fatigue resistance as compared to the furnace cooled as well as conventional treatments. The observed improvement in fatigue resistance can be attributed to twinning as the dominant mode of deformation.

ACKNOWLEDGEMENTS

The authors are grateful to Dr.P. Rama Rao, Director, DMRL for constant encouragement and kind permission to publish this work. Thanks are due to Sri G. Sundara Sarma and Sri D.V.V. Satyanarayana for their help in SEM studies and Dr.D. Banerjee and Dr.Y.R. Majahan for helpful discussions.

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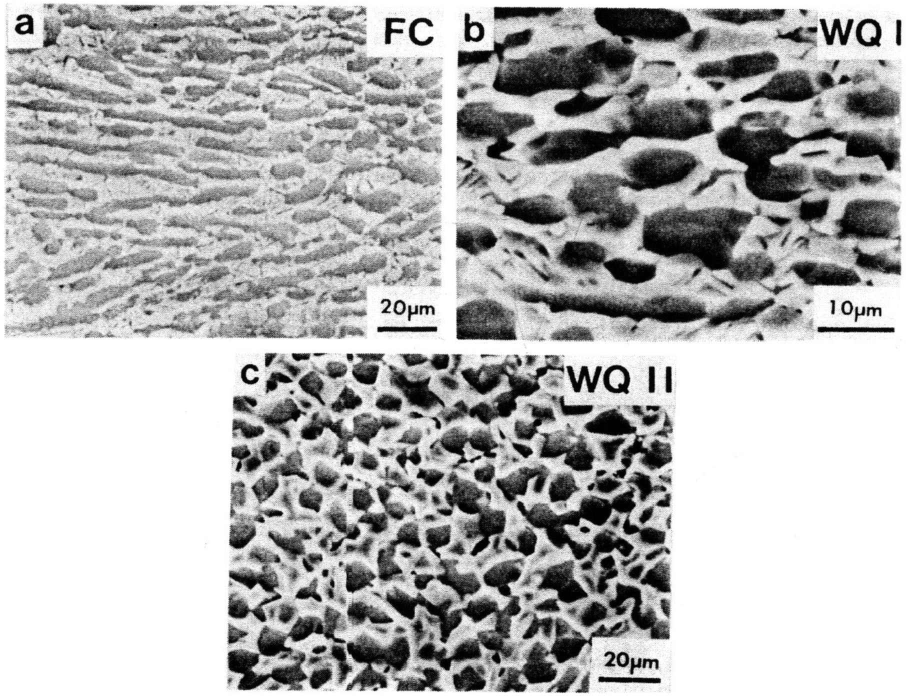

Fig. 1 : Scanning Electron Micrographs corresponding to FC, WQI and WQII conditions

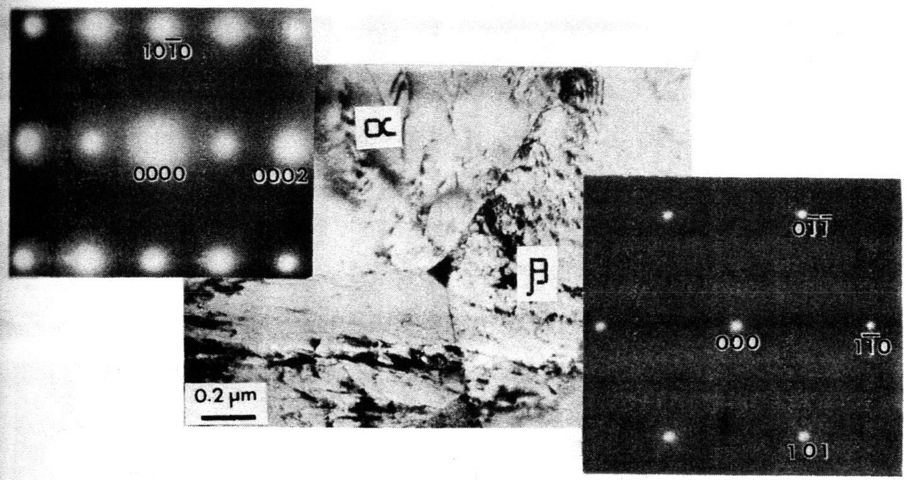

Fig. 2 : Transmission Electron Mocrograph of WQII condition with SADPs corresponding to primary α in [$\bar{2}$110] zone axis and metastable β in [11$\bar{1}$] zone axis

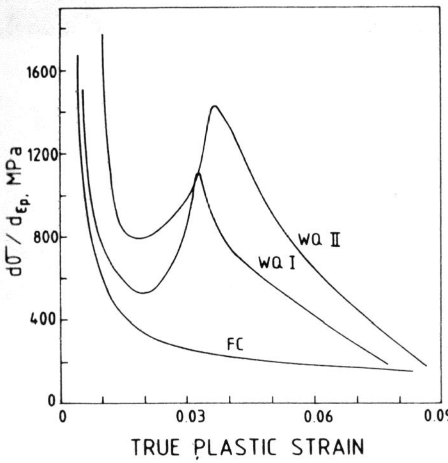

Fig. 3 : Monotonic work hardening rate as a function of plastic strain

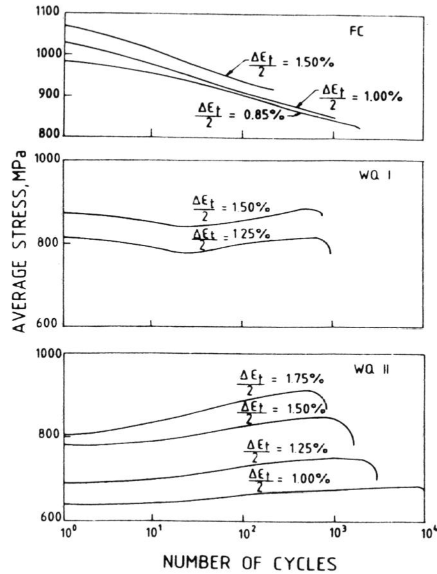

Fig. 4 : Cyclic stress response curves for FC, WQI and WQII conditions

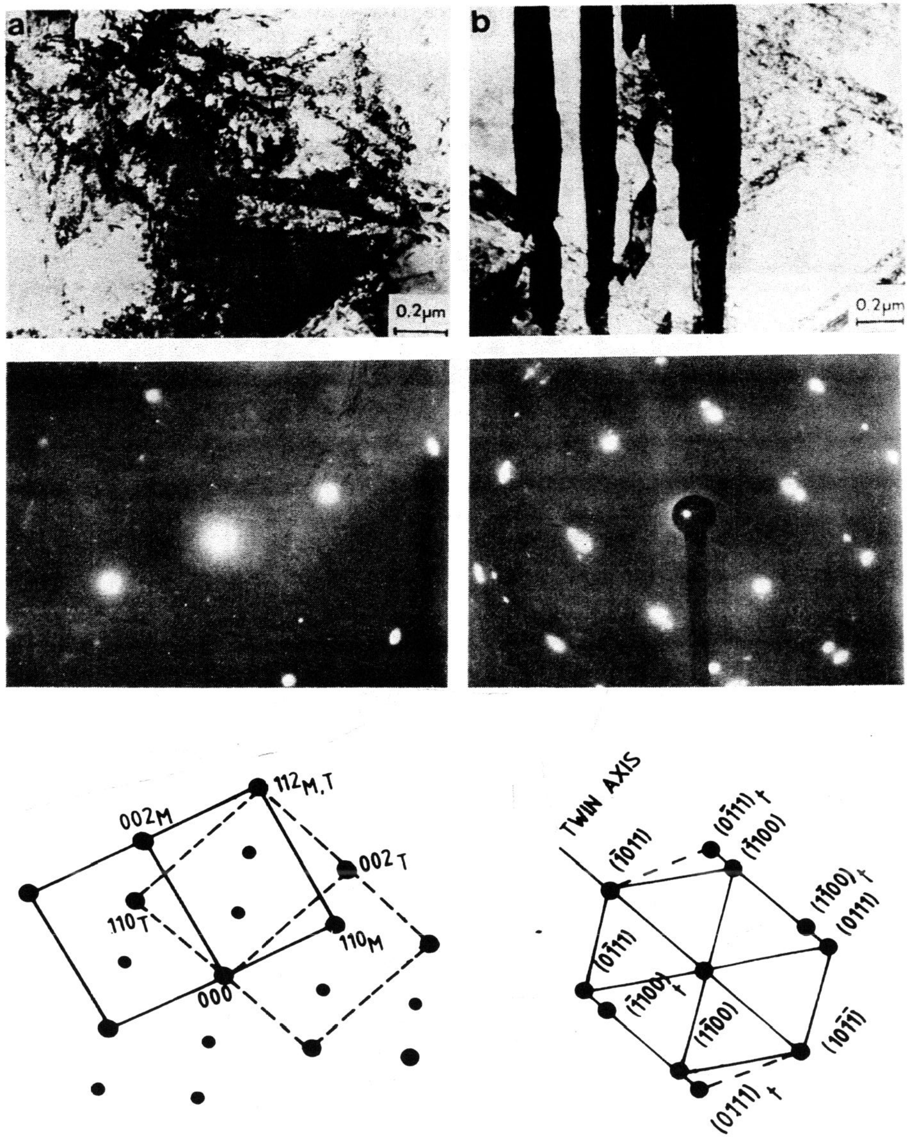

Fig. 5 : Transmission Electron Micrographs along with SADPs for the alloy in WQII condition, fatigue tested at a total strain amplitude of 1.5% showing (a) {112} ⟨111⟩ twinning in metastable β and (b) {10$\bar{1}$1} twinning in primary α

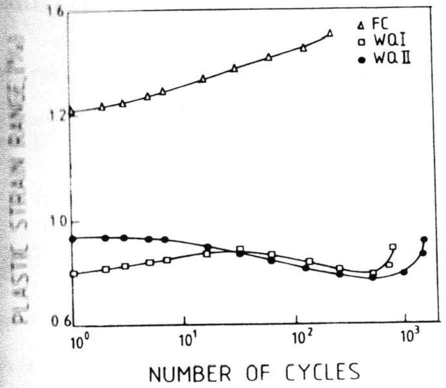

Fig. 6 : Cyclic strain response curves for FC, WQI and WQII conditions

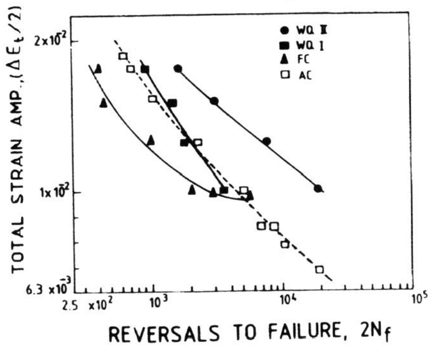

Fig. 7 : Fatigue life variation with total strain amplitude for FC, WQI, WQII and AC conditions

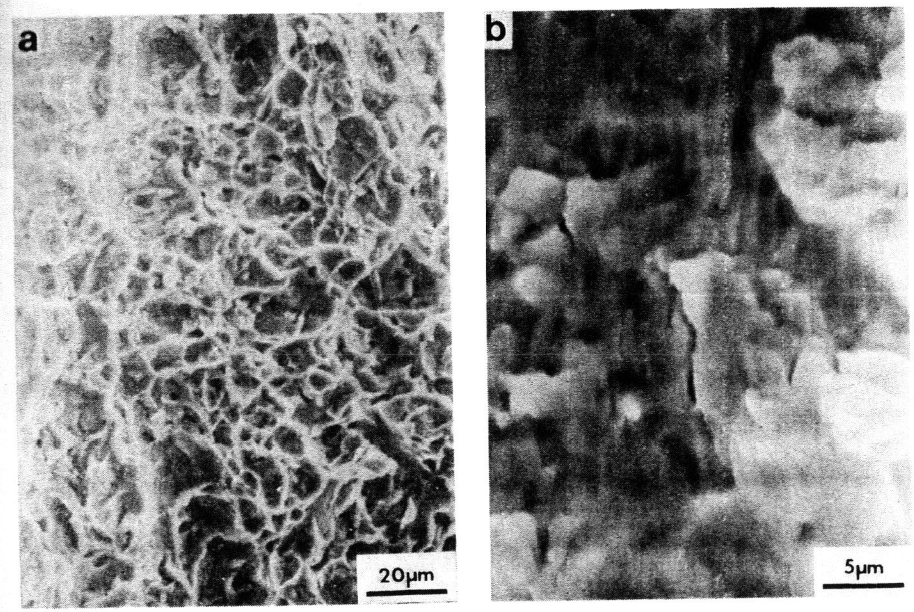

Fig. 8 : SEM fractographs corresponding to WQII condition showing (a) ductile dimpled feature and (b) striations and secondary cracks