EFFECT OF PHOSPHOROUS ON FATIGUE PROPERTIES OF INCONEL 718 ALLOY

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Abstract

High cycle fatigue and low cycle fatigue tests of Inconel 718 alloy samples containing ultra-low P(<10 ppm) and conventional P content were conducted. The results indicated that decreasing the phosphorous level did not distinctly improve fatigue properties of the superalloy at intermediate temperature. It was showed that fatigue cracks easily initiated at sites of Nb segregation (clusters of Nb carbides, Ti carbides and inclusions) by using SEM fractography observation and energy-disperse X-ray spectroscopy analysis (EDS) where were usually enriched in S regardless of P content. HCF crack origins almost were located in interior of specimen and propagated mainly along crystallographic facet of coarse grains depleted in Nb and Mo. Fluctuation of LCF life was associated with grain size, shape and distribution of δ-precipitates and segregation of Nb but not depended on P content.

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Introduction

Recently it was presented in some papers [1,2] that industrial Inconel 718 ingots melted by VIM+VAR with very low content of P<10 ppm have showed advantages of decreasing the amount and size of Laves phase particle and dendritic segregation. however, mechanical properties including 650°C tensile and stress rupture, LCF, fatigue and creep interaction properties of Inconel 718 alloy have not revealed any improvement [3,4] of very low P content in comparison with conventional one but little fatigue data on the effect of P content has been published.
The objective of this work was to investigate the effect of ultra-low P(<10ppm) on HCF and LCF properties of samples cut from four Inconel 718 turbine disks and to know microstructural factors of controlling crack initiation and growth by using SEM fractography and EDS analysis.

Experimental method

The chemical compositions of the tested alloy are given in Table I. The four ingots, A and C heats containing ultra-low P(<10ppm) and others (B and D) with conventional P content, melted by VIM+VAR were conducted with two-steps homogenization treatment i.e. 1160°C/20h→1190°C/30-40h A.C. A, B (Φ540mm) and C, D (Φ380mm) disks were produced in Fushun Steel Works and in Changcheng Steel Works respectively but subjected to same standard heat treatment. The final hot working of disk D was forged by 63T-M hammer and the others by hydraulic press.
Four groups of samples were cut chordwise from corresponding turbine disks and all of the HCF specimen located on rim and the LCF specimen on spoke. LCF tests were conducted at 550°C under load control with a triangular wave form (R=0 F=30cpm). Maximum stress tested for specimen of smooth and notch (K_t=3.7) with gauge diameter of Φ7mm was 1100 MPa and 750 MPa respectively. HCF tests were conducted at 650°C and 80 Hz. The load ratio R is 0.1 and gauge diameter of the specimens is Φ4mm.
Metallographic examinations were carried out in a plane parallel to the test piece axis. These examinations permitted to relate much closely the crack initiation and growth path to the specimen microstructure.

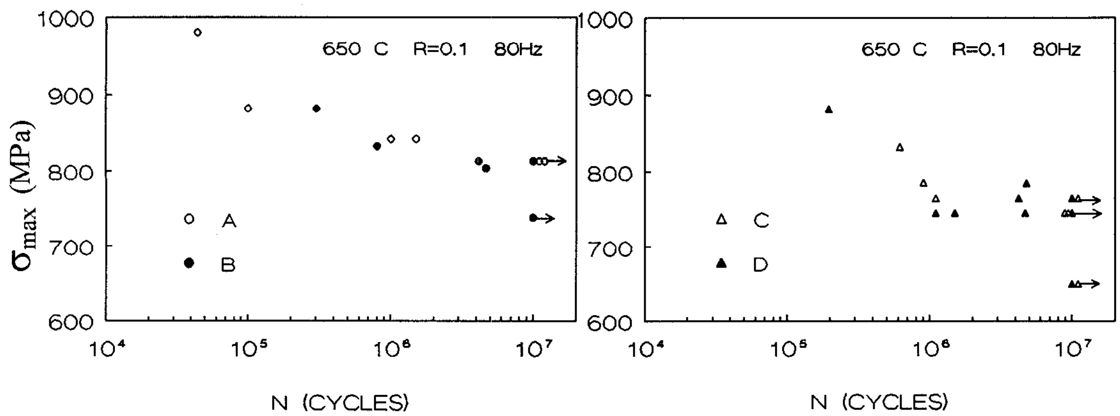
Table 1 Chemical Compositions of tested alloy (wt%)

Heat	C	Mn	Si	S	P	Ni	Cr	Mo	Al	Ti	Nb	Co	B	Mg
A	0.031	0.02	0.040	0.0035	0.0005	52.52	18.23	2.97	0.52	1.03	5.15	0.040	0.0040	0.0018
B	0.036	0.02	0.090	0.0020	0.0030	52.48	18.66	2.94	0.54	1.02	5.01	0.050	0.0036	0.0018
C	0.039	0.02	0.080	0.0054	0.0005	52.84	18.50	2.08	0.60	1.00	5.14	0.009	0.0050	0.0037
D	0.040	0.03	0.100	0.0120	0.0070	51.81	18.58	3.01	0.53	0.97	5.25	0.016	0.0043	0.0062

Results and Discussion

Fatigue test

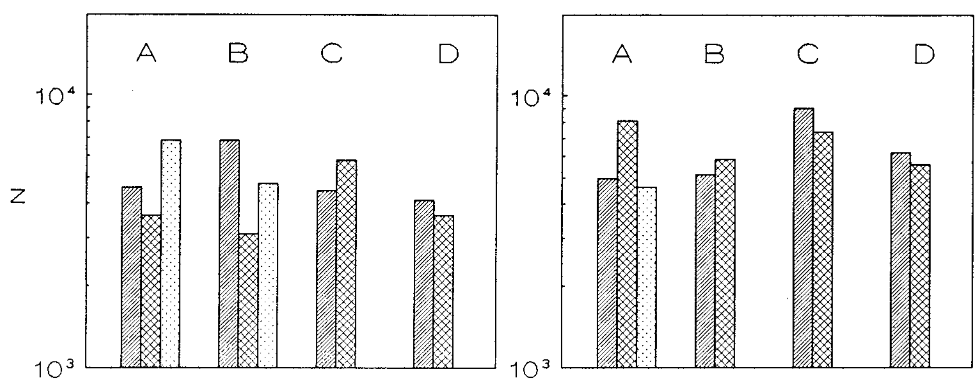
Fig.1 and Fig.2 show the test data of HCF and LCF and it can be seen that ultra-low P content has almost no effect on the fatigue properties compared with conventional P content but HCF strength at 10^7 cycles for both groups of A and B disks is 8% higher than that of C and D disks. it may be related to the divergence on microstructure of disks made in two steel works due to



(a) Data of disks of A and B made in Fushun Steel Works

(b) Data of disks of C and D made in Changcheng Steel Works

Fig.1 HCF data of inconel 718 alloy specimens from four disks (A and C ultra-low P content; B and D conventional P content)



(a) Smooth (σ_{max}=1100Mpa)

(b) Notch (Kt=3.7, σ_{max}=750 Mpa)

Fig.2 LCF life of specimens cut from four disc (R=0, T=550°C, F=30cpm)

controlling different technological parameters which well proved by microscopic analysis. It is also seen from Fig.2 that a fluctuation of LCF life for four groups falls in a same range which is 4626/9041 cycles for smooth specimens and 6860/3098 cycles for notched specimens and independent on P content. Even though different specimen taken from the same disk A with ultra-low P content also have the same life fluctuation. The fatigue lives of smooth specimens of group C tend to upper limit and those of group D of notched ones to lower limit.

Fractographic analysis

Fig.3-Fig.5 show typical microstructure of the longitudinal section near to LCF fracture

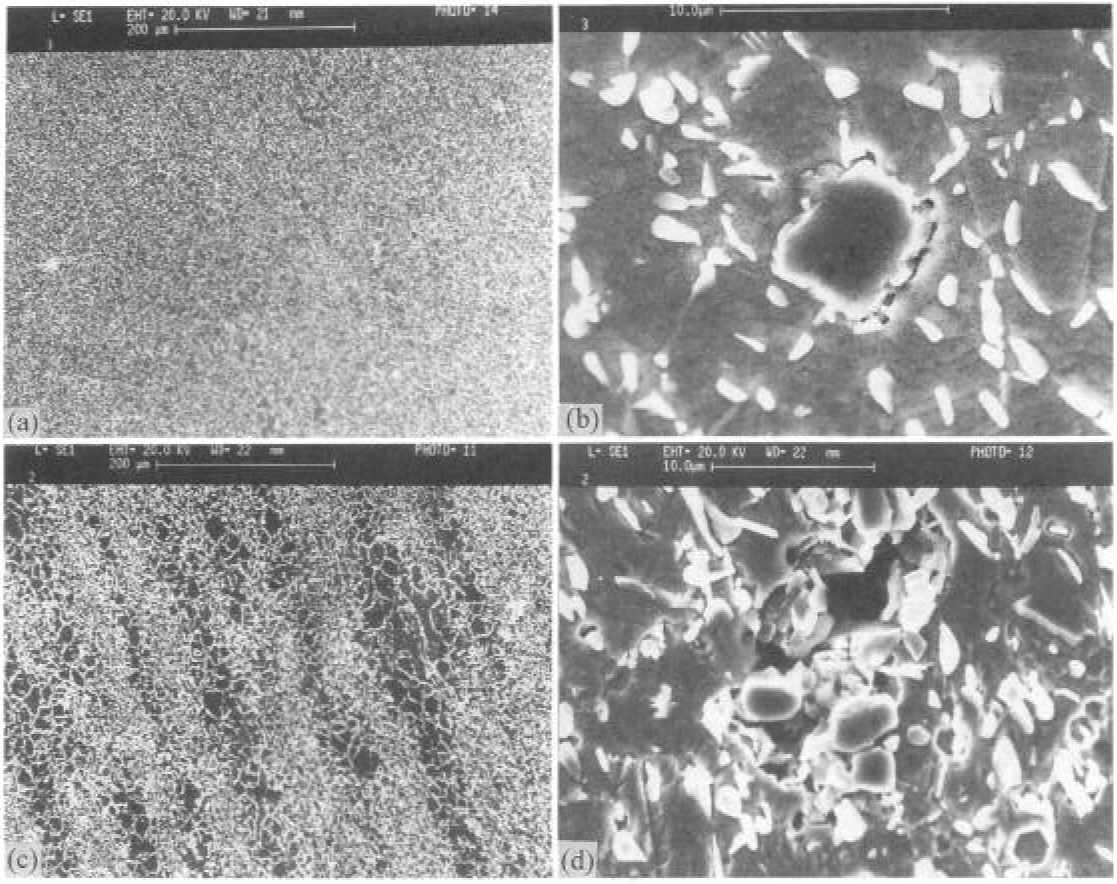


Fig.3 Microstructure of LCF specimens from disk A (P<10ppm)
(a) and (b) N=8095 cycles; (c) and (d) N=4981 cycles

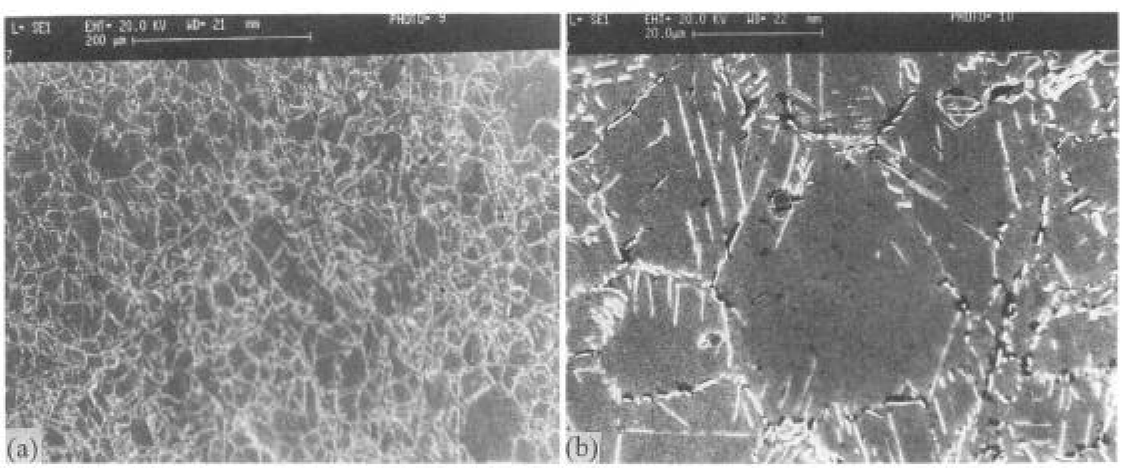


Fig.4 Microstructure of LCF specimens from disk B (conventional P content).
(a) and (b) N=5856 cycles

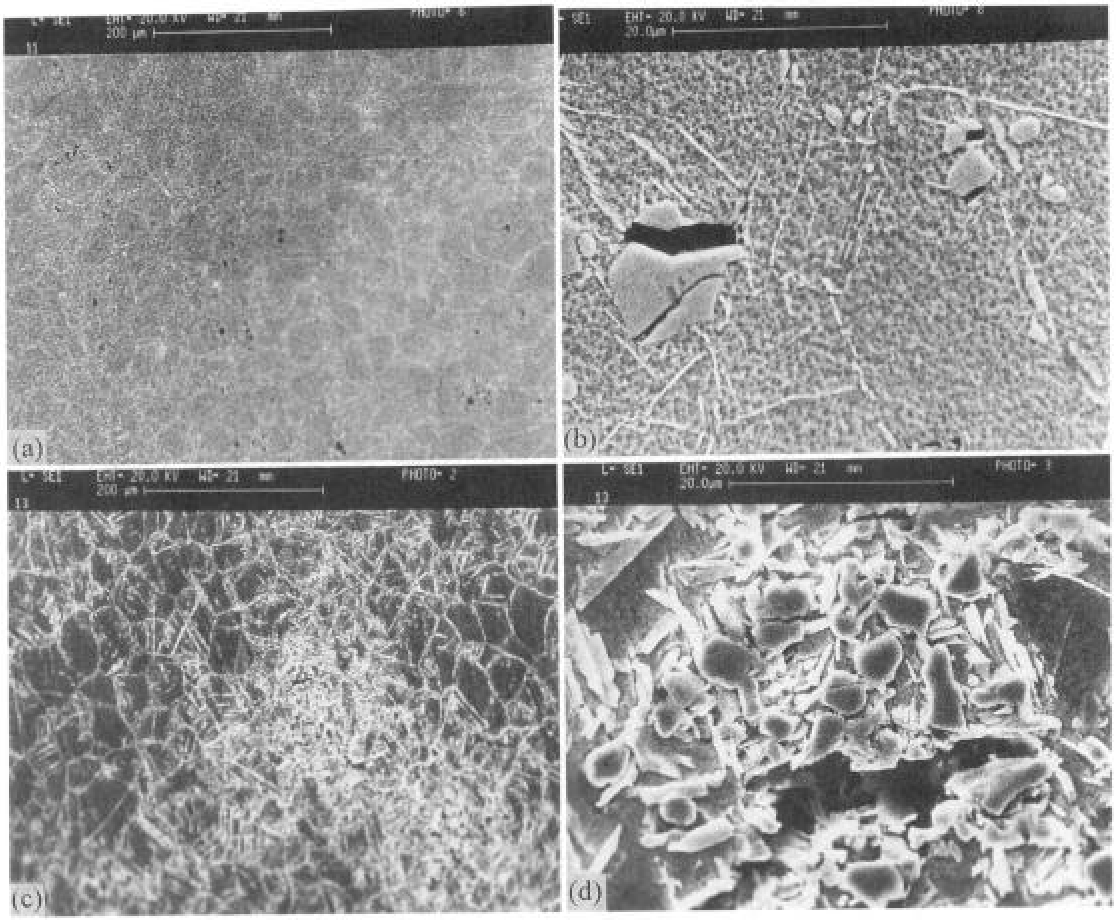


Fig.5 Microstructure of LCF specimens from disk C (P<10 ppm) and D (conventional P content) (a) and (b) N=7407 cycles; (c) and (d) N=5636 cycles

surface. The homogeneity of grain size has distinct divergence for two specimens taken from the same A disk with ultra-low P content as show in Fig.3. In Fig.3a and 3b reveals characteristic of fine grain (ASTM 10) and homogeneously dispersed globular or small rod-liked precipitates, which has upper limit of life (8095 cycles). But the inhomogeneous grains together with segregation of δ phase and NbC lead to reduce life to a lower limit (4981 cycles) as show in Fig.3c and 3d. Slight coarse grain size (ASTM 8) is shown in Fig.4a ad 4b, that is the microstructure of specimen with lower limit life from disk B with conventional P content and a lot of microcracks have been produced along Nb segregation areas containing δ phase and NbC, where was enriched in Nb of 22% determined by EDS. More coarse grain size (ASTM6) is present in those specimens from disk C and D (Fig.5a and 5c).Because the former has homogeneous disperse fine δ precipitates and the cracks initiate only at interface between carbides and matrix (Fig.5b), that gives upper limit life. This special microstructure different from other disks may be caused by fast deformation forged by hammer. However sites with serious segregation of Nb obviously became origins of cracks (Fig5d) that led to lower LCF life, especially notched life, and it may be recognized as a result of higher S content in disk D and independent on P content. EDS analysis of crack origins on fracture surface for a number of specimens further provided some evidence. As same as microstructure of LCF specimen, metallographic observation of HCF specimen as a whole indicated the grain size in groups A

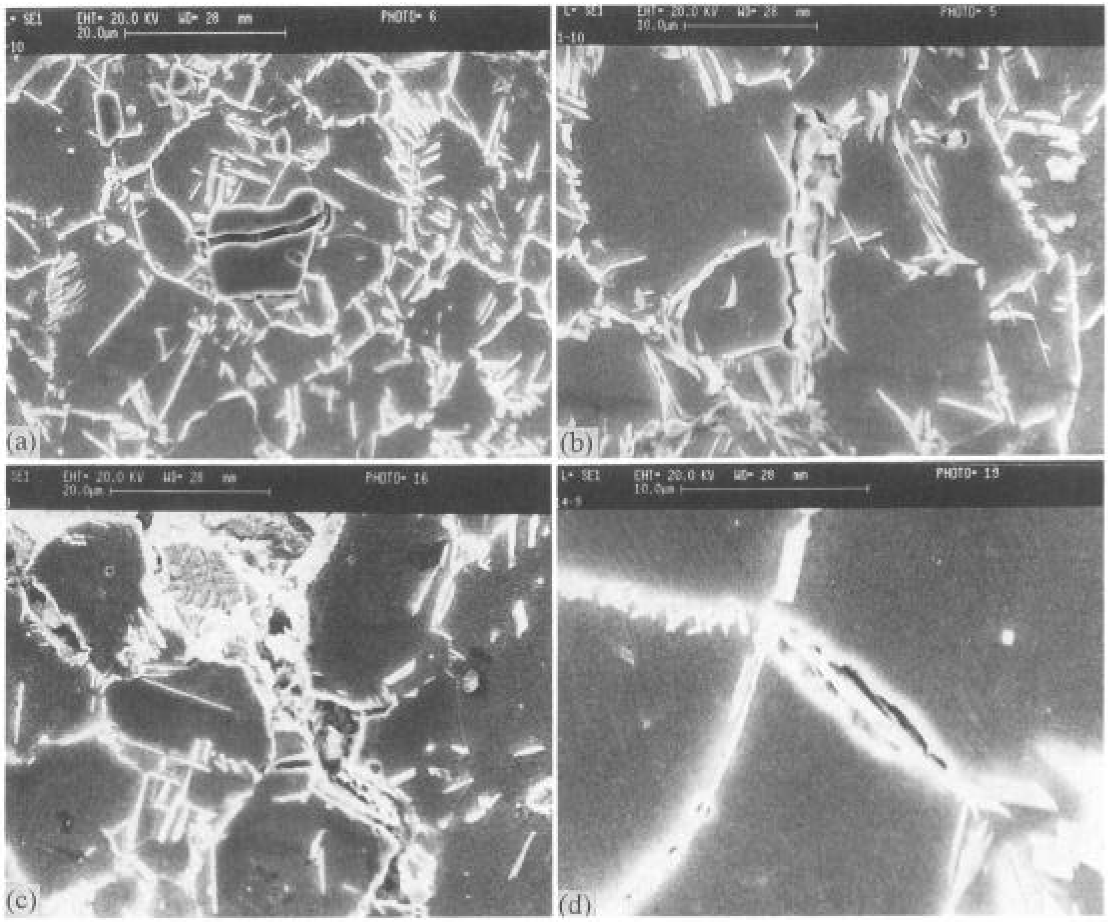


Fig.6 Sites of crack initiation of HCF specimens (a) cracked carbide; (b) cracked interface between inclusion and matrix; (c) intergranular cracking area enriched in Nb and Al; (d) cracking interface between acicular δ precipitate and matrix.

and B was finer than that in groups C and D despite the fact that the imhomogeniety of microstructure of various specimens from different locations in an identical disk was present. In addition HCF cracks were also easily initiated at the carbides (Fig.6a), sulfide-rich (22%S) inclusions (Fig.6b) and grain boundaries with segregation of coarse δ precipitation or NbC particles (Fig.6c and 6d).

SEM observations of HCF fracture surface illustrate that the fatigue crack origins were located always at sub-surface or interior of the specimens when the fracture life exceeded 10^6 cycles. As indicated by metallographic analysis, cracks were initiated always at segregation areas of Nb or other inclusions. In addition the cracks preferentially propagated along favorable orientated crystallographic facets of coarse grains i.e. in stage I of fatigue crack propagation. It was found that the origin area in Fig.7b contained Mg (10.51%), Al (11.4%) and S(2.25%) while that in Fig.c-Fig.f enriched in Nb (6.3-16.6%) and S (0.17-0.37%). The smooth facets were depleted of Nb (1-3%) and Mo(0.87-2%). Table 2 shows an example in the comparison of compositions at facet and matrix. By using observation of back reflection of SEM, the pattern of facets was obtained to reveal darker contrast due to depleting of heavy elements of Nb and Mo in comparison with peripheral non-faceted areas and specially bright particles closed to the facet are aggregates of NbC or δ phases (Fig.7e and 7f) where have been cracked as crack origins in

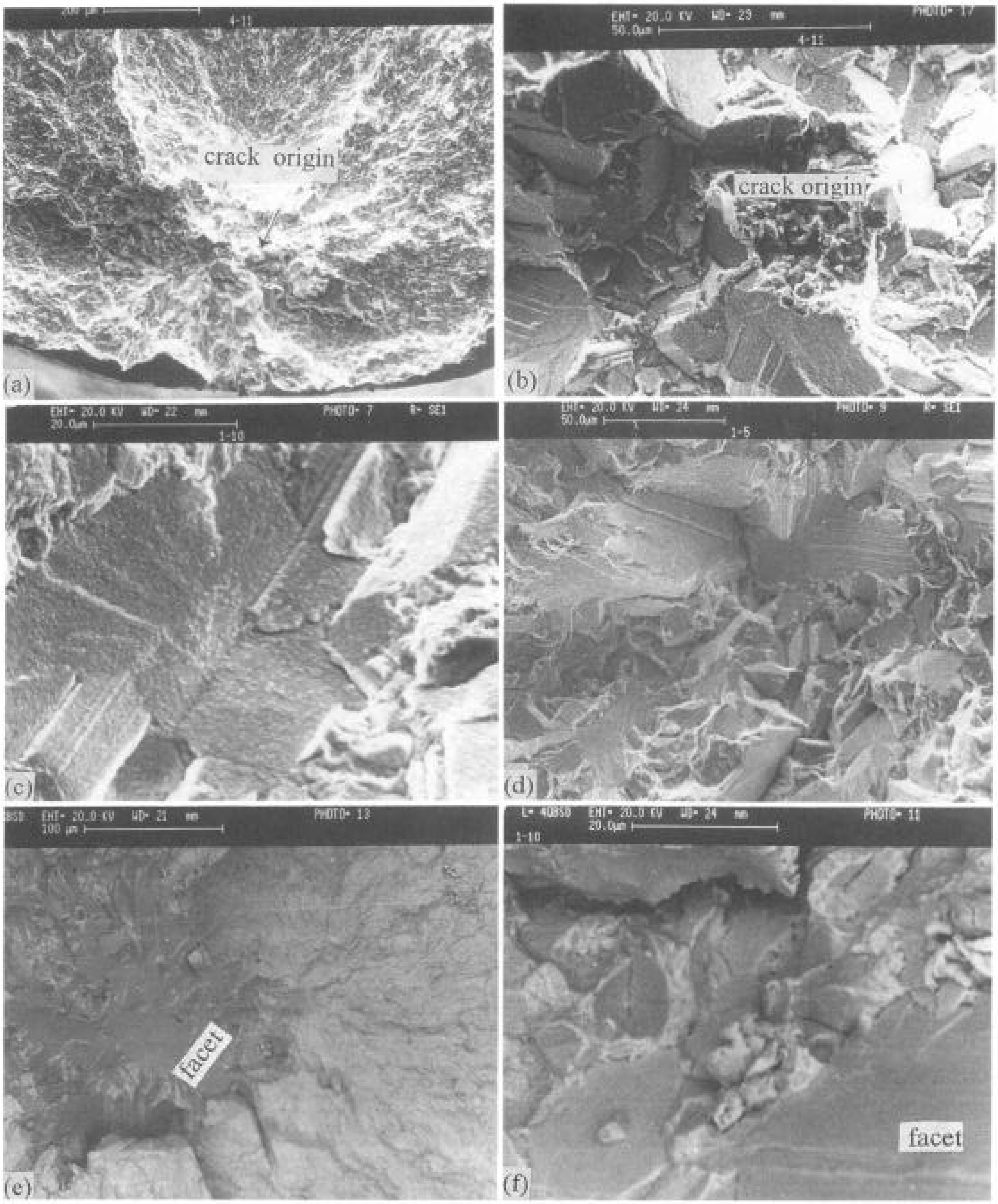


Fig.7 HCF fracture surface (a) interior origin (b) crack origin at inclusions contained in Mg, Al and S; (c) and (d) facets depleted in Nb and Mo; (e) and (f) darker facet image by back reflection of SEM.

the early stage. The fact that HCF cracks easily propagated along crystallographic facets in coarse grains is believed that the resistance of dislocation movement is decreased by lack of Nb and Mo enough which are important alloying elements needed for strengthening in Inconel 718 alloy. It is known that the initiation and stage I propagation of HCF crack consumes a large portion of fatigue life. Obviously HCF strength for Inconel 718 is highly sensitive to

Table 2, All elmts analyzed, NORMALISED

	facet of Fig7d			non - facetecl area of Fig7d		
ELMT	ZAF	%ELMT	ATOM.%	ZAF	%ELMT	ATOM.%
Ni K	0.940	50.806	48.604	0.949	47.885	47.014
Cr K	1.094	22.619	24.431	1.033	19.481	21.595
Mo L	0.700	0.189	0.111	0.713	3.161	1.899
Al K	0.405	0.407	0.847	0.422	0.800	1.709
Ti K	1.017	0.771	0.904	0.990	1.013	1.218
Nb L	0.669	1.884	1.139	0.683	6.097	3.783
P K	0.831	0.000	0.000	0.853	0.157	0.293
S K	0.772	0.457	0.801	0.787	0.243	0.437
Si K	0.533	0.168	0.336	0.550	0.205	0.422
Fe K	1.008	22.700	22.828	1.010	20.959	21.631
Total		100.000	100.000		100.000	100.000

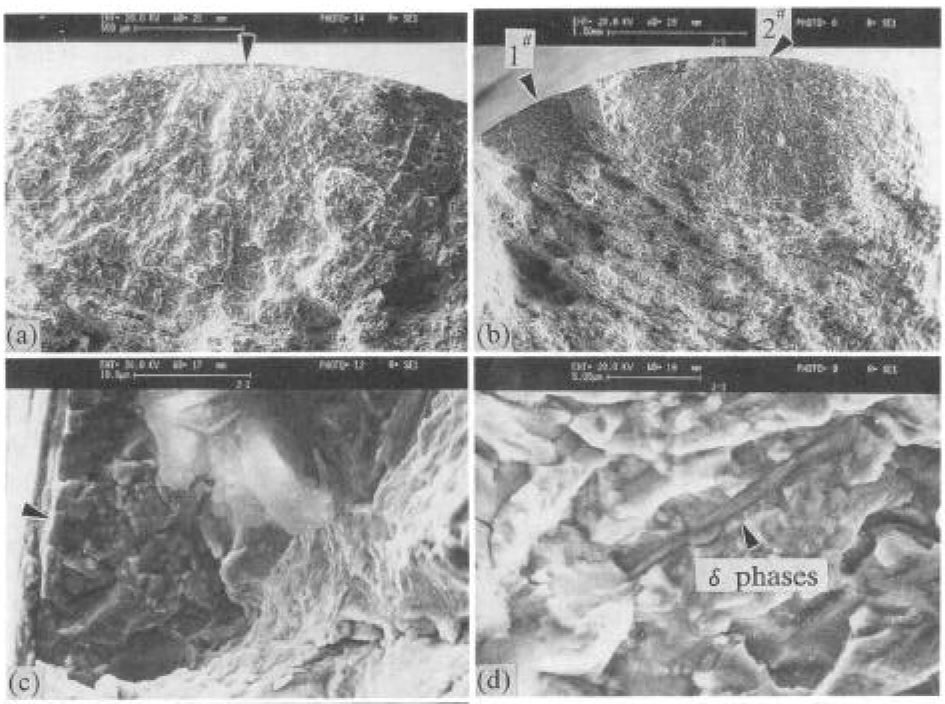


Fig.8 LCF fracture surface (a) an origin on surface of specimen (N=8095 cycles); (b) duplex origins (N=4981 cycles) (c) NbC and inclusions enriched in Si at origin pointed by 1# arrow in Fig.8b. (d) segregation of acicular and rod-like δ precipitates in crack growth area. (e) striations near to crack origin at segregation of NbC.

grain size and homogeneity of composition on microscopic scale that results in the different of HCF strength between the groups A, B and C, D. Fig.8 shows LCF fracture surface and the crack origins are almost located at surface of specimen (Fig.8a and 8b). The segregation of carbides or inclusions and S content (0.3-1.6%) in the origins appear to be much serious as show in Fig.8d-8e. For the upper limit life specimen as described previously in Fig.3a, a unique origin was commonly observed (Fig.8a), but the multiple crack origins usually occurred on the fracture surface of lower life specimen as show in Fig.8b. no existence of stage I and whole stage II propagation were found on LCF fracture surface of Inconel 718. Fig.8e shows the striations close to segregation area of Nb carbide and further indicates that stage II growth should be started as soon as the crack initiated. Above characteristic of fatigue fracture surface was not related to P content but S content can really promote fatigue crack formation. It makes sure of the reasons to understand that high grade Inconel 718 disks with homogeneous finer microstructure and excellent fatigue properties can be obtained by the best match of various technological parameters from smelting to forging and cannot be realized by lowering the phosphorous content to ultra-low level.

Conclusions

1. Ultra-low P content has no obvious effect on HCF and LCF properties of Inconel 718 alloy at the intermediate temperature.
2. HCF and LCF cracks are easily initiated at segregation areas with Nb carbides, δ precipitates and inclusions enriched in S.
3. Fluctuation of LCF life is attributed to the existence of inhomogeneous microstructure and composition in Inconel 718 disks.
4. HCF cracks easily propagate along crystallographic facets in coarse grains and the crack initiation and stage I growth in mode of concentrated planar slip controls life of HCF of the Inconel 718 alloy, so the HCF strength is highly sensitive to grain size and composition homogeneity on microscopic scale.

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