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Fractographic Characterization Of INCONEL601

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ABSTRACT
Fractographic characterization of fatigued INCONEL601 revealed two fracture zones, one brittle and one ductile in character. Crack initiation was identified at multiple and single sites with reducing stress levels. The initial zone was characterized as brittle fracture cleavage and the second zone that developed was characterized by ductile fracture as signified by features such as dimples and striations. It is suggested that such fatigue striations increase with increasing cyclic deformation.
***Keywords* -** Brittle, crack initiation, crack propagation, dimple, ductile, fatigue, striation

I. INTRODUCTION

INCONEL601 superalloys are widely used especially for components of turbines, shafts, and blades in aircraft engines because of their high strength, excellent fatigue resistance, and good corrosion endurance in aggressive conditions [1,2]. During the past few decades, extensive investigations have been made of the low and high cycle fatigue properties of INCONEL601 superalloys [3-6]. Recently, low and, more importantly, high cycle fatigue properties of high strength metals and their alloys have become more and more significant, ever since the finding of fatigue failure and endurance limit of these alloys [7]. During high cycle fatigue small plastic deformation can form at high applied stress and the as the number of cycles increases the plastic deformation increases and initiates a crack. As the number of cycles continues growing the crack propagates, and after a period of time the crack will cause failure in the component. The crack often propagates along the slip bands and grain boundaries [8]. Unlike the theoretical studies, the experimental fatigue studies are complex owing to the many factors that affect the result in a reduction in fatigue life, these factors include; mean stress, stress concentration, residual stress, specimen dimensions, microstructure, heat treatment, frequency, and surface finish.

The objective of this study was to examine the fatigue fracture surface of INCONEL601 and to carry out fractographic analyses with respect to the effect of the number of cycles to failure.

II. EXPERIMENTAL PROCEDURES

The material under investigation was air cooled nickel-based superalloy INCONEL601 whose chemical composition is shown in "Table 1".

Table-1 chemical composition of INCONEL601

Element	App Conc.	Intensity Corrn.	Weight %	Weight% Sigma	Atomic %
C K	2.02	0.3557	4.36	0.68	18.57
Si K	0.00	0.6146	0.00	0.00	0.00
P K	0.00	0.9953	0.00	0.00	0.00
S K	0.00	0.8153	0.00	0.00	0.00
Cr K	29.08	1.0153	21.93	0.65	21.60
Mn K	0.00	1.0335	0.00	0.00	0.00
Fe K	3.49	1.0385	2.58	0.31	2.36
Co K	0.00	0.9318	0.00	0.00	0.00
Ni K	75.44	0.9723	59.41	1.30	51.82
Y L	0.00	0.5787	0.00	0.00	0.00
Mo L	8.53	0.6997	9.34	1.53	4.98
W M	1.69	0.5389	2.39	0.59	0.67
Totals			100.00		

Fatigue tests were performed in an ambient atmosphere at room temperature using a servohydraulic INSTRON testing machine. The fatigued, fractured samples were first investigated by SEM and then sectioned, polished and etched for further investigation by disclosed SEM.

Secondary electron images (SEI) of a polished INCONEL601 specimen display compositional contrasts (grains are black and triangular carbides and slip bands are white in color) with the different colours being a result of the grain composition "Fig.1a".

The Energy Dispersive Spectroscopy (EDS) spectrum of the entire scan area is displayed in digitized form with the x-axis representing X-ray energy (in channel 20eV wide) and the y-axis representing the number of counts per channel. EDS is used to identify the chemical composition "Fig.1b".

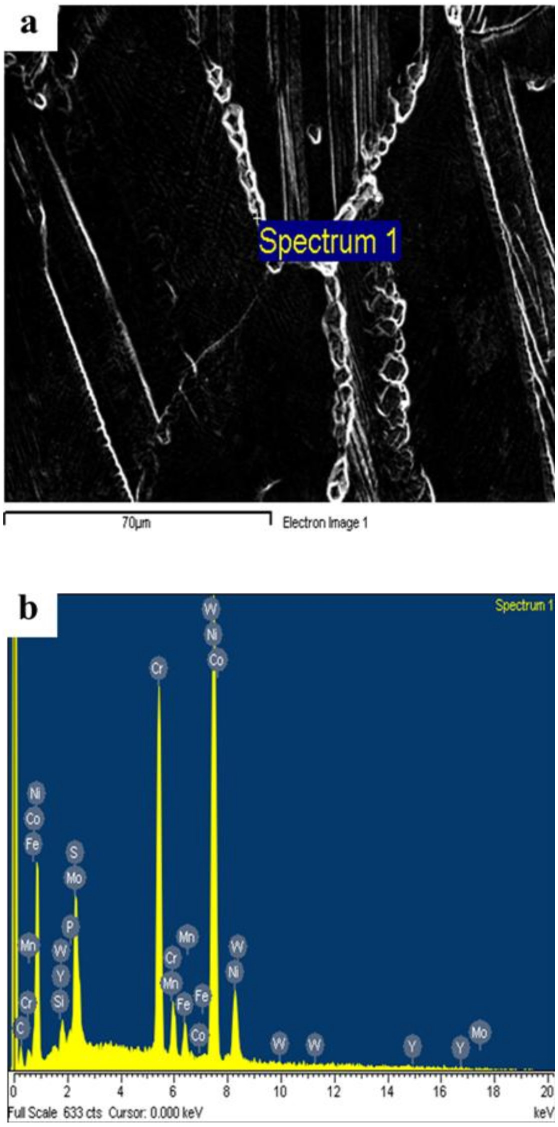


Figure1: INCONEL601 specimen, (a) SEI of polished specimen showing triangular carbides at the grain boundaries and slip bands, and (b) EDS X-ray spectra.

III. RESULTS AND DISCUSSIONS

"Fig.2" shows the S-N curve of INCONEL601 superalloy obtained from the fatigue test using the Instron servohydraulic testing machine. Note that most of the data points on the S-N curve are for cycles up to 10^6. However, several specimens were taken to over 10^7 cycles with no sign of fracture as indicated for the two specimens with an arrow sign (arrows indicate specimens that did not fracture). The test results can be regarded as direct evidence of INCONEL601 fracture in the high cycle fatigue regime at room temperature on the assumption that the specimen was free of any surface or subsurface defects.

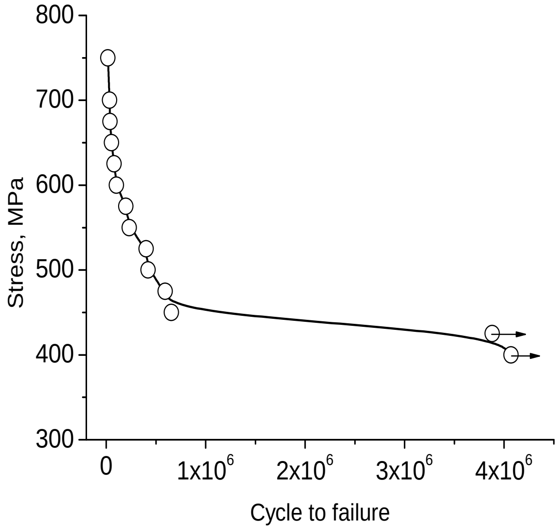
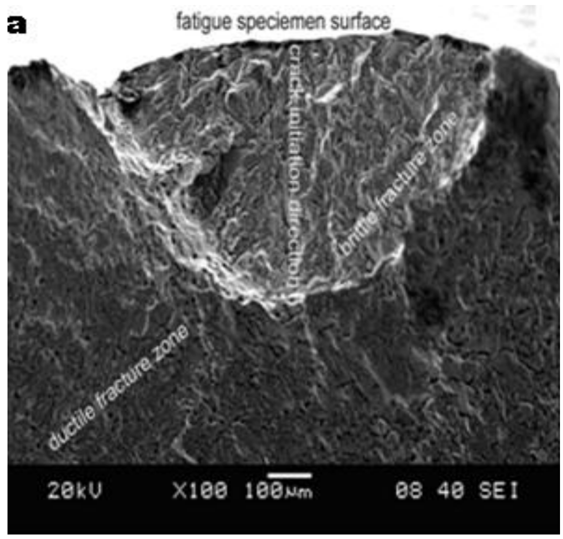


Figure 2: S-N curve of INCONEL601 showing that no fracture occurs below 500MPa.

"Fig.3" shows fracture surfaces that are fracture initiation sites. At high stress levels, fatigue cracks initiated from several sites, as shown in "Fig.3a". In this case, as the propagation of several cracks may not necessarily originate on the same plane, the final coalescence of these cracks initiating at several sites will lead to macroscopic fluctuant fracture surfaces. With reducing stress level, the number of crack initiation sites reduces correspondingly. In this case, the fracture surface may initiate from a single crack site that often display less surface roughness "Fig.3b" than fracture surfaces at several sites "Fig.3a". Such crack initiation can be occur at a minor surface scratch and is then enlarged with increasing number of cycles to form a macro crack initiation that leads to final fracture "Fig.3".



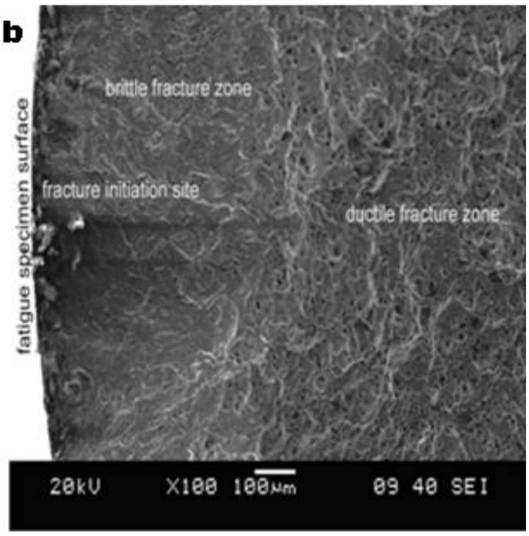


Figure 3: INCONEL601 specimen fracture surface shows brittle and ductile zones, (a) Fracture at 250,000 cycles, and (b) at 350,000 cycles.

From "Fig.3", it is observed that the fracture surfaces have two distinct zones. The first zone initiates as a relatively flat cleavage fracture surface (brittle-like fracture) while the second zone, known as the propagation zone, is characterized by traces of dimples (ductile-like fracture). From scanning electron microscope analysis, the fractographic observations revealed that the fatigue crack initiation sites developed at the specimen's surface and then propagated deeper towards the center of the specimen.

It was found that fatigue crack initiation transitions from multiple origins to single origin with increasing fatigue life as shown in "Fig.2a" and "Fig.2b", respectively. It was also noted in the fatigue tests that the normal stress on the cross section has a radial gradient, which makes the crack preferentially initiate from casting micropores, scratches and pits in the outer surface (oxide layer).

To clarify the fracture mechanisms in different zones of high cycle fatigue we need to point out the amount of plastic deformation in the later-developed zone is higher than in the initiation. It is reasonable to expect that the crack will propagate after the formation of the relatively flat area and cleavage facets (brittle fracture zone) in the vicinity of the crack origin, i.e., the surface semi-elliptical or subsurface elliptical or circular zone "Fig.2a" and "Fig.2b". The brittle fracture initiation zone with its cleavage facets is generally on the order of several grains in size, beyond which the fatigue life is dominated by crack growth.

As the number of cycles increases a mixed mode of cleavage and quasi cleavage like fractures becomes more pronounced especially after the cracks extend over several grains in depth and become predominant with the advance of crack length (brittle fracture zone) "Fig.4". In the later stages of the initiating brittle zone, quasi-cleavages associated with striations are observed "Fig.4".

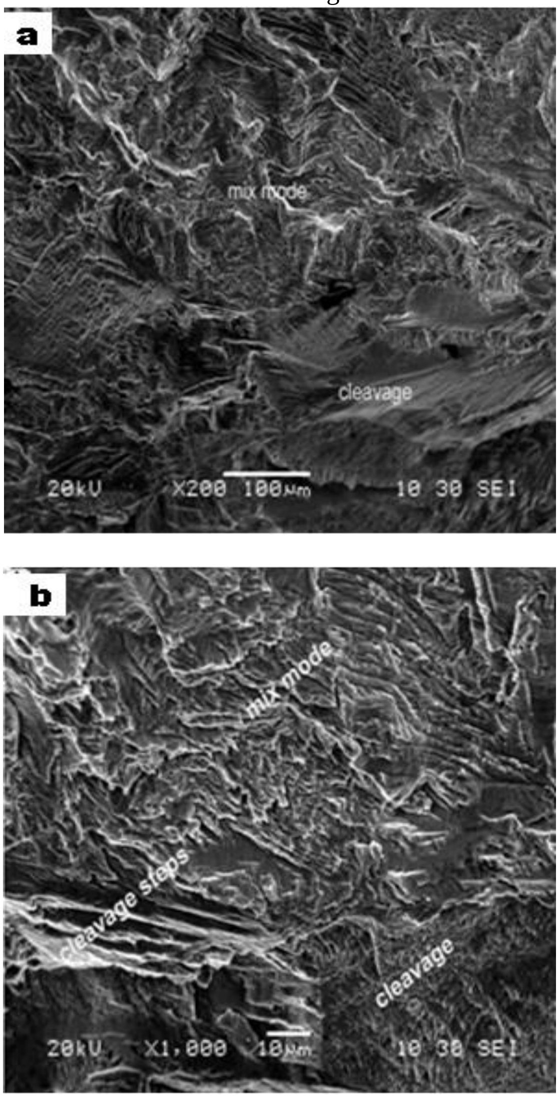


Figure 4: INCONEL601 specimen shows cleavage and mixed mode at 400,000 cycles, at low and high magnification (a), and (b) respectively.

As the number of cycles increases the fatigue striations become more obvious "Fig.5" and "Fig.6" are a sign of continuous and stable crack propagation. The ductile-dimple fracture mode can be clearly observed especially at higher magnifications in "Fig.5b".

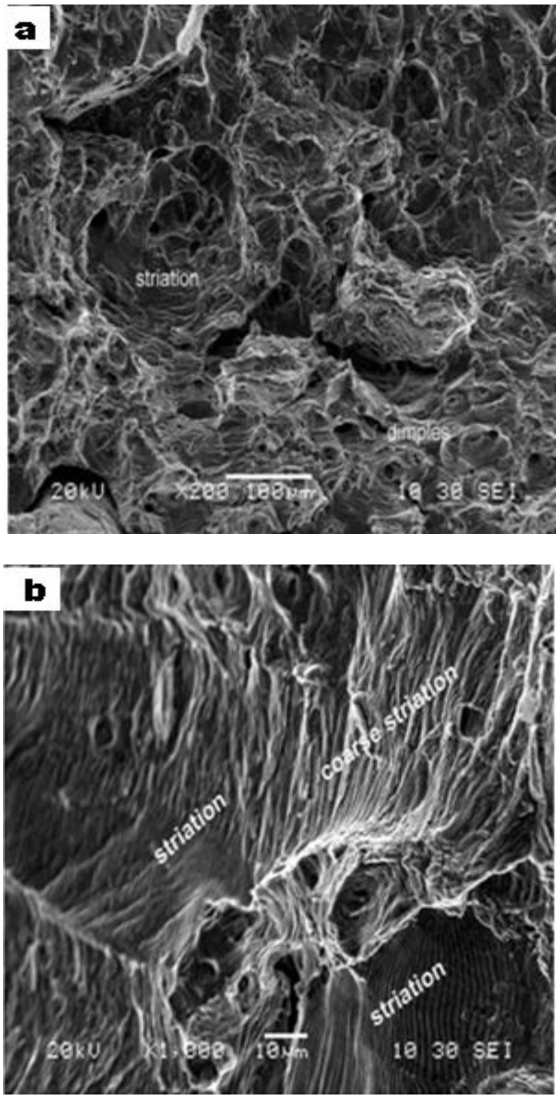


Figure 6: INCONEL601 specimen shows dimples and striation at 550,000, at low (a) and high magnification (b).

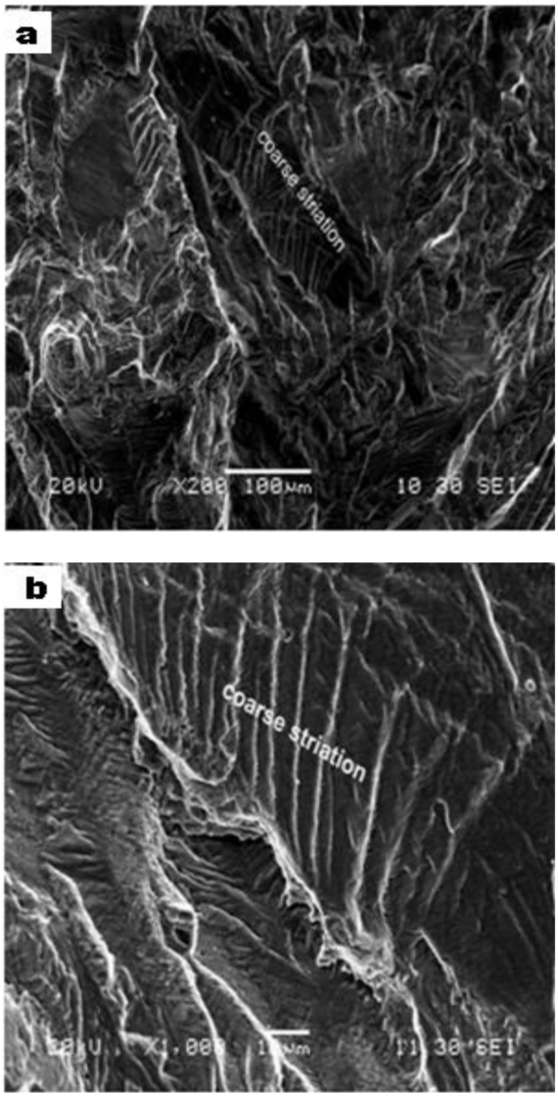


Figure 7: INCONEL601 specimen show dimples and larger striations at 650,000 cycles, at low (a) and high magnification (b).

Striations can be increasingly observed as the crack propagates stably with increasing fatigue loading cycles as indicated in “Fig. 5” to “Fig.7”. Striations grow coarser and their separation is more distinct “Fig.7”. These classical striation morphologies indicate increasing levels of plasticity as indicated in “Fig.5” to “Fig.7”.

Fatigue fracture in the high cycle range is caused by the gradual growth of microcracks initiated in slip bands on the specimen surface “Fig.1a”, because the surface has favourable conditions for the nucleation and growth of cracks compared to the interior region where geometric-mechanical constraints arise.

“Fig.1a” show slip bands after specimens were high cycle fatigued. Careful examination reveals that crack nucleation and propagation in the early state of deformation occur preferentially along slip bands. Crack nucleation can also form from carbides precipitating during the cyclic loading; the carbide precipitates are continuously generating some discontinuity at the interface between slip bands and carbide precipitates and at the location of carbide precipitates within the grain boundaries “Fig.1a”.

As the cyclic number increases striations become more developed and distinct; some striations are associated with secondary crack branches “Fig.7b”. It is clear that the fracture surface tends to become more ductile and softening with increasing number of cycles to failure. Some of this tendency may be due to the increasing interactions between carbide precipitates and slip deformation bands with the cyclic loading. These interactions promote the shearing of carbide precipitates and, as a consequence, the development of many more discontinuity regions where striation and slip deformation easily nucleate and grow. Developing ductile fracture with increasing stress cycling is therefore observed “Fig.1”.

IV. CONCLUSION

For INCONEL601 specimens subjected to cyclic stress, no fracturing occurs below applied stresses of 500MPa and below as indicated by the geometry of the S-N curve. The fractography of the fatigue fracture surface revealed two distinct crack zones- the initiation and propagation zones. The crack initiation zone is identified by cleavage facets and a brittle-like fracture, whereas the propagation zones are marked by the appearance of dimples and a ductile-like fracture. In the latter zone, striations were observed and became more dominant with increasing number of cycles.

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