# Surface Corrosion Cracks of Cyclic Deformation of Inconel Containing $M_{23}C_6$ Precipitates

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**Abstract**

*The fatigue fracture behaviour of Inconel alloy containing $M_{23}C_6$ precipitates is investigated at constant applied stress in a ferric chloride environment and at ambient temperature. In the early stage of cyclic deformation, the initial primary crack nucleates at the specimen surface and develops along the primary slip plane (110). With further cycling the deflection of the primary crack takes place into the nearby soft regions, and eventually the zigzag primary crack forms roughly along the primary slip, accompanied with a few secondary cracks formed in soft region textures etched by ferric chloride ($FeCl_3$). In addition, the fracture surface seems to become more ductile-like with increasing cycles to failure and also exhibited striation broadening and enlarging with number of cycles to failure. It is suggested that such a fatigue fracture behaviour is mainly bound up with the enhanced strain localization resulting from the dissolution of $M_{23}C_6$ precipitates during cycling.*

## 1. Introduction

Selection of the right materials and heat treatments are the primary reasons for success in obtaining good corrosion properties of metallic alloys, including nickel alloys that mainly comprise nickel, chromium, iron, carbon, and molybdenum in solid-solution [1]. Many investigations have been devoted to cyclic deformation and damage mechanisms in metals and alloys with face-centred cubic structures [2–6]. It is commonly accepted that in face-centred cubic crystal structures, fatal cracks form preferentially at those slip bands with large local strains [2–4]. Others reported that shear bands form in cyclically deformed metals and alloys with a body-centred cubic crystal structure in which cracks are rapidly initiated along shear bands [7].

Another study reported that in the fatigue behaviour of iron-based chromium alloy with a body-centred cubic crystal structure with a primary slip bands, the fatigue cracks are initiated preferentially along some developed slip bands [8].

By contrast, few investigations have been performed on the fatigue cracking behaviour of precipitation-hardened, body-centred cubic crystal structure alloys. Our previous work has examined the cyclic deformation behaviour of nickel-based chromium alloy in a sodium chloride aqueous solution [9, 10]. The present paper focuses on the effect of $M_{23}C_6$ precipitates on the fatigue fracture behaviour of this alloy in a ferric chloride solution.



## 2. Experimental procedures

The detailed experimental procedures, primarily the metallographic specimen preparation of Inconel alloy containing $M_{23}C_6$ precipitates and the processing of the fatigue specimens with the tension–tension fatigue test procedure at constant applied stress, can be found in a previous paper [10]. After tension–tension fatigue test, the surface deformation features morphology and fracture surfaces were examined by scanning electron microscopy (SEM).

## 3. Results and discussion

A cyclic polarization curve test for the Inconel alloy with $M_{23}C_6$ precipitates was conducted in a ferric chloride environment at ambient temperature. The $FeCl_3$ solution had a pH value of 3.4. Figure 1 show cyclic polarization scans of the alloy. As can be seen from the plot, the rest potential is approximately $1.0x10^2$ volts, and as the potential increased, the alloy exhibited active behaviour up to a point of a passivation potential of approximately of $1x10^7$. The values obtained from the cyclic polarization test was a current density ($I_{corr}$) $1.593x10^4$ (nA/cm$^2$) and a corrosion potential ($E_{corr}$) -0.333 volts.

Figure 1 shows no evidence of a distinct passive region followed by initiation of oxide film breakdown and pitting at 0.6 volt. The alloy indicates a susceptibility to pitting corrosion as it exhibited active behaviour with no sign of a passive region.

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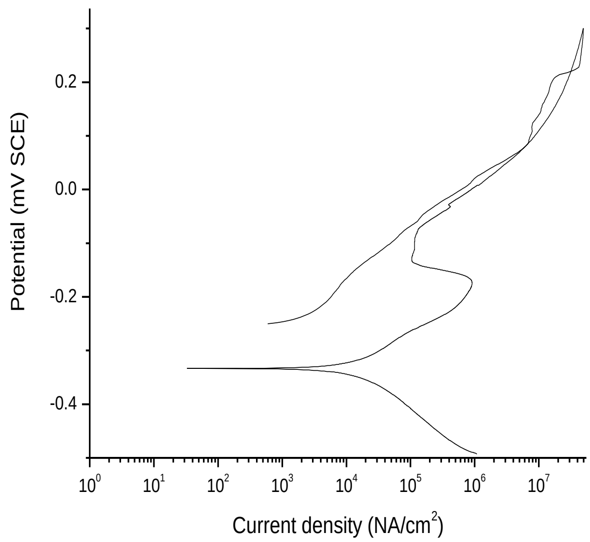



*Figure 1 Cyclic polarization curve Inconel alloy containing* $M_{23}C_6$ *precipitates in ferric chloride solution at a pH value of 3.4.*

Figure 2 shows the relationship between the maximum applied stress and the number of cycles to failure (S-N curve). The arrows indicate the Inconel alloy specimens did not fracture which indicate fatigue limit of this alloy in ferric chloride solution.

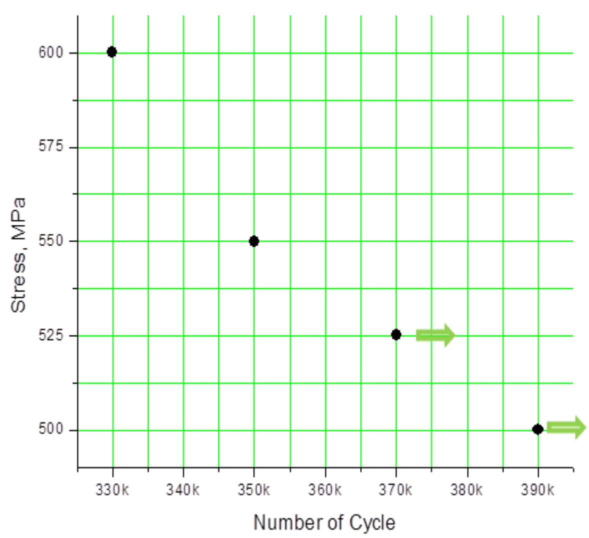



*Figure 2 S-N curve of Inconel alloy specimens fatigued in ferric chloride solution.*

Figure 3 shows points of the specimen surface investigation in a side view and the fracture surface view using electron microscopy SEM. Figure 4 shows SEM images of the Inconel alloy with $M_{23}C_6$ precipitates specimens with surface cracks along the slip plane (110) when deformed cyclically in ferric chloride solution $FeCl_3$. Figure 4 (a) shows a continuous primary crack while Figure 4 (b) shows a continuous secondary crack. From Figure 4 it can be deduced that the fracture surfaces were affected by and etched due to the ferric chloride solution.

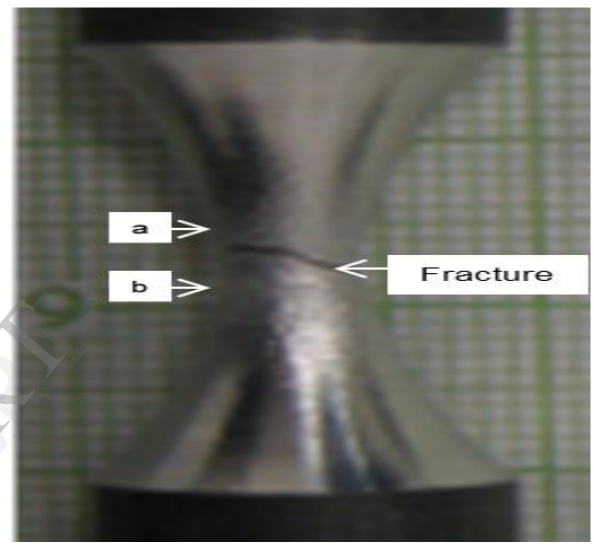



*Figure 3 shows specimen after fracture and points of surface investigation using SEM.*



Figure 4 shows the fracture surface is clearly affected by ferric chloride solution; the surface cracks are intergranular fractures (Figure 4). These images were obtained from the specimen's gauge area and reveal primary and secondary cracks traces of the most favourable slip planes together with the crack directions as shown in Figure 3 (a) and Figure 3(b), respectively.

The primary crack develops almost entirely along the primary slip plane with little deflection (Figure 4). However, as the number of cycles is increased there is further propagation of the primary crack and a new secondary crack is developed, despite the fact that the primary crack propagates mostly along the slip plane (110) plane. Deflections of the cracking direction from this plane can be clearly observed (Figure 4 and Figure 5).

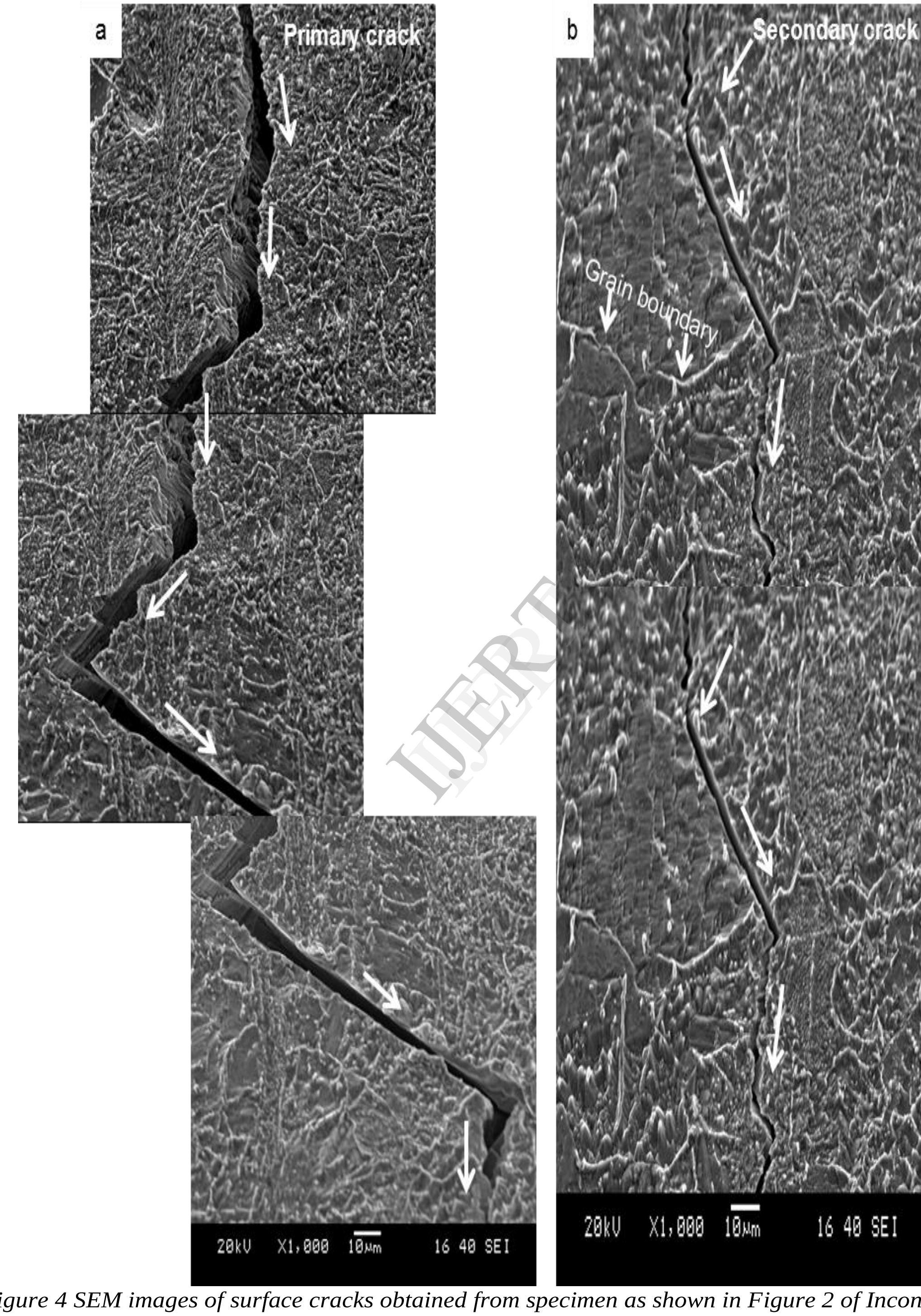



*Figure 4 SEM images of surface cracks obtained from specimen as shown in Figure 2 of Inconel alloy containing $M_{23}C_6$ precipitates cyclically deformed in ferric chloride solution at 330,000 cycles, with (a) continuous primary cracks, and (b) continuous secondary crack.*

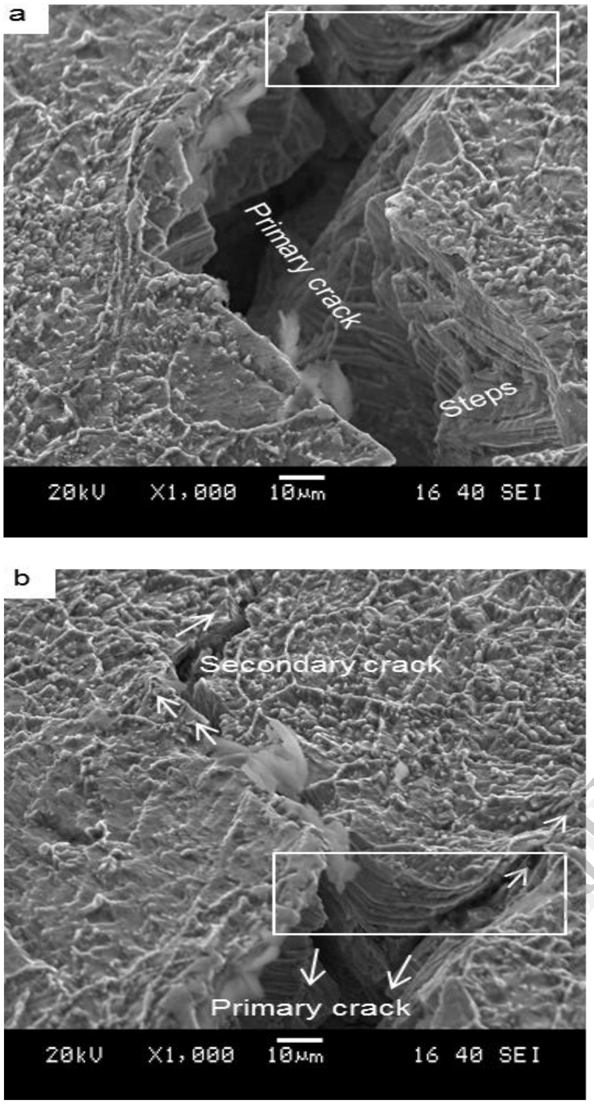
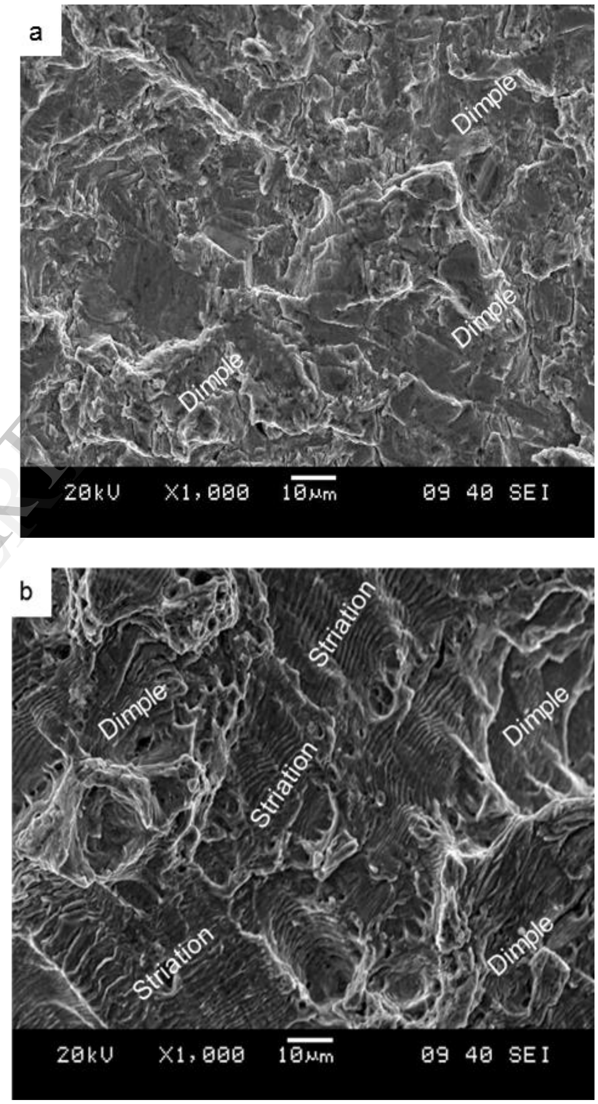



*Figure 5 SEM images of (a) primary and (b) secondary crack nucleation and propagation of Inconel alloy.*

Based on these experimental scanning electron microscopy observations, the process of fatigue crack nucleation and propagation in fatigued specimens of Inconel alloy containing $M_{23}C_6$ precipitates is demonstrated to be continuous (Figure 4). In the early stage of cycling, the initial primary crack nucleates at the specimen surface and along the primary slip band, as shown in Figure 5. As the specimen is further cycled, it develops soft region and the primary crack is deflected (Figure 5); this process leads to a marked material softening [11, 12]. From scanning electron microscopy observations, the zigzag primary crack forms approximately along the primary slip plane, accompanied with a few secondary cracks, as indicated in Figure 4. In a word, such a fatigue cracking behaviour appears to be closely related to the enhanced strain localization resulting from the dissolution of Inconel alloy containing $M_{23}C_6$ precipitates during cycling as well as to the special macroscopic state of stress.



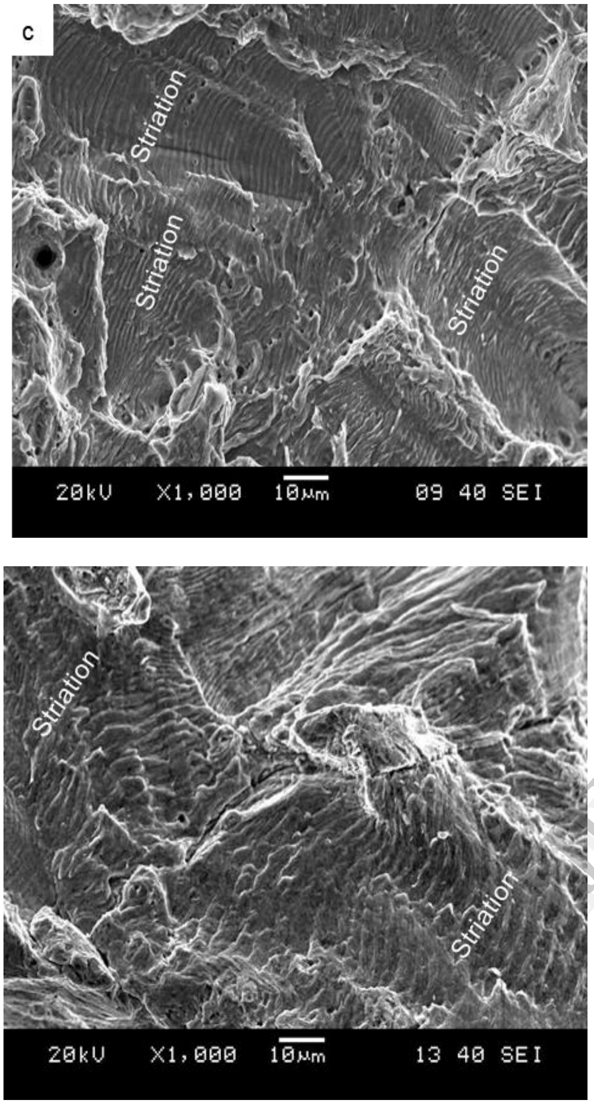



*Figure 6 SEM images of fracture surface morphology of Inconel alloy containing $M_{23}C_6$ precipitates fatigued in ferric chloride solution at different number of cycle, (a) ductile like fracture and dimples at 330, 000 cycles, (b) dimples and striations at 340, 000 cycles, (c) dimples and striations at 350,000 cycles and (d) striations, further broadening at 360,000 cycles. Note that corrosion fatigue striations broaden with number of cycles.*

Further examinations of the surface fracture of specimens indicate that the morphology and features of the fracture surface changed with increasing number of cycles at selected number of cycles to failure and exhibited clear mixed mode fracture characteristics such as ductile dimples and voids (Figure 6 (a)), and ductile dimple and fatigue striations covering part of the fracture surface (Figure 6 (b)). As the number of cycles increased, the formation of fatigue striations also increased as shown in Figure 6 (b) - 6 (d)). These fatigue striations enlarged and broadened with number of cycles and the total amount of time under attack by ferric chloride solution (Figure 6 (d)). It thus seems that the fracture surface tends to become more ductile with increasing number of cycles to failure. This tendency might be due to the enhanced interactions between $M_{23}C_6$ precipitates with induced dislocations at higher number of cycles in the ferric chloride solution. Such enhanced interactions facilitate the notable dissolution of $M_{23}C_6$ precipitates into the matrix and to the development of softening regions where cracks easily nucleate and grow. A greatly decreased fatigue life with increasing number of cycles to failure and total exposed time to ferric chloride solutions is thereby observed in Figure 4 and Figure 5.

## 4. Conclusions

From this short summary, it is demonstrated that the fatigue life of Inconel alloy containing $M_{23}C_6$ precipitates decreases with number of cycles and also with increasing time exposed to ferric chloride solutions. The initial primary crack nucleates at the specimen surface and propagates almost entirely along the primary slip plane (110) but includes some obvious deflections from this general path. The specimens often finally cracked along this plane. The fractured surface exhibits a pronounced fatigue striation at higher number of cycles. This behavior is regarded as correlated with the dissolution of $M_{23}C_6$ precipitates during the special macroscopic state of the S-N curve data.

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