RELATIONSHIP BETWEEN SUBSURFACE FATIGUE CRACK GENERATION AND STRAIN INCOMPATIBILITY

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ABSTRACT: The arguments on subsurface fatigue crack generation have been integrated from a viewpoint of strain incompatibility to progress the understanding of cyclic damage and microcracking stages. Phenomenological aspects of subsurface crack generation in both high-cycle fatigue and rolling contact fatigue were reviewed. Strain incompatibility may give an essential origin for a microcracking, but no evidences have been available to show microcrack initiated at localized deformation structure directly. Not only heterogeneous microplasticity due to planar slip and restricted system in high-cycle fatigue but also localized slip due to strain gradient in rolling contact fatigue are considered to play an important role on making the subsurface crack.

KEY WORDS: subsurface fatigue crack generation, strain incompatibility, strain gradient, stress concentration, microcrack

内部疲労き裂発生とひずみ不整合の関係について

概要：内部疲労き裂発生における繰返し変形損傷と微小き裂形成に関わる理解を進めるために、ひずみ不整合の視点から議論を整理する。高サイクル疲労および転動疲労で生じる内部疲労き裂発生挙動の現象論をまとめた。そして、ひずみ不整合が本質的に微小き裂形成の原因を与えると考えるが、局所変形と微小き裂形成を直接証拠立てるものは得られていない。高サイクル疲労におけるすべり系の限定と平面すべり挙動下の極小塑性変形のみでなく、転動疲労におけるひずみ勾配がもたらす局所変形も内部き裂形成に主要な役割を果たしている。

VZNIK PODPOVRCHOVÝCH ÚNAVOVÝCH TRHLIN VE VAZBĚ NA NEKOMPATIBILITU DEFORMACE

ABSTRAKT: Zahrnutí vzniku podpovrchových únavových trhlin do koncepce deformační nekompatibility přispívá k pochopení poškozujících procesů a počátečních etap šíření trhlin. Byly posuzovány fenomenologické aspekty vzniku podpovrchových trhlin jak ve vysokocyklové únavě, tak v kontaktní únavě. Deformační nekompatibilita může být základní příčinou prvních etap šíření mikrotrhlin, ale zatím nebyl podán jednoznačný důkaz o vazbě mezi deformační substrukturou a iniciací trhlin. Nejenom heterogenní mikroplasticita, vznikající v důsledku rovinného skluzu při vysokocyklové únavě, ale také lokalizovaný skluz v důsledku deformačního gradientu při kontaktní únavě jsou hlavními příčinami vzniku podpovrchových trhlin.

1 INTRODUCTION

A number of studies have been done to clarify the substance fatigue crack generation and growth mechanisms for high strength alloys.[1] Even though the subsurface crack origins are related with various microstructural crackings or pre-existing defects, the subsurface initiation site is commonly formed as a Stage I crack in tension mode. The size is the most important parameter to determine how the crack becomes a fatal crack, and highly depends on the maximum cyclic stress range, which implies a ΔK_{th} threshold controlling mechanism. The microcrack growth and/or coalescence model can excellently explain for a formation process of Stage I crack with a critical size where a process of microcrack growth involves a large number of cycles and not by its instantaneous spread. The mechanism of subsurface crack generation, however, has not been clarified yet, especially in local damage and microcracking stages.

The dislocation structures in high-cycle fatigue are fairly planar for the materials showing the subsurface crack generation. In the very low plastic strain regime, the impeded glide of the screw dislocations in high strength alloys makes dislocation multiplication by irreversible bowing a difficult process. The fatigue limit is intrinsically related to the movement of a screw dislocation brought up thermally or by a mechanical stress. These conditions result in only a very small fraction of plastically deformed grains. The very localized deformation processes such as the elastic incompatibility at boundaries have been found to be decisive for subsurface fatigue crack generation at the lower stress level. However, those aspects represent a saturated deformation structure and do not directly correspond to the localized deformation structure related to the microcracking.

On the other hand, the extrusion-intrusion mechanism well explains localized accumulation of strain, and persistent slip bands (PSBs) play an important role in the crack initiation mechanism.[2] Furthermore, not only heterogeneous microplasticity due to planar slip and restricted system in fatigue but also localized slip due to strain gradient in rolling contact fatigue (RCF) are considered to play an important role on making the subsurface crack.[3] Rolling contact fatigue can be defined as the mechanism of crack formation and propagation caused by the near-surface alternating stress field within the rolling contact bodies, which eventually leads to material removal. The subsurface shear stresses are high due to the contact stresses under cyclic loading, especially at subsurface stress risers such as non-metallic inclusions. Such sever plastic deformation generates small internal cracks in short-life stage where decohesion of inclusion to matrix and localized deformation are closely related.
Then, it should be progressed in the understanding of damage and microcracking stages in those subsurface fatigue crack generation processes. In the present study, the arguments on subsurface fatigue crack generation have been integrated from a viewpoint of strain incompatibility.

2 PHENOMENOLOGICAL ASPECT OF SUBSURFACE FATIGUE CRAK

2.1 Microstructural cracking

The subsurface crack initiation forms a facet or facets due to a microstructural cracking. The morphology of each facet is associated with microstructure regardless of intergranularly or transgranularly formed. The nuclei for the microcrack generation are the locations where an incompatibility develops between the continuous isotropic elastic strain field and the localized planar slip in a specific inhomogeneous microstructure.[4] Thus fine grain structure with randomly distributed crystal orientation decreases the strain incompatibility at grain boundaries and increases the resistance forming a critical Stage I crack due to miniaturizing each microcrack. Furthermore, much more grains yield locally at an applied loading condition below the macro-yield range, when pre-existing movable dislocations in grains provides the source for the rearrangement and the multiplication of dislocations.[5]

2.2 Fish-eye fracture

Why does the main crack select the internal defect instead of the extrusion-intrusion flaw at the specimen surface? This can be accounted for by a difference in stress concentration magnitude around them. The fatigue cracks associated with inclusions formed through the debonding and /or cracking of inclusions.[6] Then, the crack initiation site associated with pre-existing defects in specimen interior is produced from not only the particles but also Stage I cracks. The whole size of the initiation site involving Stage I cracks is larger than that of the defect itself. A comparatively larger pre-existing defect in the specimen interior may introduce higher stress concentration than the surface flaws. Especially at lower cyclic stress, the difference is considered to become more distinct, since the extrusion-intrusion mechanism becomes less active.

2.3 Flaking by rolling contact fatigue

Developed model of flaking by RCF is proposed as shown in Fig.1. Firstly, local damage is produced in the stress concentration region of matrix near inclusion. The initial crack is generated there, grows in the horizontal direction and finally results in flaking.

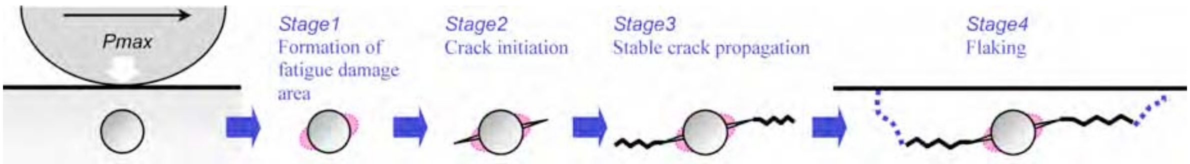

Fig.1: Model of flaking by RCF.[3]

Based on the linear mechanics relationship between stress intensity factor and critical defect size, stress intensity factor range, ΔK_{II}' was defined as follows:

$$\Delta K_{II}' = 2\tau_0\sqrt{\pi a} \qquad (1)$$

where 2a is diameter of inclusion or defect and t_0 is shear stress amplitude in the direction parallel to track at the depth of flaking. The fatigue life decreased as decreases of ΔK_{II}', although there was scatter of the life in low ΔK_{II}' regime.

3 STRAIN INCOMPATIBILITY

3.1 Strain incompatibility at a boundary

The heterogeneous microplasticity due to planar slip and restricted system remarkably causes subsurface fatigue crack especially at low stress level. When a slip is introduced in a grain, the slipped

area becomes softer than non-slipped area because of an increase in mobile dislocations. Hence necessary slips may be localized near the first slip plane. This localized slip plane may be the softest because of its crystallographic orientation. The coplanar arrays developed in a grain under the cyclic softening impinge the grain boundary and produce steps and/or protrusions, which produces a strain-gradient in the neighboring grain.[7] Thus the strain incompatibility containing shear strain field at the grain boundary is believed to be developed and to act shear stress and tensile stress to the grain boundary plane, since the grain boundary plane is inclined to the applied stress axis. Morita *et al*.[8] showed the developed dislocation structure induces the stress to open the subsurface crack.
In order to relax the internal stress due to strain incompatibility, therefore, a deformation or microcracking must occur between the neighboring grains, i.e. deformed grain, neighboring grain or grin boundary. No evidences, however, have been available to show microcrack initiated at localized deformation structure directly. Also it is not clear whether microcracking or slip off gives a nuclear of microcrack. The models of brittle cracking such as cleavage have been proposed for the subsurface crack, but they are inconsistent with experimental results on crack origin.

3.2 Localized deformation due to strain gradient

Even at high stress level, localized slip due to strain gradient is considered to play an important role on making the subsurface crack in RCF. The initial cracks under RCF in low carbon martensite steel were detected at the strain gradient regime where crack-opening stress component must exist.[3] The crystal rotation typically occurred near grain boundary in the region and resulted in the localized strain incompatibility near grain boundary. Strain developed around inclusion under RCF was also calculated by elastic-plastic FEM analysis.[3] Crack generated diagonally from the inclusion where Mode I controlled the crack initiation.

At the crack-tip, severe localized plastic deformation caused recrystallized fine grains in low carbon martensite steel as shown in Fig.2.[3] The fine grains were also formed near the crack. Such severe localized plastic deformation was detected in the regime of strain gradient.

The debonded interface to inclusion and hole surface in the matrix are a kind of free surface so that the localized plastic deformation structure in initial crack stage may be similar to the PSBs. Thus large plastic strain such as low-cycle fatigue should be introduced at around localized deformation regime. At that time the extrusion-intrusion formed on the surface may be related to the initial crack as shown in Fig.3. The cohesion of inclusion to matrix is considered to play an important role on making the subsurface crack in RCF as well as high-cycle fatigue [6].

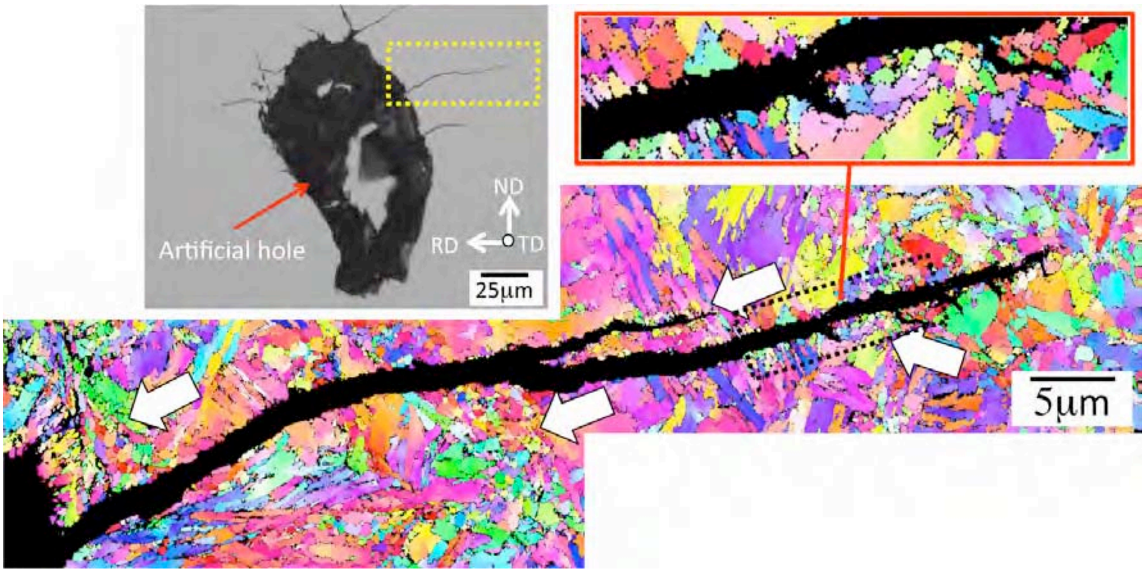

Fig.2: Fine grains (arrows) around a crack generated from an artificial hole under RCF.

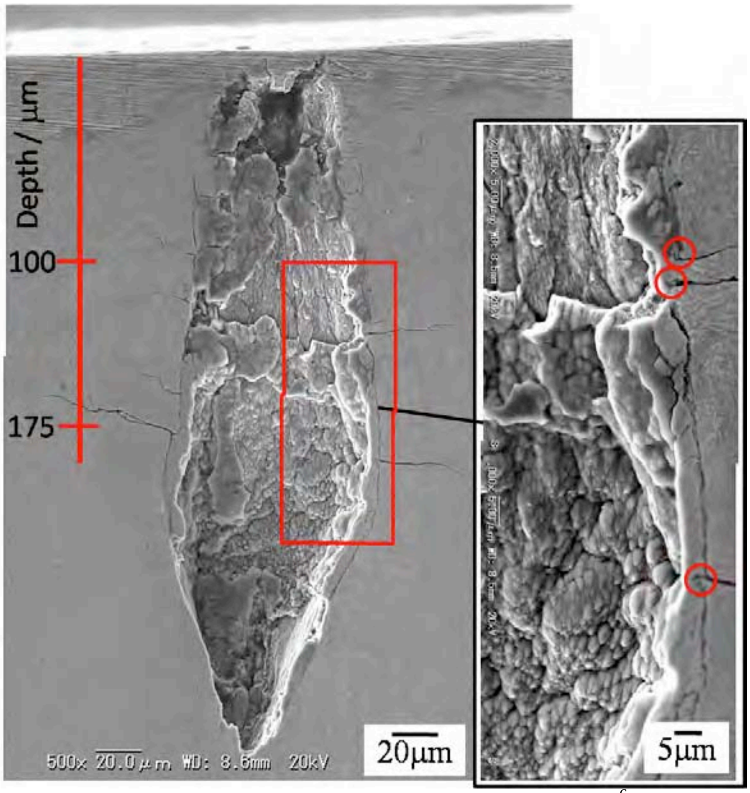

Fig.3: A longitudinal section of around an artificial hole after 3.0×10^6 cycles of RCF.

4 SUMMARY

The subsurface fatigue crack generation was discussed from a viewpoint of strain incompatibility to progress the understanding of cyclic damage and microcracking stages. Not only heterogeneous microplasticity due to planar slip and restricted system in fatigue but also localized slip due to strain gradient were considered to play an important role on making the subsurface crack. No evidences have been available to show microcrack initiated at localized deformation structure except PSBs, and then we need to proceed in further experiments to prove models.

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