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DAMAGE ACCUMULATION MODE FATIGUE CRACK PROPAGATION AND PROPAGATION BEHAVIOR PREDICTION METHOD

Shigeru Hamada[1]*, Yudai Yamaguchi[2], Yudai Okawa[2], and Yamato Araki[2]

[1] Faculty of Engineering, Kyushu University, 744 Moto-oka, Nishi-ku Fukuoka 819-0395, Japan,
[2] Graduate School of Engineering, Kyushu University, Fukuoka, Japan
** Presenting Author email: hamada@mech.kyushu-u.ac.jp*

Abstract

To achieve high-strength steels, their microstructures are complicated. However, with effort, these high-strength steels do not exhibit the fatigue limits expected from their hardness or tensile strength. The low fatigue limit due to inclusions in the steels can be predicted as a fatigue limit problem for metallic materials with small defects. However, the threshold stress intensity factor range of high-strength steel of a long crack is still not as high as expected from the hardness. Currently, there is no clear explanation for this reason. Therefore, the material cannot be used with confidence. The authors propose that this is due to a different crack extension mechanism. In other words, the authors point out the existence of a different mechanism of fatigue crack extension from the generally accepted mechanism of fatigue crack extension due to plastic deformation by alternating slip. Based on the mechanism, the mode of fatigue crack extension is called damage accumulation mode fatigue crack propagation. This name differs from the conventional name focusing on the loading mode, i.e., Modes I, II, and III, and is focused on the extension mechanism. This study discusses a method to predict the fatigue crack propagation behavior.

1. Introduction

When a cracked metallic material is subjected to cyclic Mode II loading, fatigue cracks often extend along the plane of principal stress in the tensile mode. However, certain materials and under certain conditions extend in the plane of maximum shear stress in the shear mode. The resistance to tensile fatigue crack extension is almost proportional to hardness up to a certain degree. Furthermore, shear mode fatigue crack extension may or may not occur in the same material and under the same conditions, and its behavior is highly variable even if it does occur. Therefore, it can be imagined that shear mode fatigue crack extension has a different fatigue crack extension mechanism from tensile mode and its fatigue crack extension plane and mechanical driving force.

2. Damage Accumulation (DA) Mode Fatigue Crack Propagation

The authors conducted an experiment in which a sharp notch, which could be regarded as a pre-crack, was introduced into a cold-rolled ferritic stainless steel SUS430 with a texture using a Focused Iron Beam (FIB) and subjected to cyclic pure Mode II load. The results showed that the void initiation, growth, and coalescence ahead of the extending crack tip as the external cyclic force was applied and that the fatigue cracks extended intermittently as the secondary fatigue crack initiated ahead of the main crack and coalesced with the main crack. Based on the fatigue crack extension mechanism, the tensile mode fatigue crack extension is referred to as plastic deformation (PD) mode fatigue crack growth, and the shear mode fatigue crack extension is referred to as damage accumulation (DA) mode fatigue crack propagation. The conventionally used names, Mode II fatigue crack propagation, Mode II fatigue crack growth, and shear mode fatigue crack growth, are all based on the loading mode and not on the fatigue crack extension mechanism.

DA mode fatigue crack propagation is considered to occur even not under cyclic pure Mode II loading. The DA mode propagation is because the fatigue crack tip is always subjected to cyclic shear stress when the focused plane is changed. In general, the PD mode occurs preferentially over the DA mode. Therefore, fatigue crack extends in the PD mode is observed. And as mentioned earlier, for a given material and under a given condition, the DA mode is considered to exceed the PD mode, resulting in the DA mode. The authors reported cases of DA mode fatigue crack propagation in other steels than cold-rolled SUS430, such as precipitation-strengthened steel and high entropy steel. All of them are high-strength steel. High-strength steels are characterized by their fatigue limit, and the threshold stress intensity factor range is lower than those predicted by their hardness compared to those of general steels. The authors believe this is due to DA mode fatigue crack propagation, which occurs due to the accumulation of damage caused by cyclic loading at loads lower than the lower limit of the PD mode. In this case, the damage is dislocation and vacancy.

Table 1 lists the PD and DA modes. The most significant difference between the modes is whether the phenomenon occurs for each load cycle. The phenomenon is the crack extension.

Table 1 Comparison between PD mode and DA mode fatigue crack extension

	PD mode fatigue crack growth	DA mode fatigue crack propagation
d*a*/d*N* (Fatigue crack extension amount per one cycle) concept	Valid Grow by every single cycle	Invalid Successive propagation by DA
ΔK concept (→ d*a*/d*N*-ΔK)	Valid Dislocation emission relates to ΔK	Invalid (?) Relation between DA and ΔK (?)
PICC (Brake for the crack extension)	Valid	Invalid
RICC (RISS) (Brake for the crack extension)	Valid	Invalid (?)
Ductile striation	Formed	Not formed
Work hardening effect	Good effect Hardness improved	Bad effect Some “damage” is accumulated
Mean compressive stress effect	Good effect ΔK_{eff}	Unrelated No effect on crack initiation
Microstructure	Small effect	Effect strongly Damage localization?

3. DA Mode Fatigue Crack Propagation Prediction Method

The nominal cyclic shear plastic strain range $\Delta\gamma^p$ has been empirically used as the mechanical driving force to control the fatigue crack initiation life of smooth materials. Since this study’s fatigue crack initiation phenomenon is a local, rather than smooth, phenomenon, the highly localized plastic strain is considered to dominate the phenomenon. However, the problem for materials with a crack is strain distribution and how to define the nominal cyclic shear plastic strain. The authors propose to use the average value of the shear plastic strain range in a certain region near the crack tip. The shear plastic strain produced during a pure cyclic Mode II loading test is measured using the Digital Image Correlation (DIC) method, and a method for determining the region is discussed.

4. Results

The test results showed that the plastic zone was localized ahead of the crack tip. In addition, the shape of the plastic zone was longer in the crack direction than the shape calculated, assuming an isotropic continuum body. Therefore, the cause of the plastic zone shape is considered the result of strain localization by the effect of microstructure. Since localization is a material property that should be treated as a material property, in the presentation, the author will discuss a method for predicting DA mode fatigue crack propagation, including quantification of this material property.

5. Conclusions

Damage accumulation mode fatigue crack propagation is caused by strain localization. Therefore, the prediction method for the extension behavior is considered by average shear plastic strain in a certain area.

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