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EBSD analysis of cyclic load effect on final misorientation distribution of post-mortem low alloy steel: A new method for fatigue crack tip driving force prediction

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ABSTRACT

The effect of applied cyclic load, including the maximum plastic strain ε^{p}_{max} and the plastic strain amplitude ε^{p}_{a} on final misorientation level of post-mortem low alloy steel after low cycle fatigue (LCF) test, was analyzed by Electron Back-Scattered Diffraction (EBSD) in this research at first. Two misorientation parameters widely used in EBSD analysis, Kernel Average Misorientation (**KAM**) and Grain Reference Orientation Deviation (**GROD**), are compared in terms of accumulated plasticity characterization after LCF failure, where a bilinear function is found between final **KAM** and applied cyclic load ε^{p}_{max} & ε^{p}_{a}. Then the cyclic load effect on final misorientation distribution of post-mortem low alloy steel after fatigue crack propagation (FCP) test was further analyzed by EBSD based on the above bilinear function between final **KAM** and ε^{p}_{max} & ε^{p}_{a}, as well as the equivalent $\bar{\varepsilon}^{p}_{max}$ & $\Delta\bar{\varepsilon}^{p}$ distribution functions given by HRR field. $-1/2$ power law is established to describe final **KAM** distribution near crack path. The area $\mathbf{S}_{\mathrm{KAM}}$ between final **KAM** distribution curve and undeformed $\mathbf{KAM}_0$ base line within a certain range, rather than $\mathbf{S}_{\mathrm{GROD}}$, is proposed as a better measurement of fatigue crack tip driving force $\Delta\mathbf{K}$ in constant load ratio $\boldsymbol{R}$ condition. Meanwhile, the influence of load ratio $\boldsymbol{R}$ on final misorientation distribution is also discussed.

1. Introduction

EBSD misorientation analysis is an important technical method for plasticity characterization, which is widely used in failure analysis of polycrystalline alloys (low alloy steel, austenitic stainless steel, nickel-based superalloy, etc.) under various working conditions (tensile, impact, creep [1,2], creep-fatigue [3,4], fatigue crack propagation [5], etc.). The accumulated plasticity in polycrystalline alloys (both in monotonic and cyclic condition) will cause the dislocation multiplication and lattice curvature inside the grain, which can be measured by EBSD misorientation parameters, such as **KAM** and **GROD**. In our previous study [6], the fracture modes of low alloy steels were identified by EBSD misorientation analysis according to different plasticity distribution characteristics.

LCF failure of polycrystalline alloys is a complex physical process involving plasticity accumulation, crack initiation and propagation, which is different from tensile rupture. Compared with qualitative fracture mode identification between tension and fatigue, quantitative fatigue crack tip driving force prediction is more strongly required by the heavy industry. For monotonic deformation, the accumulated plasticity can be singly weighted by nominal plastic strain ε^{p}, and the misorientation parameter (such as **KAM**) is reported to be a linear function $f(\varepsilon^{p})$ of the nominal plastic strain [7]. But for cyclic deformation, the accumulated plasticity is influenced by the maximum plastic strain ε^{p}_{max}, the plastic strain amplitude ε^{p}_{a}, and the number of cycles $\boldsymbol{N}$. Thus, **KAM** becomes a trivariate function $g(\varepsilon^{p}_{max},\varepsilon^{p}_{a},\boldsymbol{N})$ of the above three factors, as shown in Fig. 1.

Many researchers have focused on the evolution of EBSD misorientation parameters as a function of $\boldsymbol{N}$ during the cyclic deformation. The in-situ EBSD observation of type 16MnR steel in Zhang's work [8] showed that **KAM** increased with the number of cycles rapidly before $\boldsymbol{N} = 10^5$, and then slowed down within the scope of $\boldsymbol{N} = 10^5$–10^6. Hayakawa [9] pointed out that **GROD** increased with fatigue life fraction before crack initiation, and then remained constant. Some

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Nomenclature

LCF	low cycle fatigue
ε^{p}	nominal plastic strain
ε_{max}	maximum strain
ε^{p}_{max}	maximum plastic strain
$\Delta\varepsilon^{t}$	total strain variation ($= 2\varepsilon_{a}$)
$\Delta\varepsilon^{p}$	plastic strain variation ($= 2\varepsilon^{p}_{a}$)
$\bar{\varepsilon}^{p}_{max}$	equivalent maximum plastic strain
$\mathbf{K}_{max}$	maximum stress intensity factor
$\Delta\mathbf{K}_{\mathrm{eff}}$	effective stress intensity factor range
$\boldsymbol{da/dN}$	fatigue crack propagation rate
α,β,γ	coefficients in bilinear function
r	distance from fatigue crack path
GROD	Grain Reference Orientation Deviation
$\mathbf{S}_{\mathbf{GROD}}$	area under **GROD** distribution curve
FCP	fatigue crack propagation
δ	material elongation
ε_{a}	strain amplitude
ε^{p}_{a}	plastic strain amplitude
$\Delta\varepsilon^{e}$	elastic strain variation
$\Delta\bar{\varepsilon}^{p}$	equivalent plastic strain variation
$\boldsymbol{N}/\ \boldsymbol{N_f}$	number of cycles / fatigue life
$\Delta\mathbf{K}$	stress intensity factor range
$\boldsymbol{R}$	load ratio
$\mathrm{U}(\boldsymbol{R})$	crack tip closure degree
$C_{1\sim4}(\boldsymbol{R})$	coefficients in $-1/2$ power function
n	material work-hardening exponent
KAM	Kernel Average Misorientation
$\mathbf{S}_{\mathbf{KAM}}$	area under **KAM** distribution curve

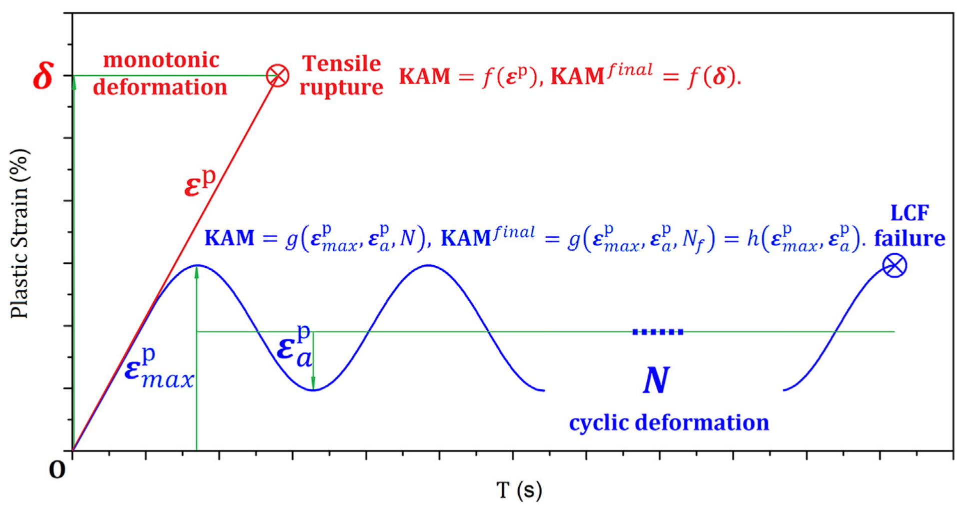

Fig. 1. Sketch of misorientation evolution in monotonic and cyclic deformation conditions.

scholars have noticed that the strain amplitude has a significant influence on the misorientation evolution during the cyclic deformation. Kamaya et al. [10,11] reported that austenitic stainless steel experiencing the same fatigue life fraction had different $\mathbf{M}_{\mathrm{ave}}$ (equivalent to averaged **KAM**) values in various strain amplitudes. Bouquerel et al. [12] reported that final **GOS** (equivalent to averaged **GROD**) of Fe-3Si steel after LCF failure increased with the total strain variation rapidly above $\Delta\varepsilon^{t} = 0.7\%$. Compared with the unique final misorientation level $f(\delta)$ related to the elongation of specific material after tensile rupture, the final misorientation function $g(\varepsilon^{p}_{max},\varepsilon^{p}_{a},\boldsymbol{N_f})$ of the same material after LCF failure obviously depends on ε^{p}_{max}, ε^{p}_{a} and $\boldsymbol{N_f}$. According to the Manson-Coffin law [13,14], the fatigue life $\boldsymbol{N_f}$ here also depends on ε^{p}_{a}. Therefore, the final misorientation level of polycrystalline alloys after LCF failure can be expressed by a bivariate function $h(\varepsilon^{p}_{max},\varepsilon^{p}_{a})$.

Apart from the bulk plasticity accumulation during the cyclic deformation before fatigue crack initiation, the local plasticity accumulation will also occur near the crack path during the FCP. Our previous study [6] showed that local **KAM** distribution perpendicular to the crack path was significantly influenced by the local fatigue crack tip driving force, i.e. the stress intensity factor range $\Delta\mathbf{K}$. Under constant stress intensity factor range (CK) loading condition, final **KAM** distribution curves at different positions of crack path are overlapped with each other. Under constant stress amplitude (CA) loading condition, final **KAM** distribution curves at identical positions are separated with each other, and the larger the local $\Delta\mathbf{K}$ value is, the higher the **KAM** curve becomes. This result indicates the possibility of $\Delta\mathbf{K}$ prediction by detailed EBSD observation on the cross section of crack path, which is an important procedure for the failure analysis of post-mortem polycrystalline alloys after fatigue fracture. The conventional fractographic analysis of fracture surface can only predict the crack propagation rate indirectly by measuring the fatigue striations spacing. However, this method becomes hard to be conducted when the fatigue striations are not obvious or environmentally damaged. EBSD misorientation analysis rather than fractographic analysis will provide an alternative approach for both indirect crack propagation rate measurement [5] and direct crack tip driving force $\Delta\mathbf{K}$ prediction.

In this research, we conducted the LCF test by standard round bar (RB) specimens under variable ε_{max} and variable ε_{a} respectively at first, to investigate the effect of applied cyclic load ε^{p}_{max} & ε^{p}_{a} on the final misorientation level of post-mortem low alloy steel, i.e., to find out the specific form of the bivariate function $\mathbf{KAM}^{final} = h(\varepsilon^{p}_{max},\varepsilon^{p}_{a})$ for low alloy steel. Then we continued to conduct the FCP test by standard compact tension (CT) specimens under variable $\Delta\mathbf{K}$ and variable $\boldsymbol{R}$ respectively, to investigate the effect of loading parameters $\Delta\mathbf{K}$ & $\boldsymbol{R}$ on the final misorientation distribution perpendicular to the crack path of post-mortem low alloy steel. Based on the clarified bivariate function $\mathbf{KAM}^{final} = h(\varepsilon^{p}_{max},\varepsilon^{p}_{a})$, as well as the equivalent $\bar{\varepsilon}^{p}_{max}$ & $\Delta\bar{\varepsilon}^{p}$ distribution function given by HRR field, the relationship between loading parameters $\Delta\mathbf{K}$ & $\boldsymbol{R}$ and final **KAM** distribution perpendicular to the crack path is further clarified. At the same time, the area $\mathbf{S}_{\mathbf{KAM}}$ between the final **KAM** distribution curve and undeformed $\mathbf{KAM}_{0}$ base line within a certain range, rather than $\mathbf{S}_{\mathbf{GROD}}$, is proposed as a better measurement of $\Delta\mathbf{K}$, for its good linearity with local $\Delta\mathbf{K}$ value in constant $\boldsymbol{R}$ condition. The influence of load ratio $\boldsymbol{R}$ on the final misorientation distribution perpendicular to the crack path is also discussed in details when the $\Delta\mathbf{K}$ value is constant.