SIMULATION ON MICROCRACK INITIATION IN F82H MARTENSITIC STEEL

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ABSTRACT

The studied material is a Japanese stainless steel F82H with martensitic lath microstructure. Low cycle fatigue was carried out with strain ratio R=-1, strain rate $\dot{e} = 8 \times 10^{-4} / s$. The total strain range De varied from 0.44% to 0.90%. From the observation on the specimen surfaces, it was found that the initiated small cracks were distributed in the whole surface and their number increased with fatigue cycles during early fatigue life. The average size of one-segment crack is 79µm. The orientations of small cracks are parallel to the martensitic laths and empirical distribution is non-uniform with a peak about 45° to the loading axis. The observation suggests one-grain failure once a time caused by dislocation pileups and it strongly depends on the material microstructure and local properties. The simulation model is based on a representative volume element (RVE) including 100 grains with similar microstructure. The heterogeneous local stress distribution, caused by the mismatch of grains and initiated small cracks, is obtained by finite element analysis. The fatigue model proposed by Tanaka and Mura is applied to estimate the fatigue life of small crack initiation. A group of programs is developed to create the RVE, calculate the average shear stress on the crack plane, and introduce cracks according to given criteria. From simulation results, the crack densities varying with fatigue cycles are obtained. For most of the strain ranges, the simulation results correspond with tests quite well.

1. INTRODUCTION

The failures of most components are caused by fatigue cracks initiation and propagation. For some materials, as well as the material studied in this paper, the microcracks formed on slip band grow to the size of one grain rapidly and then stop at grain boundaries (R.G. Tryon [1] and Brückner-Foit [2]). In these cases, the small crack propagation rate is rather high inside grains but on grain boundaries it becomes very low. The crack propagation rate scatter is rather large in the early stage of fatigue life. Therefore it is difficult to predict fatigue life with crack propagation rate. To reach fatigue life prediction for this problem, simulation based on this phenomenon, which is referred as crack initiation, was carried out. The significant characteristics of this simulation is that the inhomogeneous microstructure caused by grain mismatch and, when crack initiated, caused by microcracks together, had been taken into account as main influencing factors. For most of the strain ranges, the simulation results correspond quite well with experiment data. It indicates that this simulation represents the microcrack behaviour for studied material and may lead to proper prediction of fatigue life.

2. MATERIAL AND TEST DATA

The studied material is a Japanese stainless steel F82H with heat treatment 1040 °C/0.5h +750°C/1h after fabrication. Its chemical components are shown in Tab.1. The microstructure obtained is martensitic laths decorated with secondary precipitates of the type $M_{23}C_6$, as shown in

Fig.1. The average size of prior austenite grain is 52µm and the average lath width is 1.82µm. Some mechanical properties are listed in Tab.2.

Tab.1 Chemical component

Fe	C	Cr	Ni	Mo	V	W	Mn	Ta	Cu
Basis	0.09	7.62	0.02	0.003	0.16	1.95	0.16	0.02	0.01
	Al	Si	Ti	Co	Nb	S	P	N	B
	0.003	0.11	0.01	0.005	0.0001	0.001	0.002	0.007	0.0002

Fig.1 The microstructure of martensitic steel

Tab.2 Mechanical properties

Young's Modulus	E[GPa]	217
Yield stress	$R_{p\,0.2}$ [MPa]	530
Ultimate Tensile Stress	R_m[MPa]	635
Elongation	δ[%]	13

Continuous strain controlled push-pull cycling fatigue has been applied with strain ratio R = -1 and strain rate $\dot{e} = 8\times10^{-4}/s$. The total strain range De varies from 0.44% to 0.90%. In each fatigue test several scans of the specimen surface at pre-defined cycles were recorded by triggering a camera automatically at maximum strain. After testing, the specimens were further investigated by metallographic method. Fatigue data expressed by total strain range De and lifetime Ni for all specimens are listed in Tab.3. These fatigue tests were finished in a previous project (Bertsch[3]).

From the observation on the specimen surfaces, it is found that the initiated microcracks were distributed in the whole surface and their number increased almost linearly with fatigue cycles during early fatigue life. After continuous fatigue loading, some of these microcracks coalesced and gradually macrocracks formed. Specimen failure happened by growing macrocracks. Statistics for the characteristics of microcracks in terms of length, segmentation and orientation show that the average size of one-segment crack is 79µm. The orientations of microcracks are parallel to the martensitic laths, as shown in Fig.2, and empirical distribution is non-uniform with a peak about 45° to the loading axis (Meyer[4]). A group of pictures in Fig.3 shows the development of crack with cycles. The observation suggests that one-grain failure once a time is caused by dislocation pileups and it strongly depends on the material microstructure and local properties.

Tab.3 Fatigue experiment data

Strain range De[%]	Cycles of life N_i
0.90	2700
0.90	2740
0.88	4600
0.81	2690
0.76	5180
0.76	6950
0.66	6890
0.61	5940
0.60	8210
0.55	13170
0.50	16860
0.44	45800

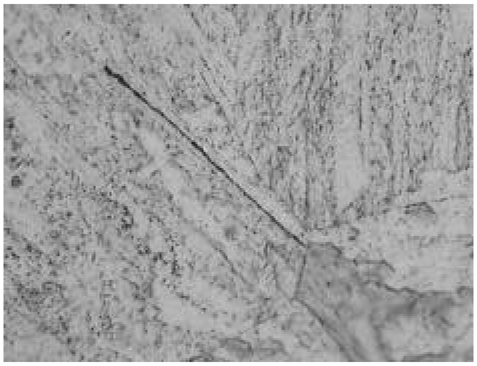

Fig. 2 One-segment microcrack along martensitic lath

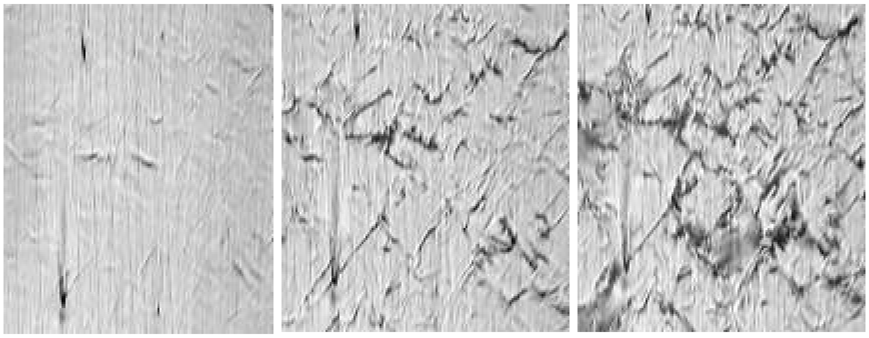

Fig.3 Microcracks development with fatigue cycles, *De* = 0.76%

3. SIMULATION MODEL

The simulation model is based on a 2-dimension representative volume element (RVE) created by the Voronoi tessellation method. The properties of Voronoi cells are much similar to metallurgical structure’s (Stoyan[5]). Each cell represents one prior austenite grain. Since the boundaries between martensitic laths in one packet are low-angle boundaries (Kim[6]), it is assumed that all laths are parallel in one packet and for convenience, one grain consists of one packet of these paralleled martensitic laths. According to the work in literature (Z. Guo[7]), martensitic laths share {110} slip planes, which lie along the axis of laths. Therefore the potential crack paths are assumed 45° degree to grain directions, which are the direction of martensitic laths. The axes x of local coordinates are in the directions of crack paths. Crack paths pass through the centres of gravity of grains and stop at the grain boundaries. Fig.4 is the scheme to illustrate the relations between grain direction, martensitic lath, crack path and local coordinate in the simulation model. The heterogeneous local stress distribution, caused by the mismatch of grains and initiated small cracks, is calculated by the finite element analysis code ABAQUS.

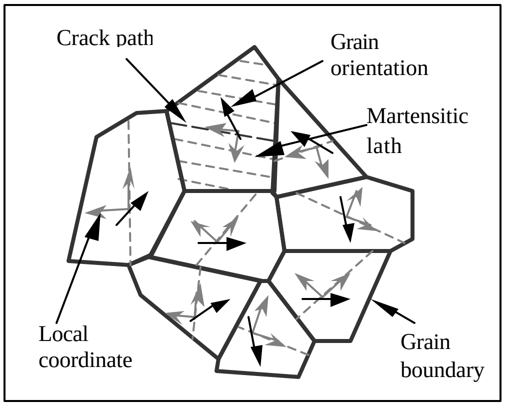

Fig.4 Illustration of RVE with crack paths

The fatigue model proposed by Tanaka and Mura (Tanaka[8]) is applied to estimate the fatigue life of microcrack initiation.

$$N_i = \frac{8GW_c}{p\,(1-n\,)d\,(\Delta\,t_{res} - 2t_c)^2}$$

Here G is the shear modulus, n is Poisson's ratio, d is the length of slip line, Δt_{res} is the resolved shear stress range under tension, t_c is the critical shear stress and W_c is the fracture energy per unit area. In this simulation, the resolved shear stress is calculated by the average shear stress on crack path t_a from FE analysis. For the whole loading from minimum to maximum stress, Δt_{res} = $t_{max} - t_{min}$, i.e. $2\,t_a$. The length of slip line is the length of crack path calculated from RVE. The material parameters applied are G=81GPa, ν=0.27, W_c=2.0kJ/m^2, τ_c=108MPa (Hoshide[9]).

The fatigue initiation life is calculated by eq.(1) for all the crack paths. The path with the shortest life is taken as the initiated crack, which is introduced into RVE model if it is not close to the RVE boundary. The stress distribution in RVE with introduced cracks is somewhat different from previous and this is caused by stress concentration near crack tips and stress free along crack surfaces. From FE analysis, however, it is found that the influence is locally affected only on some adjacent grains. Based on this redistributed stress, the fatigue life is calculated again for all crack paths. In this way, the next crack can be obtained. The simulation continues until required crack density is reached. A group of programs is developed to create RVE, calculate the averaged shear stress on crack plane, and introduce cracks according to the given criteria as mentioned above. From simulation results, the crack density varying with fatigue cycles can be obtained. A series of images of RVE with local shear stress distributions and cracks is obtained by PATRAN from simulation results, as shown in Fig.5.

The crack initiation probability P_i (crack density) is assumed as a function of fatigue cycles N as the following equation

$$P_i = 1 - e^{-l\,N} \qquad (2)$$

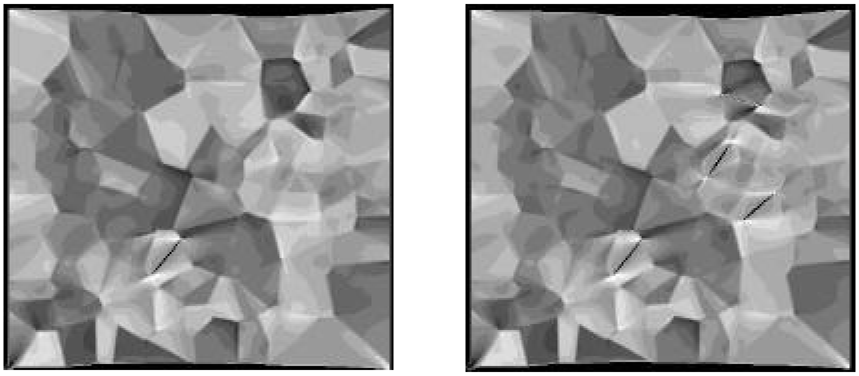

Fig.5 The RVE with a) one and b) three one-segment crack(s). The grey gradient shows local shear stress

Here λ is the risk parameter of grain fracture per load cycle and *N* is the number of load cycles. And P_i = (Number of one-segment cracks at *N*)/(Total number of grains).

Both from experimental data and simulation data, the parameter λ can be derived for every strain range. To compare with experimental data, crack initiation life is taken as 20% of failure life.

4. RESULTS AND DISCUSSION

In Fig.6, the quite similar morphology can be seen from the crack patterns simulated (at upper left corner, obtained from FE results on RVE with stress distribution) and observed on specimen surface. From the curves of parameter λ versus strain range calculated from simulation

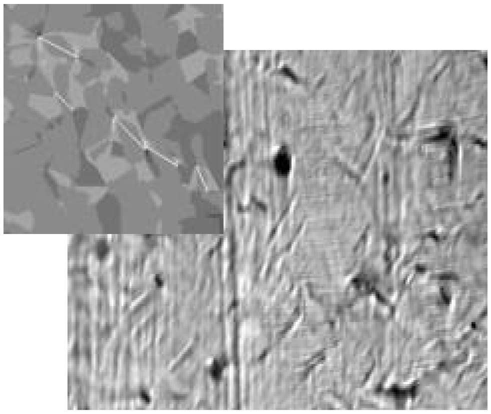

Fig.6 Crack morphology in *De* =0.76 %, *N* =10%N_f

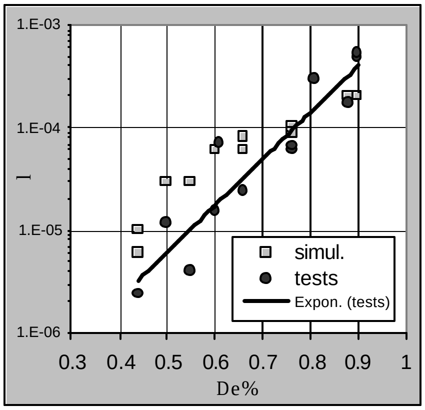

Fig.7 Comparison of parameter λ

and experimental data in Fig.7, it is found that the crack densities from simulation results are a little bit higher than experiment results in lower strain ranges. For the other strain ranges, simulation results correspond with tests quite well. Data scatter are regarded as the influence of inhomogeneous microstructure on specimens as well as on the simulation model.

5. CONCLUSION

1) The model developed in this work is a 2D RVE model, with random grain size and orientation. Only basic parameters and assumptions based on observation of experiment are applied.
2) The simulation results show the significant microstructure influences on fatigue crack initiation and scatter nature.
3) The simulation results for crack initiation from middle to higher strain range correspond data obtained in experiment very well.

6. REFERENCES

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