FATIGUE CRACK GROWTH UNDER MIXED MODE LOADING OF 18CRMO4 STEEL

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Abstract

The mechanical properties of 18CrMo4 steel under multiaxial stress field loading have been investigated. Especially crack growth rate analysis under mixed model crack loading was carried out in this work. A numerical model result of fatigue crack growth and the results from experimental studies using two different specimen geometries and loading conditions are discussed. The main aim of this work is to develop mathematical model in order to predict the response of materials and state the crack propagation under mixed mode fatigue loading typical for wide range of applications.

Keywords: crack growth rate, fatigue crack, mixed-mode.

1. INTRODUCTION

Typically the study of fatigue crack behavior in high strength steel using fracture mechanics has been largely focused on model I loading. However engineering components of structures are usually subjected to both normal and shear loading which can be usually mode II and mode III type. This multiaxial fatigue problem was usually studied using classical fatigue analysis (S-N curve approach) or the mixed-mode fatigue crack problem within the context of fracture mechanics. In this work the main aim is focused on high strength low alloyed steel (HSLA) fatigue crack growth analysis under mixed model fatigue loading and crack path orientation analysis. Application of high strength steel for shafts and gear wheels production brings typical complex stress state which caused the mixed model crack tip loading.

The basic solution for multiaxial fatigue is application of some fatigue criteria function. There are many of criteria function to predict tensile stress dominated of shear dominated fracture. In the case of this study the maximal tangential stress criteria is used and the predicted crack path direction is compared with experimental fracture behavior.

2. MATERIAL CHEMICAL COMPOSITION AND HEAT TREATMENT

The study was carried out using a commercial grade steel. Two steel of different chemical composition were studied. The steel samples marked as CSN ISO 15 124 and JIS SCM420H were studied. Those two kinds of steels are commonly used for shaft and highly load structural parts. Chemical composition is state in Table 1. Samples were heat treated to achieve typical mechanical properties according graph which is shown in Fig. 1. Oil-quenching was carried from the temperature 850 °C and tempering at 450 °C during 30 minutes cycle. Mechanical properties like tensile properties and Vickers hardness of steel are summarize in the Table 1.

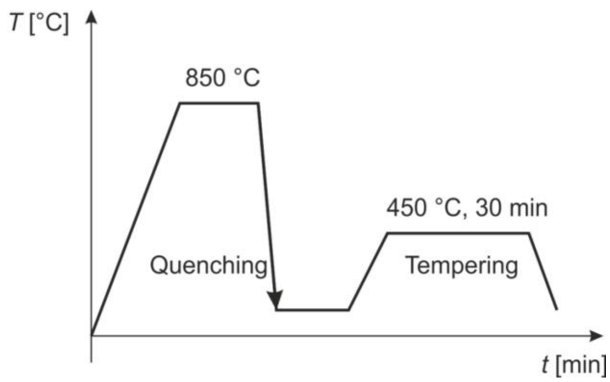

Fig. 1. Heat treatment diagram

Table 1 Chemical composition of materials

Specimen	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
15124	0.18	0.3	1.21	0.01	0.019	0.112	0.908	0.2	0.016
SCM420H	0.21	0.24	0.84	0.01	0.017	0.02	1.09	0.16	0.1

[% of volume contain]

Table 2 Mechanical properties

Specimen	*HV*	σ_y MPa	σ_{UTS} MPa
15124	421	890	980
SCM420H	462	930	1030

Note: $\sigma_{y,}$ σ_{UTS} evaluated using tensile test

3. EXPERIMENTAL MODEL

For the fatigue experimental analysis the single edge notch flat speciment was taken into the study. Experimental model was designed according to plane strain condition and mixed mode crack tip loading.

3.1. Flat specimen

Higher strength and lower value of fracture toughness are typical mechanical properties of studied steel. To achieve plane strain state the geometrical dimension of the test sample fit the condition which is based on the equation (1). According this the sample thickness *B* = 3 mm. Geometry of samples for fatigue crack growth rate analysis is ilustrated on Fig. 2b. Mixed mode which combine in plane mode I and mode II crack tip loading is achieved using wedge system which is shown on the Fig. 2a.

$$B, a, w - a \geq 2.5\left(\frac{K_{Ic}}{\sigma_y}\right)^2, \qquad (1)$$

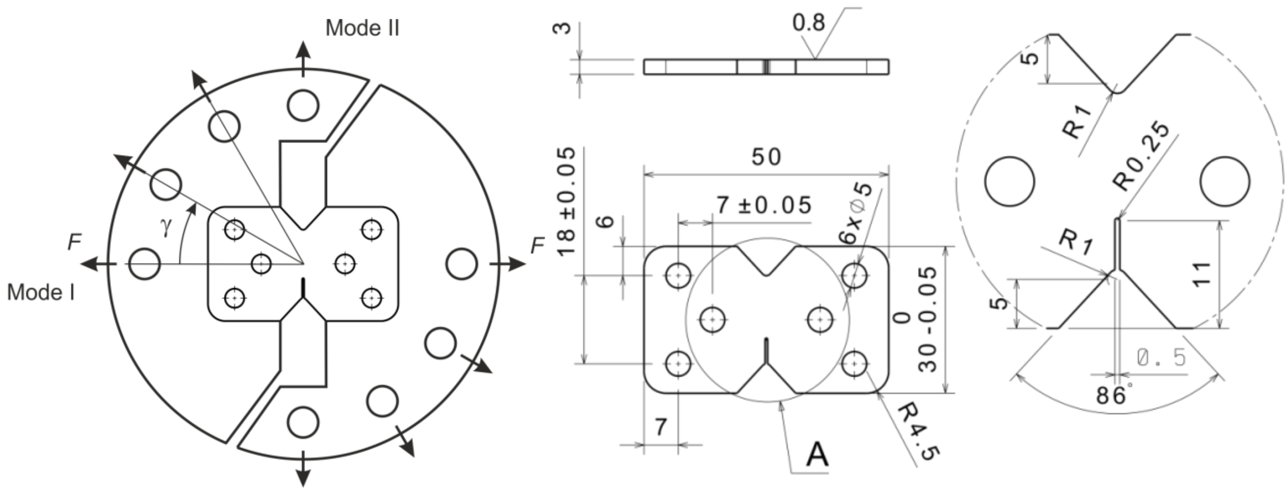

Fig. 2. a) Mixed mode loading jig **b**) SEN sample geometry drawing

3.2 LEFM model

Application of linear elastic fracture mechanics brings the problem of analysis stress state near the crack. The effective stress intensity factor value has to be evaluated to achieve real fracture loading condition. Parameters like crack surface friction and crack path are taken into the analysis. To evaluate stress field the finite element method is applied. Geometrical model and boundary condition are equal to real sample size and loading condition as is ilustrated on the Fig. 2a.

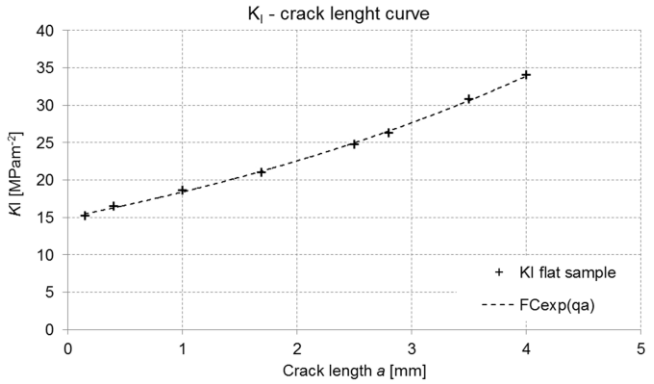

Fig. 3. Approximation function for K_I factor under pure mode I loading

Numerical model considerate the real stress state of the sample loading condition. To predict crack path trajectory maximum tangential stress (MTS) criterion is used. This criterion is widely used due to its simplicity and good agreement with experimental observation. MTS criterion was proposed by Erdogan and Sih [7], [8]. The crack propagation direction is defined like the perpendicular to maximum tangential stress in front of the crack tip. Mathematically the condition for the crack growth direction can be expressed as:

$$\frac{\partial \sigma_\theta}{\partial \theta} = 0 \text{ a } \frac{\partial^2 \sigma_\theta}{\partial \theta^2} < 0 , \tag{2}$$

where, σ_θ is tangential stress.

Mathematical model to was build to analyse in plane fracture behavior using K_I a K_{II} modeling. Assessment of the size and loading type aproximation function was state for crack lenght interval in the range *a* <1; 4.5> mm. On this interval the function for stress intensity factor mode I can be writen in the form K_I = f(F, a, B), where *F* is loading force, *a* crack lenght and *B* is the sample thickness. Then the aproximation function can be expressed as:

$$K_{I(a,F,B)} = FC \exp(qa) , \tag{3}$$

Where, the constant *C* = 0.15 and exponent *q* = 0.2.

3.3 Crack growth rate analysis

Aim of the experimental work is to establish methodological approach to crack growth rate analysis under the biaxial loading. Paris Law in equation (4) is used to crack growth description. The increment of crack growth takes the form given below where *C* is the Paris Law constant, *m* is the Paris Law exponent, *N* is the number of cycles.

$$\frac{da}{dN} = C\left(\Delta K_{I,II}\right)^m , \tag{4}$$

3.4 Fatigue crack path

However, biaxial experiments are required to determine the crack path direction which is influenced by loading more ratio or material microstructure. In the case of mixed mode loading the trajectory of crack path is influenced by material and loading condition. Measurement of crack path direction angle of is shown on the Fig. 4.

4 RESULTS

Based on experimental observation the crack growth rate curve for mode I and model II were analyzed. Crack path was traced using digital camera and lenses with fixed focusing. Calibration of the optical system was made by optical microscope and calibration grid. There are plotted fatigue crack growth curves obtained by two sets of specimens of two material types. Crack growth rate curves and Paris – Erdogan law data fit are plotted in graphs on the Fig. 5 and Fig. 6. There is comparison of tensile stress mode and shear stress mode of crack tip loading. The parameters of power law of crack growth are summarized in the Table 3.

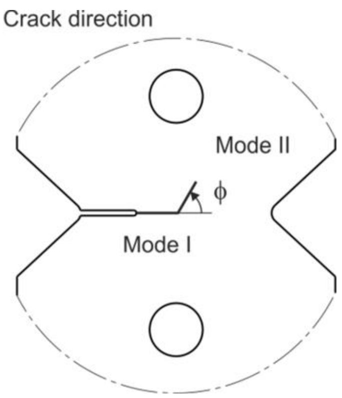

Fig. 4. Crack path direction under Mode I and Mode II loading

Table 3 Fatigue crack growth rate parameters

	Mode I		Mode II	
Specimen	C_I	n_I	C_{II}	n_{II}
15124	$1.59\ 10^{-15}$	3.61	$1.06\ 10^{-22}$	10.53
SCM420H	$4.89\ 10^{-15}$	3.58	$5.01\ 10^{-22}$	10.15

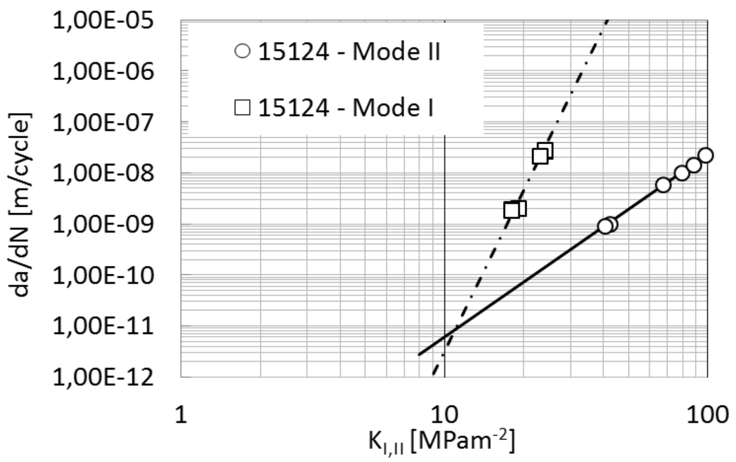

Fig. 5. Crack growth rate curves for Mode I and Mode II specimen A (CSN ISO 15124)

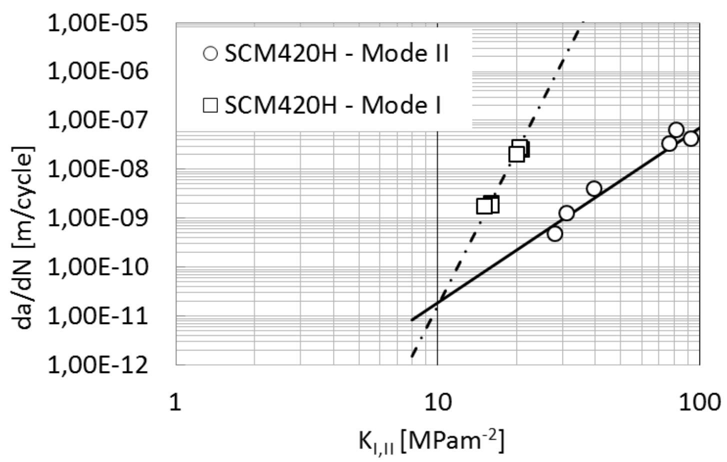

Fig. 6. Crack growth rate curves for Mode I and Mode II, specimen B (JIS SCM420H)

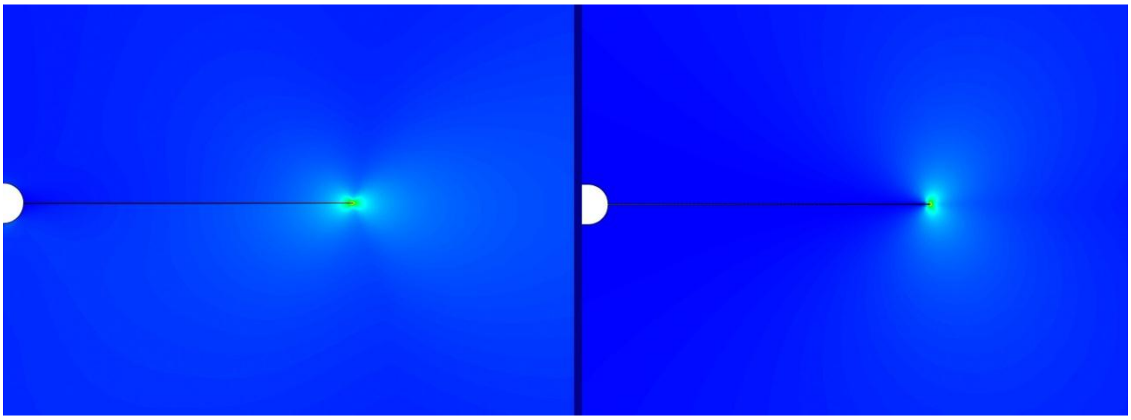

Fig. 7. Numerical model of the test - equivalent stress distribution

The influence of loading on the crack path direction is illustrated in Fig. 8, considering the four values of loading direction *γ*. MTS criterion prediction using FE calculation is compared with the experimental crack path of studied materials.

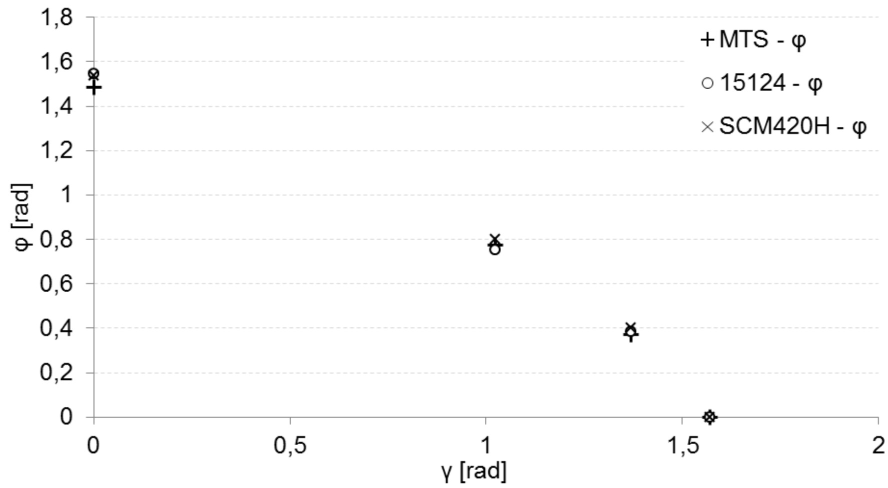

Fig. 8. Crack path direction under mixed mode loading

Crack growth tracking using optical analysis is illustrated on Fig. 9. In this result image is plotted sample A2 (15 124 steel) after mode I and mode II loading.

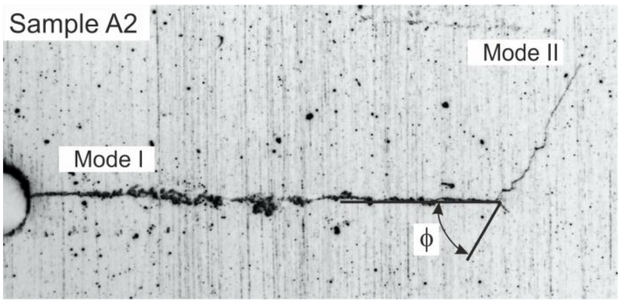

Fig. 9. Fatigue crack path SEN specimen and crack declination angle φ (pure shear mode)

5 CONCLUSION

The results of fatigue crack growth rate analysis are summarized in this work. New experimental procedure was proposed to achieve mixed model crack tip loading. Crack growth rate curves were described based on the experimental observation which was studied of 18CrMo4 grade steel with two different chemical composition set. The differences of crack growth rate were observed and SCM420H steel achieves higher crack growth rate under the mode I and mode II loading than 15124 steel. Experimental data provide material properties of this steel grade for future crack growth modeling of rolling contact fatigue problem. New experimental test proposal allowed optimization of chemical and technological parameters.

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