Determination of Effective Stress Intensity Factor Range of Mode II Fatigue Crack Propagation Using Improved Experimental Method

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Abstract Many cases of rolling contact fatigue failure, such as those that occur in railway rails, rolling bearings, and gears, are due to repeated high shear load. In order to prevent such fatigue failures, the resistance of a material against to repeated high shear load must be determined. The fatigue crack growth rate is dependent on the stress intensity factor range of Mode II ΔK_{II}. However, Mode II crack propagation characteristics vary according to the method by which they are determined. We improved the experimental method proposed by Murakami and measured the effective stress intensity factor range of Mode II $\Delta K_{\mathrm{IIeff}}$. Changes to the jigs and specimen were made and the experimental method was such that the ideal mechanical model was expected to be approached. Furthermore, to measure the $\Delta K_{\mathrm{IIeff}}$, several strain gauges were applied to the specimen around the crack tip. Using the improved method, some $\Delta K_{\mathrm{IIeff}}$ values during the Mode II fatigue crack propagation tests can be measured.

Introduction

Mechanical failures such as spalling and pitting can happen in rails, rollers, or other components made of metal when they are under heavy repeated contact loading. To prevent such types of failure, it is necessary to determine the resistance of certain materials to this type of failure. A crack under repeated contact loading, which is what leads to the failure, propagates in Mode II. Therefore, the resistance to crack propagation can be evaluated by using the Mode II fatigue threshold stress intensity factor range, ΔK_{IIth}.

Methods for determining Mode I fatigue crack propagation have already been established [1]. However, for Mode II fatigue crack propagation, systematic research is limited because this type of crack propagation is difficult to be produce in the laboratory and there are no standard tests. Early systematic research was done by Otsuka et al. [2]. However, the method they developed could only be applied to soft metals such as aluminium alloys. After this study, Murakami et al. [3, 4] developed an experimental method which could also be applied to hard metals such as bearing steel. Later, Otsuka et al. [5] improved their method so it could also be applied to hard metals. However, the threshold stress intensity factor range ΔK_{IIth} obtained when these two methods [4, 5] were used with the same material was different. It seems that interference by the crack faces affected the result. The study conducted by Matsunaga et al. [6] on the shear mode threshold proved that friction on the crack face increases the value of ΔK_{IIth}. Therefore, it is necessary to take the friction on the crack faces into account when determining the Mode II effective stress intensity factor, $\Delta K_{\mathrm{IIeff}}$.

In the previous work by the authors [7], a new method was proposed to measure the friction at the crack faces. However, from the results, several problems were found with the experimental method. Therefore, for this paper, the method was improved. The improvements were made by changing the shapes of the jigs and specimen, which solved the problems. Moreover, a more appropriate assumption of the friction distribution on the crack faces was made and a new method was proposed.

Experimental Procedures

Mechanical Model. Figure 1(a) shows the mechanical model proposed by Murakami et al. [3]. This model is called the former mechanical model in this paper. Load P was applied to the upper cantilever. By inserting a ceramic cylinder in the slit, the load P was assumed to be divided into two equal halves and applied to both cantilevers. Compressive load S was applied by the pre-tightening force of the bolts. However, because of the deformation of the specimen where the cylinders made contact with the specimen, the load P could not be divided as expected. Dents were found on the specimen where the ceramic cylinder inserted into the slit contacts and a considerable reduction in the slit width was observed during the experiment. The reduction in the slit width is thought to be caused by a gap formed due to the plastic deformation as the load was applied and, as a result, the load applied to the lower cantilever was thought to be considerably reduced. In order to divide the load P to each cantilever equally, a new mechanical model has been proposed in this paper.

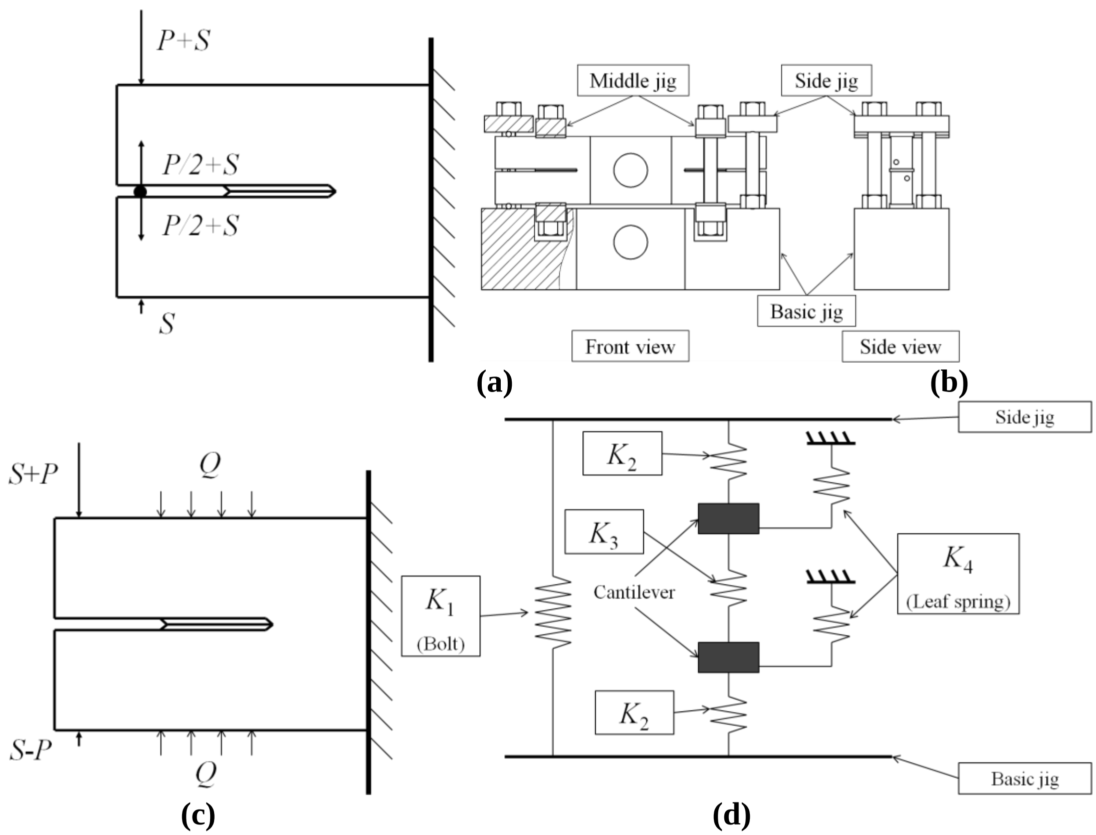


Fig. 1. Mechanical model of the Mode II experimental method. (a) Former mechanical model. (b) Experimental setup. (c) New mechanical model (front view). (d) New mechanical model (side view).

Figures 1(c) and (d) show the front view and side view of the new mechanical model, respectively. The new mechanical model is based on the side view the experimental setup shown in Fig. 1(b). The new model is made with springs and rigid blocks and takes the elastic deformation into account. The two bolts are represented by a long spring with a spring coefficient of K_1. Because the parts of the specimen that make contact with the ceramic cylinder deform, they are represented by springs. The spring coefficients are K_2 and K_3 according to the diameter of the ceramic cylinder at the places where the specimen makes contact with the cylinder. Thus, the cantilevers are represented by two rigid masses attached to leaf springs with a spring coefficient of K_4 and one end fixed. As shown in

Fig. 2, if the pretightening force *S* is larger than *P*/2, the load is be divided into two equal halves and applied to both cantilevers, and the width of the slit does not change during the experiment even if a cylinder is not in place.

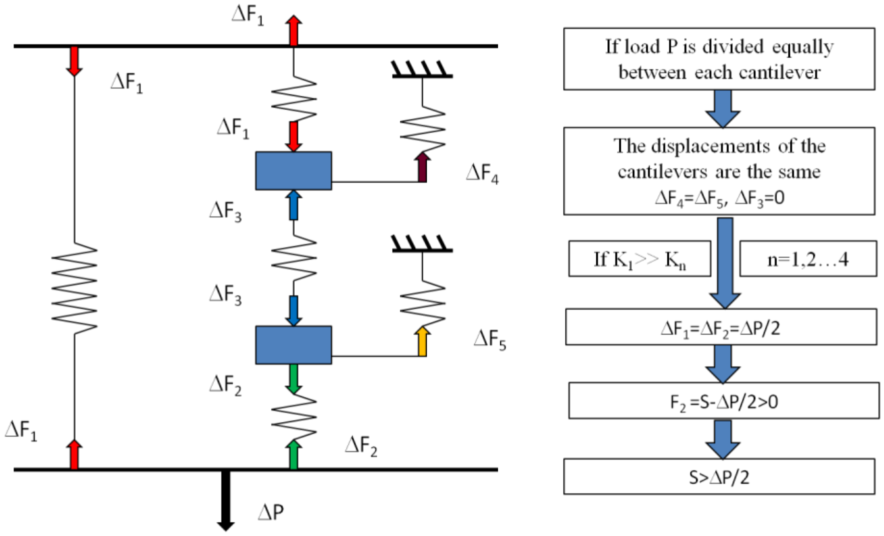
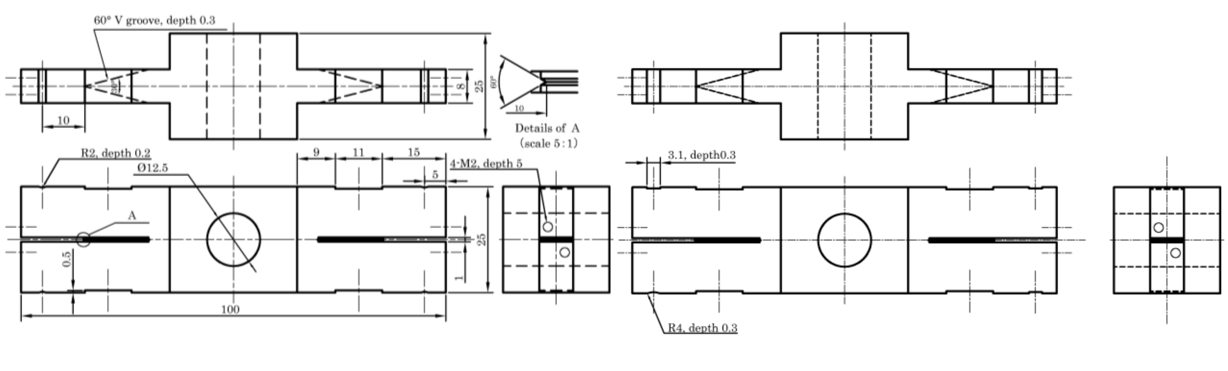


Fig. 2. Conclusions obtained from the new mechanical model.

Material. The experiments were carried out using commercial grade Japanese Industrial Standards (JIS) SS400 steel. The chemical composition is shown in Table 1.

Table 1. Chemical composition of specimen (mass %).

C	Si	Mn	P	S	Fe
0.11	0.27	0.55	0.021	0.023	Bal.



(a) (b)

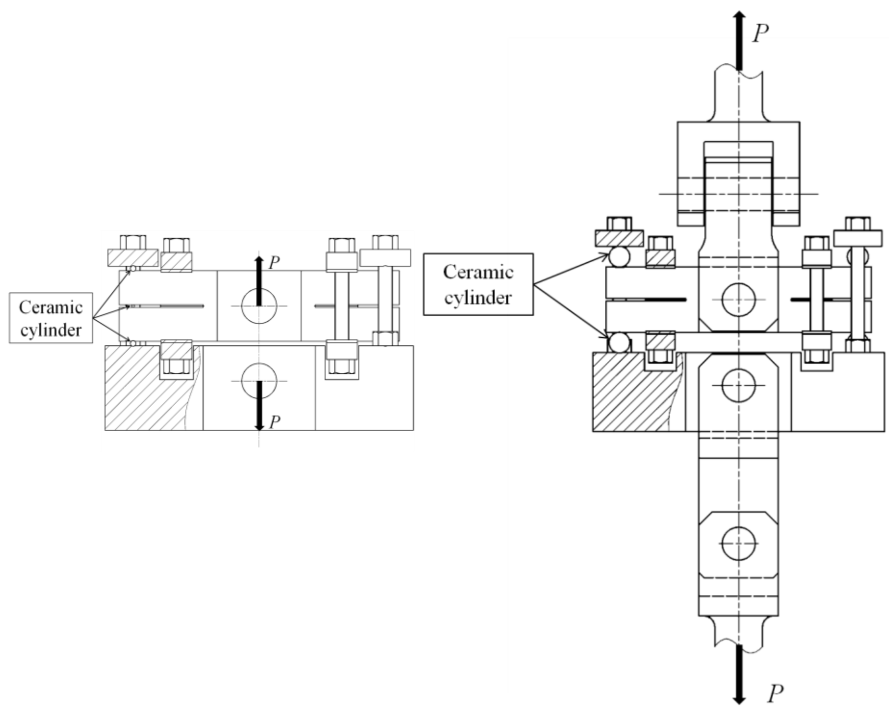
Fig. 3. Shapes and dimensions of the specimen. (a) Former specimen. (b) New specimen.

Specimen. Figure 3(a) shows the shapes and dimensions of the specimen in the previous work. The specimen has a chevron notch and side grooves. The fatigue crack initiates at the tip of the chevron notch. The 60° V-shape groove on the side of the chevron notch causes Mode II fatigue crack growth in the section of maximum shear stress and prevents the crack branching in the direction of the maximum tensile stress, which is a Mode I crack. Two crack propagations were carried out on one specimen at a time, and compressive force Q was applied on the crack face with the middle jig to avoid crack branching in Mode I.

Figure 3(b) shows the shapes and the dimensions of the new specimen. In order to reduce the unexpected horizontal force applied to the specimen, three of the four circular grooves on the end of the specimen were made flat and one was made larger with a radius of 1 mm to 4 mm. The three flat grooves allowed for the relative displacement caused by the elastic deformation between the specimen and the jigs. The large circular groove prevented the specimen from moving.

Experimental setup. Figure 4(a) shows the setup of the experiment in the previous work. Six ceramic cylinders were placed between the cantilever and the jigs, and between the cantilevers. As a result, the load applied to the specimen was divided into two equal halves on the cantilevers. A cyclic tensile load P in a sine wave ranging from 0.5 kN to 10 kN was applied to the holes in the jig and specimen through two pins by a servo-hydraulic fatigue testing machine operating at a frequency of 6 Hz. In order to suppress the tendency for Mode I crack branching, the pre-tightening force S of a bolt was applied to the ends of the cantilevers and vertical compressive force Q was applied to the crack faces by the jigs.

Figure 4(b) shows the setup of the experiment in this work. According to the new mechanical model, the pre-tightening force was expected to increase. As a result, bolts of a larger size were used and all the jigs were enlarged. The two ceramic cylinders in the slits were removed while other cylinders were enlarged to a radius of 4 mm in order to reduce the plastic deformation of the specimen on the contact face. Moreover, a set of new jigs was used to cancel out the unexpected moment applied to the specimen.



(a) (b)

Fig. 4. Experimental setup. (a) Former experimental setup. (b) New experimental setup.

Measuring method. The crack length was measured by using the AC potential method [3]. The electrodes were connected to the end of the specimen as shown in Fig. 5. As the crack grew, the electrical resistance between these two electrode points increased. The ratio of the increase in the electric potential (ΔE) caused by the crack growth to the electric potential at the beginning of the test (E_0) correlated with the crack length. Thus, the crack length could be measured without interrupting the test. The specimen was insulated from the jig by the ceramic cylinders. Furthermore, two strain gauges were placed on the specimen. The friction force on the crack face was derived from the load-strain curve over one cycle as described in the next section.

Derivation of friction between crack faces

The friction between crack faces is derived the load-strain curve over a cycle. Figure 6 shows the basic model of derivation of friction. A mass-spring model with a rough ground and the mass is subjected to a cyclic load *P*. The load-displacement curve over a cycle is shown in Fig. 6(b). Because the direction of the friction changes over a cycle, the friction can be derived from the hysteresis in the load-displacement curve.

However, for the real experiment, the curve became more complicated. When the loading began, the part of the crack faces at the notch began to slide and all the other parts of crack faces soon followed. As a result, the linear part of the curve marked (i) became nonlinear. Thus, because of the plastic deformation that occurred around the crack tip, part of the linear portion of the curve marked (ii) also became nonlinear. The same things also happened to the portions marked (iii) and (iv). Therefore, the load-strain curve over one cycle was estimated to be what is shown in Fig. 7. The friction could still be derived from the load-strain curve. The vertical dash line shown in Fig. 7 starts from point A and has an intersection point B with the extended line of the elastic portion of the curve at the unloading. The length of dash line AB is related to friction and the relation is determined using a finite element method.

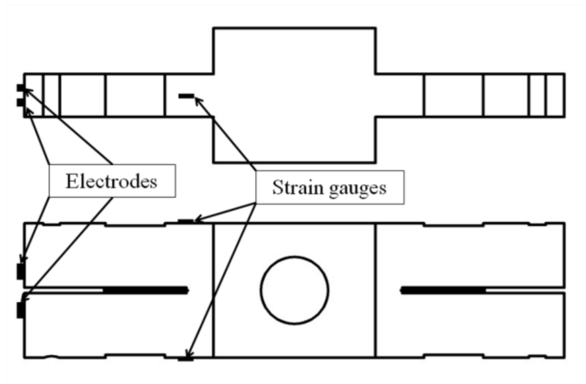
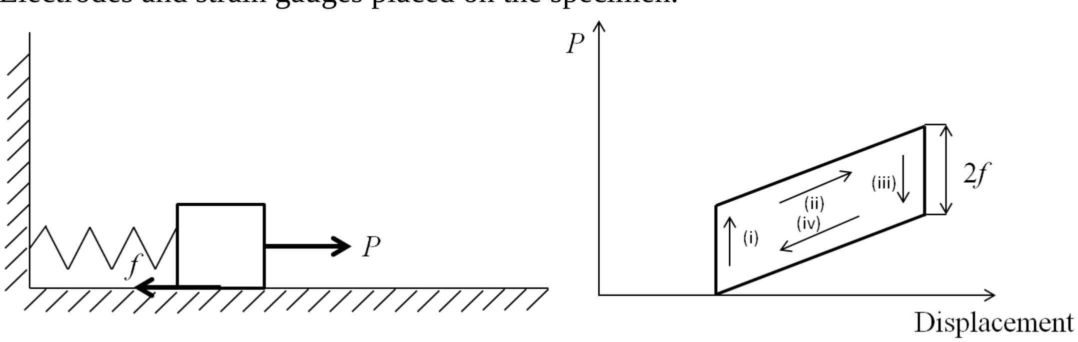


Fig. 5. Electrodes and strain gauges placed on the specimen.



(a) (b)

Fig. 6. Model for the derivation of friction. (a)Mass-spring model. (b) Load-displacement curve.

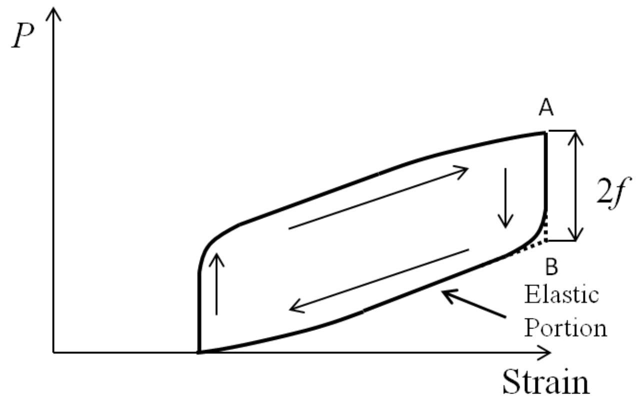


Fig. 7. Estimated load-strain curve.

Numerical method

A finite element model (FEM) of double cantilever (DC) specimens was developed to investigate the friction. The model was based on the load-strain curve over one cycle. The friction coefficient on the crack face was assumed to be large at the crack tip, then to reduce along the crack length linearly to a value of 0.5, which is determined in the previous experience, and to stay constant along the notch. The upper cantilever was pushed down by the pre-tightening force S and half of the load P applied to the ends, while the lower cantilever was pushed up by the pre-tightening force S minus half of the load P. The compress force Q is represented by a pressure load.

Result and discussion

A test was conducted to demonstrate that the mechanical behavior of the new experimental setup was correct. Figure 8 shows a strain gauge placed vertically straddling the slit of the specimen to measure the variation in the slit width over one load cycle. Figure 9(a) shows the result for the former experiment setup. The load-strain curve was basically divided into three sections with the inflection points at a load of around 6 kN and 1.5 kN. According to the new mechanical model, if the pre-tightening force S is large enough, the variation of the strain over one cycle is expected to be zero or proportional to the load considering the bolt is not perfectly rigid. Therefore, the inflection at a load of around 6 kN was considered to be due to the pre-tightening force S being insufficient. The reason for the inflection at a load of around 1.5 kN was due to an unexpected moment being applied to the specimen. Thus, the pre-tightening force S was enlarged to 2.5 kN according to the new mechanical model and new jigs were added to cancel out the unexpected moment. As a result, Fig. 9(b) shows that the strain varied proportionally to the load, which is in good agreement with the new mechanical model. The friction can be derived from the load-strain curve and the value of $\Delta K_{\mathrm{IIeff}}$ can be determined.

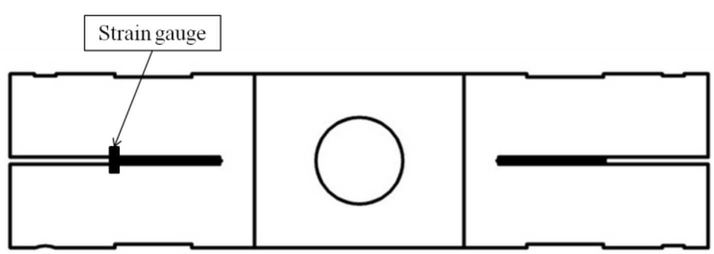
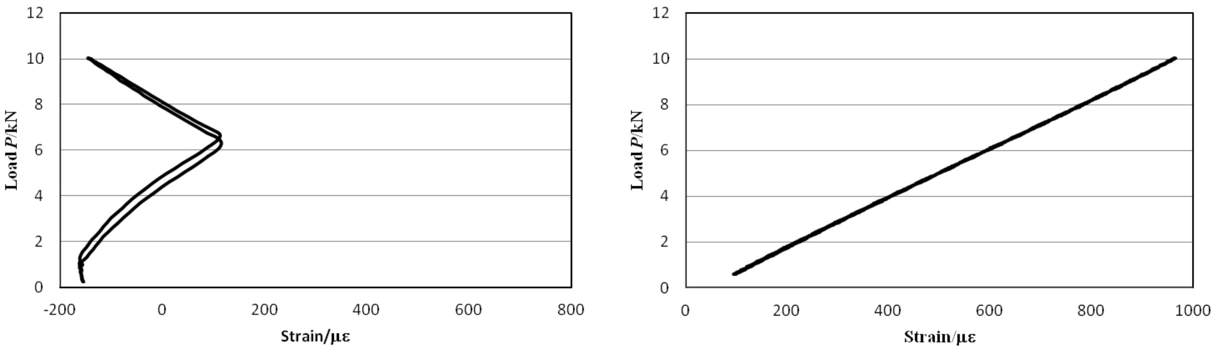


Fig. 8. Measuring point of the demonstration test of mechanical behavior.



(a) (b)

Fig. 9. Results of the demonstration test of the experimental setup. (a) Result for the former experimental setup. (b) Result for the new experimental setup.

Conclusions

The mechanical model of the Mode II experimental method proposed in the previous paper was modified. Thus, the load is considered to be equally divided into two halves and applied to each cantilever of the specimen. Furthermore, a new method for determining the friction between crack faces was proposed. The crack length and friction between the crack faces were supposed to be measured by an AC potential method and deduced from the load-strain curve, respectively. From this measurement and deduction, ΔK_{IIeff} can be determined. However, the value of ΔK_{IIeff} has not been determined. It will be determined by this method in a future study.

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