Evaluation of the Effect of Surface Roughness on Crack Initiation Life

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1. Introduction

The surface finish for machine elements is considered to be very important process influencing the fatigue crack initiation life that predominantly determines the total fatigue life. The surface roughness, the residual stress and the structure of the surface lay are main characteristics depending on the surface finish process. At present, the effects of these factors on the fatigue strength have not yet been evaluated precisely; in strength design, engineers have to introduce the surface-finish factor or roughness factor to modify the fatigue limit in practical strength design. However, this modification method is considered not so reasonable and accurate for the evaluation of the effects of the surface conditions on the fatigue strength [1].

Surface roughness is considered as an important factor in fatigue strength design evaluation. Many researchers have carried out much work to evaluate the effects of surface roughness on fatigue strength based on the differences in *S-N* curves [2-5]. However, with the consideration that the fatigue life can be divided as the fatigue crack initiation life and the fatigue crack growth life, the effects of the surface roughness on the fatigue strength should be restricted to the fatigue crack initiation stage, in addition that the fatigue crack initiation life predominantly determines the total fatigue life of a machine element [6-8], the evaluation of the effects of the surface roughness on the fatigue strength based on the changes in the crack initiation lives obtained under the different roughness conditions will be more reasonable and accurate. The method defining the crack initiation life becomes necessary for the evaluation. Many studies have been carried out on the detection of fatigue crack initiation [9-13]. The methods used in these studies require special monitoring systems, and the judgment of the crack initiation based on the monitoring signal requires a long time and much work; in addition, those methods can be applied only to the special test pieces with a slit or small hole inducing a severe stress concentration that is quite different from the actual situations in the machine elements. Meanwhile, the authors presented a very simple and practical method for the detection of a fatigue crack initiation using an ion-sputtered film [14], which was applied to the three-point bending fatigue tests. This method makes it possible to investigate the fatigue crack initiation lives under the different surface roughness. In this research, the effect of surface roughness on crack initiation life is evaluated by the detections of the crack initiation in the three-point bending tests.

2. Crack Initiation Detection Method Using an Ion-sputtered film

If a metal film is formed on the notch surface of the three-point bending test piece, and the film is made as thin as only several tens of nanometers by the ion-sputtered method, a small surface crack will crack the film as soon as the crack initiates during the fatigue test. The electric resistance of the film will increase simultaneously due to the crack initiation as shown in Fig. 1. The starting point of the increase in the electric resistance of the film corresponds to the instant of crack initiation. In the previous experiments for the crack initiation detection, the starting points of the remarkable increase in electric resistance were confirmed by the investigating the recorded electric resistance after the fatigue tests.

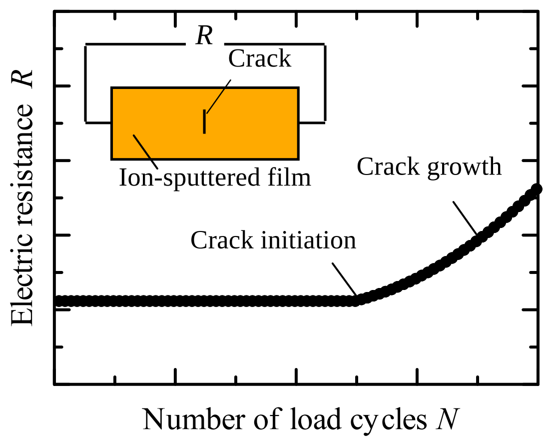

Fig. 1 Change in the electric resistance of an ion-sputtered film due to crack initiation and crack growth

3. Test Pieces and Test Method

3.1 Three-point bending test piece. The fatigue tests were performed using the specially designed three-point bending test pieces to investigate the crack initiation life and crack growth life. Considering that the crack initiates from stress concentration situations in machine elements such as shafts and gears and the convenience to form the ion-sputtered film, the notch in the test piece should be round rather than the V-shape or the U-shape used in standard test pieces. The test pieces were made to have a round notch, which was crowned so that the crack could initiate at the middle of the notch. The dimensions of test piece are shown in Fig. 2. The test piece was 100mm long, 10mm thick and 20mm high, and the supporting span in the test was 80mm. The radius of the round notch was about 4mm, the depth of the notch top T was about 5mm and the crowning radius R was about 5mm. The test pieces were made of carbon steel (S50C JIS) and normalized. The hardness was 180-230HB.

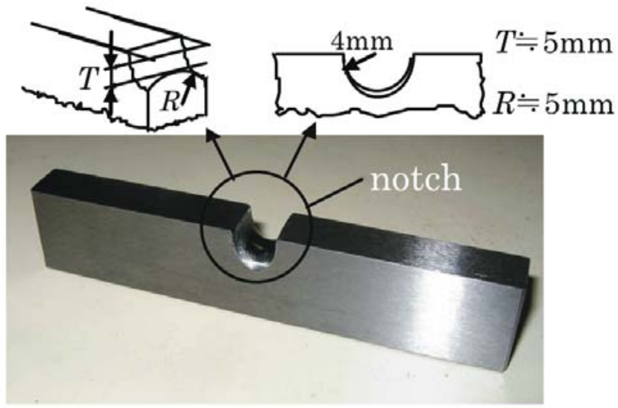

Fig. 2 Test piece with a round notch

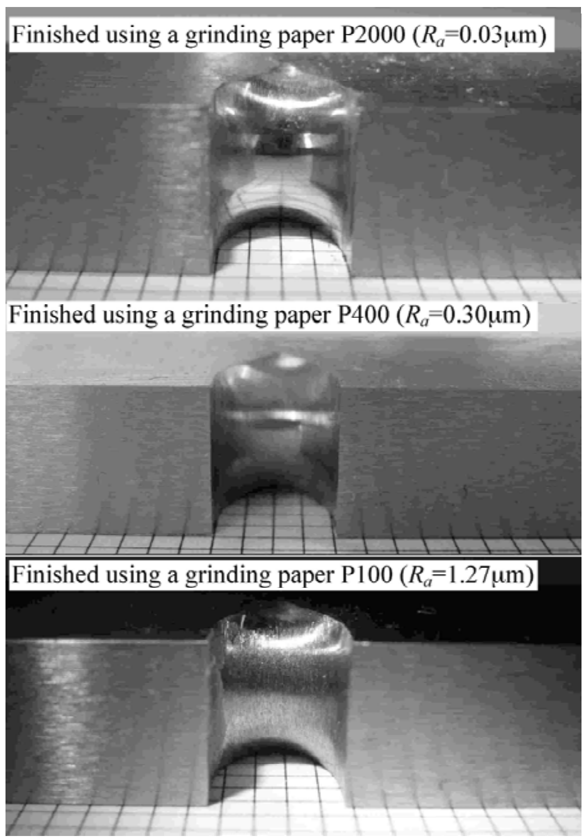

Fig. 3 A view of the three types of notches

All of the test pieces were ground by hand with sand-papers and finally mirror-polished using the emery papers of JIS P2000 to remove the influence of the notch machining process on the conditions of the notch surface; and some test pieces were ground after the polish process using the grinding papers of P400 and P100 (JIS) to get another two types of surface roughness. The coated abrasive sizes of P400 and P100 are 25-81μm and 125-180μm respectively. The views of the notches of these three types of the test pieces were shown in Fig. 3. The mean average roughness R_a of the polished test pieces and the ground test pieces are 0.03μm, 0.30μm and 1.27μm respectively. Since the finish processes were performed by hand at a very low speed, there were not any differences in the residual stress and the structure in the notch surface lay between the different finish processes; so, the changes in the fatigue life will be considered primarily caused by the surface roughness.

3.2 Ion-sputtered film and insulating film. Since the test pieces were mode of steel, a very thin insulating film is necessary between the ion-sputtered film and the steel surface for the good response of the ion-sputtered film to the crack initiation. An insulating spray paint was varnished on the notch surface. The paint was the coating agent AY-302 made by Sunhayato Co., which is commonly used in the insulation of printed circuit boards and its main component is polyvinyl resin. Wiping the steel surface with absorbent cotton wetted by the paint can make a very thin insulating film of the thickness of about 1-2μm.

Figure 4 shows the section view of the insulating film, the ion-sputtered film and the wring method. The ion-sputtered film was formed over the insulating film. The length of the film along the direction of the test-piece length was about 10mm, the width was about 5mm and the thickness of the film was 10-50nm. The material used for the film was pure gold (Au). The initial electric resistance of the film was about several ten ohms; and the insulating electric resistance between the ion-sputtered film and the test piece surface was over several kiloohms.

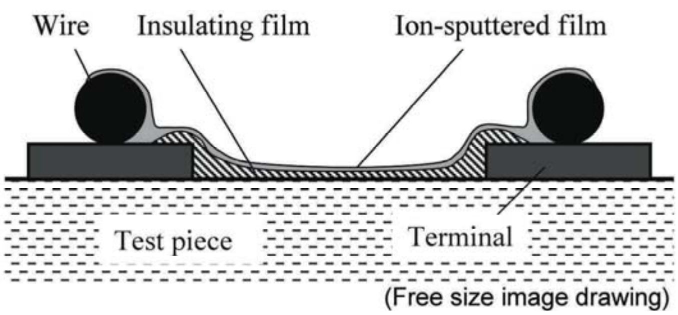

Fig. 4 Section view of the crack initiation detection spot

3.3 Test method. A hydroelectric servo pulsating fatigue test rig was used for the fatigue tests. The loading frequency was 30Hz. The load ratio (P_{min}/P_{max}) was about 0.05. A view of the test piece, the ion-sputtered film and the loading method are shown in Fig. 5. The true maximum bending stress at the notch of the test pieces was constant of 800MPa. The relationship between the true maximum bending stress at the notch surface and the maximum load was obtained by finite element method analysis.

A very simple measurement system, as shown in Fig. 6, was used to measure the electric resistance of the ion-sputtered film. The system consists of a DC power

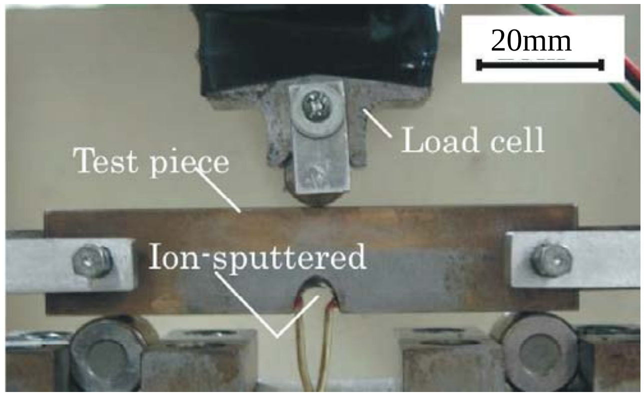

Fig. 5 A view of the test piece with an ion-sputtered film during the test

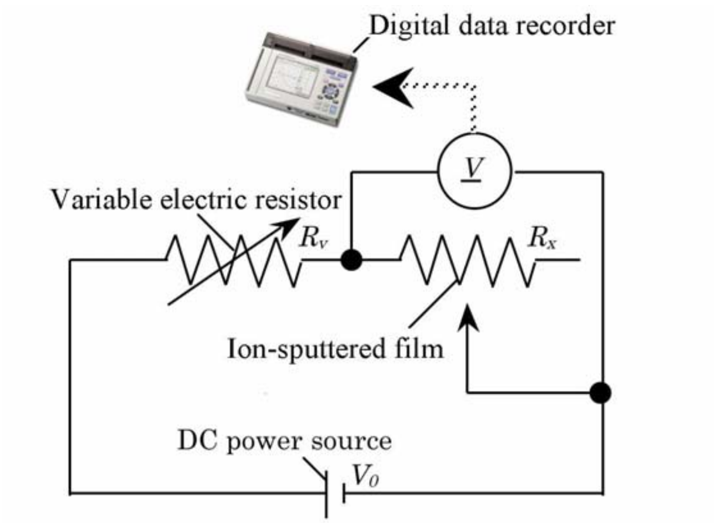

Fig. 6 System used to measure the electric resistance of the film

source, a variable electric resistor and a digital data recorder for sampling the voltage of the ion-sputtered film at a frequency of 10Hz. To avoid the generation of heat in the film, the voltage of the power source and the resistance of the variable electric resistor were adjusted so that the current of the circuit was lower than 50mA.

4. Crack Initiation Life and Crack Growth Life

The variation in the recorded voltage on the ion-sputtered film during a fatigue test is shown in Fig. 7. The crack initiation point can be pointed out from Fig. 7 by watching the tendency of the voltage changes. The point where the voltage curve leaves from the extension line of the stable voltage is considered to be the crack initiation instant. Thus, the fatigue live can be divided into the crack initiation life and crack growth life by this point.

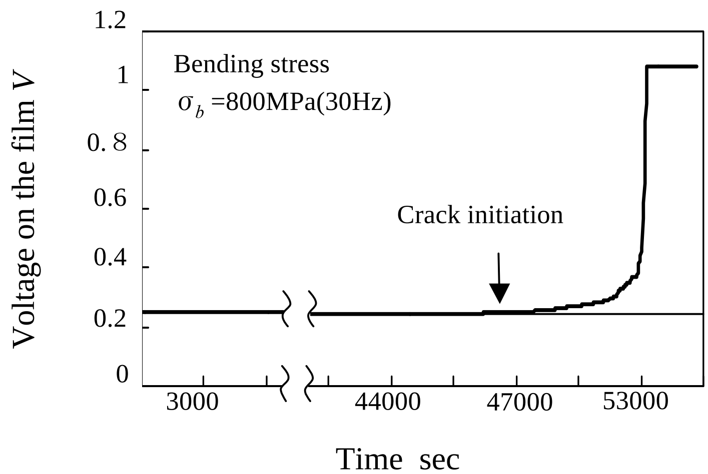

Fig. 7 Electric resistance of the ion-sputtered film during a fatigue test

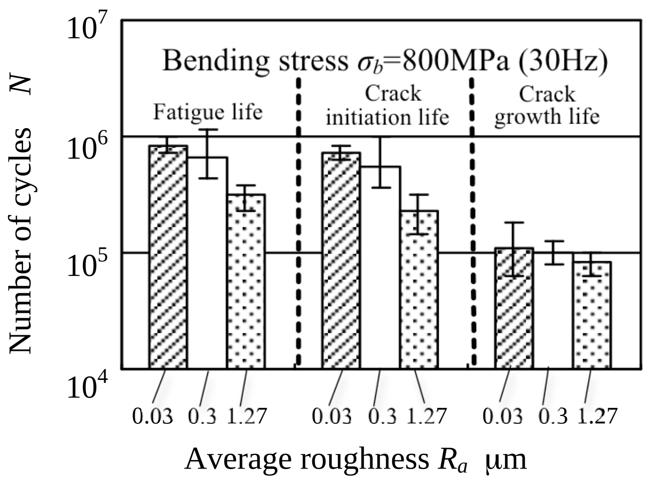

Fig. 8 The fatigue lives of the test pieces in different roughness

4.1 Effect of surface roughness on crack initiation life. The fatigue lives, crack initiation lives and crack growth lives of the test pieces in different roughness are shown in Fig. 8, the range bars indicate the maximum and minimum values. The bending stress σ_b at the notch is 800MPa and the maximum load P_{max} is 6200N. It can be concluded from Fig. 8 that the crack initiation life predominantly determines the fatigue life since the crack initiation life shares over 90% of the fatigue life. A rougher surface will reduce the crack initiation life and have a shorter the fatigue life consequently because the fatigue crack initiate more easily on a rough surface. The mechanism by which surface roughness influences the fatigue life is commonly explained to be due to the stress concentration and surface flaw [2,3]. Since the effects of the surface conditions on the fatigue strength is considered to be restricted to the stage of fatigue crack initiation, and the crack growth rate depends on the stress intensity factor and the characteristics of the material, the differences in the crack growth lives between the experiments are small compared to the crack initiation lives. Figure 9 shows the change in the

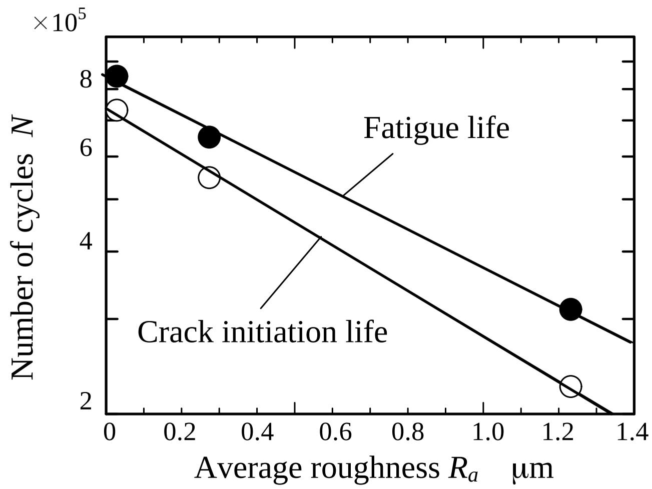

Fig. 9 The fatigue life and crack initiation life vs. the surface roughness

fatigue life and crack initiation life related to the surface roughness. The determination of the clear correlation between crack initiation life or the fatigue life with the surface roughness requires much more work, however, figure 9 indicates proximately linear relationships between the life in logarithm scale ($\log N$) and surface roughness R_a.

5. Conclusions

The crack initiation detection method using an ion-sputtered film was used as a practical method to investigate the effects of the surface roughness on the crack initiation life in the three-point bending tests. Three types of the test pieces finished with different grinding processes were used in the fatigue tests. As the results obtained in this research, it is confirmed that the crack initiation life predominantly determines the fatigue life, and the effect of surface roughness on the fatigue life is restricted only to the crack initiation stage; the crack initiation life decreases with the increase of the surface roughness. Proximately linear relationships between the fatigue life, crack initiation life and the surface roughness are indicated.

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