Effect of Surface Roughness on Fatigue Life of Notched Carbon Steel

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Abstract— **The effects of surface roughness on the fatigue life of carbon steel have been investigated. Rotational bending specimens have been machined and tested in fatigue. Specimens with surface roughness changed by emery papers (Grit #600, #400, #100) were prepared. The fatigue experiments were carried out at room temperature, applying a fully reversed cyclic load with the frequency of 50Hz, with mean stress equal to zero (R= -1), on a cantilever rotating-bending fatigue testing machine. The stress ratio was kept constant throughout the experiment. Regarding the effect of surface roughness, the number of cycles to failure of finer specimens was a little bigger than those of the courser specimens. Morphological observation on fracture surface of specimens was done using Optical and Scanning Electron Microscope (SEM). The result shows the number of possible fatigue crack initiation sites of courser specimen are higher compare to finer one. In addition, the specimens were broken in transgranular fracture.**

***Index Term*— Surface roughness, fatigue limit, carbon steel, fracture surface, transgranular fracture.**

I. INTRODUCTION

Fatigue failure is caused by many factors such as material type, notch geometry, surface quality, environment effect and etc. However, three parameters are usually proposed to describe surface quality: geometrical parameter or surface roughness, residual stress and microstructure. These parameters can vary separately according to the machining conditions.

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In engineering design, the effects of these parameters are commonly accounted for by using empirical reduction factors which modify the endurance limit of the material [1]. These entire factors are able to reduce the fatigue strength of the component of machines, vehicle and structures and can cause catastrophic failure even the stress applied is much lower than the ultimate strength of the materials. In product design process, the notch is sometimes very difficult to be avoided. It is frequently introduced especially in developing the product that requires a lot of joint and etc. In addition, the environmental effects also are very difficult to predict. Since the surface finish of the products/components can be controlled during machining, it is frequently considered by manufacturers in order to increase the life of the products. Therefore it is important to study the effects of surface roughness of materials on fatigue life.

Various kinds of surface effects can be great importance for the fatigue life. Surface effects include all conditions which can reduce or enhance the crack initiation period [2]. In other words, they cover the phenomena which have an influence on the crack initiation mechanisms. Surface roughness implies that the free surface is no longer perfectly flat. As a consequence, small sized stress concentration will rapidly fade away from the surface; it is still significant for promoting cyclic slip and crack nucleation at the material surface. Since fatigue cracks generally initiate on the specimen surface, it is well known that the surface roughness of a specimen has a great effect on its fatigue strength. It is also reported that, with respect to the direction of surface roughness, the fatigue strength is more strongly influenced by circumferential direction roughness normal to the stress direction than in the axial direction, that the effect is more marked with greater surface roughness [3].

Taylor and et al. [4] have compared the fatigue limit of the AISI 4140 steel, using four types of machined surfaces produced by polishing, grinding, milling and shaping. The residual stress was eliminated by heat treatment. They found that fatigue limit of ground surfaces decreased when compared to polished specimens, that is, the fatigue limit decreased with increasing surface roughness. However, a comparison of the fatigue limits of the specimens with ground surfaces with those of milled surface specimens showed an opposite tendency, that is, an increasing of fatigue limit with increasing surface roughness.

The effects of surface roughness on cracking initiation and S-N curves of a Ni-Cr-Mo steel were studied by Itoga et al. [5]. Surface roughness was the most important influencing factor in short life regime, and the fatigue life was found to decrease with increasing surface roughness. Arola and Williams [6] found that the high-cycle fatigue life of machined specimens of AISI 4130 steel is surface-texture dependent, and that the fatigue strength decreased with an increase in surface roughness from 2 to 6 µm.

This study has been carried out by using comparatively lower surface roughness, Ra values using cantilever rotating bending machine since only few researches have been done using this type of machine. In addition, there are only few researchers investigate the surface fracture of the materials. Therefore, the objectives of this study are to clarify the effects of the surface roughness and to investigate the surface fracture of the material.

II. Methodology

A. Material

The material used in this study was carbon steel with 0.2C (wt %). The chemical compositions of the material have been identified by using spectrometer machine. The chemical compositions and mechanical properties of the specimens' material are tabulated in Table I and Table II respectively.

TABLE I
CHEMICAL COMPOSITIONS OF CARBON STEEL (wt%)

Element	%
Fe	98.5
C	0.214
Mn	0.725
Si	0.133
S	<0.05
P	<0.05
Cr+Mo+Ni+Sn	<0.32

TABLE II
MECHANICAL PROPERTIES OF CARBON STEEL

Tensile Strength [MPa]	Yield Strength [MPa]	Elongation [%]
483	375	15

B. Specimen Preparation

The specimens were prepared by machining raw materials using conventional lathe machine. Twenty pieces of specimens were prepared with three different surface roughness levels. As for the surface roughness specimens, the specimens were prepared by circumferentially scratching the area around the notch of the minimum diameter of specimen. The specimen was attached to a lathe for 50 revolutions and was scratched by using #600, #400 and #100 emery papers. They were first machined in the same parameters of feed rate and spindle speed, and then scratched. The detail dimension of the cantilever rotating bending specimen is shown in Figure 1.

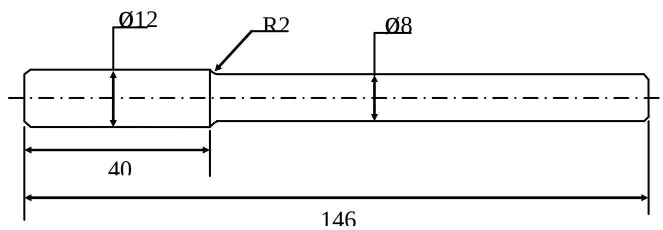


Fig. 1. Detail dimension of fatigue specimens (mm)

C. Surface Roughness Measurement

Once the scratching process was done, the surface roughness of the specimens was then measured. The portable perthometer machine was used for the measurement. In order to reduce human errors during the measurement, the reading was taken for three times at different points. The process was repeated to all specimens. Then, the average surface roughness, Ra is calculated and is summarized in Table III.

TABLE III
SURFACE ROUGHNESS, Ra FOR DIFFERENT EMERY PAPER GRIT

Emery Paper Grit	Roughness, Ra [µm]
#600	1.778
#400	2.885
#100	5.484

D. High Cycle Fatigue Test

The fatigue testing machine used was a single cantilever rotating bending model with a maximum capacity of 0.3 kN. Fatigue tests were carried out at room temperature (293 K) with constant frequency of 50Hz. A sinusoidal cyclic load with a stress ratio R = -1 (minimum load/maximum load) was applied throughout the experiment. The specimen was griped using the chuck at one end while the load is applied at the other end whereby was connected to the load bearing. The load is applied just after the specimen started to rotate. Once the specimen was broken, the shut down sensor stopped the machine automatically. The number of cycle to failure was then counted and displayed on the screen of the machine. The experiment was conducted by repeating twenty similar procedure tests for all specimens. Figure 2 shows the experiment setup for rotating bending fatigue test.

Fig. 2. Close-up on the experiment set-up

III. RESULTS

A High-Cycle Fatigue Properties

Figure 3 represents the S–N curve of the specimens with three different surface roughnesses. The S–N curve shows the specimen shifted to a higher stress level or longer life side with a decreasing level of roughness, indicating increased fatigue strength. The fatigue strength of the Ra = 5.484μm and Ra = 2.884μm roughness specimens are slightly lower in the higher stress level or shorter life side region than the finer specimen of Ra = 1.778μm. In the lower stress level or longer life side region, however, the degree of decrease in fatigue strength is larger. The finer specimens gave much higher number of fatigue cycles to failure compared to courser specimens. It is also shown that the specimen with Ra = 1.778μm are not broken at stress level of 120MPa.

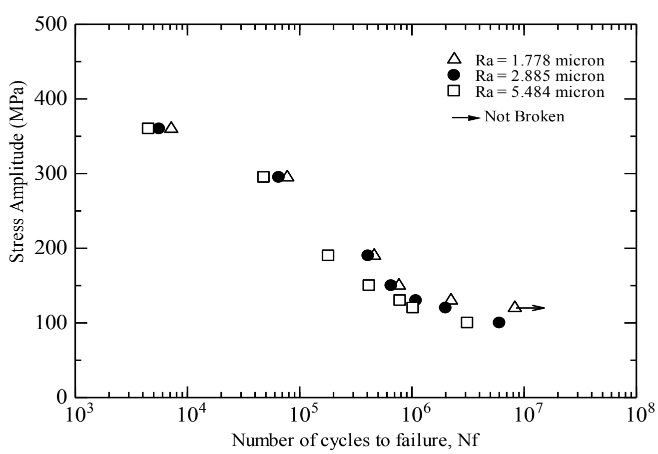


Fig. 3. S-N curve for different surface roughness

The influence of surface roughness on fatigue limits of all machined specimens is summarized in Figure 4. The fatigue limit decreases almost linear with the increasing level of roughness. The fatigue limit of the specimen was taken when the number of cycles to failure, N is greater than $3(10^6)$. It was showed that there is little significant changes in fatigue limit with the increasing of surface roughness from Ra = 1.778μm to Ra = 2.885 μm.

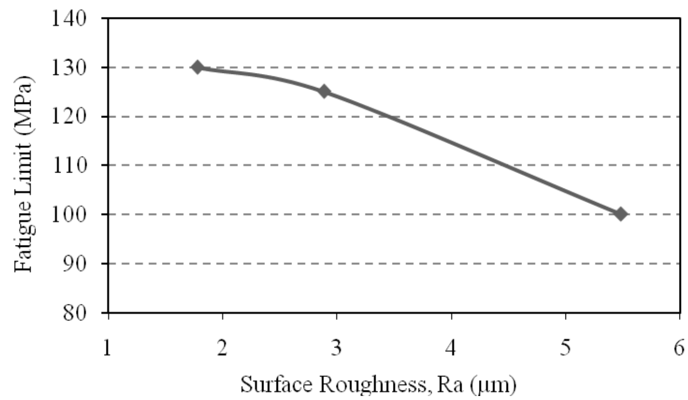
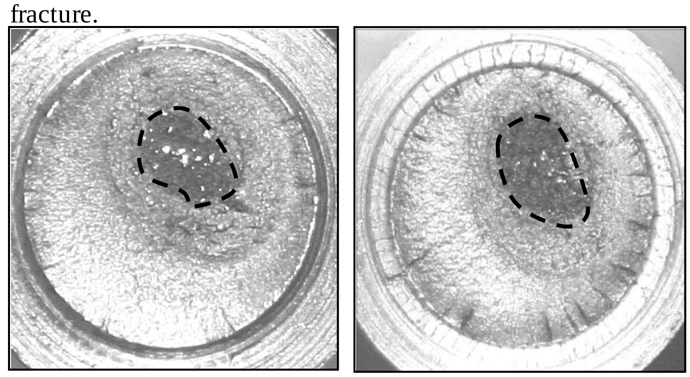


Fig. 4. Summary of fatigue limits of analyzed specimens.

B Morphology Observation

Fracture surfaces of failed specimens have been analyzed using Optical Microscope (OM) and Scanning Electron Microscope Zeiss EVO 50. It was observed that the fracture surface among specimens is different. Higher number of possible crack initiation sites existed in the specimen with higher surface roughness (Ra = 5.484μm). The stress raiser points increase proportionally with the surface roughness. Therefore, the crack can start propagate at any point where there is the highest stress raiser. As a comparison, the number of possible crack initiation sites are slightly lower for the specimen with surface roughness, Ra = 2.884μm. On the other hand, the result shows the crack start propagates almost equally from the machined notch for the finer specimen. It is because the stress raiser is eliminated by reducing the specimen surface roughness. Figure 5 shows the different surface fracture for courser and finer specimens with different roughnesses of Ra. The pictures were taken at stress amplitude of 120MPa. The dashed curve areas show the stage 3 of rapid fracture.



(a) (b)

Fig 5. Micrographs of fatigue fracture surface at stress amplitude of 120MPa for (a) Ra = 1.778μm and (b) Ra = 5.484μm.

Fig. 6 and 7 show the surface fracture micrograph that has been analyzed using SEM. It is clearly showed that there are two distinct regions generated when the specimen was subjected to cyclic stresses. At first region (point 1), it shows the stable crack propagation region and after certain length of propagation, the specimen cannot withstand with the applied stress anymore. Therefore, it failed rapidly when entering the second region (point 2) which is sometimes known as rapid fracture region. Detailed observation on first region shows the specimens were failed in transgranular fracture.

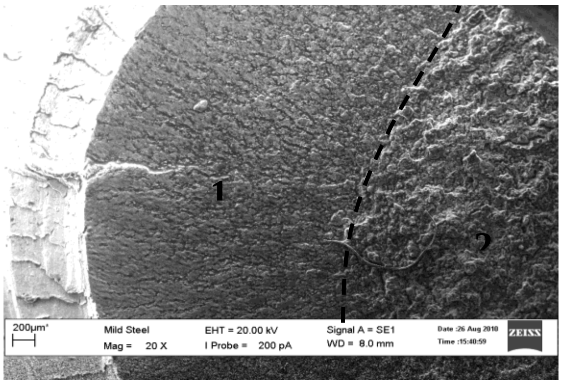


Fig. 6. SEM micrograph of different region of fracture surface

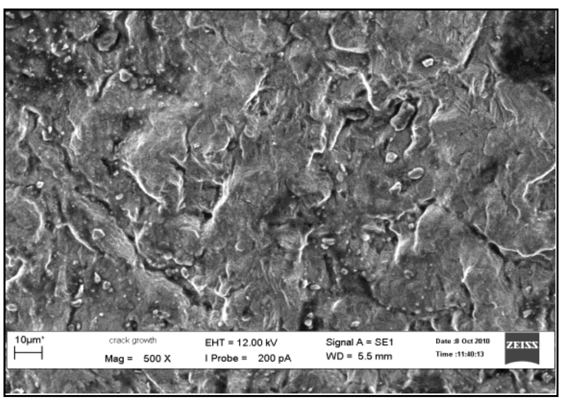


Fig. 7. SEM micrograph of fatigue fracture surface for stable crack propagation region

IV. CONCLUSION

Cantilever rotating bending fatigue test was carried out on carbon steel to study the effect of surface roughness on fatigue life of notches specimen. The findings can be summarized as follows:

1. There is no significant difference in fatigue life among specimens at low fatigue cycle region of $N<10^5$. However, at high fatigue cycle region, $N>10^5$ the finer specimens give much higher fatigue cycle compared to others.
2. Based on fracture surface observation, the number of possible crack initiation sites increase for courser specimens that introduce the stress raiser on the specimens and reduces the crack initiation life. In addition, transgranular fracture was observed in fracture surface for all specimens.

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