Effects of surface microstructure on low cycle bending fatigue strength of gas carburized low alloy steel

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The effect of surface microstructure on low cycle bending fatigue strength of gas carburized low alloy steel was investigated. In particular, the effects of gas carburizing surface abnormal structure and residual stress were evaluated in detail by dividing the low-cycle bending fatigue fracture into the crack initiation process and the crack propagation process. The crack initiation life in the low cycle region is greatly improved by shot peening and chemical polishing. CP steel has a higher crack initiation life than SP steel, and it is found that removal of gas carburized abnormal structure is more effective than residual stress in the low cycle life region. On the other hand, the crack propagation life is the same for Base steel, SP steel, and CP steel. This result shows that the residual stress and the removal of carburized abnormal structures do not affect the crack propagation life.

Keywords: *Low cycle bending fatigue, Gear, Gas carburizing*

1. Introduction

In recent years, with the spread of electric vehicles, there is a demand for smaller and stronger gear units such as transmission gears and differential gears. Gears are subjected to surface hardening treatments such as carburizing and nitriding in order to achieve both high fatigue strength and machinability. The microstructure of the surface layer of the gear becomes a high-carbon martensite by carburizing. Pitting on the tooth flank and breakage on the root of the gear with high-cycle bending are the most common types of fatigue failure in transmission gears, and many reports have been made on the factors affecting them[1-3]. For example, it is effective to remove the abnormal structure of the gas carburized surface layer by chemical polishing, or to apply compressive residual stress by shot peening[4].

Differential gears are subjected to a strong impact bending load when the vehicle starts suddenly or runs on the shoulder, so differential gears are required to have improved low-cycle bending fatigue strength. It has been reported that the initiation point of low-cycle bending fatigue fracture in carburized steel is the intergranular fracture surface[5-7], and that the fatigue strength is correlated with the steel phosphorus content[5], steel sulfur content[5], carbon content[6], and core hardness[7]. However, there are few reports on the effects of chemical polishing and shot peening on low-cycle bending fatigue strength. In this study, the effects of surface structure and residual stress on low-cycle bending fatigue strength were investigated by evaluating the low-cycle bending fatigue fracture by dividing it into the crack initiation process and the crack propagation process.

2. Experiment

2.1 Test material

Table 1 shows the chemical composition of the test material. We used SCM420 steel which is often used for carburized gears. After melting with vacuum melting of 50 kg, hot forging and normalizing heat treatment were performed. The fatigue specimens shown in Fig.1 were machined from the heat-treated material. The specimens were gas- carburized with the condition as shown in Fig. 2 to make the carbon concentration 0.8%C in the surface layer. After that, a tempering heat treatment was performed at 453K for 120 minutes, followed by air cooling to prepare a base material. In addition, SP material with a compressive residual stress of about 1200 MPa by shot peening (SP conditions: steel ball size φ0.6mm, projection pressure 0.4MPa, coverage 300%) and CP material with 50 μm of carburized abnormal structure removed by chemical polishing were produced.

Table 1 Chemical composition of the alloy (mass %)

Alloy	C	Si	Mn	P	S	Cr	Mo
SCM420	0.21	0.25	0.86	0.008	0.012	1.11	0.16

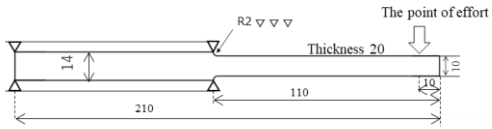

Fig.1 Specimen geometries used for the low cycle bending fatigue test (unit:mm).

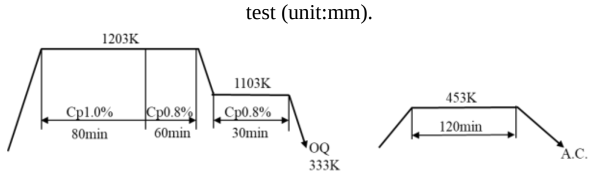

Fig.2 Conditions of heat treatment.

2.2 Evaluation of low-cycle bending fatigue strength

For the evaluation of low-cycle bending fatigue strength, a fatigue test was performed on a cantilever beam using a 50kN electro-hydraulic servo fatigue testing machine. A load was repeatedly applied at a position 10 mm from the end of the bending fatigue test piece shown in Fig. 2 with a stress ratio of R = 0.1. The strain rate of the fillet is about 0.1/s. In addition, the fatigue crack initiation life and growth life were evaluated by the following methods. A strain gauge (gauge length: 1 mm) was attached to the fillet portion of the test piece, and it was confirmed that disconnection of the strain gauge occurred at the same time as cracking occurred. The number of repetitions until strain gage disconnection was defined as the number of repetitions until crack initiation (NI), and the number of repetitions from crack initiation to crack propagation (NP) was calculated by subtracting NI from the final number of repetitions until fracture (NF).

NF: Number of cycles to fracture

NI: Number of cycles to crack initiation

NP=NF-NI: Number of cycles required for crack propagation

In order to clarify the origin of cracks in some specimens, fatigue cracks were visualized by the heat tinting method. In this observation, the specimens were heated up to 573K and held for 1h to apply temper color to the cracks.

3. Results

Figure 3 shows the fatigue test results. Crack initiation life was greatly improved by shot peening and chemical polishing. For example, the crack initiation life at P=4500N was 30 times longer for the SP material and 100 times longer for the CP material than the Base material. The CP material has a longer crack initiation life than the SP material, and it can be seen that removal of gas carburized abnormal structures is more effective than residual stress in the low cycle life region. On the other hand, the crack propagation life is the same for Base material, SP material, and CP material. This result indicates that removal of residual stress and carburized abnormal structure does not affect crack propagation life.

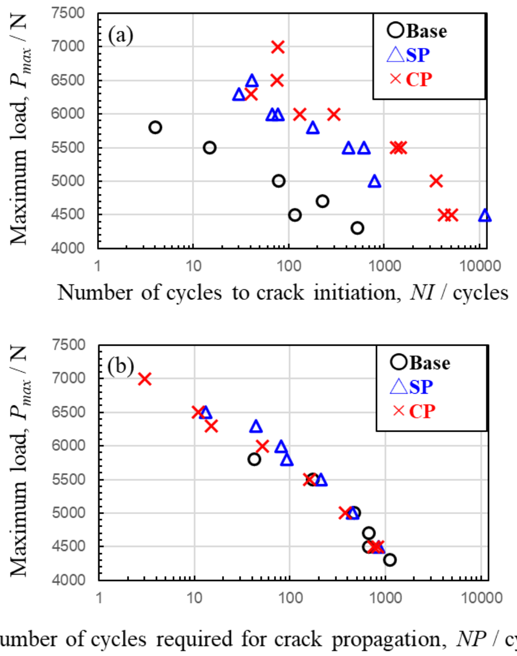

Fig.3 (a) S-N diagram of crack initiation (*NI*) and (b)S-N diagram of crack propagation (*NP*) obtained by low-cycle bending fatigue test of gas carburizing and quenching SCM420.

4. Discussion

In order to clarify the reason why the crack growth life of the base material, CP material and SP material does not change, the test was stopped immediately after the crack initiation and the crack was observed. The crack length was confirmed to be about 500 μm. The compressive residual stress of SP material is up to about 100 μm from the surface layer, and both CP material and SP material have the same structure and residual stress as the base material at the position of 500 μm from the surface layer. Therefore, it is considered that the crack propagation life is constant without being affected by chemical polishing or shot peening.

The crack initiation life of the SP material subjected to shot peening was improved over that of the Base material. In the low-cycle bending fatigue test, a stress higher than the yield stress is applied, which suggests the possibility that the residual stress is released by plastic deformation. Therefore, we investigated the residual stress of the SP material in which the fatigue test was interrupted before the crack occurred. After 100 cycles of fatigue testing at 5.5 kN (nominal stress 2400 MPa), the surface residual stress of the SP material was -800 MPa. Although the surface residual stress decreased slightly from 1200 MPa to 800 MPa during the fatigue test, it was confirmed that it was almost maintained. The equivalent plastic strain of the specimen fillet after loading and unloading a rigid body on the specimen with compressive residual stress was calculated by FEM calculation . The calculation shows the compressive residual stress reduces the equivalent plastic strain. This strain reduction is considered to improve the crack initiation life.

5. Conclusions

1) Crack initiation life in the low cycle region is greatly improved by shot peening and chemical polishing. On the other hand, the crack propagation life is the same for Base material, SP material, and CP material.

2) The reason why the crack propagation life of the Base material, CP material, and SP material is the same is that the crack length is as deep as 500 μm from the surface layer, and there is no effect of shot peening or chemical polishing.

3) The reason why the crack initiation life of the SP material was improved is that most of the compressive residual stress due to shot peening remained during the fatigue test, and crack initiation was suppressed by the compressive residual stress.

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