INFLUENCE OF NONMETALLIC INCLUSION ON FATIGUE STRENGTH OF CARBURIZED AND SHOT PEENED GEAR STEEL

H. Kagawa*, M. Ishiguro* and S. Hisamatsu**
*NKK Corporation, Japan, **Isuzu Motors Limited, Japan

ABSTRACT

In order to clarify influences of nonmetallic inclusion on fatigue strength of carburized and shot peened gear steel, bending fatigue tests and pitting fatigue tests were carried out on a clean steel with oxygen content of 9ppm and a conventional steel with oxygen content of 20ppm, respectively. As a result, it was revealed that the clean steel showed higher fatigue strength than the conventional steel in both of the fatigue tests. The test result was discussed from a view point of the size and the density of nonmetallic inclusion.

KEYWORDS

Carburizing, Shot peening, Electropolishing, Fatigue strength, Pitting, Clean steel, oxide inclusion, MnS inclusion

INTRODUCTION

Recently engines of automobiles become more and more powerful, furthermore the transmissions are required to become smaller. As a result, it is required to increase the strength of gears especially against fatigue. Shot peening is one of the most effective methods to increase the fatigue strength of steel members, and it is widely applied to carburized gears of automobiles. The objective of this study is to improve the fatigue strength of gear steel under the carburized and shot peened conditions. In such conditions, fatigue crack tends to initiate from nonmetallic inclusion inside the gear (fish-eye fracture mode), because compressive residual stress exists near surface. Therefore, it is expected that the fatigue strength of gear can be improved by reducing the number and the size of inclusions in steel.

Rotating fatigue properties of the clean steel with low oxygen content were studied by Toyoda et al.(1,2) and they reported that ①the clean steel (O_2:9ppm) showed about 10% higher fatigue strength than the conventional steel (O_2:21ppm) in the case of fish-eye fracture mode, ②oxide inclusions were observed at the fatigue crack initiation points, and ③the average size of inclusions observed at crack initiation points was smaller in the case of clean steel compared with that of conventional steel.

In the present paper, further practical studies on the fatigue strength of clean steel was conducted. Gear fatigue tests which could precisely simulate the fatigue process of actual gear were carried out on the clean steel and the result was compared with that of the conventional steel. The fractured surfaces of gear specimens were observed in detail, and the fatigue test results were discussed in conjunction with the inclusions observed in the fractured surfaces. Roller pitting fatigue tests were also performed in order to clarify the influence of inclusion on the pitting fatigue strength.

MATERIALS

The material used in the present study was Cr-Mo steel (JIS SCM420H). The chemical compositions are shown in Table1. The oxygen content of clean steel is 9ppm, while that of conventional steel is 20ppm.

EXPERIMENTAL PROCEDURE

Method of Gear Fatigue Test

The gear fatigue test was carried out using a couple of gear specimens. The dimensions of gear specimens are shown in Table2. The mechanism of gear fatigue test machine is schematically shown in Fig.1. The test procedure is as follows: ①remove the coupling nuts and fix the coupling by the stopper ②apply torsional load by the weights ③fix the coupling nuts ④remove the weights and the lever ⑤remove the stopper ⑥rotate the gear specimens by the motor. Thus the gear specimens can be rotated under the constant torque condition.

Specimen conditions of the gear fatigue tests were as follows : ①as carburized ②carburized and shot peened by a centrifugal wheel type machine (X

Table1 Chemical compositions of tested materials (wt%)

	C	Si	Mn	P	S	Ni	Mo	t.O
Clean steel	0.19	0.28	0.79	0.007	0.018	1.12	0.17	0.009
Conventional steel	0.21	0.22	0.83	0.016	0.016	1.04	0.16	0.020

Table2 Dimensions of gear specimens

	Large gear	Small gear
Type of gear	spur gear	
Number of teeth	32	28
Module	2.5	
Cutter pressure angle	20°	
Face width	10mm	
Center distance	75mm	

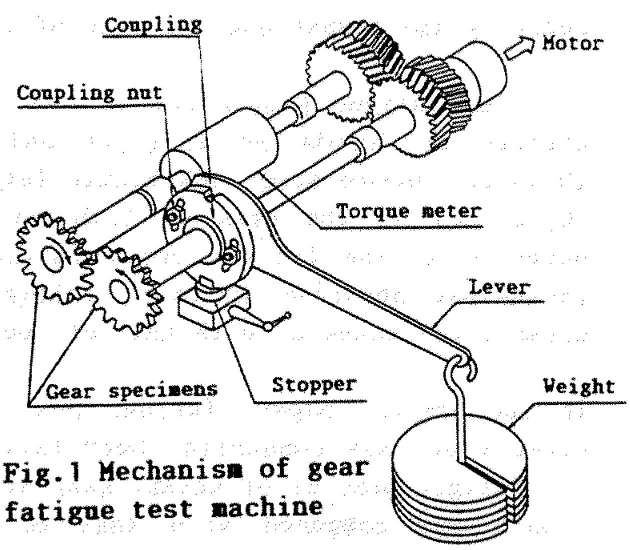


Fig.1 Mechanism of gear fatigue test machine

type) ③carburized and shot peened by an air nozzle type machine(Y type) ④carburized, shot peened(Y type) and electropolished(surface layer of about 40μm thickness was removed by the electropolishing). Table3 shows the shot peening conditions.

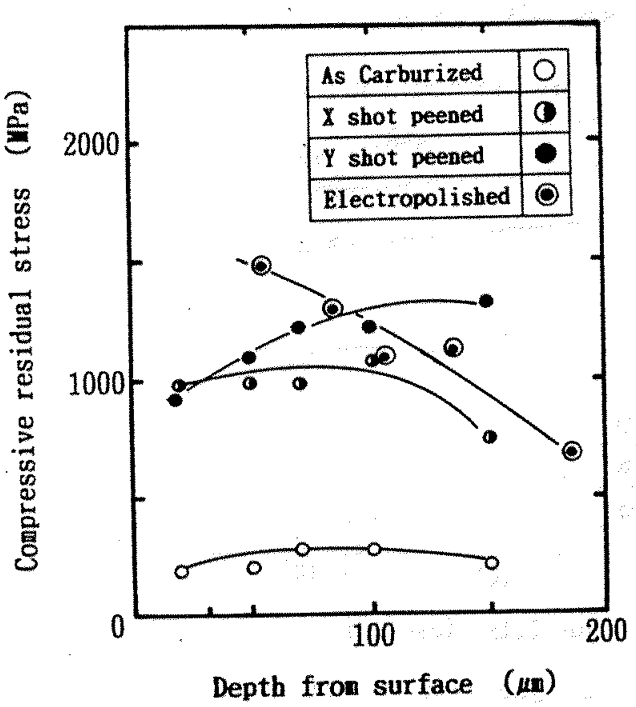
Residual stress was measured at the bottom point of gear by X-ray diffraction method. Figure2 shows the compressive residual stress distributions of the above four specimen conditions. The maximum compressive residual stress in as carburized specimen is about 300MPa, while those of X shot peened and Y shot peened specimens are about 1000MPa and 1300MPa, respectively. Comparing the compressive residual stress distribution of electropolished specimen with that of Y shot peened specimen, it is seen that the compressive residual stress near surface(0~100μm depth) is increased by electropolishing.

Method of Roller Pitting Fatigue Test

The roller pitting fatigue test was performed using a couple of roller specimens. The configurations of specimens are shown in Fig.3. The roller B is set up to contact with the middle part of the roller A in order to rotate under the constant contact pressure condition. The roller specimens were lubricated during the test, and temperature of the lubricant was kept to be 60℃. The rotational slide ratio between the rollers A and B was controlled to be 40% during the test.

Table3 Shot peening conditions

Type	Size	Hardness	Coverage	Arc height
Centrifugal wheel	ϕ0.8mm	HRC 53	300%	0.45A
Air nozzle				0.30C (1.1A)



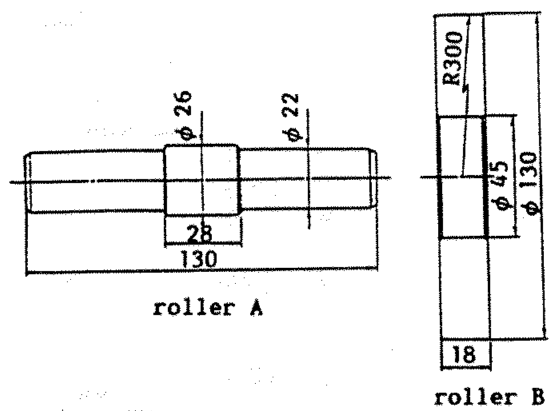


Fig.3 Configuration of roller pitting fatigue specimen

Fig.2 Compressive residual stress in tooth trace direction at the bottom point of gear

The roller pitting fatigue tests were performed under the as carburized condition and carburized and Y shot peened condition, respectively.

TEST RESULTS

Results of Gear Fatigue Test

The relationships between the applied torque and the fatigue life of gear specimen are shown in Fig.4. The fatigue limit (applied torque at 10^7 cycle) of clean steel is almost the same as that of the conventional steel under the as carburized condition. In the case of X shot peened condition, the fatigue limit of clean steel is higher than that of the conventional steel, but the difference is 15N•m(5%) at most. On the other hand, comparing with the conventional steel, the fatigue limit of the clean steel is 14% higher in the Y shot peened condition and 26% higher in the electropolished condition, respectively.

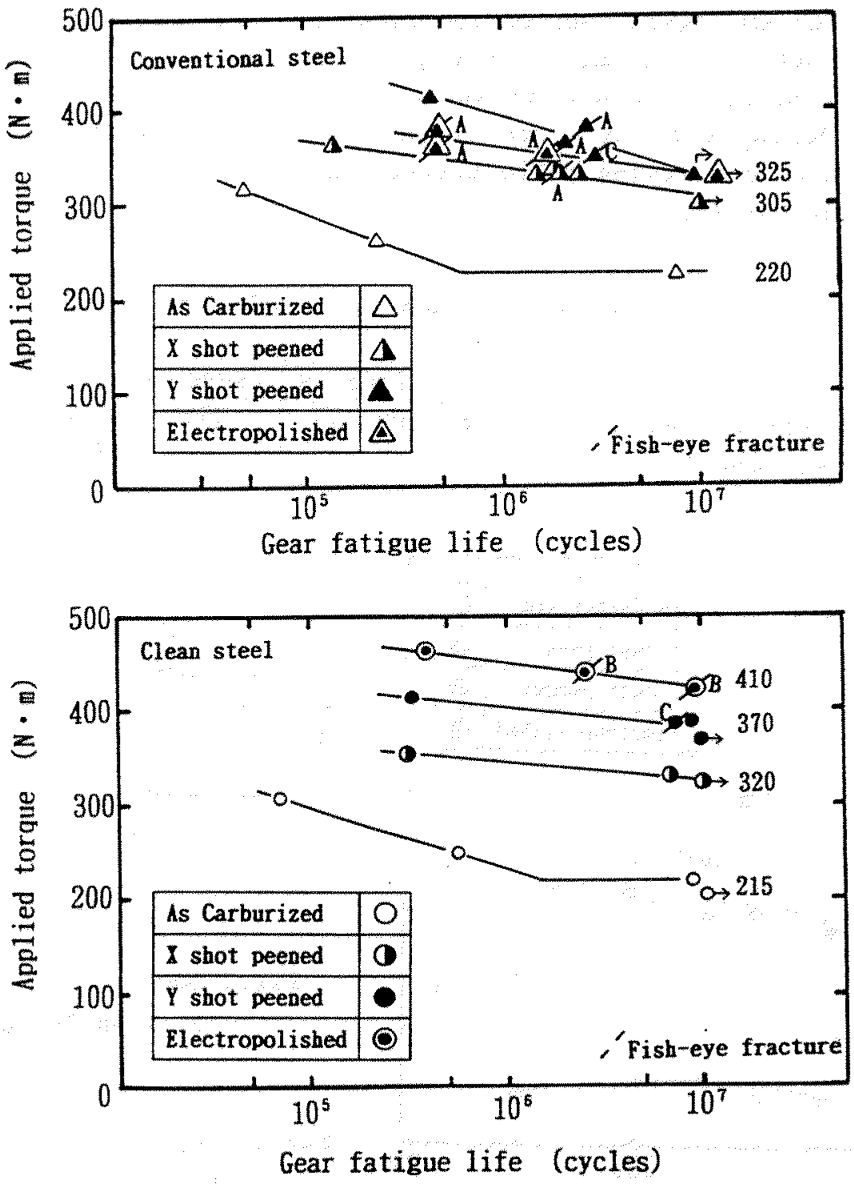
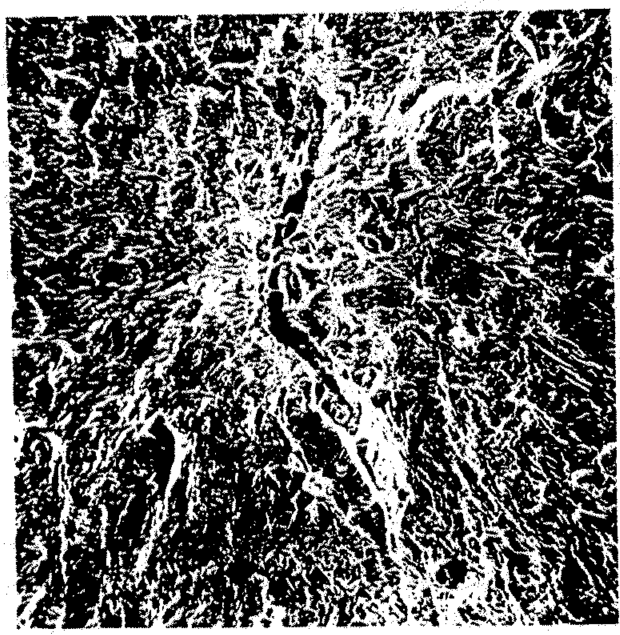
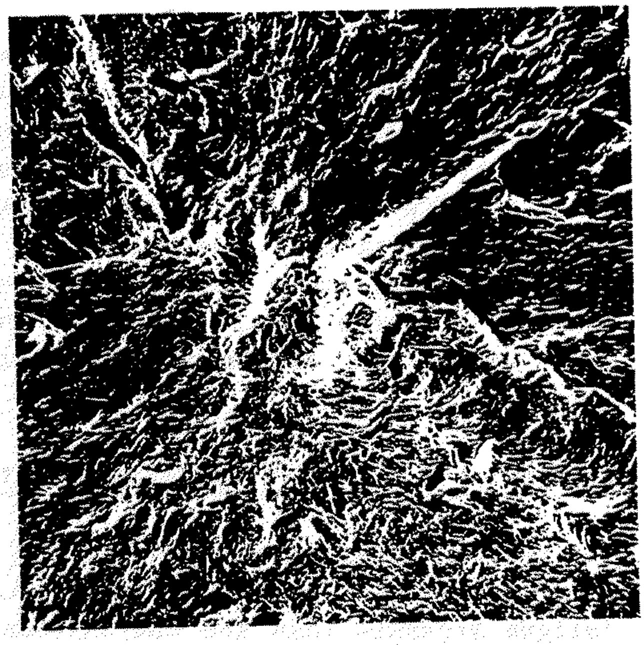


Fig.4 Gear fatigue test result

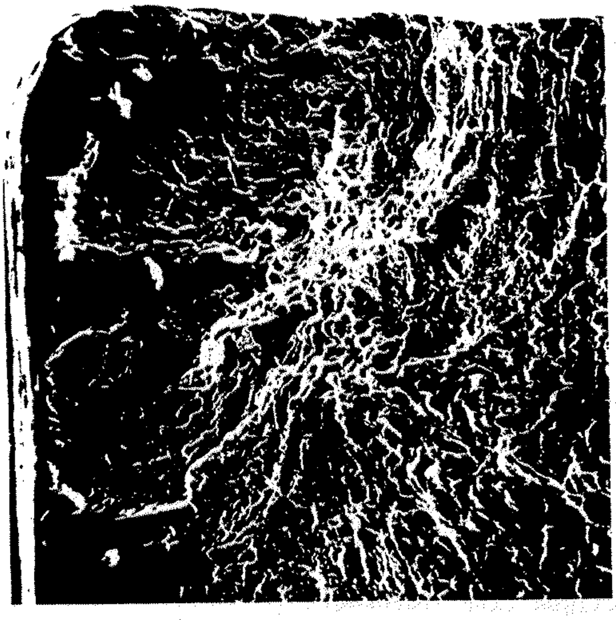
The results plotted with ' in Fig.4 indicate fish-eye fracture mode. In other specimens, fatigue cracks initiated at surfaces of the specimens (surface fracture mode). The notes A, B, C in the figure indicate features of crack initiation points in fish-eye fractured specimens. MnS inclusions were observed at the crack initiation points in specimens with A, while no inclusion was observed in specimens with B. In the case of specimens with C, fish-eye fractures occured at the corner parts of gear teeth and intergranular fracture surfaces were observed at the crack initiation points. Examples of SEM observations are shown in Photo.1 for specimens with A, B and C, respectively.



Type A 20μ



Type B 20μ



Type C 80μ

Photo.1 Examples of SEM observations of fish-eye fracture surfaces in gear fatigue specimens

In the as carburized condition and in the X shot peened condition, almost all specimens except for one showed surface fracture mode. In such fracture mode, the fatigue strength is mainly affected by surface condition of the specimen. It seems that the reduction of oxygen content in steel was not effective to improve the surface condition of specimen, therfore it could not to lead much improvement of the fatigue strength in the as carburized and the X shot peened conditions. In the Y shot peened condition, three specimens out of four showed fish-eye fracture mode in the conventional steel, while in the clean steel, two specimens out of three showed surface fracture mode in spite of compressive residual stress near surface. This defference in fracture mode under the Y shot peened condition seems to be attributable to the difference in number and size of nonmetallic inclusions. That is to say, fewer number and smaller size of inclusions in the clean steel seem to improve internal fatigue strength and restrain the fish-eye fracture. In the case of electropolished condition, even the clean steel showed fish-eye fracture mode because the compressive residual stress near surface was increased by electropolishing as shown in Fig.2. As a result, the electropolished specimens showed higher fatigue strength than specimens with Y shot peening only. In the conventional steel, however, since the specimens with Y shot peening only already showed fish-eye fracture mode, further increase of the compressive residual stress near surface by electropolishing could not lead to improve the fatigue strength.

Results of Roller Pitting Fatigue Test

The relationships between the applied contact pressure and the pitting fatigue life of roller A are shown in Fig.5. The clean steel showed higher pitting fatigue strength than the conventional steel under both of the as carburized condition and the Y shot peened condition. In the Y shot peened condition, the fatigue strength of clean steel was 3~4% higher than that of the conventional steel.

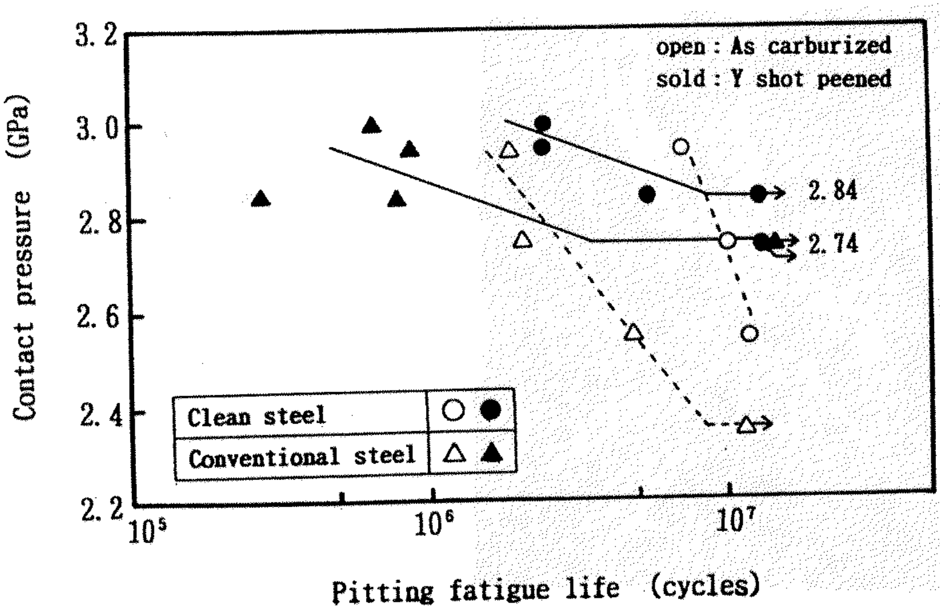


Fig.5 Pitting fatigue test result

DISCUSSION

It was clarified from the gear fatigue tests that the reduction of oxygen content in steel was effective to improve the fatigue strength in the case of fish-eye fracture mode. At the center of fish-eye fracture surface, MnS inclusion was observed in the conventional steel, while no inclusion was observed in the clean steel. In order to clarify the influence of MnS inclusion on the fatigue strength, the distributions of MnS sizes were measured in the clean steel and the conventional steel, respectively. Samples were machined from the root parts of gears and 90 photographs of MnS inclusions were taken in magnification of 400 for each steel. Then, 30 photographs out of 90 which contained larger MnS inclusions were selected for each steel. Using these photographs, the distributions of MnS sizes were measured by picture processing technique. Total area observed was 3.2mm^2 for each steel. The result is shown in Fig 6. Tendency can be seen from the figure that the number of large MnS inclusions in the clean steel is fewer than that in the conventional steel although the sulpher contents of the two steels are almost the same. One assumption which can interpret the difference in the number of large MnS inclusions between the clean steel and the conventional steel is considerd as follows: ①generally the size of oxide inclusion is smaller in the steel with lower oxygen content, ②many of MnS inclusions nucleate from oxide inclusions, ③therfore the size of MnS inclusion becomes smaller in the steel with lower oxygen content. However, in order to clarify more detailed reasons correctly, further studies are necessitated.

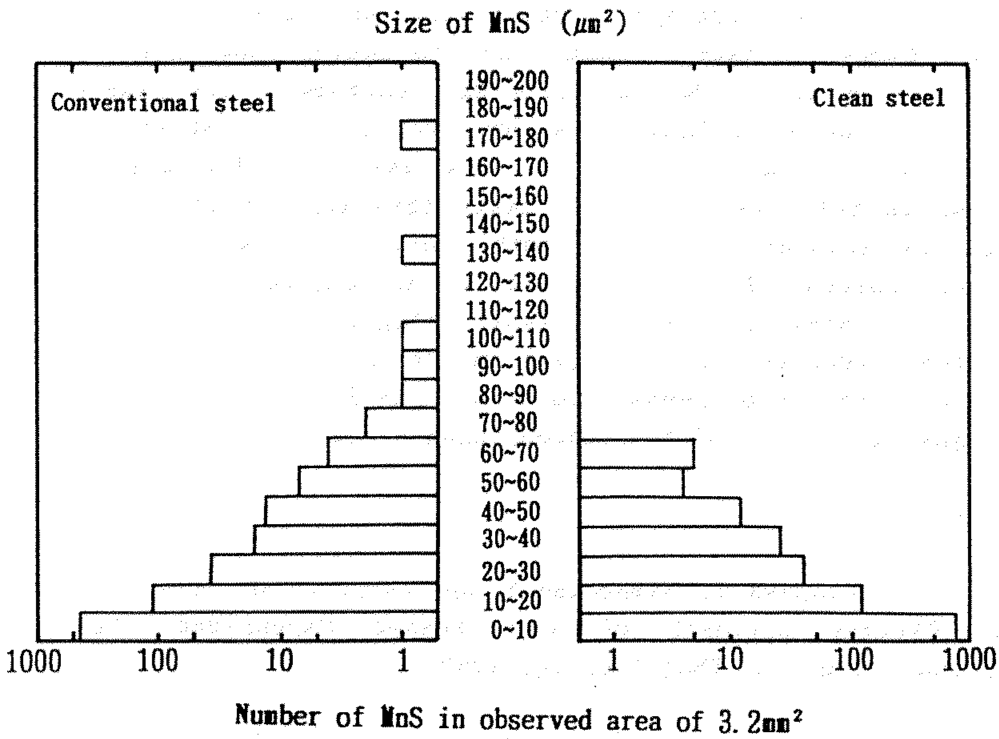


Fig.6 Distribution of MnS size

In the case of rotating bending fatigue test(1,2), it was reported that oxide inclusion was observed in the center of fish-eye fracture surface. On the other hand, in the present gear fatigue test, MnS inclusion was observed although almost the same materials were used for the test. This difference is attributable to the difference in the directions between applied tensile stress and the elongated MnS inclusion. In the case of lotating bending fatigue, MnS inclusion did not cause stress concentration because tensile stress was applied parallel to the longitudinal direction of elongated MnS inclusion. Therfore, the fish-eye fracture did not initiate from MnS but from oxide inclusion which caused certain stress concentration in any direction of applied tensile stress because of its round shape. In the case of gear fatigue, MnS inclusion caused strong stress concentration because tensile stress was applied in normal to the longitudinal direction of MnS inclusion, therefore the fish-eye fracture initiated from the MnS inclusion.

CONCLUSIONS

In order to clarify the influence of nonmetallic inclusion on the fatigue strength of gear steel under the carburized and shot peened condition, the gear fatigue test and the roller pitting fatigue test were performed on clean steel (O_2:9ppm) and conventional steel (O_2:20ppm). Obtained results are summarized as follows:

(1) In the hardly shot peened condition on gear fatigue test, the clean steel showed surface fracture mode while the conventional steel showed fish-eye fracture mode, and in this case, the fatigue strength of clean steel was 14% higher than that of conventional steel. In the electropolished condition, both of the steels showed fish-eye fracture mode, and in this case, the clean steel showed 26% higher fatigue strength than the conventional steel. At the fatigue crack initiation point, MnS inclusion was observed in the case of conventional steel, while none of inclusions was observed in the clean steel.

(2) The distributions of MnS size were measured. The number of large MnS inclusions in the clean steel was fewer than that in the conventional steel, although the sulpher content of both steels was almost the same level. The result was discussed from a view point of MnS nucleation.

(3) The clean steel also showed higher fatigue strength in the roller pitting fatigue test under the as carburized and the hardly shot peened conditions. In the case of hardly shot peened condition, the fatigue limit of clean steel was 3～4% higher than that of the conventional steel.

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