# INFLUENCE OF INCLUSIONS ON THE FATIGUE STRENGTH OF SHOT PEENED CARBURIZED STEEL

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## ABSTRACT

Shot peening method is widely applied to gas carburized gears for automobile to improve the fatigue strength. When the strength is improved by shot peening, the fracture origins tend to shift from the surface toward the inside. In the case of inside fracture, cracks often originate from non-metallic inclusions existing in the steels. The purpose here is to investigate the influence of inclusions on the fatigue strength of shot peened carburized steels. The fatigue strength values were obtained by rotating bending fatigue tests using two kinds of steels which have different oxygen contents. When high arc-height shot peening was treated, the low oxygen contents steel, which contained less inclusions, exhibited higher strength than that of conventional steel.

## KEYWORDS

Shot peening, Inclusions, Carburizing, Fatigue strength, Gear, Residual stress

## INTRODUCTION

To improve the strength of carburized gears is required because of elevating the engine power and miniaturizing the transmission. Shot peening was found out to be very effective for improvement of the fatigue strength and this method is widely applied.(1~3)
With shot peening , the origins of the fatigue fractures tend to shift from the surface toward the inside because the strength of surface is improved by shot peening. (4) In the case of inside fracture, cracks often originate from non-metallic inclusions existing in the steels.
The purpose of this paper is to investigate the influence of the non-metallic inclusions on the fatigue strength of carburized and shot peened steels. Rotating bending fatigue tests were carried out. The

specimens were made from two kinds of steels which have different oxygen contents, and treated by conventional shot peening or high arc-height shot peening. We investigated the size and the location of inclusions causing the inside fractures, and discussed the relationship between the fatigue strength and the inclusions.

## SPECIMENS AND EXPERIMENTAL PROCEDURE

Chemical composition of Cr-Mo steels (JIS SCM420H) used in this study is shown in Table 1. One had conventional oxygen content of 21ppm and the other had low oxygen contnet of 9ppm.
After normalizing, these materials were processed to the shape shown in Fig.1. Then, the specimens were gas carburized to the total case depth of 1.0mm.
After carburizing, these specimens were applied with shot peening. Shot peening conditions are shown in Table 2. The conventional centrifugal wheel type shot peening with the arc height of 0.45A and the new air nozzle type shot peening with arc height of 0.30C (e.q.1.10A) were applied.
Fig.2 shows hardness distributions in the surface layers of specimens. The hardness of surface was increased by shot peening. The strong shot peening (high arc height shot peening) had larger effect than conventional shot peening.
Residual stress distributions are shown in Fig.3. High compressive stresses were induced in near the surface by shot peening.

Table 1 Chemical composition (ladle analysis, %)

| Steel | C | Si | Mn | P | S | Cr | Mo | t.O |
|---|---|---|---|---|---|---|---|---|
| Conventional | 0.22 | 0.27 | 0.79 | 0.018 | 0.007 | 1.11 | 0.18 | 0.0021 |
| Low oxygen | 0.19 | 0.28 | 0.79 | 0.007 | 0.018 | 1.12 | 0.17 | 0.0009 |

Table 2 Shot peening Treatment

| Type | Size | Hardness | Coverage | Arc height |
|---|---|---|---|---|
| Centrifugal wheel | $\phi$0.8mm | HRC 53 | 300% | 0.45A |
| Air nozzle | | | | 0.30C (e.q. 1.1A) |

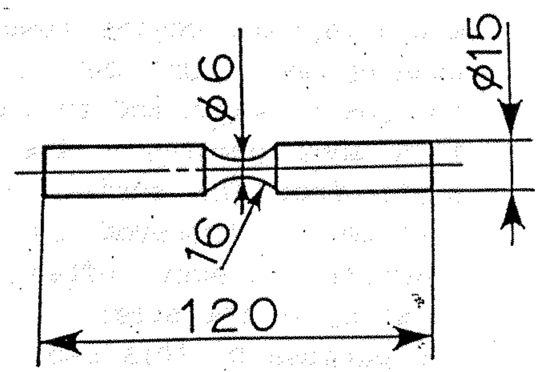


Fig.1 Shape of specimen

## RESULTS AND DISCUSSION

### Results of the rotating bending fatigue tests

The results of the fatigue tests are shown in Fig.4 and Fig.5. The fatigue strength of 0.45A shot peened specimen was 58% higher than that of as carburized specimen. With 0.45A shot peening, there was not much difference in the fatigue strength between conventional steel and low oxygen steel.

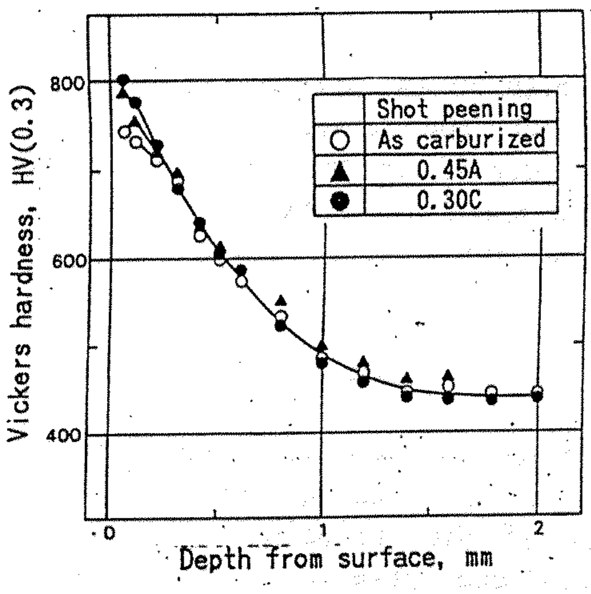


Fig.2 Influence of shot peening on microhardness distribution

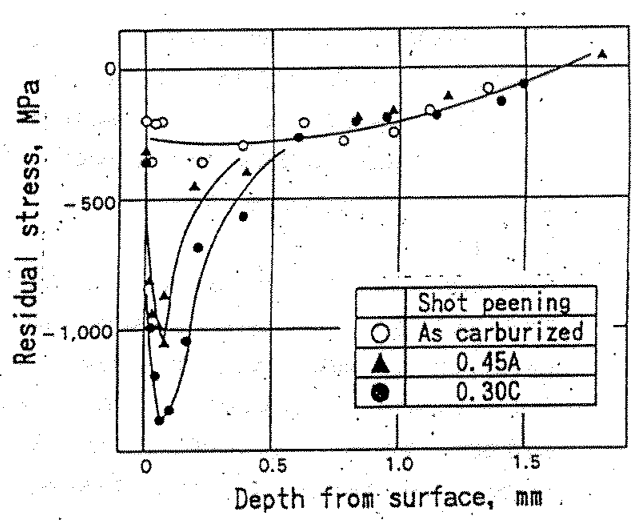


Fig.3 Influence of shot peening on residual stress distribution

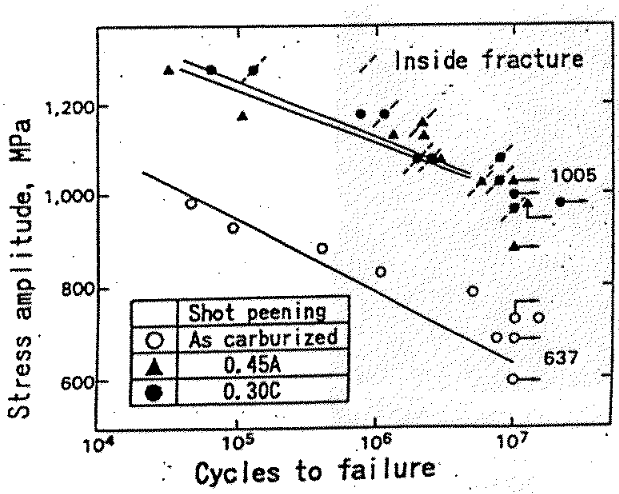


Fig.4 S-N curves of conventional steel

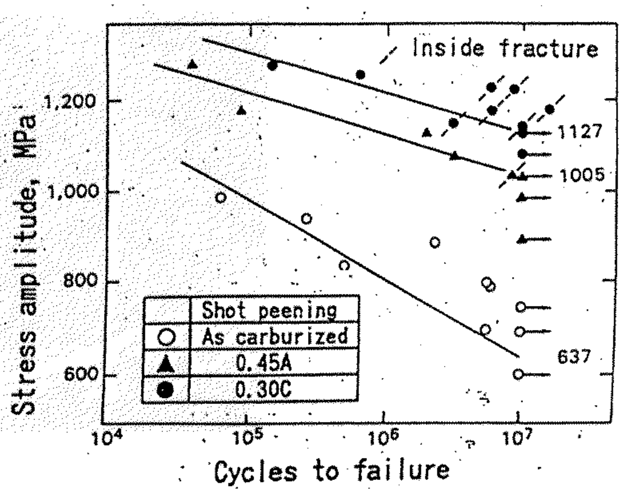


Fig.5 S-N curves of low oxygen steel

When 0.30C shot peening was applied, however, the fatigue strength of low oxygen steel was not equal to that of conventional steel. In the case of low oxygen steel, the strength of strong shot peened specimen was more increased than that of 0.45A shot peened specimen. On the other hand, in the case of conventional steel, strong shot peening could not increase the fatigue strength more than 0.45A shot peening.
The slash marks(/) in these figures show the inside fractures. When 0.30C shot peening was applied, the inside fractures occured both conventionalsteel and low oxygen steel. The difference of the fatigue strength, therefore, was due to the inside strength.

Results of fractgraphy

An example of an SEM fractgraph with crack origins at inside non-metallic inclusion is shown in Fig.6. The fatigue crack originated at the center of the smooth, flat circle in the fracture surface. The fatigue crack proceeded at slow speed from the initiation site, and the fracture grew rapidly after the fatigue crack reached the surface.
Non-metallic inclusions induced fractures in most case of inside fractures. The inclusions were Al-Ca-O-S complex according to the results of analysis by EPMA.
The size (diameter), the depth from the surface, and the axial offset from the center of the inclusions causing the fracture are shown in Table 3. The average size of the inclusions of low oxygen steel was smaller than that of conventional steel.
The location of the inclusions of conventional steel was similar to that of low oxygen steel. Inclusion-originated fatigue cracks were observed in the carburized case (0.2~0.8mm depth from the surface).

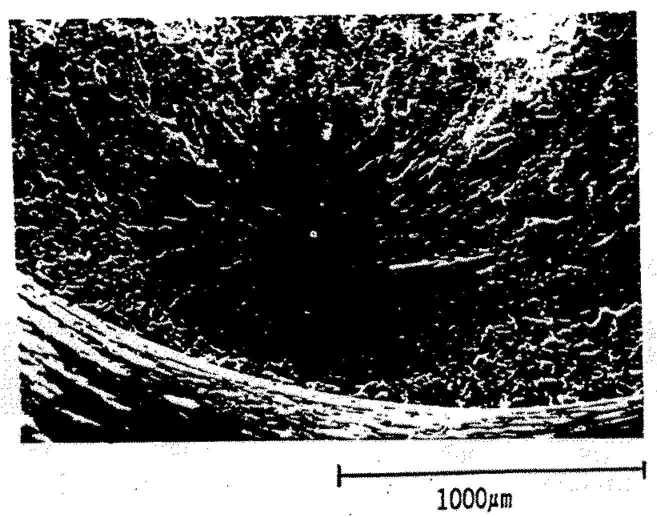


Fig.6 SEM fractograph
with inside crack origins

## Relationship between the inclusions and the fatigue strength

Murakami et al. (5) studied the influence of small defects on the fatigue strength of high hardness steels. In the research, they estimated the results of fatigue tests using the parameter of hardness and projected area of the principal stress direction of the defect.
We tried to estimate the influence of inclusions on the fatigue strength by the following experimental equation based on Murakami's equation with due regard for the residual stress induced by carburizing and shot peening.

$$\sigma w = 1.56(HV+120)/(\sqrt{area})^{1/6} - \sigma r/2 \qquad (1)$$

$\sigma w$ : fatigue strength (MPa)
HV : Vickers hardness at crack origins
area : projected area of the principal stress direction of the inclusions ($\mu m^2$)
$\sigma r$ : residual stress (MPa)

Fig.7 shows the relation between the ratio of $\sigma'$ (the nominal applied stress at the crack origins) to $\sigma w$ (estimated fatigue strength) and the number of cycles to failure Nf.
The linear relationship between $\sigma'/\sigma w$ and Nf is expressed and is similar to S-N curves. As the $\sigma'/\sigma w$ value is 1.0 at $10^7$ cycle, it is found that the fatigue strength can be estimated from the size of the inclusions, the hardness and the residual stress at the crack origins.

Table 3 Size and location of the inclusions causing fatigue cracks

| Steel | | Conventional | Low oxygen |
|---|---|---|---|
| location | Depth from surface (mm) | 0.25~0.76<br>X=0.40 | 0.24~0.76<br>X=0.45 |
| | Axial offset from center (mm) | 0.1~ 1.5<br>X=0.50 | 0.2~ 2.0<br>X=1.09 |
| Diameter of inclusions (μm) | | 10.0~48.2<br>X=26.9 | 9.6~27.0<br>X=16.7 |

Fig.8 shows the estimated critical size of inclusions according to equation (1), by measuring HV and $\sigma r$. The critical size of the inclusions is large in the surface and drops remarkably at 0.2mm depth from the surface, and then increases gradually. The size of inclusions causing fatigue fracture exceeds the critical size, and the location of crack origins nearly conforms to the calculation results.

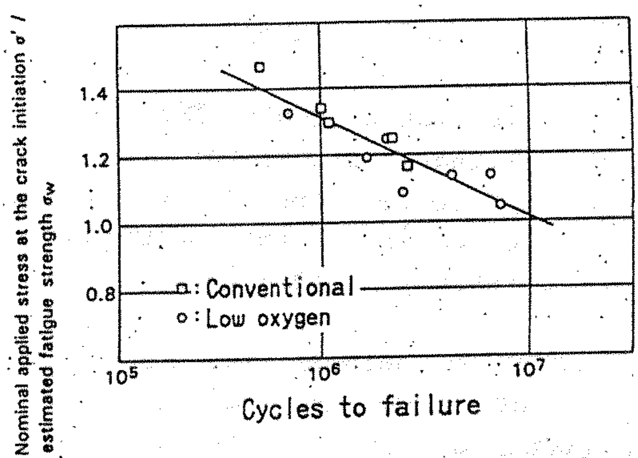


Fig.7 Relationship between the ratio of the nominal applied stress $\sigma'$ at the crack origins to estimated fatigue strength $\sigma w$ and number of cycles to failure

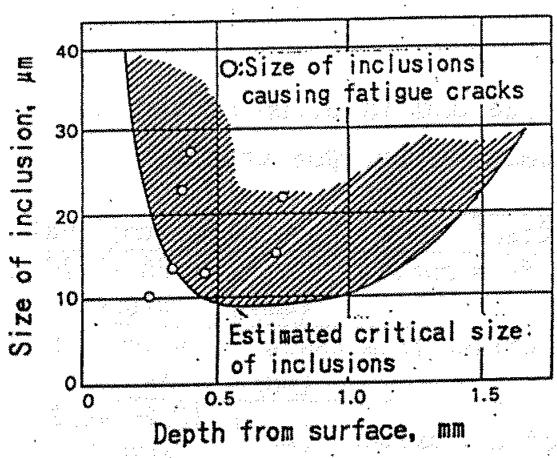


Fig.8 Relationship between estimated critical size of inclusion and size of inclusions causing fatigue cracks (fatigue strength: 1127MPa)

## Relationship between the number of inclusions in steel and the fatigue strength

A number of large inclusions over 20 $\mu$m in diameter in steel are shown in Fig.9. In the mesurement process, 5 g of steel were dissolved in 500m$\ell$ of (1+3) $HNO_3$, and then the residue was extracted by a fine-mesh metal filter of 20 $\mu$m mesh size for the purpose of counting the number of inclusions under a microscope.

The number of inclusions over 20 $\mu$m decreased remarkably by the reduction of oxygen content in steel. It is found that the decrease of the number of large inclusions strengthens the low oxygen steel, as the mean size of the inclusions observed on the inside fractures for low oxygen steel is smaller than for conventional steel.

The number of inclusions over 20 $\mu$m existing in the domain is shown in Table 4. It is found that about 2~4 pieces of inclusions of size equivalent to that of inclusions causing inside fractures exist in the dangerous zone.

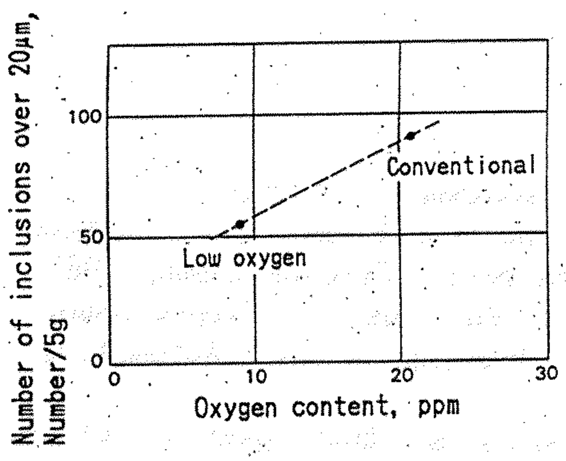


Fig.9 Relationship between oxygen content and number of inclusions

Table 4 Number of inclusions over 20μm existing in dangerous zone

| Steel | Fatigue strength (MPa) | Average size of inclusions causing fatigue cracks | Volume of dangerous zone (V) | Number of Inclusions over 20μm existing in (V) of steel |
|---|---|---|---|---|
| Conventional | 1005 | 27 μm | 0.23 g | 4.1 |
| Low oxygen | 1127 | 17 μm | | 2.5 |

## SUMMARY


(1) The low oxygen steel, which contains less non-metallic inclusions, exhibits 12% higher fatigue strength than that of conventional steel in the case where the crack starts under the surface.

(2) The influence of the inclusions on the fatigue strength is estimated by the following equation, which adds the residual stress to Murakami's equation.

$$\sigma w = 1.56(HV+120)/(\sqrt{area})^{1/6} - \sigma r/2 \qquad (1)$$

$\sigma w$ : fatigue strength (MPa)
HV : Vickers hardness at crack origins
area : projected area of the principal stress direction of the inclusions ($\mu m^2$)
$\sigma r$ : residual stress (MPa)

(3) As the above results show, it is found that not only inducement of high compressive residual stress by shot peening but also decreasing the inclusions by reducing the oxygen content are necessary in order to strengthen carburized steel.


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