EFFECT OF SHOT PEENING ON THE FATIGUE STRENGTH OF CARBURIZED STEELS

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ABSTRACT

To better understand the mechanism by which compressive residual stress improves the fatigue strength of carburized gears, a crack in a rotating bending fatigue test specimen was closely examined by scanning electron microscope. Low-carbon carburizing steels were used for fatigue test specimens, which were carburized and shot peened. Based on the findings, the effect of shot peening on the improvement of the fatigue strength was analyzed, and methods of increasing fatigue strength by shot peening are discussed. A fatigue crack initiates at an early stage even if the applied stress range is lower than the fatigue limit. To increase the fatigue limit, it is important to arrest the fatigue crack at the beginning of its propagation. The improvement of fatigue properties by increasing the compressive residual stress is due to decreasing the effective tensile stress at the crack tip. The compressive residual stress of gear surface is effectively increased by increasing the peening intensity.

KEYWORDS

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

INTRODUCTION

As the output power of automobile engines increases with improved engines, the power train components have to withstand higher loads. In particular, carburized gears have to meet the demand for high fatigue strength. It is widely known that the fatigue strength of a gear tooth root can be greatly improved by shot peening. It is thought that the improvement is caused by the increase of compressive residual stresses in the surface layer [1, 2]. However, there are no previous reports in which the effect of shot peening on fatigue strength was analyzed on the basis of the close observation of fatigue fracture process. Furthermore, the relation among the increase of compressive residual stress, the peening intensity and the amount of retained austenite in the carburized case is not clearly understood.

In the present study the initiation and propagation of fatigue cracks were observed by scanning electron microscope (SEM). Based on the findings, the effect of shot peening on the improvement of the fatigue strength of gear was analyzed, and methods of increasing fatigue strength by shot peening were presented.

EXPERIMENTAL PROCEDURE

Specimen

The chemical compositions of steels used in this study are given in Table 1. The chemical compositions were varied in order to change the amount of retained austenite. Figure 1 illustrates the process of preparing the fatigue test specimens. These steels were made by vacuum-melting. The ingots were hot-forged to 20 mm diameter bars and the bars machined into specimens. The specimens were carburized (930°C×3h, C.P.=0.8) and tempered (170°C×1h), then shot peened. The shot peening machine used is of rotating blowing type.

Table 1. Chemical compositions of specimens (wt.%)

	C	Si	Mn	P	S	Cr	Mo	Ni
A	0.21	0.23	0.75	0.002	0.020	0.95	0.18	----
B	0.20	0.26	0.73	0.002	0.020	0.61	----	----
C	0.20	0.26	0.72	0.002	0.020	0.98	----	----
D	0.22	0.21	0.80	0.003	0.020	1.04	0.23	3.16

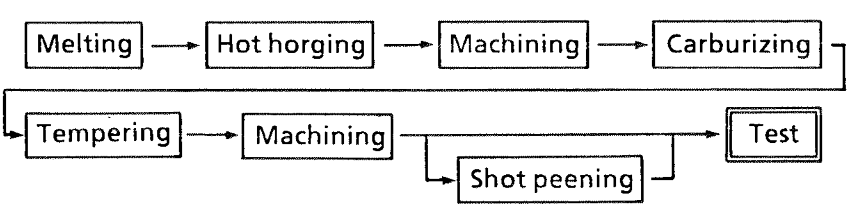

Fig. 1 Process of preparing the test specimens

Fatigue Testing Method

The fatigue testing machine employed was a rotating bending machine. The propagation of fatigue cracks was investigated by the following method. After the test with an applied stress amplitude was once stopped prior to final fracture, the test was started again with an increased applied stress amplitude of 1.37 GPa and continued until fracture. The crack length generated with the initial stress amplitude was measured using SEM photographs.

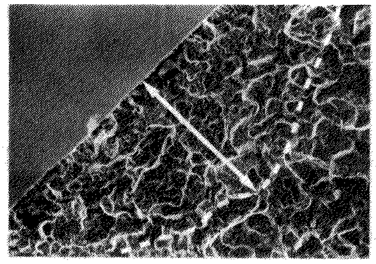

Fig. 2 Example of the fractured surface after rotating bending fatigue test

Figure 2 shows an example of the fractured surface obtained by this method. The fatigue crack generated with the initial stress amplitude is distinguished from that with a stress amplitude of 1.37 GPa by the difference in their appearance.

Measurement of Residual Stress and Retained Austenite

The amounts of residual stress and retained austenite were measured by X-ray diffraction. The conditions of measurement are shown in Table 2.

Table 2. Conditions of X-ray measurements

Characteristic X-ray	Cr-Kα
Tube voltage, kV	30
Tube current, mA	10
Counter	Position Sensitive Proportional Counter
Measuring time, sec	30
Irradiated area, mm^2	2 × 3

RESULTS

Fatigue Crack Propagation Behavior

The S-N curve in Figure 3 shows the results of rotating bending fatigue test on the non-peened carburized specimens of steel A. The cracks in the specimens of 0.69, 0.74 and 0.98 GPa stress amplitudes were examined using SEM photographs. The relation between crack length and cycles at each applied stress amplitude is shown in Figure 4. The fatigue life is over 10^7 cycles for 0.69 GPa, 1.5×10^6 cycles for 0.74 GPa and 6×10^4 cycles for 0.98 GPa. Even at a low applied stress amplitude of 0.69 GPa, a fatigue crack initiated at the early stage of loading, probably not more than 10^4 cycles. Although this crack propagated to a length of about 150 μm by 10^6 cycles, it did not grow further. On the other hand, the crack generated with an applied stress amplitude of 0.74 GPa had the similar initiation cycle number and the similar propagation behavior to those of 0.69 GPa until an about 100 μm depth, the crack continued to propagate until fracture.

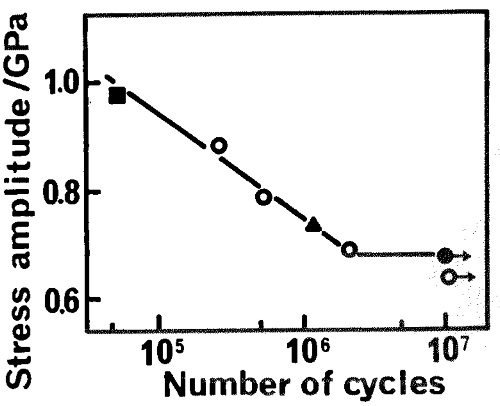

Fig. 3 S-N curve of rotating bending fatigue test on the non-peened carburized specimens of steel A

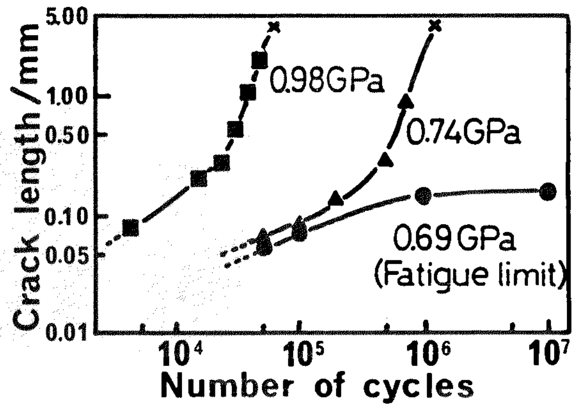

Fig. 4 Relation between crack length and cycles

Effect of Shot Peening on Fatigue Strength

Figure 5 shows the relation between the fatigue limit and the residual stress at a distance of 80 μm from the surface. The closed marks in this figure indicate the results for the shot peened specimens. As the figure clearly shows, the fatigue limit increases with compressive residual stress. Even in the peened specimens, cracks not leading to final fracture were found.

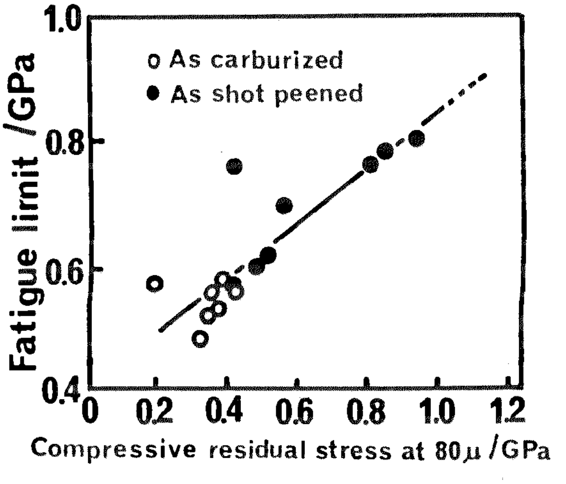

Fig. 5 Relation between fatigue limit and compressive residual stress at 80μ from the surface

Change of Physical Properties in Carburized Case by Shot Peening

Figure 6 shows examples of the change of residual stress, retained austenite and hardness distribution in the carburized case by shot peening. Residual stress changed most definitely among the properties.

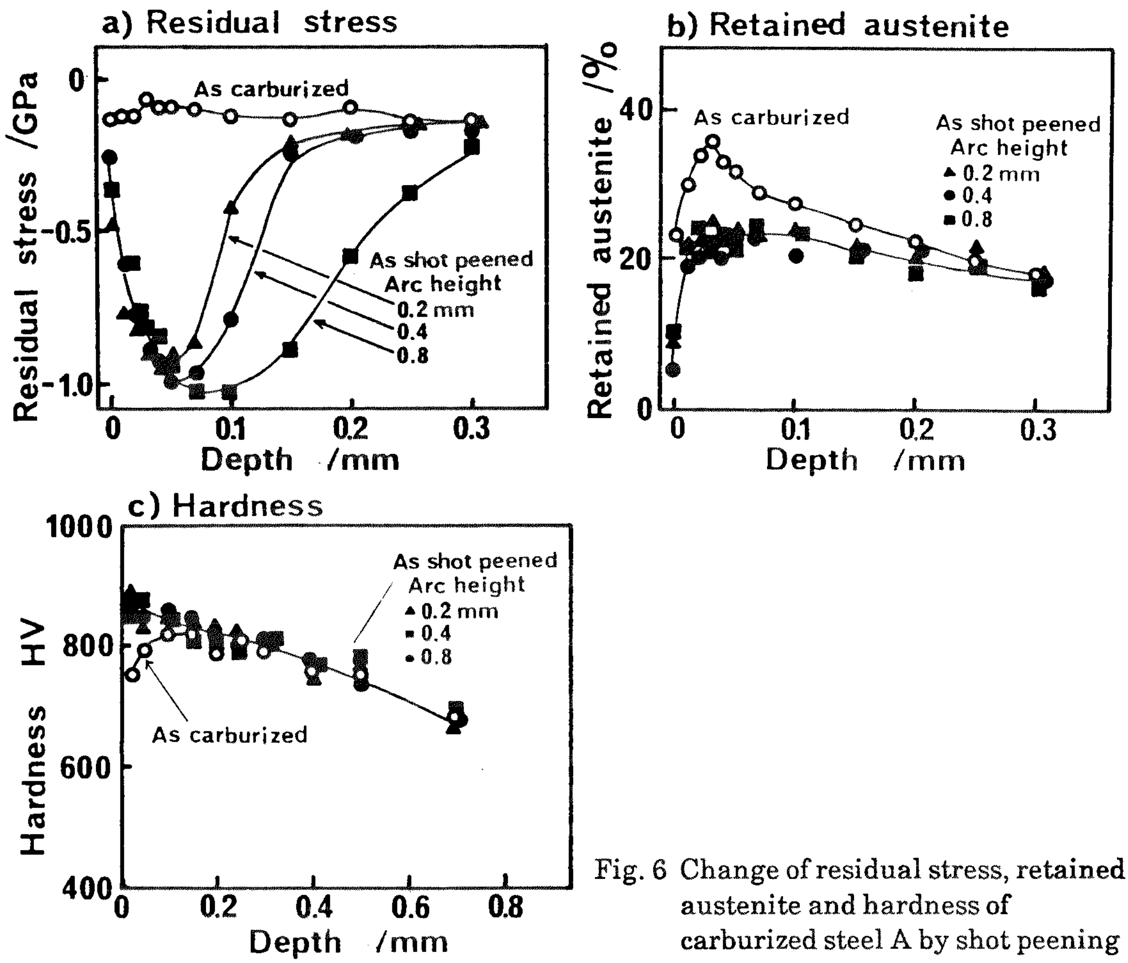

Fig. 6 Change of residual stress, retained austenite and hardness of carburized steel A by shot peening

Figure 7 shows the relation among the maximum value, σ_{peak} and the integral average value, $\Sigma\sigma_r$ of the compressive residual stress from the peened surface to a depth of 200 μm, and the arc height of Almen strip A after shot peening. In the range of the arc height from zero to 0.2 mm, the peak value sharply increased by shot peening, but the increase of the arc height over 0.2 mm resulted in the slight increase of the peak value. Conversely the integral average value linearly increased with arc height. The chemical composition exerted only weak influence on these values.

DISCUSSION

Factors Controlling Fatigue Strength

As can be seen in Figure 4, a fatigue crack initiates at an early stage of loading, probably at a cycle of about 0.1% of 10^7, even if the applied stress is lower than the fatigue limit stress. This means that the fatigue strength of carburized gears is controlled by the crack propagation rather than the crack nucleation and initiation. Thus it is important to arrest the fatigue crack at its beginning stage in order to increase the fatigue limit. From this standpoint, improvement of crack-arrestability is effective in enhancing the bending fatigue characteristics of a gear.

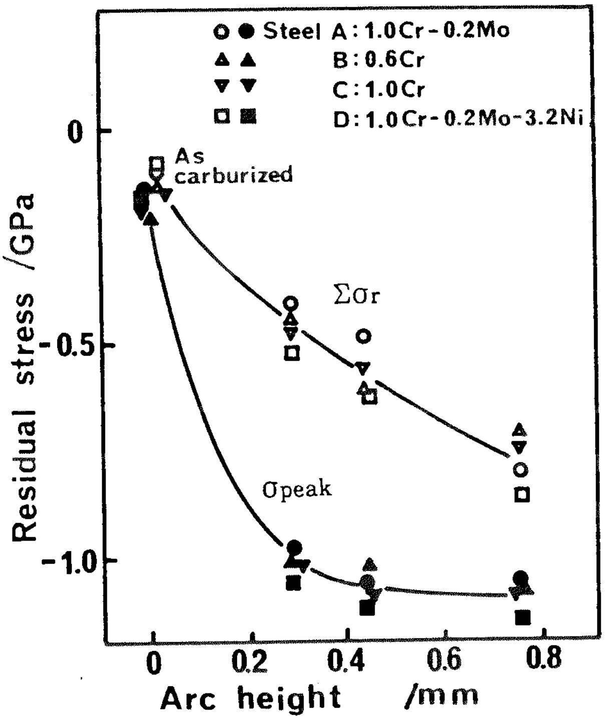

Fig. 7 Relation between the maximum value and the integral average value of compressive residual stress and arc height of Almen strip A after shot peening

The conditions for preventing propagation of a crack are given by the following expressions using stress-intensity factor [3]:

$$\Delta K_{eff} \leq \Delta K_{eff,th}$$

$$\Delta K_{eff} = \sigma_{max}\sqrt{\pi a} - K_{op}$$

As shown in Figure 8, ΔK_{eff} is effective stress-intensity factor range at the crack tip, $\Delta K_{eff,th}$ is the threshold range of ΔK_{eff} for preventing propagation of a crack, σ_{max} is the maximum stress(applied stress amplitude), "a" is the crack length, K_{op} is the crack opening stress-intensity factor.

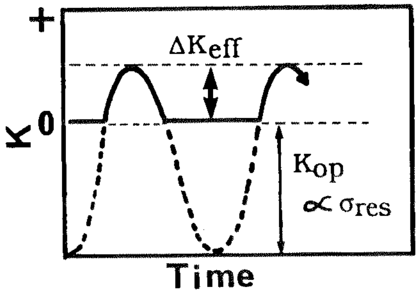

Fig. 8 Schematic illustration of effective stress intensity factor ; ΔK_{eff} at the crack tip

$\Delta K_{eff.th}$ for steels does not depend on the hardness of the steels and is almost constant for steels [4]. Usually, K_{op} increases according to compressive residual stress, σ_{res}. Therefore, the propagation characteristics of a crack can be controlled by residual stress through crack closure. To enhance the fatigue properties, it is effective to increase compressive residual stress and intensify the steel properties for the crack-closure. When these measures are taken, the effective tensile stress at the crack tip decreases, thus improving the fatigue properties. The reason why the fatigue strength is improved by shot peening is that the increased compressive residual stress causes the initiated crack to assume a non-propagating nature.

Mechanism of the Increase of Compressive Residual Stress by Shot Peening

The major causes giving rise to compressive residual stress in steels are the local plastic deformation at the surface and the transformation of retained austenite to martensite [5]. As Figure 6-b shows, reduction of the amount of retained austenite is so slight that retained austenite does not affect the residual stress. The relation between the maximum value and the integral average value of residual stress and the arc height can be explained as follows. The residual compressive stress below the surface depends upon the elastic strain induced there. Because the strain hardening of tempered martensite is slight as shown in Figure 9-a, the increment of elastic strain is small when the steel is plastically deformed from A to B. Therefore, the maximum value of residual stress does not become higher with arc height. On the other hand, the integral value of compressive stress depends on the plastic deformation zone depth, as illustrated in Figure 9-b. Since the plastic deformation zone depth increases with arc height, the integral value increases with arc height.

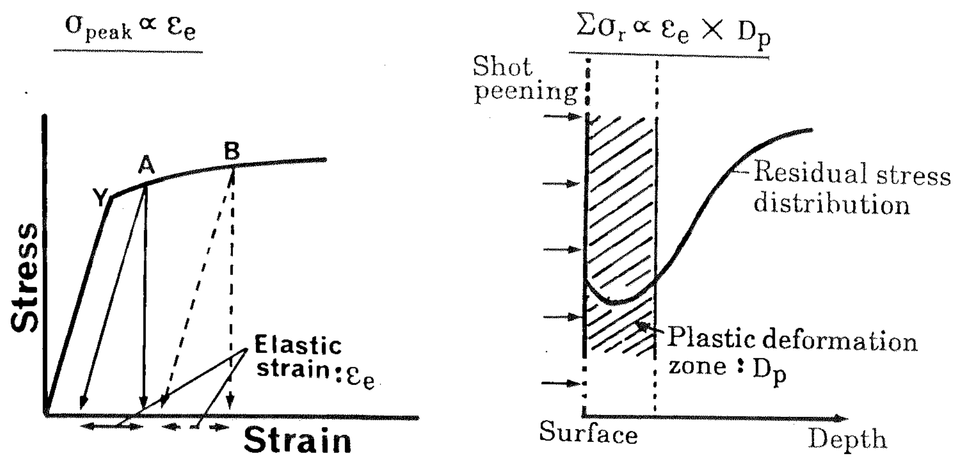

Fig. 9 Schematic illustrations of the effect of shot peening on residual stress distribution

Method of Intensifying the Effect of Shot Peening on Fatigue Strength.

The effect of arc height and the material strength on the maximum value and the integral average value of residual stress was analyzed by the finite-element-method (FEM). The results are shown in Figure 10, and it is confirmed that the above-mentionedmechanism is valid. As Figure 4 indicates, it is important for improving fatigue properties to avoid the propagation of initiated cracks. In order to close the initiated cracks, the maximum and the integral value of residual stress should be as great as possible. The results of FEM analysis indicate that the increase of the peening intensity is effective for increasing residual stress and the greater peening intensity is needed for enhanced gear case hardness.

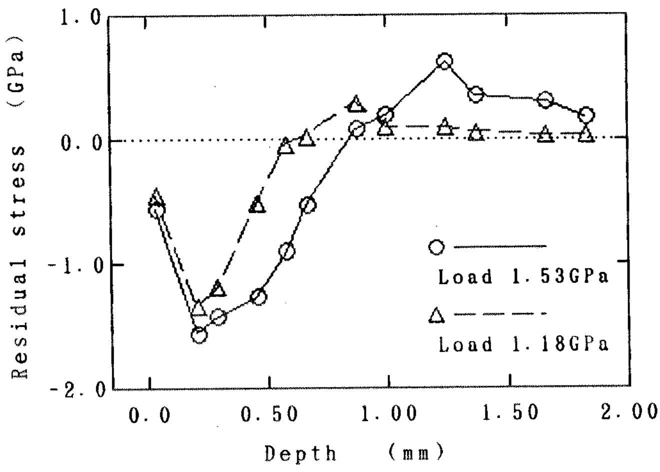

Fig. 10 Residual stress distributions obtained by the finite-element-method analysis

CONCLUSIONS

The mechanism by which compressive residual stress improves the fatigue strength was studied by analyzing the process of fatigue fracture and the way for increasing the compressive residual stress in carburized steels by shot peening was studied. The results obtained are as follows:
(a) A fatigue crack initiates at an early stage even if the applied stress range in rotating bending fatigue test is lower than the fatigue limit stress. Therefore, it is important for increasing fatigue limit to arrest the fatigue crack at the beginning of its propagation.
(b) The improvement of fatigue properties by increasing the compressive residual stress is due to decreasing effective tensile stress at the crack tip.
(c) The compressive residual stress of gear surface is effectively increased by increasing the peening intensity. This is because the compressive residual stress is controlled by the depth of plastic deformation zone and the amount of elastic strain.

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