Effect of Residual Stress on Fatigue Strength of Steel Modified by WPC Process

D. YONEKURA[1], H. AKEBONO[2], J. KOMOTORI[2],M SHIMIZU[2] and H. SHIMIZU[3]

[1]Dept. of Mech. Eng., The University of Tokushima,2-1 Minami-josanjima-cho, Tokushima, Japan
[2]Faculty of Science and Technology, Keio University, 3-14-1,Hiyoshi, Kouhoku-ku, Yokohama, Japan
[3]N.E. LTD., 4-5-12, Sagamidai, Kanagawa, Japan

Abstract
Rotational bending fatigue tests were carried out on low carbon Cr-Mo steel modified by a combination of Wide Peening Cleaning (WPC) and carburizing, with special attention focused on the effect of surface residual stress on fatigue properties. By combining the carburizing and the WPC process, it is possible to generate a high compressive residual stress near the surface, maintaining a deep layer of compressive residual stress associated with the carburizing. The notched specimens modified by the combined process show significantly higher fatigue strength compared to those modified by single process of carburizing. This is because the extremely high compressive residual stress remained after stress cycling at the surface of the specimens modified by the combined process.

Key Words: WPC process, shot peening, fatigue, residual stress, surface modification

1. INTRODUCTION

The Wide Peening Cleaning (WPC) process is one of the new surface modifying techniques. The features of the WPC process are as follows: (1) extremely fine and hard particles are used as shot particles and (2) the velocity of shot particles is much higher than that of conventional shot peening methods. The resulting product offers remarkable fatigue resistance relative to that modified by conventional technique. As a consequence, the application of the WPC process to machine parts such as gears and car shafts, has been intensively attempted. However, the reasons for the improvement of fatigue strength have not been well understood.

In our previous work [1], it was clarified that the residual stress formed by the WPC process alone has a maximum value close to the surface and is stable under cyclic loading. Such residual stress effectively prevents propagation of small fatigue cracks. However, the ability to suppress crack propagation is limited in a very shallow depth beneath the surface, since the compressive residual stress layer formed by the WPC is very shallow. Thus, the WPC process has a problem in that the fatigue strength is not improved as much as it is expected from the effect of work hardening and of high compressive residual stress at the surface.

To make the effect of WPC on fatigue strength of the steel more effectively, it is necessary to develop a new surface treatment technique in which compressive residual stress is distributed over a deeper layer, while keeping the features of the residual stress produced by WPC. In order to produce such residual stress distribution, it seems to be useful to combine WPC with other surface treatment method which can give a deeper compressive residual stress layer.

In this study, we selected the carburizing process in combination with WPC. Attention was focussed on the distribution of residual stress and the effect of residual stress generated by the combined process on fatigue properties.

2. EXPERIMENTAL

A low carbon Cr-Mo steel (JIS SCM420H) with a chemical composition as listed in Table 1 was used. A 20mm diameter steel bar was machined into shape, which is described in Figure 1, and then finished by electrochemical polishing. After the carburizing process, the WPC process was applied. Table 2 shows the process parameters used in this study.

A Vickers microhardness tester was used to measure the microhardness of samples. X-ray diffraction equipment was used to examine the residual stress distribution in hardened layers.

The fatigue tests were performed using a rotational bending fatigue testing machine (3000rpm) at room temperature in a laboratory environment. After the fatigue test, crack initiation sites were examined by using an optical microscope and a scanning electron microscope (SEM).

Table.1 Chemical Composition

C	Si	Mn	P	S	Cr	Mo	Cu	Ni
0.21	0.30	0.74	0.017	0.015	1.04	0.15	0.14	0.09

Table.2 Condition of WPC and Shot Peening

	Particle diameter (μm)	Air pressure (MPa)	Shooting time (sec)	Particle material
WPC	120-170	0.4	60	FHS

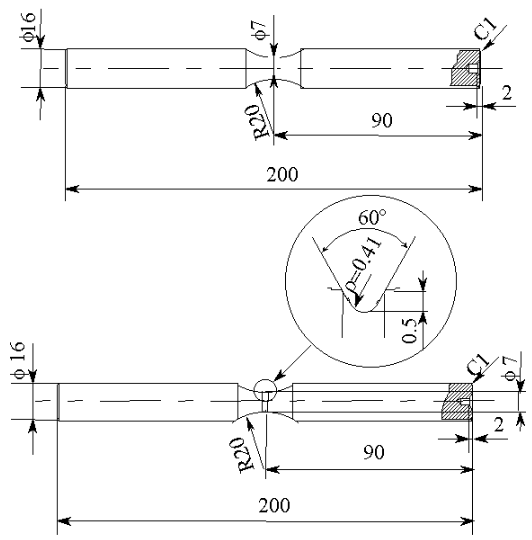


Fig. 1 Specimen configuration

3.RESULTS AND DISCUSSION

3.1 Characterization of hardened layer

Figure 2 shows Vickers microhardness distributions on the cross section of the carburized specimen and the specimen modified by the combined process. By carburizing, a hardened layer has been formed in a wide region over 1000μm depth. With additional WPC process, remarkable increase in hardness can be observed in the shallow region at subsurface.

Figures 3 shows the distribution of residual stress near the surface. The carburized specimen shows a residual stress of -250MPa at the surface, and the depth of the compressive residual stress layer is over 200μm. In the specimen modified with the combined process, the existence of a large compressive residual stress over -1200MPa can be observed near the surface. It should be noted that such a region with the large compressive residual stress correspond to the region in which a remarkable increase in hardness has appeared in Fig.2.

From the results mentioned above, it is obvious that due to the combined process a high compressive residual stress can be generated near the surface while keeping a deeper compressive residual stress layer associated with the carburizing.

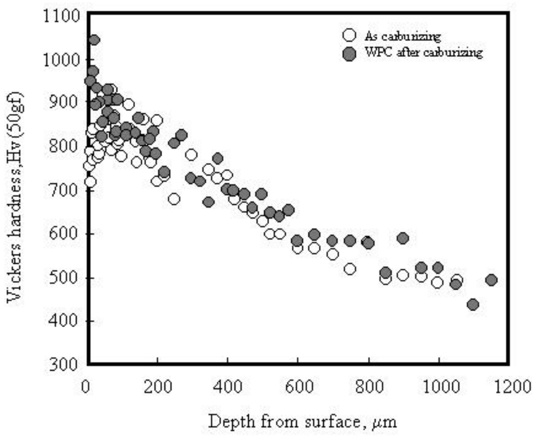


Fig. 2 Vickers hardness distribution

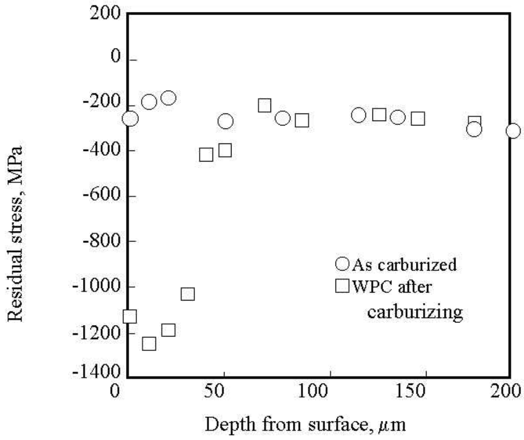


Fig.3 Residual stress distribution

3.2 Fatigue test of unnotched specimen

Figure 4 shows the results of fatigue tests of un-notched specimens. In this figure, the symbol "○" represents the results for the carburized specimen; the symbol "□" represents the combined processed specimen. If the effect of the residual stress on fatigue strength can be considered to be equivalent to that

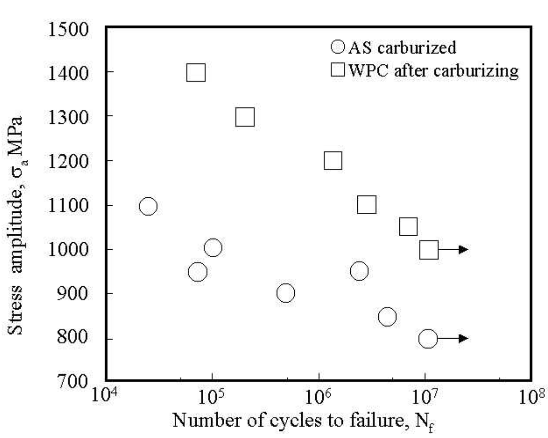


Fig.4 Results of fatigue tests

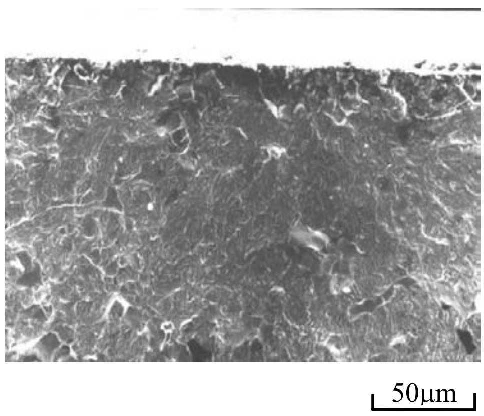
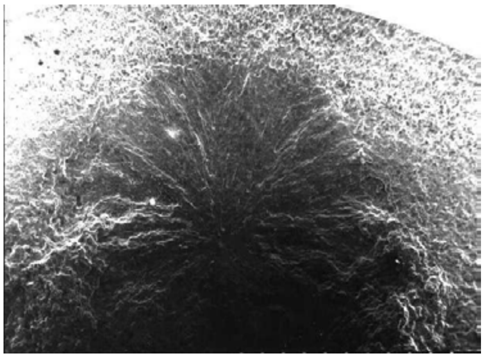


Fig.5 Typical feature of fracture surface
(as carburized σ_a=849MPa, N_f=4.24×10^6 cycles)

of the mean stress as proposed by Matsumoto[2], an increase in fatigue strength of about as much as 500MPa could be expected due to the combined process. However, the result is not true for the present case, where the increase of fatigue strength is about 200MPa. In order to examine the cause, SEM observation of the fracture surface was performed with special attention to the fracture origin in both types of specimens.



500μm

Fig.6 Typical feature of fracture surface
(WPC after carburizing,
σ_a=1050MPa, N_f=6.56×10^5 cycles)

Figure 5 and 6 show the fracture surfaces of the specimen treated by the carburizing and the combined process, respectively. In the carburized specimens, a fatigue crack initiated at the surface of specimen leads to the final fracture. In the combined processed specimen, however, the final fracture was resulted from the fatigue crack initiated from the inside of the specimen.

From the results mentioned above, it is clear that the surface modification due to the combined process is not effective for the improvement of the fatigue strength, because the fracture occurs inside the specimen without occurring in the surface modified layer as shown in Figure 6. Consequently, the small increase in fatigue strength due to the combined process can be attributed to the transition of the fracture mode from surface to internal one.

3.3 Fatigue tests of notched specimen

In order to examine the effect of the surface modified layer generated by the combined process on fatigue properties, it is necessary to study the fatigue properties of the notched specimen in which the fatigue crack starts at the specimen surface. Additional fatigue tests were carried out using notched specimen with a stress concentration factor of α=2.3.

The results are shown in Figure 7. In the case of notched specimens, the fatigue strength is remarkably improved by the combined process; the extent of improvement of fatigue strength for the notched specimen is much higher than that of the un-notched specimen. In this case, the fatigue crack started at

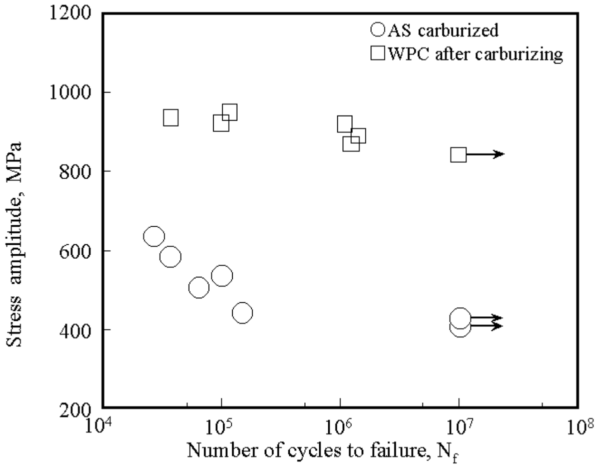
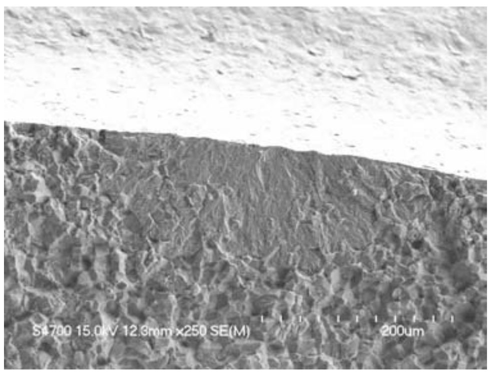


Fig.7 Results of fatigue tests for notched specimen



100μm

Fig.8 crack initiation site of notched specimen
(WPC after carburizing, σ_a= 950MPa, N_f=3.6×10^4)

the surface (notch root, Figure 8). This implies that the high compressive residual stress generated by the combined process results in an improvement of fatigue strength.

3.4. Residual stress under cyclic loading

In order to explain why the combined process is effective for the improvement of the fatigue strength of the notched specimen, the stability of residual stress within the surface modified layer was investigated. We measured the change in residual stress under cyclic loading. The results are shown in Figure 9, where the residual compressive residual stress remains unchanged after stress cycles $n=10^5$ in the specimen modified by the combined process.

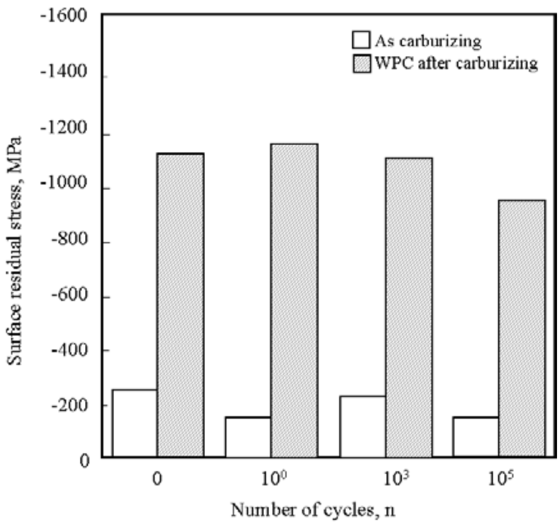


Fig.9 Release behavior of residual stress (σ_a=950MPa)

From the results, it could be concluded that the initiation and propagation of small surface crack can be suppressed by the compressive residual stress in the surface layer with a high hardness, resulting in a remarkable improvement of fatigue strength.

4. CONCLUSION

(1) By combining carburizing and the WPC process, it is possible to generate a high compressive residual stress near the surface, while keeping a deep compressive residual stress layer associated with the carburizing.

(2) In the specimens modified by the combined process, compressive residual stress maintains a high-level at the surface after stress cycling. The compressive residual stress in the surface layer with a high hardness effectively suppresses initiation and propagation of small surface cracks, and remarkably improves the fatigue strength.

(3) In the un-notched specimen where the stress gradient is gentle, the surface modified layer is not effective for the improvement of fatigue strength, because the fracture occurs from the inside of the specimen. In the notched specimens, however, the surface modifying effect for the improvement of the fatigue strength can act more effectively than in plain specimen, because the fatigue crack initiates at the specimen surface in notched specimen.

References

1. D. Yonekura, J. Noda, J. Komotori, M. Shimizu, Y. Miyasaka, Advanced Materials Development & Performance, Procs. of 2nd Inter. Conf. on Advanced Materials Development, Performance Evaluation and Application, Tokushima, Japan, Vol.1,Tokushima, Japan, Nov.23-26, 1999, pp.64-67
2. .K. Matsumoto, T. Sanpei, T. Toyota, T. Kanazawa, Proc. '90 M&M Conf. JSME, No. 900-86,1990, pp.275-277