EFFECT OF SHOT PEENING AFTER CARBONITRIDING ON THE CONTACT FATIGUE STRENGTH OF CHROMIUM-CONTAINING STEEL

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ABSTRACT

The effect of shot peening on the contact fatigue strength of carbonitrided steel has been investigated by roller-pitting testing under conditions similar to those experienced by automatic transmission gears. Results show that the shot peening process improves the resistance to softening and has a greater effect after carbonitriding compared to carburizing. Consequently, the combination of shot peening and carbonitriding process improves the contact fatigue strength (pitting life) more than the combination of carburizing and shot peening.

KEY WORDS

Gear, Shot Peening, Contact Fatigue Strength, Carburizing, Carbonitriding, Resistance to Softening

INTRODUCTION

At the present time, case-hardened parts, such as gears for transmission components, roller and discs in continuous variable transmission (M. Nakano et al 1998), etc., are required to have higher strength in order to cope with increasingly higher engine outputs, and to meet requirements for longer lives. This is due to that not only engine performance has been improved, but also that the size and weight of parts have been reduced in order to increase fuel efficiency. To enable this, the bending fatigue strength and contact fatigue strength in term of pitting and/or wear resistance of such gear should be improved significantly.

There are many reports (N. K. Burrell 1985, S. Hisamatsu 1987, M. Izumine 1989) which indicate that shot peening is an important process to improve the bending fatigue strength of gear teeth, and this is achieved by selecting an optimum peening condition to obtain a high level of residual compressive stress in the superficial layer of tooth root. However, there are only limited numbers of studies (D.P. Townsend 1989, Y. Watanabe et al 1998) on the effect of shot peening on the contact fatigue strength; pitting resistance of case-hardened gears and its mechanism (H.S. Cheng et al 1982, S.T.S. Al-Hassani 1982) is not yet to be clarified.

According to this, the present investigation was aimed at clarifying the effect of shot peening on the contact fatigue strength of carbonitrided steel. The results are also compared with carburized steel.

METHODS

The chemical composition of steel used in the present study is given in Table 1. It has been reported by Y. Watanabe et al 2000 that this chemical composition was found to be optimal for carbonitriding to a high amount of nitrogen contents. The schematic drawing of specimens for the roller-pitting fatigue test is shown in Figure 1, which was cut off from a normalized steel bar of 40mm in diameter. The specimens were carbonitrided at 1173K for 4hrs and then at 1113K for 4hrs in an atmosphere of endothermic gas enriched with butane gas and 7 vol% of ammonia gas mixture, so as to diffuse carbon and nitrogen simultaneously into tested steel, followed by quenching in oil at temperature of 323K (Figure 2). Also, some numbers of specimens were subjected to gas carburization for comparison. The surface carbon and nitrogen contents after heat treatment were measured by chemical analysis of cut powder, which has been collected during machining of heat treated samples to a depth of 50μm from the surface, and results are shown in Table 2.

Table 1 Chemical composition of steel used (mass%)

C	Si	Mn	P	S	Cr	Mo
0.22	0.67	0.30	0.009	0.024	1.50	0.44

Table 2 Carbon and nitrogen content at surface of as-heat treated specimens

Treatment	Surface Content, mass%	
	Carbon	Nitrogen
Carburizing	0.69	0.05
Carbonitriding	0.85	1.14

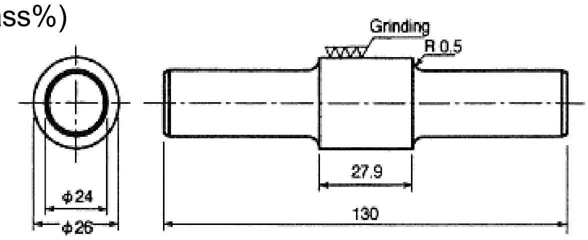

Figure 1 Schematic drawing of specimens for roller pitting fatigue test

Typical cross-sectional surface microstructures of as-carburized and as-carbonitrided specimens are shown in Figure 3. The main microstructure at the surface after both heat treatments is martensite with some retained austenite. It should be noted in Figure 3(a) that internal oxides are formed at a depth of up to about 20μm in the case of carburizing. In contrast, the addition of ammonia gas to the atmosphere in the

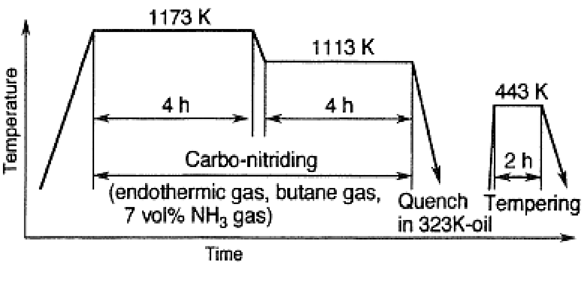

Figure 2 Schematic diagram of carbonitriding and tempering process

Table 3 Shot peening conditions

Machine Type	Compressed Air
Shot Media	Cast Steel (Φ0.6mm, 700Hv)
Blasting Pressure	0.5MPa
Shot Velocity	135m/s
Arc Height	0.92mmA
Coverage	More than 300%

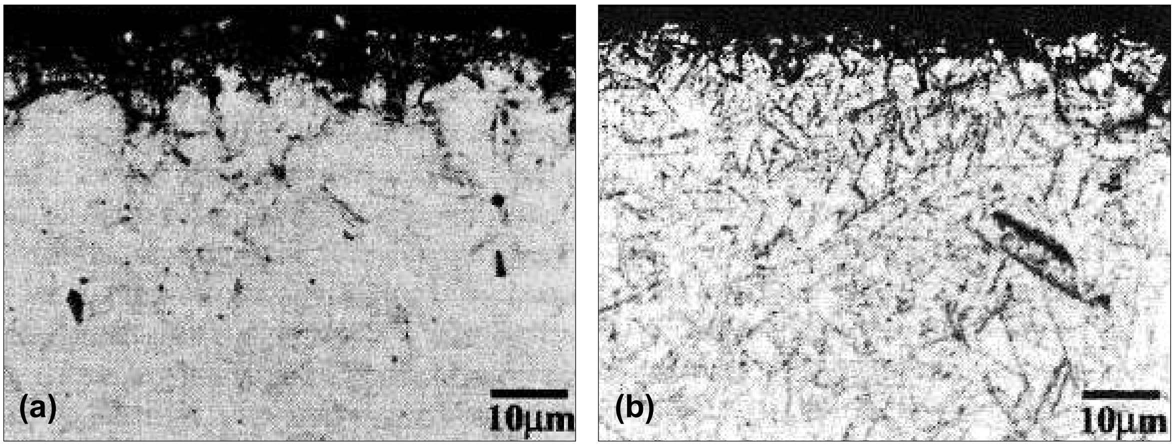

Figure 3 Typical cross-sectional surface microstructures after (a) carburizing and (b) carbonitriding

carburizing process, i.e. carbonitriding, results in reduction of internal oxidation (Figure 3(b)).

Specimens were subjected to shot peening under conditions shown in Table 3, following by grinding to eliminate the effect of internal oxidation on contact fatigue strength. Contact fatigue strength was estimated by using a roller-pitting test apparatus. Testing was done at Herzian stress ranging from 3.0 to 3.86GPa and a rotation speed of 1.43 m/s with negative slip (slip ratio: -60%; slip speed: 1.22m/s). The loading rollers were made from steel JIS SUJ2 (SAE 52100) with hardness of more than 61HRC. Automatic-transmission oil at a temperature of 353K was used as a lubricant.

RESULTS

Figure 4 shows Weibull plots of the number of cycles to surface pitting fracture. It has been reported previously by Y. Watanabe *et al* 1998 that the shot peening process leads to increase of around 5 times in contact fatigue strength (pitting life) of specimens subjected to carburizing. From our results (Figure 4), it is clearly seen that the combination of shot peening and carbonitriding gives the further improvement in the contact fatigue strength by 4.5 times in comparison to a combination of shot peening and carburizing. It is well known that an increase in the pitting life of shot peened specimens can be associated with surface characteristics, such as microstructure and hardness before contact fatigue tests. According to that, let us clarify the effect of a combination of shot peening and case-hardening processes.

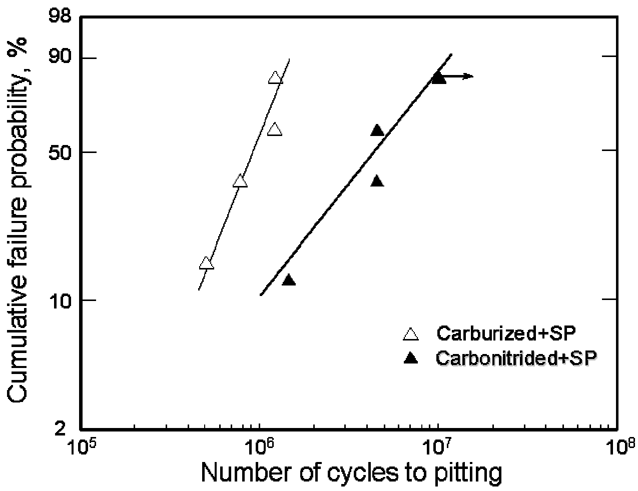

Figure 4 Weibull distribution of the results of roller-pitting fatigue tests

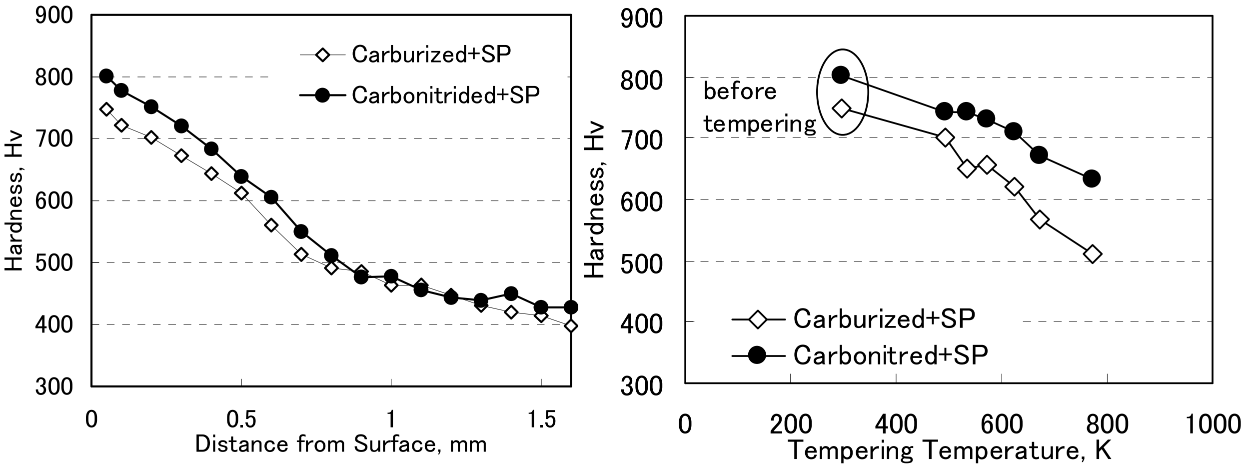

Figure 5 (a) Hardness profile before contact fatigue tests and (b) softening resistance

Figure 5 shows (a) the hardness distributions of roller-pitting specimens before contact fatigue tests and (b) retardation of softening during tempering in the range of 493K to 773K for holding time of 3hrs. The surface hardness of samples before shot peening was roughly the same after both heat treatment and equal around 710HV. It can be seen in Figure 5(a) that hardness after shot peening of carbonitrided samples reached a value of 800HV at surface (at a depth of 50μm) and then decreased to a value of about 430HV at a depth of 1mm from surface. In contrast, shot peening after carburizing leads to a small increase in surface hardness up to about 750HV yet also a decrease to roughly the same core hardness of carbonitred and shot peened samples at a depth of 1mm. It can be concluded that there is a difference in surface hardness before the contact fatigue test of about 50HV. It should be noted that the effect of the combination of shot peening and carbonitriding on the retardation of softening is much higher than that of shot peening and carburizing (Figure 5(b)). For example, the difference in hardness after tempering at 573K is around 100HV. It may be suggested that the greatest effect of the combination of shot peening and carbonitriding is higher surface hardness and retarding to softening.

Figure 6 shows the typical microstructures of surface layers of carburized and carbonitrided samples subjected to shot peening. It can be seen that fully martensitic

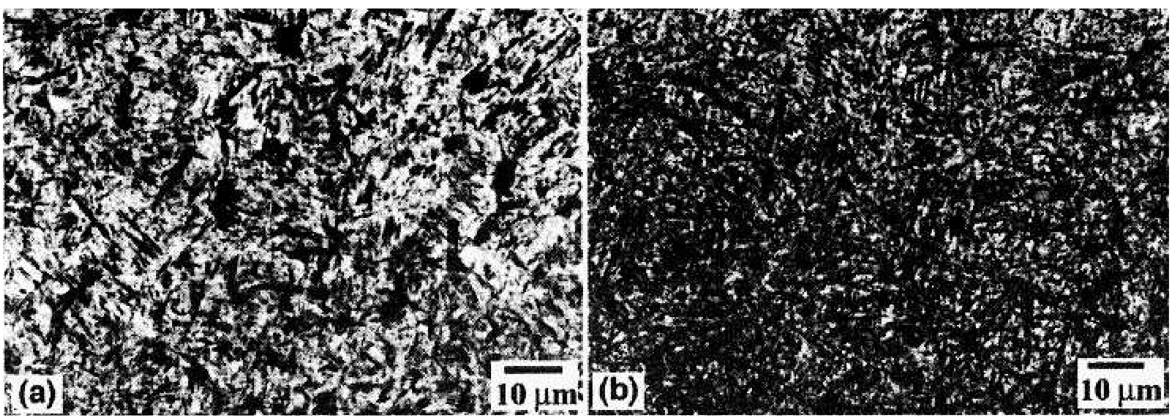

Figure 6 Typical microstructure after shot peening.
Previously (a) carburized and (b) carbonitrided.

structure with slight amounts of retained austenite are formed after both treatments. However, the carbonitrided samples seem to have a finer structure and lower amount of retained austenite after shot peening than that of the carburized samples. For more detail investigation of microstructure, transmission electron microscopy and X-ray observations were carried out at a depth of around 50μm. It can be seen in Figure 7 that there is formation of fine size chromium nitrides in the martensitic structure. The average size of these nitrides is about 500nm and they are homogeneously distributed in the whole area. Figure 8 shows x-ray diffraction patterns of samples tempered at various temperatures between 443K and 673K after carbonitriding. It can be seen that the precipitation of γ\`-Fe_4N (fcc: a=0.3787nm) (K.H. Jack 1948) takes place from the supersaturated solid solution of nitrogen (martensite and retained austenite) at 523K and higher. In contrast, the formation of these fine particles has not been observed in carburized samples.

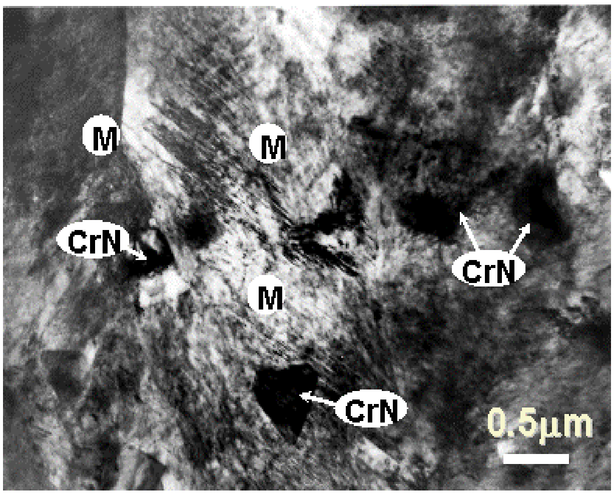

Figure 7 TEM micrograph of surface layer of carbonitrided specimen

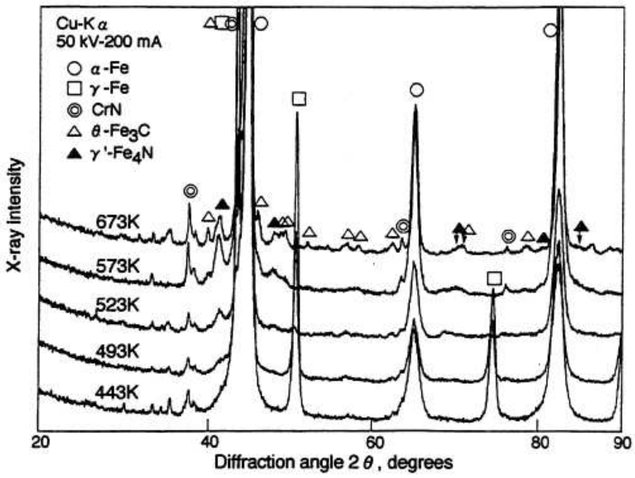

Figure 8 X-ray diffraction patterns of samples tempered at 443K for 2hrs, and subsequently tempered at a temperature of up to 673K from 493K for 3hrs

DISCUSSION

It is well known that the structure generated by the case-hardening process, such as carburizing and carbonitriding, consists mostly of martensite and a certain amount of retained austenite, which is higher in case of carbonitriding. Retained austenite has never had a good reputation in the heat treatment technology because of its low hardness. However, from this study we can conclude that the fatigue contact strength can be improved more by a combination of shot peening and carbonitriding compared to that of shot peening and carburizing. It is well known that the shot peening process leads to an increase in hardness primarily due to the transformation of retained austenite into deformation martensite, following by an increase in dislocation density. However, the amount of retained austenite, surface hardness and the residual stress in the virgin samples cannot explain their pitting durability. It has been reported by Y. Watanabe *et al* 1998 that the hardened layer's resistance to softening during tempering at temperature of 573K is a very important factor affecting on the surface pitting fracture. Increase in resistance to softening results in an increasing of pitting life (Figures 4 and 5(b)). The resistance to softening during tempering is improved more effectively by shot peening after carbonitriding than after carburizing, because the recovery of dislocations introduced by shot peening is delayed by solute nitrogen and precipitation of fine particles, such as γ`-Fe_4N. It can be concluded that shot peening process after carbonitriding with high nitrogen content is the most effective process for increasing contact fatigue strength.

CONCLUSIONS

The effect of shot peening on the contact fatigue strength can be summarized as followed.

1. Resistance to softening during tempering after carbonitriding is higher than that after carburizing surface modification process. Improvement of softening resistance may be closely connected with precipitation of γ`-Fe_4N during tempering.
2. Following shot peening process improves the resistance to softening and has greater effect after carbonitriding compared to carburizing. It may be because the recovery of dislocations introduced by shot peening is delayed by precipitations of γ`-Fe_4N and by solute nitrogen.
3. The combination of carbonitriding and shot peening process improves the contact fatigue strength (pitting life) more than a combination of carburizing and shot peening.

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