

On the Laser Quenching of the Groove of the Piston Head in Large Diesel Engines

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The service life of piston heads and the stability of large diesel engines are remarkably affected by the wear resistance of the groove of the piston head. Unfortunately, conventional high-frequency quenching methods result in several deleterious effects that may impair the antifriction and wear properties of the groove of the piston head. Excellent wear resistance characteristics may be achieved provided the groove surface is properly surface treated. Laser surface quenching is a new candidate technique. A 2 kW CW CO_2 laser was employed for the laser quenching of the groove of the piston head in large diesel engines. The hardness and depth of the laser quenched layer reached 750 HV and 0.59 mm, respectively. The microstructure of the quenched layer is composed of martensite and retained austenite. Wear tests were performed using laser quenching and high-frequency quenching samples, and wear resistance was compared by using a method of mass loss. The results show that the wear resistances of laser quenched samples are 1.3× higher than that resulting from the high-frequency quenching method. Practical application of laser quenched piston heads in diesel power plants indicate that it is an effective way to prolong the service life of the piston head in large diesel engines.

Keywords application, laser quenching, piston head, wear resistance

1. Introduction

The piston head is one of the key components of large diesel engines and is widely used in diesel power plants. In working processes, the piston head suffers high pressure and temperature resulting from combustion. Conversely, the lubricant condition of the groove of the piston head may be poor, contributing to the friction losses of the groove of the piston head. Therefore, the service life of the piston and the stability of the diesel engines are remarkably affected by the wear resistance of the groove of the piston head, generating a great interest in improving their wear resistance (Ref 1). Conventional high-frequency quenching methods result in several deleterious effects that may impair the antifriction and wear properties of the groove of the piston head, such as lower hardness and surface decarburization. Excellent wear resistance characteristics are able to be achieved provided the groove surface is properly surface treated.

Laser surface quenching, a new candidate technique, has been employed in many industries because of its technical and economical advantages (Ref 2-5). The advantages for laser quenching, compared with the high-frequency quenching method, are (Ref 6): no external quenching, minimal distortion, high-speed processing, precise control of case depth, selective hardening, improved surface properties, and low input power. The primary objective in laser quenching is the selective transformation of the hardened surface layer with a complete absence of surface melting. In steels, a laser beam heats the surface to a temperature below the melting point and subsequent self-quenching of the layers by the substrate permits the transformation of austenite to martensite. Rapid heating and quenching are the key characteristics of laser quenching that enable the formation of novel microstructures and thereby improve the hardness and the wear resistance (Ref 7-10).

Because the study of laser quenching of the groove of the piston head in large diesel engines is scarce, it is performed in the present study.

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2. Experimental Details

2.1 Materials Involved

The piston head of 400 mm diam was used. Its material is commercially available 40CrNiMoA steel, which is a Chinese standard steel. The chemical composition of 40CrNiMoA steel is listed in Table 1. The piston head was austenized at 860 °C for 2 h, then oil quenched, and finally tempered at 550 °C for 3 h. Before being laser quenched, their initial microstructures were composed of tempered sorbite. The resulting hardness ranged from 32 to 35 HRC.

Table 1 Chemical composition of 40CrNiMoA steel

Element	Chemical composition, wt%
C	0.38
Cr	0.721
Ni	1.26
Mo	0.188
Si	0.228
Mn	0.597
P	0.0148
S	0.0119

2.2 Experimental Apparatus

Figure 1 illustrates schematically the apparatus used for the laser quenching of the groove of the piston head. A 2 kW CW CO_2 laser was used. The beam with the mutimode was focused through a 300 mm focal GaAs lens, while compressed air flowed axially to the laser beam axis to protect the lens. An energy-power meter was placed in the path of the laser beam to measure the instantaneous laser output power. The piston head was mounted on an inclined turntable. In the experiments, the laser beam was kept stationary, while the workpiece was moved by the CNC-controlled table.

2.3 Absorbent Coating

The efficiency of laser quenching depends on the absorption of light energy by the workpiece. The absorptivity of ferrous alloys is estimated (Ref 11) to be approximately 15% at room temperature, so that absorbent coatings are used almost invariably during laser quenching. A black organic absorbent coating was used to enhance the absorptivity of the groove surface.

2.4 Processing Parameters

The laser quenching process includes the two stages of heating and cooling. Due to the rapid heating rate and cooling speed of laser quenching, generally, to realize self-quenching, only the controlled technology parameters of laser quenching are considered. Thus exist the best processing conditions, in accordance with the optimized processing parameters. The optimum processing parameters are listed in Table 2.

2.5 Measurement

After laser quenching, small pieces were cut from the piston head using a wire-cut machine. The metallographic specimens were ground on SiC abrasive paper of 1000 mesh size and polished afterward with 1 μm diamond paste. The width and depth of each quenched zone were then examined and measured using the micrometer stage of a microscope. The microhardness of different depths from the surface on a vertical section was measured by a Shimazu microhardness tester using a 500 g load. The profile and microstructure of the quenched zone were studied with a scanning electron microscope (SEM) and the x-ray diffractometer.

2.6 Wear Test

A conventional MM200 type wear machine with a block-on-ring configuration was used to investigate the wear resistance of the groove of the piston head. To produce a wear specimen for a block-on-ring type machine, $12 \times 10 \times 10$ mm^3 samples were cut from the laser quenched piston head. Ring specimens, 10 mm in width and 40 mm in outer diameter, were made of cemented carbide and were rotated at a speed of 200 rpm. The tests were performed for a period of 2 h using a constant load of 98 N at room temperature in air under dry conditions. Mass losses were obtained by weighing the samples to an accuracy of 0.1 mg using an electronic microbalance. All specimens were cleaned with acetone before and after the experiment. Worn surfaces of samples were investigated using a SEM.

3. Results and Discussion

3.1 Hardness and Microstructure

Using the optimum processing parameters, every groove surface was quenched with two passes with no overlapping, and the width and depth were 5.48 mm and 0.59 mm, respectively. The hardness reaches 750 HV. This can meet the needs of practical application.

Table 2 Optimum processing parameters

Processing parameters	Value
Laser power,W	1400
Traverse speed, mm/s	35
Incident angle, degree	60
Absorbent coating	Black organic
Gas flow rate, m^3/h	0.9
Defocusing distance, mm	10

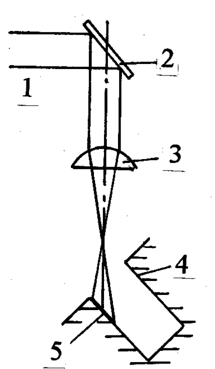


Fig. 1 Schematic apparatus used for the laser quenching of the groove of the piston head: 1, laser beam, 2, reflector, 3, focal lens, 4, piston head, and 5, quenched layer

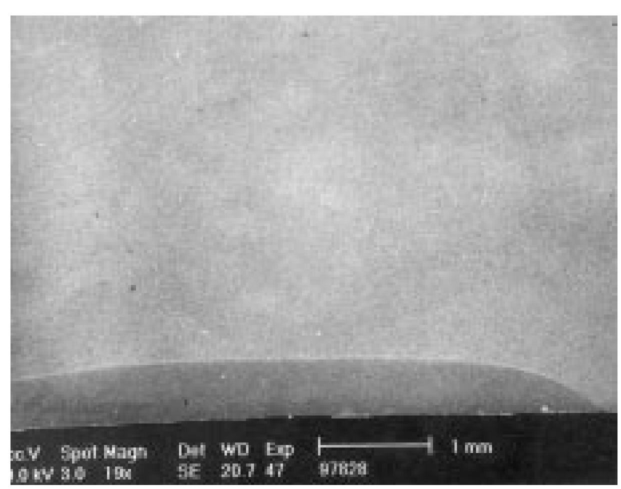
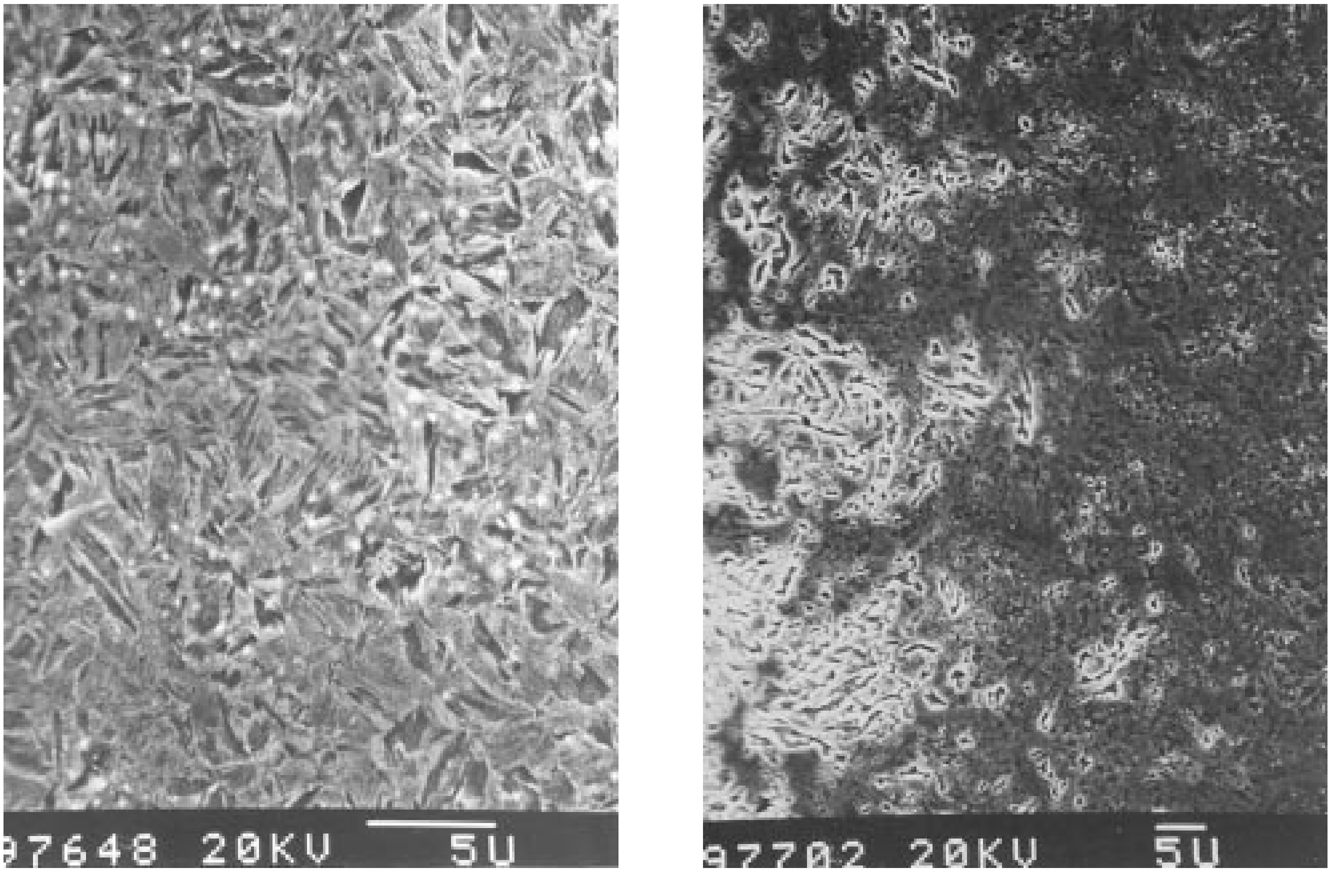


Fig. 2 A full view of the quenched zone near the outside corner of the groove. (Art has been enlarged to 133% of its original size for printing.)



(a) **(b)**

Fig. 3 Metallographic structure of the (a) laser quenched zone and (b) the transition zone

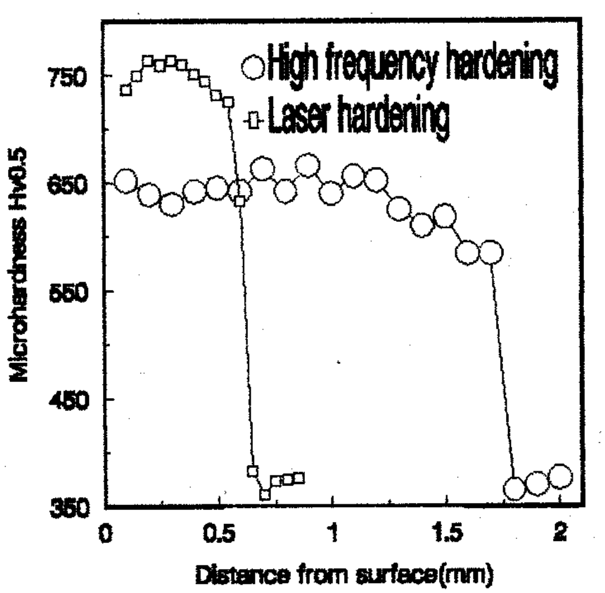


Fig. 4 Comparison of hardness resulting from laser quenching and previous high-frequency quenching processing method

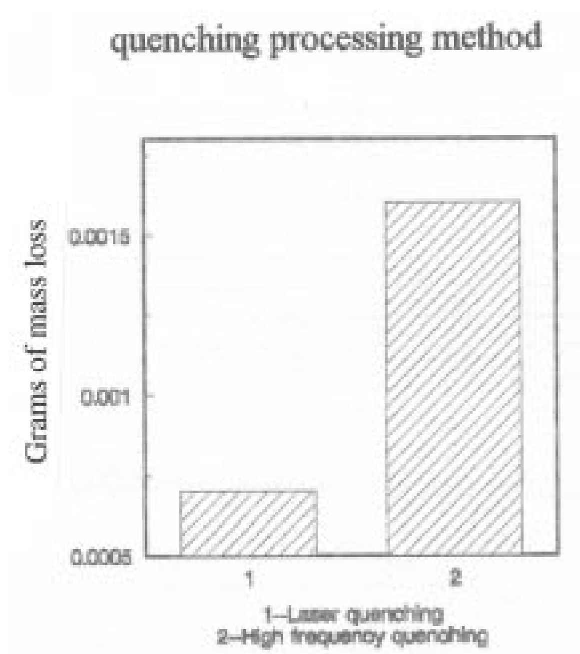


Fig. 5 Result of the wear test

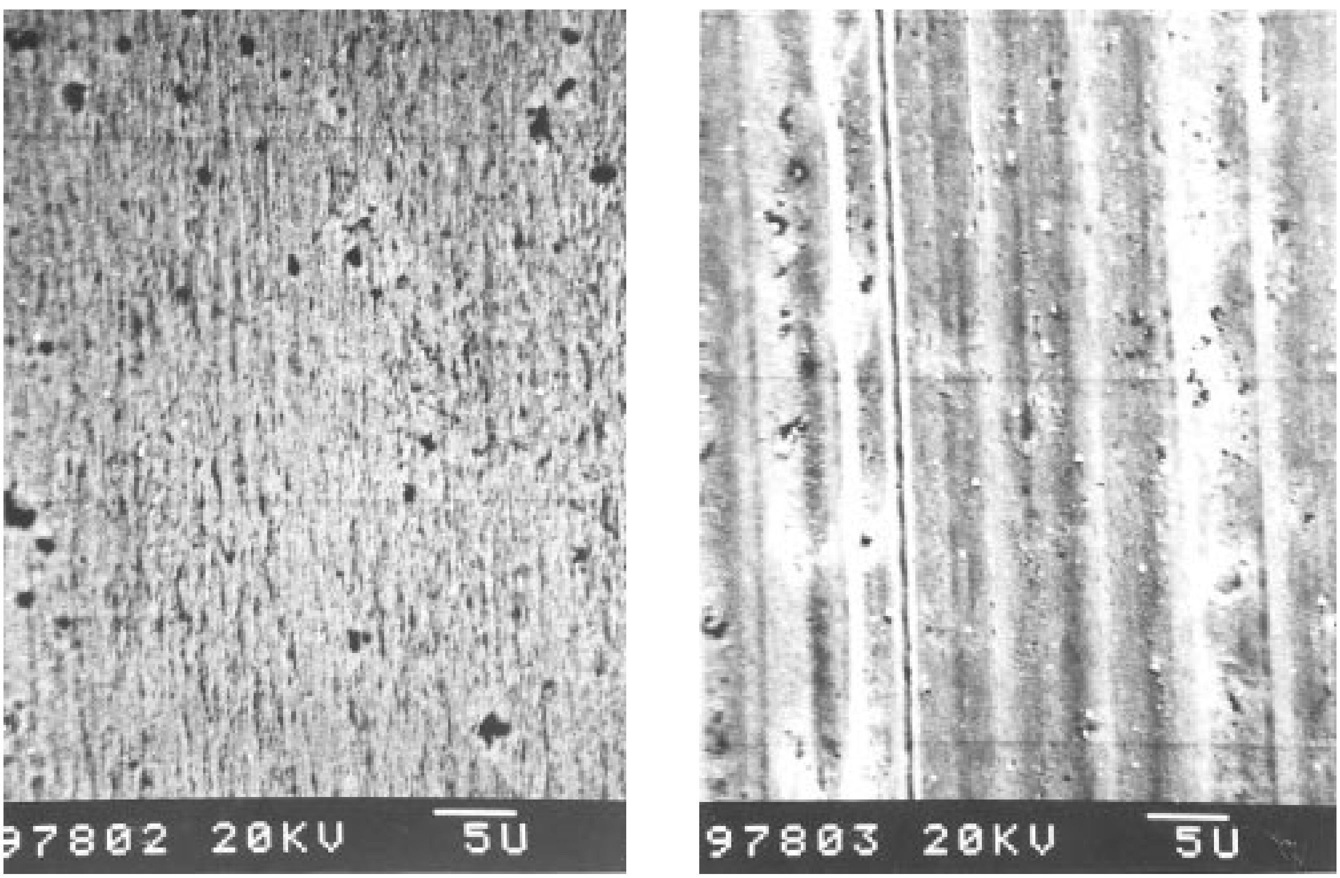
Because of the fast heating and rapid cooling involved, the substrate underwent a severe variation. Figure 2 is a transverse section of laser quenched zone near the outside corner of the groove. From the surface to the bulk body, the microstructures produced by laser quenching can be divided into three parts, the quenched zone, the transition zone, and the substrate. Results of the x-ray diffraction indicate that the microstructures of the quenched zone are composed of martensite and retained austenite. Figure 3 shows the metallographic structure of the laser quenched zone and the transition zone, respectively. Heating by laser results in coarser martensite at or near the surface (Fig. 3a) rather than that near the substrate (Fig. 3b).

The reasons for the formation of the two special martensites are as follows. First, the fast heating of the laser generates high transformation superheat and brings about rapid creation of austenitic grains. Also, the initial austensite is fine because of the short heating time. Second, the different influence of the cooling conditions gives rise to two types of martensite. Heat is conducted faster near the substrate rather than the surface. Thus, superfine martensite is generated near the substrate.

Figure 4 shows the comparison of hardness resulting from laser quenching and the previous high-frequency quenching processing method. It is apparent from the results that the hardness of the laser quenched layer is substantially higher than that resulting from high-frequency quench and temper treatment. Because of the very short times involved in the austenitization during laser quenching, the finer austenite grain size resulted in the formation of unusually fine martensitic structures and little

Table 3 Practical measured results

Serial number of piston head	Measuring position	Initial dimensions, mm	Running time, h	Measured dimensions, mm	Wearing capacity, mm
	First groove, width	8.20	2500	8.2447	~0.015
ZN9502010	Second groove, width	8.17	2500	8.2025	<0.01
	Third groove, width	8.17	2500	8.2020	<0.01
ZN9502009	First groove, width	8.20	5000	8.24-8.26	~0.01-0.03
	Second groove, width	8.17	5000	8.185	<0.02
	Third groove, width	8.17	5000	8.185	<0.02



(a) (b)

Fig. 6 Worn morphologies of laser quenched specimen and that produced by high-frequency quenching method. (a) laser quenching and (b) high-frequency quenching retained austenite. The presence of alloy carbides possibly produced the dispersion-hardening effect. The greater increase in hardness of the laser quenched zone can be contributed to these microstructural features. The hardness at the surface of the laser quenched zone is usually lower because the quenching rate obtainable is lower. The hardness at the borderline is lower also, due to the lower austenitizing temperature and the shorter interaction time available for austenitization.

3.2 Wear Resistance

Figure 5 shows the result of the wear test. The mass loss value shown represents the mean value. It can be found that the wear resistance of laser quenched samples is 1.3× higher than that resulting from previous high-frequency quenching technology. SEM micrographs of worn surfaces of specimens are shown in Fig. 6. Analysis of micrographs of the wear surface show that the well-known plastic microplowing and microcutting mechanism for abrasive wear described elsewhere (Ref 12-15) was observed.

Laser quenching technology produces a hardened layer, which results in a high hardness and also a surface stress, including residual compressive stress. The high hardness on the groove surface results in a high resistance to wear, scuffing, and seizing, even under poor lubrication conditions. The high residual stress and surface compressive stress also result in a high fatigue strength. The high hardness and compressive residual stresses, therefore, are mainly responsible for the low wear rates. Thus, the laser quenched layer has much better wear-resisting properties when compared with the high-frequency quenching layer.

4. Application

The laser quenched piston heads until now have been used in diesel power plants for more than 10,000 h. To check the wear resistance of laser quenched groove surfaces, practical dimensions of grooves were measured after the piston heads ran 2500 h and 5000 h, respectively. The results are listed in Table 3.

As described, the increase of width of every groove resulting from the wear is remarkably reduced. Meanwhile, no obvious horn phenomenon arises. The wear resistance of the groove of the piston head is improved by means of laser quenching. It is an effective way to enhance the service life of the piston head in large diesel engines.

5. Conclusions

Wear resistance and microstructure of the groove of the piston head in large diesel engines were studied. Main conclusions are given.

- Using the optimum processing parameters, every groove surface was quenched with two passes with no overlapping. The width and depth being, 5.48 mm and 0.59 mm, respectively. The microstructure of the quenched layer is composed of martensite and retained austenite.
- The hardness of the quenched groove surface reached 750 HV and is substantially higher than that resulting from the high-frequency quenching method.
- The results of wear testing show that the wear resistance of laser quenched specimens is 1.3× higher than that of a high-frequency quenching specimen.
- Practical application of laser quenched piston head in diesel power plants indicates that it is an effective way to prolong the service life of the piston head in large diesel engines.

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