Laser Surface Hardening of Gray Cast Iron Used for Piston Ring

Jong-Hyun Hwang, Yun-Sig Lee, Dae-Young Kim, and Joong-Geun Youn

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The process parameters for laser surface-hardening has been experimentally established for improving the wear life of piston rings used for marine diesel engines by the formation of a proper hardened layer on it. The parameters of interest were the laser power and travel speed. Various hardened layers of gray cast iron were analyzed with respect to microstructure, hardness value, hardening depth, surface roughness, and wear resistance. The hardness of the laser-hardened layer was in a range between 840 and 950 Hv0.1, regardless of the laser power and travel speed range studied. Both the surface roughness and hardening depth increased in an almost linear manner with the increase in the heat input applied. Thus, the hardened layers formed with heat input ranges between 30 and 45 J/mm satisfied the piston ring application requirements for surface roughness (<6.3 μm in Ra) and the minimum effective hardening depth of 0.3 mm (>450 in Vickers number). Wear-test results obtained using a pin-on-disk-type wear-test machine showed that the wear life of the laser-hardened layer was almost twice that of the untreated one. This was directly attributed to the formation of the martensitic microstructure.

Keywords cylinder liner, gray cast iron, laser hardening, piston ring, wear

1. Introduction

Currently, many marine diesel engines are designed and operated under more severe conditions such as higher power, higher pressure, and higher piston speed in order to improve their performance. These severe operating conditions might cause the marine diesel engine to be subjected to wear problems of reciprocating parts such as cylinder liners and piston rings.[1] The wear problem of the piston ring is a more severe problem in marine engines because of the usage of low-grade fuel for reducing fuel cost. The piston ring should prevent combustion gases from escaping into the crankcase of the scavenging space and also should prevent too much lubricating oil from getting into the necessary combustion chamber. Wear of the piston ring thus causes, for example, blow-by and abnormal consumption of lubricating oil. Therefore, we need to improve the wear resistance of the piston ring, while keeping its higher thermal and mechanical properties to ensure the performance, efficiency, and reliability of the engine. Many efforts have been made to improve the wear resistance of the piston ring through surface hardening or surface modification technologies (for example, plating, nitriding, and plasma-sprayed coatings).[2-6] These processes have been applied to a wide range of applications, but also have many disadvantages, in terms of both their properties, such as thickness and bonding strength, and other problems, such as environmental pollution and high production cost. To overcome these disadvantages, alternative surface-hardening technologies have been studied. One is a laser surface-hardening technology, which is well known to produce a hardened layer having unique characteristics such as high hardness, deep hardening depth, smooth surface, less distortion, and higher productivity.[7-9]

The purpose of this study was to improve the wear life of the piston ring (gray cast iron) used for marine diesel engines by a laser surface-hardening method. The properties of the hardened layer required are the smooth surface with roughness <6.3 μm in Ra (arithmetic average value) and a minimum effective hardening depth of 0.3 mm, having a hardness of >450 in Vickers number. These are the required specifications that are applicable to the piston ring used for current marine diesel engines. The effect of laser power and travel speed on the microstructure, hardness, hardening depth, and surface roughness of the laser-hardened layer of a gray cast iron was investigated in order to establish a proper window for laser process parameters that can satisfy the industrial requirement. A wear test was then performed on the laser-hardened layers formed using the proper processing window. The wear characteristics of the laser-hardened layer were also compared to those of a plasma-coated layer, which currently is being used for the piston ring.

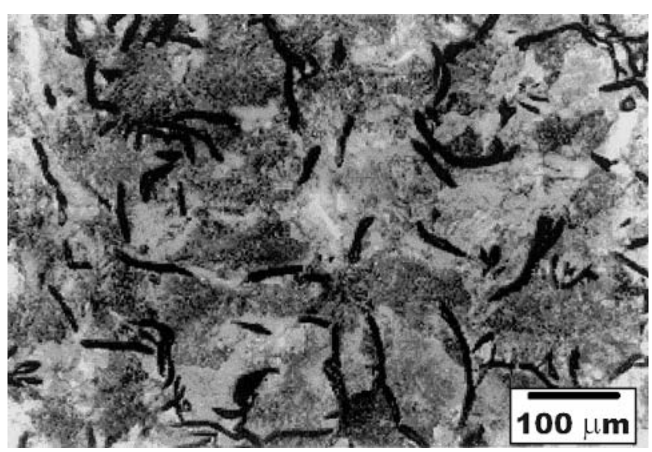

Fig. 1 Microstructure of the gray cast iron (piston ring) used

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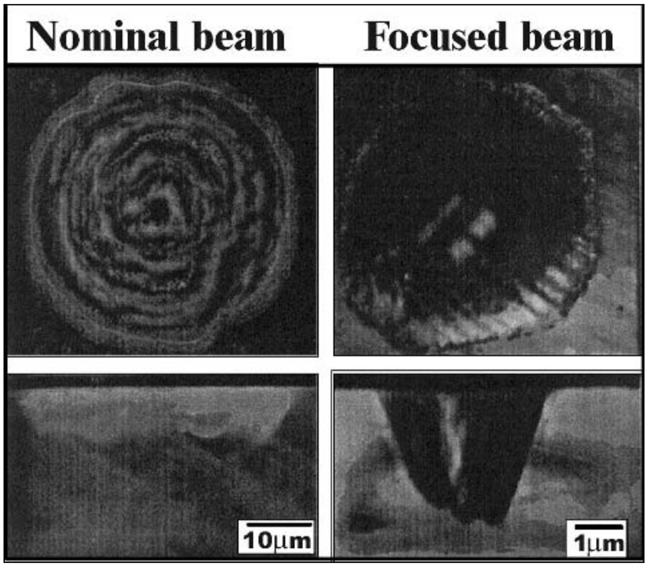
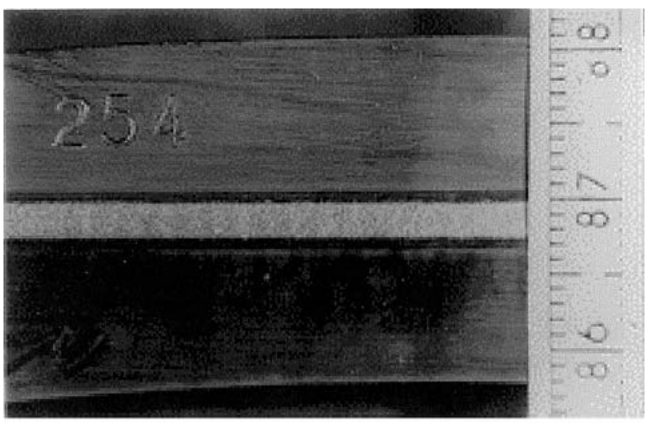
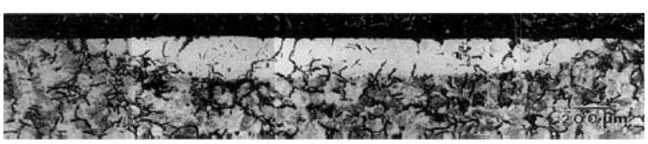


Fig. 2 Laser beam mode used in this study



(a)



(b)

Fig. 3 A typical hardened layer formed by one-pass laser treatment: **(a)** planar view; and **(b)** cross-sectional view

Table 1 Chemical Composition and Mechanical Properties of the Gray Cast Iron Used(a)

Chemical Composition (wt.%)									Mechanical Properties	
C	Si	Mn	P	S	Mo	Cu	V	Ti	T.S. (MPa)	Hardness (HB)
3.07	1.34	0.86	0.059	0.035	0.69	0.87	0.03	0.03	332	226

(a) wt.%, weight percent.

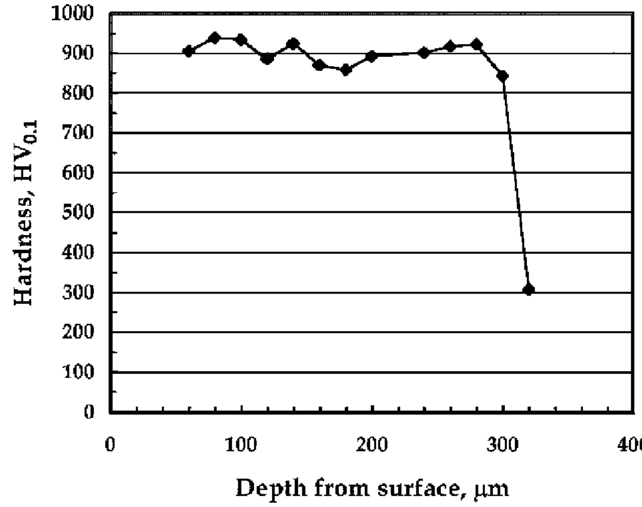
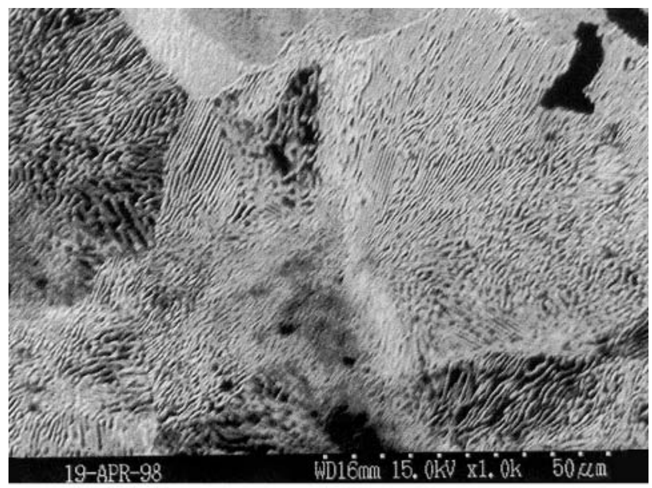
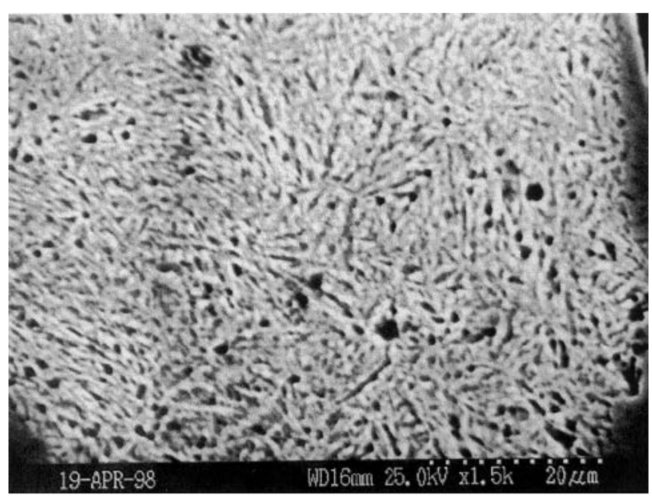


Fig. 4 Hardness distribution along the thickness direction of the laser heat-treated region



(a)



(b)

Fig. 5 Microstructure of **(a)** the parent metal (gray cast iron) and **(b)** the laser-hardened layer

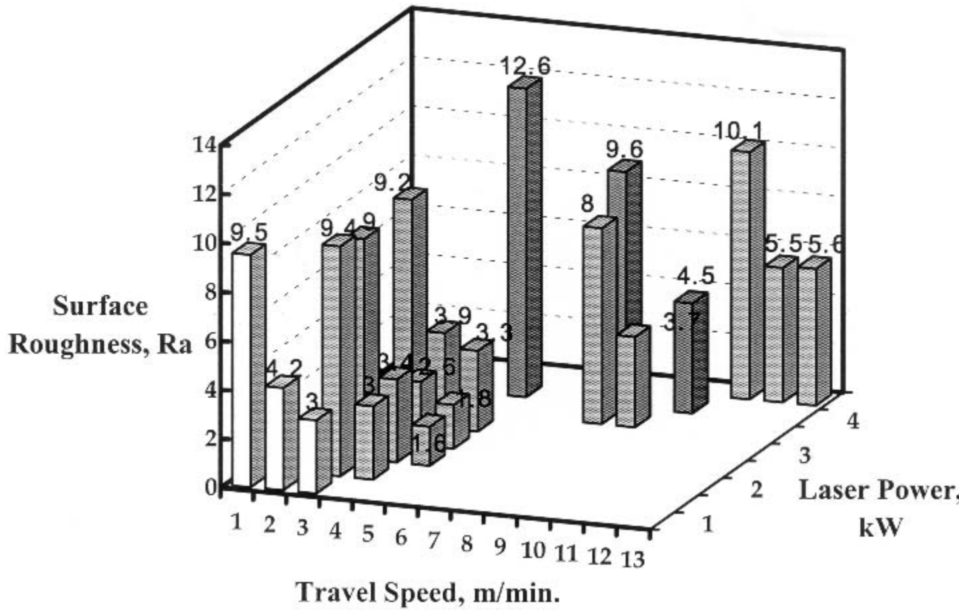


Fig. 6 Variation of the surface roughness of the laser-hardened layer with laser power and travel speed

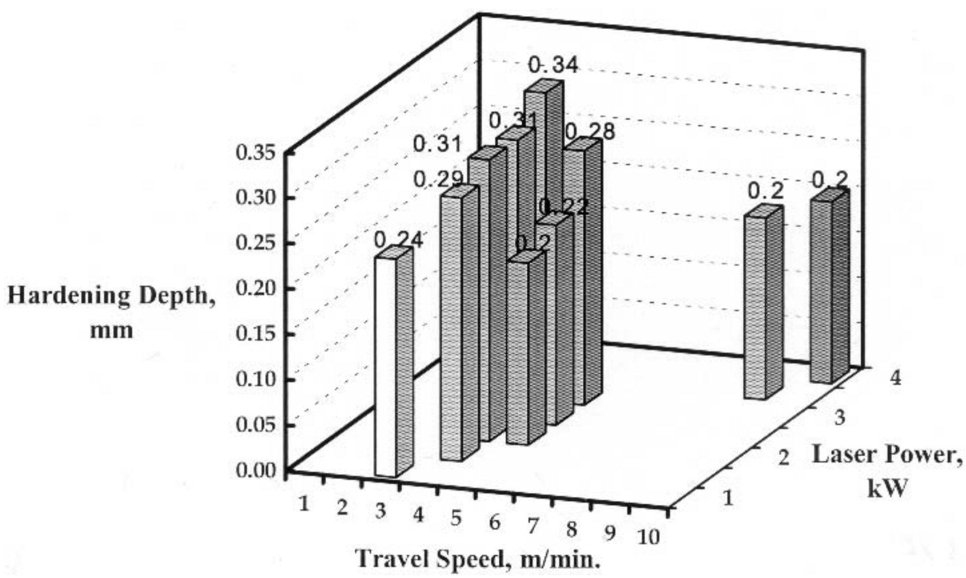


Fig. 7 Variation of the hardening depth of the laser-hardened layer with laser power and travel speed

2. Procedures

The material used was a gray cast iron that is widely used for piston rings for marine diesel engines. The chemical composition and mechanical properties are given in Table 1. The microstructure of the gray cast iron consists of lamellar pearlite with a small amount of cementite and randomly distributed steadite that consists of iron phosphite, cementite, and ferrite, as shown in Fig. 1. Laser-hardening treatments were conducted using a 5 kW CO_2 laser system, which consisted of a power generator, a beam-delivery system, and a Numerical Control (NC) work-piece handling system. In order to obtain a proper beam mode for the laser hardening, a beam delivery system was made with two copper reflecting mirrors and a segmented molybdenum integrating focusing mirror. As shown in Fig. 2, the nominal beam of about 40 mm diameter was changed into the focused beam within 3×3 mm^2, which means it has a very high-energy density. Surface-hardened specimens were made by an exposure of the continuous focused laser beam. All the specimens had been coated with colloidal graphite having a thickness of about 40 μm in order to improve the absorption efficiency of the laser beam. Beam power and travel speed were changed from 1.0 to 4.5 kW and from 1 to 13 m/min, respectively. During the laser treatment, the focal length of the beam was a constant 311 mm and the beam incident angle was perpendicular to the surface. The surface roughness of the laser-hardened layer was evaluated by the arithmetic average value (Ra) using a stylus-type surface roughness tester. Surface hardness and hardening depth were also evaluated by the Vickers indentation method. The microstructure of the hardened layers was observed using a scanning electron microscope (SEM) and an optical microscope in order to investigate the extent of surface melting and to confirm the martensitic transformation. Wear resistance of the laser-hardened layer was evaluated using a pin-on-disk-type wear tester.

3. Results and Discussion

3.1 Hardened Layer Characteristics by Single Pass Treatment

Figure 3 shows the planar and cross-sectional view of a typical hardened layer (bright region in figure) of the gray cast iron formed by one-pass laser treatment. As can be seen in the figure, the laser heat-treated region is uniform. The surface is quite smooth, and its measured roughness value is very low, about 2.6 μm in Ra. The hardening depth is about 310 μm. A notable result of this test in this result is the uniform hardening depth, which is directly attributed to the rectangular beam mode produced in this study. The corresponding hardness distribution along the thickness direction of the heat-treated region is shown in Fig. 4. The hardness value ranges from 840 to 950 in Vickers number. The hardening is associated with the transformed microstructure, as shown in Fig. 5. Due to the fast cooling after laser treatment, the pearlite matrix of the gray cast iron was transformed into a needle-type martensitic structure. This microstructure was transformed from the austenite having a high carbon content. No significant effect of the process parameters, such as laser power and travel speed, on the hardness values and microstructure of the hardened layer were found.

Figure 6 shows a variation of the surface roughness of the hardened layer as a function of laser power and travel speed. The surface roughness of the layer decreases with an increase in travel speed for a given laser power and also increases with a decrease in laser power for a given travel speed. Lower travel speed and higher laser power cause surface melting of the layer. For a proper combination (or window) of travel speed and laser power, surface roughness of the layer is in the range between 1.6 and 12.6 μm in Ra. In this processing window, the effect of laser power and travel speed on the hardening depth of the layer is shown in Fig. 7. The harden-

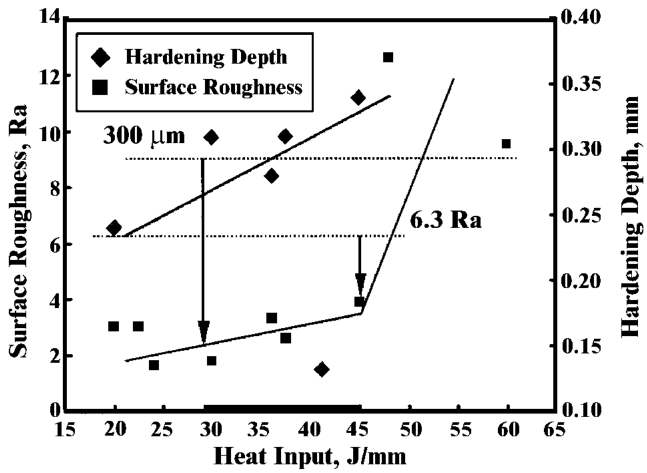


Fig. 8 Effect of heat input on the surface roughness and hardening depth of the laser-hardened layer

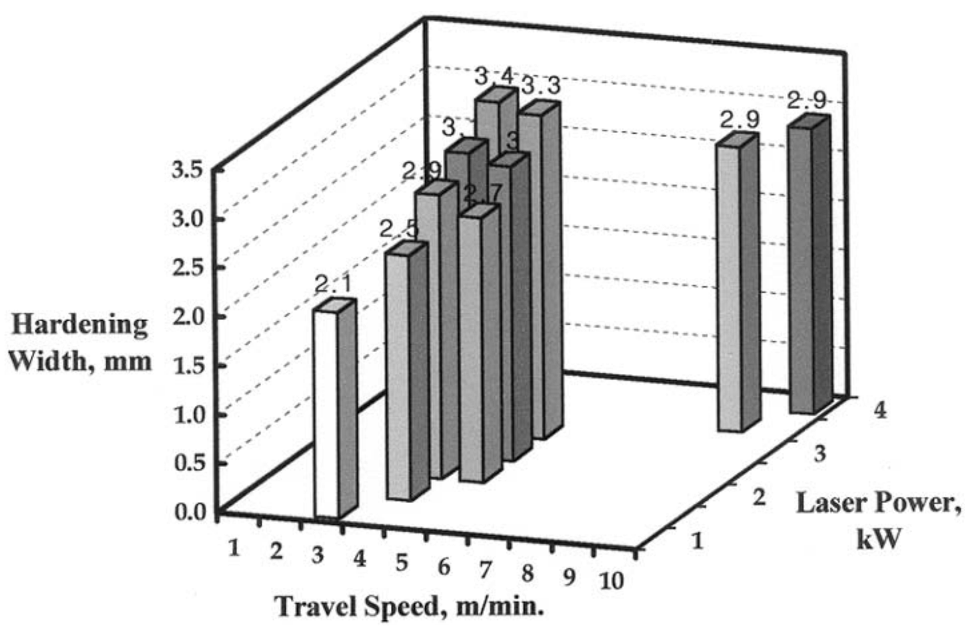


Fig. 9 Variation of the hardening width of the laser-hardened layer with laser power and travel speed

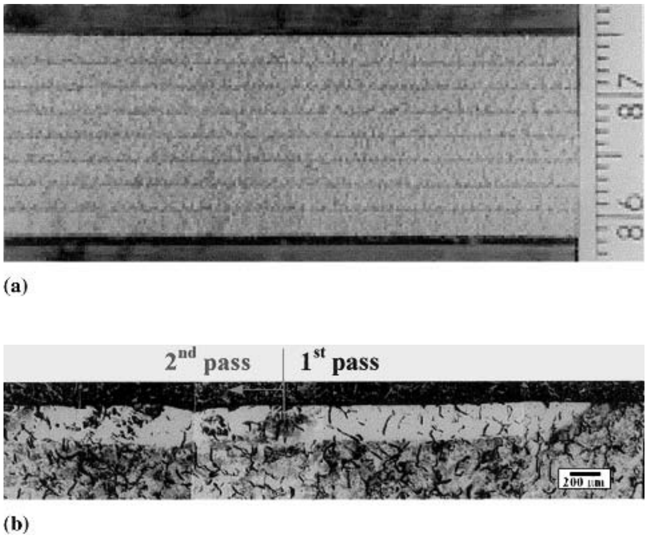


Fig. 10 A typical hardened layer formed by eight-pass laser treatment: **(a)** planar view; and **(b)** cross-sectional view

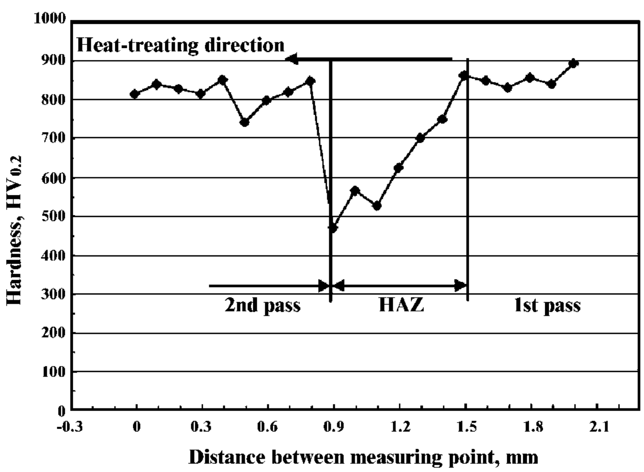


Fig. 11 Hardness distribution across the hardening area between the first and second passes

Table 2 Pin-on-Disk-Type Wear-Test Condition

Lubrication	Rotating Speed	Load	Sliding Distance
None	2 m/sec.	3 kg, 5 kg	12 km

ing depth of the layer increases with an increase in laser power for a given travel speed and does so with a decrease in travel speed for a given laser power. The hardened depth of the layer ranges from 0.2 to 0.34 mm, which was the result of a proper combination of laser power and travel speed. In order to clearly understand the effect of laser power and travel speed on the characteristics of the layer described above, the surface roughness and hardening depth of the layer are replotted in Fig.

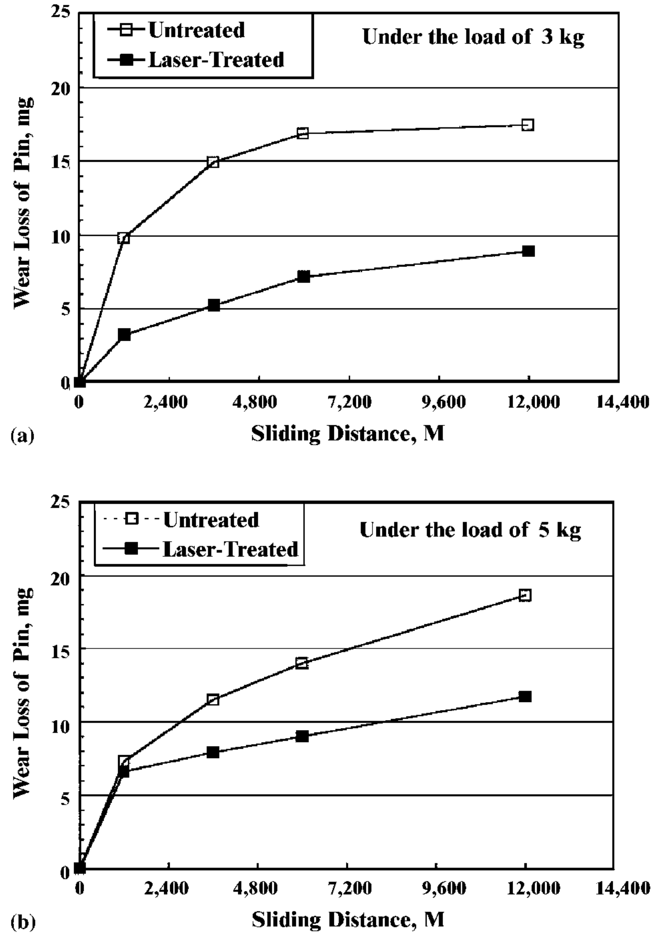


Fig. 12 Variation of wear loss with sliding distance under a constant load: **(a)** 3 kg; and **(b)** 5 kg

8 with reference to the heat input applied during laser heat treatment. The hardening depth of the layer increases almost in a linear manner with an increase in applied heat input. The surface roughness of the layer increases slightly up to a heat input of 45 J/mm and then increases drastically with an increase in the applied heat input. A drastic increase of the surface roughness is attributed to surface melting. For the piston rings in a marine diesel application, the surface roughness of the layer should be <6.3 μm in Ra and the effective hardening (>450 in Vickers number) depth of the layer should be >0.3 mm. Based on these requirements, a proper heat input range for laser surface hardening can be established as 30 to 45 J/mm.

3.2 Hardened Layer Characteristics by Multipass Treatments

In order to apply laser hardening to a piston ring for marine diesel engines, multipass treatments are necessary because of the narrow width of the laser-hardened layer. Figure 9 shows the effect of laser power and travel speed on the width of the hardened layer. The width increases in a linear manner with an increase in laser power for a given travel speed. For the proper heat input range described above, the width of the layer ranges from 2.9-3.4 mm. Since the actual width of the piston ring of interest is 20 mm, seven to eight hardening treatments (or passes) are required. Figure 10 shows the planar and cross-sectional view of a typical hardened layer obtained by eight hardening passes with an overlapping method. The laser-treated area is quite uniform. The surface is also smooth, having a surface roughness of about 5.4 μm in Ra. The minimum hardening depth is 310 μm. Figure 11 shows a typical hardness distribution across the laser-treated area, in particular between the first and second pass. A width of about 500 μm of the initial laser-hardened region (first pass) became softened down to 470 in Vickers number by the following (second) pass. This is attributed to the tempering effect on the martensitic structure. However, the lowest hardness value is still higher than the minimum aim value of 450 Vickers number. This result implies that a laser surface-hardening process can be applied to the hardening of the actual piston ring.

3.3 Wear Characteristics

Wear tests were carried out with the conditions given in Table 2 under ASTM G99 using a pin-on-disk-type wear-test machine. The pin was made from the gray cast iron and was subjected to the laser-hardening treatment. Since the pin diameter required was 10 mm, a four-pass laser treatment was performed. For the purpose of comparison, the pin was also made from the gray cast iron (bulk material) and was left untreated. The disk material was a typical cast iron used for the cylinder liner in order to simulate the relative wear between the piston ring and the liner. The effect of laser hardening on the wear loss of the gray cast iron is shown in Fig. 12. Figures 12(a) and (b) shows the test results as a function of sliding distance, which were obtained under constant loads of 3 and 5 kg, respectively. Figure 12 shows that the laser-hardened pin has better resistance against wear, and the wear life of the laser-hardened layer was determined to be almost double that of the untreated one. As shown in Fig. 12, the wear rate is high at an initial stage and then gradually decreases. This is attributed to the fact that increasing the contacting area with progressing wear phenomena reduces the pressure per unit area. The actual wear condition in a marine engine is the relative wear between the piston ring and the cylinder liner. It is important to consider the wear of the cylinder liner at the same time. Figure 13 shows the relative wear loss between the pin (or piston ring) and the disk (or cylinder liner). Laser hardening clearly improves the wear life of both the piston ring and the cylinder liner. In order to understand the wear mechanism, the surface was observed after the wear test using an SEM, as shown in Fig. 14. The surface of the untreated material shows both the nature of the metallic wear formed by the material transfer phenomenon and the adhesive wear features such as plastic flow and tearing damage, which are caused by the effect of severe contact wear,[10] whereas in the laser-treated material, tearing damage occurred only around graphite flakes by the mild wear resulting from the higher hardness.[9] This can cause a relatively lower amount of wear loss in the cylinder liner.

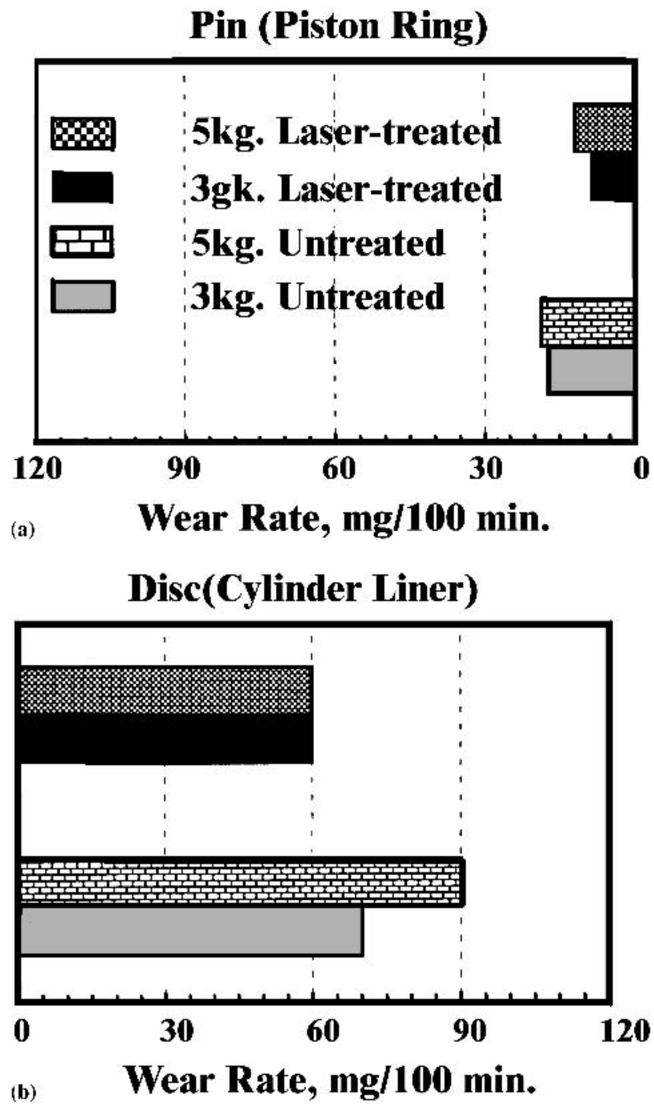
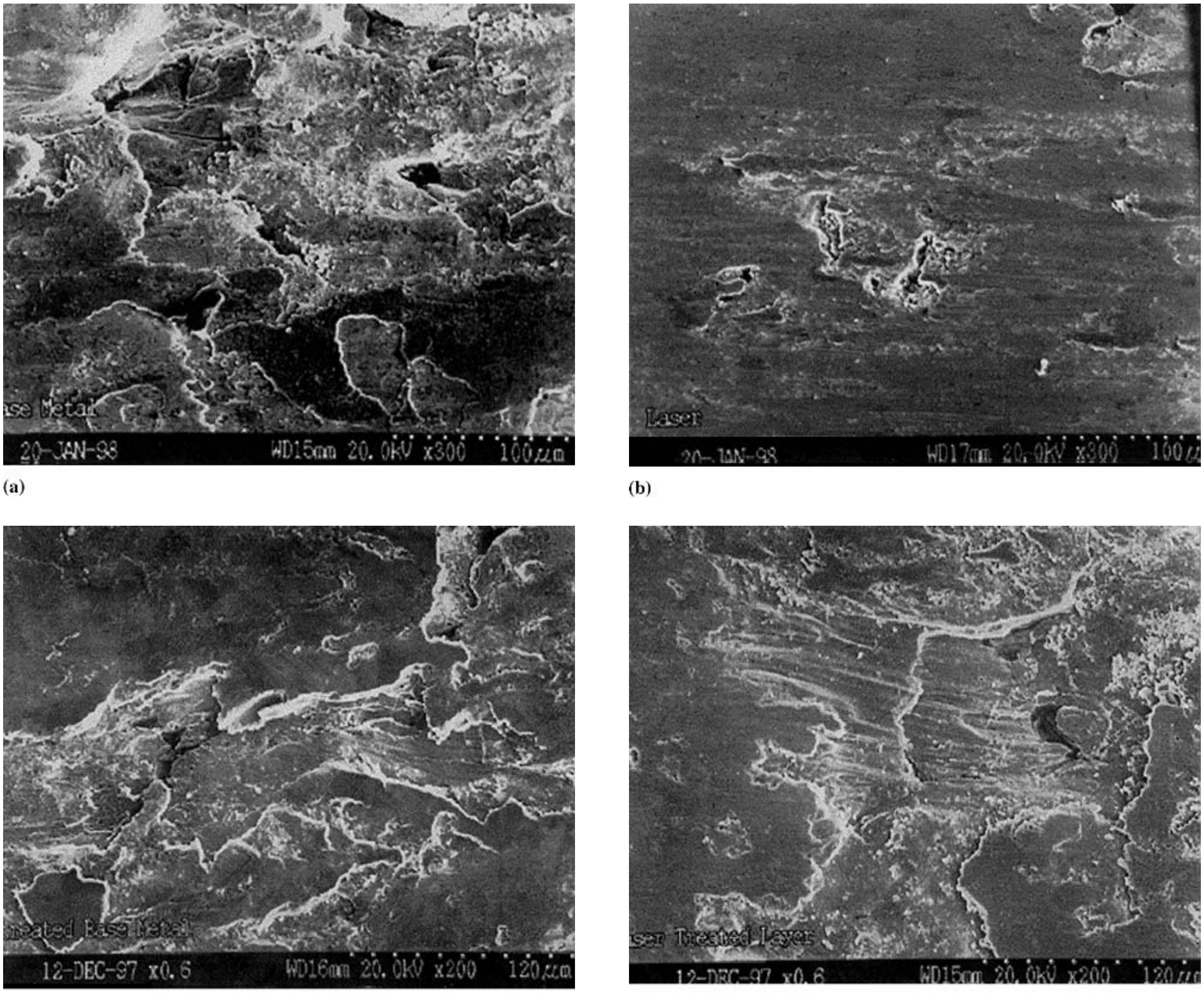


Fig. 13 Relative wear loss between **(a)** the pin (piston ring) and **(b)** the disc (cylinder liner)

4. Conclusions

The effect of laser power and travel speed on the characteristics of the laser-hardened layer of gray cast iron was investigated in order to establish a proper processing window for laser process parameters, which can satisfy the industrial application requirement.

1) The hardness of the laser-hardened layer was in a range between 800 and 950 Hv0.1, regardless of the laser power and travel speed range studied.
2) A proper processing window for laser hardening was established as a heat input range of between 30 and 45 J/mm.
3) The wear life of the laser-hardened layer was double that of the untreated layer.



(a) (b) (c) (d)

Fig. 14 SEM micrographs of the worn surface after the wear test: **(a)** untreated, (3 kg); **(b)** laser-treated (3 kg); **(c)** untreated (5 kg); and **(d)** laser-treated (5 kg)

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