

## Pulsed Laser Surface Hardening of Ferrous Alloys

Zhiyue Xu,<sup>1</sup> Claude B. Reed<sup>1</sup>, Keng H. Leong<sup>2</sup> and Boyd V. Hunter<sup>3</sup>

<sup>1</sup> Technology Development Division, Argonne National Laboratory,  
9700 S. Cass Avenue, Building 360, Argonne, IL 60439

<sup>2</sup> Applied Research Laboratory, The Pennsylvania State University  
State College, PA 16804

<sup>3</sup> LightPath Technologies, Inc., 6820 Academy Parkway East, NE  
Albuquerque, NM 87109

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## **ABSTRACT**

A high power pulsed Nd:YAG laser and special optics were used to produce surface hardening on 1045 steel and gray cast iron by varying the process parameters. Unlike CO<sub>2</sub> lasers, where absorptive coatings are required, the higher absorptivity of ferrous alloys at the Nd:YAG laser wavelength eliminates the necessity of applying a coating before processing. Metallurgical analysis of the treated tracks showed that very fine and hard martensitic microstructure (1045 steel) or inhomogeneous martensite (gray cast iron) were obtained without surface melting, giving maximum hardness of HRC 61 and HRC 40 for 1045 steel and gray cast iron respectively. The corresponding maximum case depths for both alloys at the above hardness are 0.6 mm. Gray cast iron was more difficult to harden without surface melting because of its lower melting temperature and a significantly longer time-at-temperature required to diffuse carbon atoms from the graphite flakes into the austenite matrix during laser heating. The thermal distortion was characterized in term of flatness changes after surface hardening.

## **INTRODUCTION**

Transformation surface hardening, selective austenitization and martensitization of local surface region of previously toughened material by rapid heating and cooling, is widely applied to many moving components such as cam or ring gears that must have a very hard surface to resist wear, along with a tough interior to resist the impact that occurs during operation. The conventional methods used to harden the surface of the ferrous materials include flame and induction hardening. Case hardened depths of several millimeters are obtained but with significant thermal distortion of the components such that rework is usually required.<sup>[1,2]</sup> Laser transformation surface hardening is an alternative technique that selectively hardens the wear surface only with the rest of the component providing the heat sink. This self-quenching eliminates the need to use oil or water quenching baths. Most attractively, laser surface hardening generates rare thermal distortion so refinishing of the part can be eliminated.

Both high power CO<sub>2</sub> and Nd:YAG laser have been used to carry out surface hardening of ferrous alloys. On bare, polished metals, the absorptivity of the 10.6  $\mu\text{m}$  radiation from a CO<sub>2</sub> laser is on the order of 10% for irradiances less than 10<sup>5</sup> W/cm<sup>2</sup>. The absorptivity of 1.06  $\mu\text{m}$  radiation from a Nd:YAG laser for bare polished metals is 35-45%.<sup>[3]</sup> Since transformation surface hardening requires a controlled heating of the materials, enough to cause a phase transformation without melting the surface, much lower irradiances, on the order of 10<sup>3</sup> to 10<sup>4</sup> W/cm<sup>2</sup> are used.<sup>[4]</sup> In order to get reasonable coupling between the laser and the metal, some coating is generally required which adds the cost to the process. Since bare metals absorb the more energetic 1.06  $\mu\text{m}$  photons much more readily than the 10.6  $\mu\text{m}$  photons, there is the possibility of surface hardening without coatings. In this study, surface hardening without coatings was applied

to two ferrous materials, 1045 steel and gray cast iron (3.10-3.50 wt% carbon content). The tests were carried out with an available high power pulsed Nd:YAG laser that adequately approximated a CW effect. The results of the heat treatment, such as range of processing parameters and the resulted hardness, case depth and microstructure of the treated layers were presented. Also in this study, an infrared processing monitor was used to monitor in real-time the infrared emissions during laser surface hardening. The signal from the monitor was correlated with the hardness of the laser-treated tracks. Thermal distortion was also characterized by the term of flatness change of the treated surface.

## EXPERIMENTAL PROCEDURES

A pulsed 1.6 kW Nd:YAG laser (Elctrox) with fiber optic beam delivery through a 1000  $\mu\text{m}$  step-index fiber and a highly astigmatic combination of the 127 mm cylindrical lens and a 75 mm spherical lens were used to conduct the surface hardening treatment. This lens combination is shown in Figure 1. An oval beam profile was achieved by the combined lens. The oval beam profile was chosen because of the aspect ratio and the steepness of the irradiance gradient along the minor axis (the beam was translated parallel to the major axis) which minimized waste of energy. The treated tracks were made on 1045 steel and gray cast iron (3.10-3.50 wt% carbon content) at dbeam travel speeds ranging from 1 to 5 cm/s provided by moving the workpiece on a CNC stage

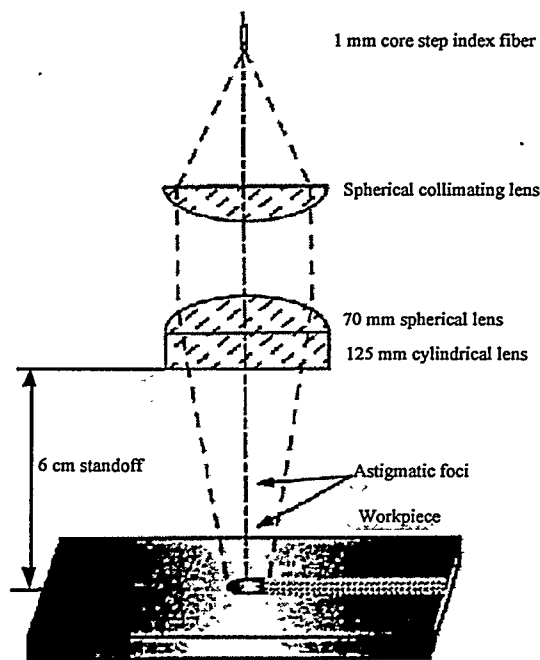


Figure 1 Layout of lenses used for heat treatment with Nd:YAG system

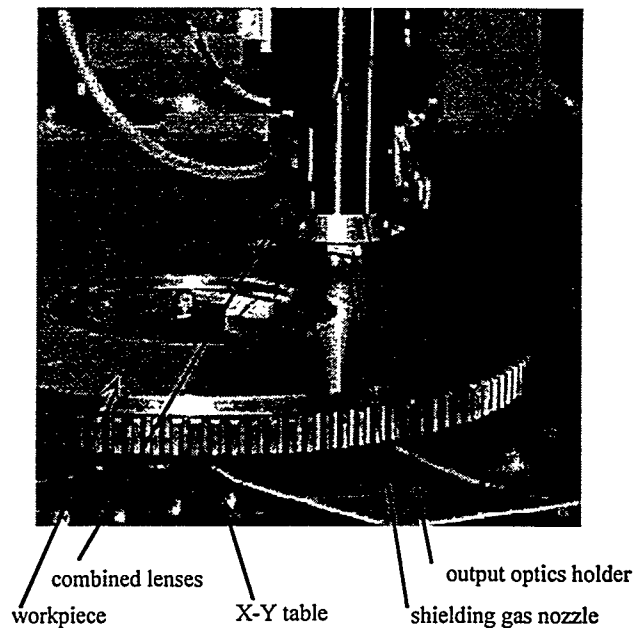


Figure 2 Annotated photograph of Nd:YAG laser surface hardening

under the stationary laser head. The average power was 1200 watts (3.0 kW peak power) at the workpiece, in which the pulse width was 2 ms and the repetition rate was 200 Hz. The pulse parameters were set to simulate the effect of a cw laser taking into account the thermal relaxation time of the metal. The same pulse settings were used for both alloys. The oval beam, after being defocused, had a minor axis of 4 mm and major axis of 6 mm. Then the area of the oval beam was 0.75  $\text{cm}^2$ , giving the peak irradiance of the beam of  $3.89 \times 10^3 \text{ W/cm}^2$ . Top gas shielding was provided by a 25 lpm flow of nitrogen in a trailing jet configuration delivered by a 0.8 cm diameter

tube oriented at  $15^\circ$  from the surface,  $45^\circ$  from the horizontal and 10 mm from beam spot. The annotated photograph of the set-up of YAG laser surface hardening is shown in Figure 2. An infrared weld monitor, successfully used to monitor the weld quality [5,6] was utilized to monitor the processing of surface hardening. The monitor was integrated into the YAG beam delivery optics and uses oversized, off-axis optics to collect the infrared emission signal associated with laser beam surface hardening. Monitor voltages as a function of time were collected using data acquisition hardware and software (GW Instruments, Somerville, MA) with an Apple Macintosh computer. The data collection rate was 2500 to 5000 Hz. The Rockwell C hardnesses along the treated tracks were measured using a portable hardness tester. The corresponding monitor voltage for each hardness measurement on a treated track was obtained from the monitor voltage-time plot. After surface hardening, the treated tracks were sectioned, polished, and etched to determine microstructure, case depth, and width. The deviation of the flatness after the treatment was measured using a Starrett's dial indicator with an accuracy of 0.001".

## RESULTS AND DISCUSSION

The microstructures of laser treated and untreated 1045 steel are shown in Figure 3. There are a completed hardened zone and a transition zone in the laser treated case (Fig. 3 (a)). Ferrite phase on the original pearlite boundaries remained in the transition zone because of the temperature distribution along the case depth as shown in Figure 4. When the material temperature was larger than  $A_{c3}$ , all the phases at room temperature transformed into austenite. After the self-quenching, the austenite transformed into martensite. At temperatures in the range between  $A_{c1}$  and  $A_{c3}$ , a part of ferrite phase still remained besides the austenite phase. After self-quenching, the ferrite phase

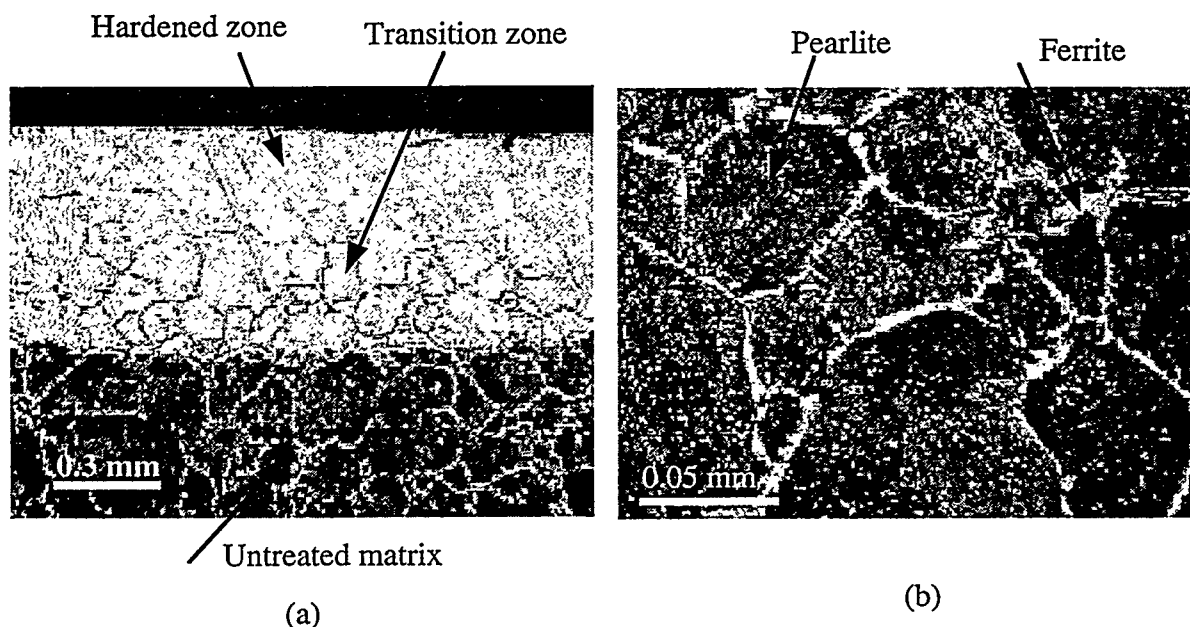


Figure 3 Micrographs of laser surface hardening of 1045 steel for beam power 1200 W, pulse width 2 ms, pulse frequency 200 Hz and beam travel speed of 2 cm/s. (a) 50 X and (b) untreated zone at 400 X.

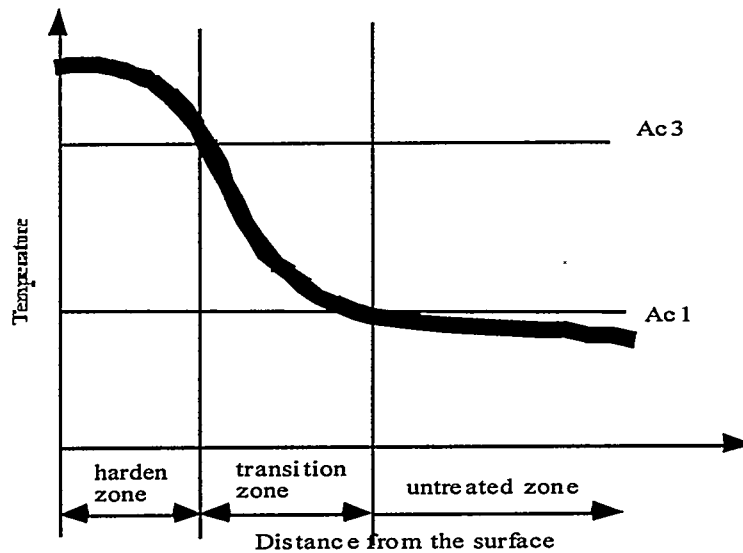


Figure 4. Schematic of temperature distribution versus distance from the workpiece surface.

remained. Below  $A_{c1}$ , there is no phase transformation. The typical annealed microstructure of pearlite (black phase) plus ferrite (white phase) was observed for untreated matrix (Fig. 3 (b)). Since the temperature distribution changes with beam travel speed, the case depth changes. As the beam travel speed increased at fixed beam power, the case depth decreased. So did the thickness of

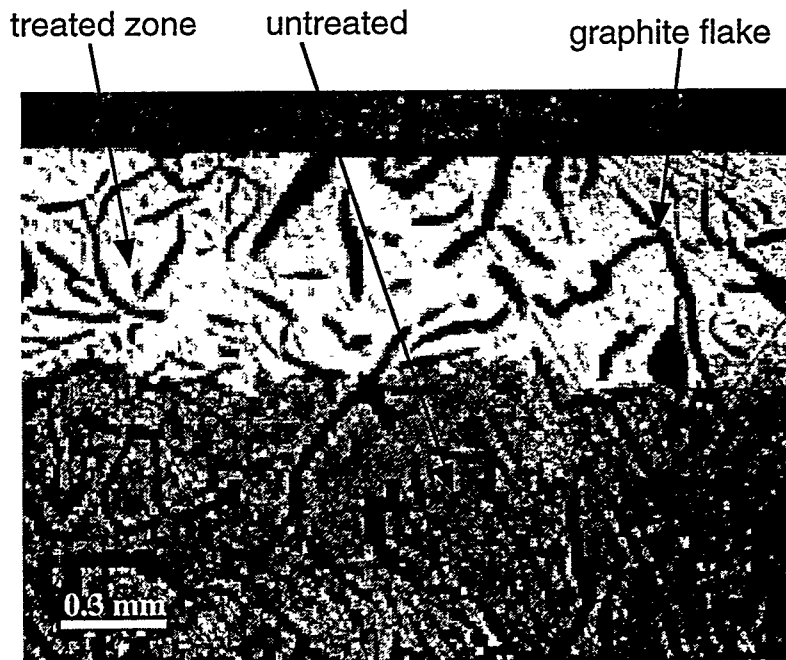


Figure 5 Micrograph showing laser treated surface layer (white) and untreated matrix.

the transition zone. Figure 5 shows the microstructures after laser surface hardening of gray cast iron. The graphite flakes kept unchanged. The hardness for laser treated gray cast iron and 1045 steel at varied beam travel speeds are shown in Figure 6. The beam travel speeds for surface melting were indicated by the vertical lines below which the surface melting occurred. The maximum hardness possible without surface melting for 1045 was HRC 61 and HRC 40 for gray cast iron. The gray cast iron is more difficult to harden without surface melting because of its lower melting point (1154 °C) and a significantly longer time-at-temperature required to diffuse carbon atoms from the graphite flakes into the matrix during laser heating,[7,8,9] Since the pulse frequency was set to mimic CW operation and the beam was scanned over the the workpiece surface, the interaction time between the beam and workpiece can be expressed as:[10]

$$\text{Interaction Time} = \frac{\text{Beam length in beam travel direction}}{\text{Beam travel speed}}$$

Therefore, the interaction time was in the range of 0.12 to 0.60 seconds for beam travel speed of 5 cm/s to 1 cm/s with a beam length in beam travel direction of 6 mm. For gray cast iron, this short

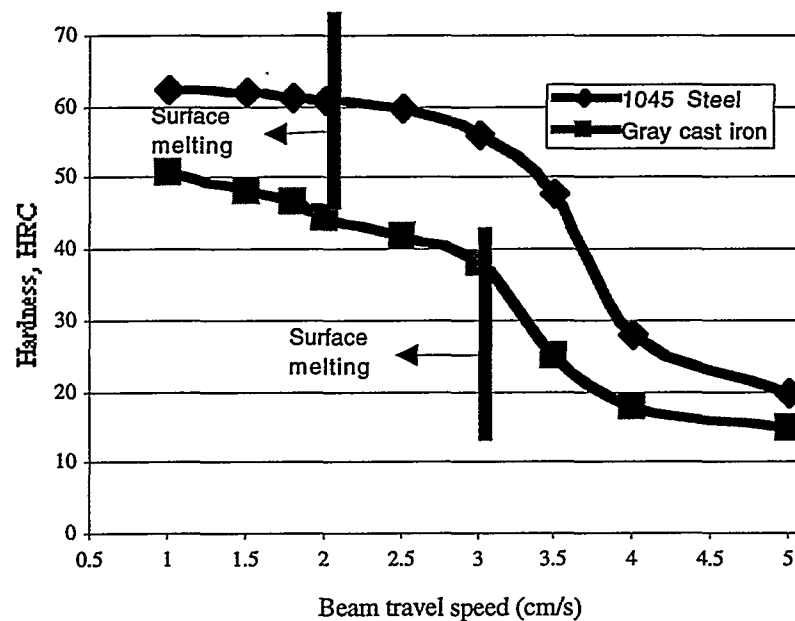


Figure 6 Hardness at varied beam travel speeds on 1045 steel and gray cast iron for 1200 W of Nd:YAG.

austenitizing cycle time can not provide enough time-at-temperature to form a homogeneous austenite containing all available carbon so that the hardest possible martensite would form upon cooling. On the other hand, 1045 steel has a higher melting temperature, 1460 °C. The higher the austenitizing temperature, the longer the time that laser can heat the certain volume of material without surface melting, the shorter the time-at-temperature required to diffuse certain amount of carbon atoms and the more available carbon in the austenite phase. Therefore, 1045 steel can harden to higher hardness level (HRC 61) compared to gray cast iron at the same beam travel speed (2.5 cm/s) and beam parameters. The typical case depth profiles hardened at beam travel speed of 2.5 cm/s on a 1045 steel and gray cast iron are shown in Figure 7. The longitudinal hardness



profile and transverse hardness profile hardened at beam travel speed of 2.5 cm/s on a 1045 steel plate are shown in Figure 8 and 9. A case depth of 0.6 mm with hardness of HRC 61 for 1045 steel and HRC 40 for gray cast iron was obtained. Longitudinal and transverse hardness profile show that very uniform hardness obtained on the treated track indicating the good quality of the beam achieved through the special optics. The deviations measured on a gray cast iron component before and after laser surface treatment at 2.5 cm/s are shown in Figure 10. The thermal distortion due to the laser surface hardening was less than 16  $\mu\text{m}$ , which is much less than the limitation of thermal distortion required for fitup of parts.

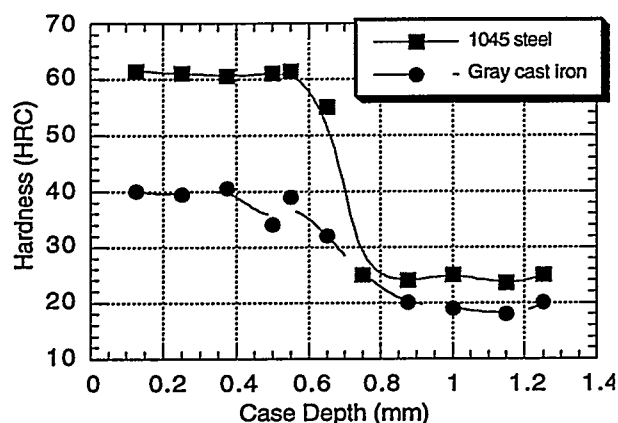


Figure 7 Case depth for 1200 W of Nd:YAG hardened at 2.5 cm/s on 1045 steel and gray cast iron plates

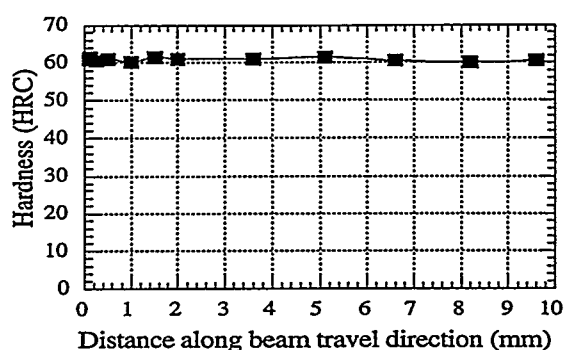


Figure 8 Longitudinal hardness profile for 1200 W of Nd:YAG at 2.5 cm/s on 1045 steel plate.

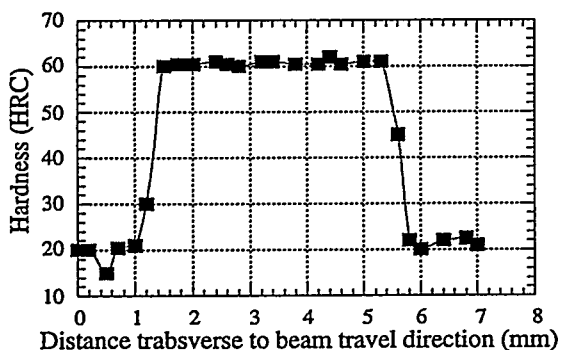


Figure 9 Transverse hardness profile for 1200 W of Nd:YAG at 2.5 cm/s on 1045 steel plate.

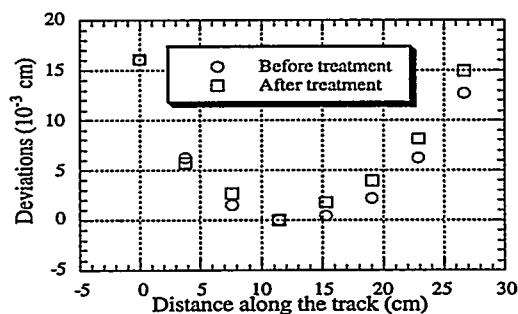


Figure 10 Deviations measured along the laser-treated track on a gray cast iron component before and after the treatment at a beam travel speed of 2.5 cm/s.

## CONCLUSIONS

Nd:YAG laser can be used efficiently to laser-harden uncoated 1045 steel and partially harden gray cast iron without surface melting. The beam travel speed for surface melting was found to be 2 cm/s for 1045 steel and 3 cm/s for gray cast iron for a laser beam power of 1200 watts. Case depth of 0.6 mm with Rockwell C 61 and 40 were achieved without surface melting for laser-treated 1045 steel and gray cast iron respectively.

## ACKNOWLEDGMENTS

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