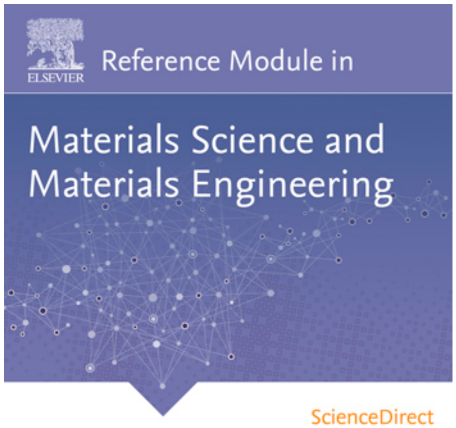

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Material Response With High Power Laser in Surface Treatment of Ferrous Alloys

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1 Introduction

The unique properties of the laser beam, such as high intensity, coherency, monochromatic, highly directional nature, and ability to deliver controlled amounts of confined energy to desired regions at a high rate have made it an important tool in improving hardness, wear, and fatigue properties of many engineering materials [1–8]. It offers some technical and economic benefits compared to conventional methods and electron beam heating process. When a beam of high power laser light impinges on a material's surface, energy is partially reflected, partially absorbed, and partially transmitted depending on the material type and laser wavelength. Once the light energy impinges on the surface, the portion that is absorbed is of interest in material processing. The specific mechanisms by which the absorption occurs will depend on the type of material. In metals, optical absorption is dominated by the free electrons through such mechanisms as inverse bremsstrahlung [9]. Energy is subsequently transferred to lattice phonons by collisions. Light is absorbed in the form of electronic and vibration excitation of the atoms, and energy converts into heat, which dissipates to adjacent atoms. As more and more photons are absorbed, the material temperature increases, thereby increasing the fraction of light absorbed. The process sets off a chain reaction resulting in a rapid rise in temperature in a very short time typically within a millisecond. The rate of temperature rise depends on a balance between energy absorption and energy dissipated by the material. Depending on the interaction time between the laser beam with the matter, laser beam power density, and thermos-physical properties of the matter, the surface temperature may exceed the melting point or reaches boiling point in a very short time.

Several regimes can be obtained from this interaction, such as heating below melting point, melting, and evaporation. **Fig. 1** shows the power density – interaction time diagram for different surface hardening processes [10]. From the diagram, it appears that transformation hardening process requires low power density 10^3–10^5 W/cm^2 and long interaction time 0.1 to 1 s in the contrary to the laser cutting and welding which required high power density and short interaction time. The following sections give a review about the use of high power lasers in transformation hardening especially for steel and cast iron which are widely used in automotive industry.

2 Basic Principles of Laser Heat Treatment

Steels and cast irons are the primary candidates for laser heat treatment. In this process, a thin layer of the substrate is rapidly heated well into austenizing temperature by laser beam heating and subsequently cooled at a very fast rate. The large temperature gradients achieved with localized laser heating can lead to rapid self-quenching of the material, trapping in highly nonequilibrium structures. Also, the rapid generation of large temperature gradients can induce thermal stresses and thermoelastic excitation of

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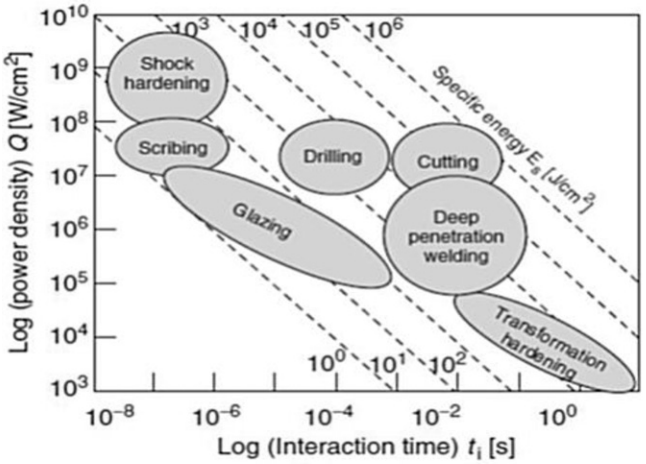

Fig. 1 Dependence of power density, specific energy and interaction time at laser metalworking processes [10].

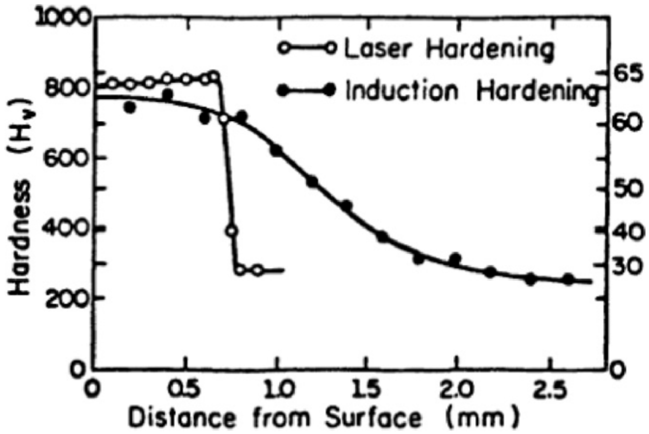

Fig. 2 Hardness profile across the depth for laser hardening and induction hardening methods [11].

acoustic waves. These stresses can contribute to the mechanical response of the material, such as work hardening, warping, or cracking. In order to perform heat treatment by laser beam, it is necessary to notice the three most important criteria which are:

1. Temperature for the zone being harden must reach well into austenization zone.
2. Between heating and cooling cycles, the substrate should be maintained at austenization temperature long enough time for carbon diffusion.
3. There should be enough mass so that the cooling rate by self-diffusion is such that it could satisfy the critical quenching rate requirement.

Metallurgical considerations for laser heating are similar to that conventional heat treating processes. The process does, however, differ from conventional process in the following aspects:

1. Extremely rapid heating and cooling rates inherent in laser heating makes the hardening of low carbon steel possible with relative ease. Differences in hardenability between carbon steels and alloy steels are not as prominent as conventional processes since cooling rates since cooling rate in laser heat treatment is high enough to the critical cooling rate.
2. Often hardness is higher than those observed in conventional processes are reported as shown in **Fig. 2**. Kikuuchi *et al.* [11] suggested that during laser heat treatment, martensite is formed under unusually high restraint due to localized and rapid heating and cooling rates. This leads to the formation of unusually deformed martensite which in turn produces higher hardness.
3. Alloys requiring high soaking time, such as steels containing spheroidal carbides, or cast iron containing mostly graphite and no pearlite would be difficult candidates for laser heat treating. This is because the longer soak time required for carbon diffusion would restrict the laser operating parameters and such process would lose its inherent advantage of rapid heating and cooling rate.

However, cast irons with a combination of pearlite and graphite can be successfully heat treated. Hence while pearlite is being dissolved to become austenite and subsequently transformed to martensite, some carbon diffusion will take place out of graphite flakes which will produce martensite around the graphite flakes. However, transformation of pearlite will dominate the hardening mechanism.

3 Laser Heat Treatments Variables

Laser heat treatment process is controlled by two important phenomena which are heat transfer and mass transfer and these are influenced by laser processing parameters. Some of the independent parameters are related to the laser such as laser beam diameter which determines the power density and traverse speed which determine the interaction time between the laser beam and the substrate surface. Other parameters related to material to be heat treated and these include absorptivity of the laser beam energy and thermos-physical properties. The dependent variables are the hardness, the depth of hardening, geometry of the heat affected zone, the microstructure, and metallurgical properties of the laser heat treated zone. In order to understand the process of hardening by laser it is important to study the processing parameters and their relations in more detail as discussed below.

3.1 Laser Beam Diameter and Intensity Distribution

Spatial intensity distribution is one of the fundamental parameters that indicate how a laser beam will behave in an application. For example, in a materials processing situation, it is easily understandable why two beams of identical power and diameter leave different burn marks on a substrate if one beam features a Gaussian or near-Gaussian profile (maximum intensity in the beam center from the center decreasing rapidly with distance), while the other beam features a so-called donut profile (very little power intensity in the beam center and increase rapidly as the distance increase from the center). Theory can sometimes predict the behavior of a beam, but manufacturing tolerances in lenses and mirrors, as well as ambient conditions affecting the laser cavity, necessitate verification. Consequently, it is crucial for researchers, system designers, and laser manufacturers to be able to verify spatial intensity distribution (intensity profile).

3.2 Power Density

Generally speaking, the higher the power density, the deeper the hardened depth. However, if all other variables are fixed, there is a maximum depth that can be achieved. When that limit is exceeded, surface melting will occur.

3.3 Travel Speed

Traverse speed determines the interaction time. It is inversely proportional to the hardened depth. If, after maximizing all variables, travel speed is increased, the hardened depth will be decreased until there is no reaction with the material. Decreased travel speed will cause significant surface melting and/or a lower hardness.

3.4 Absorptivity

The efficiency of laser heat treatment depends on the absorption of light energy by the work piece so, any heat transfer calculation for laser processing is based on the absorbed energy. The absorptivity of CO_2 laser is very low due to the longer wavelength (10.6 μm) as compared to 1.06 μm the wavelength of Nd-YAG laser. The most commonly absorbent coatings used include colloidal graphite and manganese. Therefore some absorbent coatings are required to improve coupling efficiency between laser beam and substrate surface specially when CO_2 laser is used since phosphate, zinc phosphate, and black paint. A mixture of sodium and potassium silicate is also known to produce very high absorptivity. It has been found by many researchers an increase in absorptivity of between 60 and 80% after applying these coatings. However, coating thickness, coarseness, and adherence to the substrate will always influence the absorptivity [7]. For treatment by Nd-YAG laser, no need to use coating due to its shorter wavelength and higher degree of absorption.

The relationship between the reflectivity of various metals and the wavelength of the incident light is shown in **Fig. 3**. The absorptivity of the surface is not only dependent on the wavelength of the incident light but also on the angle of incidence, if the light is polarized. Gutu *et al.* [12] observed a 2.2–4-fold increase in the surface absorption of the incident polarized light from a CO_2 laser for an incident angle in the range 70–80 degree. Gutu *et al.* [12] also noted that this principle can also be applied to other laser types and is not restricted to CO_2 lasers [13]. It is important to mention that CO_2 and Nd:YAG lasers which have a Gaussian distributed beam with a high intensity at the center of the beam, decreasing rapidly with distance from the center. This is generally unfavorable for hardening.

3.5 Thermophysical Properties of the Materials

The most significant thermophysical property of a material for laser hardening is its thermal diffusivity, α, where $\alpha = K/\rho c$ (where K is the thermal conductivity, ρ the density and c the heat capacitance). This factor is involved in all unsteady-state heat flow processes and its significance is that it determines how rapidly a material will accept and conduct thermal energy.

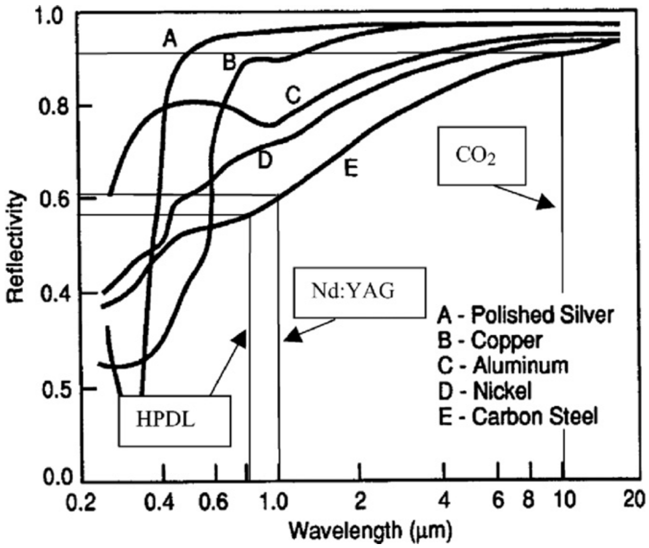

Fig. 3 Reflectivity as a function of wavelength for various materials [7].

4 Suitable Laser Types

Three different types of laser sources including CO_2, Nd:YAG, and high power diode lasers used to be the alternatives used for laser surface treatment. Until the end of last century, CO_2 laser was almost the only laser type that was capable to provide the combination of power density and interaction time required for laser hardening [7]. Since late 1990s, the development of multi-kilowatt Nd:YAG lasers with both flash lamp and diode pumping provide an alternative source with several advantages. One of the main benefits of Nd:YAG laser is that the wavelength of the laser light (typically 1.06 µm) allows the beam to be delivered via an optical fiber with relatively low energy loss. This enables flexible delivery of the laser beam at the processing head. Consequently, Nd:YAG lasers providing high levels of laser power can be manipulated with robot, making them ideal for three-dimensional processing. More recently, multi-kilowatt diode lasers were developed with the wavelength of approximately 8 µm, which are compact and can be mounted directly on a robot for hardening of components with complex geometries. Compared with the wavelength of a CO_2 laser (around 10.6 µm), the beam wavelengths of Nd:YAG and diode lasers increase the absorptivity on metal surface significantly and thus absorptive coatings are no longer needed, simplifying the operation and reducing the cost of production.

High power Nd:YAG and diode lasers have been applied in various treatments of steel and its alloys [4,7,14]. Besides, various types of special shaping optics were developed as an advanced solution to produce desirable shapes and sizes of laser irradiated area with relatively homogeneous energy distribution.

During the last decade or so, high power fiber lasers have been developed in a dramatic manner. From lab setups delivering milli watt-scale output power in the early 1990s, fiber lasers have evolved to multi-kilowatt devices for use in industrial material processing. Two technical developments promoted the progress of fiber laser: the optical communication industry provided the preparation technologies for highly transmissive single-mode fibers and the optoelectronics industry made available the high-power laser diodes required for the pumping of fibers. The increased power level of fiber laser is to a large extent based on the availability of reliable and long-life diode pump systems [15,16].

5 Laser Transformation Hardening

All types of steels can be treated by laser, the response of steel to hardening increases with increasing carbon content. However, plain carbon steel (0.2%C) will harden at very high cooling rates. The hardenability of cast irons is controlled by the amount of pearlite present and the spacing between Fe3C lamella, and only martensitic stainless steels will respond to heat-treating. Automobile components, such as camshafts, crankshafts, brake drums, internal combustion engine valve and valve seat and gears were improved by this method. **Table 1** showed industry sector, component and materials which have been used for laser hardening. The automotive and machine tool industries have been responsible for much of the laser heat treatment process development [13,17–25].

5.1 Microstructure and Hardness Improvement

Babu *et al.* [25] have studied the effects of laser hardening process parameters on the microstructure and hardness during laser hardening of EN25 steel treated with a high power Nd-YAG laser. The surface hardness of EN25 material (360–380 HV0:5) was

Table 1 Optics applied in laser hardening and corresponding features

Industry sector	*Component*	*Material*
Automotive	Torsion springs	DIN 58CrV4 steel [13]
Automotive	Blanking die	Tool steel [17]
Automotive	Engine valve	Alloy steel [18]
Automotive	Hand brake ratchet	Low carbon steel [19]
Domestic goods	Typewriter interposer	AISI 1065 steel [20]
Machine tools	Cutting edge	Steel [19]
Machinery	Gear teeth	AISI 1060/low alloy steel [21]
Machinery	Capstan	AISI 1045 Steel [22]
Machinery	Mandrel	Martensitic stainless steel [23]
Power generation	Turbine blade edge	Martensitic stainless steel [24]

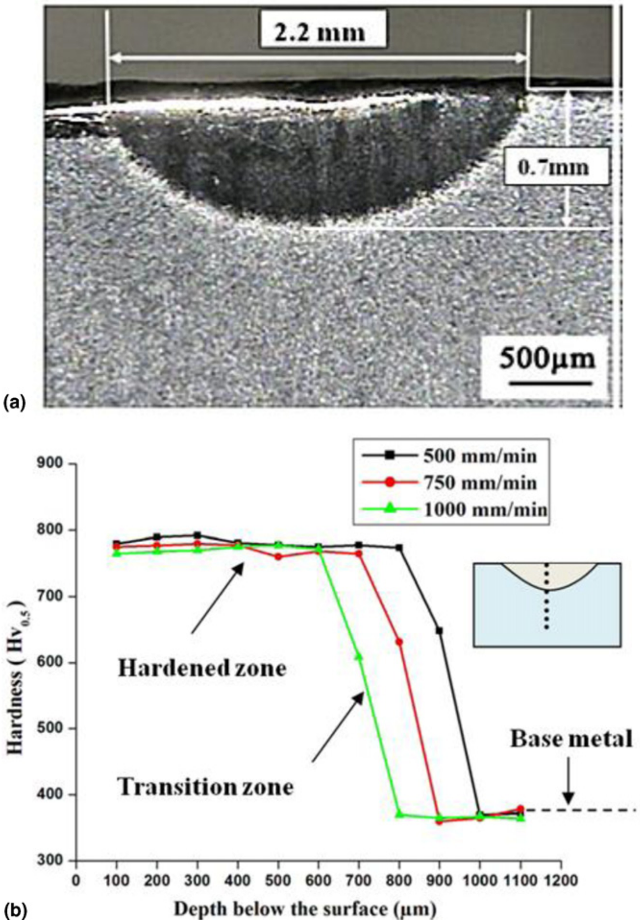

Fig. 4 (a) Macrostructure of laser treated sample for the for the power density of 4×10^4 W/cm^2 at $\times 40$ magnification at 500 mm/min. (b) Effect of traverse speed on hardness of low alloy steel (EN25) along depth for the power density of 4×104 W/cm^2, for three scanning rates [25].

increased more than twofold (782 HV0:5) by laser hardening method. The hardened zone of the laser treated surfaces was ranged in depths of 0.55–0.7 mm depended on scanning speed and laser power density (Fig. 4(a) and (b)). The hardened zone microstructure consists mainly of plate martensite in the upper zone with a thin transition zone consisting of mixed microstructure of martensite and tempered bainite in the lower part. Melting was occurred at higher power density 5.3×10^4 and 6.6×10^4 W/cm^2 which was overcome by increase of scanning speed.

SeDao *et al.* [26] studied the change of crystalline structure and composition of the treated DF-2 cold work tool steel surface layers before and after laser treatments. Their measured microhardness values indicated a significant improvement of the hardness of the treated surface, which is due to the formation of fine martensite. Penetration depth of the micro-hardness changes mainly with the laser irradiating parameters that recursively results in different microstructures; the laser irradiation parameters allowed

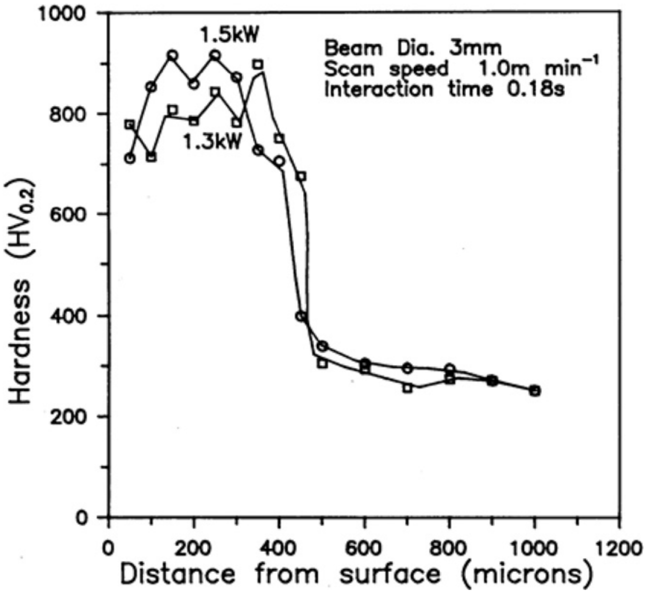

Fig. 5 Hardness profile along depth direction of laser-hardened En18 steel [26].

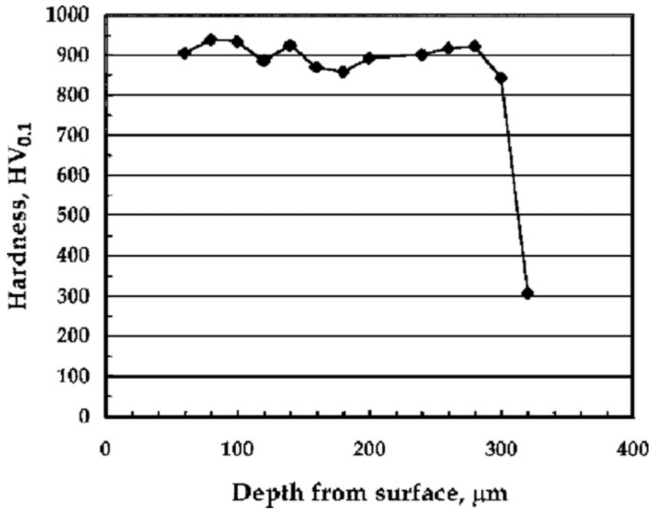

Fig. 6 Hardness distribution along the thickness direction of the laser heat treated region (single pass) [28].

the fulfilment of highest micro-hardness at the outermost surface. **Fig. 5** shows the hardness profile for laser-hardened samples at 1.5 and 1.3 kW under a scan speed of 1 m min^{-1} and with a beam diameter of 3 mm.

Pashby *et al.* [27] have demonstrated the technical capability of diode lasers in surface hardening both plain carbon and alloy steel with practical case depths being achieved. They have treated medium carbon steel and alloy steel using 1.2 kW diode laser operated at scanning speed 50–1700 mm/min. Microstructural examination of the treated surfaces revealed that conditions within the range examined were capable of producing structural changes and associated increases in hardness. Affected depths and maximum hardness achieved varied with power and speed, as well as with steel type. Hardened depths of greater than 0.5 mm were observed in both the plain carbon and the alloy steels. As would be expected, the maximum hardening effect was observed in the alloy steel, as was the maximum hardness.

For cast irons, numerous researches have been carried out to increase the hardness and improve wear resistance. The initial microstructure of the cast iron plays important role in determining the maximum hardness. Jong-Hyun Hwang *et al.* [28] have carried out laser surface hardening for cast iron which is used in piston ring. The homogeneity of hardness and hardened depth with different processing parameters were investigated. The initial microstructure consisted of fine graphite flakes embedded in a pealitic matrix. A significant increase in hardness after laser treatment from 250 to 900 HV extended to a depth of 0.31 mm was reported (see **Fig. 6**); also hardness distribution across the depth was very uniform for a single pass.

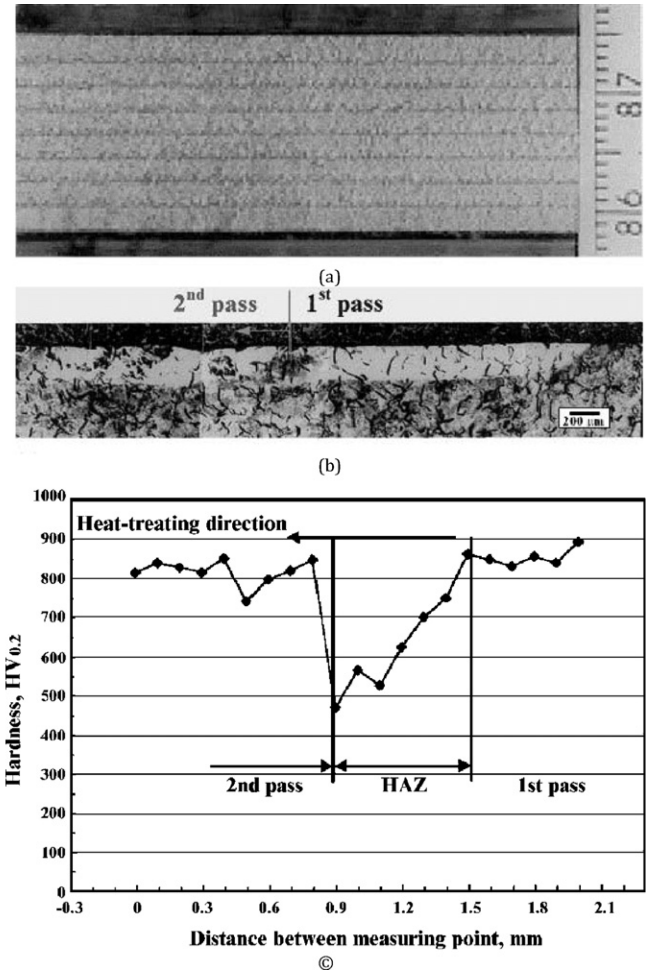

Fig. 7 (a) A series of overlapped covered the whole surface, (b) transverse section, and (c) hardness distribution across the hardening area between the first and second passes (multiplied passes) (Ref. [28]).

However, a drawback of laser hardening when it is necessary to make multiple passes with the laser over the surface of the work piece if the beam spot size is not large enough to cover the entire area. Lateral heat flow into the previously hardened track may cause "back tempering" which can reduce the hardness in the affected area considerably. **Fig. 7** shows tempering effect during multipasses surface hardening of the cast iron ring. Despite tempering effect, the wear life of the laser-hardened layer was double that of the untreated layer. 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 whereas in the laser-treated material, tearing damage occurred only around graphite flakes by the mild wear resulting from the higher hardness. This can cause a relatively lower amount of wear loss in the cylinder.

The problem of back tempering effect can be reduced or eliminated by using beam integrator [29] which produces a broad beam with uniform intensity distribution. A beam integrator consists of a focusing mirror with several segments of individual mirrors focused on the same on the same focal plane [29]. The rastering of a finally focused beam to cover a large area is another technique to avoid tempering effects. The use of doughnut shaped TEM beam with toric mirrors is also a better solution.

Xiu-bo *et al.* [30] used Nd:YAG laser for hardening the gray cast iron. The obtained microhardness level in the hardened layer is 700 HV, which is significantly higher than the microhardness of the substrate region which is 200 HV. It showed also that the laser surface hardened layers for gray cast iron has good wear resistance under severe tribological service conditions.

Liu *et al.* [31] used a 2 kW continuous wave CO_2 laser for the laser quenching of the groove of the piston head in large diesel engines. The hardness and depth of the laser quenched layer attained 750 HV and 0.59 mm respectively and is substantially higher than that resulting from the high-frequency quenching method. The microstructure of the quenched layer composed of martensite and retained austenite. The wear testing results showed that the wear resistance of laser quenched specimens was 1.3 times more than that of a high frequency quenching specimen.

5.2 Wear Improvement

To diminish wear in tribological systems it is not always necessary to provide the entire surface with a wear resistant layer. Depending on the application it is sufficient to harden locally the load carrying areas which are subjected to wear. Such areas can be treated properly by a laser, either totally or partially. The effects of laser line hardening on the wear behavior of carbon steel AISI 1045 against ball bearing steel AISI 5210 has been studied by Vischer *et al.* [32]; 1.8 kW laser beam was applied with a beam integrator to generate a homogeneous energy distribution in the beam. The scan speed was in this case varied at 3, 6, and 12 mm/s. It is shown that the wear resistance of carbon steel AISI 1045 can be improved considerably by line hardening the surface. The wear resistance of the laser line hardened surfaces is comparable with that of carburized steel AISI 1045. However, the properties of the laser line hardened areas determine the wear behavior of the entire system. The experimental work has indicated that the type of heat treatment, carried out prior to line hardening in order to improve the microstructure of the steel, has no significant effect on the wear behavior of the tribological system. Furthermore, the experimental results showed that surfaces containing hardened lines parallel to the sliding direction did not show much difference in wear resistance from those containing lines perpendicular to the sliding direction. Wear tests with carburized and line hardened plates of steel AISI 1045 against a pin of steel AISI 52100 gave primarily a mixture of mild oxidative and micro-abrasive wear in contrast to adhesive wear in the untreated 1045 steel.

The wear of the piston ring is a more severe problem in marine diesel engines as it is operated under adverse conditions, such as higher power, higher pressure, and higher piston speed. Jong-Hyun Hwang *et al.* [28] found the optimum process parameters for laser surface-hardening to improve the wear life of piston rings. The resultant hardness of the laser-hardened layer is in the range of 840–950 VHN. The hardened layers formed with heat input ranges between 30 and 45 J/mm and satisfied the piston ring application with the minimum effective hardening depth of 0.3 mm. Pin-on-disk wear-test was carried out which showed that the wear life of the laser-hardened layer was almost twice that of the untreated one.

5.3 Fatigue Improvement

Several researchers have reported a significant improvement in fatigue properties of steel and cast irons after laser heat treatments [33,34]. Singh *et al.* [33] have reported an improvement in fatigue life by 30% over untreated materials. A range of compressive stresses between 364 and 512 MPa developed after laser treatment. Kikuchi *et al.* [11] also reported an increased in fatigue strength by 10 kg/mm^2 for various types of carbon steels.

Oh *et al.* [34] have studied the influence of surface heat treatment using high power diode laser radiation on the fatigue strength and corresponding microstructural evolution of AISI 4140 alloy steel. Laser power was controlled to give constant surface temperatures, 600, 700, and 800°C, measured using a pyrometer. The laser heat treatment prior to the peening further improved the fatigue behavior by promoting the phase transformation into martensite (**Fig. 8**). However, various laser temperatures between 600, 700, and 800°C caused a difference in austenization of proeutectoid ferrite and pearlite phases, affecting the fatigue behavior by the amount of martensitic transformation. With the 600°C laser, no phase transformation occurred because the temperature is far below the eutectoid temperature of iron–carbon alloy system. The temperature of 700°C is near the eutectoid temperature so that only small portion of ferrite and pearlite was austenized and transformed into the martensite. At the laser temperature of

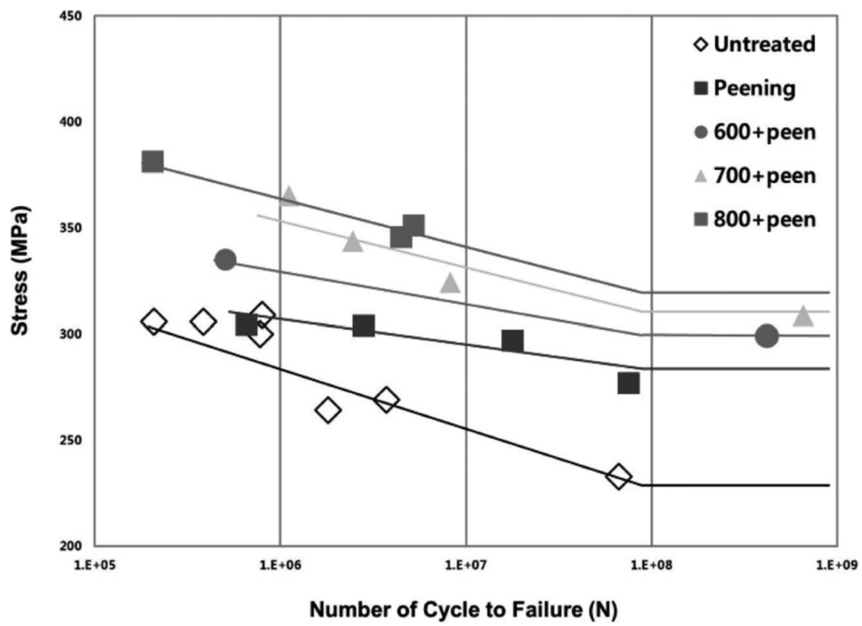

Fig. 8 S–N curves of AISI 4140 from the ultrasonic fatigue test depending on different surface treatment condition (Ref. [35]).

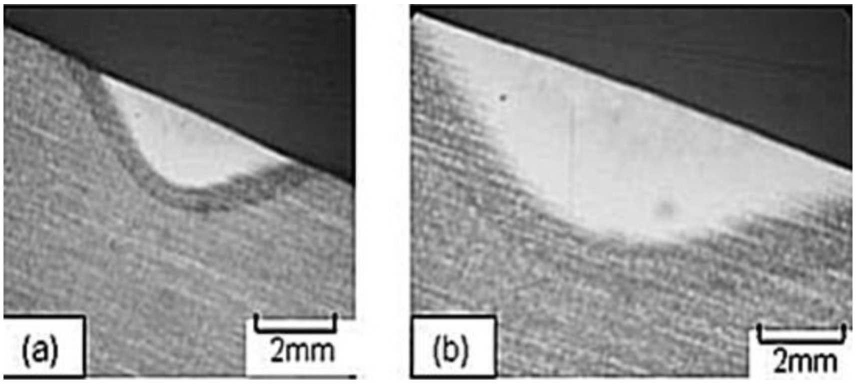

Fig. 9 Macrographs of cross sections taken from laser surface heat treated specimens produced using 4 mm laser spot size, 0.5 m/min processing speed and two different laser powers. (a) 400 W and (b) 1800 W.

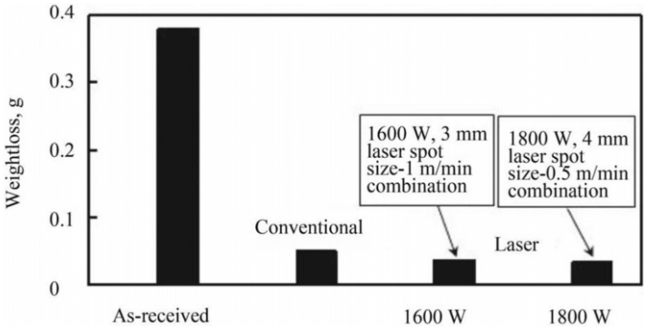

Fig. 10 Wear behavior of laser surface treated specimens as a function of laser processing parameters, together with that of conventionally heat treated specimen and as-received base metal [35].

800°C, the proeutectoid ferrite and pearlite phases are fully austenized and transformed into the martensite in the surface regions. The greatest fatigue behavior was achieved in this study when the specimen was heat treated by 800°C laser and subsequently peened, which is about 40% enhanced fatigue limit compared with the untreated condition. This improvement is attributed to appropriate contribution of the martensitic transformation and compressive residual stress on the surface (**Fig. 9**).

5.4 Optimization of Laser Processing Parameters

Optimization of laser processing parameters including laser power, laser spot size, and processing speed combination is of considerable importance for achieving maximum surface hardness and deepest hardened zone. In other words, laser processing parameters should be optimized for having surface temperature high enough for complete austenitization, without partial surface melting that in turn results in a homogeneous hard microstructure. El-Batahgy *et al.* [35] have optimized laser processing parameters of transformation hardening M2 HSS tool steel using Nd-YAG laser operated at different powers and beam size diameters. A series of laser power (400–1800 W, laser beam size diameter (1–4 mm), and scanning speed (0.5–4 m/min)) were used to optimize the process. Hardened zone with 1.25 mm depth and 996 HV surface hardness was produced using 1800 W laser power, 4 mm laser spot size and 0.5 m/min laser processing speed. The obtained maximum hardness of laser surface treated specimen is 23% higher than that of conventionally heat treated one. In general, higher laser power, larger spot size, and lower processing speed are more efficient for obtaining deeper hardened depth. Wear resistance of laser surface treated specimen is 30% higher than that of conventionally heat treated one and 90% higher than that of untreated base metal. Such higher wear resistance in case of laser surface treatment is related to higher hardness as a result of fine martensite and chromium carbides in the hardened zone. Wear resistance of laser surface treated specimens is about 30% higher than that of conventionally heat treated specimen and about 90% higher than that of untreated base metal. It is believed that the high hardness level obtained in case of laser surface heat treated specimens is responsible for high wear resistant of these specimens (**Fig. 10**).

The effect of laser processing parameters on the case depth of 4340 steel of cylindrical shape has been studied and analyzed statically by Noureddin *et al.* [36]; Taguchi method was used to optimize the process parameters. The obtained results were analyzed using ANOVA method to extract the effect and the interaction between the processing factors. A range of laser powers from 1250 to 1750 W, scanning speeds from 3 to 8 mm/s, and specimen revolution speeds from 500 to 8000 RPM were used in

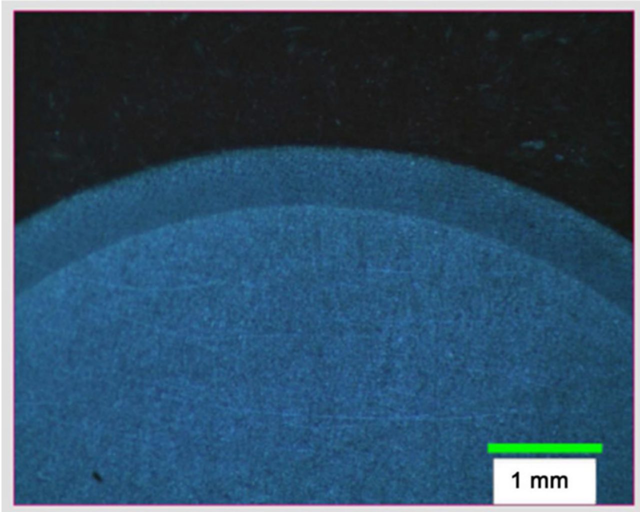

Fig. 11 A metallographic image representing the hardness profile obtained with 1550 W, 5 mm/s and 4000 RPM (Ref. [36]).

this work. The results showed that the case depth increased linearly from 0.4 mm at 1250 W to 1.1 mm at power 1750 W while the case depth decreased with increasing scanning speed. The scanning speed has a greater influence on the case depth while the laser power has a great effect on the hardness (**Fig. 11**).

5.5 Modeling of Transformation Hardening Process

Heat transfer is a fundamental and crucial factor that has significant influence on the intermediate process and the result of laser surface treatment [37–39]. To investigate the thermodynamic process, qualitative, and quantitative analysis using mathematical methods are thus required. In practice, a simply defocused Gaussian laser beam is often used as the heat source for surface treatment, although special optics can be installed for desired shape and energy distribution of laser irradiation. The defocused beam profile inherits the Gaussian energy distribution of the raw laser beam [40–42]. Some previous studies were attempted to solve the temperature field induced by a moving heat source. One of the earliest works was done in 1950s by Rykalin who developed an analytical solution for the temperature distribution in a semi-infinite solid with a point heat source moving on the surface [43]. Cline and Anthony used the heat-source superimposition method to give a numerical solution for heating a semi-infinite domain with a Gaussian heat source [44]. Manca *et al.* solved the temperature distribution induced by a moving Gaussian heat source in a finite domain [45]. Despite the previous studies, further modelized study is needed to develop equations for the important parameters of laser surface treatment of steel (e.g., phase transformation boundary and cooling rate) and provide solutions for them. Influence of laser power, laser traverse speed and depth of the workpiece are also studied. To solve the temperature distribution in a finite-depth solid with a moving Gaussian heat source, an analytical solution can be very complicated but the calculation can be done numerically with very high precision via computational tools [46].

Ashby and Easterling [47] have modeled laser surface hardening of hypoeutcetoid steels. The models developed combine an approximate solution for the temperature held with equations describing the kinetics of structural changes. They predict the structure and hardness of the transformed surface as a function of depth below the treated surface. The results are assembled into diagrams which show the structure and hardness of the surface as a function of the process variables, of which the most important are the energy density (MJ/m^2), the beam interaction time (s), and, of course the composition and microstructure of the steel. The equation was used to construct "laser-processing diagrams" which show the influence of the process variables and metallurgy of the steel on the final product. They have obvious application in selecting the best conditions for industrial laser processing.

The diagrams show that:

(a) Steels with a carbon content below about 0.1 wt% do not respond to transformation hardening: the low volume fraction of martensite, and its low carbon content, combine to give a surface with a hardness which is hardly changed by the process.
(b) There is an optimum combination of process variables which give maximum surface hardness without surface melting: the procedure developed here gives a rapid, precise way of choosing these, and of examining how changing the process variables changes both the hardness and the depth to which it extends.
(c) The method has generality, and could be extended to laser glazing and laser surface alloying. The calculations and plotting of the diagrams can be done quickly on a small microcomputer so the procedure can be used in the workshop.

Fig. 12 showed a laser-processing diagram for a 0.6 wt% plain carbon steel. The horizontal axes are incident energy density, q/w, and beam radius, r. These are the variables that determine the heat cycle in the transformed zone. The vertical axis is the depth, z, below the surface. Within the shaded region, melting occurs. Outside the melt zone, the diagram shows temperature contours

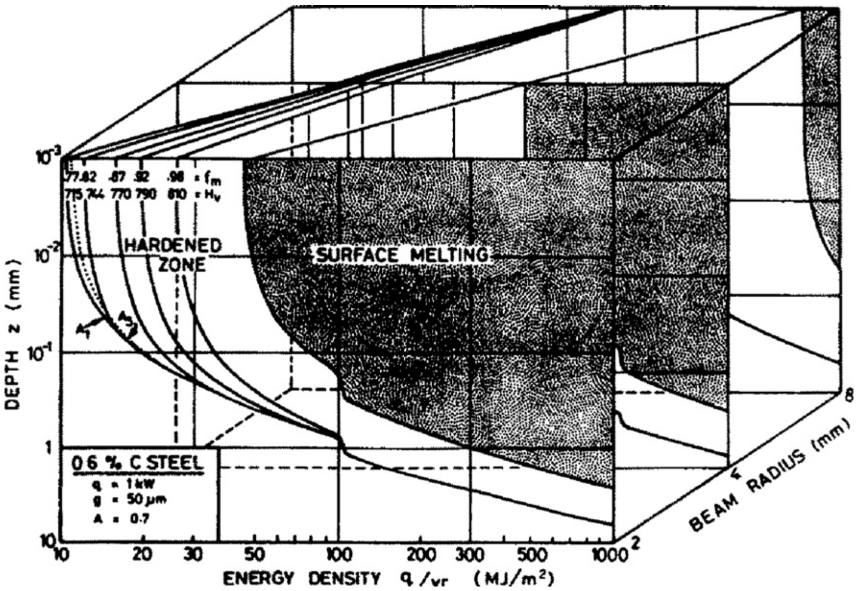

Fig. 12 A diagram describing the laser processing of a 0.6 wt% steel [47].

(dotted lines) along which the peak temperature just reaches A, the temperatures for the steel. It further shows contours of martensite volume fraction, increasing as the melt boundary is approached. The volume fraction and carbon content of the martensite are used to calculate the hardness of the transformed region.

6 Conclusions

Based on the results achieved in these investigations, it has been concluded that:

1. The unique interaction of laser light with a material can lead to permanent changes in the material's properties not easily achievable through other means. The main issue here is the ability to precisely deposit a large amount of a stable energy into a material over a short time scale and in a spatially confined region near the surface.
2. Optimization of laser processing parameters including laser power, laser spot size, and processing speed are of considerable importance for achieving maximum surface hardness and deepest hardened zone. In other words, laser processing parameters should be optimized for having surface temperature high enough for complete austenitization, without partial surface melting that in turn results in a homogeneous hard microstructure.
3. Numerical analysis is very important tool and used for calculations of surface temperature and cooling rate of other different laser processing parameters.
4. Transformation hardening process by laser beam require a high power density and relatively a slow scanning speed to produce deep hardened zone without causing any melting since melting reduces the hardness and produce uneven surface contour. Therefore laser power, beam diameter, and scanning speed need to be optimize carefully.
5. Different type of lasers optics create different laser beam profiles which probably have significant influence on the hardening results.

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