EXPERIMENTAL STUDIES ON THE MICROSTRUCTURE AND HARDNESS OF LASER TRANSFORMATION HARDENING OF LOW ALLOY STEEL

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ABSTRACT

An experimental investigation with Nd:YAG laser system was carried out to study the effects of laser hardening process parameters on the microstructure and hardness during laser hardening of EN25 steel. The laser beam is allowed to scan on the surface of the work piece by varying the laser beam power (750–1250 W) and travel speed (500–1000 mm/min) of the work table. The microstructural features of the laser hardened EN25 steel were analysed using optical microscope. The microstructure of the surface layer was found to consist of plate martensite. A substantial increase in surface hardness was achieved, by a factor of 2 times the base material hardness.

Keywords: laser transformation hardening; hardened depth and width; hardness; microstructure; power density; low alloy steel.

ÉTUDES EXPÉRIMENTALES SUR LA MICROSTRUCTURE ET LA DURETÉ AU COURS DU DURCISSEMENT PAR TRANSFORMATION LASER D’UN ACIER FAIBLEMENT ALLIÉ

RÉSUMÉ

Une enquête expérimentale utilisant le système laser Nd :YAG a été réalisée pour étudier les effets des paramètres d’un procédé de durcissement par laser sur la microstructure et la dureté au cours du durcissement d’un acier EN25. On permet au faisceau laser de balayer la surface de la pièce à usiner en faisant varier la puissance du faisceau laser (750–1250 W) et la vitesse de déplacement (500—1000 mm/min) de la table de travail. Les caractéristiques microstructurales de l’acier EN25 durci par laser ont été analysées en utilisant un microscope optique. On a constaté que la microstructure de la couche de surface se compose de plaques de martensite, et on a réalisé que la dureté de la surface du matériau de base a été augmentée de manière substantielle, d’un facteur de 2.

Mots-clés : durcissement par transformation laser ; profondeur et largeur du durci ; dureté ; microstructure ; densité de puissance ; acier faiblement allié.
1. INTRODUCTION

Surface microstructure and composition play a crucial role in determining the surface dependent engineering properties (wear, corrosion and oxidation resistance) of a component. Surface engineering aims at orientation of the microstructure and composition of the near surface region of the component without affecting the bulk material. Traditionally, surface treatment processes like (flame hardening, induction hardening, carburizing, nitriding, carbonitriding and different hard facing techniques) are commonly employed in enhancing the wear resistance property of Fe-based component. The conventional surface treatment processes possess several limitations, i.e., high time and energy consumption, complex heat treatment schedule, wider heat affected zone, lack of solid solubility limit and slower kinetics. Furthermore, few of the above mentioned techniques are not environment friendly [1]. On the other hand, when a high power laser beam is used as a source of heat for surface treatment, it will avoid most of the limitations as observed in conventional surface treatment [2,3].

Laser transformation hardening (LTH) is the process used for producing a hard, wear resistant surface on components through the action of a scanned laser beam. As the heating duration is short, the hardened zone presents less distortion and surface oxidation than that obtained in flame or induction hardening. Figure 1 shows the distribution of hardness values obtained after laser hardening as compared to induction hardening. The higher values for laser hardening near the surface are due to the much finer and highly restrained martensites in the laser-hardened microstructures compared to the other case [4]. LTH process is suitable for selective surface treatments and is primarily used in steels with sufficient hardenability for improvement of wear resistance and fatigue strength [5–7]. Cast iron, medium-carbon steel and tool steel can be laser hardened to increase their wear and corrosion resistance [8,9].

![Fig. 1. Hardness distribution comparison between laser hardening and induction hardening [4].](image)

High-strength medium carbon low-alloy steels like EN25 are designed to provide better mechanical properties and greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition. These steels are ordinarily quenched and tempered to specific hardness, but for critical applications it may be necessary to surface hardened without any distortion. High strength steels are structural steels with yield strengths that can exceed 1380 MPa. The product forms include billet, bar, rod, forgings, sheet, tubing, and welding wire [10]. To ensure the high hardness and wear resistance of the working surface layers of machine components, it is necessary to use treatment with high concentration energy sources, in particular, laser treatment. The tribological properties and the durability of automobile components such as camshafts, crankshafts, brake drums, internal combustion engine valve and valve seat and gears were improved by this method [11].
Laser sources can provide a controllable low heat input and high density energy deposition in the selected areas for producing thin hardened surface layers. When a laser beam impinges on the surface of a workpiece, part of its energy is absorbed by the surface and suddenly turns into thermal energy. If this absorbed energy is high enough, heat is generated in this region at a rate higher than the rate at which it flows to the bulk of the material by conduction. In these circumstances, the temperature of the surface layers increases very quickly and in this region austenitization may occur, being the bulk temperature of the material essentially unaffected. Moving the workpiece with respect to the laser source, a region on the surface of the workpiece within the beam track is rapidly heated by the laser source, and is rapidly cooled by heat conduction to the bulk of the material after the beam has passed. The heating and cooling of the metallic material may be suitably controlled in order to allow hard martensite to form at the surface by laser treatment [12,13].

The LTH process is competing now against the most widely used flame and induction hardening methods. The process presents considerable advantages over these alternative methods. The most significant are high degree of controllability and automation, low part distortion and capability of very selective and precise treatment [14]. Due to the small volume of the treated material, contained in a few millimeters for each path, the transition zone is small and the distortion is minimum. Hence laser transformation hardening is becoming the optimal technological solution for the laser surface treatment of small and complex components.

Figure 2 shows the maximum hardness of the steels including different carbon content. The broken line indicates the hardness after conventional heat treatment. The tendency is also found to increase the hardness up to a carbon content of 0.6% and to maintain constant value of more than 0.6% carbon content after the laser heat treatment. Especially, the hardness after this heat treatment indicates higher values (50 HV) than conventional one in the case of less than 0.6% carbon content [15]. The advantages of using laser for surface processing results from its highly directional nature and the ability to deliver controlled amounts of heat energy to desired regions. The energy input is dependent on the absorptivity of the material. Only a fraction of the laser energy is absorbed by the material and the remaining portion is reflected from the surface. The absorption of a polished metal surface depends strongly on the wavelength of irradiation. In the case of steels, the absorptivity increases when the wavelength is short. The wave length of Nd:YAG laser beam is 1.064 µm whereas the CO\textsubscript{2} laser beam is 10.6 µm. So the Nd:YAG laser which is having shorter wave length is suitable for surface hardening of steel [16].

![Fig. 2. Relationship between carbon content and maximum hardness](image)

From the literature survey, it is found that material AISI 304, AISI 440C, 2Cr13 martensitic stainless steel, EN18, EN24, U13A, AISI 1045, AISI 420, AISI H13, AISI 4140, EN8, titanium, manganese steel etc., were considered for laser transformation hardening process [17–19]. The EN25 steel, which is used for many high
temperature applications [10], is not yet taken for laser hardening analysis. So in this current work EN25 steel is taken for laser processing and this will be useful for automobile, aircraft and transportation industries. The effect of the process on the hardened depth depends strongly on the process parameters used, as well as on the thermo-physical properties of the material [20]. The major process parameters involved are laser beam power and spot size, focal length, relative travel speed between the laser beam and the workpiece, and the absorptivity of the surface to laser radiation [21,22].

Laser transformation hardening is a method in which the high power laser beam quickly irradiates the workpiece surface to increase rapidly the workpiece surface temperature that is higher than the austenite transformation temperature and lower than the melting point. After passing of the laser beam from specified zone, the cooling base quickly cools the heated region to quench by itself so that the specimen surface is hardened and its performance is modified and improved [23]. Figure 3(a) shows dependence of power density, specific energy and interaction time at laser metalworking processes. The interaction time for LTH is between $10^{-2}$ and $10^1$ second. Also power density and specific energy is in the range of $10^3 - 10^5$ W/cm$^2$ and $5 \times 10^2 - 3 \times 10^4$ W/cm$^2$ respectively. The power density of the laser beam at the material surface, of the order of $10^3 - 10^5$ W/cm$^2$ with a short interaction time of 0.1–0.3 seconds can produce martensite structure in steel [24]. Figure 3(b) shows that, the data for heating (hardening). It can be seen that an order of magnitude increase in energy density is required to change the processing mechanism from heating to melting, and from melting to vaporization. This is observed over wide ranges of power density and interaction time [25].

![figure 3](image)

**Fig. 3.** (a) Dependence of power density, specific energy and interaction time at laser metalworking processes [24]; (b) Range of power density for laser processing of metals and alloys [25].

### 2. EXPERIMENTAL ARRANGEMENTS

The material investigated in this study is EN25, which is nickel chromium molybdenum (HSLA) medium carbon steel, used in various industries like the aircraft, automobile and transport industries [26]. Prior to the actual experiment, all necessary precautions and safety measures were taken as per the stipulated norms [27]. Care was taken to clamp the specimen to avoid any misalignment with the beam movement. Since high-power laser is suitable for laser transformation hardening [28], a CNC-controlled 2 kW CW Nd:YAG laser
system is used for experiments as shown in Fig. 4 [29]. The focusing length of the laser beam is 300 mm, it is defocused to \(-10\) mm to increase the beam coverage area and to reduce the power density.

![Schematic sketch of Nd:YAG laser surface hardening system](image)

Fig. 4. Schematic sketch of Nd:YAG laser surface hardening system [29].

The chemical compositions of EN25 steel specimen is given in Table 1. A plate of 155 mm length, 55 mm width and 9 mm thickness sectioned from commercial grade plate was used for the laser treatment. The experimental matrix used for laser hardening trails is presented in Table 2. Laser transformation hardening is performed by varying the laser beam power and the work table travel speed. Prior to hardening the base material is cleaned to avoid contamination. After the laser treatment, different zones within the surface area were occurred as shown in Fig. 5.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
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<tbody>
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<td>0.31</td>
<td>0.25</td>
<td>0.60</td>
<td>2.50</td>
<td>0.65</td>
<td>0.50</td>
<td>0.02</td>
<td>0.02</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 1. Composition of EN25 steel specimen in (wt. %).

At the top region, a completely martensitic structure develops, which is called as hardened zone (HZ). The transition zone (TZ) consists of partly austenised and eventually hardened microstructure, and the rest is base material which did not undergo any modification during the laser irradiation. After the LTH the specimens were cut normal to the scanning direction, the required surface of each specimen was ground and polished with various grade of emery sheets.

The specimens were finally etched with 1.5 % nital solution and made ready for the study of microstructure and to measure the hardness. Phase transformations occurred in the laser-hardened track were analyzed using an optical microscope. The hardness over the depth of the laser-treated zone was measured using the shimadzu micro hardness tester.
Table 2. Experimental trial matrix of laser transformation hardening.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Power (W)</th>
<th>Travel speed (mm/min)</th>
<th>Spot diameter (mm)</th>
<th>Beam coverage area (mm²)</th>
<th>Focal length (mm)</th>
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<tr>
<td>1</td>
<td>750</td>
<td>500</td>
<td>1.55</td>
<td>1.8</td>
<td>310</td>
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<tr>
<td></td>
<td>750</td>
<td>1.55</td>
<td>1.8</td>
<td></td>
<td>310</td>
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<tr>
<td></td>
<td>1000</td>
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<td>1.8</td>
<td></td>
<td>310</td>
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<tr>
<td></td>
<td>500</td>
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<td>1.8</td>
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<td>310</td>
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<tr>
<td></td>
<td>500</td>
<td>1.55</td>
<td>1.8</td>
<td></td>
<td>310</td>
</tr>
<tr>
<td>3</td>
<td>1250</td>
<td>750</td>
<td>1.55</td>
<td>1.8</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1.55</td>
<td>1.8</td>
<td></td>
<td>310</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

3.1. Effect of Power and Travel Speed on Laser Transformation Hardening

LTH is a localized heat treatment process involving only heating, with relatively low values of energy density (to avoid surface melting) [25]. The energy density of the radiation may be varied by defocusing the beam, i.e., displacement of the irradiated surface by a certain distance from the focal plane of the laser’s objective lens [30]. The calculation of energy density was performed by using Eq. (1) [15]:

\[
\text{Energy density (ED)} = \frac{P}{DV},
\]

where \( P \) is the laser beam power and \( V \) is the travel speed of the beam. Based on the \( M^2 \) value, the laser spot diameter \( D \) is calculated using the Eq. (2) [31]:

\[
\text{Laser beam spot diameter (D)} = \frac{4M^2 \lambda f}{\pi D},
\]

where \( \lambda \) is the wave length (\( \mu \)m); \( f \) is the lens focal length (mm); \( D \) is input beam diameter at the lens (mm); \( M^2 \) is the beam mode parameter, which expresses how quickly a given beam diverges while propagating. The
power density \((PD)\) directly related to the laser power \((P)\) and the beam coverage area \((A)\) in the material. It can be calculated from the equation \(PD = P/A\), where \(A = \pi r^2\), \(r\) is the radius of the spot diameter.

The power density for the lower power (750 W) is \(3.97 \times 10^4\) W/cm\(^2\), which gives the maximum hardened depth and width without melting the surface of the material. The power density for medium power (1000 W) is \(5.3 \times 10^4\) W/cm\(^2\), for high power (1250 W) it is \(6.6 \times 10^4\) W/cm\(^2\). These medium and high powers melt the surface of the material due to its high power density. The hardened area for the lower to higher power was measured using the image analyser software of optical microscope. When the power density increased, the hardened area (HA) is also increased because of the high hardened depth and hardened width (HW).

From the Table 3 it is observed that the maximum hardened depth (HD) is 0.7 mm is obtained for the travel speed of 500 mm/min at the power density of \(3.97 \times 10^4\) W/cm\(^2\). The hardened depth is reduced to 0.55 mm for the travel speed of 1000 mm/min. For the travel speed of 750 mm/min the hardened depth obtained is 0.62 mm. When the travel speed is increased further above the 1000 mm/min the depth of hardening may be decreased further. From this we can conclude that the travel speed range of 500–1000 mm/min for the power density of \(3.97 \times 10^4\) W/cm\(^2\) is in the acceptable range. Hence, for hardening the HSLA steel without melting the laser system has to be operated in the power 750 W with the travel speeds 500, 750 and 1000 mm/min.

### Table 3

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Power (W)</th>
<th>Travel speed (mm/min)</th>
<th>ED ((\times 10^3) J/cm(^2))</th>
<th>PD ((\times 10^4) W/cm(^2))</th>
<th>HD (mm)</th>
<th>HW (mm)</th>
<th>HA (mm(^2))</th>
<th>Melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>500</td>
<td>5.83</td>
<td>3.97</td>
<td>0.7</td>
<td>2.2</td>
<td>1.1</td>
<td>No melting</td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>500</td>
<td>3.87</td>
<td>0.62</td>
<td>2.1</td>
<td>0.94</td>
<td></td>
<td>No melting</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>500</td>
<td>2.97</td>
<td>0.55</td>
<td>2.0</td>
<td>0.84</td>
<td></td>
<td>No melting</td>
</tr>
<tr>
<td></td>
<td>1000</td>
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<td>7.77</td>
<td>1.12</td>
<td>2.5</td>
<td>1.94</td>
<td></td>
<td>Melting up to a depth of 0.64 mm</td>
</tr>
<tr>
<td>2</td>
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<td>750</td>
<td>5.16</td>
<td>5.3</td>
<td>0.85</td>
<td>2.3</td>
<td>1.37</td>
<td>Melting up to a depth of 0.45 mm</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>500</td>
<td>3.87</td>
<td>0.80</td>
<td>2.2</td>
<td>1.17</td>
<td></td>
<td>Melting up to a depth of 0.4 mm</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>750</td>
<td>9.72</td>
<td>1.5</td>
<td>2.7</td>
<td>2.84</td>
<td></td>
<td>Melting up to a depth of 1 mm</td>
</tr>
<tr>
<td>3</td>
<td>1250</td>
<td>750</td>
<td>6.45</td>
<td>6.6</td>
<td>1.2</td>
<td>2.6</td>
<td>2.19</td>
<td>Melting up to a depth of 0.8 mm</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>750</td>
<td>4.84</td>
<td>1.0</td>
<td>2.4</td>
<td>1.75</td>
<td></td>
<td>Melting up to a depth of 0.6 mm</td>
</tr>
</tbody>
</table>

Table 3. Power density (PD), energy density (ED), hardened depth (HD), hardened width (HW) and hardened area (HA).

### 3.2. Microstructural Observations

The microstructure of laser hardened parts should be examined under a metallurgical microscope because any property change during hardening is closely related to the microstructural change. The microstructural evaluation are needed in order to obtain a more informative and quantitative result. An image analyser is used to accomplish the quantitative analysis of microstructure of the LTH layer. In LTH, the mechanical and
structural properties of the bulk material are retained, because of the high temperature gradient and high rate of change of temperature that are unattainable by conventional methods [32].

The experiments included single passes of the laser beam on the specimen surfaces with no overlapping. In the hardened zone only transformation occurs. As it is known, during laser processing austenite forms during heating and carbides partially dissolve in the grain boundaries. During cooling, austenite transforms completely or partially to martensite and thus the microstructure of the hardened zone (HZ) consists of martensite containing a small amount of retained austenite. In the neighborhood of the HZ with the base material, a very narrow transition zone is observed, consisting of martensite, bainite and traces of the initial pearlitic structure. These are the most probable structure according to earlier works [33–35].

Figure 6(a,b) shows the microstructure of the untreated material which contains ferrite (white region), fine pearlite (dark region), and sheaves of upper bainite. This upper bainite in the structure gives more strength for the base material. It is clear from Fig. 7(a,b) that HZ consist of fine plate martensite, which gives maximum harness to the surface of the material for the speed of 500 mm/min. Figure 7(c,d) shows the fine plate martensite structure for the speed of 750 mm/min. For 1000 mm/min travel speed that hardened zone consists of coarse plate martensite as shown in Fig. 7(e,f). Figure 8(a,b) shows a thin transition zone was observed just below the HZ, of a mixed microstructure, exhibiting martensite and tempered bainite. This structure will also assist to obtain the moderate hardness and strength in the transition zone of 0.5 to 1 mm distance.

![Microstructure of base metal (EN25) at (a) 200X magnification, (b) 500X magnification.](image)

From the microstructure results for the power density of $3.97 \times 10^4$ W/cm$^2$, it is observed that for 500, 750 mm/min travel speed the microstructure attained is fine plate martensite and for 1000 mm/min the structure obtained is coarse plate martensite due to less heat input. Therefore the hardness in the coarse structure will be less than the fine plate martensite structure. Figure 9 shows the macrostructure of the laser hardened surface for the different travel speed for the same power density of $3.97 \times 10^4$ W/cm$^2$. The depth and width of hardened zone is 0.7 mm, 2.2 mm respectively for the 500 mm/min speed (Fig. 9a), it is decreased to 0.62 mm, 2.1 mm for the speed of 750 mm/min (Fig. 9b) and for the speed of 1000 mm/min it further reduced to 0.55 mm, 2.0 mm (Fig. 9c) respectively. The result shows that, when the travel speed increased the gradual decrease in depth and width of HZ was found.

Figure 10 shows the macrostructure which consist of melt zone, heat affected zone (hardened zone) and base material at different travel speed for the power density of $5.3 \times 10^4$ W/cm$^2$. Figure 10(a-c) clearly shows that, the depth and width of melt zone and heat affected zone (HAZ) is decreased when the travel speed get increased for the same power density of $5.3 \times 10^4$ W/cm$^2$. Figure 10(d-f) shows the macrostructure
Fig. 7. Microstructure of hardened zone for the power density of $3.97 \times 10^4$ W/cm$^2$ at (a) 200X (500 mm/min), (b) 500X (500 mm/min), (c) 200X (750 mm/min), (d) 500X (750 mm/min), (e) 200X (1000 mm/min), (f) 500X (1000 mm/min).
Fig. 8. Microstructure of various zones for the power density of $3.97 \times 10^4$ W/cm$^2$, 750 mm/min travel speed at (a) 200X magnification, (b) transition zone at 500X magnification.

Fig. 9. Macrostructure of laser treated sample for the power density of $3.97 \times 10^4$ W/cm$^2$ at 40X magnification at (a) 500 mm/min, (b) 750 mm/min, (c) 1000 mm/min.
of laser treated surface with the power density of \(6.6 \times 10^4\) W/cm\(^2\) at various travel speed. In the higher power densities the surface of the steel gets melted for all the travel speeds. The depth and width of the melt zone and HAZ decreased as the travel speed increases. Hence it is observed that to perform Nd:YAG laser hardening on EN25 steel the travel speed is not sufficient and higher travel speed has to be selected for medium (1000 W) and higher power (1250 W).

![Macro structure of laser treated sample](image)

Fig. 10. Macro structure of laser treated sample (at 40X magnifications) for the power density of \(5.3 \times 10^4\) W/cm\(^2\) at (a) 500 mm/min, (b) 750 mm/min, (c) 1000 mm/min and (c) for the power density of \(6.6 \times 10^4\) W/cm\(^2\), (d) 500 mm/min, (e) 750 mm/min, (f) 1000 mm/min.
3.3. Hardness Observations

The hardness data is obtained through Shimadzu micro hardness tester. Hardness on the top surface and the cross sectional region of the EN25 steel in the as-received condition and after laser hardening has been taken for the vickers load of 0.5 kg.

The hardness of the base material is in the range of 360–380 HV$_{0.5}$ as shown in Fig. 11, which indicates hardness is almost uniform in the surface of the base material. EN25 steel is mainly used for high temperature application, the required hardness must be around 650–750 HV$_{0.5}$. Therefore to obtain this hardness range LTH can be used for localized heating.

![Fig. 11. Hardness in the surface of the base material (EN25 steel).](image)

3.3.1. Effect of travel speed in hardened depth

The travel speed of the laser beam is one of the main factors in transformation hardening which alter the depth and width of hardened zone to obtain desired surface properties. Table 4 shows the effect of travel speed in the cross section hardness along depth direction for the power density of $3.97 \times 10^4$ W/cm$^2$.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Power (W)</th>
<th>Travel speed (mm/min)</th>
<th>Hardness (HV$_{0.5}$) at different depths from top surface (µm)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
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<td>A</td>
<td>750</td>
<td>500</td>
<td></td>
<td>780</td>
<td>790</td>
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<td>370</td>
<td>365</td>
<td>367</td>
<td>364</td>
</tr>
</tbody>
</table>

Table 4. Hardness values at various travel speed for the power density of $3.97 \times 10^4$ W/cm$^2$.

In sample A, the case depth hardness (782 HV$_{0.5}$) is almost uniform up to a depth of 0.7 mm because of the plate martensite structure in the hardened zone and after that a small transition zone around 0.1 mm is
formed with the hardness of 648 HV$_{0.5}$. The base material hardness (360–380 HV$_{0.5}$) is maintained with same properties, without affecting by the laser heat. The average hardness in the hardened zone of sample B is 773 HV$_{0.5}$; it is maintained up to a depth of 0.62 mm, in transition zone it is 631 HV$_{0.5}$. In sample C the case depth is uniform up to a depth of 0.55 mm and it is decreased to 609 HV$_{0.5}$ in the TZ. From the results it is observed that the average hardness in the HZ is almost same for the different travel speed of 500–1000 mm/min, but depth of hardening is more (0.7 mm) for the travel speed of 500 mm/min.

Tables 5 and 6 gives the effect on hardness values at different travel speed in depth direction. Melting occurred in 0.4–1 mm distance (along depth) for both the medium (1000 W) and high (1250 W) powers in the travel speed of 500–1000 mm/min. In samples D to I melting occurred in 0.64, 0.45, 0.4, 1.0, 0.8, 0.6 mm respectively and heat affected zone (hardened zone) in followed after the melt zone for 0.4–0.6 mm distance (along depth). The average hardness in the samples (D-I) is less than the hardness achieved by the samples A-C due to the melting. Melting is not acceptable in the transformation hardening process. Hence the chosen parameter window cannot be used for hardening process. Therefore new operational window have to be determined based on this investigation.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Power (W)</th>
<th>Travel speed (mm/min)</th>
<th>Hardness (HV$_{0.5}$) at different depths from top surface (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1000</td>
<td>500</td>
<td>737 735 730 732 761 763 500 365 372</td>
</tr>
<tr>
<td>E</td>
<td>1000</td>
<td>750</td>
<td>728 726 723 769 782 650 358 362 370</td>
</tr>
<tr>
<td>F</td>
<td>1000</td>
<td>1000</td>
<td>748 767 759 790 781 600 366 370 365</td>
</tr>
</tbody>
</table>

Table 5. Hardness values at various travel speed for the power density of 5.3×10$^4$ W/cm$^2$.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Power (W)</th>
<th>Travel speed (mm/min)</th>
<th>Hardness (HV$_{0.5}$) at different depths from top surface (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>1250</td>
<td>500</td>
<td>682 700 685 692 695 742 730 568 374</td>
</tr>
<tr>
<td>H</td>
<td>1250</td>
<td>750</td>
<td>719 718 720 717 761 765 558 357 367</td>
</tr>
<tr>
<td>I</td>
<td>1250</td>
<td>1000</td>
<td>734 749 750 787 790 636 370 365 368</td>
</tr>
</tbody>
</table>

Table 6. Hardness values at various travel speed for the power density of 6.6×10$^4$ W/cm$^2$.

Figure 12(a) shows the effect of travel speed on hardness profile beneath the surface for the low alloy steel (EN25) for the power density of 3.97×10$^4$ W/cm$^2$. It is clear that, as the travel speed increases, the average hardness in depth direction decreases. The average hardness in the hardened zone are 782, 773, 771 HV$_{0.5}$ for the travel speed of 500, 750, 1000 mm/min respectively. The average hardness in the transition zone for 500, 750, 1000 mm/min speeds are 648, 631, 609 HV$_{0.5}$ respectively. Below the transition zone the base metal hardness is maintained in the same level of 360–380 HV$_{0.5}$ without any changes. Figure 12(b) shows the hardness along the depth direction in different travel speed for the power
density of $5.3 \times 10^4$ W/cm$^2$. The average hardness in the melt zone are 734, 726, 758 HV$_{0.5}$, which is less than the heat affected zone (hardened zone) hardness 762, 776, 786 HV$_{0.5}$ for the travel speed of 500, 750, 1000 mm/min respectively.

Figure 12. Effect of traverse speed on hardness along depth for the power density of (a) $3.97 \times 10^4$ W/cm$^2$, (b) $5.3 \times 10^4$ W/cm$^2$. 

Figure 13(a) shows the hardness along the depth direction for different travel speed at the power density of $6.6 \times 10^4$ W/cm$^2$. The average hardness in the melt zone are 691, 719, 744 HV$_{0.5}$, which is also less than the heat affected zone (hardened zone) hardness 736, 763, 789 HV$_{0.5}$ for the travel speed of 500, 750, 1000 mm/min respectively. Base metal hardness is not changed in both the power density. The hardness along the width direction measured from the centre of the laser track for the power density of $3.97 \times 10^4$ W/cm$^2$ is shown in Fig. 13(b), from which it is clear that the hardness in the hardened zone is maximum and is slightly varying with respect to the travel speed and in the transition zone hardness is less than the HZ.

Fig. 13. Effect of travel speed on hardness (a) along depth for the power density of $6.6 \times 10^4$ W/cm$^2$, (b) along width for the power density of $3.97 \times 10^4$ W/cm$^2$. 

In Fig. 14(a-b) the hardness along the width in the melt zone is less than the HAZ. Due to the high power density for at 1000 and 1250 W, the surface of the material exceeds the austenizing temperature which melts the surface and cooling time is not enough to achieve the maximum hardness. In the medium power (1000 W), high power (1250 W) melting occurred in the surface of the material for the travel speed of 500–1000 mm/min, which is usually undesirable for the LTH process. Further increment in the travel speed (more than 1000 mm/min) for the same power may provide the required surface properties without melting the surface.

![Fig. 14. Effect of travel speed on hardness along width for the power density of (a) 5.3×10^4 W/cm^2, (b) 6.6×10^4 W/cm^2.](image)

4. CONCLUSIONS

The following conclusions are made based on this investigation:

EN25 steel can be successfully hardened using high power Nd:YAG laser. The surface hardness of EN25 material (360–380 HV_{0.5}) can be increased more than two fold (782 HV_{0.5}) by laser hardening method. The hardened zone of the laser treated surfaces was ranging in depths of 0.55–0.7 mm and width of 2.0–2.2 mm by varying travel speed of laser beam.

The hardened zone consists of plate martensite. A thin transition zone was observed just below the hardened zone with a mixed microstructure of martensite and tempered bainite. The microstructure of the base material consists of upper bainite.

Due to the sudden cooling in the laser hardening process, the upper bainitic structure in the base metal is transformed to plate martensite structure in the hardened zone, which provides the maximum hardness to the steel.

Based on the microstructure analysis for 750 W of laser power for hardening, at various travel speed, it is observed that the higher travel speed (1000 mm/min) gives the coarse plate martensite structure and lower travel speed (500 mm/min) results in fine plate martensite, which is having higher hardness than the coarse structure.

From the investigation it is observed that for the lower power of 750 W a maximum hardened depth of 0.7 mm and width of 2.2 mm is obtained with the power density of 3.97×10^4 W/cm^2. With the power density of 5.3×10^4 W/cm^2 the depth of hardening is 0.8–1.12 mm, width is 2.2–2.5 mm. For the power density of
6.6×10⁴ W/cm² the depth of hardening is 1.0–1.5 mm and width is 2.4–2.7 mm. But melting occurred in both the power densities, namely 5.3×10⁴ W/cm², 6.6×10⁴ W/cm², which can be overcome by increasing the travel speed to higher than 1000 mm/min, to achieve the hardened depth and width without melting.

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REFERENCES
