The effect of laser surface hardening on the surface hardness of mild steel

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Abstract. Laser surface hardening (LSH) has become the most vital process in order to increase the hardness of a mild steel surface, especially to overcome the wear issues in machining parts, where mild steel was hugely applied. This is due to its advantages such as less air pollution, low cost of maintenance and easy to handle compared to other conventional surface hardening process. The laser surface hardening of mild steel has been performed using fibre laser machine which is having a maximum peak power of 30 Watt, with 1060 nm of wavelength above the surface of mild steel having dimension of 15 × 15 × 6 mm. The Vickers hardness test on the laser hardened surface of this metal were measured by a load of 0.5 kgf and 10 seconds dwell time for ten indentation points, randomly. It was found that the highest average microhardness value was 281.72 HV on the surface of sample hardened by a laser power of 21 Watt and 40 mm/s scanning speed. Across the cross sectional area, the affected hardened depth was measured at 19 ± 2.5 μm from the surface. In this region, the fine martensitic grain structure was observed, which contributes to the higher microhardness value. Higher laser power produced higher surface hardness, meanwhile higher scanning speed lead to lower surface hardness.

Keywords: Laser Surface Hardening; Mild Steel; Fibre Laser; Vickers’s Hardness; surface hardness.

1. Introduction

Surface hardening is a process which includes a wide variety of techniques used in order to improve the wear resistance of parts without affecting the most soft, tough interior of the part [1].

This combination of hard surface and resistance to breakage upon impact is useful in parts such as a cam or ring gear, bearings or shafts, turbine applications, and automotive components that need the hard surface to resist wears [2]. Most surface treatments resulting in compressive residual stresses at the surface, where it reduces the probability of crack initiation and helped arrested crack propagation at the case-core interface.

Furthermore, the surface hardening of steel has an advantage over through hardening because less expensive low-carbon and medium carbon steels can be surface hardened with minimal problems of distortion and cracking associated [3]. Mild steel is a type of carbon steel with low carbon content, which generally ranged between 0.05 to 0.25 percent by its weight [4].
Surface hardening of mild steel had been done by forging, TIG arcing, thermal plasma, and laser processing [5-8]. The usage of fibre laser for modifying surface properties of mild steel had been studied in order to investigate the corrosion inhibition [8].

It was found that surface modified by pulse fibre laser improved the corrosion resistance of mild steel. The application of laser surface modification on mild steel could increase the application of this conventional steel, especially in machinery parts applications where the wear defects have been the main issue [9].

A fibre laser is a laser in which the active gain medium is an optical fibre doped with rare-earth elements such as Ytterbium (Yb). Fibre laser has developed quickly and has the advantages of high flexibility and good beam quality, which being applied in the electrical and automotive industries [10, 11].

Over the last decade, fibre lasers have been shown remarkable progress in performance, leading to the rapid replacement of existing lasers and development of numerous new applications. The advantages of using fibre laser are the light is already coupled into a flexible fibre and can be delivered to a movable focusing element [12].

This is advantageous for the application of laser marking, laser brazing and laser hardening. Laser surface modification of a mild steel had been done by high power lasers, which is not significant due to the high operation costs [13]. However, pulsed laser application has been introduced for the surface modification of metallic materials by using the maximum laser power below than 30 Watt [14].

There were different types of experimental works regarding on the laser surface modifying of mild steels. The main aim of this recent work is to investigate the relationship between the effects of the pulse laser process parameter, which are laser power and scanning speeds on the surface hardness of mild steel.

2. Research methodology

Mild steel (0.05 – 0.25 wt% of Carbon) sheet with dimension of 15 × 15 × 6 mm was prepared by electric-discharge machine (EDM) wire cut in this experiment. The surface of the metal was ground vertically by using 240 grit of sandpaper, and then cleaned with ethanol prior to process in order to remove any residual oil contamination and excess removed surfaces.

Table 1 shows the chemical composition of mild steel used in this experiment. The average Vickers hardness of the surface of the as-received mild steel was measured at 111.46 Hv.

| Element | C   | Si  | Mn  | Cu  | Ni  | Cr  | Fe  |
|---------|-----|-----|-----|-----|-----|-----|-----|
| Wt. %   | 0.15| 0.21| 0.40| 0.02| 0.02| 0.15| Bal.|

Table 1. Chemical composition of as-received mild steel.
Figure 1. Schematic illustration of laser surface hardening of mild steel.

For laser surface hardening process, a fibre laser machine which having a maximum peak power of 30 Watt was used. This laser was operated in a pulse wave mode, where the wavelength is 1060 nm with 0.4 mm of focus beam diameter.

The effect of laser parameters on surface hardness was studied in this experimental work. The area of laser beam operation was 15 × 15 mm above the metal surface. Figure 1 shows the illustration of experimental condition for the laser surface hardening process of mild steel surface. 90 degrees of laser scanning direction was applied and the distance between the hatching lines was fixed to be at 100 μm.

Table 2 shows the laser surface hardening parameters for the surface hardening experiment of mild steel. Laser power and the scanning speed were the variable parameters and the constant parameters are 200 kHz frequency and 96 mm of focus length. The effect of laser power and scanning speed on the hardness of mild steels surface was investigated.

| Sample | Laser Power (Watt) | Scanning Speed (mm/s) | Pulse Frequency (kHz) | Focus Length (mm) |
|--------|-------------------|----------------------|-----------------------|-------------------|
| 1      | 6                 |                      |                       |                   |
| 2      | 12                | 40                   |                       |                   |
| 3      | 18                |                      |                       |                   |
| 4      | 21                |                      |                       |                   |
| 5      | 80                | 200                  | 96                    |                   |
| 6      | 21                | 120                  |                       |                   |
| 7      | 160               |                       |                       |                   |
| 8      | 200               |                       |                       |                   |

Microhardness of all nine samples, including as-received sample were tested using the Vickers hardness test with 0.5 kgf load and 10 seconds of dwell time. Ten indentation points were performed on the surface of all samples of mild steel randomly and the average hardness value was calculated.
The highest surface hardness sample parameters (laser power and scanning speed) were selected and the hardness variation at the cross section starting from the top surface to the base metal region was carried out. The schematic illustration for the hardness indentation point is as shown in figure 2.

![Figure 2. Indentation point for (a) samples surface and (b) cross section of highest hardness value.](image)

3. Results and discussion

3.1. Microhardness of laser hardened surface

The results of the Vickers hardness test for the as-received and laser hardened surface of mild steel was collected. Table 3 shows the results of hardness value for as-received and hardened surface of mild steel with variant laser power and constant scanning speed, frequency, and focal length.

Based on table 3, it was observed that the highest average microhardness value, 271.82 Hv was possessed by the sample scanned with the highest laser power, 21 Watt at constant scanning speed of 40 mm/s. The lowest hardness value was found to be 142.07 Hv using a laser power of 6 Watt, which is higher by 24.5 % than the surface of the as-received sample, which is 114.46 Hv.

The standard deviation was also lower, indicating that ten data points of each hardness value tend to be close to the mean value. This means that the distribution of the data was centred and spread out approximately near to the mean values. The graph of average microhardness values versus laser power for the variant laser power experiment was constructed as shown in figure 3.

| Table 3. Results of Vickers hardness for variant laser power. |
|---------------------------------------------------------------|
| Vickers Hardness (HV) | As-received | Laser Power, Watt |
|                      |            | 6   | 12  | 18  | 21  |
| 1 indent             | 103.5      | 131.9| 156.0| 171.7| 272.2|
| 2 indent             | 109.0      | 134.5| 156.0| 176.0| 274.5|
| 3 indent             | 109.9      | 136.8| 158.3| 176.7| 275.7|
| 4 indent             | 112.0      | 138.0| 158.8| 178.1| 279.6|
| 5 indent             | 112.2      | 142.9| 160.9| 79.7 | 282.6|
| 6 indent             | 112.2      | 144.8| 163.3| 180.2| 282.8|
| 7 indent             | 113.1      | 146.8| 166.0| 180.6| 282.9|
| 8 indent             | 113.9      | 147.7| 166.8| 186.1| 283.3|
| 9 indent             | 114.4      | 148.6| 166.9| 187.3| 284.4|
| 10 indent            | 114.4      | 148.7| 167.5| 187.6| 299.2|
From Figure 3, it was observed that the increment of surface hardness of mild steel using variant values of laser powers. Laser power of 0 W represents the as-received sample which having a surface hardness of 111.46 Hv. By using a 21 Watt, the microhardness value was increased by 137 % from the as-received sample. From this figure, it was observed that the microhardness value of laser hardened surface was higher with the increasing value of laser power.

**Figure 3.** The relationship between laser power and average hardness of mild steel surface.

**Table 4.** Results of Vickers hardness for variant scanning speed.

| Vickers Hardness (HV) | Scanning Speed, mm/s | 40  | 80  | 120 | 160 | 200 |
|-----------------------|----------------------|-----|-----|-----|-----|-----|
| 1 indent              |                      | 262.2 | 226.4 | 203.0 | 184.3 | 179.8 |
| 2 indent              |                      | 266.1 | 227.6 | 204.0 | 190.8 | 180.7 |
| 3 indent              |                      | 267.5 | 231.5 | 205.0 | 193.1 | 181.5 |
| 4 indent              |                      | 267.5 | 231.8 | 205.2 | 194.8 | 182.4 |
| 5 indent              |                      | 269.6 | 232.6 | 205.3 | 195.3 | 182.5 |
| 6 indent              |                      | 274.2 | 234.0 | 206.3 | 195.4 | 185.1 |
| 7 indent              |                      | 274.5 | 234.1 | 207.5 | 197.8 | 185.2 |
| 8 indent              |                      | 275.7 | 235.4 | 208.6 | 198.1 | 185.2 |
| 9 indent              |                      | 277.9 | 240.8 | 215.6 | 198.5 | 187.1 |
| 10 indent             |                      | 282.9 | 249.5 | 219.0 | 199.3 | 188.1 |
| Mean                  |                      | 271.81 Hv | 237.37 Hv | 207.95 Hv | 197.74 Hv | 183.76 Hv |
Table 4 shows the results of hardness value of hardened surface of mild steel with variant scanning speed and constant laser power, frequency, and focal length. From this table, it was found that the highest surface hardness value, which is 271.82, was possessed by sample scanned with scanning speed of 40 mm/s. It was found that the hardness value was approximately similar to the previous laser surface hardened with 21 Watt and 40 mm/s. This is due to the 21 Watt of laser power was constant for the variant scanning speed experiment.

Lower hardness value of 183.76 Hv was found to be at scanning speed of 200 mm/s. However, with 21 W of laser power with higher scanning speed (200 mm/s) still manage to produce the surface with 64.9 % of the increment of the surface hardness compared to the as-received sample. Graph of average hardness versus scanning speed was plotted as shown in figure 4.

Figure 4. The relationship between scanning speed and average hardness of mild steel surfaces.

Based on figure 4, it shows that the highest increment of surface hardness was made by using 40 mm/s of scanning speed. The hardness tends to decrease as the scanning speed was increased from 40 to 200 mm/s.

It was observed that the average microhardness values of laser hardened surfaces of mild steel decrease with the increment values of scanning speed. It could be supported that lower scanning speed with higher laser power producing higher heat input, which can manage to alter the microstructure of the mild steel.

Sample with laser surface hardened using a laser power of 21 Watt and 40 mm/s of scanning speed was selected in order to observe the effect of laser surface hardened to the cross section area by the Vickers hardness test.

3.2. Microhardness of cross section
An experiment was re-conducted using the selected laser parameters, which is the 21 Watt of laser power, 40 mm/s of scanning speed, 200 kHz of pulse frequency, and 196 mm of focal length. Figure 5 shows the image for laser hardened surface of the selected parameter sample with 10 and 50 times magnifications using optical microscope.
Figure 5. Optical microscope view above laser hardened surface for (a) 10 × (b) 50 × magnification.

Figure 5 (a) shows the laser scanning pattern where it consists of scanned and un-scanned regions. Zooming to 50 times magnification, it was observed that the line pattern was irregular in shape. The scanned region width was measured to be averagely at 82 ± 5 μm.

The length between the scan region from the centre of the scanned area was measured to be averagely at 100 ± 3 μm. This is due to the parameters setting for the line distance between the hatching lines for laser scanning process, which was set constantly to be at 100 μm.

From figure 5 (b), it can be clearly seen that the structure of the mild steels surface has been changed due to the effect of heat from the scanning process. A laser scanning process usually produces high heat input with a rapid cooling process which could change the microstructure of a metal [11, 15], especially at the surface of the metal in the case of laser surface hardening process.

The effect of the heat of laser scanning can clearly be seen in the cross section region of the laser hardened sample. Figure 6 shows the cross section region of the laser surface hardened of mild steel.

Figure 6. Microstructure image at cross section region of laser hardened surface for (a) 50 × (b) 100 × Magnification.

Figure 6 (a) shows the image of cross section area at 50 times magnifications. It was observed that a stable laser beam has changed the microstructure of mild steel from larger grain size into a very fine grain structure which could contribute to the higher microhardness value.
From this figure, the affected depth was measured to be approximately $19 \pm 2.5 \, \mu m$, which is practically suitable for a surface hardening process, since the base metal region was not affected by the heat from the laser. It was observed that the base metal of the as-received mild steel consists of ferrite and pearlite structure.

The average grain size of the base metal was measured to be approximately $17.8 \, \mu m$. Meanwhile, a very fine martensitic grain structure was observed in the laser hardened regions as shown in figure 6 (b). The average grain size in this region ranged between 2 to $6 \, \mu m$. Grain structures play an important role in contributing to the hardness and strength of a metal [16].

In confirming the hardness distribution across the cross section area, an experiment was conducted by using the Vickers hardness test in order to distinguish the scanned parts and the unaffected base metal. The same parameters were used, which is using load of $0.5 \, \text{kgf}$ and 10 seconds of dwell time. Figure 7 shows the hardness test indentation point was done until reached the similar value of Hv, which is represented as base metal region.

![Macrostructure images of laser surface hardened of the mild steel cross section.](image)

Figure 7. Macrostructure images of laser surface hardened of the mild steel cross section.

From figure 7, ten indentation point was carried out for measuring the average microhardness values at base metal (BM). It was calculated that the average hardness value of BM at the cross section area was approximately $143.9 \, \text{Hv}$. Meanwhile, 5 indentation points were carried out from the surface region starting from $3 \, \mu m$ until the BM region as shown in figure 8.

![Hardness indention position from surface to base metal at cross section region.](image)

Figure 8. Hardness indention position from surface to base metal at cross section region.

The distance between each indentation point was constantly fixed at $10 \, \mu m$. 5 times repetition of the Vickers hardness test at different locations was done and the results were collected in table 5. From
Table 5, it was observed that the average hardness value for indentation 1 from 5 different locations was 292.42 Hv.

Table 5. Vickers hardness results across the cross section area.

| Ind. | Distance from surface (μm) | Vickers Hardness (Hv) at Different Location from Surface | Avg. Hv |
|------|---------------------------|--------------------------------------------------------|---------|
| 1    | 30                        | 281.5 275.5 279.4 270.6 275.1                         | 276.42  |
| 2    | 128                       | 167.0 148.8 163.1 160.1 145.5                         | 156.90  |
| 3    | 226                       | 135.0 142.8 144.1 148.0 143.5                         | 142.68  |
| 4    | 324                       | 141.6 148.8 148.1 144.9 147.3                         | 146.14  |
| 5    | 422                       | 144.1 146.1 146.8 145.4 144.2                         | 145.32  |

Indention 2 shows a slightly higher average hardness value than the base metal, which is calculated to be 156.90 Hv. This is due to the affection of heat from the surface which altered the microstructure. Indention 3 to 5 shows approximately similar average hardness values which ranged between 142 to 146 Hv. A graph of average hardness value versus distance of indention points from the surface was constructed as shown in figure 9.

Figure 9. Relationship of Vickers hardness value and the indention distance from surface.
From figure 9, black line indicating the plot for five indention regions. Meanwhile, the red dot line shows the average base metal hardness line. From this figure, it was found that the maximum average hardness value was 276.42 Hv at a distance of 30 μm from the surface.

The average grain size of microstructure in this region was measured ranged between 2 to 6 μm, which is very fine. The hardness value was then decreased approximately at a distance of 200 to 250 μm from the surface, which tends to change to the hardness at the base metal region.

It was supporting the evidence that the affected hardened depth as observed in figure 6 (a), which is calculated approximately 19 ± 2.5 μm. It was observed that the laser hardened region was 30 μm from the hardened surface of the mild steel.

At a distance of 226 μm and above, the average hardness value was approximately similar to the average hardness of base metal, which is ranged between 142 to 146 Hv. It can be clearly observed that the hardness values were approximately same to the average hardness value of the base metal.

The average grain size in this region was measured to be 17.8 μm, which is larger than the laser hardened region as shown in figure 9. It was observed that finer grain structures contribute to the higher microhardness values of the mild steel. It was vice versa for the microhardness result in the region consists of larger grain structures.

4. Conclusion

Based on the experimental work which had been carried out to investigate the effect of laser surface hardening on the surface of mild steel, some conclusions have been drawn.

Firstly, both laser power and scanning speed give different effects on the surface hardness of the mild steel. Average surface hardness was increased as the laser power increased, and it was vice versa when the laser scanning speed was increased.

Secondly, the affected depth from the laser hardened surface to the cross section area was adequate for a surface hardening process.

Thirdly, laser scanning on the surface changed the microstructure at the surface hardened region to a very fine martensitic grain, which leads to the higher microhardness value.

However, it does not give much effect towards the base metal of mild steel, which is suitable for a laser surface hardening product. It was concluded that higher laser power with lower scanning speed produce higher surface hardness of mild steel.

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