Experimental investigation and effects of laser hardening process parameters on microhardness of En24 steel

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Abstract. In presented paper through experimental investigation is carried out with fiber laser system so as to evaluate the effects of laser surface hardening process parameters on the microhardness (width and depth) of the laser treated En24 steel using a Taguchi method. The optical microscope and microhardness tester is used to examine the microstructure, microhardness (width and depth) of the laser hardened samples across the heat affected zone. The selected process parameters were laser beam power (210, 225 and 300 W), laser scanning speed (1.0, 5.5 and 10.0 mm/s) and standoff distance (175, 200 and 225 mm) respectively. The laser treated hardened surface layer has a microhardness of 728.1 HV0.3 and reached a microhardness depth of 2471.44 µm, which is twice as high as untreated samples of En24 steel. From this study, it can be summarized that the microhardness of laser treated samples is maximized by controlling laser beam power, laser scanning speed and standoff distance, which improves the service life of laser-treated En24 steel components. The percentage error within the acceptable range was found to be small and was obtained by comparing the microhardness values obtained from the experimental results and predicted microhardness values obtained by using nonlinear regression equation.

1. Introduction

The laser hardening is a unique surface treatment process that has recently been used to enhance mechanical properties and wear resistance compared to conventional surface hardening. The benefit of this process is that only the selected area can be hardened which is required for the particular applications and the rest of the surface of bulk material remains unchanged in the form of mechanical properties. The laser hardening process was also used by the steel metal industry to boost the service life of the steel parts. In this study, the En24 steel material is used for research which is attributed to its uses in manufacturing of mechanical components like gears, kicker rods and bolts. Balasubramanian et al. [1] studied the effects of laser hardening process parameters like laser power and laser scanning speed on hardness, depth of hardness, microstructure change and wear for the materials from En8, En24, En36 and HCHCr. Zhang et al. [2] considered the impacts of laser hardening process to enhance wear and frictional properties of laser hardened En31 steel specimen. Rana et al. [3] investigated the
microstructure and hardness of the different carbon composition laser-treated steel samples by weight percentages of 0.28, 0.40 and 0.46 respectively. The effects of process parameters such as laser power, traverse speed and spot size on the microstructure and microhardness were analyzed and the most important parameters which observed was traverse speed. Gisario et al. [4] evaluated the laser surface treatment capability tested on average roughness, the surface texture of laser hardened AISI 304 stainless steel with high power diode laser system. Waghal et al. [5] applied Taguchi’s orthogonal array approach and investigated the impact of laser hardening process parameters on mechanical and wear properties of laser hardened CK45 steel. Visscher et al. [6] studied the impact of laser line hardening process on the wear action of AISI 1045 carbon steel compared to AISI 52100 ball bearing steel. It was investigated that wear resistance of a laser line hardened surface is minimum compared to the conventional carburization process. Grum and Sturm [7] evaluated that the laser hardening process is useful for increasing the hardness and wear resistance of the nodular iron 500-7 laser treated specimen. Pellizzari and De Flora [8] examined the impact of the laser hardening process parameters on the hardness of laser treated AF63CrMnMo6. The parent metal hardness was 300 HV and when the laser surface treatment is applied the hardness increased to 800 HV with the case depth from 1.2 - 2.0 mm. Zhang et al. [9] studied the effects of laser hardening on the microstructure, hardness and wear resistance of Cr2Mo and 45 steel treated laser. The cross section of the area affected by heat was divided into three zones (overheated zone, the hardening zone and the transition zone). It was observed that the hardness within the overheated zone was lower than that of the hardening zone with the same values of laser process parameters. Prashanthi et al. [10] studied the effects of laser hardening process parameters to achieve maximum hardness for improving the working life of carbon steel, non-malleable cast iron and X20Cr13 materials. Babu et al. [11] investigated the results of laser hardening process parameters to improve the hardness and wear resistance of laser treated EN25 steel materials using the methodology of the response surface. Mahapatra et al. [12] studied the effects of erosion wear process parameters such as impingement angle, fiber loading, erodent size and standoff distance on glass fiber reinforced polyester composites material using the Taguchi’s approach. Zhang et al. [13] studied the impact of laser surface remelting on the performance of H21 steel microstructure, microhardness and thermal fatigue, observed microhardness values after laser surface melting was 780 HV and a microhardness depth of 650 µm achieved respectively.

2. Experimental details

2.1 Material used for experimentation
Nowadays, En24 steel is used for manufacturing of gear, kicker rods and bolts etc. Therefore, for the present experimental work, En24 steel is used as testing material. Table 1 shows the elemental composition in weight percent.

| Elements | C  | Si  | S  | P  | Mn  | Cr  | Ni  | Mo  |
|----------|----|-----|----|----|-----|-----|-----|-----|
| Composition weight % | 0.386 | 0.228 | 0.028 | 0.014 | 0.542 | 1.364 | 1.392 | 0.241 |

Figure 1 shows the SEM image of En24 steel specimens (a) parent metal and (b) after the laser hardening process respectively.

2.2 Experimental set-up and sample preparation
Figure 2 shows the image of fiber laser system 400 W continuous wave (CW) modes and 1070 nm laser wavelength. The experiments were conducted on the same laser system. The parameters of the laser hardening process used 210, 255 and 300 W laser beam power, 1.0, 5.5 and 10.0 mm/s laser scanning speed, standoff distance of 175, 200 and 225 mm as appeared in Table 2. The argon gas used as shielding gas at a flow rate of 10 liters/min and laser beam diameter of 2.1 mm. The specimens
were cut to 30 mm × 8 mm × 8 mm by a wire electrical discharge machine. The standard specimen preparations technique was used to prepare and examine the specimen.

![SEM image of En24 steel](image1.png)  
(a)  
(b)  

**Figure 1.** SEM image of En24 steel (a) base material (b) after laser hardening.

![Image of Fiber laser system](image2.png)  

**Figure 2.** Fiber laser system 400 W

**Table 2.** Experimental testing parameters and their levels for laser hardening expt.

| Sr. No. | Laser Parameters       | Unit | Levels   |
|---------|------------------------|------|----------|
| 1       | Laser beam power (P)   | W    | 210 255 300 |
| 2       | Laser scan speed (v)   | mm/s | 1 5.5 10 |
| 3       | Standoff distance (f)  | mm   | 175 200 225 |
2.3 Metallographic and microstructural analysis
Optimized parameters of laser hardening process were used to take a laser track on the En24 steel specimen. The laser hardened cross sectional area of the samples treated with laser was polished using emery papers of required grades to achieve mirror finish of the specimen. The microscopic examination is carried out to check the width and depth of microhardness and microstructure of the heat affected zone. The microhardness of the parent metal and laser-treated samples was checked by microhardness testing machine at a load of 300 gm with 10 seconds dual time.

2.4 Experimental Design
For the analysis of the influencing significant process parameters, the design of the experimental technique was used and based on that an output response model was developed. In the laser hardening process, three input parameters such as laser beam power, laser scanning speed and standoff distance are taken whereas microhardness was considered as an output response. Table 2 shows the levels of process parameters used for the experiment. Table 3 displays the laser hardening process parameters and the output response of all runs, such as microhardness, microhardness width and microhardness depth. The output response values are translated to signal to noise ratio using Taguchi’s $L_9$ orthogonal array method.

| Sr. No. | Laser beam power (w) | Laser scan speed (mm/s) | Standoff distance (mm) | Depth of HAZ ($\mu$m) | Microhardness HV$_{0.3}$ | S/N Ratio |
|---------|----------------------|------------------------|-----------------------|-----------------------|--------------------------|-----------|
| 1       | 210                  | 1                      | 175                   | 1103.55               | 637.5                    | 56.08     |
| 2       | 210                  | 5.5                    | 200                   | 876.07                | 545.1                    | 54.72     |
| 3       | 210                  | 10                     | 225                   | 246.46                | 516.3                    | 54.25     |
| 4       | 255                  | 1                      | 200                   | 2237.30               | 689.5                    | 56.77     |
| 5       | 255                  | 5.5                    | 225                   | 989.30                | 656.6                    | 56.34     |
| 6       | 255                  | 10                     | 175                   | 444.79                | 618.3                    | 55.82     |
| 7       | 300                  | 1                      | 225                   | 2471.44               | 728.1                    | 57.24     |
| 8       | 300                  | 5.5                    | 175                   | 1063.85               | 687.8                    | 56.74     |
| 9       | 300                  | 10                     | 200                   | 535.01                | 651.7                    | 56.28     |

For each variable rate combination, the signal to noise ratio was determined. The formula for the higher is better criteria as per Taguchi’s signal to noise ratio is shown in Equation (1).

\[
\text{Signal to noise ratio} = -10 \log \left( \sum \frac{1}{Y^2} \right) / n
\]  

(1)

Where, Y is the output response for the provided level combination and n is the number of factors levels combination output responses.

3. Results and Discussion
3.1 Microhardness analysis by Taguchi’s experimental design
The results of the present experimental work are analyzed using MINITAB 14 software. Taguchi’s orthogonal array $L_9$, design is used perform the experimental work. Table 3 shows details of the experimental parameters and respective results of S/N ratio for all the nine sets of experiments. The present experiment aims to increase the value of microhardness. Therefore, ‘the larger the better’ quality characteristic is selected and used for the present Taguchi’s analysis. Table 4 shows the signal to noise response values for existing experimental conditions and the higher the characteristic of better quality.

In accordance to the analysis shown in Table 4 it can be concluded that laser beam power is the most significant control parameter to achieve surface microhardness. In affecting the surface microhardness of En24 steel, the remaining two parameters, namely laser scan speed and standoff
distances, are rated in the second and third positions. The main effect plots of process parameters such as laser beam power, laser scan speed and standoff distances based on signal to noise ratio are shown in Figure 3. The optimum or maximum microhardness can be achieved at 300 W laser beam power, 1.0 mm/s laser scanning speed and standoff distance of 175 mm.

Table 4. S/N ratio response table using the larger the better characteristics

| Level | Laser beam power | Laser scan speed | Standoff distance |
|-------|------------------|------------------|------------------|
| I     | 55.03            | 56.70            | 56.22            |
| II    | 56.31            | 55.94            | 55.93            |
| III   | 56.76            | 55.45            | 55.95            |
| Delta | 1.73             | 1.25             | 0.29             |
| Rank  | 1                | 2                | 3                |

Figure 3. Main effects plot for signal to noise ratios.

3.2 Effect of laser power on microhardness
As the laser beam power increases from 210 to 300 W, the microhardness of the laser hardened sample also increases as shown in Figure 3. This is attributed due to the fact that at higher laser beam power maximum heating of surface takes place which further tends to form a martensitic structure. Moreover at higher laser power maximum heat energy concentrates on the available surface per unit time which allows maximum temperature difference for cooling and hence forming a microstructure tending towards martensitic nature.

3.3 Effects of laser scan speed on microhardness
From the main effect plots of Figure 3 the effect of laser scan speed can be simply illustrated from the nature. It is observed that that the microhardness of the surface decreases with increment in laser scan speed, this is attributed due to the fact that as scanning speed increases the heat energy concentration per unit time decreases. Hence it is observed that the microhardness value decreases with the increase in the laser scan speed at constant laser beam power and variations in the standoff distance.

3.4 Surface morphology using microstructure
Figure 4 displays the microstructure of the laser-treated En24 steel specimens (a) shows a laser treated specimen microstructure using 210 W laser beam power, 5.5 mm/s laser scanning speed and 200 mm
standoff distance, (b) displays a laser treated specimen microstructure using laser beam power 255 W, laser scan speed 5.5 mm/s and standoff distance 225 mm and (c) shows microstructure of laser treated specimen using laser beam power 300 W, laser scanning speed 5.5 mm/s and standoff distance 175 mm. From this analysis, it is indicated that the formation of fine martensite with carbide dissolution may result in an increase in the microhardness of the treated layers. The highly hardened area consisting of homogeneously dispersed martensite plates with a few pockets of undissolved carbides and austenite is retained.

![Microstructure of laser-treated En24 steel specimens](image)

**Figure 4.** Microstructure of the laser-treated En24 steel specimens

3.5 Hardness prediction using predictive equation

From the obtained values of microhardness as per the experimentation performed with reference to L9 array, a regression equation is generated using MINITAB 14 software. This equation can be used to predict the values of microhardness at any levels of processing parameters. The generated equation is also tested by R² values and it is given a 93.1% which is accurate and hence useful to predict the responses at required levels. The generated regression equation is shown below in equation 2.

\[
\text{Microhardness} = 400 + 1.37(P) - 9.96(v) - 0.284(f)
\]  

This equation is used to find the microhardness at any given set of input process parameters. Here, the experimental results and the predicted results at each experimental condition are calculated and shown in Table 5.

| Sr. No. | Results obtained from the experiments | Results obtained from the predictive equation | Percentage error (%) |
|---------|--------------------------------------|---------------------------------------------|----------------------|
| 1       | 637.5                                | 628.0                                       | 1.50                 |
| 2       | 545.1                                | 576.1                                       | 5.38                 |
| 3       | 516.3                                | 524.2                                       | 1.50                 |
| 4       | 689.5                                | 682.5                                       | 1.01                 |
| 5       | 656.6                                | 630.6                                       | 4.11                 |
| 6       | 618.3                                | 600.1                                       | 3.04                 |
| 7       | 728.1                                | 737.1                                       | 1.22                 |
| 8       | 687.8                                | 706.5                                       | 2.65                 |
| 9       | 651.7                                | 654.6                                       | 0.44                 |

A validation test was also performed on the En24 steel sample by considering optimal test parameters. The microhardness is obtained by using both nonlinear regression equation and confirmation experimental results are shown in Table 6. Approximately 3.42 % deviation was found which is to be
acceptable by comparing the experimental results and analytical results. Therefore, the derived nonlinear regression equation with different control factors having a reasonable degree of approximation of the microhardness of the En24 steel material.

| Laser beam power (W) | Laser scan speed (mm/s) | Standoff distance (mm) | Hardness obtained from the experiments | Hardness obtained from the predictive equation | % error |
|----------------------|-------------------------|------------------------|----------------------------------------|-----------------------------------------------|---------|
| 300                  | 1                       | 175                    | 725.6                                  | 751.34                                        | 3.42    |

4. Conclusions
The research study’s major findings are summarized as follows:
- The optimum process parameters are found to be, laser beam power of 300 W, laser scanning speed of 1.0 mm/s and standoff distance of 175 mm to the En24 steel specimen.
- The base metal microhardness before laser hardening was observed 208.2 HV,0.3 and after laser surface hardening the microhardness of the treated laser specimens was observed from 516.3 HV,0.3 to 728.1 HV,0.3 respectively.
- The microhardness of the measured laser treated specimen increases twice in addition to the microhardness of the base metal without laser treated.
- The range of depth of the hardened surface layer is reached for the laser treated specimen from 246.46 to 2471.44 µm respectively.
- Laser beam power is the most influential laser hardening factor of En24 steel, followed laser scanning speed and standoff distance, respectively, from all three factors.

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