Effects of laser hardening process parameters on hardness depth of Ck45 steel using Taguchi’s optimization technique

Santoshkumar V. Wagh\textsuperscript{a}, Dhananjay V. Bhatt\textsuperscript{b}, Jyoti V. Menghani\textsuperscript{c}, Shivnanda S. Bhavikatti\textsuperscript{d}

\textsuperscript{a}Assistant Professor, Department of Mechanical Engineering, College of Engineering Pune, Pune-411005, India
\textsuperscript{b}Professor, Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat-395007, India
\textsuperscript{c}Associate Professor, Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat-395007, India
\textsuperscript{d}Associate Professor, Department of Mechanical Engineering, College of Engineering Pune, Pune-411005, India.

Corresponding author email:waghsv@gmail.com

Abstract

Laser hardening is one of the reasonable procedures utilized to improve surface mechanical and wear resistance of target materials. This process is easy to use for improving surface properties of complex shape components with minimum time requirement. The beauty of this process is that it is possible to improve only selective surface properties without altering the remaining surface properties of bulk material. Ck45 steel has various important properties like hardness, superior wear resistance and frictional performance etc. These properties are useful in various industrial applications. The existing study is an attempt to analyse results on surface properties with the aid of process parameters of a laser hardening process on hardness depth and microstructure of laser hardened Ck45 steel the use of a design of experimental approach. From this analysis, it can be summarized that the depth of the surface layer hardness is maximized by controlling the laser beam power, laser scan speed and standoff distance, which improves the service life of Ck45 steel components hardened by laser. Comparing the experimental consequences with the effects of L9 orthogonal array approach, the proportion error was observed to be negligible with a higher correlation coefficient ($r^2$) of 0.905.

Keywords: Ck45 steel, laser hardening process, hardness depth, Taguchi’s design of experiment method and microstructure.

1. Introduction

Laser surface hardening strategy is utilized to move forward laser hardened surface quality and wear resistance of components utilized for mechanical applications such as pipe, liner, crankshafts, bearing, gears and ring groves. To improve structural and mechanical properties such as hardness and wear resistance, the effects of laser hardening process on Ck45 steel cylindrical samples was investigated.[1].
Barka et al. [2] investigated the effects of laser hardening technique parameters on case depth of laser hardened 4340 metal cylindrical specimens by using the usage of a statistical evaluation approach. The laser scanning speed has the foremost significant impacts of the process parameter on the hardness depth and the impact on the surface hardness of laser beam power. Rezagholizadeh et al. [3] studied Ck45 steel that had a low cost and was easily available material for industrial applications, but its limitations was due to wear and corrosion resistance. In this research the focus was on the improvement of tribological properties and corrosion of Ck45 steel by Ni-B-B4C composite coating. Wagh et al. [4,5] considered impacts of parameters of laser hardening process on Ck45 steel and cast iron materials mechanical and wear properties utilizing an orthogonal array technique. Sagaro et al. [6] studied effects of laser hardening process parameters on U13A steel, microstructure, tribological performance and improvement in hardness depth of 260µm. Palaniraj et al. [7] investigated the hardness and depth of case by means of optimization techniques in the laser hardening process. C. Hu et al. [8] studied a demonstrate utilizing the super position of Gaussian sources in two dimensions developed and utilized for the expectation of hardness depth of laser hardened medium carbon steel by utilizing CO2 laser system. Patwa et al. [9] utilized prescient demonstrating and considered impacts laser hardening process parameters on case depth and hardness of AISI5150H steel and theoretically come to a hardness value was 63Rc and case depth of 0.5 mm. More et al. [10] used Taguchi’s method of experimentation for investigating the significant parameters used for erosion wear study on SS304 material. The orthogonal array method was utilized to consider the effects of laser hardening process parameters on hardness depth of Ck45 steel. The process of laser hardening was completed with a laser fiber system of 400 W.

2. Experimental Details

2.1 Material utilized for the experimentation

Table 1. Elemental weight percentage of CK45 steel

| Elements | C   | Si   | S    | P    | Mn   |
|----------|-----|------|------|------|------|
| Composition weight | 0.540 | 0.320 | 0.039 | 0.035 | 0.760 |

Now a days, Ck45 steel is used in bolts, axles, connecting rods and hydraulic clamps. Therefore, for the present experimental work, Ck45 steel is used as testing material. Table 1 shows the elemental composition in weight percent. SEM picture of the base material of CK45 steel is as shown in Fig. 1.

Fig. 1. SEM picture of the base material of CK45 steel

2.2 Experimental set-up and preparation of specimens

Figure 2 shows the image of fiber laser system continuous wave of 400 watt and 1070 nm laser wavelength. The experiments were conducted on the same laser system. The parameters of the laser hardening process used 210, 270 and 330 watt laser beam power, 1.0, 8.5 and 16.0 mm/s laser scanning speed and 200, 250 and 300 mm standoff distance as presented in Table 2. A laser beam diameter of 1.4
mm and argon gas used for creation of protective atmosphere during laser hardening process at a flow rate of 10 liters/min. The specimen’s preparations were conducted using acetone. The specimens were cut into 20 mm x 8 mm x 8 mm by a wire electrical discharge machine.

Fig. 2. Fiber laser system (SPI 400 CW, Laser Science Pvt. Ltd. Mumbai)

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

| Sr. No. | Laser parameters          | Unit | Levels     |
|---------|---------------------------|------|------------|
| 1       | Laser beam power (P)      | W    | 210 270 330|
| 2       | Laser scanning speed (v)  | mm/s | 1.0  8.5 16.0|
| 3       | Standoff distance (f)     | mm   | 200 250 300|

2.3 Metallographic and microstructure examination

To take a laser track on the sample, optimized were process parameters were used. The laser tracks were taken on the surface of the specimen and therefore the laser treated cross sectional area was polished using an emery paper of different grades using each of them as 4 % Nital to examine the cross sectional area microstructure of the laser treated samples. By using a microscope, the width, depth and microstructure were studied in the heat affected area by using a microscope made by Conat ion Technologies Pune. A machine was used for microhardness test at 300 gram load with 10 seconds dual time and microhardness was check on the laser hardened area of the laser hardened samples. Future Tech Corporation Japan, Vicker microhardness testing machine of model number FM700 was used to check microhardness. The microhardness was checked using heat affected zone and the base metal along the laser hardened cross sectional area.

2.4 Experimental Design

For the analysis of the influencing significant process parameters, the design of experiment technique was used and on the basis of that an output response model was developed. In the process of laser hardening, three input parameters influenced hardness depth which had out response. Taguchi’s design of experiment method was more flexible to find effects on hardness depth by every input process parameter compared to other analytical methods. In this analysis study, power of laser beam power, speed of laser scanning and standoff distance were used as laser hardening process parameters to check effects on output as a hardness depth of laser treated Ck45 steel sample. Table 2 appears the levels of process parameters utilized for the experiment. Table 3 shows the process parameters. The hardness depth is that the output response and therefore the signal to noise ratio relation of the complete run. The output response values are converted to signal to noise ratio using Taguchi’s L0 experiment method. The signal to noise ratio was determined for each factor level combination. The equation for the largest was a better signal to noise ratio using a 10 log base as shown in Equation 1.

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

---

3
where, $Y$ is the response to the given combination of the factor level and $n$ is the number of responses in the combination of the factor level.

3. Results and Discussion

3.1 Hardness depth analysis by Taguchi’s Experimental Design

The results of the present experimental work were analyzed using MINITAB 14. Taguchi’s orthogonal array L9 design was used to analyze the experimental work. Table 3 shows details of the experimental parameters and respective results of S/N ratio for all the nine sets of the experiments. The aim of the present experiment was to increase the value of hardness depth. Therefore, ‘the larger the better’ quality characteristic was selected and used for the present Taguchi’s analysis. Table 4 shows the value of signal to noise ratio as response for the present experimental condition and the larger the better quality characteristic. Laser scanning speed was the most important significant control process parameter among all three factors that laser hardness surface as shown in Table 4, causing the hardness depth of Ck45 steel laser treated specimens. In the second and third position, i.e. laser beam power and standoff distances, the remaining two parameters were rated. The main effect plots for signal to noise ratio are graphically shown in Fig. 3. The surface hardness depth value of laser hardened sample of Ck45 steel was found maximum at 330 watt laser power, 1.0 mm/s laser scanning speed and 300 mm standoff distance.

![Main Effects Plot for S/N ratios](image)

Fig. 3. Main effects plot for S/N ratios

3.2 The effect of laser power on the depth of hardness

As the power of the laser beam increases between 210 and 330 watts, the value of the signal to noise ratio and hardness depth of laser hardened sample increase too which is shown in Fig. 3. It is observed from Table 3 that increments in the hardness depth are 308.51, 325.14 and 340.25 µm respectively of laser hardened samples of Ck45 steel with variations in the laser beam power of 210, 270 and 330 watt at constant 1.0 mm/s laser scan speed and the maximum achieved hardness depth is 340.25 µm.

3.3 The effect of laser scanning speed on the depth of hardness

The effects of the process parameters as a laser scanning speed on the laser treated samples hardness depth value shows that a curve trend graph is inversely proportional as shown in Fig. 3. As the variations in the laser scanning speeds are 1.0, 8.5 and 16.0 mm/s at 330 watt constant laser beam power is observed. Table 3 shows the effects of laser scanning speed which decreases the hardness depth to 340.25, 322.32 and 300.34 µm respectively and decreases the signal to noise ratio values.

3.4 Morphology of the surface using microstructure
Figure 4 provides an overview of the nine laser hardened specimen’s microstructure according to Taguchi’s test sets and one untreated sample. Fig. 4(a) shows untreated sample and Fig. 4(b-j) shows nine sets of experiments as per Table 3. The effect of change in laser scanning speed on microstructure is shown in Fig. 4(b-d). The laser scanning speed varies from 1.0, 8.5 and 16.0 mm/s at 210 watt constant laser beam power. Fig. 4(b-d) presents a change in hardness width and decrease the hardness depth due to the increased laser scanning speed. Similar results can be observed in Fig. 4(e-g, h-j) at laser beam powers of 270 and 330 watt, laser scanning speed of 1.0, 8.5 and 16.0 mm/s and standoff distance of 200, 250 and 300 mm respectively. Fig. 4(e & h) presents maximum hardness depth at 270 watt, 1.0 mm/s and 250 mm and 330 watt, 1.0 mm/s and 300 mm respectively. Fig. 4(b-d, e-g and h-j) depicts constant laser beam power of 210, 270 and 330 watt and the variation in the laser scanning speed of 1.0, 8.5 and 16.0 mm/s that affects the hardness depth and it decreases that is to say that laser scan speed effects on hardness depth.

Table 3. Experimental CK45 steel laser hardness depth matrix Taguchi L9

| Sr. No. | Laser Power (w) | Laser scanning speed (mm/s) | Standoff distance (mm) | Width (μm) Ck45 | Hardness depth of HAZ(μm) | S/N Ratio |
|---------|-----------------|-----------------------------|------------------------|------------------|--------------------------|----------|
| 1.      | 210             | 1                           | 200                    | 1114.81          | 308.51                   | 49.7854  |
| 2.      | 210             | 8.5                         | 250                    | 1088.34          | 249.10                   | 47.9275  |
| 3.      | 210             | 16                          | 300                    | 1037.75          | 220.13                   | 46.8536  |
| 4.      | 270             | 1                           | 250                    | 1094.68          | 325.14                   | 50.2414  |
| 5.      | 270             | 8.5                         | 300                    | 1022.67          | 264.18                   | 48.4380  |
| 6.      | 270             | 16                          | 200                    | 1063.68          | 231.32                   | 47.2843  |
| 7.      | 330             | 1                           | 300                    | 1090.14          | 340.25                   | 50.6360  |
| 8.      | 330             | 8.5                         | 200                    | 1093.22          | 322.32                   | 50.1657  |
| 9.      | 330             | 16                          | 250                    | 1027.93          | 300.34                   | 49.5523  |

Table 4. Signal to noise ratios response table larger is a better option.

| Level | Laser scanning speed | Laser beam power | Standoff distance |
|-------|----------------------|------------------|-------------------|
| I     | 50.22                | 48.19            | 49.08             |
| II    | 48.84                | 48.65            | 49.24             |
| III   | 47.90                | 50.12            | 48.64             |
| Delta | 2.32                 | 1.93             | 0.60              |
| Rank  | 1                    | 2                | 3                 |
Base metal

A

P = 210 W, v = 1 mm/s and f = 200 mm

B

P = 210 W, v = 1 mm/s and f = 200 mm

C

P = 210 W, v = 8.5 mm/s and f = 250 mm

D

P = 210 W, v = 16 mm/s and f = 300 mm

E

P = 270 W, v = 1 mm/s and f = 250 mm

F

P = 270 W, v = 8.5 mm/s and f = 300 mm

G

P = 270 W, v = 16 mm/s and f = 200 mm

H

P = 270 W, v = 16 mm/s and f = 200 mm

I

P = 330 W, v = 1 mm/s and f = 300 mm

J
P = 330 W, v = 8.5 mm/s and f = 200 mm

P = 330 W, v = 16 mm/s and f = 250 mm

Fig. 4. Samples classified as per L_9 experiments by microstructure of Ck45 steel (a) Base metal and (b-j) laser treated

Table 5. Comparison of the experimental and predictive hardness depth values.

| Expt. No. | Results obtained from the experiments | Results obtained from the predictive equation | Percentage error (%) |
|-----------|--------------------------------------|-----------------------------------------------|----------------------|
| 1.        | 308.51                               | 297.00                                        | 3.88                 |
| 2.        | 249.10                               | 253.70                                        | 1.81                 |
| 3.        | 220.13                               | 210.40                                        | 4.62                 |
| 4.        | 325.14                               | 321.59                                        | 1.10                 |
| 5.        | 264.18                               | 278.29                                        | 5.07                 |
| 6.        | 231.32                               | 253.74                                        | 8.84                 |
| 7.        | 340.25                               | 364.18                                        | 1.71                 |
| 8.        | 322.32                               | 321.63                                        | 0.21                 |
| 9.        | 300.34                               | 278.33                                        | 7.91                 |

3.5 Prediction of depth of hardness using predictive equation

Due to the laser beam power, laser scan speed and standoff distance, the laser treated sample hardness depth was calculated employing a nonlinear regression formula to illustrate the relationship between the hardness depth and the combination of process control parameters. This analysis of regression was performed using Minitab 14 Software. The following regression equation from was obtained:

Hardness depth = 219 + 0.514(Laser beam power) - 4.94(Laser scan speed) -0.125(Standoff distance) - \( \ldots \) (2)

In Equation 2, all the constant values are calculated by using Minitab 14 Software. The accuracy of the measured constants was verified since Equation 2 obtained a strong correlation coefficient (r^2) of 0.905. The relation between the hardness depth obtained from experimental results and the predictive formula is shown in Table 5. An affirmation test might have been performed on Ck45 steel specimen. The optimal test parameters values are used for trial i.e. laser beam power, laser scanning speed and standoff distance which acquired that maximum hardness depth. Due to the laser hardening process, the depth of hardness is obtained in the Ck45 steel product by using both nonlinear regression equation and experimental affirmation results which are shown in Table 6.

Table 6 Affirmation test comes about for hardness depth of Ck45 steel.

| Laser beam power (W) | Laser scan speed (mm/s) | Standoff distance (mm) | Hardness depth in test | Hardness depth by equation | % error |
|----------------------|-------------------------|------------------------|------------------------|---------------------------|---------|
| 330                  | 1.0                     | 250                    | 333.75                 | 352.43                    | 5.30    |

A deviation of approximately 5.30 percent was found to be agreeable by comparing the experimental
results and analytical results. Therefore, the derived nonlinear regression formula is shown to explain with a reasonable degree of approximation the hardness depth of the Ck45 steel material with different control factors.

4 Conclusions
The most remarkable conclusions drawn from the investigation are summarized below:
- From all the three variables, laser scanning speed is the foremost impacting noteworthy calculates of laser hardness depth of Ck45 steel, taken after by the laser beam power and standoff distance separate individually.
- The maximum hardness depth attained is at 330 watt laser beam power, 1.0 mm/s laser scan speed and 300 mm standoff distance of Ck45 steel by laser hardening process.
- Microstructure of laser hardness depth specimens of Ck45 steel highlights two different zones. The first one is the heat affected area and the second one is the base metal area. These are the main characteristics of a laser hardening process.
- The hardness layer depth range is achieved from 220.13 µm and 340.25 µm for laser treated specimens.
- The deviation in the hardness depth percentage error between predicted and experimental result was between 0.21 and 8.84 %. A higher correlation coefficient value of \( r^2 \) of 0.905 which shows the correctness of the mathematical model used. Therefore, the model is more suitable for future study.
- From this analysis, it can be concluded that the laser surface hardness depth is maximized by monitoring the speed of laser scanning, power of laser beam and standoff distance, making progress in the gain life of the Ck45 steel specimens with laser hardened.

5. Acknowledgments
- The authors place on record their sincere thanks for the assistance provided for the experimental facility from the Department of Mechanical Engineering and Metallurgy and Material Science Department, College of Engineering Pune, Maharashtra, India.
- The authors also wish to thank the Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, India for their kind support.

6. References
[1] Adel K. M., “Enhancement of dry sliding wear characteristics of CK45 steel alloy by laser surface hardening processing”, Procedia Materials Science, 6 (2014) pp. 1639-1643.
[2] N. Barka, and A. El. Ouafi, “Effects of Laser Hardening Process Parameters on Case Depth of 4340 Steel Cylindrical Specimen- A Statistical Analysis”, Journal of Surface Engineered Materials and Advanced Technology. 5 (2015), pp.124-135.
[3] Rezagholizadeh, M. Ghaderi, A. Heidary and S. M. Monirvaghefi, “The effect of B4C nanoparticles on the corrosion and tribological behavior of electroless Ni-B-B4C composite coatings”, Surface engineering and applied electrochemistry”, 51-1 (2015), pp.18-24.
[4] S. V. Wagh, D. V. Bhatt, J. V. Menghani and Shivananda S. Bhavikatti, “Effects of laser hardening process parameters on the mechanical and wear properties of ck45 steel using an orthogonal array”, International Journal of Modern Manufacturing Technologies, X (2018), pp. 86-93.
[5] S. V. Wagh, Sudeep Ingole, D. V. Bhatt, J. V. Menghani and M. J. Rathod, [2019], “Effect of process parameters on surface properties of laser-hardened cast iron”, The Minerals, Metals and Materials Society, TMS 2019, 148th, annual meeting and exhibition supplemental proceedings, pp. 732-743.
[6] Sagaro, J. S. Ceballos, A. Blanco, J. Mascarell, “Tribological behavior of line hardening of Steel U13A with Nd:YAG laser ”, Wear, 225-229 (1999), pp. 575-580.
[7] Palaniradja, N. Alagumurthi and V. Soundararajan, “Hardness and case depth analysis through optimization techniques in surface hardening process”, The open materials science journal, 4 (2010), pp.38-63.
[8] C. Hu and T. N. Baker, “Prediction of laser transformation hardening depth using a line source model”, Acta metal, mater, 43 (1995), pp. 3563-3569.
[9] Rahul Patwa and Yung C. Shin, “Predictive modeling of laser hardening of AISI5150H steels”, International Journal of Machine Tools and Manufacturing, 47 (2007), pp. 307-320.
[10] S. R. More, D. V. Bhatt, and J. V. Menghani, “Study of the Parametric Performance of Solid Particle Erosion Wear under the Slurry Pot Test Rig”, International Journal of Industrial Tribology, 39-4, (2017), pp. 471-481.