EFFECTS OF LASER HARDENING PROCESS PARAMETERS ON THE MECHANICAL AND WEAR PROPERTIES OF CK45 STEEL USING AN ORTHOGONAL ARRAY

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Abstract: Ck45 steel is commonly used in jig manufacturing, tool making, special purpose machinery, ship, military uses, mould, apparatus and plant construction. The applications of Ck45 steel are mostly in chemical, oil and gas industries, power plants, food processing industries heat exchangers, rack gears, machined and engineering parts etc., because of the material properties like good in machinability, dimensions stability and high impact resistance. In this study, experimental investigation of the influence of laser power, scan speed and stand-off distance on laser hardening process and dry sliding wear of Ck45 steel using 400 W fiber laser system and pin on disc test rig respectively are carried out. In this study, the design of experiments is considered using a Taguchi's technique. A comparison has been made for the experimental and Taguchi's technique results. The micro-hardness and wear morphology are studied using microstructure and micrograph obtained by optical micro-scope and scanning electron microscope (SEM) analysis respectively. It has been found that laser power is the most influencing factor than laser scan speed and stand-off distance for both micro-hardness and wear analysis. From this investigation, it can be concluded that micro-hardness is maximized and dry sliding wear is minimized by controlling laser power, laser scan speed and stand-off distance which improves the wear resistance and service life of the Ck45 steel components. From the comparison of experimental results and Taguchi's results, it has been found that the percentage deviation is very less with a higher correlation coefficient of r^2 0.922 for micro-hardness and 0.985 for dry sliding wear which is agreeable.

Key words: Laser hardening process, Ck45 steel, Taguchi's method, micro-hardness and wear resistance.

1. INTRODUCTION

Laser hardening is used to improve surface properties of different types of metallic components. It is largly used due to its beauty that only selective surface area properties can be improved without changing the remaining bulk material surface properties. Ck45 steel is low carbon steel used in various industrial applications. Most of the researchers try to attempt to improve surface properties of various steel grade materials using a laser hardening process.

Adel, [1], has investigated the effects of laser hardening process on wear resistance of Ck45 steel alloy laser treated specimen. He observed that the wear particle size of a laser treated sample was smaller in size compared to the un-treated sample of Ck45 steel after a dry wear test, the size of wear particle decreases which means that there is an increase in hardness and it obtains a fine microstructure that increases the wear resistance. Selman et. al., [2], investigated the effects of a laser hardening process on mechanical properties of Ck45 steel after a laser surface treatment. Yang and Shang, [3, 4], experimentally investigated effects of a laser hardening process on tool steel material. They found that the laser beam diameter affects mainly on the width and depth of the hardened zone after laser treatment on the surface of the steel tool. Pashby, Skvarenina, and Miokovic, [5-7], used a high power diode laser system for investigating the effects of a laser surface treatment process on case depth and hardness of plain carbon steel and alloy steel used as material with different process parameters. They found that the laser hardening process affects on hardness depth and hardness achieved by the optimization of parameters laser power, laser scan speed. Song et. al., [8], investigated the laser surface treatment of AISI D3 steel tool by using an electron beam surface hardening process. They found that the harden layer microstructure consists of martensite, fine carbides, retained austenite, and tempered sorbite observed in the transition area of the heat affected zone. The micro-hardness of the harden layer found to be improved compared to base metal. Feuerhahn et. al., [9], applied a selective laser melting process for steel tool material for an improvement in hardness. They found that the selective laser melted samples were microscopical defect free, no cracks but small voids were observed with a homogeneous microstructure and high hardness was achieved. Shin et. al., [10], investigated the effects of a laser hardening process parameters on surface hardness of S45C medium carbon steel by using Nd:YAG laser system. They found effects of newly developed heat treatment optical system on surface hardness, achieved surface hardness three times more compared to defocused focal position used for laser hardening of S45C medium carbon steel.

The design of experiments is one of the best methods of selecting optimum process parameters for any application and process. Badkar et. al., [11], used Taguchi's L9 orthogonal array methodology for the optimization of laser hardening process parameters. They investigated significant factors such as laser power, laser scan speed, focal position for laser hardening of commercially pure titanium by using Nd:YAG laser system, for minimizing the hardness depth and maximizing the hardness width. They observed that the laser scan speed was the most significant factor, and followed by a focal position and laser power for minimizing the hardness depth and maximizing the hardness width. Ming-der et. al., [12], investigated effects of an electron beam hardening process on wear resistance of cast iron by using Taguchi's method. They found that accelerating voltage is the most significant process parameter affecting the wear volume than travel speed, current and post-heat treatment respectively. Barka et. al., [13], investigated the effect of laser hardening process on hardness and hardness depth of 4340 steel cylindrical sample by using statistical analysis. They found that the laser scan speed significantly affected on the hardness depth and laser power had the most significant factor effect on hardness and at the third level effect of revolution speed. Babu et. al., [14], investigated the effect of laser hardening process on low alloy steel EN25 using a response surface methodology. They found that laser power was a more significant parameter than the travel speed. They developed a quadratic regression model to predict the response as hardness width, hardness depth, and hardness area using a response surface methodology. Based on the mathematical model, direct and interaction effects of process parameters on laser hardening process were investigated for maximizing the hardness width, minimizing the hardness depth, and the hardness area.

Selvan et. al., [15], investigated the effect of laser hardening on En18 (AISI 5135) steel. They observed that the laser hardening process improved the tribological properties, working life and two times increases in wear resistance of laser treated samples compared to as-received material. Adel et. al., [16], investigated the effects of laser hardening process on the wear and friction characteristics of acicular bainitic ductile iron. They observed that improvements in the wear and friction resistance of laser harden samples by their refined microstructure and increased hardness in the harden layer as compared to base metal. Taltavull et. al., [18], studied the dry wear behaviour of laser treated AMB60B magnesium alloy. They performed a wear test on dry sliding pin-on-disc and calculated the wear rate, friction coefficients and surface oxidation measured. The scanning electron microscopy was used to analysis of worn surface of wear tested specimens. They found that laser treated, wear tested samples had homogeneous wear behaviour, and there was no severe plastic deformation compared to the base material. Sagaro et. al., [18], experimentally investigated the effects of a laser hardening process on tribological behaviour of steel U13A. They found that wear resistance of laser treated samples of steel U13A was greater than the conventional heat treatment process. More et. al., [19], conducted an experimental work on the investigation of effects of erosion wear process parameters on stainless steel 304 for wear rate and behaviour of erosion wear using Taguchi's L9 orthogonal array. They found that velocity is the most factor responsible followed by particle size, impact angle and solid concentration.

The objective of this research study is to improve mechanical properties like micro-hardness, wear resistance and working life of Ck45 steel component by using a laser hardening process. The laser hardening process is carried out with a 400 W fiber laser system. The design of the experiment (DOE) methodology is used to find significant influencing operating process parameters for laser hardening of Ck45 steel.

2. EXPERIMENTAL DETAILS

2.1 Material used for the experimentation

Experimental trials were conducted on Ck45 steel commercially used in oil and gas industry, chemical industry, power plant, heat exchanger, and food processing industry. Figure 1 shows the SEM image of the base material and chemical compositions in weight percentage of Ck45 steel are given in Table 1.

2.2 Experimental set-up and sample preparation

The experiments were performed on SPI 400 W continuous wave mode fiber laser system of 1070 µm laser wavelength, as shown in Figure 2. The laser processing parameters used laser power 240, 250 and 260 W, laser scan speed 10, 15 and 20 mm/s and stand-off distance 250, 260 and 270 mm as shown in Table 2. A laser beam diameter of 1.4 mm, argon gas was used as shielding at 10 l/min flow rate. The preparations of samples were done using acetone. The samples cut by a wire electrical discharge machine have dimensions of 20 mm in length, 8 mm in width and 8 mm in thickness.

Table 1. Chemical compositions of Ck45 steel specimen in weight percentage

Elements	C	Si	S	P	Mn
Composition weight %	0.45	0.19	0.023	0.024	0.72

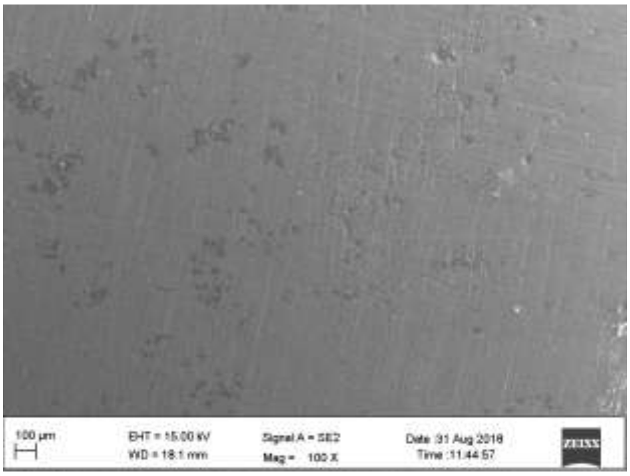


Fig. 1. SEM image of Ck45 steel base material

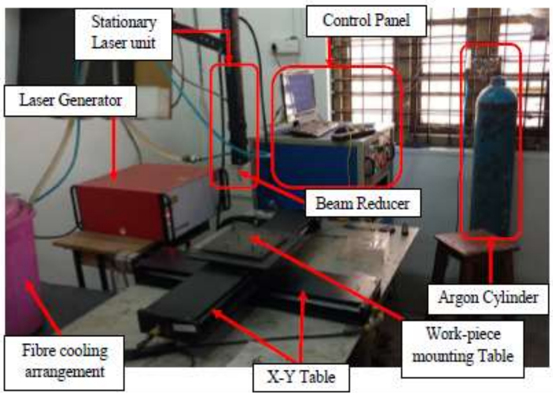


Fig. 2. Fiber laser system (SPI 400 CW, Laser Science Pvt. Ltd. Mumbai)

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

Sr. No.	Laser parameters	Unit/ Symbol	Level		
			1	2	3
1	Laser power (P)	Watt (P)	240	250	260
2	Laser scan speed (s)	mm/s (s)	10	15	20
3	Stand-off distance (f)	mm (f)	250	260	270

2.3 Metallographic and micro-structural analysis

Laser tracks were taken on the surface of Ck45 steel samples with optimized processing parameters. After laser hardening, they were polished with different grades of emery paper and were finally mirror finished on lapping machine, etched the cross section of sample with 4% Nital. The depths of micro-hardened layer were checked with the help of an optical microscope. The microstructure of the hardened region was analyzed by using an optical microscope (SuXma Met-I Series, Conation Technologies, Pune). The micro-hardness test was conducted on Ck45 steel laser treated sample surface and across the heat affected zone at a load of 300gm by using Vickers microhardness testing device (FM-700, Future Tech. Corporation, Japan).

2.4 Experimental Design

For the design of the experiments, a technique is used for analyzing the significant influence of control parameters and the development of a model on the performance output. Using this method, the effect of each single condition can easily be studied. In a laser hardening process, the output response is micro-hardness which depends on three input parameters namely laser power, laser scan speed and stand-off distance. Taguchi's design of experiments is considered because it is more flexible than other analytical techniques for identifying the influence of each input parameter on the micro-hardness of the laser treated samples. The Taguchi's design of experiment approach L9 orthogonal array method is applied because it reduces the experimental cost and time.

In all the experiments, the testing parameters and levels used are shown in Table 2. The operating parameters, results and signal-to-noise(S/N) ratio of each experimental run are shown in Table 3. The experimental results were changed into a S/N ratio.

The characteristics of S/N ratios are smaller the better, nominal the best, and larger the better. The larger is the better characteristic of S/N ratio was considering for studying the maximum micro-hardness as shown in equation 1.

$$S/N = -10\log\left\{\frac{1}{n}\sum_{n=1}^{n}\frac{1}{y_2}\right\} \qquad (1)$$

where, n the is number of observations and y is the response for the given factor level combination [11].

3. RESULTS AND DISCUSSION

3.1 Micro-hardness analysis using Taguchi's experimental design

MINITAB 14 Software package is used for the analysis of the present experiment. Taguchi's L9 orthogonal array design along with S/N ratio for the analysis of obtains micro-hardness from experimental results are shown in Table 3. The larger the better quality characteristic is selected to obtain optimal possible parameters for the laser hardening process.

Laser power was the most influencing significant control parameter among all the three factors for causing the surface micro-hardness of Ck45 steel as shown in Table 4. The remaining two parameters i.e. laser scan speed and stand-off distance are ranked at the second and the third positions respectively influencing the surface micro-hardness of Ck45 steel. The graphical results of the main effect of plot for the S/N ratio are represented in Figure 3. The micro-hardness values of laser treated samples of Ck45 steel are observed to be higher at 260 W laser power, 10 mm/s laser scan speed and 270 mm stand-off distance. Therefore, it is found that micro-hardness of the laser treated Ck45 steel sample is influenced by laser power, laser scan speed and stand-off distance.

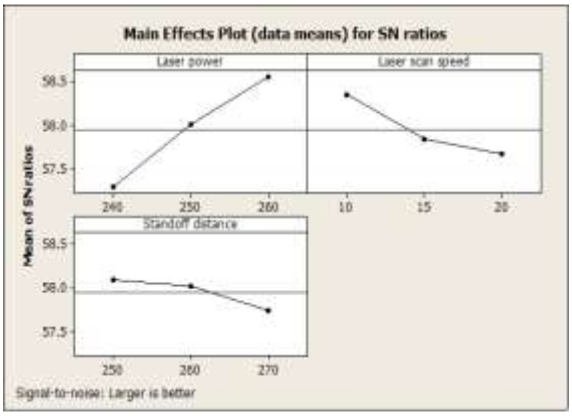


Fig. 3. Main effects of plot for S/N ratios

Table 3 Experimental Taguchi's L9 matrix for laser hardening of Ck 45 steel

Sr. No.	P (W)	s (mm/s)	f (mm)	$HV_{0.3}$	S/N Ratio
1	240	10	250	767.30	57.69
2	240	15	260	743.70	57.42
3	240	20	270	688.10	56.75
4	250	10	260	833.10	58.41
5	250	15	270	753.70	57.54
6	250	20	250	798.80	58.04
7	260	10	270	884.80	58.93
8	260	15	250	843.80	58.52
9	260	20	260	813.90	58.21

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

Level	Laser power	Laser scan speed	Stand-off distance
I	57.29	58.35	58.09
II	58.00	57.83	58.02
III	58.56	57.67	57.74
Delta	1.26	0.68	0.35
Rank	1	2	3

3.2 Effect of laser power on micro-hardness

Figure 3 shows the effect of laser hardening process parameters on surface micro-hardness of laser treated Ck45 steel samples. It shows that surface micro-hardness is directly proportional to laser power. Figure 3 shows that the variation in laser power from 240 W to 260 W increases S/N ratio value i.e. micro-hardness of the laser treated sample increases. Table 3 shows that at the constant laser scan speed of 10 mm/s, and variations in laser power from 240, 250 and 260 W respectively, effect on the micro-hardness values are increases 767.30, 833.10 and 884.80 $HV_{0.3}$ respectively. The optimum value of laser power is 260 W for present investigation. Table 3 shows that the maximum micro-hardness achieved was 884.80 $HV_{0.3}$ is two times of base metal mico-hardness of 249$HV_{0.3}$.

3.3 Effect of laser scan speed on micro-hardness

Figure 3 shows the effect of laser scan speed on the micro-hardness value of the laser treated samples. The result shows exactly a reverse trend as compared to laser power. The effect of the laser scan speed is inversely proportional to micro-hardness. Figure 3 shows that the laser scan speed increases from 10, 15 to 20 mm/s and it decreases the S/N ratio value i.e. the value of micro-hardness of laser treated samples was decreases at constant laser power. Table 3 shows that the output response i.e. micro-hardness decreases from 884.80, 843.80 and 813.90 $HV_{0.3}$ for increases laser scan speed from 10, 15 and 20 mm/s respectively at constant laser power of 260 W. The optimum surface micro-hardness value of laser treated sample observed at 10 mm/s for the present set of experiments.

3.4 Surface morphology using microstructure

Figure 4 (a) shows the microstructure of base metal. Figure 4 (b) shows the microstructure of the laser treated samples as per the experimental sets shown in Table 3. Figure 4 (b) highlights the microstructure changes observed at the process parameters laser scan speed of 10 mm/s, stand-off distance of 270 mm and laser power of 260 W respectively. The maximum micro-hardness values were obtained is shows in Table 3.

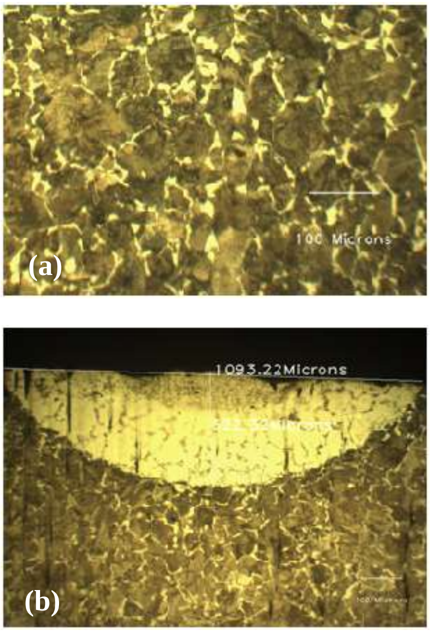


Fig. 4. Microstructure of (a) base metal and (b) laser treated samples at laser power of 260W, laser scan speed of 10 mm/s and stand-off distance of 270mm

3.5 Micro-hardness predication using predictive equation

The micro-hardness of the laser treated samples effects by laser hardening process parameters laser power, laser scan speed and stand-off distance help to predict the nonlinear regression equation. This regression analysis study is carried out by using Minitab 14 Software. The following form of regression is used as shown in Equation 2. The values of all constants were calculated with the help of Minitab 14 Software and by using these values in Equation 2.

$$Microhardness = -186 + 5.72(P) - 6.15(s) - 1.39(f) \quad (2)$$

The accuracy of the calculated constants was confirmed because the high correlation coefficient r^2 of 0.922 was obtained from Equation 2. The comparison of micro-hardness values obtained from predictive equation and experiment results is shown in Table 5.

Table 5. Comparison of experimental and predictive values for micro-hardness

Expt. No.	Results obtained from experiments	Results obtained from predictive equation	Percentage error (%)
1	767.30	777.80	1.35
2	743.70	733.15	1.43
3	688.10	688.50	0.05
4	833.10	821.10	1.46
5	753.70	776.45	2.92
6	798.80	773.50	3.27
7	884.80	864.40	2.36
8	843.80	861.45	2.04
9	813.90	816.80	0.35

Table 6. Confirmation experimental results for micro-hardness of Ck45 steel

P (W)	s (mm/s)	f (mm)	Micro-hardness in test	Micro-hardness by equation	% error
260	10	250	878.10	892.20	1.58

A confirmation test is performed on the Ck45 steel sample by considering as optimal test parameters like laser power, laser scan speed and stand-off distance which give a maximum micro-hardness value. The micro-hardness value of the laser treated Ck45 steel sample can be calculated by using a nonlinear regression equation and the results of the experiment confirmation test are shown in Table 6. By comparing the experimental result and analytical result, the deviation is observed is 1.58 % which is within an acceptable range. Therefore, it is shown that the derived nonlinear regression equation describes the micro-hardness values of the Ck45 steel material with various control factors with a reasonable degree of approximation.

3.6 Wear analysis using Taguchi's experimental design

In this study, a wear tests is conducted on Ck45 steel laser treated and un-treated samples, prior and after the wear test measure weight of the samples for the study of weight loss by a dry sliding wear test. The Pin-on-disc sliding wear testing machine makes Ducom used for dry sliding wear testing, the wear test setup is shown in Figure 5. The wear rate is measured by a weight loss method using an analytical balance (AnaMatrix Instrument Technologic Pvt. Ltd., HZK-FA210) having maximum capacity of 210 gm, readability 0.1 mg sensitivity. For wear rate calculation by using the relationship given in below said Equation 3, [1, 16]:

$$wearrate = \Delta W / SD \text{ (gm/cm)} \quad (3)$$

where,
ΔW= Weight loss (gm);
SD = Sliding distance (cm);
$\Delta W = W_1 - W_2$

where,
W_1=Initial weight of the test specimen (gm);
W_2=Final weight of the test specimen (gm).

The applied normal load is 30N, sliding speed of 440rpm, sliding distance of 5000m, track diameter of 120 mm and the hardness of the counter disk is 65HRc. The duration of each test was 30 minutes and the dry sliding wear test is performed at normal room temperature and atmospheric conditions.

Fig. 5. Experimental set up of pin on disc for wear testing

The process parameters and levels used in all the experiments are shown in Table 2. The operating

parameters, results and S/N ratio of each experimental run are shown in Table 7. The experimental results changed into a S/N ratio.
The characteristic of S/N ratios are smaller the better, nominal the best, and larger the better. The smaller the better characteristic of S/N ratio is consider for studying the minimum wear rate as shown in Equation 4.
The smaller the better characteristics as follows:

$$S/N = -10\log\frac{1}{2}\left(\sum y^2\right) \qquad (4)$$

where, n is the number of observations and y is the response for the given factor level combination [12].
L9 orthogonal array design along with S/N ratio for the analysis of wear rate experimental results are shown in Table 7. The smaller the better quality characteristic was selected to obtain the optimal possible parameters for the dry sliding wear test.

Table 7. Experimental Taguchi's L9 matrix used to calculate the wear rate

Sr. No.	P (W)	s (mm/s)	f (mm)	Wear rate (gm/cm) x 10^{-9}	S/N Ratio
1.	240	10	250	2.4	-7.60422
2.	240	15	260	2.5	-7.95880
3.	240	20	270	2.7	-8.62728
4.	250	10	260	2.2	-6.84845
5.	250	15	270	2.4	-7.60422
6.	250	20	250	2.5	-7.95880
7.	260	10	270	2.0	-6.02060
8.	260	15	250	2.1	-6.44439
9.	260	20	260	2.3	-7.23456

Table 8. S/N ratio response table using the characteristics of the smaller the better

Level	Laser power	Laser scan speed	Stand-off distance
I	-8.063	-6.824	-7.336
II	-7.470	-7.336	-7.347
III	-6.567	-7.940	-7.417
Delta	1.497	1.116	0.082
Rank	1	2	3

The response table for the S/N ratio obtained is shown in Table 7. Laser beam power is the most influencing significant control parameter among all the three factors for causing the surface micro-hardness of Ck45 steel as shown in Table 8. Laser power was the most significant process control parameter among all the three parameters viz. laser scan speed and stand-off distance, causing the wear rate of laser treated of Ck45 steel.
The remaining two parameters of laser scan speed and stand-off distance are ranked at the second and the third positions respectively for the influencing the wear rate. The graphical results of the main effect of plot for the S/N ratio are represented in Figure 6.

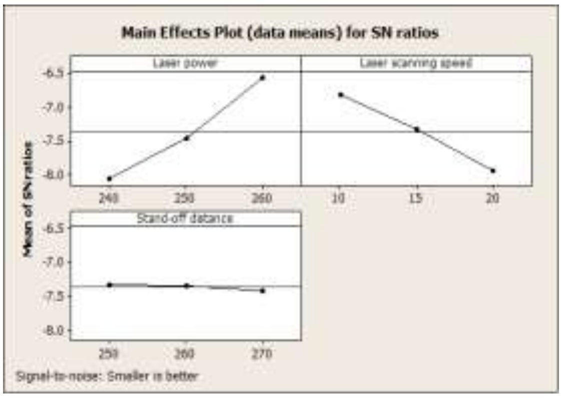


Fig. 6. Main effects of plot for S/N ratios

The wear rate value of Ck45 steel laser treated sample after wear test is observed to be smaller. The setting of process parameters as per L9 ortogonal array table are laser power of 260 W, laser scan speed of 10 mm/s and stand-off distance of 270 mm. Therefore, it is found that wear rate of Ck45 steel laser treated sample was influenced by process parameters like laser power, laser scan speed and stand-off distance.

3.7 Wear rate predication using a predictive equation

The effect on the wear rate of the laser treated Ck45 steel samples by the process parameters i.e. laser power, laser scan speed and stand-off distance, is predicted by using a nonlinear regression equation, showing the relationship between wear rate and the combination of control process parameters. The following form of the regression Equation (5) was obtained:

$$wearrate = 6.46 - 0.0200(P) + 0.0300(s) + \\ + 0.00176(f) \qquad (5)$$

The accuracy of the calculated constants is confirmed because the high correlation coefficient r^2 of 0.985 is obtained from Equation (5). The comparison between the wear rate obtained from experimental results and predictive equation are shown in Table 9.
A confirmation test was performed on the Ck45 steel laser treated sample by considering optimal test parameters laser power, laser scan speed and stand-off distance, the wear rate was minimum. A minimum wear rate was observed after the wear test performed on Ck45 steel laser treated and untreated samples, because of the application of laser hardening process by using a nonlinear regression equation and the confirmation experiment test results are shown in Table 10.

Table 9. Comparison of experimental and predictive values for wear rate

Expt. No.	Results obtained from experiments	Results obtained from predictive equation	Percentage error (%)
1	2.40	2.37	0.94
2	2.50	2.54	1.73
3	2.70	2.71	0.40
4	2.20	2.19	0.26
5	2.40	2.36	1.65
6	2.50	2.47	0.90
7	2.00	2.01	0.54
8	2.10	2.12	1.29
9	2.30	2.29	0.25

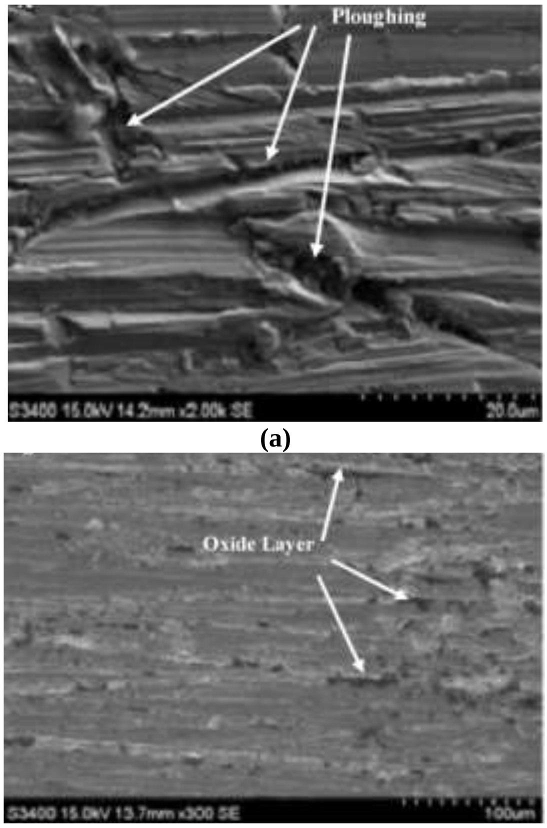
Table 10. Confirmation experimental results for wear rate of Ck45 steel

P (W)	s (mm/s)	f (mm)	Wear rate in test	Wear rate by equation	% error
260	10	250	1.95	2.00	2.50

By comparing the wear rate values obtained from the result of the experiment test and analytical equation result, a deviation of 2.50 % is found within an acceptable range. Therefore, it is shown that the non-linear regression equation predicts the wear rate value of Ck45 steel laser treated samples with various control process parameters with a reasonable degree of approximation.

3.8 Surface morphology of CK45 Steel

The wear test was performed at 30 N applied load and laser power of 260W, laser scan speed of 10 mm/s and stand-off distance of 270mm used for profile- b. The region of oxidation of the Ck45 steel sample wear mechanism map, as it is evidenced in Figure 7 (a). The worn surface of the laser treated samples is shown in Figure 7 (b), delamination is observed in both wear test conditions. However, there are some differences between the worn surface observed and shown smoother in Figure 7 (b) compared to the worn profile of surface shown in Figure 7 (a). On the other hand, a difference between the formation of cracks at the worn surface of the as-received base metal and laser treated samples has been observed in the wear test carried out at 30N. In the as-received base metal shown in Figure 7 (a), continuous cracks can be observed as shown by arrowed, cracking has not been detected. However, in the laser treated samples, as shown in Figure 7 (b), oxide layer of the cracks has been detected and it is shown by arrowed and internal cracks observed. This might be related to the increase of toughness of the laser treated samples in comparison with the as-received base metal [17].



(a)

(b)

Fig 7. SEM images of wear scars of Ck45 steel samples at constant applied load of 30NW-: a) Base metal, b) laser treated sample at P = 260W, s = 10mm/s and f = 270mm

4. CONCLUSIONS

The following conclusions have been drawn at from the results obtained from the laser hardening of Ck45 steel:

From all the three parameters, laser power is the most influencing significant parameter of laser hardening of Ck45 steel, followed by laser scan speed and stand-off distance ranked at the second and third positions respectively.

Maximum micro-hardness and minimum wear rate is achieved at 260 W laser power, 10 mm/s scanning speed and 270 mm stand-off distance of the metal Ck45 steel by the application of a laser hardening process.

The micro-hardness of base material is observed in the range of 249 $HV_{0.3}$, 258 $HV_{0.3}$. After a laser hardening process, the micro-hardness of laser treated samples was obtained in the range of 767.30 $HV_{0.3}$ to 884.80 $HV_{0.3}$.

The micro-hardness value of the laser treated Ck45 steel samples obtained was two times more compared to the un-treated sample of Ck45 steel.

From this investigation, it is concluded that Ck45 steel laser samples surface micro-hardness maximized and wear rate is minimized by the control process parameters like laser power, laser scan speed and stand-off distance, which improves the service life of the Ck 45 steel laser treated samples.

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6. REFERENCES

1. Adel, K.M., (2014), *Enhancement of dry sliding wear characteristics of Ck45 steel alloy by laser surface hardening processing*, Procedia materials science, 6, 1639-1643.
2. Selman, K.D., Mahmood, S.N., (2011), *Effect of laser surface treatment on mechanical properties of Ck45 steel*, Engineering and technology journal, 29(8).
3. Yang, L.J., Jana, S., Tam, S.C., (1990), *Laser transformation hardening of tool-steel specimens*, Journal of materials processing technology, 21, 119-130.
4. Shang, H.M., (1990), *On the width and depth of hardened zone during laser transformation hardening of tool steels*, Journal of materials processing technology, 23, 65-72.
5. Pashby, I.R., Barnes, S., Bryden, B.G., (2003), *Surface hardening of steel using a high power diode laser*, Journal of materials processing technology, 139, 585-588.
6. Skvarenina, S., Shin, Y.C., (2006), *Predictive modeling and experimental results for laser hardening of AISI 1536 steel with complex geometric features by a high power diode laser*, Surface and coating technology, 201, 2256-2269.
7. Miokovic, T., Schulze, V., Vohringer, O., Lohe, D., (2007), *Influence of cyclic temperature changes on the microstructure of AISI 4140 after laser surface hardening*, Acta materialia, 55, 589-599.
8. Song, R.G., Zhang, K., Chen, G.N., (2003), *Electron beam surface treatment. Part-I: surface hardening of AISI D3 tool steel*, Vacuum, 69, 513-516.
9. Feuerhahn, F., Schulz, A., Seefeld, T., Vollertsen, F., (2013), *Microstructure and properties of selective laser melted high hardness tool steel*, Physics procedia, 41, 843-848.
10. Shin, H.J., Yoo, Y.T., Ahn, D.G., Im, K., (2007), *Laser surface hardening of S45C medium carbon steel using Nd:YAG laser with a continuous wave*, Journal of materials processing technology, 187-188, 467-470.
11. Badkar, D.S., Pandey, K.S., Buvanashekaran, G., (2011), *Parameter optimization of laser transformation hardening by using Taguchi method and utility concept*, International journal of advanced manufacturing technology, 52, 1067–1077.
12. Ming-der, J., Yih-fong, T., (2004), *Optimisation of electron-beam surface hardening of cast iron for high wear resistance using the Taguchi method*, International journal of advanced manufacturing technology, 24, 190–198.
13. Barka, N., Ouafi, A, El., (2015), *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(03), 124-135.
14. Babu, P, D., Buvanashekaran, G., Balasubramanian, K.R., (2013), *Experimental investigation of laser transformation hardening of low alloy steel using response surface methodology*, International Journal of Advanced Manufacturing Technology, 67, 1883–1897.
15. Selvan, J.S., Subramanian, K., Nath, A.K., (1999), *Effect of laser surface hardening on En18 (AISI 5135) steel*, Journal of material processing technology, 91, 29-36.
16. Adel, K, M., Dhia, A, S., Ghazali, M, J., (2009). *The effect of laser surface hardening on the wear and friction characteristics of acicular bainitic ductile iron*, International journal of mechanical and materials engineering, 4(2), 167-171.
17. Taltavull, C., Lopez, A, J., Torres, B., Rams, J., (2013), *Dry sliding wear behavior of laser surface melting treated AM60B magnesium alloy*, Surface and coating technology, 236, 368-379.
18. Sagaro, R., Ceballos, J.S., Blanco, A., Mascarell, J., (1999), *Tribological behavior of line hardening of steel U13A with Nd:YAG laser*, Wear, 225-229, 575-580.
19. More, S.R., Bhatt, D.V., Menghani, J.V., (2017), *Study of the parametric performance of solid particle erosion wear under the slurry pot test rig*, Tribology in Industry, 39(4), 471-481.

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