Laser surface hardening of SS316L

Ganesh Dongre, Avadhoot Rajurkar, Ramesh Gondil and Nandan Jaju

Department of Industrial & Production Engineering, Vishwakarma Institute of Technology, Pune, India

Abstract. Laser surface hardening is one of the effective method to enhance the mechanical properties of localised surface area of engineering parts made of different types of steels and other metals like titanium etc. Laser surface hardening has many advantages over conventional hardening process like, self-quenching, very fast, control over energy input and localised hardening etc. This work presents the effect of different laser parameters on the micro hardness of SS316L after laser hardening. The experimental work was carried out using 30W Diode-pumped nanosecond (ns) pulsed laser. Design of Experiments One Variable at a Time (OVAT) approach was used for experimentation. Laser power, laser scanning speed, frequency and number of passes were the process parameters used for the experiments. Effects of these parameters over the micro hardness of the surface are described. Along with this, discussion of features of microstructures using optical microscope are done. It has been found that, there is around 25% increase in hardness after laser hardening. Hardened depth up to 400 microns was obtained.

Keywords: Laser surface hardening, hardening depth, micro hardness.

1. Introduction
The process of laser surface hardening is used to enhance the mechanical properties of selected surface areas of different kinds of steel. It was first reported in early 70’s. Since then lot of research is going on to develop deeper understanding of the process, modelling of process to determine the optimum parameters.

Laser surface hardening uses laser as a heat source. The beam energy is used to harden the required surface with remaining surface acting as heat sink to avoid surface melting. Initially surface to be hardened is heated to austenitic range. This is done by continuously scanning the laser over the required surface. Then material is quickly cooled down to a temperature below martensitic temperature as remaining surface act as heat sink. It can be used for hardening of shafts, pulleys, bearing sleeves, drive gears etc.

There are many advantages of laser hardening over conventional hardening processes. Laser hardening is very fast process and can produce metastable phases. In laser hardening due to localised modification, most of the bulk properties remain unchanged. No need of quenching medium as surface is self-quenched. By changing laser power, we can control energy input. With the help of computer aided process, beam can be guided over work piece surface. The main disadvantage of laser hardening is its initial high investment cost and it requires protection from radiation [8].

Laser hardening can be done using different kinds of laser. One of the kind is by using CO$_2$ laser. While using CO$_2$ laser, coatings are applied on the surface to be hardened to increase the absorptivity. The coatings generally used are colloidal graphite and MOS$_2$. Another kind is neodymium-doped yttrium
aluminium garnet (Nd: YAG). This is solid state laser with shorter wavelength which produces better laser-matter coupling. And hence coatings are not required here. Apart from these two there is one more type of laser, fiber laser. It is basically plug and play kind of industrial equipment with absence of maintenance for more than 20000 hours. In this laser light is already coupled into a flexible fiber which makes light to be easily delivered to a movable focusing element. Fiber laser is a low maintenance machine as compared to that of CO₂ and Nd: YAG laser.

Badkar et al [1] carried out parametric optimization of laser transformation hardening using Taguchi method and utility concept. Experiments were done on pure titanium using continuous wave 2kW ND: YAG laser. Through this investigation they found out that scanning speed, laser power and focal plane position were most influencing parameters for minimizing the hardened depth and maximizing hardened bead width. Higher levels of focal plane position, scanning speed in combination with lower level of laser power were necessary for minimizing hardened depth and maximizing hardened bead width. Hino et al [2] carried out surface hardening of carbon steel using high powered YAG laser. They carried out the hardening without using absorbents. Evaluation of relationship between laser processing and surface hardening were done using microstructure and hardness. According to this paper proper selection of type of assist gas and the flow rate are required to get uniform hardened zone. Goia et al [3] performed hardening on AISI D6 cold work steel using fiber laser. They carried out hardening with different combinations of laser power and focal distance. According to them best results were obtained when the superposition between laser tracks attains 80%. Selvan et al [4] performed surface hardening on EN18 (AISI 5135) steel using high power CO₂ laser. Laser power, scan velocity and beam diameters were the variable parameters used during the study. 3-fold increase in hardness and 2-fold increase in wear resistance was obtained with case depth of 0.45 and 0.65 mm at laser powers of 1.3 and 1.5 kW. P. Chandrasekar et al [5] performed the hardening of titanium-titanium boride metal matrix composite using 10kW CO₂ laser system. It was observed that with increase in incident energy, hardness was increasing. They got hardness of about 1050 Hv at incident energy of 70 kJ/m as compared to that of 513 Hv of base metal. B. Mahmoudi et al [5] compared the hardening done by pulsed laser with conventional hardening. The maximum hardness found was 90% of the maximum hardness found by conventional hardening. Also the corrosion resistance of laser hardened surface was more as compared to that of parent sample. Limaa et al [6] have done the hardening of automotive shaft (AISI 1040) using 2kw fibre laser. Laser power was process variable, ranging from 300 W to 1100 W. At higher power we get two different regions in microstructure, one is martensitic region and other is partially transformed region. With higher power we get higher case depth. M.J.Rathod et al [7] carried out hardening of ductile irons using 400W continuous wave fiber laser. He varied laser power and scanning speed and measured the hardness over the surface and along depth. Hardness value increases with increase in power and decreases with increase in scanning speed. Same is in the case of case depth.

2. Experimental Details

2.1 Experimental Setup

This paper reports on the investigations made in laser surface hardening which were carried out by using diode pumped fiber laser (NUQA 30W). The specifications of the same are mentioned in table 3. Experimentation were done on SS316L plate of 0.8mm thickness. The composition of the same is given in table 1. Laser hardening is carried on an area of 7x7 cm² surface. Important parameters of hardening with laser beam are: Scanning speed in mm/s, Number of passes, Frequency in kHz and Laser power in W. The range of process parameters used during experiments are listed in table 2. Actual machine setup is shown in figure 1. At a time only single parameter was varied keeping other parameters constant.
Table 1. Composition of SS316L

| Grade | Cr  | Mo  | Si  | Mn  | C   | P   | S   | Fe   |
|-------|-----|-----|-----|-----|-----|-----|-----|------|
| Percentage (%) | 17  | 2.50 | 0.75 | 2.00 | 0.03 | 0.045 | 0.75 | Balance |

Table 2. Process parameters range

| Sr No | Process Parameter       | Parametric Levels                      |
|-------|-------------------------|----------------------------------------|
| 1     | Laser Power (W)         | 6, 9, 12, 15                           |
| 2     | Scanning Speed (mm/s)   | 100, 200, 300, 400, 500                |
| 3     | Frequency (kHz)         | 30, 45, 60, 75                         |
| 4     | No of passes            | 1, 3, 5, 7                             |

Figure 1. Nano second fibre laser setup

Table 3. Laser Machine specification

| NUQA-1064-NA-0030-YZ |
|-----------------------|
| Output Power          | 30.0 W                  |
| Power Stability       | ± 2.5%                  |
| Beam Quality (Nominal)| M2 < 1.5                 |
| Mode of Operation     | Pulsed                  |
| Polarization          | Random                  |
| Peak Power            | 10.0 kW                 |
| Pulse Energy          | 1.0 mJ                  |
| Pulse Width           | 100 ± 20 ns             |
| Pulse Repetition Rate (PRR) | 30 – 100 kHz           |
2.2 Microstructural and metallographic characterization

The surface of the specimen was polished after hardening and then it was etched. Etching solution used is known as aqua regia which consists of 30ml distilled water, 20ml HCl, 15ml HNO₃.

It is used at room temperature for 60 seconds. Then the microstructures of the specimens were studied using an optical microscope (Conation) at 20X, 40X magnification.

![Optical images of SS316L alloy (a & b)](image)

Figure 2. Optical images of SS316L alloy (a & b)

Figure 2 shows the optical microstructure of SS316L. Austenitic grains show several annealing twins and delta ferrite which is distributed quite homogeneously.

The micro hardness of base material and laser hardened surface was measured using Vickers micro-hardness tester which is manufactured by METCO. For measuring the hardness, a load of 100g was applied on the surface for 10 sec and then, by measuring the diagonals of indentation hardness was calculated. The micro hardness of the base metal was measured to be 180 VHN.

3. Results and discussion

3.1 Laser Power-

In the first series of experiments, all the process parameters were kept constant except laser power. Laser power was varied from 6W to 15W. The details of the experiments are shown in table 4.

| Sr No | Laser Power (Watt) | Speed (mm/s) | Frequency (kHz) | No of Passes |
|-------|-------------------|--------------|----------------|-------------|
| 1     | 6                 | 800          | 60             | 3           |
| 2     | 9                 | 800          | 60             | 3           |
| 3     | 12                | 800          | 60             | 3           |
| 4     | 15                | 800          | 60             | 3           |

Experimental results show that, micro hardness and depth of hardening is increased by increasing the laser pulse energy. As we increase the laser power, power density increases which results into more heating and melting of the surface of the specimen which results into increased micro hardness.

From figure 3, it is found that with increase in laser power up to 15 W results into a micro hardness of 209 VHN.
Figure 3. Effect of laser power on micro hardness.

Figure 4 illustrates the variation of hardness along the depth at different powers. In general, as we go on increasing power, power density increases which results into higher hardened depth.

From figure 4, it is clear that, the microhardness values at sample surface (at 0 μm) and at a depth of 100 μm are almost similar. Beyond 100 μm increase in microhardness is due to the heat affected zone (HAZ). HAZ spreads into the depth of 100 μm to 300 μm.

3.2 Scanning speed
In second set of experiments only laser scanning speed was varied, keeping all other parameters constant. The details of the experiments are mentioned in below table 5.
Table 5. Process parameters for experiment number 2

| Sr No | Laser Power (Watt) | Speed (mm/s) | Frequency (kHz) | No of passes |
|-------|--------------------|--------------|----------------|--------------|
| 1     | 6                  | 100          | 60             | 3            |
| 2     | 6                  | 200          | 60             | 3            |
| 3     | 6                  | 300          | 60             | 3            |
| 4     | 6                  | 400          | 60             | 3            |

From the figure 5, it is seen that increasing the scanning speed from 100mm/s to 500mm/s, results in a decrease in hardness. It gets reduced from 243VHN at 100mm/s to 191.7VHN at 500mm/sec.

![Figure 5. Effect of speed on micro hardness.](image)

There is lesser laser-material interaction time when the laser scanning speed is higher which results in lesser heating and melting of the material. Hence, the hardness gets reduced. The highest measured micro hardness value (243 VHN) is achieved with laser process parameters as laser power 6W, pulse frequency 60KHz, scanning speed 100 and number of passes 3.

Figure 6 shows the hardness along the depth at different scanning speeds. It can be concluded from graph that; hardened depth decreases with increase in scanning speed.

From the figure 5 and 6, it is important to note that, scanning speed is the most influencing factor that affects the surface hardness and depth of hardening.
3.3 Number of passes

In third set of experiments, number of passes were varied keeping all other parameters constant. The details of the same are shown below in table 6.

| Sr No | Laser Power (Watt) | Speed (mm/s) | Frequency (kHz) | No of Passes |
|-------|--------------------|--------------|-----------------|--------------|
| 1     | 9                  | 800          | 60              | 1            |
| 2     | 9                  | 800          | 60              | 3            |
| 3     | 9                  | 800          | 60              | 5            |
| 4     | 9                  | 800          | 60              | 7            |

It is revealed that as the number of passes increases the total energy input to the material increases thereby increasing the micro hardness of the specimen. Micro hardness of 213.9 VHN was achieved at 7th pass as compared to 180 VHN of base material.
As number of passes increase, the interaction time between laser beam and work piece surface goes on increasing. This results in more heating of specimen surface, which results into higher hardness values which can be seen in the figure 7.

Figure 8 depicts hardness along depth at different number of passes. Depth of hardening also increases with increase in number of passes of laser beam.

![Figure 8. Effect of number of passes on depth of hardening.](image)

3.4 Frequency
In the 4th set of experiments, frequency was varied keeping all other parameters constant. Micro hardness of about 211.71 VHN was obtained at 75 kHz frequency as compared to that of 180 VHN of base material. The details of the experiment settings are given in table 7.

| Sr No | Laser Power (Watt) | Speed (mm/s) | Frequency (kHz) | No of Passes |
|-------|--------------------|--------------|-----------------|--------------|
| 1     | 9                  | 800          | 30              | 3            |
| 2     | 9                  | 800          | 45              | 3            |
| 3     | 9                  | 800          | 60              | 3            |
| 4     | 9                  | 800          | 75              | 3            |

From figure 9 it can be seen that, as we go on increasing the frequency from 30 kHz to 75 kHz, micro hardness also goes on increasing.
As we increase the frequency, number of pulses per cycle increases. This means a greater number of pulses is in contact with work piece during machining. This causes more heating of the work piece surface. That is why micro hardness increase with increase in frequency.

With increase in frequency, number of pulses per cycle increases, which results into the higher hardened depth. It can be seen through figure 10, with higher frequency higher hardened depth is obtained.

4. Conclusions

This paper investigates how the process parameters of the nanosecond pulsed fiber laser affects the hardening of austenitic stainless steel (SS316).

1) All the four process parameters used for the hardening of SS316L has significant effect on the micro-hardness of the specimen.
2) With increase in laser power, number of passes and laser pulse frequency causes more heating of the specimen due to increased laser-material interaction. This results in increased micro hardness of the specimen.

3) As the laser scanning speed increases, laser-material interaction decreases which results in less heating of the specimen surface. This less heating results in decrease in micro hardness of the specimen.

4) Laser-material interaction time is much more significant than other parameters which depend mainly on the scanning speed of the laser beam. The lower the scanning speed, higher is the laser-material interaction leading to more heating and melting of the material. This resulted in increased micro hardness of the specimen. This also increased the heat affected zone and depth of hardening.

5. References

[1] Badkar, D S, Pandey, K S & Buvanashekaran and G Parameter 2011 Optimization of laser transformation hardening by using Taguchi method and utility concept Int J Adv Manufacturing Technology 52 1067–77

[2] Makoto H, Minoru H, Koichi A Hitoshi K Masato T and Makoto K 1997 Surface Hardening of Carbon Steel Using High Powered YAG Laser, Materials and Manufacturing Processes, 121 37-46

[3] Goia F. and Lima M 2011 Surface Hardening of an AISI D6 Cold Work Steel Using a Fibre Laser Journal of ASTM International 8 1-9

[4] Senthil J S, Subramanian K and Nath A K 1999 Effect of laser surface hardening on En18 (AISI 5135) steel, Journal of Materials Processing Technology 911 1-3 29-36

[5] Chandrasekar P, Balusamy V, Ravi Chandran K S and Harish Kumar 2007 Laser surface hardening of titanium–titanium boride (Ti–TiB) metal matrix composite Scripta Materialia 56 7 641-44

[6] Mahmoudi B, Torkamany M J, Sabour Rouh Aghdam A R and Sabbaghzade J 2010 Laser surface hardening of AISI 420 stainless steel treated by pulsed Nd:YAG laser Materials & Design 31 5 2553-60

[7] Rathod M and Deore H 2014 Laser Surface Hardening of Ductile Irons SAE Technical Paper

[8] Grum J 2007 Comparison of different techniques of laser surface hardening Journal of Achievements in Materials and Manufacturing Engineering 24 1 17-25