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Improvement of Carbon Steel Surface Hardening and Corrosion Resistance by Using Pulse Laser

Mariam Fadel Abbas[1*] and Sameer Khudhur Yaseen[1]
[1,2]Department of Physics, College of Science for Women, University of Baghdad, Baghdad, Iraq
*Corresponding Author

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Abstract
This study examines the surface modification of steel through Nd:YAG pulsed laser processing. Laser surface hardening enables it can focus energy very precisely over very short periods of time it can focus energy very precisely over very short periods of time. The effects of laser energy and pulse number were analyzed, as both parameters significantly affect the heating-cooling cycles and, consequently, the surface microstructure. The results showed a clear increase in hardness, going from 240 HV in the untreated sample to 320 HV under the best laser conditions. This improvement is due to phase changes, especially the formation of a martensitic structure. Also, corrosion tests showed that laser-treated samples had a corrosion rate that was up to 97% lower than that of untreated steel. The better corrosion resistance is due to the combined effects of the martensitic layer and the formation of a dense iron oxide film, which work together to protect the surface in harsh conditions.
Keywords: Corrosion resistance, Laser surface hardening, Microhardness, Nd:YAG laser.

1. Introduction

Laser is light amplification by stimulated emission of radiation. It is characterized by monochromatic, coherent, and directional properties. These properties give it the ability to concentrate energy on a small, specific area[1]. It is used in many technical and scientific fields, including the preparation of nanoparticles, spectroscopy, and industrial fields [2-5]. Lasers are used in industrial fields, particularly in metals, for cutting, welding and surface treatment[6-8]. Surface treatment techniques include laser hardening, laser annealing, laser melting, laser cladding, laser polishing, laser surface alloying and laser shock peening[9-15].

The current study is laser surface hardening; its mean surface hardening processes are used as metallic surfaces are treated to provide a homogenous grain structure, which improves their physical, chemical, and mechanical qualities. Surface hardening processes are generally divided into two categories: physical and chemical. Physical hardening processes include induction, flame, electro spark, electrolyte quench, and vapor deposition. Chemical procedures include nitriding, diffusion treatment, metallic cementation, carburizing, and chemical vapor deposition[16,17]. After evolution laser techniques, laser heat modification is performed by utilizing a focused laser beam to heat the surface layer of a metal to a temperature over its transformation point, followed by rapid self-quenching as heat dissipates into the cooler underlying material. Rapid heating and cooling create a hardened surface layer without changing the metal's bulk characteristics, improving its surface performance while keeping its overall structural integrity[18].

Numerous studies have demonstrated that laser hardening technology improves hardness, corrosion resistance, and wear resistance. A previous study demonstrated phase transformations in AISI 1008 steel using a CO_2 laser, with a significant proportion of martensite being formed, improving hardness and corrosion resistance [19]. A study using 50crMo4 steel showed that pulsed lasers are better than continuous lasers because the laser heats and cools the surface without melting it and gives phase transformations with high hardness [20]. Another study on the effect of laser surface hardening on SS316 metal using a diode-pumped fiber laser with specific parameters. Increasing the energy and number of pulse frequencies leads to better hardness [21]. Another study confirmed that using a fiber laser on low carbon steel will lead to the formation of martensite and cementite, a decrease in the roughness coefficient, and an increase in hardness and corrosion resistance [22]. In another work, an Nd-YAG laser was used at a power of 3.5 kW and a frequency of 10 Hz on AISI4130 steel. Upon microscopic examination, the formation of martensite and bainite phases, an increase in hardness, a decrease in the friction coefficient, and an increase in wear resistance were found [23]. Laser surface hardening is used in metals used in biomedical applications. It was used to improve the hardness of SAE420 steel used in biomedical applications. The steel was hardened using a low power 300W fiber laser at a scanning speed of 1mm/s, which improved the hardness and the wear resistance[24.]

The goal of this study is to improve the mechanical and electrochemical properties of steel by using pulsed laser surface processing. Also, this work is to find the best processing parameters that cause good phase changes and protective surface layers by systematically looking into how laser energy and pulse number affect surface hardening and corrosion resistance. The end goal is to find a way to make steel parts last longer in harsh service environments that is both effective and good for the environment.

2. Materials and Methods

The material investigated in this study was medium carbon steel with chemical composition given in **Table1**, The chemical composition was measured using Spectro max ASTM E415-14.

Table1. Chemical analysis of medium carbon steel. (wt. %)

C %	Si %	Mn %	P %	S %	Cr %	Mo%	Ni%	Al%	Cu%	Fe%
0.425	0.221	0.723	0.014	0.011	0.024	<0.02	0.047	0.006	0.058	Bal

Samples were mechanically polished using SiC emery papers with successive grit sizes of 240, 320, 400, 600, 800, 1000, and 1200, followed by final polishing with alumina paste of 0.25 μm particle size. The specimens were then cleaned with acetone, rinsed with distilled water, and dried. Prior to laser processing, the samples were etched in a 7–10% nital solution for 10 s under fume hood ventilation. Chemical etching enhanced the absorptivity of the steel surface to the incident laser radiation by removing surface oxides and producing a uniformly darkened surface. **Figure 1** illustrates the Nd:YAG laser system employed in this study, operating at a wavelength of 1064 nm with a 4 mm spot size, directed onto a 10 mm² sample area.

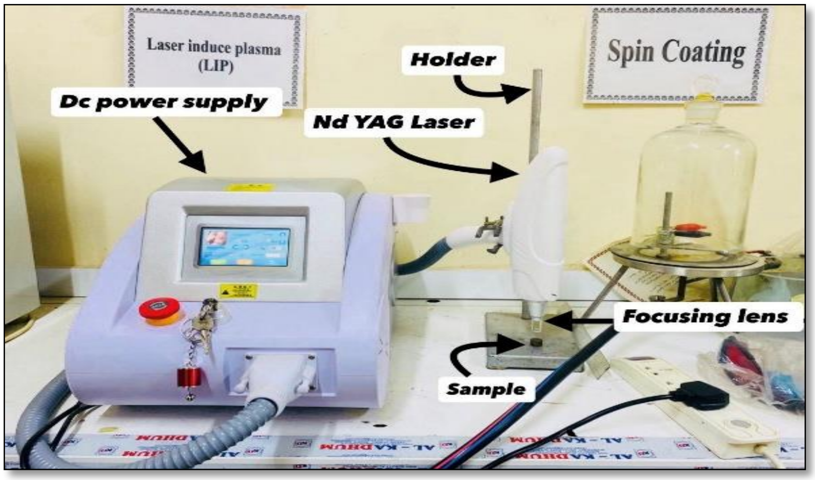

Figure 1. Image of the laser device and system components

The primary process parameters examined in the current study were laser energy and pulse count. A sufficient number of experiments were performed to elucidate the correlation between these parameters and the resultant microstructure, as well as to ascertain the optimal processing conditions **(Table 2)**. A Vickers microhardness tester with a load of 500 g was used to measure the surface microhardness of the area that was hit by the laser. Based on the hardness results, we chose the sample that performed the best for more testing. Scanning electron microscopy (SEM) was used to look at the microstructural features of the modified zone. Also, the corrosion resistance was tested by putting the untreated and laser-treated samples in a 3.5 wt.% NaCl solution (synthetic seawater) and comparing how they corroded in a systematic way.

Table 2. Parameter of laser surface treatment

Parameter	Value
Laser wavelength	1064nm
Spot diameter	4 mm
Pulse repetition rate	10 Hz
Distance to sample	10mm
Pulse duration	9ns

3. Results

This part of the research is about presenting the results of studying the effect of pulsed laser energy and the number of pulses on the hardness of the material. The change in hard values was analyzed with different laser coefficients, and then the best coefficients were selected based on the results of the hardness test. Thereafter, the microstructure and corrosion resistance of the selected coefficients were studied.

3.1. Microhardness

The laser was applied according to a specific number of pulses (40), and a pulse repetition rate of 10 Hz. The average microhardness value of the untreated sample was 240 HV. Sample measurements after laser treatment ranged between 270 HV at a pulse energy of 800 mJ and 320 HV at a pulse energy of 2000 mJ. **Table 3** shows the different laser energies of the treated samples with microhardness values.

Table3. Treated Samples different of laser energies with Microhardness hardness.

Samples	Microhardness (HV)
Untreated	240
800	270
1200	289
1600	303
2000	320

Figure 2 shows Effect laser pulse energy on microhardness.

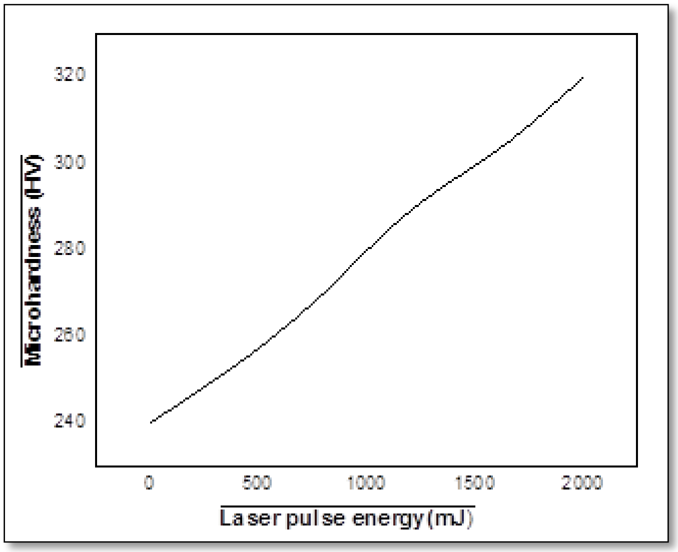

Figure 2. Effect laser pulse energy on microhardness

Figure 3 shows the effect of the number of pulses on microhardness. Laser processing was performed under constant conditions, with a laser energy of 2000 mJ and a repetition rate of 10 Hz. Increasing the number of pulses leads to an increase in the accumulated energy, and each pulse carries an amount of energy.

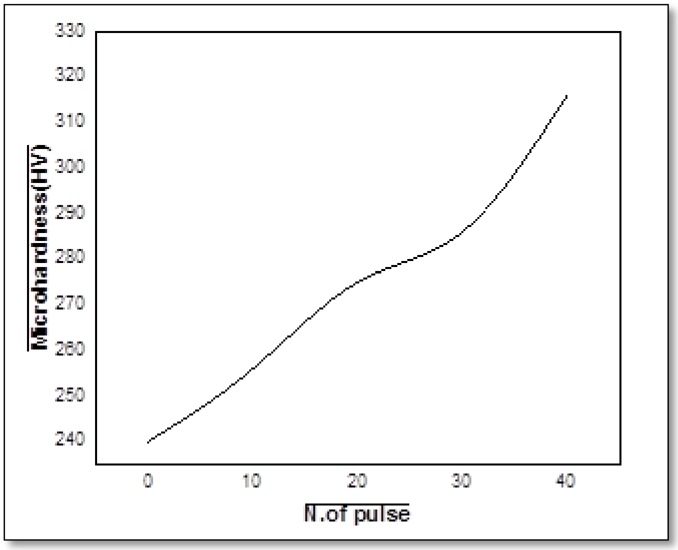

Figure 3. Effect number of pluses on microhardness

3.2. Microstructure

Figure 4 shows the microstructure of samples before and after hardening with a laser under 4000 magnifications. Laser processing was performed under optimal conditions, with a laser energy of 2000 mJ, pulse repetition rate of 10 Hz, and 40 pulses. **Figure 4a**: The surface appears rough, with raised and depressed areas and light and dark areas. **Figure 4b** shows the change of microstructure after laser hardening treatment. Phase transformations to form martensite phase.

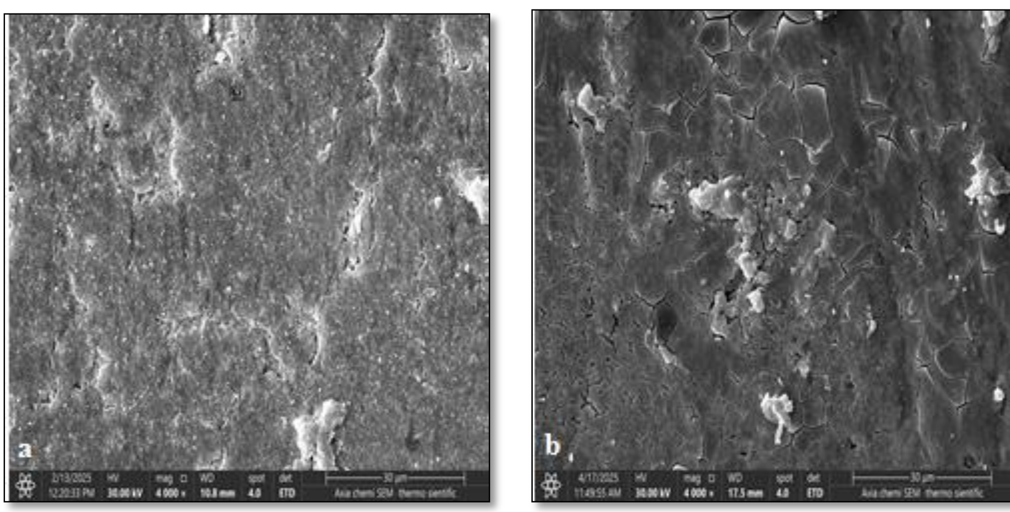

Figure 4. Microstructure of samples before a) and after Harding laser b) under 4000 magnifications.

3.3. Corrosion

The polarization curve (Tafel) test shows high improvement in corrosion rate reduction as shown in **Figure 5** and **Table 4.** The Tafel curve analysis is a powerful tool for evaluating the corrosion resistance of metals, as it allows the determination of the corrosion potential (E_corr) and corrosion current (icorr), as well as the anodic slope (βa) and cathodic slope (βc) parameters, which reflect the rate of anodic and cathodic reactions on the surface. In your experiment, the base sample of untreated steel showed E_corr = –0.927 V and icorr = 2.447×10^{-3} A/cm², whereas the values improved significantly after laser surface treatment, reaching E_corr = –0.765 V and icorr = 7.042×10^{-5} A/cm². This large decrease in corrosion current reflects a reduction in the corrosion rate from 28.37 mmpy to 2.120 mmpy. The corrosion rate was calculated using the equation:

Corr. Rate = (3.272×10-3×Icorr. Eq.wt.)/(dA) **(1)**

Icorr.: The corrosion current in amperes

EW: The equivalent weight in grams/equivalent was (7.84)

d: Density in g/cm^3 was (27.784)

A: Measurement sample area was (0.385cm^2)

Table 4. corrosion characteristics extract from Tafel curve for all samples untreated and treated by Laser.

Sample	E corr. (volt)	icorr. (Amp/cm2)	Corr. Rate mmpy	βc (V/decade)	βa (V/decade)	Eb (volt)
Base	-0.927	2.447×10^{-3}	28.37	0.130	0.417	0.582
Laser	-0.765	7.042×10^{-5}	2.120	0.217	0.283	1.308

In **Figure 5,** we clearly see that the breakdown potential (Eb) refers to the voltage at which pitting corrosion begins, and it is a key indicator of the surface's resistance to localized corrosion.

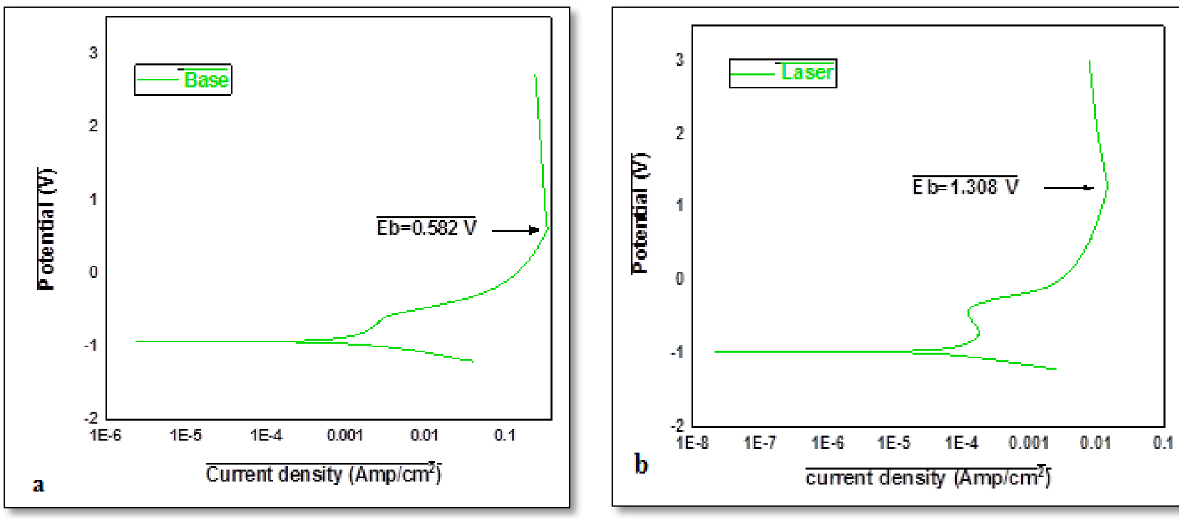

Figure 5. polarization curve (Tafel) test for(a) all samples base and (b)treated by Laser.

4. Discussion

The effect of laser energy on the hardness values of the steel surface were showed in **Figure 2**, where hardness increases with energy due to cooling and heating of the steel surface [25,26]. Hardness values for steel with number of pulses Increasing the number of pulses leads to an increase in the accumulated energy, and each pulse carries an amount of energy. When the number of pulses increases at the same point, energy accumulates, and due to compressive stresses, a layer of high hardness is formed[27] .The microstructure had melting traces and re-solidified areas of fine grain and minute surface cracks due to thermal stress induced by rapid cooling[28]. The fine-grained microstructure achieved is in accord with the greater hardness value of around 320 HV, and it confirms that laser-induced thermal gradients increase grain refinement and phase transformation. The untreated medium carbon steel surfaces used were smooth, yet rough, and contribute critically to the process of corrosion. The inherent microstructure of medium carbon steel ferrite and pearlite (a composite of softer and harder phases) does not offer any protective capability against corrosion. Microcracks, scratches, and strain-induced marks (as a result of previous machining) are surface defects that can trap stress and thereby start localized corrosion (e.g., pitting or crevice corrosion) locally. These surface flaws offer easy accessibility for corrosive ions to penetrate the steel underneath, thereby increasing the speed at which corrosion occurs[29, 30.]

This large decrease in corrosion current reflects a reduction in the corrosion rate, indicating that laser treatment effectively enhanced the steel's corrosion resistance through the formation of a denser and more robust surface layer . The breakdown potential increased after laser treatment, more than doubling the value of the untreated sample. The corrosion rate was calculated using the equation[31].This improvement reflects that the martensitic surface layer resulting from laser treatment reduces the initiation sites for pitting corrosion, thereby enhancing its electrochemical stability [32].

5. Conclusion

Laser hardening involves heating the metal surface using a pulsed laser followed by rapid self-cooling due to the temperature difference between the surface and the interior of the metal. Phase transformations occur from ferrite and bainite to martensite, which has a solid crystalline structure. The effect of energy and pulse number was studied because they are the most important variables controlling surface treatment. Increasing laser energy means that the laser beam energy is converted into thermal energy at the surface, and increasing the number of pulses means increasing the energy accumulated on the surface. SEM analysis revealed a fine granular structure and the presence of solid phases on the treated surfaces. These microstructural changes are consistent with the observed improvements in microhardness corrosion resistance. The results indicate that the synergistic effect of laser treatment is a promising and effective means to enhance surface hardness and corrosion behavior in carbon steel, making it highly relevant for industrial applications that require greater mechanical integration. Future work should include quantitative microstructural analysis (such as grain size determination and phase fraction) and statistical analysis of long-term effects to provide more comprehensive insights into the mechanisms.

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Conflict Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Clearance

The study did not involve human participants, animal subjects, or any form of personal data collection. Therefore, ethical approval and informed consent were not required.

References

1. Svelto O. Principles of lasers. 5th ed. New York: Springer; 2010. https://doi.org/10.1007/978-1-4419-1302-9
2. Al-attar HM, Azzawi MM. The influence of ablation speed on the synthesis of carbon nanostructures via pulsed laser ablation of asphalt in ethanol. Baghdad Sci J. 2023;20(5):1736-1771. https://doi.org/10.21123/bsj.2023.7204

3. Khalepha TA, Abdalameer NK. Comparative analysis of plasma generated using LIBS technique for different wavelengths of pulsed laser of a cadmium target. Baghdad Sci J. 2024;21(12):4128-4139. https://doi.org/10.21123/bsj.2024.9322
4. Ready JF. Industrial applications of lasers. 2nd ed. New York: Academic Press; 1997. https://doi.org/10.1016/B978-0-12-583961-7.X5000-5
5. Robert B. Lasers in manufacturing: a review of technologies and applications. Assembly Automation.2015; 35(2): 161-165. https://doi.org/10.1108/AA-07-2014-066
6. Naresh P, Khatak P. Laser cutting technique: A literature review. Materials Today: Proceedings. 2022;56(5):2484-2489. https://doi.org/10.1016/j.matpr.2021.08.250
7. Lisiecki A. Development of Laser Welding and Surface Treatment of Metals. Materials. 2022;15(5):1765. https://doi.org/10.3390/ma15051765
8. Jeyaprakash N, Yang C-H, Raj Kumar D. Laser Surface Modification of Materials. In: Yang D, editor. Practical Applications of Laser Ablation. London: Intech Open; 2020:1-25. https://doi.org/10.5772/intechopen.94439
9. Dinesh Babu P, Balasubramanian KR, Buvanashekaran G. Laser surface hardening: a review. International J of Sur Sci and Eng. 2011;5(2-3):131-151. https://doi.org/10.1504/IJSURFSE.2011.041398
10. Yang Y, Lu X, Tan W, Xiao L, Zhu L, Xie D. Study on laser annealing of niobium films deposited on copper for RF superconducting cavities. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2020;964:163803. https://doi.org/10.1016/j.nima.2020.163803
11. Gao B, Zhao H, Peng L, Sun Z. A Review of Research Progress in Selective Laser Melting (SLM). Micromachines 2023;14(1):57. https://doi.org/10.3390/mi14010057
12. Liu Y, Ding Y, Yang L, Sun R, Zhang T, Yang X. Research and progress of laser cladding on engineering alloys: A review. J of Manu Processes 2021;66:341-363. https://doi.org/10.1016/j.jmapro.2021.03.061
13. Manco E, Cozzolino E, Astarita A. Laser polishing of additively manufactured metal parts: a review. Surface Eng. 2022;38(3):217-233. https://doi.org/10.1080/02670844.2022.2072080
14. Yurov V, Guchenko S, Salkeeva A, Kusenova A. Laser surface alloying metals and alloys. Norwegian J of Deve of the Inter Sci. 2021;53(1):35-40. https://doi.org/10.24412/3453-9875-2021-53-1-35-40
15. Sundar R, Ganesh P, Gupta RK, Ragvendra G, Pant BK, Kain V, Ranganathan K, Kaul R, Bindra KS. Laser shock peening and its applications: A review. Lasers in Manufacturing and Materials Processing 2019;6:424–463. https://doi.org/10.1007/s40516-019-00098-8
16. Schneider MJ, Chatterjee MS. Introduction to surface hardening of steels. In: Dossett JL, Totten GE, editors. Steel Heat Treating Fundamentals and Processes. ASM International; 2013:389–398. https://doi.org/10.31399/asm.hb.v04a.a0005771
17. Senthil Kumar P, Jegadheesan C, Somasundaram P, Praveen Kumar S, Vivek Anand A, Singh AP, Jeyaprakash N. State of art: Review on laser surface hardening of alloy metals. Materials Today: Proceedings 2023. https://doi.org/10.1016/j.matpr.2023.04.259
18. Łach Ł. Recent advances in laser surface hardening: Techniques, modeling approaches, and industrial applications. Crystals 2024;14(8):726. https://doi.org/10.3390/cryst14080726
19. Abbas DH, Raheem D, Alwan AS. Enhancement the microstructures and corrosion resistance of low carbon steel using laser surface treatment. Solid State Technology. 2020;63(1):958-68.
20. Maharjan N, Wu N, Zhou W. Hardening efficiency and microstructural changes during laser surface hardening of 50CrMo4 steel. Metals 2021;11(12):2015. https://doi.org/10.3390/met11122015
21. Dongre G, Rajurkar A, Gondil R, Jaju N. Laser surface hardening of SS316L. IOP Conference Series: Materials Sci and Eng 2021;1070(1):012107. https://doi.org/10.1088/1757-899X/1070/1/012107
22. Furlani MR, Carvalho SM, Lima MS. Effect of laser surface hardening on a low carbon steel substrate wear and hardness. arXiv 2021. https://arxiv.org/abs/2111.13183
23. Bakhtiari M, Fayazi Khanigi A, Farnia A. Improving the wear properties of AISI4130 steel using laser surface hardening treatment. Arab J of Sci and Eng. 2023;48:11801–11818. https://doi.org/10.1007/s13369-022-07551-5
24. Wagh SV, More SR, Venu Madhav VV, Saxena KK, Bandhu D, Sunil BDY, Revathi V, Siddiqui MIH. Effects of low-power laser hardening on the mechanical and metallurgical properties of

biocompatible SAE 420 steel. J of Material Resc and Tech. 2024;30:1611-1619. https://doi.org/10.1016/j.jmrt.2024.03.153
25. Salleh MNM, Ishak M, Aiman MH, Zaifuddin Q, Quazi MM. The effect of laser surface hardening on the surface hardness of mild steel. IOP Conference Series: Materials Science and Engineering 2020;788(1):012014. https://doi.org/10.1088/1757-899X/788/1/012014
26. Xiong Y,HE T, LI Py, CHEN L, REN F,Alex A ,. Effects of laser pulse energy on surface microstructure and mechanical properties of high carbon steel. J of Cen South Unive 2015;22(12) :4515-4520.
27. Almohaisen AN. The influence of laser peening pulse number on hardness, residual stress and adhesive wear of AISI 316L stainless steel. The Iraqi J for Mech and Mate Eng. 2018;18(2):355-362. https://doi.org/10.32852/iqjfmme.Vol18.Iss2.99
28. Qiu F, Uusitalo J, Kujanpää V. Laser transformation hardening of carbon steel: microhardness analysis on microstructural phases. Surface Eng. 2013;29(1):34-40. https://doi.org/10.1179/1743294412Y.0000000049
29. Aziz AA, Khalid EA, Alwan AS, Jaddoa AA. The effect of ND-YAG laser surface treatment on mechanical properties of carburizing steel AISI 1006. J of Eng Sci and Tech. 2020;15(6):3891-902.
30. Khorram A, Davoodi Jamaloei A, Jafari A, Moradi M. Nd:YAG laser surface hardening of AISI 431 stainless steel; mechanical and metallurgical investigation. Optics & Laser Technology 2019;119:105617. https://doi.org/10.1016/j.optlastec.2019.105617
31. Suraj T. Techniques to Analyze Underdeposit Corrosion. MS thesis. Case West Res Unive.2010
32. Moradi M, Ghorbani D, Karami Moghadam M, Kazazi M, Rouzbahani F, Karazi S. Nd:YAG laser hardening of AISI 410 stainless steel: Microstructural evaluation, mechanical properties, and corrosion behavior. J of Alloys and Comp. 2019;795:213-222. https://doi.org/10.1016/j.jallcom.2019.05.016