Enhancement of Mechanical Properties and Corrosion Resistance of Cast Iron Alloy Using CO_2 Laser Surface Treatment

Sameer K. Fayyadh[*]
Department of Engineering Machine and Agriculture Equipment, College of Agricultural Engineering Sciences, University of Baghdad, Iraq
[*]*samir.faiad@coagri.uobaghdad.edu.iq*

Enas A. Khalid
Al-Khwarizmi College of Engineering, Department of Automated Manufacturing Engineering, University of Baghdad, Iraq

Abbas S. Alwan
Middle Technical University, Electrical Engineering Technical College, Iraq Dep. of Medical Instrumentation Techniques Engineering, Iraq

ABSTRACT

This work aimed to study the effect of laser surface treatment on the mechanical characteristics and corrosion behaviour of grey cast iron type A159. Many technical applications used conventional surface treatment, but laser surface hardening has recently been used to enhance the surface properties of many alloys. The mechanical characteristics, including microstructure, microhardness, and wear resistance of A159 grey cast iron, were studied, in addition to corrosion behaviour. The experimental laser parameters in this work were 0.9, 1.2, and 1.5 KW power with continuous wave carbon dioxide lasers with scanning speeds of 10 and 12 mm/s were used. The results found that phase-transitional alterations in microstructure were influenced by laser therapy. Also, the microhardness increased with increasing power, with the maximum reaching approximately 950 HV while the base metal has an average of approximately 260 HV. Also, we found the power laser increased corrosion resistance by lowering the corrosion rate (CR) from 21.10 for the untreated sample to 1.02 (m.p.y.), additionally, corrosion protection efficiency (CPE) increased to 95.27 percent. On the

ISSN 1823-5514, eISSN 2550-164X

https://doi.org/10.24191/jmeche.v11i1.23597

Received for review: 2022-09-23
Accepted for publication: 2022-10-18
Published: 2022-11-15

other hand, the wear test revealed that mass loss decreased as laser surface treatment power increased; it reached 0.19 g for the laser-treated samples, compared to 1.25 g for the base metal after the 50th minute of the wear experiment.

Keywords: *CO_2 Laser; Cast Iron; Hardness; Wear; Corrosion*

Introduction

A cast iron alloy is described as an iron–carbon-based alloy with a carbon content of higher than 2.06 wt.%. Despite the ongoing introduction of new functional and structural materials, cast iron is still extensively used in mechanical engineering. Cast iron is a basic material used in a variety of goods, including industrial and mechanical equipment. Surface treatments aimed at appropriate surface modification are undertaken to improve the surface properties such as corrosion resistance, fatigue strength and wear of cast iron, depending on the application. Grey irons are the most common cast iron [1]–[4]. Grey cast iron is a ferrous substance containing graphite flakes embedded in a matrix. Owing to its unique features, such as superior machinability, galling resistance, high machinability and high vibration absorption, and high castability, cast iron has quickly become one of the most essential engineering materials. Grey cast iron has long been used in the manufacture of automotive parts such as guide rails, gears, and cylinder liners for diesel engines.

Direct surface touch with applied relative movement and pressure is typically required for alloy engineering parts. To maintain long service life and optimal working performance, superior wear resistance is essential. As the demand for high performance and durability in industrial applications increases, efforts to enhance the strength, wear and hardness, of engine components through coating or hardening of ferrous alloy surfaces are necessary. Heat treatments and surface-hardening treatments have been the most prevalent approaches for improving the anti-wear and corrosion performance of ferrous-alloy mechanical components. The modification of cast-iron surfaces using laser energy has been extensively studied [5]–[9]. the technology of surface treatment is one of the key approaches for creating materials with improved mechanical qualities. Surface treatments are commonly used to enhance the surface properties of alloys and materials such as hardness, corrosion and wear resistance, to achieve high-performance requirements of industrial applications [10]–[12].

In recent years, innovative methods of alloy surface modification, like laser surface treatment, have received considerable attention, and have acquired significant acceptability for improving surface qualities such as corrosion resistance, microhardness, fatigue strength, wear resistance, and high temperature, this method extends the service life of engineering parts. Most of the constraints of traditional treatments, such as time, energy consumption, areas impacted by uncontrollable heat, non-contamination of the surface, the need for quenching, and complex heat treatment instances during the process, can be eliminated using this method [13]–[16]. the laser can be considered An excellent solution to modify the surfaces of solids, due to the ability of the high-power laser to locally melt the surface within a very short time, then rapid re-solidification by self-quenching (1×10^{-3} °C/sec) which leads to a change in the surface properties [17]–[19]. This property makes the laser an excellent tool for acquiring certain qualities for metal surfaces as a result of microstructural changes or chemical composition changes (if a material or more is added to the molten pool). During this procedure, the laser acts as a source heating a thin layer of a metal surface to get the required temperature.

In industrial or scientific applications many types of lasers are used, including carbon dioxide laser (CO_2), with a wavelength of (10.6 nm) [20], [21]. The CO_2 laser is widely used in material processing applications due to its ability to deliver very high energy with accepted efficiency. These lasers have an output power ranging from less than (1W) to greater than (10 kW) [22]- [23]. The problem with this work is due to the difficult heat treatment of narrow areas in grey casting, such as an engine cylinder, when using the traditional heat treatment processes. Therefore, to solve the problem, a laser beam is applied in this area. In view of the above, this study aims at improving the mechanical surface properties of grey cast iron type A159 such as microstructure, hardness, and wear and corrosion resistance after changing the laser parameters. The novelty of these studies contributes to solving problems due to the applications they offer.

Materials and Methods

Material and preparation of samples

To prepare samples, two strips with dimensions (70×15) mm were cut from an ASTM A159 grey cast iron plate with a thickness of 4 mm, strips surfaces were cleaned using silicon carbide paper, washed with diluted alcohol to remove oils and dust, and left to dry in the air, to prepare the laser processes. After laser processing, the strips were cut into groups of squares samples with dimensions of (15×15) mm, and samples were prepared for subsequent examinations and tests (microstructure, hardness, Corrosion and wear). Tables 1 and 2 show the chemical composition of grey cast iron type ASTM A159 and its mechanical properties respectively.

Table 1: Chemical composition of ASTM A159

Elements	Carbon C	Manganese Mn	Silicon Si	Phosphorus P	Sulphur S	Iron Fe
Actual Value %	3.25	0.78	1.9	0.09	0.11	Bal.
Standard Value %	3.00-3.30	0.7-1.0	1.8-2.1	0.1 max	0.15 max	Bal.

Table 2: Mechanical Properties

Hardness Brinell	Tensile Strength Ultimate	Modulus of Elasticity	Shear Modulus	Shear Strength
217-269	252 MPa	100-119 GPa	40 - 48 GPa	334 MPa

Laser surface treatment processes

A CO_2 continuous wave laser with a maximum power of 5 KW and 10.6 μm wavelength was used in this study, under the processing conditions determined by the preliminary experiments, the processes parameters were selected, and laser processes were done at a power of (0.9, 1.2 and 1.5 kW), beam diameter (4 mm) and Shielding was performed using argon gas. Table 3 shows the laser parameters.

Table 3: Laser CO_2 Parameters

laser energy E (kW)	scan speed $\boldsymbol{\tau}$ (*m*m/s)	Beam diameter $\boldsymbol{D_b}$ (mm)	Wavelength $\boldsymbol{\lambda}$ (nm)	spot area A (mm^2)	Medium	Over lapping
0.9, 1.2, 1.5	10, 12	4	1064	0.321	Argon	50%

Examination and tests

The microstructures of as received and laser processes samples were characterized using optical microscopy (OM) and scanning electron microscopy (SEM). The samples were prepared for OM and SEM examinations using conventional methods. An X-ray test was used to determine the phase's transformation. A Microhardness test was carried out using a 0.5 kg load. An electrochemical corrosion test using the Tafel extrapolation method was carried out in cases of untreated one and different laser power; (0.9, 1.2, and 1.5 kW), it was conducted using CHI 604E POTENTIOSTAT (CHINA). The experiments were carried out in a standard three-electrode electrochemical cell using work samples as the working electrode, a Pt counter electrode, and a saturated Ag/AgCl as a reference electrode, the experiments were performed with an exposed area of 1.0 cm^2 in a 0.35% NaCl solution at room temperature. Weight losses were used as a function of the wear test.

Results and Discussion

Effects of laser processes on microstructure

Three different energy values; 0.9, 1.2 and 1.5 Kw applied to the surface of grey cast iron. Figure 1 shows a low magnification SEM image of base metal microstructure, which Contains graphite flakes embedded in a ferrite matrix. Figure 2 illustrates the cross-section of samples after being treated with various laser powers; 0.9, 1.2 and 1.5 kW. In the section, three regions can be observed; the molten zone (MZ), heat affected zone and base metal (unaffected zone), it was observed that the pool size was increased with an increase in laser power. Table 4 show the result of x-ray diffraction which shown the phases consist of alpha iron Fe (α) with small amount of carbon carbide Fe_3C. While Table 5 shows the structure consisting of martensite due to the high cooling rate after laser treatment, the grey cast iron pearlite matrix was converted into a needle-type martensite structure containing dendritic arms. Also, in all the cases, residual graphite dispersed in a martensitic matrix was recognized, which indicates that the graphite dissolved to form cementite. The solidification of Hypoeutectic or eutectic irons at a very rapid cooling rate causes the carbon dissolved in the iron at high temperatures to be deposited as graphite on the pre-existing flakes during cooling. This is how heat treatment affects the development of graphite.

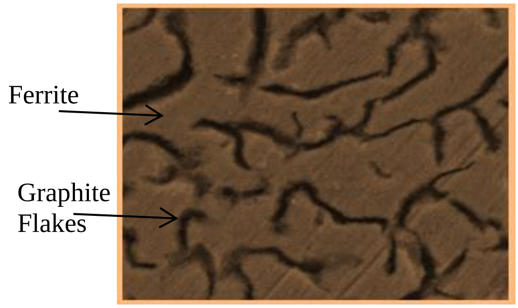
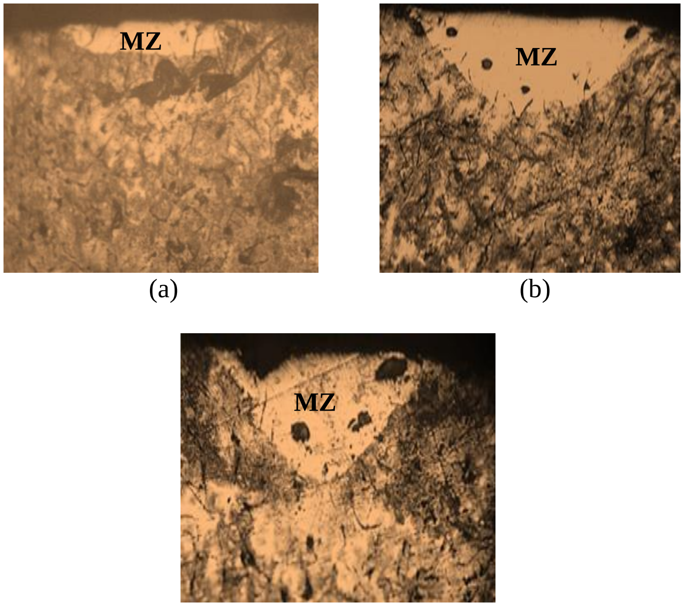


Figure 1: SEM image for untreated sample (base metal), 100X



(a) (b) (c)

Figure 2: A cross section of samples processed with the laser power of; (a) 0.9, (b) 1.2, and (c) 1.5 kW), 100X

Table 4: X- Ray result before laser treated (untreated)

2θ	d; measure	d; stander	I/I_O	Phase
38	2.360	2.38	3137	Fe_3C
64.4	1.444	1.43	3843	Fe (α)
81.9	1.174	1.17	4549	Fe (α)
87.5	1.112	1.113	4352	Fe (α)

Table 5: X- Ray result after laser treated

2θ	d; measure	d; stander	I/I_O	Phase
38	2.361	2.38	3136	Fe_3C
64.4	1.444	1.43	3843	Fe C
81.9	1.174	1.17	4549	Fe
87.5	1.112	1.113	4352	Fe_3C

Effect of laser processes on hardening

The hardening process is associated with the type of phase transformation that occurs in the mechanism of microstructure due to the laser surface treatment conditions and as a result of increasing temperatures, the carbon content amount dissolved in the austenite is increased. From Figure 3, it can be seen, that the change in both the Vickers microhardness values and the depth of the region is affected by the hardening process resulting from laser processes. In the center of the beam laser radiation, in general, the depth of the hardened region was between 0.6 and 1.2 mm depending on the differences in the laser process parameters, and the hardened region depth increased with an increase of laser power at a given beam laser scan speed. It was also noted that the microhardness values for all cases significantly increased by approximately between 310% and 350% on the surface compared with the region that was unaffected by the laser process; this increase in microhardness is a result of the change in microstructure, which transformed to a martensitic structure, that occurred as a result of laser processes characterized by a very high cooling rate, which leads to the formation of a fine grain size structure that increases the grain boundaries, which caused an increase in hardness of microstructure; in general, the maximum microhardness reached approximately 950 HV, depending on the laser power at a given scan speed compared with that of the base metal which has an average hardness of approximately 260 HV, this outcome is agree with what Kotarska noticed while using a laser process to harden ductile cast iron [24]. On the other hand, it was observed that the highest microhardness was in the (HAZ) region in all cases, then it gradually decreases towards the unaffected region, the explanation for this noted is due to cooling rate in (HAZ) was greater than that for melting region, because the heat lost through the metal material is greater than that lost through the air for the molten region, due to the difference in thermal conductivity factor. The effect of laser power was clear in this region, and the microhardness values increase as the laser power increased. From Figure 4, can be observed that the depth of the hardened region was inversely proportional to the scan speed of the laser beam, the depth of the hardened region slightly increased as scan speed decreased at a certain laser power, and became clearer with increasing laser power, the reason for this when the scan speed decreases, the heating time increases, thereby increase the heat input, which increases the depth of the hardened region. This result agrees with what was obtained by Samar Reda Al-Sayed et al. [12]

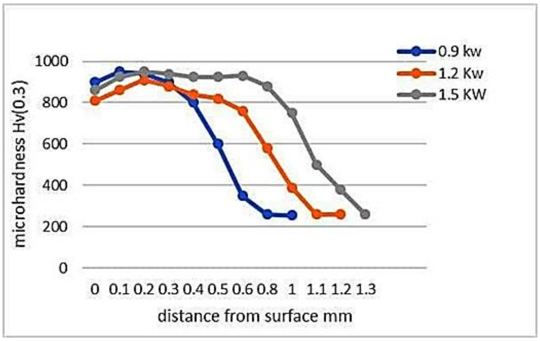


Figure 3: Microhardness with different power

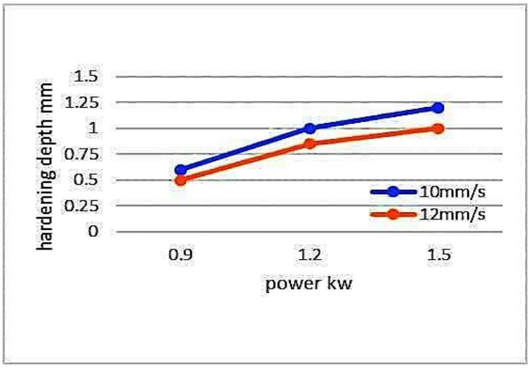


Figure 4: Effect of scan speed on hardened depth

Effect of laser processes on corrosion

The test of polarization was carried out by potentiostatic device on grey cast iron in 3.5% NaCl solution with cases of untreated one and different laser power (0.9, 1.2, and 1.5 kW). Figure 5 shows the Tafel polarization curves of all specimens, results showed a significant improvement in the corrosion resistance of all samples which were treated with the laser, this is evident by the significant decrease in the current density, which indicates a decrease in the corrosion rate, that means an increase in the corrosion resistance, on the other hand, the decrease in the corrosion rate increases as power of laser increases. This improvement in the corrosion resistance and the decrease in the corrosion rate are the result of the changes in the microstructure that occurred due to the high cooling rate, which is one of the characteristics of laser processes. The increase in the cooling rate leads to the emergence of new phases and the formation of a fine structure of grain size that increases the grain boundaries, which helps in increasing the resistance to corrosion., the results of Tafel polarization show that the current density Icorr. shifts from 49.05 (uA/cm^2) for the untreated samples to lower Icorr. (6.88, 3.97, 2.32 uA/cm^2) for the treated samples with (0.9, 1.2, and 1.5 kW) respectively, and corrosion rate decreased from 21.1 (m.p.y) for the untreated samples to a lower corrosion rate, (2.96, 1.65, 1.02 (m.p.y)) for the treated samples with (0.9, 1.2, and 1.5 kW) respectively. These results agree with what was obtained by Wang et al. [25]. Also, corrosion protection efficiency (CPE) can be used a compare the preventive effect of treated samples. To calculate the CPE, the following equation was used [26].

$$CPE(\%) = \frac{(I^o\text{corr}--I^C\,corr)}{I^o corr} 100\% \tag{1}$$

where I^ocorr is the corrosion current density of base metal, and I^ccorr is the corrosion current density of the laser-treated specimens. According to the results, the (CPE) reached (85.97%, 91.9%, and 95.27%) for samples treated with a laser of (0.9, 1.2, and 1.5 kW), respectively, and this indicates a significant improvement in the corrosion resistance of the samples for laser treatment.

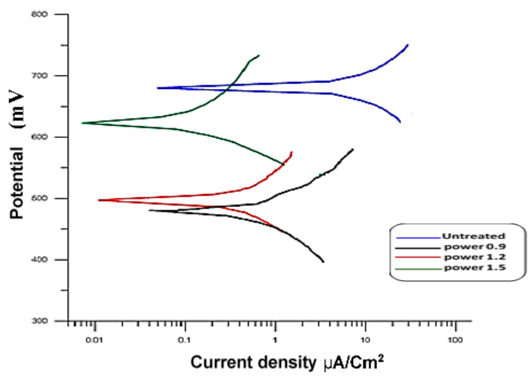


Figure 5: Polarization curves of laser treated and untreated samples

Effect of power laser on wear test

Figure 6 shows the typical variation of amount of mass lost as a function of the testing time of samples A, B, C and D with different power laser surface (0.9, 1.2 and 1.5 kW) respectively. It's clear that mass lost decreased in all specimens treated with laser, which means an increase in wear resistance, and the increase in wear resistance increases as laser power increased, this improvement in wear resistance occurred due to the increase in the surface hardness of the samples that were treated with the laser. The best specimen, which has good wear resistance, has the lowest lost mass in materials as a specimen with laser power (1.5 kW) compared with an untreated sample (base metal). On the other hand, it was observed that the difference in the amount of mass lost between the laser-treated samples and the non-laser-treated samples increases with the increase in time, as we can notice that after 10 minutes the difference in the lost weight reached 0.54 g, while this difference reached 1.05 g after the 50th minute (that is nearly double). It was also noted that the amount of mass lost became approximately constant after 30 minutes for the samples that were treated with the laser, while the mass lost continued to increase for the non-laser treated samples. Figure 7 shows the worn surfaces after the wear test with different laser power, decreased the pit and scratch with increased laser power are a function of the surface hardness. These results agree with what was obtained by Aziz et al. [21].

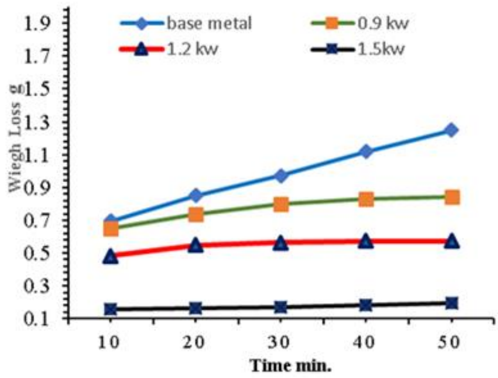


Figure 6: Variation of specific mass loss of sapeles as function of power laser with testing time

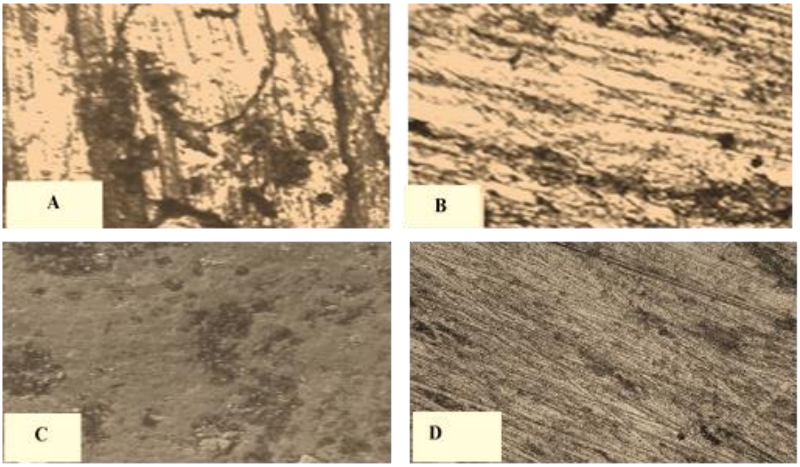


Figure 7: Topography worn surfaces of the samples A, B, C, and D with different powers: 0.9, 1.2, and 1.5 kW respectively, (270 X)

Conclusions

The following can be deduced from the findings of surface laser processing of grey cast iron A159.

i. The microstructure after laser treatment revealed a uniform martensite structure with randomly dispersed graphite residues.
ii. With increased laser power, the microhardness has improved approximately between 300% and 350% in comparison to the base metal.
iii. After the laser process, there is a substantial improvement in corrosion resistance due to a decrease in the corrosion rate. The corrosion rate was reduced from 21.1 for the base metal to 1.02 for the laser-treated samples, and the amount of this decrease increases as laser power increases.
iv. The lost mass was reduced from 1.25 g for the base metal to 0.96 g for the laser-treated samples, showing a certain increase in the wear resistance.
v. decreased the pit and scratch with increased laser power is a function of the worn surface.

Acknowledgement

The authors would like to thank the microscopy and X-ray laboratories at the Nano Technology and Advanced Materials Research Center, University of Technology, as well as the corrosion laboratory in the Materials Research Department of the Science and Technology Authority.

References

[1] U. Reisgen et al., "Influence of Preheating on Lamellar Grey Cast Iron for Surface Layer Welding applications with Plasma-Transferred Arc Powder and Metal Inert Gas Welding Processes with Duplex Steel as Filler Material," *J. Therm. Spray Technol.*, vol. 29, no. 4, pp. 724–740, 2020, doi: 10.1007/s11666-020-01014-9.

[2] D. Boldyrev, R. Dema, O. Latypov, A. Zhilenkov, V. Emelianov, and A. Nedelkin, "Influence of melt treatment parameters on the characteristics of modified cast iron in the metallurgical industry using intellectual analysis methods," *Eastern-European J. Enterp. Technol.*, vol. 2, no. 12–110, pp. 52–58, 2021, doi: 10.15587/1729-4061.2021.229642.

[3] Y. Hoshiyama, K. Chiba, and T. Maruoka, "Effect of active screen plasma nitriding on mechanical properties of spheroidal graphite cast iron," *Metals (Basel).*, vol. 11, no. 3, pp. 1–9, Mar. 2021, doi: 10.3390/MET11030412.

[4] A. Wube Dametew, "Experimental Investigation on Weld Ability of Cast Iron," *Sci. Discov.*, vol. 3, no. 6, p. 71, 2015, doi: 10.11648/j.sd.20150306.15.

[5] J. Yu, Y. Liu, B. Song, and J. Wang, "Microstructure and properties of Fe-based alloy coating on grey cast iron fabricated using induction cladding," *Coatings*, vol. 10, no. 9, Sep. 2020, doi: 10.3390/COATINGS10090801.

[6] S. Dizdar, Y. Lyu, C. Lampa, and U. Olofsson, "Grey Cast iron brake discs laser cladded with nickel-tungsten carbide-Friction, wear and airborne wear particle emission," *Atmosphere (Basel).*, vol. 11, no. 6, 2020, doi: 10.3390/atmos11060621.

[7] J. Sertucha, G. Artola, U. de La Torre, and J. Lacaze, "Chunky Graphite in Low and High Silicon Spheroidal Graphite Cast Irons–Occurrence, Control and Effect on Mechanical Properties," *Mater.* 2020, Vol. 13, Page 5402, vol. 13, no. 23, p. 5402, Nov. 2020, doi: 10.3390/MA13235402.

[8] N. Catalán, E. Ramos-Moore, A. Boccardo, and D. Celentano, "Surface Laser Treatment of Cast Irons: A Review," *Metals (Basel).*, vol 12, no. 4, pp. 1-29, 2022, doi: 10.3390/met12040562.

[9] B. Wang, G. C. Barber, R. Wang, and Y. Pan, "Comparison of wear

performance of austempered and quench-tempered grey cast irons enhanced by laser hardening treatment," *Appl. Sci*., vol. 10, no. 9, 2020, doi: 10.3390/app10093049.

[10] M. A. Tolcha, M. G. Jiru, and H. G. Lemu, "Experimental investigation of al-cumgmn alloy developed by laser beam surface modification for wear resistance," *Metals (Basel).*, vol. 11, no. 5, pp. 1–15, 2021, doi: 10.3390/met11050712.

[11] J. Il Jeong, J. H. Kim, S. G. Choi, Y. T. Cho, C. K. Kim, and H. Lee, "Mechanical properties of white metal on scm440 alloy steel by laser cladding treatment," *Appl. Sci*., vol. 11, no. 6, Mar. 2021, doi: 10.3390/APP11062836.

[12] S. R. Al-Sayed, A. M. Elshazli, and A. H. A. Hussein, "Laser surface hardening of Ni-hard white cast iron," *Metals (Basel).*, vol. 10, no. 6, pp. 1–19, Jun. 2020, doi: 10.3390/met10060795.

[13] I. Ruzankina, V. Parfenov, O. Vasiliev, O. Zotov, and A. Zotova, " Laser Treatment as a New Approach to the Passivation of Iron-Based Historical Monuments", *Quantum Beam Sci.* vol. 6, no. 1, pp. 1-10, 2022, doi: 10.3390/qubs6010009

[14] D. M. Stefanescu et al., "ASM Handbook W Volume 1A Cast Iron Science and Technology", 1st ed. Publisher, USA, 2021. doi.org/10.31399/asm.hb.v01a. 9781627081795

[15] A. Karakassides, A. Karakassides, M. Konstantinidou, A. S. Paipetis, and P. Papakonstantinou, "Enhanced out of plane electrical conductivity in polymer composites induced by CO_2 laser irradiation of carbon fibers," Appl. Sci., vol. 10, no. 10, 2020, doi: 10.3390/app10103561.

[16] S. S. Aziz, A. S. Alwan, and K. A. Abed, "Influence of Nd-Yag Laser Beam on Microstructure and Wear Characteristics of Gray Cast Iron," *Biochem. Cell. Arch.*, vol. 19, no. 1, pp. 1587–1592, 2019, doi: 10.35124/bca.

[17] H. M. Al-Tamimi, A. O. Al-Roubaiy, and N. M. Dawood, "Improvement of microstructure and wear resistance of X12 tool steel by using laser surface re-melting technique", *Mater. Sci*. Forum, vol. 1021, no. February, pp. 260–269, 2021, doi: 10.4028/ www.scientific.net/MSF.1021.260.

[18] S. I. Jafar, M. J. Kadhim, S. K. Fayyadh "Effect of Laser Surface Melting on Chromium Carbide of 304 Stainless Steels", *Engineering and Technology Journal*, vol. 36, no. 3, pp. 344-349, 2018.

[19] A. S. Alwan and S. K. Fayyadh, "Experimental and Numerical Analysis of Laser Surface Melting by Using Enthalpy Method Experimental and Numerical Analysis of Laser Surface Melting by Using Enthalpy Method," no. March, 2020, doi: 10.1088/1757-899X/745/1/012060.

[20] A. S. Jassim, S. N. Rashid, and H. M. Yaseen, "Effect of CO_2 laser irradiation on the topographic and optical properties of CdO thin films," *Baghdad Sci. J*., vol. 17, no. 1, pp. 318–328, 2020, doi: 10.21123/

BSJ.2020.17.1(SUPPL.).0318.

[21] A. A. Aziz, E. A. Khalid, A. S. Alwan, and A. A. Jaddoa, “The Effect of Nd-Yag Laser Surface Treatment on Mechanical Properties of Carburizing Steel AISI 1006,” *J. Eng. Sci. Technol*., vol. 15, no. 6, pp. 3891–3902, 2020.

[22] S. P. Marathe, “Experimental investigation of process parameters of fibre laser on cutting quality of stainless steel 304- A review” *International Journal of Advance Research in Engineering, Science & Technology*,” vol. 3, no. 4, pp. 550-555, 2016.

[23] A. S. Alwan and S. K. Fayyadh, “Improvement the Surface Properties of Metal Valves Used in Agriculture Engine by Using CO_2 Laser Beam,” *Biochem. Cell. Arch* Vol. 19, No. 1, pp. 1581-1585, 2019 doi: 10.35124/bca.2019.19.1.1581.

[24] A. Kotarska, “The laser alloying process of ductile cast iron surface with titanium,” *Metals (Basel).,* vol. 11, no. 2, pp. 1–13, 2021, doi: 10.3390/met11020282.

[25] R. Wang, C. Ouyang, Q. Li, Q. Bai, C. Zhao, and Y. Liu, “Study of the Microstructure and Corrosion Properties of a Ni-Based Alloy Coating Deposited onto the Surface of Ductile Cast Iron Using High-Speed Laser Cladding,” *Materials,* vol. 15, no. 5, 1643. 2022, doi.org/10.3390/ ma15051643

[26] M. Zhang, H. Wang, T. Nie, J. Bai, F. Zhao, and S. Ma, “Enhancement of barrier and anti-corrosive performance of zinc-rich epoxy coatings using nano-silica/graphene oxide hybrid,” *Corros. Rev.,* vol. 38, no. 6, pp. 497–513, 2020, doi: 10.1515/corrrev-2020-0034.