Wear Testing

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Tribological and braking performance comparison of martensitic stainless steel coatings deposited by laser cladding and HVOF

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Abstract: In this study, a martensitic stainless steel (431L grade) based coating material was applied to brake discs produced from grey cast iron (GG20) using laser cladding and HVOF methods and the braking performance was investigated in terms of tribological, NVH and corrosion. The experiments were conducted using original ventilated front brake discs and brake pads manufactured. The wear resistance and braking performance of coated and uncoated disc-pad pairs were simulated using a full-scale inertial dynamometer. Brake performance was compared based on the friction coefficient trend and brake torque values according to the bench test results. Experimental test results show that the coated disc has a more stable friction coefficient, indicating better braking performance with more uniform wear. By comparing the wear ratio caused by the disc-pad friction surfaces before and after the test, it was found that the couple of coated disc-pad had less amount of wear with higher wear resistance. Compared to uncoated discs, laser cladding performed 4.5 times better and HVOF 1.9 times better. In addition, the corrosion test results demonstrated that the coating significantly improved the corrosion resistance. The laser cladding brake disc exhibited a well-bonded and uniform coating layer with strong metallurgical integrity.

Keywords: HVOF; laser cladding; brake disc; coating technologies; thermal spray coating

1 Introduction

The brake system is an important safety mechanism for driver and passenger safety by stopping or slowing down a moving vehicle and it represents one of the most essential subsystems among the numerous components of an automobile, as it plays a decisive role in ensuring occupant safety [1], [2]. The brake system basically consists of a disc, a caliper, a couple of friction elements (pads), and additional auxiliary components. The working principle of the brake system is based on the conversion of kinetic energy into friction energy during braking by applying pressure and friction to the brake discs of the brake pads [3], [4]. The brake disc has a crucial role in the braking system since it converts kinetic energy into thermal energy through friction and dissipates the generated heat, directly influencing the overall braking performance [5], [6], [7].

The brake disc is generally produced of gray cast iron due to its advantages such as low cost relatively, good castability, and machinability [8], [9]. However gray cast-iron brake disc is not able to meet the expectation of new-generation electric vehicles over high braking performance [10]. Also, regulations on vehicle emissions are increasing day by day and the low wear resistance of cast iron brake discs contributes to the total emissions of vehicles. For these reasons, the need for coating the brake discs has arisen to improve the friction surface properties of the brake disc [11], [12], [13]. The coating process of brake discs seriously affects braking performance and surface quality [14], [15], [16].

Thermally based coating methods are a strong way to coat brake discs because of providing excellent adhesion to the applied surface. In literature, many researchers have used various thermally based coating techniques when producing coating layers to improve the braking performance and increase the wear resistance of brake discs. Mutlu et al., used the APS method to coat the cast iron brake

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disc with 55TiO2–Cr2O3 ceramic powder [17]. As a result of this study, the coated brake discs exhibited lower surface roughness, less wear, and a longer service life compared to the uncoated disc. In addition, although the friction coefficient was similar, the amount of wear on the brake pad was lower with the coated disc. Rajaei et al. investigated martensitic stainless steel coatings with and without 5 wt% MnS, produced by laser cladding on pearlitic grey cast iron [18]. The addition of MnS reduced the coefficient of friction and wear rate, lowered emissions, and improved the tribological performance. Ksiazek et al., [19] applied (Cr_3C_2–NiCr + Ni)-based materials onto ductile cast iron substrates using the HVOF process and investigated the microstructural, tribological, and corrosion behaviors of these coatings. Tribological evaluations demonstrated that the coating significantly reduced the coefficient of friction and markedly enhanced the wear resistance compared to the uncoated ductile cast iron. Moreover, the coating effectively protected the substrate in corrosive environments and substantially decreased the corrosion rate. Tonolini et al., [20] investigated the wear resistance of pearlitic matrix gray cast iron brake discs coated by laser cladding using WC-reinforced and non-reinforced stainless steel powder as the coating material. The results indicated that WC-reinforced stainless steel coating by laser cladding improved the wear resistance of grey cast iron brake discs, while the unreinforced coating showed poor performance. Although its wear rate was slightly higher than that of the HVOF coating, the laser cladding process was considered a more economical and environmentally friendly alternative.

In this study, brake discs were coated using thermally-based surface coating methods, including laser cladding and high-velocity oxygen fuel (HVOF) spraying. Commercial coating powder product based on martensitic stainless steel (431L) were used as coating material. Corrosion resistances of all brake discs were evaluated by performing salt fog test. Original (uncoated) and coated brake discs were tested on a full scale inertial dynamometer to evaluate braking performance and wear resistance. In addition, the coated brake disc samples were produced for the metallographic examination, and microscopic analysis was performed with the images taken under SEM. Moreover, the mechanical properties of coated and uncoated disc sample surfaces were compared by measuring Vickers microhardness.

2 Experimental procedure

In this study, OEM (Original Equipment Manufacturer) brake discs for passenger cars, measuring 281 mm × 26 mm and made of GG20 cast iron material with four ventilation channels, were used. The GG20 cast iron has a pearlitic microstructure. The chemical properties of GG20 are given in Table 1. The mechanical properties of GG20 cast iron, which is listed as follows: tensile strength 200–300 MPa, elongation 0.3–0.8 %, modulus of elasticity 88–113 GPa, density 7.15 g*cm^{-3}. In all coating processes, 431L stainless steel powder with a powder size of 45–150 µm and a hardness of 560 ± 15 HV was used.

Table 1: Chemical composition of GG20 cast iron and 431L stainless steel powder (wt.%).

	C	Si	Mn	*P*	*S*	Cr	Ni	Fe
GG20	3.1–3.4	1.9–2.3	0.6–0.9	<0.15	<0.15	–	–	Bal
431L	0.03	0.75	<1	–	–	16	1.8	Bal

Brake disc thicknesses were reduced with the grinding process by 1 mm in total from each side surface equally of the disc before the coating processes. In this way, it has remained within the dimensional tolerance range with the coating layer added. As a surface preparation process before coating, sandblasting was applied to the surfaces to be coated, during which impurities and contaminants were removed from the material while the surface was roughened to enhance the adhesion of the coating layer. This process was carried out using alumina-based 70 mesh grits at a pressure of 5 bar, a nozzle distance of 120 mm from the surface, and a spraying angle of 80°0 for 40 s. The coating processes were performed on the cleaned surfaces using the laser cladding method at UniqueTech Engineering Ltd. and HVOF methods at Sakarya University's Thermal Spray Research and Application Laboratory. The coating process method-material combination is given in Table 2. In addition, all tests performed with the brake disc–pad pairs employed a commercially available OEM NAO-class brake pad that has been widely used in passenger vehicles for many years.

The HVOF and laser cladding process parameters are shown in Figure 1. In order to achieve a stable coating process, the HVOF was carried out with robot control in the multicoat coating unit (DJ 2600 Oerlikon Metco). HVOF coating was performed by spraying 431L grade stainless steel powder, carried by Nitrogen gas, onto the surface of thickness-reduced disc using a high-velocity flame generated from Hydrogen and Oxygen combustion. Laser cladding process was carried out by simultaneously directing the laser beam emitted from the laser head, the powder material fed through the nozzle, and the Argon shielding gas onto the surface of the thickness-reduced disc. The laser coating layer was formed as the molten coating material interacted with the base material in the melt pool, creating a metallurgical

Table 2: Coating process method-material combination.

Coating method	Coating material
Uncoated (OEM)	GG20 gray cast iron
High velocity flame spray (HVOF)	431L stainless steel
Laser cladding	431L stainless steel

A single type of commercial brake pad was used in the tests.

Table 3: HVOF process parameters.

Powder feeding rate (g·min^{-1})	Oxygen flow rate (l·min^{-1})	Hydrogen flow rate (l·min^{-1})	Number of passes	Spray distance (mm)
32	250	45	12	180

bond. After coating, the surfaces were processed by grinding to bring the surfaces into compliance with industrial standards. The HVOF and laser cladding process parameters are given in Table 3 and Table 4, respectively.

For metallurgical analysis, coated disc samples were cut to appropriate dimensions for bakelite processing using a Metkon brand SERVOCUT 302 metallurgical sample cutting device. The cut samples were hot Bakelite processed using a Metkon brand ECOPRESS 50 device. To remove scratches, the Bakelite samples were then subjected to a series of sanding processes, ranging from coarse to fine (600 µm, 800 µm, 1,000 µm) and polishing (9-6-3-1 µm diamond paste). Vega brand TESCAN II model scanning electron microscope (SEM-EDS) was used for coating characterization. The surface morphology and microstructural properties of the material were evaluated with SEM images taken at different magnifications.

In order to analyze the performance and quality of the coated disc the microhardness measurement, dynamometer test, corrosion test, visual inspection, microstructural examination, SEM-EDX analysis were performed. After the coating applications, cross-sections taken from coated brake disc samples were measured (HV0.3) using a Shimadzu brand Vickers microhardness tester under a 300 g load for 10 s, in accordance with ASTM-E384. Six measurements were taken for each cross-section surface, and the results were averaged. Based on this, the hardness values were examined comparatively.

In real road conditions, disc-pad tests are quite costly, so road conditions need to be simulated. Real road conditions were simulated with dynamometer performance testing. The inertial dynamometer test system is shown in Figure 2. Tests are carried out under different short and long-term braking scenarios according to OEM standards. Coated discs were tested on an inertial dynamometer by Kale Balata Automotive Industry and Trade Inc. with original pads used in commercial passenger vehicles. The inertial dynamometer's operating principle uses mechanical inertial masses fixed in increments to a rotating shaft to simulate the kinetic energy of a moving vehicle mass. An electric motor accelerates the rotating masses to a predetermined speed. When the specified speed is reached, the engine releases control, and the braking system then works to stop the rotating mass. The energy lost during braking simulates the energy expended by the vehicle during braking [21]. In a dynamometer test system, variations in the friction coefficient and brake torque forces were monitored at different temperatures, and the experimental results were compared with those obtained from uncoated discs. After the dynamometer test, weight and dimension measurements were made at each brake-temperature stage applied in the brake cycles determined according to the dynamometer test procedure and the wear amounts were examined comparatively. The dynamometer testing procedure is shown in Table 5. Additionally, Brake systems are subject to corrosion due to exposure to atmospheric external influences under

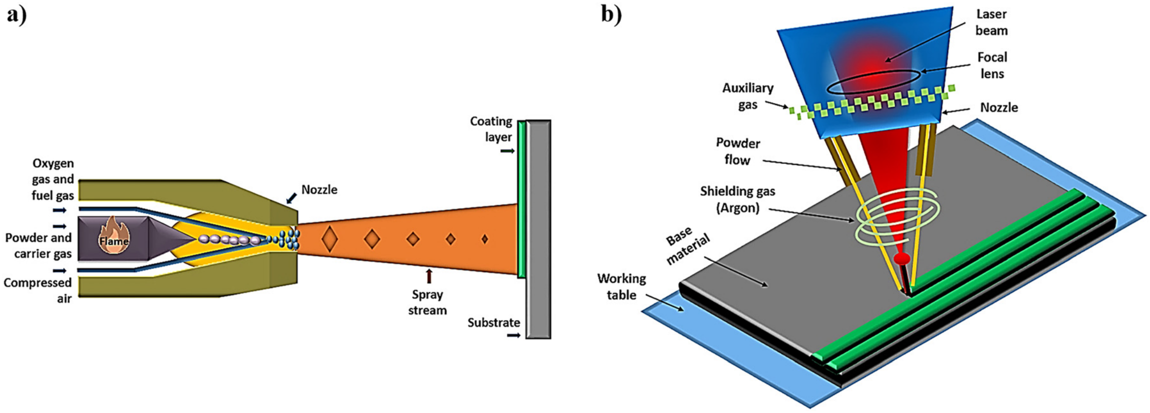

Figure 1: a) HVOF process schematic view, b) laser cladding process schematic view.

Table 4: Laser cladding process parameters.

Laser power (kW)	Speed (mm• s^{-1})	Powder feeding rate (l•min^{-1})	Shielding gas flow rate (l•min^{-1})	Carrier gas flow rate (l•min^{-1})	Overlap (mm)	Spot width (mm)	Laser clad height (avg•min^{-1})
1.35	13	4.5	15	5	1.8	1.5	1

real-world road conditions. The salt fog test was performed in a 5 % sodium chloride solution according to ASTM B117 to simulate corrosive environmental conditions. The brake discs were subjected to a salt fog test in an aggressive corrosion environment and the test periods during which red rust formation was observed were recorded.

3 Results and discussion

The SEM-EDX images taken from the 431L coating powder are shown in Figure 3. In the SEM image, the coating powder dimensions measured between 89.45 and 100.95 µm in diameter. In the chemical composition analysis of the coating powders, Fe, Cr and Ni are found prominently, while there is a trace amount of Mn. The SEM image of GG20 quality grey cast iron at 300× magnification is shown in Figure 4a. In the microstructure image, the lamellae graphite cast iron structure was clearly observed. The graphite lamellae in cast iron form irregular paths within the matrix [22]. Graphite lamellae have high thermal conductivity and vibration damping capabilities. The high heat generated by friction during braking is thus quickly transferred to the disc. It also contributes to dampening braking noise. The cross-sectional microstructure image coated brake disc with the HVOF method is shown in Figure 4b and c. The coating thickness was measured on the microstructure as 160.63 µm and 217.33 µm at two distinct points. A successful coating of an average thickness of 189 µm was achieved on the surface.

Table 5: Dynamometer test procedure.

Parameters	Bedding	T2	T3	T4	T5
Starting temperature (°C)	100	200	300	400	500
Starting speed (km•h^{-1})	80	100	100	100	100
End speed (km•h^{-1})	5	50	50	50	50
Standard number of brake (cycles)	100	300	300	300	300
Shortened number of brake (cycles)	100	100	100	200	200
Braking pressure (bar)	20	50	50	50	50

Due to the characteristic feature of the HVOF coating method, lamellar structures formed by the accumulation of molten coating material on top of each other were observed in the microstructure. In this coating, mechanical bonding occurs between the coating and the substrate material as well as between the deposited layers. Micropores, cracks and interlamellar spaces were identified in the microstructure of the coating layer. Various studies in the literature support the results of this study by stating that micropores and cracks may occur on the surface during the HVOF process [23], [24]. It was observed that a wavy coating line was formed on the brake disc surface. The cross-sectional microstructure image coated brake disc with the laser cladding method is shown in Figure 4d and e. It was observed that the coating adhered successfully to the brake disc surface. In the laser cladding method, bonding between the coating and the base material occurs through a metallurgical bond formed by partial melting at the interface. In the

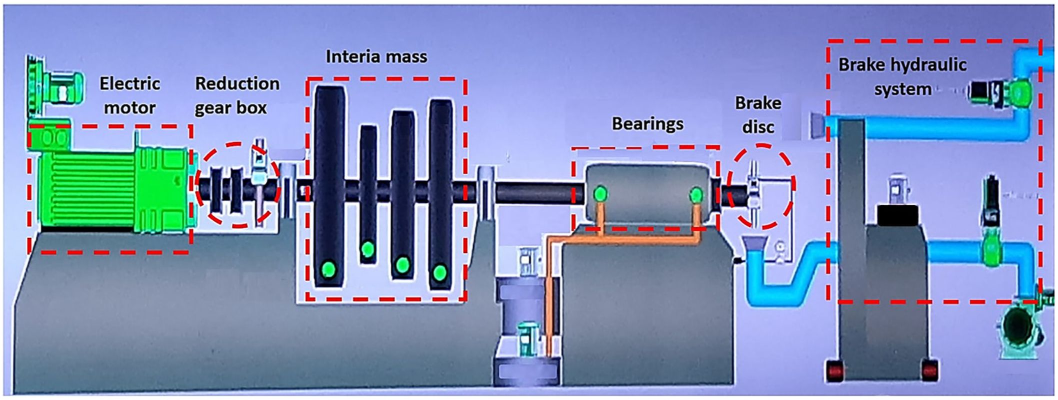

Figure 2: Schematic of inertial dynamometer test system (Kale Balata Automotive Inc.).

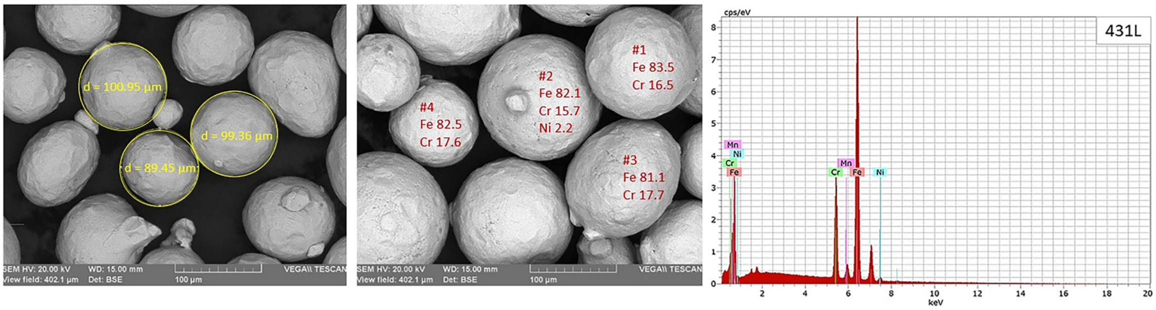

Figure 3: 431L coating powder SEM image and chemical analysis.

microstructure, it was determined that a heat affected zone (HAZ) was formed between the base material and the coating material Figure 4e. The coating thickness was measured on the microstructure as 1,088.63 µm and 1,110.45 µm at two distinct points. A successful coating of an average thickness of 1,050 µm was achieved on the surface. In the coated sample cross-sections, acceptable microporosity, unmelted parts and discontinuities were detected. This can be attributed to the coating process, rapid cooling and residual stresses.

The Vickers microhardness measurements were performed on the coating surfaces and the brake disc base material. Measurements were taken from 6 points of each sample and the measurement results were averaged. The average microhardness values are shown in Figure 5. The hardness of a sample obtained from the original GG20 brake disc base material was determined to be 225 ± 5 HV(0.3). The target microhardness value was to be higher than that of gray cast iron. The average hardness values of brake disc surfaces coated with the HVOF and laser cladding processes were measured as 332 ± 7 HV(0.3) and 547 ± 12 HV(0.3), respectively. The hardness values of coated brake disc surfaces were measured higher than those of uncoated brake discs. This indicates that the coating process has significant effects on microhardness.

The brake discs were subjected to a salt fog test in an aggressively corrosive environment with the goal of providing at least 240 h of corrosion resistance. The results of the salt fog test are shown in Figure 6. The corrosion resistance of the brake discs was evaluated by recording the time at which the first red rust appeared on each surface during the test. Accordingly, the laser cladded brake disc showed

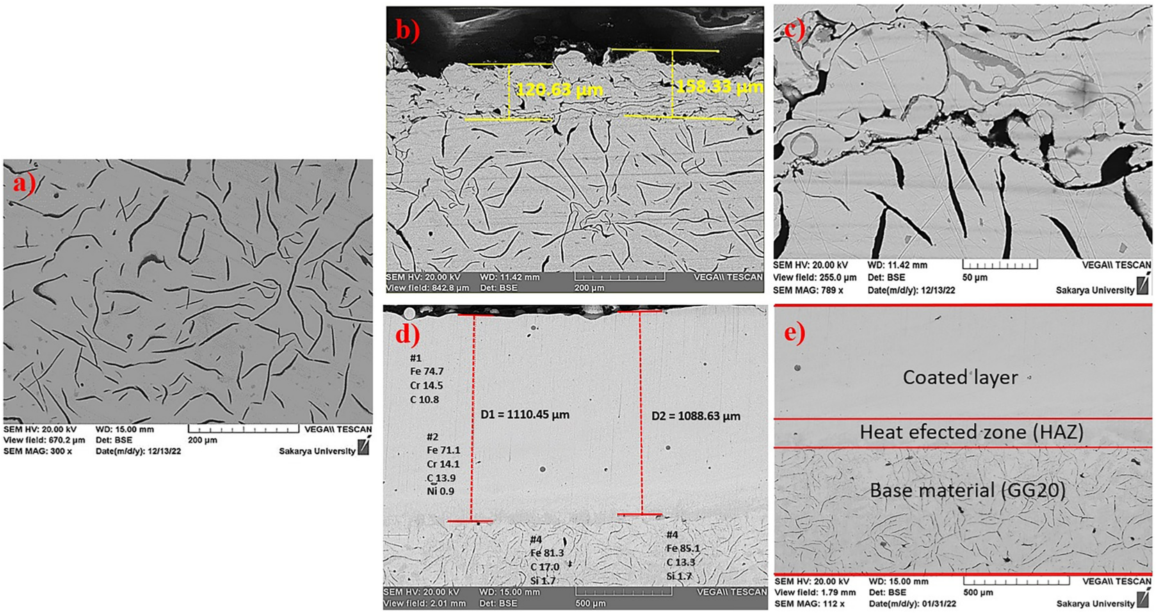

Figure 4: a) SEM image of GG20 disc, b) coating thicknesses HVOF, c) SEM image of HVOF coating, d) coating thicknesses laser cladding, e) SEM image of laser cladding.

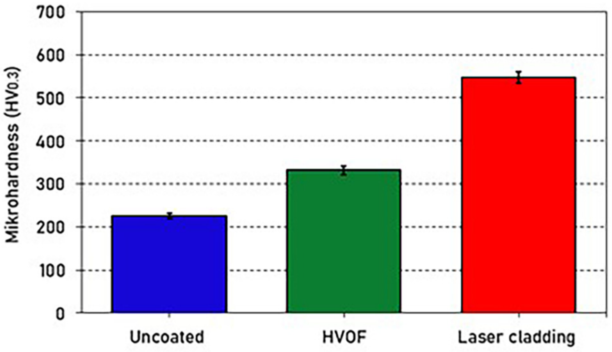

Figure 5: Brake disc surface microhardness.

corrosion resistance for 540 h, and the HVOF coating disc showed 320 h, while the original disc resisted red rust formation for approximately 70 h. It is considered that the laser-coated disc provides superior corrosion resistance compared to the disc coated by the HVOF, owing to its denser and less porous coating layer. In comparison with the uncoated disc, both the HVOF and laser-cladded discs exhibited higher corrosion resistance.

The coefficient of friction (CoF) generated during braking plays a crucial role in vehicle safety, and a stable CoF value ensures reliable braking performance of the vehicle. Consistent with this, the braking performance of the uncoated and coated discs with OEM brake pads was evaluated by analysing the CoF values obtained during the brake tests. The CoF trend graph was created after the dynamometer test using the values recorded at different brake temperatures for all disc-pad pairs during 700 brake cycles (Figure 7a). The average CoF values of all disc-pad pairs measured at different brake temperatures in Fiqure 7b. The average CoF measured at all temperatures and standard deviation values are shown in Figure 7c. The laser cladded disc gave the most stable CoF curve in all brake test cycles. The average CoF value was measured as 0.4 in all braking temperatures and the lowest standard deviation value was calculated as 0.008. The HVOF-coated disc showed a more stable CoF trend curve than the uncoated disc, especially after 500 cycles, but less stable and more flactuated than the laser-coated disc. The HVOF-coated disc exhibited an average coefficient of friction (CoF) value of 0.44 at all braking temperatures, and the second-highest standard deviation value after the laser-coated disc, 0.033, was calculated for this disc. The uncoated disc exhibited the lowest coefficient of friction value of 0.39, along with the highest standard deviation of 0.045. Notably,

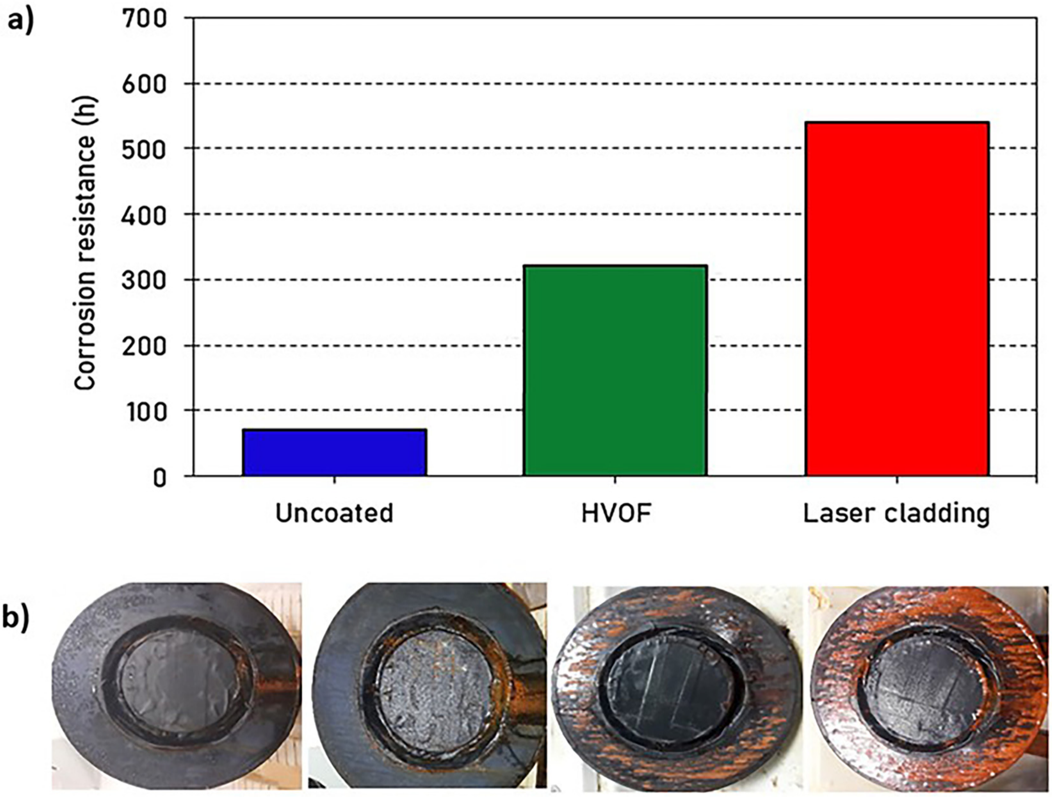

Figure 6: a) Comparison of corrosion resistance of uncoated and coated discs during the salt fog test, b) brake disc appearances with red rust observed during salt fog corrosion test.

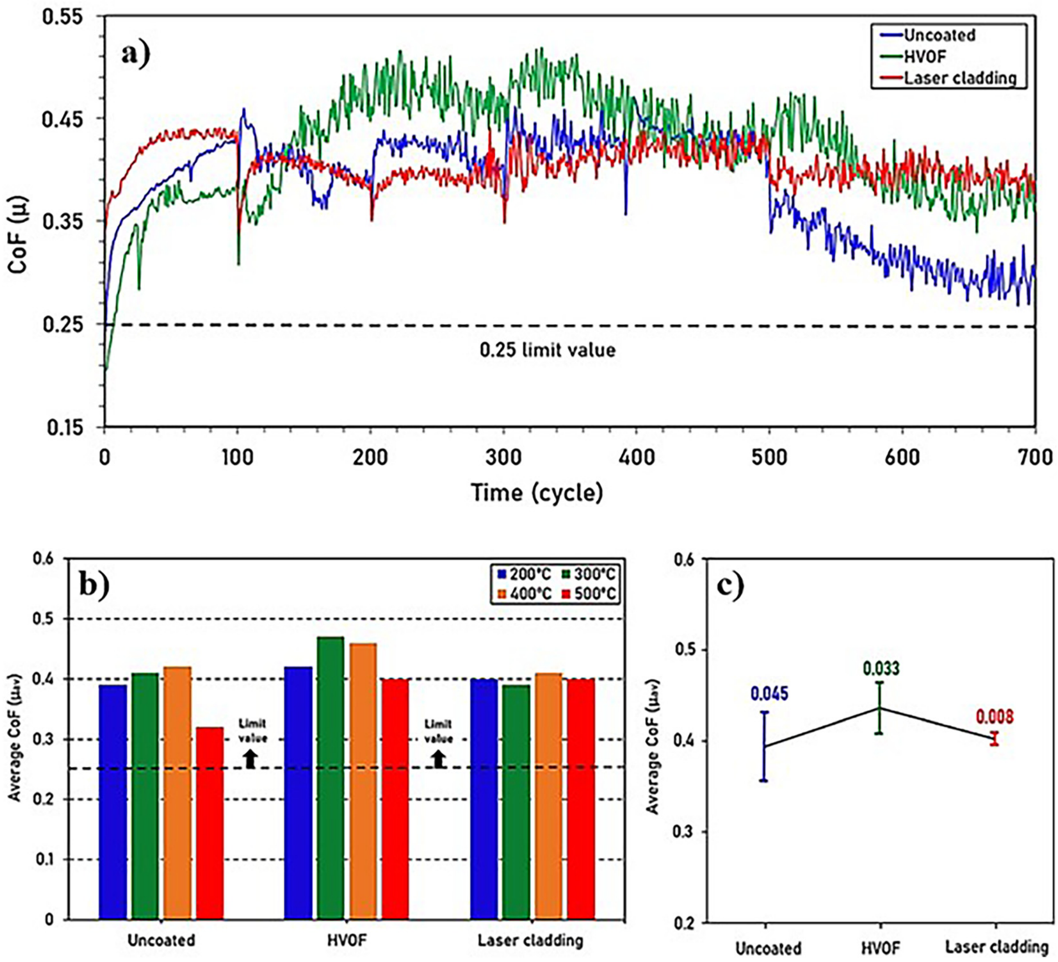

Figure 7: a) Comparative graph of the friction coefficient trend of the uncoated, HVOF-coated and laser cladded discs during the braking cycle, b) average friction coeeficient of uncoated, HVOF-coated and laser cladded discs at different brake temperatures, c) average friction coeeficient during the braking test with standard deviation values.

signs of unstable or critical braking behavior were detected, particularly during the final phase of the braking test (cycles 500–700), where a sudden decline in the CoF trend curve was observed, approaching the limit value that could be regarded as indicative of test failure. According to the CoF results, none of the discs exhibited a CoF value below the limit of 0.25 at any braking temperature during the test. In OEM specifications, CoF values above this limit are considered indicative of safe braking performance [14]. While the uncoated disc is currently used in passenger vehicles, the results demonstrate that both HVOF-coated and laser cladded disc can also be considered viable alternatives to the uncoated disc in terms of ensuring safe braking performance.

In ideal situation, a homogeneous contact pressure between the brake disc and pad surfaces is assumed. However, as observed from the changes in the coefficient of friction (CoF) measured during braking, uneven contact occurs between the surfaces due to design factors or manufacturing metots of disc-pads in real. This leads to high thermal stresses and thermal shocks, while the mechanical loads generated during repeated braking and heating cycles further increase the thermal stresses on the disc surface. The combined effects of thermal and mechanical stresses occurring during braking cycles cause deformations on the surfaces [25]. Images of the brake disc and pad surfaces taken after each test stage at different brake temperatures throughout the brake test are shown in Figure 8. Accordingly, as the brake cycle increases with increasing temperature, the traces of deformation observed on both the pad and the brake disc surfaces.

A comparative graph of the braking torques obtained from the dynamometer test is shown in Figure 9. While the torque of the uncoated disc generally tends to increase with increasing temperatures, a significant torque drop observed at 500 °C indicates a sudden decrease in braking performance. The HVOF-coated disc exhibited notably fluctuating

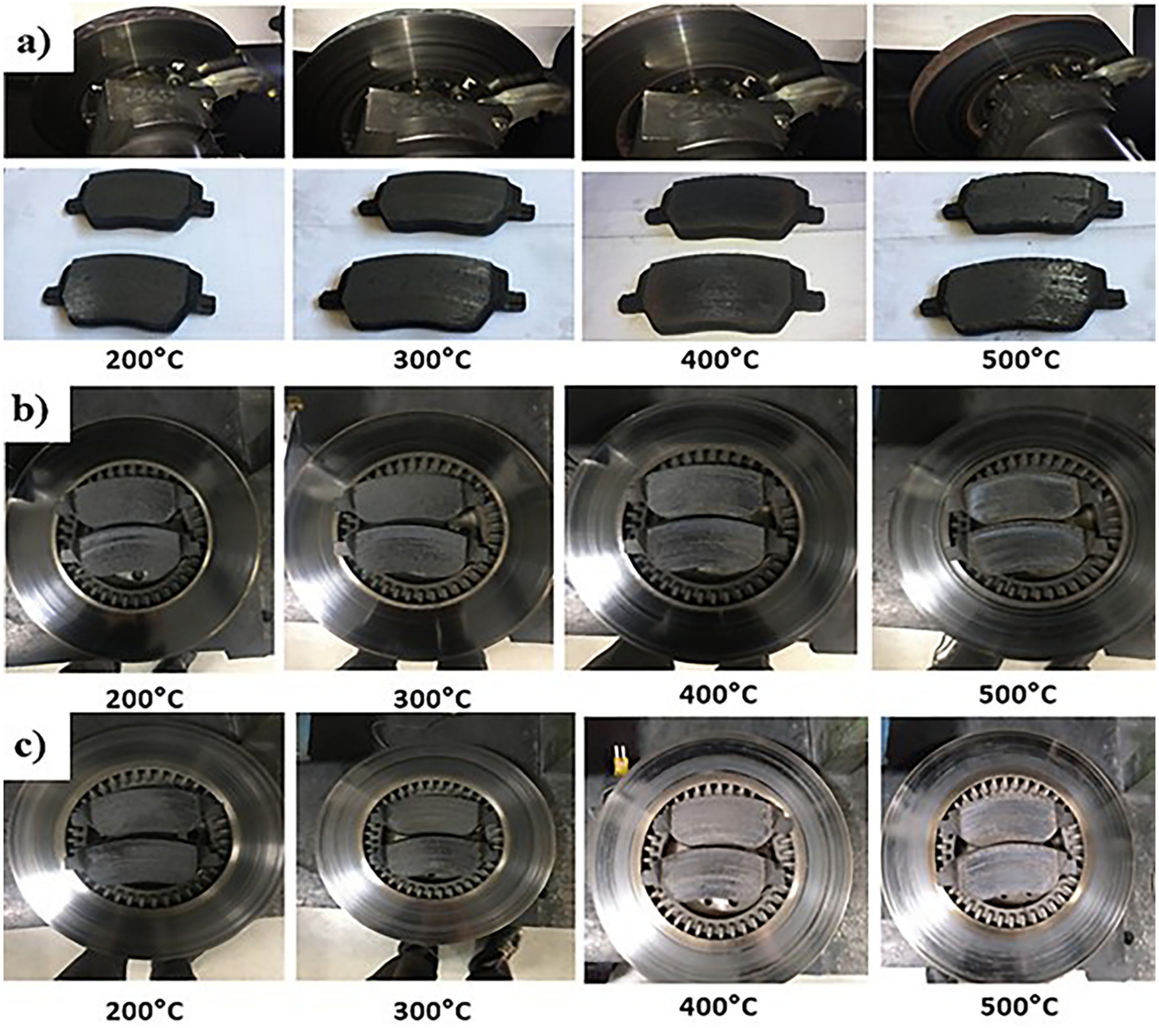

Figure 8: Images of a) uncoated discs-pad, b) HVOF coated disc-pad and c) laser cladded coated disc-pad surfaces at different temperatures during the brake test.

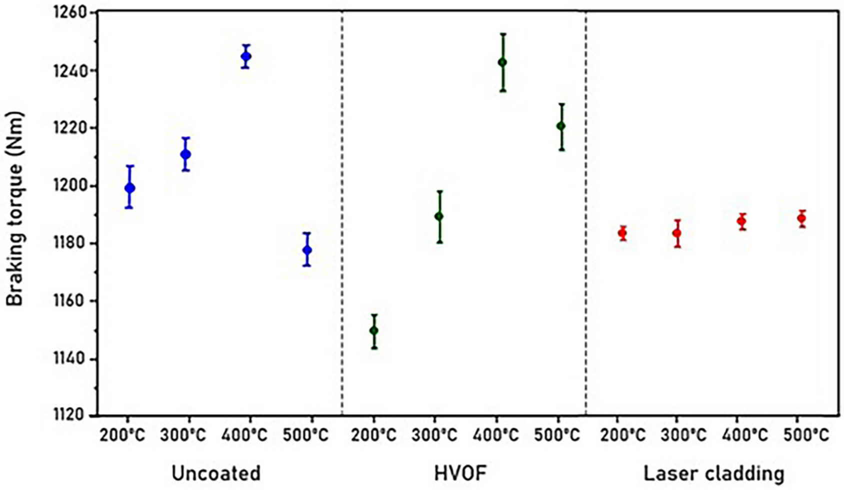

Figure 9: Comparison of braking torque of coated and uncoated discs at different brake temperatures.

torque values compared to the original disc, suggesting the need for improved coating quality; however, unlike the uncoated disc, there was no sudden drop at 500 °C. The most stable torque behavior was observed for the laser cladded disc, indicating that this disc provides more consistent and reliable braking performance.

The comparison of wear rates of the coated discs and the original disc at different brake temperatures is shown in Figure 10a. In this figure, the wear rate was determined by dividing the measured thickness reduction obtained after each test stage by the number of cycles corresponding to that stage. According to the graph, the original disc exhibited a significantly higher wear rate than the coated discs, particularly after the initial bedding stage, and continued to show faster wear at all braking temperatures. In contrast, the laser-clad coated disc demonstrated lower wear rates throughout all temperature stages of the test.

Figure 10b shows the brake pad wear rates at different brake temperature. According to the results, the highest pad wear rate was observed in the uncoated disc. The pad wear rate of the laser cladded disc was lower than that of the uncoated disc but higher than that of the HVOF coated disc. This was attributed to the fact that the higher hardness of the laser cladded disc may cause greater wear on the pad compared to the HVOF coated disc. Although the uncoated disc exhibits lower hardness than the coated ones, its pad wear rate is the highest. This can be attributed to the inferior surface condition of the uncoated disc, which likely increases the abrasive interaction with the pad. Therefore, improving the surface properties of the uncoated disc is expected to result in a more homogeneous pad–disc contact area and reduced wear. Furthermore, due to the GG20 material characteristics of the uncoated disc, the sharp-edged lamellar graphite structures present in the microstructure may become more pronounced during wear and act as abrasive particles on the pad surface.

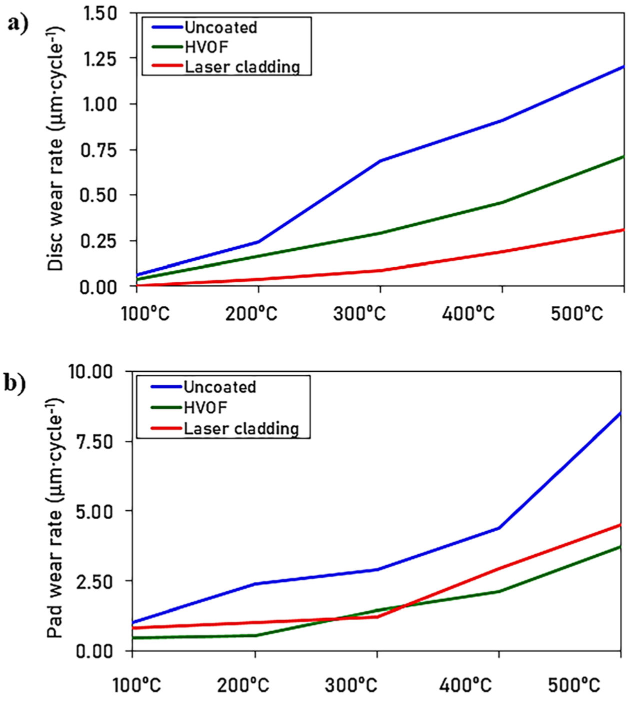

Figure 10: Comparison of a) disc wear rates, b) pad wear rates at different brake temperatures.

Brake disc wear measurements provide the basis for interpreting brake disc braking and disc service life. During the dynamometer test, the wear on the brake discs was measured after each test stage at different brake temperatures, and these measurement results are presented comparatively in Figure 11a. Accordingly, the uncoated brake disc showed the most wear during the test, with 13.21 g of wear. Coated discs exhibit significantly less wear than the original disc. At the end of the test, the HVOF-coated disc showed 6.85 g of wear, while the laser-clad-coated disc had 2.90 g of brake dusct. Laser cladded disc exhibited superior wear resistance, with approximately 4.5 times less wear than the original disc. These results clearly indicate that surface coating methods, particularly laser cladding, provide effective protection against wear under braking conditions.

The wear performance of brake pads used with uncoated and coated brake discs after the brake test was evaluated under different temperature conditions. The wear rates of pads in contact with the discs are shown

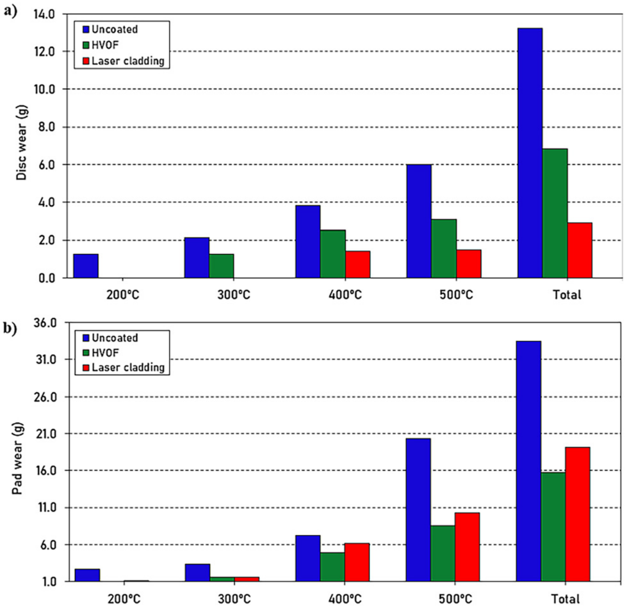

Figure 11: Wear at different brake temperatures, a) disc, b) pad.

comparatively in Figure 11b. Here, the average wear rates of the inner and outer pad surfaces of the pad pair were plotted graphically, using values taken from the measurement points of the pad surfaces of both disc connections. According to the percentage wear rates of the coated disc and the original disc pads, the highest pad wear (39.19 %) occurred on the original brake disc, the second highest pad wear rate (22.43 %) occurred on the laser-clad-coated brake disc, and the lowest pad wear (18.44 %) occurred on the HVOF disc. The laser-clad-coated brake disc, due to its high-performance coating material, wears the pad material more than the other coated disc, while the original disc experiences higher pad wear due to uneven braking.

Noise data obtained under different brake conditions during dynamometer tests were systematically recorded. The recorded decibel (db) values were grouped into 70–80 dB (the acceptable low-intensity brake noise range), 80–90 dB (the moderate-intensity range), and 90–120 dB (the high-intensity range, representing the outliers) based on the data clustering. For the noise profile analysis, the number of brake cycles corresponding to these data groups, depending on the disc type, is shown in Figure 12. While the reference values used as limits vary depending on the test conditions and vehicle types, the primary objective of brake noise measurements is to minimize high-frequency noise. All data from the couple of uncoated disc and pad combination, was recorded at 70–80 dB over 700 brake cycles. As expected, the data from this disc, used in the OEM, produced a valid low-frequency profile within the 70–80 dB noise reference range over the entire brake cycle. Brake noise frequencies of coated discs were present at various rates outside the 70–80 dB limit range, unlike the uncoated disc. However, the noise data in the laser cladded disc, the closest data to the original disc noise profile was obtained and its off-reference data corresponds to 1.3 % of the total of 700 brake cycles.

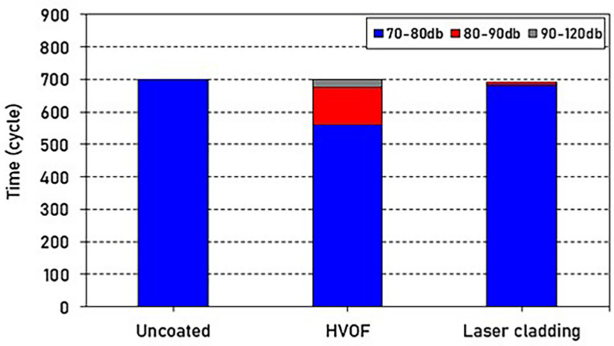

Figure 12: Comparison of brake noise measurement.

4 Conclusions

In this study, the braking performances of uncoated, HVOF coating, and laser cladding brake discs were compared and a coated disc with superior braking performance was presented as an alternative to uncoated discs in passenger vehicles. The main results obtained from this experimental study are listed below.

Laser cladding exhibited superior corrosion performance comparison of the disc coated by HVOF and uncoated since it provided a dense and uniform coating with strong adhesion to the substrate, minimizing defects such as porosity and cracks. Coated brake discs exhibited enhanced braking performance with more stable coefficient of friction trend and torque values compared to uncoated brake disc during brake test. However, the braking performance of HVOF-coated discs was more limited than that of laser-cladded discs due to the lower coating quality (the coating is formed by mechanical bonding and the coating layer is unevenly bonded to the base material, discontinuities in the coating microstructure and significant microporosity, etc.). Coated brake discs exhibited higher wear resistance than uncoated brake discs. The laser-cladded disc experienced about 4.5 times less wear, while the HVOF-coated disc showed about 1.9 times less wear compared to the uncoated disc. Pad wear was highest for the uncoated disc, followed by the laser-cladded and HVOF-coated discs respectively. The uncoated disc caused the greatest wear on the pad surface due to its low surface quality and irregular braking performance. According to the brake disc noise measurement data, the uncoated and laser-cladded discs exhibited noise profiles compliant with automotive specifications, whereas the HVOF-coated disc showed unacceptable noise performance. In future studies, it is recommended to develop a brake pad formulation compatible with the laser-cladded disc. Research focusing on pads that can operate effectively with laser-cladded discs exhibiting significantly reduced wear will also contribute to ongoing efforts to reduce carbon emissions.

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