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RESEARCH ARTICLE

A comparative study of brake wear performance with recent coating methods

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Abstract

With the increase in the environmental awareness of the societies around the world and the increase in technological opportunities, the expectations from the brake discs used in vehicles are increasing day by day. In addition to this, studies are being carried out on the legal regulations that are expected to be implemented in Europe and America in the near future, limiting the particles released from the brake system. Gray cast iron-based brake discs are safe and economical parts that are exposed to high wear and corrosion in the face of increasing vehicle speeds and road conditions. Trends and developments in electric vehicles; weight reduction, higher wear and corrosion resistance, lower replacement costs, and minimum brake dust are desired without loss of brake performance on the new generation brake discs. Hard coat implementation on the rubbing surface of the brake disc is a promising solution that is being studied by the brake system developers. Within the scope of this experimental studies, stainless-steel coating by laser cladding and ferritic nitrocarburizing (FNC) processes were separately applied to the rubbing surface of the cast iron brake discs. The same cycle dynamometer tests carried out with the normal and coated brake discs and a standard type of OEM pads. Braking and friction performance findings are presented comparatively.

1. Introduction

Brake system [1] as per its working principle, the disc-pad friction surface is exposed to wear by a braking force during braking. Thermal behaviour management is critical to obtain the desired wear performance on the rubbing surface of the brake discs. The heat that is created on brake surfaces during braking time dissipates mostly by convection from the ventilation channel geometry [2]. Therefore, the brake disc ventilation geometry should be designed to provide optimum airflow performance. In the brake disc development phase, these optimization and validation studies can be performed via virtual analysis and bench-test correlations [3]. Besides, dust emission legislation efforts force OEMs to minimize brake dust caused by pad-disc friction surface wear and be prepared for upcoming dust emission legislation. In addition, with the increasing use of new generation electric vehicle, customer dissatisfaction is growing more significantly due to rust on the wheels of vehicles caused by the regeneration braking system. For these reasons, many researchers are working on the improvement of the brake discs in order to prevent all these problems caused by disc failure and to meet the needs of the sector with new generation vehicles in recent years [4-5]. In conventional brake disc applications, the friction surfaces of the brake disc with the lining are not exposed to any coating. The reason for this is that braking is a tribological application and any coating applied to the surface adversely affects the performance of the brake disc in terms of safety and comfort. However, advanced thermal coating technologies enable coating to be applied in a way that does not adversely affect the thermal capacity and shock absorption properties of the brake disc. In addition, wear materials compatible with coated brake discs are also being developed.

The brake disc, which is one of the active safety parts of the automobile, causes critical damage in case of failure. Adin et. al. [6] investigated brake discs that were damaged and subjected to abrasion. Brake disc material selection is of great importance in order to prevent the problems caused by disc failure [6, 7]. However, there are limited types of materials that meet the techno-economic requirements for use in the automotive industry. In general, gray cast iron [8,9] (GG15-25, DIN1561) is most widely preferred for use in disc material due to its low cost, excellent casting properties, good machinability, vibration damping ability, etc. Furthermore, gray cast iron can no longer adequately meet the service conditions during the development of rapid vehicles equipped with high-quality materials [10-12].

There are many studies [13-20] in the literature to improve discs through coating by various surface treatment processes such as laser cladding, FNC, HVOF, APS. Shi et al. used the laser cladding technology as a fast and eco-friendly process to avoid brake disc failure caused by wear. They coated the surface of brake disc using Ni-based alloy powder to increase the wear resistance of the brake disc by laser cladding and then systematically examined of the coating layer [13]. Rajaei et al. [20] also studied on laser cladded brake disc and they claid that MnS containing brake disc coat has been reduced both friction coefficient and wear rate to levels comparable with those obtained in case of uncoated gray cast iron discs. Federici et al. investigated pearlitic cast iron brake discs with two types of coatings based on Cr_3C_2-NiCr and WC-CoCr components by HVOF technology. The coated surfaces were tested by pin-on-disc wear test and here, the characteristics of the friction layer

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were evaluated in relation to the friction and wear behaviour of the coated disc [14]. Oz et al. studied on coating original gray cast iron brake discs of a light commercial vehicle with ceramic chromium oxide (Cr_2O_3) powder using NiAl inter binder by the plasma spray method. Coated discs were investigated for bending and thermal vibration properties in an inertial dynamometer. In the end of investigation, they have evaluated average friction coefficient, NVH values and disc final temperature for both different materials [15]. The common motivation of all studies is to improve the brake disc performance because of the meeting of driver's satisfaction, industrial expectations such as its investment costs and operating costs. For this reason, coating method and material selection is very critical. Laser cladding and FNC methods are widely used the ones for higher wear performance, good corrosion resistance, generating consistent braking torque and better NVH characteristics. However, in generally the use of the technologies are limited high process cost in the industry.

In this study, the variation of friction coefficient trend, braking torque and wear variation of coated (by using laser cladding and FNC technologies) & uncoated discs and counter pad materials at different test temperatures were compared under dynamometer performance test.

2. Experimental Procedure

2.1 Laser Cladding Process

According to work principle of laser cladding process, the laser beam comes from the laser head, the feeding powder material is transferred from the nozzle and also the shielding gas is sent to the base material (Fig. 1). By means of the laser beam, the powder and base material melts and forms a welding pool. The laser head is advanced on the surface to be coated and the process continues. Shielding gas (Argon gas is commonly) protects the material in the melt pool from oxidation.

Table 1. Laser Cladding Parameters.

Power (W)	Velocity (mm/s)	Powder (1/min)	Shielding gas (l/min)	Carrier gas (l/min)	Power (W)	Velocity (mm/s)	Powder (1/min)	Shielding gas (l/min)
1000-1350	10-13	4.5-5	15-20	5-7	1,5-1,8	1.5	60-75	1-1,5

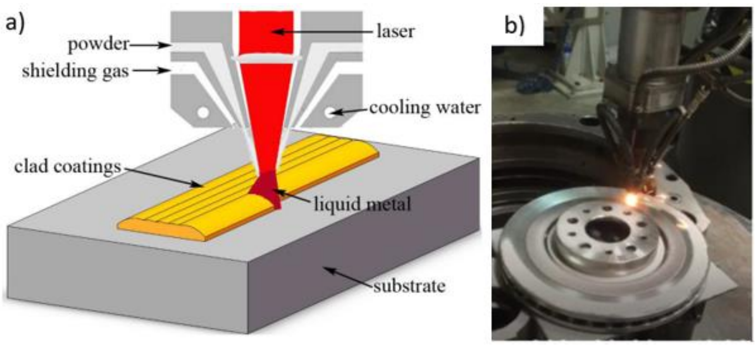

Figure 1. a) The schematic diagram of laser cladding [21] b) Brake disc laser cladding process.

Process control can be done depending on the laser cladding operation parameters (Table1 for this study). After the process, the desired surface quality can be obtained by machining process. ITAB is limited as there is no high heat input to the part [22].

Laser cladding has a wide range of using materials, process performance is directly related to the selection of the appropriate coating material. Depending on the properties expected from the coating, metallic or metal composite-based materials can be used in the form of a wide variety of powders or wires. In the literature, martensitic stainless steel is widely used as a coating material due to its advantages such as increasing the strength, hardness and corrosion resistance of the components [23]. In this study, the AISI 431L stainless steel powder was used as a coating material in the laser cladding process. The measured hardness of the samples was 650 HV in average.

2.2 FNC Process

In the FNC process, the parts are first cleaned to eliminate surface contamination. The process is conducted completely within the ferrite phase, at a temperature usually around 570 °C (1,058 °F) with a process time that ranges from one to four hours (Fig. 2.). A diffusion layer followed by a compound layer at the surface is formed. The surface layer depth varies from 0.00015 to 0.0015" (0.004 to 0.04mm). The primary objective of ferritic nitro-carburising treatment is to improve the anti-friction characteristics of components. The compound layer exhibits significant improvement in adhesive wear resistance [24]. With the introduction of nitrogen in the diffused zone fatigue properties are enhanced. The obtained surface hardness was 589 HV in average.

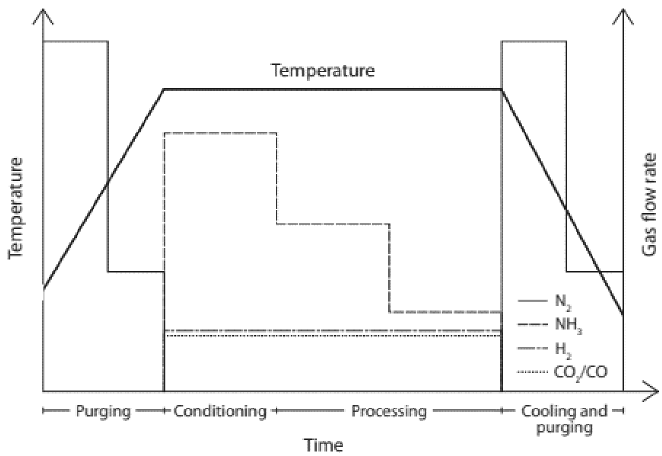

Figure 2. FNC process diagram of brake disc

2.3. Wear Performance Test

The wear tests were performed in a full-scale dyno bench according to the relevant test procedure. The friction material used in the wear performance tests were selected from the same production batch of the original products. The measurements were carried out in accordance with relevant test standard and temperature, friction coefficient, braking torque, pressure, pad and rotor wear changes were recorded at each significant temperature step of the test. In order to provide realistic data, new brake pads were subjected to the brake bedding stage before the data acquisition.

3. Results and Discussion

Original brake disc material is from gray cast iron (DIN 1561: GG20). The section of uncoated and coated brake discs were analyzed and the SEM micrographs are shown in Fig. 4.

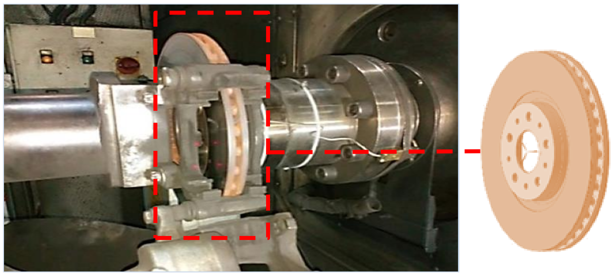

Figure 3. The brake disc on the brake performance test rig

The surface roughness of laser cladded brake disc is over Ra: 4.5 (Fig. 5c). Due to the fact that the grinding or machining operation is mandatory for optimizing surface roughness. In this study, the laser cladded discs were grinded by industrial diamond tool (Fig. 5d).

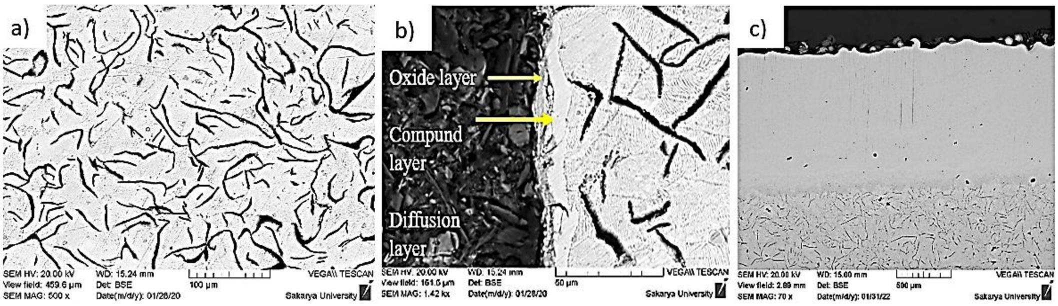

Figure 4. SEM analysis with a) laminar graphite cast iron b) coating layer treated by FNC c) laser cladded layer.

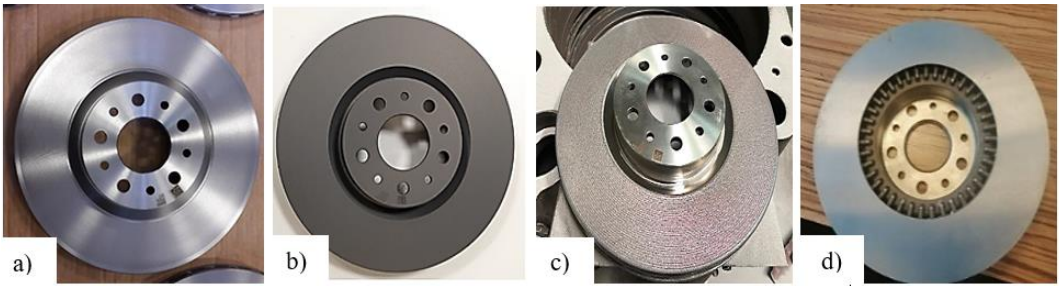

Figure 5. Brake disc surfaces a) uncoated b) FNC treated c) laser cladded d) cladded after grinding

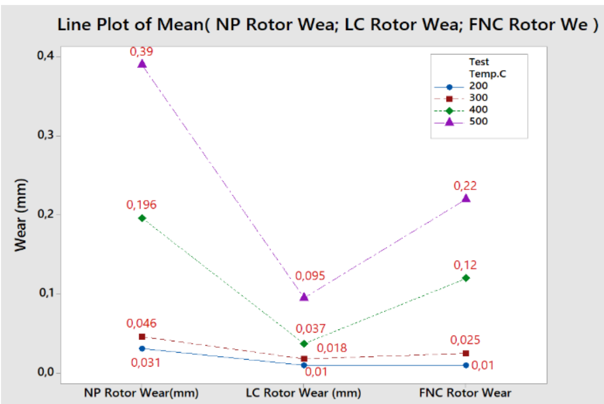

Figure 6. Wear comparison graph of rotors for uncoated disc-pad (NP) and coated disc-pad (LC) pairs at different temperatures.

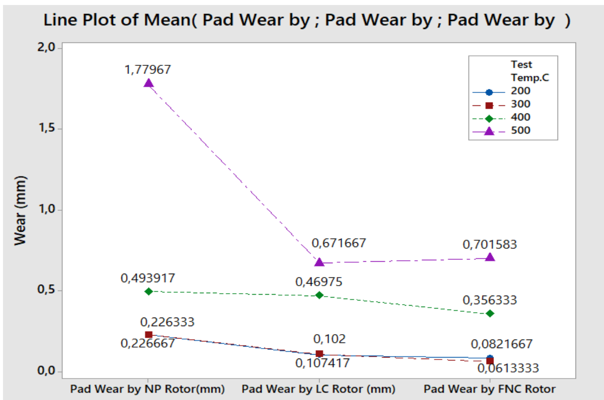

Figure 7. Wear comparison graph of pads for uncoated disc-pad (NP), coated disc-pad (LC) pairs, and coated disc-pad (FNC) pairs at different temperatures.

The brake disc samples were tested on the full-scale brake test bench and measured their wear characteristics. In figure 6, the wear graph of the discs is displayed depending on the test temperature. The wear rate is highest in the uncoated disc in all temperatures. If the wear-related thickness changes of the laser-cladded and FNC-treated discs are compared, it can be seen that the wear loss of the laser cladded disc is a quite low. Although the same type of standard friction materials was used in the tests, the lowest wear level obtained in the stainless-steel coated brake rotors. The main contributor reason for that result is the hardness of the laser cladded surface was the highest in the tested samples. The other assumption for supporting to this result, the stainless-steel coating retains its thermal stability better at elevated temperatures. Low irregularity creation on the friction surface provides less wear from the each rubbing surface.

In figure 7, the test results of the pad wear in contact with the disc are displayed. Similarly, for uncoated discs, it is observed that the pad wear increases, and the thickness decreases with temperature. A significant degradation occurred on the pad surface in contact with the uncoated disc. It can be said that the coating has a reducing effect on both disc and pad wear (Figure 8). This is very important in terms of long disc life and international demands for brake dust reduction.

Figure 8. Disc-pad friction surfaces after wear test

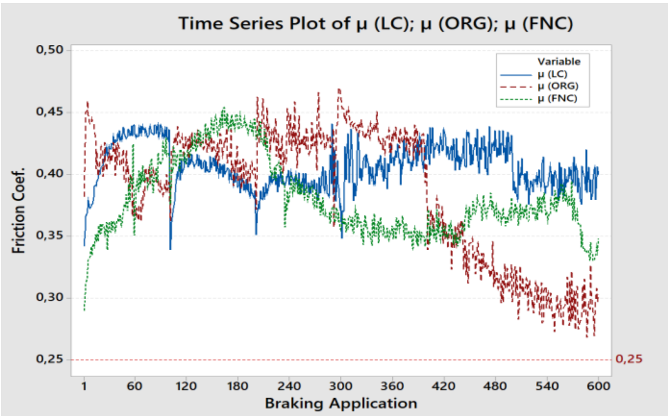

Figure 9. Disc-pad friction coefficient trend at the different braking cycles.

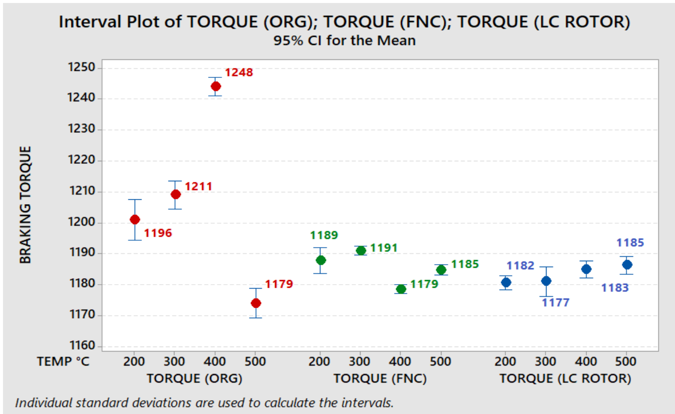

Figure 10. Brake torque variations at the elevated test temperatures

The trend of friction coefficient with increasing temperature of the wear test is one of the important characteristics taken into account in evaluating brake efficiency. After the bedding step of the wear test, the friction coefficient is measured and and corresponding values are reported with increasing test temperature. It was observed that the coated discs stayed more stable compared to the friction coefficient trend of the uncoated disc in the wear test (Fig. 9). The friction coefficient limit, which is determined according to the selected brake disc and pad characteristics, is a minimum of 0.25, and if it falls below this value, fading problems may occur in the brakes. Accordingly, in the all wear performance tests, the friction coefficient trend has generally remained above this value and meets the safety requirements.

Brake torque is the force applied at the brake wheel to stop the motion of the moving equipment. Instable and fluctuated brake torque is an indicator of brake fading. This phenomenon normally is expected to be realized at higher temperatures of 400°C because of the lower friction coefficient. The stopping distance of the vehicle gets longer when the brakes have faded.

$Tb = 2 \cdot \mu \cdot Fn \cdot re$ [25]

(Braking Torque (Tb) is the moment of braking force about the center of rotation. Clamping Force (Fn) is the force pressing each brake pad against the disc. μ is the coefficient of friction between the pad and the disc. Effective radius (re) is the effective brake disc radius)

The variation of braking torque was investigated depending on the temperature (Fig. 10). As can be seen, it is observed that the torque force fluctuation / instability decreases with the coating processes. While the average torque forces are 1208N/m in the uncoated state, they decrease to relatively lower levels (average values of FNC; 1186 N/m and laser cladding; 1181 N/m) with the coating processes. The desired braking torque trend for the brake efficiency is that the torque curve should not fluctuate by the elevated temperatures. Therefore, the best result is obtained in the test with stainless steel coated brake disc by laser cladding.

4. Conclusion

In this study, we compared the wear and brake performance tests of 3 brake discs with a standard friction material, uncoated, FNC applied and stainless steel coated with laser cladding. Due to the higher surface hardness of the coated discs, it is an expected result that the wear performance is better than the normal disc. Likewise, with the increase in temperature, the friction coefficient of coated discs does not decrease much compared to normal discs, which makes coated discs stand out in brake performance. When we compare the results of the two coated discs, the stainless steel coated brake disc wears less than the FNC treated disc due to its surface properties. We can say that the main reason for this is that the surface hardness is higher than the FNC applied disc. However, we can also evaluate that the thermal conductivity of the 431-grade coating applied with laser cladding may be better and therefore less exposed to thermal stress and less worn while preserving the surface geometry. As a result, we can interpret that it wears less and is one step ahead of the FNC application.

In general, both coating applications are solutions that can be industrialized in the future after process optimizations are achieved in brake disc coating to reduce brake dust emissions.

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Author contributions

Ekrem Altuncu: Supervision, methodology, editing

Recep Akyüz: Project administration, conceptualization, data curation, validation

Çiğdem Dindar: Investigation, Visualization, Writing

Hakan Aydin: Formal analyses, editing

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