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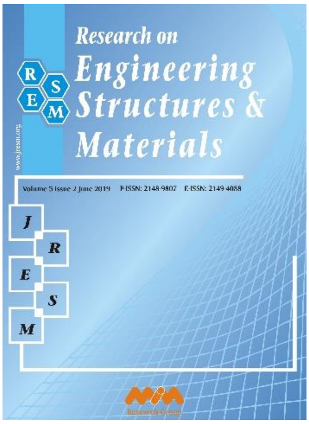

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Technical Note

Applicability investigation of alumina-titania based plasma spray coating on cast iron brake discs for battery electric vehicles

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Abstract

Automobile brake disc are subjected to cyclic thermal, mechanical and corrosive effects. In general, gray cast iron grades are preferred as disc brake materials. Lamellar cast iron disc brakes have a limited lifetime and are replaced periodically during the maintenance-service process. With the growing interest in the number of Battery Electric Vehicles (BEV), there is a need for disc brake with longer service life on discs. Therefore, in the automotive sector, in line with increasing competition and user demands, there is an interest in new coating types and materials with corrosion free properties, a longer service life and high brake performance. Wear and corrosion resistant plasma spray coatings are the key to increasing the service life and braking performance of cast iron discs. In this study, the discs (GG20) are coated with Alumina- Titania based ceramic material by atmospheric plasma spray method. The ceramic coated disc brakes were installed on the road driving test vehicle and disc brake thickness reduction were measured periodically according to wear test plan throughout 20.000 km. The test results show that the ceramic coating provides 18 times more wear resistance compared to uncoated disc brake. In addition, coated disc brakes exhibited superior performance in corrosion tests. As a result of the investigations carried out on disc brakes, it is understood that plasma spray ceramic coatings can be used alternatively in brake disc systems.

1. Introduction

The basic principle of the automobile braking system is to convert the kinetic energy of the vehicle into thermal energy as output of brakeage. To stop the vehicle, friction is created between two mechanical components (brake disc-pad), giving rise to heat generated between those two components and reduction in kinetic energy of vehicle which decreases vehicle velocity [1-3]. Due to the increase temperature in the interface of disc brakes and pads, high melting point materials are preferred. The brake discs must resist the atmospheric conditions and have the appropriate thermal properties. Cast iron materials have both technical and economic use potentials for brake discs. Grey cast iron (GG15-25) disc brake (rotor) and pad (friction materials) couples are one of the critical safety components in motor vehicles. High friction forces are formed from the moment the disc brake comes into contact with the brake pads. In variable road conditions, friction forces turn into heat in a short time. Therefore, the disc brake is exposed to both

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high mechanical stresses and thermal loads. Wet corrosion is also generated depending on the atmospheric road conditions on the discs. Factors such as rain, snow, salt and other road sprays can cause in corrosion on disc surfaces. That means, exposed parts, such as disc brakes can quickly become rusty, which is not satisfied for aesthetical expectations. In severe driving conditions, braking may cause the temperature on the disc brake-pad interface to rise up to 800 °C. At such a temperature, polymeric compounds of pad are disrupted, coefficient of friction (CoF) decreases between pad and disc brake, and the rate of counter wear increases exponentially [4,5,6]. In the new generation of brake system designs (regenerative brake systems), the interest in coated disc brake has increased to improve the disc brake service life and braking performance. Thermal spray coating methods are an effective surface engineering solution to improve the performance of disc brakes [7-11]. Coated with high velocity oxy fuel (HVOF) spray method, cermet (metal-carbide) based disc brakes are high-cost applications in luxury vehicles. Alumina - Titania based ceramics can be used for coating machinery components where very dense and smooth deposits with high wear resistance are required under corrosive media [9-10]. In this study, it is aimed to investigate the applicability of plasma spray coatings on automobile discs in detail. In this direction Alumina-Titania based coatings were deposited on the gray cast iron discs by plasma spray process, and the brake performance and salt spray corrosion performance were evaluated.

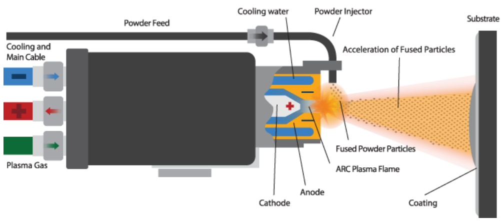
2. Experimental Procedures: Materials and Methods

Grey cast iron (GG20/ EN-GJL-200) brake discs have been used in these experimental studies. Plasma spray coating method was preferred because of its superiority over other coating and heat treatment methods. Plasma spraying is a coating process in which powders of the coating materials are fed into the plasma jet at around 10000K. Any material with the capability of melting without experiencing decomposition is suitable for thermal spraying. Plasma spraying has been successfully applied in numerous fields, such as corrosion and oxidation resistance, high-temperature protection, wear and erosion resistant coatings. The high cost efficiency and good quality of the coatings obtained by using APS have led to a successful implementation in automotive industry. The coating operation generally has three stages. These are surface preparation before coating, coating process and post-coating processes. Surface preparation is the most critical step in a plasma spraying operations. Coating adhesion quality is directly related to the cleanliness and roughness of the substrate surface, especially when spraying onto preheated metal surface. The brake discs were sandblasted and cleaned from any oxide and grease with acetone. Grit blasting was carried out with a highly efficient sand blaster with alumina grit size of 10-20 mesh, a sand blaster with a 10 mm nozzle, operating at a blasting pressure of >0.5 MPa. The distance between the substrate and nozzle was 120 mm at a 90° angle. The grit blasting is used prior to depositing in order to improve coating adhesion to substrate. The mechanical adhesion of the plasma spray coating depends mainly on substrate surface morphology and cohesion between the deposited particles. When the heated particles are accelerated towards the substrate, they flatten upon impact in a disc shape splats, followed by rapid cooling and mechanical anchorage to the irregularities of the surface.

In this study, two layered coating was produced onto brake disc using atmospheric plasma spray (APS) system with F4MB spray gun equipment (Fig 1.). Firstly, NiCr (Ni+wt.%20Cr) based bond layer (BC) was coated on grit blasted disc surface through atmospheric plasma spray (APS) process and then Al_2O_3-TiO_2 (Al_2O_3-wt%10-13 TiO_2) based ceramic top layer (TC) was deposited by APS (Fig 1b). Spray deposition parameters are presented in Table 1. Microstructural characterization was carried out with scanning electron microscopy (SEM-EDX). Vickers microhardness ($HV_{0,3}$) tests were performed on polished surfaces of the ceramic coatings with a 300gr normal load and a dwell time of 15 s. The surface roughness was measured with the profilometer.

In order to determine the resistance of the coated disc brake to atmospheric corrosion conditions, salt spray test was performed and then the disc brake surface was visually examined. Corrosion test was carried out in accordance with ASTM B117 (ISO-9227) standard. Brake disc friction performance tests were carried out with dynamometer test in accordance with the OEM specifications in different temperature and braking regimes. The total thickness change and disc thickness variation (DTV) was monitored over 20,000 km.

Table 1. Plasma spraying process and spray parameters



Schematic plasma spray gun

Process	APS	
Spray Gun	F4-MB	
Layer	BC	TC
Current, Ampere	550	550-600
Plasma Gases	Ar /H2	
Gas flow rates nlpm	40/8	40-50/ 6-12
Spray Dist. mm	100	90-125
Feed Rate gr/min.	30	25-40

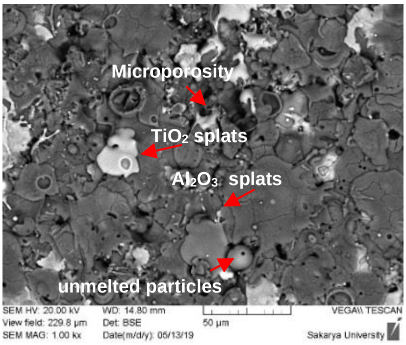
The plasma sprayed ceramic based surface of the brake disc (brake disc thickness: 26 mm) is presented in the Fig.1. After coating deposition, the coated surface is machined, and the surface roughness (Ra) is measured 0.8 µm.

a) Before coating b) After coating

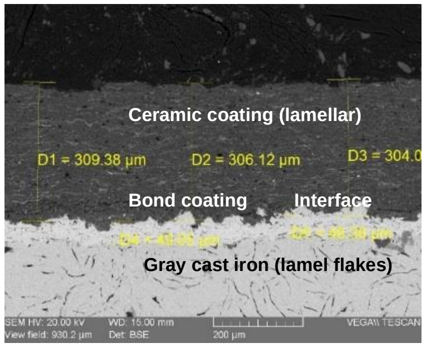
Fig. 1 Brake discs photographs before and after plasma spraying

3. Experimental Results and Discussions

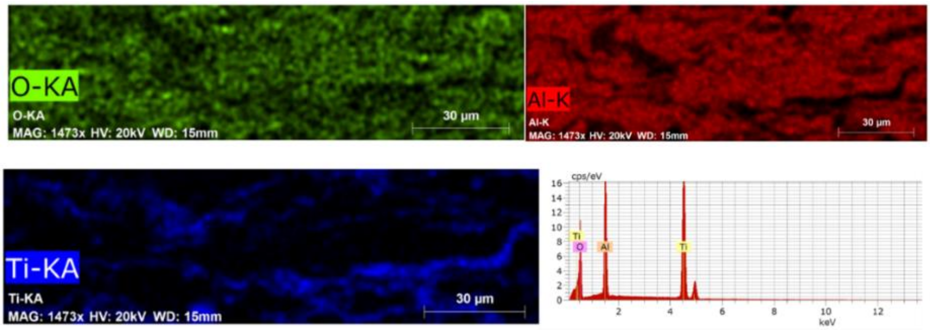
During the plasma spray coating formation, splat layers of impacted and accelerated particles are formed on top of the previously molten particles which spread and flatten on the disc surface. The process continues with an increasing number of spray passes. Spray pass number determine the coating layer thickness. The quality of plasma-sprayed coating depends on the substrate/coating interface adhesion strength and the cohesion of buildup layers. By optimizing the spray parameters, mechanical properties and microstructure can be controlled. Technically, optimum spray distance is important to ensure good adherence of coating. Too short spraying distance will produce lower adherence due to overheating and resulting internal stress inside the coating. In contrast, too long spraying distance will decrease the adherence bonding due to cooling and deceleration of the particles flying in the plasma jet. In ensuring homogenous and less porosity ceramic coating layers, the plasma current also should be increased to ensure the powders is melted properly when the powder flow rate was increased. Spray parameters are optimized by experimental design (plasma current 580A, Ar/ H2:44/8 gas flow rates, 115mm spray distance, feedstock rate 32 gr/min.). Microstructure of the plasma spray coating cross section investigations were carried out after standard metallographic sample preparations. After precise sectioning without damaging the coating structure, cold mounting, grinding (200-400-800-1000 mesh for 4 min., water coolant) and polishing (9-6-3µm diamond paste for 2 min.) steps were completed respectively. When the microstructure of the top surface (Fig 2a) is examined by scanning electron microscope (SEM), two different colored structures are seen. In the EDX analysis (Fig. 2c), it was found that the light-colored structure (TiO_2 rich phase) included Ti, O elements, dark structure (Al_2O_3 rich phase) has Al, and O elements. It can be seen that the splats on the surface of the coating is well formed. The morphology of the splat is very important in the coating layer. Homogeneous and well-spreaded splat formation reduces porosity and increases adhesion strength. As can be seen from the Figure 2a, the desired coating properties could be achieved with optimized parameters. SEM micrographs of the cross section of coatings showed a lamellar layered structure. Typically, unmelted or semi-melted particles, small sized micro cracks and low porosity is observed in the coating structure. It can be clearly seen that the lamellars adhere very well (Fig 2b). Coating thicknesses were measured in cross - sectional examinations. NiCr based bond coat layer in thickness range 30-50 µm, Alumina- Titania based top coat layer in thickness 340±25 µm (in Fig 2b). As can be seen, the desired coating thickness can be achieved. In general, the coating layer thickness is not desired to be too high. Increased coating thickness increases internal stresses and may cause the delamination. The structural properties and discontinuities of the coating control the mechanical properties of the coating. Microhardness and adhesion strentgh are the most important mechanical properties of the coatings. The average micro hardness of the top coating is 900±15 $HV_{0.3}$, 255±20 $HV_{0,3}$ for bond coating and the gray cast iron is 240±15 $HV_{0,3}$. Improper coating process parameters may result in fluctuations in hardness values. This has a negative effect on the wear performance of the coated disc. The hardness of the coating is directly related to the wear resistance. Increased hardness reduces wear loss. The ceramic coating obtained by plasma spray process contributed to increase the surface resistance and wear resistance of cast iron disc.



a)top surface



b)cross section



c) EDX mapping analysis of the coating

Fig. 2 SEM images and EDX analysis of coating

The wear performance of the brake disc was monitored by 20.000 km intervals on the vehicle and the thickness changes were measured periodically (Fig. 3). The coated disc surface becomes metallic appearance after friction losses over time. Numerous brakes of varying intensity have been applied over 20.000 km. Even after 20.000 km, the coating is still on the disc surface. When disc surface was examined, no delamination or cracking was observed on the coating. It is understood that the coating provides sufficient adhesion strength and heat resistance. Under the test conditions the coating has heat resistant and corrosive. There is no distortion and deformation on the disk.

During the test, disc thickness measurements were taken each of 5000 km and the driver's reports on the brake performance were evaluated. It should be noted that the braking efficiency and disc brake-pad compatibility is very critical. In this respect, DTV (Disc Thickness Variation) measurements should be evaluated. When the thickness variation of the disc brake exceeds 20 µm, the pads oscillate back and forth causing a pulsation in the hydraulic circuit back to the brake pedal. This brake pad osculation also causes a variation in brake torque as the brake pads grab and release over the higher portion of the disc brake thickness. It is typically noticed in the steering wheel as the brake torque from the left and right axles is different and out of sequence.

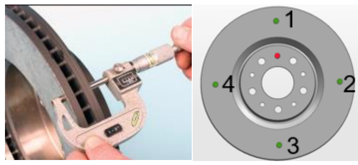
a) 0 km

b) 5.000 km

c)10.000 km

d) 15.000 km

e) 20.000 km



f) Thickness measurement method

Fig. 3. On vehicle test: plasma spray coated disc images and measurement method

The wear test results and thickness loss of the coated and uncoated disc brakes were compared to the thickness change on different four points of brake disc surfaces. Brake disc runout and DTV (Disk Thickness Variation) are important measurements in understanding braking performance and disc wear life. Disc runout and DTV can give valuable insights into how brakes are performing and can be used to diagnose faults and even design issues. Brake disc thickness variation (DTV) causes uneven wear on brake discs, brake disc -shaped automotive parts that are squeezed between brake pads to slow or stop a vehicle's wheels. When a disc brake has areas of different thickness, the amount of clamping force that's applied across the disc brake's surface varies. These differences in clamping force lead to differentiation in torque which may cause brake juddering, pulsating or vibration. DTV test is one of the most important performance criteria for brake discs. Table 2. shows the total thickness change of the disc in the service life test. Measurements made from 4 different points do not show a significant change in brake disc (left or right side) thickness. When ceramic coated disc compared with uncoated cast iron disc, it has approximately 18 times longer service life in terms of minimum thickness criteria.

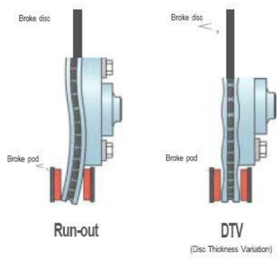
Table 2. Coated brake disc thickness change measurements in service life test

Vehicle mileage (km)	Right brake disc thickness (mm)				Left brake disc thickness (mm)			
	Point 1	Point 2	Point 3	Point 4	Point 1	Point 2	Point 3	Point 4
0	26,45	26,46	26,46	26,45	26,5	26,5	26,5	26,49
300	26,44	26,45	26,45	26,45	26,5	26,5	26,5	26,49
500	26,45	26,46	26,45	26,45	26,5	26,5	26,5	26,48
1600	26,45	26,46	26,46	26,45	26,5	26,5	26,5	26,49
5000	26,45	26,44	26,45	26,45	26,5	26,51	26,5	26,49
7500	26,44	26,45	26,45	26,44	26,49	26,51	26,5	26,49
10000	26,44	26,45	26,44	26,44	26,49	26,49	26,49	26,49
15000	26,425	26,43	26,44	26,43	26,48	26,49	26,49	26,48
20000	26,425	26,43	26,43	26,425	26,48	26,48	26,48	26,475
Total thickness change	-0,015	-0,03	-0,03	-0,025	-0,02	-0,020	-0,020	-0,015

Table 3. presents DTV and runout generation test results. The measurements were done by signified three circles. Also, it is observed that, runout values improved according to starting condition on braking surface.

Table 3. DTV and runout comparison in ceramic coated and uncoated discs

Ceramic coated disc		DTV (μm)			Runout (μm)
Right	0 km	17	21	29	55,5
	20000 km	8	10	19	35
Left	0 km	16	20	21	20
	20000 km	8	8	9	20,5
Uncoated disc		**DTV (μm)**			**Runout (μm)**
Right	0 km	1,6	3,5	2,93	8,80
	20000 km	21	31	25,7	32
Left	0 km	2,9	2	2,8	11
	20000 km	24,3	27	41,5	37,7



Another important control parameter regarded with customer cycle is vibration occurrence in the on-road test. The vibration occurrence was not observed during on-road tests both with coated and uncoated disc brake. During execution of test, original friction material (pad) has been used. The pad surface was deformed, and binding elements were burnt because of the undissipated heat between pads and disc brake (Fig 4). Besides, occurrence of amorphous (glassy) structure was observed on the interface of disc brake and pad because of coming out high and undissipated heat. In this case, the requirement for the development of specific friction material for coated disc brake has emerged.

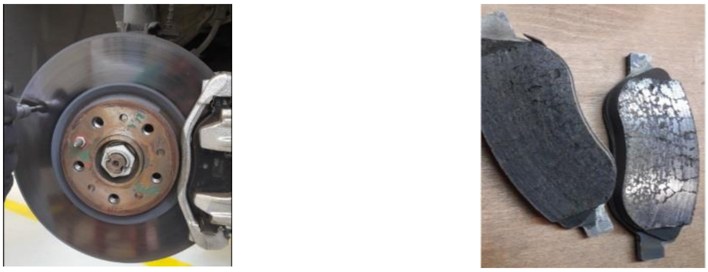


Fig. 4 Disc and pad surface photographs after vehicle road test

Salt spray test. The salt spray (or called as salt fog) test is a standardized and popular corrosion test method, used to check corrosion resistance of materials and surface coatings. The appearance of corrosion products (red rust or other oxides) is evaluated after a pre-determined period. In order to determine corrosion resistance, the disc brakes were tested in a salt spray (in %5 NaCl solution) cupboard and checked red rust occurrence periodically. Coated disc brakes exhibited superior performance in salt spray corrosion tests (Fig 5). No red corrosion was observed on the coating surface after 720 hours. Uncoated discs can withstand up to 48 hours under corrosive media and red rust (heavy corrosion products) are observed.

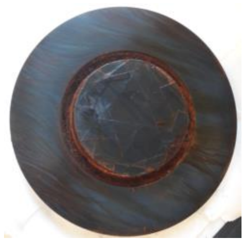


Fig. 5 Coated disc brake surface after salt spray corrosion test

4. General Conclusions

In experimental studies, Alumina–Titania (Al_2O_3-wt%10-13TiO_2) coatings can be deposited successfully on cast iron disc brake surface with an intermediate bond coat of Ni20Cr by optimized atmospheric plasma spray parameters. The plasma spray gun parameters such as powder flow rate, plasma gases flow rate, plasma current, and stand-off-distance has directly influenced the mechanical properties and structure of the coating. After many experimental trials for coating optimization, coatings with suitable properties and thickness were obtained. The plasma spray coating structure can be controlled with effective process parameters. The reproducibility of the coatings is very high and for mass production potential is very convenient. The validation testing process required for automobile disc applications has long and very strict requirements due to reliability. Alumina–Titania coated discs have tested on vehicles and passed all the brake pre-performance tests successfully. Dynamometry tests, even at high temperatures, the coefficient of friction is within a reliable range. The dynamometer tests showed good stability in CoF of the coated disc (0.39) compared with the uncoated disc (0.42). Results of on-road service life test on coated discs show superior performance compared to uncoated ones. Coated discs exhibited high performance (above 720 hr.) in salt spray corrosion tests. Salt spray test results showed negligible weight loss in case of plasma coating systems. Also, ceramic coated disc brakes were exhibited preferable performance in terms of DTV and runout occurrence in road test. Plasma spray process (APS) offers high coating quality and wear performance for brake discs. Coated disc displayed a significantly reduced weight loss than the uncoated disc with the pad wear remaining largely unchanged, as shown in Figure 6. It is understood that plasma spray ceramic coatings can be used effectively in automotive disc brake systems.

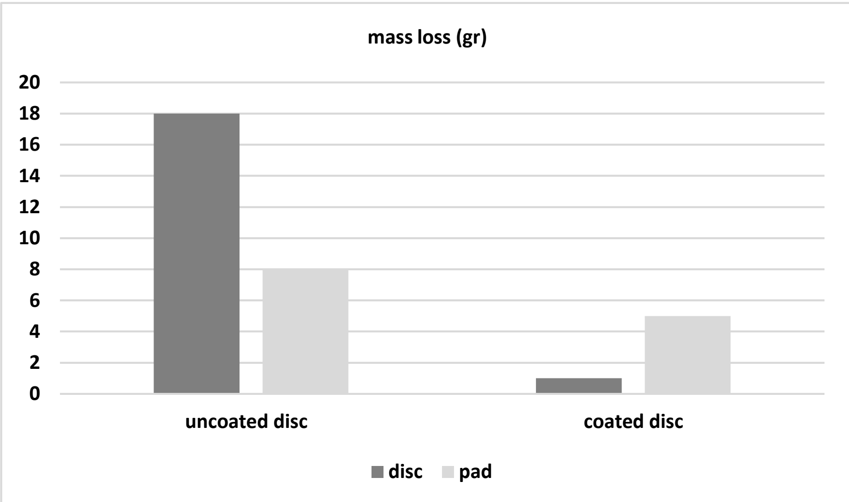


Fig. 6 Comparative mass loss of APS Al2O3-TiO2 coated and uncoated brake discs and corresponding pad mass loss

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