Development of protective thermal spray coatings for lightweight Al brake rotor discs

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Publisher's version / Version de l'éditeur:

[Proceedings of the Conference], 2018-05

Development of Protective Thermal Spray Coatings for Lightweight Al Brake Rotor Discs

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Abstract

This paper reports on the performance evaluation of stainless steel (SS) thermal spray coatings aimed at shielding lightweight aluminum (Al) brake rotor disks from excessive heat and providing an adequate tribological surface in contact with brake pads. Coating wear, corrosion and heat resistance performances were evaluated using pin-on-disk, cyclic corrosion tests and thermal cycling using a custom laser rig, respectively. Arc spray optimized coatings displayed lower or equivalent wear rates when compared with the baseline gray cast iron disks, with similar frictional behavior. However, arc spray coating exhibited low adhesion which limits the maximum coating thicknesses achievable and leads to early coating spalling after about 1000 thermal cycles. Arc sprayed coatings also corroded and delaminated under corrosion tests. Optimized cold spray coatings present high corrosion resistance and could resist above 10,000 thermal cycles without spalling. However, cold spray coatings exhibit wear rates at least 4 times those of the cast iron. Taking advantage of both types of coatings, it was found that the production of a duplex coating made of a cold spray bond coat and an arc spray top coat could meet the requirements for protecting Al disks, with near 50% weight reduction.

Introduction

In the last years, the automotive industry has been facing increasing pressure to decrease the weight of its vehicles, as this is one of the primary means to reduce fuel consumption as well as the associated emissions [1]. As a consequence, there has been a trend toward the use of dissimilar material assemblies to benefit from the low density of light metals while maintaining some of the desirable mechanical properties of steels others [2]. In the automotive mass manufacturing, thermal spray is a technology of choice to protect light metals parts as it is generally low cost, can easily be incorporated into integrated manufacturing facilities and can be applied at atmospheric pressure and temperature, with little effect on the receiving component [3].

For instance, thermally sprayed Fe-based coating on the surface of engine cylinder bores are currently used to provide the required wear and heat resistance while a significant weight reduction is obtained from the Al core engine block [3,4,5]. Similarly, it is envisioned that Al could replace steel or cast iron in brake rotors provide a coating is added to shield the Al part from excessive heat and to offer an adequate tribological surface in contact with the brake pads.

In addition to heat and wear resistance, coating must present several other features to be considered for such application. First of all, an adequate and reliable substrate-coating bonding is required to withstand the mechanical and thermal stresses involved during braking. Coating adhesion is typically controlled by an adequate surface preparation. Besides conventional grit blast, a number of surface preparation methods have been investigated for automotive applications, such as surface roughening by water jet or by EDM and addition of fluxes for surface oxide removal [3]. Bond coat and laser treatments for cleaning or roughening were also attempted by Bobzyn et al.[4] Overall, adhesion improvements from 15-30 MPa to 50 MPa were achieved.

To withstand the temperature variations during braking, coating must also present high resistance to thermal cycling. In addition to coating adhesion, coating resistance to thermal cycling will be affected by thermal expansion mismatch between coating and substrate as well as coating toughness [6].

At last, the coating to be used to shield an Al brake rotor needs to present corrosion resistance. It must not debond once exposed to atmospheric conditions or rust in an excessive way.

This paper presents the coating development work, including characterization and performance assessment, toward the achievement of a light weight brake rotor disc for applications in cars and light trucks. Arc sprayed, cold sprayed and hybrid steel-based coatings were produced and characterized in terms of adhesion, microstructure and hardness. Their performances under wear, thermal cycling and in corrosive environment were assessed at the lab scale. Finally, a disk brake prototype was produced.

Experimental Procedures

Materials

Coatings were deposited on Al 356 substrates machined out from ingots by wire EDM. Pucks of 1” diameter and 5/8” in length were used for general characterization, pull tests and thermal cycling while discs of 3.4” diameter were dedicated to wear and environmental chamber testing. Stainless steel-based coating feedstocks were selected for low cost, corrosion resistance and compatibility with current braking pads. The feedstock wire and powder used to produce the coatings were

procured from Praxair, Danbury, USA) and are listed in Table 1 and powder morphology and size are presented in Fig. 1.

Table 1: Feedstock

Feedstock	Commercial Name	Composition
Wire	80T	SS304-type; 18Cr, 8Ni, 1.5Mn, 0.5Si, 0.12C, Fe bal.
Powder	FE-101	SS316-type; 17Cr, 12Ni, 2.5Mo, Fe bal.

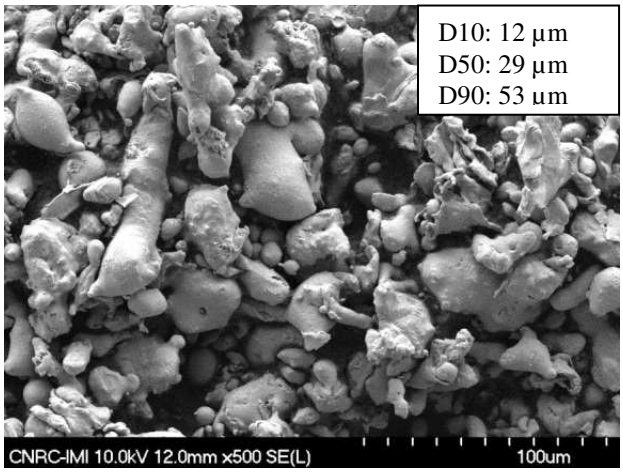


Figure 1: Fe-101 powder morphology and size

Thermal Spray

Arc spraying was performed using Oerlikon-Metco (Pfaffikon, Switzerland) SmartArc (SA) or Miller (M) equipment (Appleton, USA) while cold spray was performed using Kinetiks 4000 system from CGT GmbH (Ampfing, Germany). Substrates were grit blasted with alumina (Al_2O_3) grit 24 prior to arc sprayed trials, while degreasing only was used for cold sprayed coatings. Arc spray current, atomizing gas pressure and spraying distance were adjusted to maximize coating adhesion. Cold spray conditions were adjusted to maximize particle velocity while preventing gun clogging. Table 2 presents the spraying conditions used for this study.

Characterization

Cross-sectioned coatings were cold vacuum mounted in an epoxy resin and ground then polished using standard metallographic preparation procedures. The field-emission scanning electron microscope S-4700 from Hitachi (Tokyo, Japan) was used in backscattered electron imaging (BSEI) mode for coating cross-section imaging and in secondary imaging (SEI) modes for powder morphology. BSEI mode (10 images at a magnification of 500X) and image analysis software (Visilog, St-Aubin, France) were utilized on as-polished samples to measure through thickness coating cross-section porosity and, when applicable, oxide content.

Table 2: Spraying Conditions

Coating ID	Equipment	Feedstock	Current or Gas Temperature	Gas pressure	SOD (cm)
SA	SA	80T	100A	60 psi	15
M	M	80T	100A	60 psi	10
CS	CGT	FE-101	700°C	40 bars	8

Vickers microhardness measurements were performed on coating polished cross-sections with a Buehler Micromet II Tester (Lake Bluff, USA). Tests were achieved under 300 gf loads for 15 seconds penetration time, averaging at least 10 indentations per specimen. Coating adhesion strength tests were performed according to ASTM C-633-01 standard.

Wear Tests

A Falex Multispecimen wear test rig (Sugar Grove, USA) was used to evaluate the wear performance of the developed coatings with a pin-on-disk contact configuration. Test pins were cut from a brake pad. The apparent contact area dimensions of the pins were 5 mm x 5 mm with a length of about 13 mm. Cuting of the test pins was such that the wear surface was parallel with the original brake pad surface. Test disks had a diameter of 86.36 mm and thickness of 10.16 mm (dia 3.4” x 0.4”).

The following testing protocol was used: speed, load (apparent contact pressure), total sliding distance and wear track diameter were 1 m/s, 4 MPa, 48,000 m and 63.5 mm (2.5”), respectively.

Wear rate of the test disks was expressed in volume loss per sliding distance, mm3/m, and was obtained through weight loss measurement and estimated material density. During the sliding test, coefficient of friction (COF) was measured and recorded using Labview.

Environmental Tests

During their service life, automobile brake disks are submitted to a variety of environmental conditions modulated by temperature, humidity, and the presence of aggressive chemical species typically found in deicing salts. In order to simulate the effect of the most corrosive conditions encountered by brake disks, a laboratory cyclic corrosion test inspired by standard ISO 14993 was used to perform a comparative corrosion resistance evaluation of coated Al disks. One (1) cycle of the cyclic corrosion procedure employed is defined as follow:

Step 1. Salt-spray with 5% NaCl at 34±3°C (100%RH) (for 3 hours)

Step 2. Drying at 59±6°C and 27±7%RH (for 5 hours)

Step 3. Wetting at 48±7°C and > 95%RH (for 4 hours)

The samples were inspected after each cycles and the test stopped at coating failure of 120 cycles.

Thermal Cycling

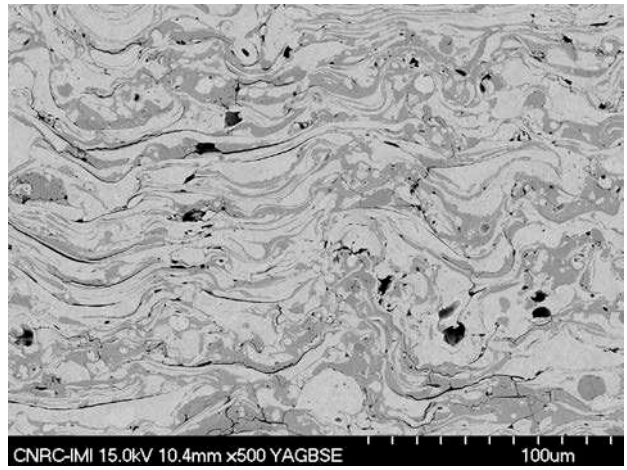
The coating behavior upon thermal cycling was assessed using a custom laser rig [6]. Coated samples were successively heated by a 2 kW CW YAG laser and cooled down by a compressed air flow through the motion of a sample holder. A pyrometer and an infrared camera recorded the temperature of the sample being heated. A heating time of 4 seconds and a laser power of 1300W were selected to attain a heating rate of about 50-55°C/s. Once steady state was reached, cycles with maximum and minimum sample temperatures of 470°C and 250°C respectively were obtained.

Once partial delamination of the coating occurs, the gap of low thermal conductivity between the coating and the substrate generates hot spots on the coating in the heating zone upon cycling. 25% hot spot was chosen as the spalling criteria and the number of thermal cycles needed to reach this level recorded for each sample.

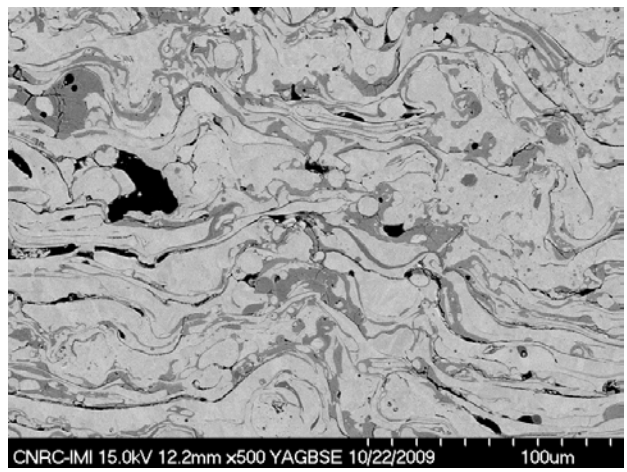
Results and Discussion

Coating Characterization

Figure 2 presents arc spray and cold spray coating microstructures and Table 2 presents the adhesion, microhardness, porosity and oxide levels obtained for the three types of coatings tested. As expected, arc spray coatings present high levels of oxide, at about 20% and significant porosity, between 2 and 3%. Adhesion for a coating thickness of about 500 um was about 30MPa, which is typical for arc sprayed coatings, where adhesion is provided through mechanical interlocking [3]. On the opposite, cold spray coating microstructure shows near 100%density without oxidation. Adhesion exceeded the test glue adhesion value of 76 MPa, which is consistent with the values obtained elsewhere for similar spraying conditions [7]. This is partly attributed to the ability of the steel particles to penetrate in the relatively soft Al substrate [7]. Indeed, the substrate surface, originally flat (no grit blasting), now present embedded steel particles as shown in Figure 2c. Other mechanisms, such as adiabatic shear instability, may also have contributed to the bonding [8]. Coating hardnesses are relatively similar, at about 300HV, which are twice the values typically reported for the bulk counterpart. The higher hardness values of arc spray coatings are attributed to the presence of hard oxide phase or solute atoms [9]. In the case of the cold spray coating, cold working is most probably at the origin of the high coating hardness [8].



(a)



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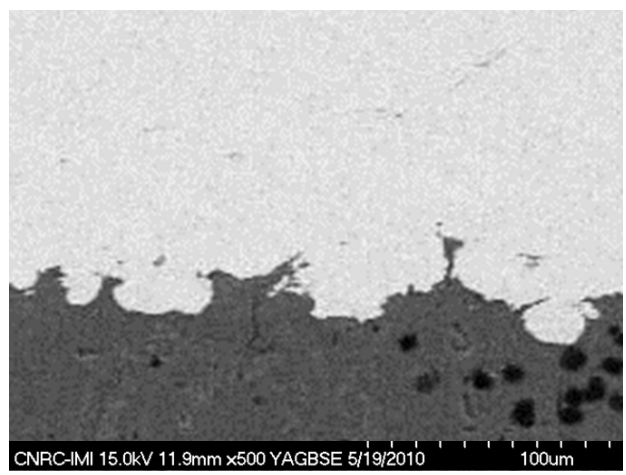


(c)

Figure 2: Coating microstructures (a) SA coating (b) M coating (c) Interface CS coating / Al 356

Table 2: Selected Coatings - Properties

Coating	Adhesion (t~500µm, MPa)	Hv 300gf	Porosity (%)	Oxide (%)
SA	32	317	2.1	23
M	24	273	2.9	20
CS	>76*	335	0.2	n/a

* measurements were limited by the strength of the adhesive used for pull tests

Performance Testing and Duplex Coating

Table 3 presents the wear rate of different coatings compared with this study benchmarks, grey cast iron as well as bulk SS304. Arc sprayed samples present wear rates near those of grey cast iron and much lower than bulk SS304, with COF equivalent to grey cast iron. The good wear resistance of arc spray coatings is related to the composite microstructure composed of metal matrix and oxide layers on splats. This structure prevents the formation of large wear debris particles and is conducive to the development of wear-protective compact particle layers.

The wear rate of cold spray coating, altough better than bulk SS304, was significantly higher than that of the arc sprayed samples. Wear improvement over bulk material is attributed to the higher hardness of the cold spray coating.

Table 3: Coating wear rate and coefficient of friction

Samples	Wear rate (10^{-5} mm^3/m)	COF
Gray cast iron	1.294±0.166	0.36
Bulk SS304	45.303±25.483	0.72
SA	1.524±0.672	0.36
M	0.73±0.27	0.35
CS	4.774±1.664	0.38
Duplex SA	0.751±0.067	0.42

Figure 4 presents the adhesion and number of thermal cycles prior to spalling for several coatings. Arc sprayed coatings displayed the lowest resistance to spalling under thermal cycling, probably due to their lower initial adhesion. Cold sprayed coating present the highest resistance to thermal cycling, with 10,000 cycles withstood without spalling.

Following those results, it was desired to produce a coating that would display the adhesion and thermal cycling resistance of cold spray coatings while presenting the wear performance of arc sprayed coatings. As a consequence, the concept of a hybrid, or duplex, coating with a cold spray bond coat and an arc spray top coat (either SA or M) was introduced. Microstructure of duplex SA coating is shown in Fig. 4.

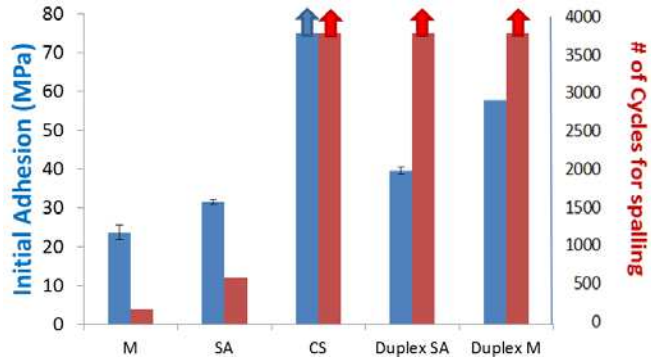


Figure 3: Coating initial adhesion and number of thermal cycles prior to spalling

Wear tests performed on the duplex SA coating (Table 3) confirmed that wear behavior equivalent to arc sprayed coatings were obtained – as it could be expected from this surface test only soliciting the top coat. Duplex adhesion was found to be lower than cold spray coatings at 40-60 MPa – as delamination between the arc sprayed layer and the cold spray layer occurred prior to cold spray delamination from the substrate. Still, resistance of the duplex coatings to thermal cycling was found to be very high, at 10,000 cycles without spalling (Fig. 3).

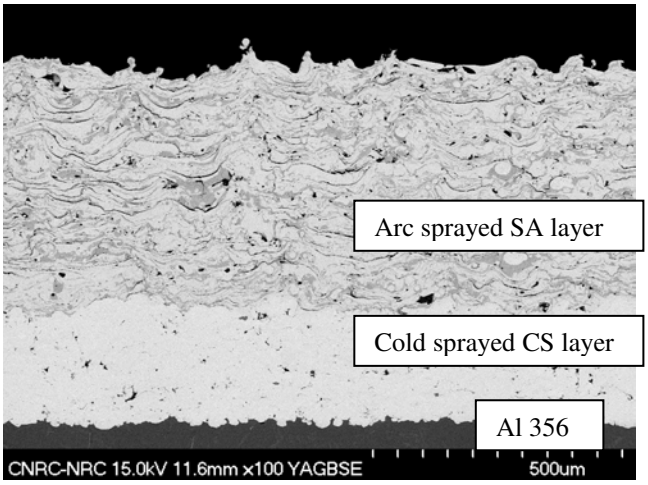
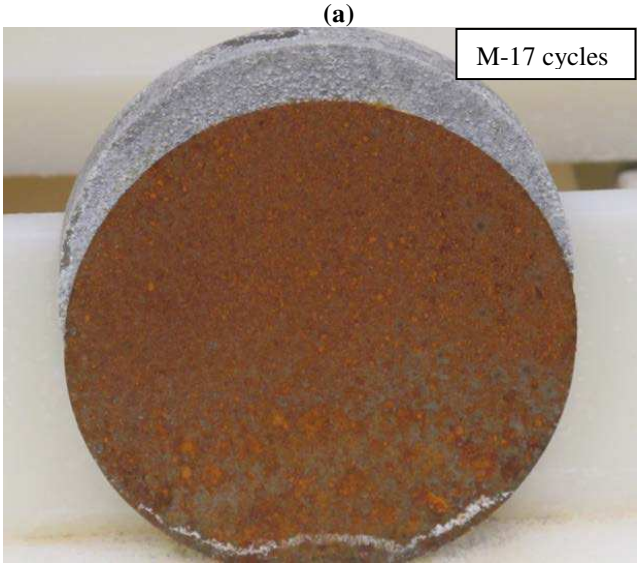


Figure 4: Duplex coating microstructure

The different types of coatings were finally submitted to corrosion evaluation. Figure 6 shows photographs of selected samples after accelerated cyclic corrosion tests. Figure 5 a-b shows that arc sprayed coatings suffered from general corrosion similar to carbon steels. The thin chromium oxide layer, usually responsible for the passive behaviour of SS, was not observed on the deposited coatings. Indeed, most of the chromium was already oxidized during the arc sprayed process. Saline moisture also penetrated through porous coatings and caused corrosion at the Al/steel interface (favored by galvanic coupling). Al corrosion products generated blisters. Coating debonding occurred after 17 (SA) and 24 (M) cycles only. Galvanic corrosion of Al was also observed close to the SS-Al interface, i.e. the "bulk" Al substrate was less affected than Al at the SS-Al interface. The coating was not affected by galvanic corrosion.

(a)



(b)

(c)

(d)

(e)

Figure 5: Samples after accelerated cyclic corrosion (a) SA (b) M (c) CS (d) duplex SA (e) duplex M

On the opposite, cold spray coating (Fig. 5(c)) was highly corrosion resistant. It went through the whole test duration of 120 cycles without debonding. The absence of oxidation and pores within coating appears highly beneficial as the chromium remains available for corrosion protection and no blistering was observed. However, Al disks were strongly corroded and pitting was observed at the Al-SS interfacial region, due to the galvanic coupling between SS and Al. Galvanic corrosion should be further investigated to see how critical it is for the targeted application and if mitigation measures can be taken, such as sealant, design of coating/Al part transition, etc.

Duplex coatings were also found to be resistant to corrosion with no coating debonding after the 120 test cycles (Figs. 5(d-e)). Few small blisters were observed, as well as limited general corrosion. This indicates that the cold spray bond coat is efficient in acting as a barrier for the saline humidity. Further coating investigations have shown area of surface substrate porosity that can create a discontinuity in the bond coat, as shown in Fig. 5(e). Although a direct link could not been confirmed, it is believe that the few blisters observed on the duplex coatings could origin from such discontinuity.

Prototyping

Figure 6: Picture of the prototype disk (coating is darker than the Al disk)

To understand the value of applying a thermal spray coating to lightweight a disc brake rotor, a comparator with current cast iron brake rotors was created. This was done by obtaining an Al 6061 plate and machining it to the same dimensions as a commercially-available cast iron rotor. In addition, a series of 1 mm deep grooves were machined into the brake pad surface of the Al rotor to improve the mechanical attachment of the coating with the surface. Duplex SA coating was applied onto the brake pad surface (Figure 6); the sprayed coating was then machined to a consistent, uniform thickness so that the overall thickness of the brake pad surface was consistent with that of the commercially-available cast iron rotor.

The two rotors were then compared on the basis of mass. Compared to the commercially-available disc, the overall weight was decreased from 4.28 to 1.77 kg; this yielded a reduction of nearly 60%. It must be mentioned that this weight reduction represents a maximum possible value. In practice, the weight reduction for a specific component would probably be lower since the design might need to be adjusted. This adjustment would need to take into account the difference in mechanical properties between cast iron and of the Al, such as the lower stiffness.

Conclusions

This paper summarizes the results obtained developing a thermal spray coated Al brake rotor disc for application in cars and light trucks. Arc and cold sprayed deposition methods were first investigated as coating processes. It was found that arc sprayed SS coatings exhibit promising wear behavior: they displayed superior or equivalent wear resistance as compared with the baseline gray cast iron disks with similar frictional behavior. This was attributed to the composite microstructure compassed of metal matrix and oxide layers on splats, formed during coating deposition. However, arc sprayed coatings over Al present relatively low adhesion that is essential both for the buildup of thick coatings and to sustain the stresses caused by thermo-mechanical cycling. Arc sprayed coatings are also sensitive to corrosion. The presence of porosity allows penetration of the saline moisture and generated corrosion products at the interface that causes blister and even debonding. Furthermore, chromium depletion of the metal matrix during spraying allows subsequent general corrosion (similarly to current brake disks).

Cold sprayed coatings present high bond strength and thermal cycling resistance. Thanks to their high density, adhesion and the absence of in-flight oxidation during deposition, they also exhibit very good resistance to corrosion (high resistance to general corrosion, blistering or debonding during salt spray tests). However, cold sprayed coatings exhibit poor wear resistance (in the best case, 4 times the wear rate of grey cast iron but 7 times better than bulk 304 SS).

Duplex coatings made of a cold sprayed bond coat and an arc sprayed top coat were investigated. The cold sprayed bond coat was found to significantly improve the coating adhesion (initial and upon thermal cycling) providing a good protection for corrosion (blistering and debonding). The arc sprayed top coat offers a wear resistance similar to the arc sprayed only coatings. Duplex coatings showed good potential for protecting Al brake rotor disks.

Acknowledgments

The authors would like to thank James Boileau and Tim Potter, from Ford Research and Innovation Center, for their contributions to the project. The authors would also like to acknowledge the technical assistance of F. Belval, B. Harvey,

J.Sykes, J.F. Alarie, D.de Lagrave, M. Thibodeau, K. Théberge and M. Lamontagne.

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