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Metal-NdFeB composite permanent magnets produced by cold spray

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Summary

Hybrid and electric vehicles play an increasing role to alleviate the effects of our transportation needs on the environment. Permanent magnets are a key component of electric motors and represent a significant proportion of their total cost. We report on the fabrication of metal-NdFeB composite permanent magnets made using cold spray processes. In order to control the magnetic properties, coatings' microstructure was varied using powders with various compositions, size distributions and morphologies. The obtained magnetic and mechanical properties results confirm the feasibility of using cold spray as an effective technology to deposit hard magnet coatings directly on the rotor surface.

Keywords: Rare earth material, permanent magnet motor, demonstration, materials, Canada

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1 Introduction

The development of sintered permanent magnets based on tetragonal NdFeB using powder metallurgy techniques dates back to the early 80s. Since then, NdFeB has been the best performing material for the fabrication of permanent magnets (PM).[1] The technical developments of the last decades have brought down the size and weight of high efficiency permanent magnet synchronous motors to a point where they became the most popular electric motor design for electrical and hybrid-electrical vehicles (EVs and HEVs).[2] According to the most recent technology, one electrical motor requires a few kilograms of high performance NdFeB material. Based on a recent U.S. department of Energy report, the cost of the magnets represent 53% of the total cost of an interior permanent magnet motor (IPM)[3] and the cost of rare-earth represent up to 80% of the cost of the magnet itself.[4] Indeed, in addition to the use of Nd, heavy rare-earth (HREE) such as Dy and Tb are used to increase the magnetic properties thermal stability at the electric motor operating temperature (~150°C). Typically, the addition of HREE increases the magnet coercivity at the expense of a decrease in remanence. For hybrid motors, the level of HREE can be as high as 10% leading to a major cost increase since these elements are much scarcer than Nd.[1] Since the cost of rare-earth and heavy rare-earth elements represents a significant portion of the price of electrical motors, important cost reduction can be achieved by optimizing motor design and material performance to reduce rare-earth elements use.

Traditionally, dense rare-earth permanent magnets have been fabricated using powder metallurgy technologies. The standard procedure involves the compaction of the powder materials in a die having the shape of the components to be produced.[5] The powder metallurgy route does not offer a lot of flexibility for the shape of the magnets thus limiting the motor design. From a manufacturing point of view, the magnets (more than a hundred per motor) are currently either inserted in a slotted machined rotor or assembled with epoxies. These approaches lead to long production time and are posing challenging geometrical problems in terms of magnets alignment and air gap minimization. In this paper, a new manufacturing approach based on cold spray technologies is proposed. It consists of depositing a magnetic coating directly onto the rotor therefore eliminating the assembly steps while adding shape flexibility via the highly automated spray techniques.

NdFeB materials have been sprayed by several authors using different techniques such as arc spray,[6] plasma spray [7-9] and flame spray.[10] One common problem faced by these authors is conserving the initial powder stoechiometry. Indeed, plasma and flame spray processes uses high gas temperatures causing powder oxidation resulting in a drastic decrease of the magnetic performance of the deposited coatings. One way around this issue is to use higher velocity and lower temperature techniques such as cold spray. Very little work was performed on the deposition of metal-matrix composite NdFeB by thermal spray.[11-12] There is a significant unexplored research area on the possibility of mixing a high performance magnetic phase such as NdFeB to a functional matrix used for corrosion and oxidation resistance and heat dissipation. This paper will discuss the effect of NdFeB powder morphology and cold spray parameters on the magnetic performance of Al/NdFeB composites. The ability to deposit thick Al/NdFeB coating for prototyping will also be discussed.

2 Experimental Procedures

2.1 Material and Processing

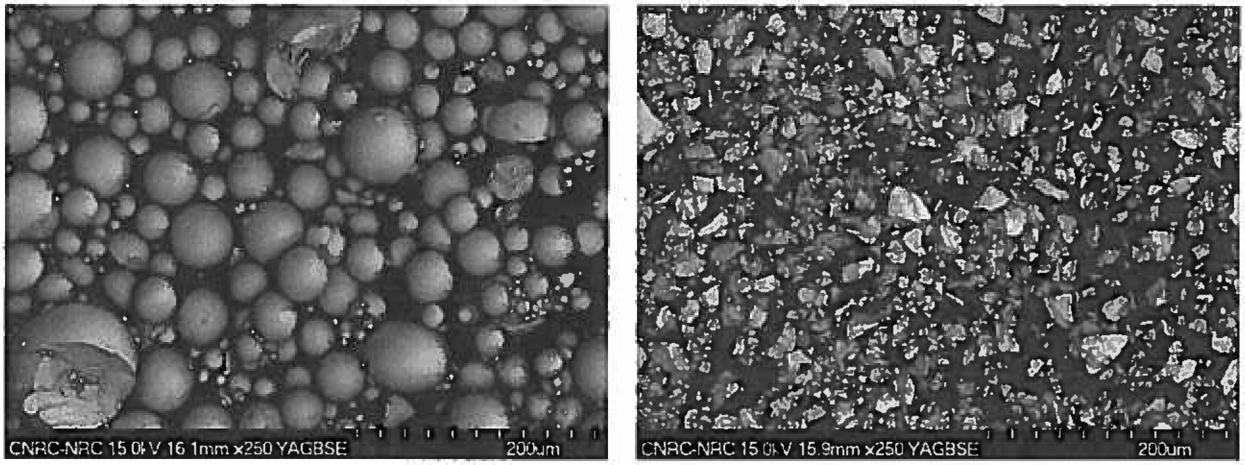
Al/NdFeB composite permanent magnets were deposited using the cold spray technology. Cold spray is a process where a coating is formed onto a substrate by the deformation and bonding of impacting high velocity particles. Particles are accelerated using a heated high pressure gas, such as nitrogen, fed through a convergent divergent nozzle typically using the de Laval configuration. Particle speed of several hundred meters per second can be obtained thus the resulting coatings are very dense (< 1% porosity) and exhibit adhesion values generally higher than what can be obtained using more conventional thermal spray technologies. It is important to mention that while the gas temperature is several hundred °C, the actual powder temperature is much cooler.

In this study, the process was carried out using a Plasma Giken 800 gun with a main gas temperature of 300 to 600°C and a maximal pressure of 5 MPa. The used temperature depended on the powder composition. The used a spray distance was 80 mm while the robot traverse speed and steps were dependent of the sprayed geometry: plates for mechanical and magnetic testing and cylinders for prototyping. Coatings were deposited on aluminium and grit-blasted mild steel substrates. Two different system configurations were used: single and dual powder feeder. In the first configuration, the binder and magnetic powder were pre-mixed prior to the spray process. In the latest configuration, one feeder was filled using the binder material while the magnetic powder was placed in the second hopper. During the spray process, great care was taken to minimize the temperature rise of the magnetic powder such as to limit oxidation and magnetic properties degradation. Substrate air cooling and wait periods between the gun passes are strategies that were employed.

Three different commercially available NdFeB base powders, all from Magnequench (Molycorp), selected for their low cost (low heavy rare earth content) and different size and shape were tested. Their compositions, size distributions, morphologies and magnetic performances are detailed in Table 1. Also is included the description of the aluminum powder (Valimet, H15). Figure 1 shows the micrographs of two of the studied powders. The MQP-S-11-9 powder contains mostly spherical particles with a larger size distribution than the smaller angular MQFP-B powder.

Table 1: Description of NdFeB and Al powder used in cold spray trials

Powder type	Composition	Size d_{50}, µm	Morphology	B_r, mT	H_{ci}, kA/m
MQP-S-11-9	Nd-Pr-Fe-Co-TiZr-B	49.8	Spherical	745	710
MQFP-B	Nd-Pr-Fe-B	10.2	Angular	880	752
MQFP-1412	Nd-Fe-Nb-B	10.7	Angular	817	961
H15	Aluminium	15	Spherical	-	-



(a) (b)

Figure 1: Size and morphology of the (a) MQP-S-11-9 and (b) MQFP-B base NdFeB powder.

2.2 Coating Characterization

Deposited coating microstructures were evaluated on polished metallographic samples using the Clemex Vision image analysis system. Figure 2 illustrates the threshold image analysis routine that was used to determine the volume fraction of the NdFeB. In the figure 2 images, NdFeB is visible in dark gray (red) and the Al matrix in light gray (green) in the conventional (threshold) images. Less than 1% porosity was observed in the coating (blue).

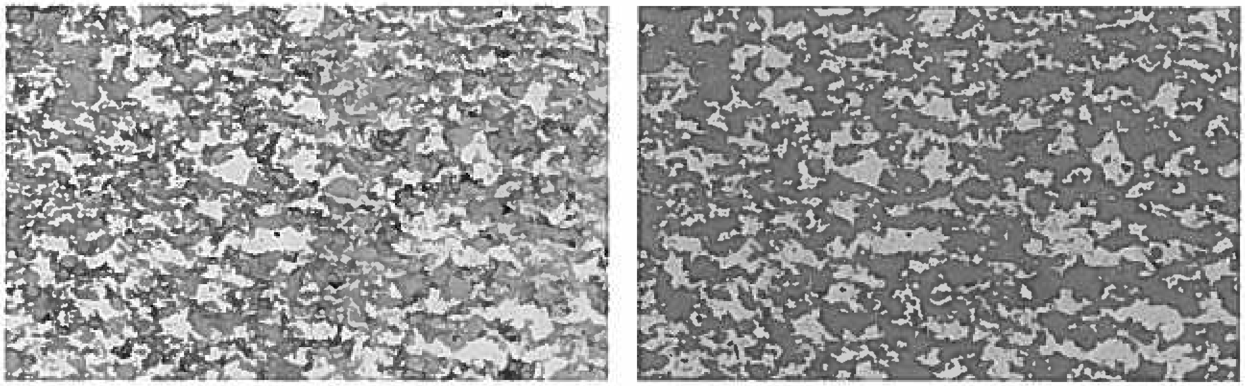


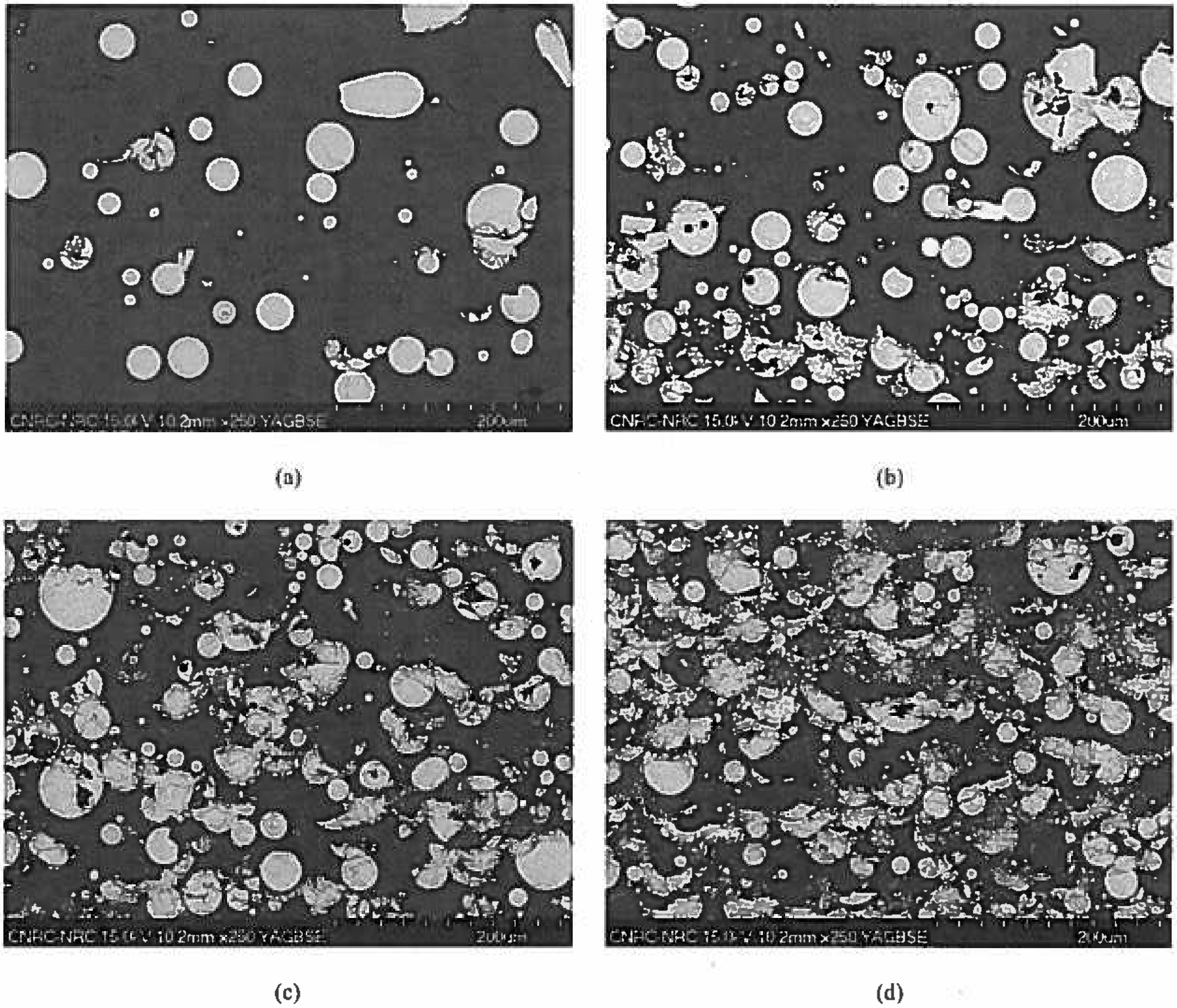
Figure 2: Metallography of Al-NdFeB coating (a) polished sample and (b) image analysis segmentation

Coating magnetic properties were evaluated using a Permagraph L, hysterisigraph on 25 mm diameter, 4 mm thick machined disks. While the hysteresis curves are generated for the first and second quadrant, only the second quadrant will be shown in the results section. Composite cohesion/adhesion was measured using a standardized pull test according to ASTM C633 procedure.

3 Results and Discussion

3.1 Coating Microstructure

In order to conveniently evaluate the maximum load fraction of magnetic material that can be obtained in a Al/NdFeB composite coating, a two-hopper feeding system was used. The first hopper contained NdFeB powder while the second was filled with the aluminum powder. This system allows varying continuously the magnetic load by simply changing the feed ratio between the binder containing and magnetic containing hoppers without the need to pre-mix large quantities of powder. The experiments were carried out with the aim of maintaining low coating porosity and a good deposition efficiency. The effect of the ratio of feeding rate (feeding rate of NdFeB/feeding rate of aluminum) on the magnetic content is shown in Figure 3 for the MQP-S-11-9 base powder. One can observe an increase of the magnetic content up to 60 vol.% for the maximum NdFeB/Al feed rate ratio. It is also possible to observe the damage to the brittle MQP-S-11-9 spherical particles when an NdFeB-NdFeB impact occurs. Figure 4 shows an example of the coating obtained with the angular MQFP-B powder. With both powders, very dense coatings containing more than 60 vol.% of magnetic particles were obtained. No cracks or delamination were observed.



(a) (b)

(c) (d)

Figure 3: SEM micrograph of a Al-NdFeB coating obtained using a feed rate ratio of (a) 0.1, (b) 0.7, (c) 1.0 and (d) 2.0

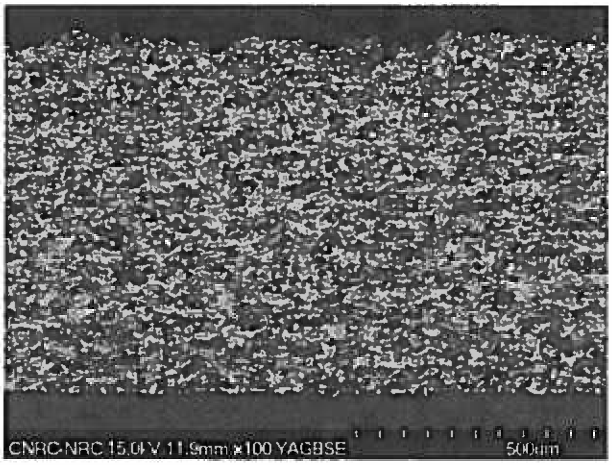


Figure 4: SEM micrograph of a Al-NdFeB coating using the MQFP-B base powder for a feed rate ratio of 2.0

3.2 Magnetic Properties

The impact of the spraying process on the magnetic performance of the coating was measured using pre-mixed Al/NdFeB powders. The remanence of the coating, B_{rcoat}, was compared to a theoretical remanence, B_{rtheo}, based on the measured fraction of the NdFeB phase, F_v, and the intrinsic remanence of the powder, $B_{rpowder}$, given by the supplier datasheet. Figure 5 and Table 2 summarize the results for the MQFP-B and MQFP-14-12 coatings made using the same spraying parameters. Comparing the measured performance of the coatings to the theoretical calculations, it was found that the coating remanence is 5% lower than the calculated value for both materials. It was also observed that the coercivity of the coating, H_{ci}, is 5% and 3% lower than the reference value for the MQFP-B and MQFP-14-12 respectively.

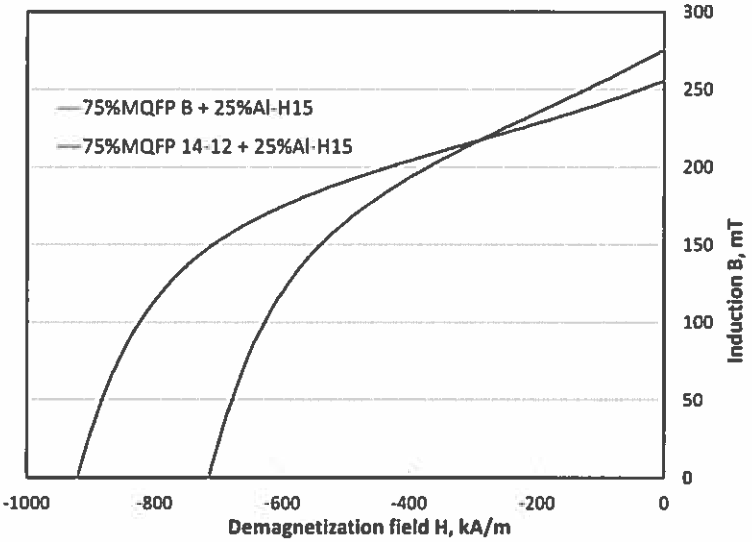
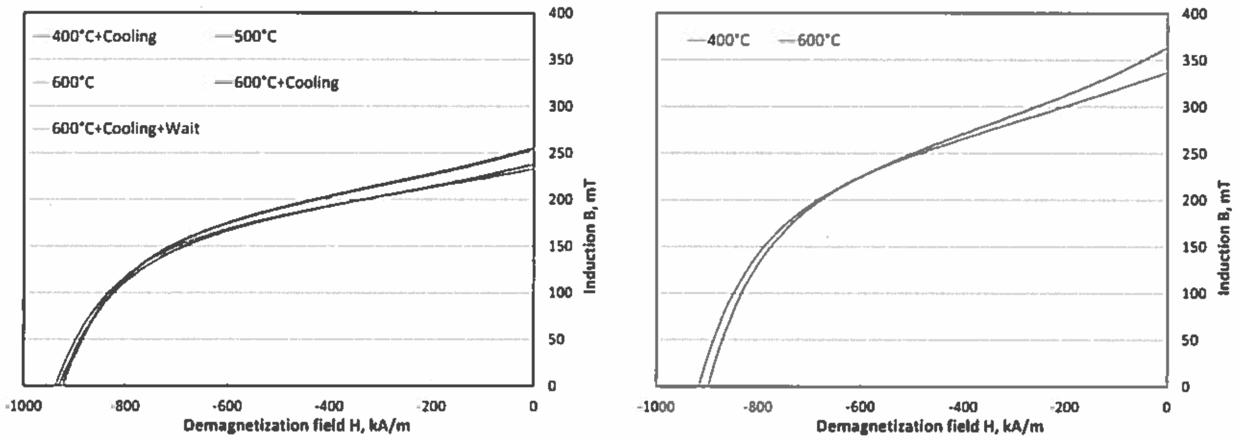


Figure 5: Demagnetization curves for coatings produced using pre-mixed powder with 75 wt.% of NdFeB and 25% of Al.

Table 2: Comparison of coating performance with theoretical value for two types of powder

Coating composition	H_{ci} coating, kA/m	H_{ci} datasheet, kA/m	B_{rcoat}, mT	$B_{rtheo}(F_v*B_{rpowder})$, mT
75%MQFP B+25%Al-H15	715	752	276	291
75%MQFP 14-12+25%Al-H15	930	961	257	270

To evaluate if these small reductions in coating performance were due to the high temperature exposure during the spray process, a series of test were carried out. Coatings were produced with the following nitrogen carrier gas temperatures: 400°C, 500°C and 600°C. Also, the effect of substrate cooling and wait period between the passes was evaluated. Two pre-mixed powder concentrations were studied for these trials: 75% and 90% mass fraction of magnetic powders. Figure 6 and Table 3 summarize the results.



(a) (b)

Figure 6: Demagnetization curves for coatings produced using MQFP 14-12/H15 pre-mixed powders with weight fractions of (a) 75% and (b) 90%

Table 3: Effect of the carrier gas temperature on the magnetic performance of Al/NdFeB coatings

Pre-mix composition	Spray process parameter			H_{ci} measured, kA/m	Diff.%	B_{rcoat}, mT	B_{rtheo}, mT	Diff. %
	Gas T (°C)	Cooling	Wait					
75%MQFP B+25%Al-H15	400	Yes	No	937	-2.5	233	233	0
	500	No	No	930	-3.2	238	251	-5.1
	600	No	No	920	-4.3	250	274	-8.7
	600	Yes	No	924	-3.9	255	269	-5.1
	600	Yes	Yes	924	-3.9	253	269	-5.9
90% MQFP B+10%Al-H15	400	No	No	917	-4.6	337	352	-4.3
	600	No	No	898	-6.6	364	386	-5.8

First, one can observe that by reducing the gas temperature from 600°C to 400°C, a small increase in the coercive field was obtained. The difference between the experimental data and the datasheet values was reduced from 4.3% to 2.5% for the 75% NdFeB coating and from 6.6% to 4.6% for the 90% NdFeB coating. The effect of substrate cooling and wait period is marginal. Process temperature does have an effect on the coatings coercivity albeit this effect is small.

The impact of the spraying temperature on the remanence is more complex. The absolute remanence of the coatings improved by 8% for a gas temperature increase of 400°C to 600°C. This result is true for both pre-mixed compositions. This is mainly due to an increase of the NdFeB content in the coating. Indeed, the higher spray temperature improves the deposition efficiency of the magnetic phase. However, when comparing to the theoretical remanence, spraying at 600°C is detrimental relatively to the powder datasheet performance. Indeed, the experimental remanence is 9% lower than what would have been expected from a 75% NdFeB pre-mix. Here the cooling of the substrate helped to reduce the negative impact on remanence. Finally, it is observed that the Brcoat increased by more than 40% when the content of NdFeB in the pre-mixed powder was increased by 20%. Starting with a more loaded content of hard NdFeB particles helps increase the magnetic loading and consequently the magnetic performance. In general, it can be observed that the powder thermal exposure was limited enough such as not to degrade significantly magnetic properties.

3.3 Mechanical bonding

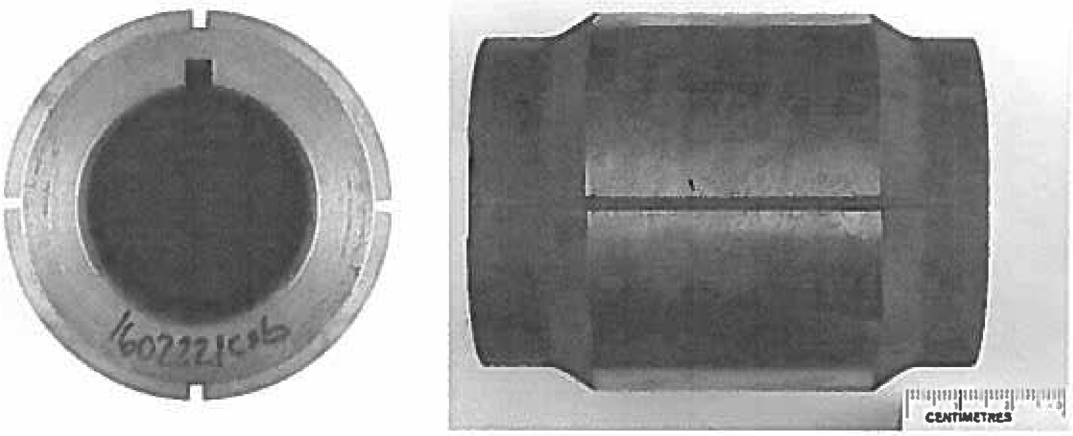
The obtained pull-tests results are summarized in table 4. All measured results were limited by the glue adhesion and cohesive strength indicating that the adhesion/cohesion of the deposited samples is minimally 82 MPa. Indeed, we did not observe any delamination or cohesion failure of the coatings. This tensile strength result is a strong indication of the excellent mechanical properties of the deposited coatings.

Table 4: Tensile testing results obtained for 90% MQFP – 10% H15 coatings.

Specimen	Maximum load (N)	Tensile stress at maximum load (MPa)
1	39914	78.77
2	42717	84.30
3	43277	85.41
4	40994	80.90
Mean	41726	82.35
Stdev	1550	3.06

3.4 Prototype fabrication

In an effort to establish the feasibility of the cold spray process to manufacture hard magnets for a permanent magnet motor, large scale parts were produced. Figure 7 shows a prototype produced using a 90% pre-mixed powder. A coating more than 5 mm thick was deposited directly on a 67 mm external diameter shaft. For magnetization purpose, the coating was first machined, using a conventional lathe, to achieve a precise 77 mm external diameter. Also, four pole gaps of 2.6° were machined by wire EDM. Neither cracks nor delamination were observed and the coating was easily machined with both processes. It was however observed that minor chipping did occur on one of the pole side during EDM.



(a) (b)

Figure 7: Al-NdFeB thick coating sprayed on the (a) outside and (b) inside surface of a 17 cm diameter cylinder.

4 Conclusion

The results presented in this paper illustrate the feasibility of using cold spray as a cost effective technology to deposit thick hard magnet coatings directly on the rotor for electrical motor applications.

- Dense and thick Al/NdFeB-Al composite coatings were deposited using cold spray technology with high deposition efficiency and up to 60 vol. % of magnetic particles.
- Coatings with magnetic performances slightly below theoretical value (-5%) were obtained.
- Adhesion of the coatings to the substrate is very high (above 82 MPa).
- Large scale parts can be produced with a 90 wt.% NdFeB and 10 wt.% Al pre-mixed powder and machined to tight dimensions without major defects.

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