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THE STATE OF THE ART OF THE INTERNAL PLASMA SPRAYING ON CYLINDER BORE IN AlSi CAST ALLOYS

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ABSTRACT–For the wear protection of cylinder bore in aluminum cast material the internal plasma spraying technology offers a new economical solution. The size and the weight of the engine blocks significantly can be decreased in comparison with the traditional cast iron sleeves. The coefficient of friction between piston ring and cylinder wall sensitively can be reduced and the wear resistance increased from several factors. The paper gives an overview of the technology from the AlSi cast alloys for engine block to the non destructive testing technology used after the machining by diamond honing. The actual results in engines of different types also will be shown. The economical advantages of the plasma spraying for the internal coating in cylinder bore also will be discussed in comparison with the different alternatives of technology. The aspect of the market introduction also will be discussed in this paper.

KEY WORDS : Plasma spraying, Cylinder bore, Coefficient of friction, Diamand honing

1. THERMAL SPRAY PROCESSES FOR COATINGS ON ENGINE CYLINDER BORES

Thermal spray technologies are important in a variety of different industries for the deposition of antiwear coatings based on metallic, carbide containing ceramic or composite materials. Plasma spraying processing has already found a wide range of applications in the automotive industry (McCune, 1995; Rao *et al.*, 1997; Byrnes *et al.*, 1997; Nakagawa *et al.*, 1994; Smith, 1991; Byrnes, 1994). The high thermal energy density available within a plasma for melting powder coupled to the ability to manufacture powder and design plasma guns for specific applications with short spray distances has rapidly promoted the use of plasma spraying (Byrnes *et al.*, 1994; Barbezat *et al.*, 1995; Barbezat, 1996; Barbezat *et al.*, 1996; Wuest *et al.*, 1997).

Different thermal spray processes are being used to provide coatings for cylinder bores. Plasma and HVOF processes are characterized differently with regard to two principal aspects. These are the thermal and kinetic energies of the sprayed particles. A comparison of atmospheric plasma spraying (APS), vacuum plasma spraying and high velocity Oxy-fuel (HVOF) spraying shows that the plasma processes offer high plasma temperatures at low velocities whereas the HVOF process is the reverse. The temperature of the HVOF spray stream though does have some dependence on the choice of fuel gas. In addition, it has to be taken into account that the HVOF spray distance is much greater than that of plasma. This means that a shorter spray distance with HVOF could lead to overheating of the substrate.

In the specific case of the coating of cylinder bores the transfer of heat into the substrate unit must be considered with priority as the engine blocks are an AlSi cast alloy and overheating during the coating can result in a non-acceptable distortion or metallurgical change in micro-structure. Additionally, since most cylinder bores have an inside diameter of 70 to 110 mm, a short spray distance is required. In order to keep the heat transfer during spraying as low as possible it is necessary to select the correct size of plasma gun, spray parameters, traversing speeds during spraying and cooling methods.

The electric wire arc spraying process is also an alternative for the coating deposition in cylinder bores. However, some restrictions regarding the choice of coating materials and the reliability of the melting process must be mentioned. Figure 1 compares schematically the three main processes for the coating of cylinder bores in AlSi cast alloys. The high degree of liberty regarding the choice of coating materials, the reliability of the melting process, and the low heat transfer to the engine block are the key advantages of the plasma process.

2. COATING REQUIREMENTS FOR CYLINDER BORES

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PROCESSES			
CRITERIA	**Plasma Transferred (wire arc process)**	**HVOF (wire or powder)**	**Rotating Plasma (powder)**
Versatility in the choice of material	Metallic alloys Restricted choice of materials **Low**	Metallic alloys Carbides, composites. Limitation for refractory materials **Medium**	Metallic alloys Carbides, ceramics, composites. High versatility **High**
Heat transfer into the engine block	**Medium**	**Very high**	**Low**
Reliability of the melting process	Formation of the melted particle is difficult to control **Medium**	**High (powder)** **Medium (wire)**	**High**
Coating properties for cylinder bores	**Medium**	**High**	**High**
Process cost	**Low**	**Very high**	**Low**

Figure 1. Comparison of the thermal spray process for the deposition of coating in engine cylinder bores.

The cylinder wall, piston ring and lubrication of an internal combustion engine interact as a tribological system and a balance has to be found between the components regarding wear and oil combustion. This leads to the following definition of the deposited coating material properties:

· Low coefficient of friction and low wear rates against piston ring materials under the boundary conditions of lubrication
· Lower wear rate than a cast iron liner for the same tribosystem
· Good resistance against thermal shock
· Consistent coating properties to provide a high reliability with regard to surface finishing

Due to the fact that the plasma process uses powder, the choice of material can be directed specifically to compositions that:

· are not based on strategic materials such as cobalt or nickel
· provide the required wear and friction characteristics
· have a defined porosity and metallurgical phase content which in combination with the oil provides the necessary lubrication characteristics

The availability of the powder material, the cost and the efficiency of the spray process regarding the coating time play also an important roll by the choice of the most adequate material. Short spray time of one minute for a cylinder bore of 80 to 100 mm is the actual feasibility. The machining process time and cost are also a sensitive aspect for the choice of a coating material.

3. SURFACE PREPARATION BEFORE DEPOSITION OF THE COATING

To obtain a reasonable bond strength of the sprayed coating on the cylinder wall, the surface must be activated shortly before the spray operation. Traditionally, grit blasting with Al_2O_3 based materials are used for this operation. However, grit blasting leads to contamination of the interface with embedded particles. A cleaning operation after blasting reduces this to a reasonable level. On AlSi cast alloys typical bond strength (measured according to ISO 4624) of 50 MPa can be obtained. However, the values depend strongly on the surface roughness (Ra and Rz), on the sprayed material (chemical composition), on the spray parameters (kinetic energy of the particles), and of the coating thickness (influence of the residual stresses).

According to the experiences of the last five years of development the coating application in cylinder bore requires a bond strength of min 30 MPa. The results of

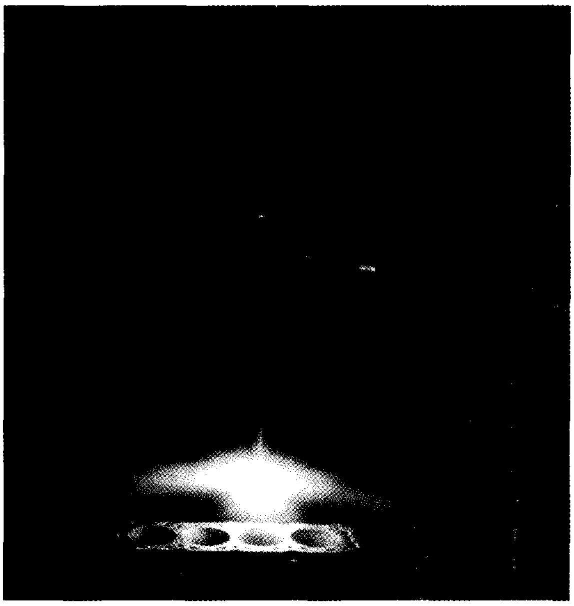

Figure 2. Plasma gun mounted on the ROTAPLASMA® 500 rotating device spraying a cylinder.

prior works showed that the required value can be reached up to a thickness of more than 300 μm (Wuest *et al.*, 1997).

Other alternatives for surface preparation include high pressure water jet and also laser technology. Both methods show an interesting technical potential, but require still an important development and a strongly reduction of the cost. In comparison today is the high pressure water jet about ten time more expensive than the classical grit blasting for the surface preparation of cylinder bore. The laser technology is now in development and some benefit can be expected in about three years for the surface preparation of cylinder bores (Barbezat *et al.*, 1998).

4. COATING DEPOSITION

Machine tooling for the plasma spray coating of cylinder bore surfaces has to take two things into account: The plasma gun has to rotate while the component remains stationary and, a plasma gun has to be available which fits in the bore with sufficient spray distance for the satisfactory deposition of the coating with the required properties.

Figure 2 shows the ROTAPLASMA® 500 together with a plasma gun for the spraying of cylinder blocks. Mounted on a robot or vertical movement device, the ROTAPLASMA® 500 provides rotation of the plasma gun up to 250 RPM together with the feed through necessary for the plasma gases, powder carrier gas and powder and cooling water supplies to the gun. The ability to rotate the gun eccentrically allows the ROTAPLASMA to spray with the maximum available spray distance.

Table 1. Typical plasma spray parameters for the Argon/ Hydrogen plasma gun SULZER METCO F 210.

Parameter	
Argon [l/min.]	50.0
Hydrogen [l/min.]	4.0
Current [A]	320
Argon powder gas [l/min.]	4.0
Powder type	Low alloy steel
Feed rate [g/min.]	50-100*
Deposition efficiency [%]	80-90

*depends on spray material (powder morphology)

For cylinder bores of 80 mm diameter and 120 mm length, a spray time of less than 60 s/bore can be obtained for coating thickness between 150 and 200 microns resulting in reasonable production times per block. Overspray can be avoided through the use of masking which can be applied under production conditions using an automatic placement system.

With the optimal particle size distribution and spray parameters using the new developed internal gun F 210 the deposition efficiency accrued is between 80 and 90% for metallic alloys sprayed in cylinder bores of 80 mm diameter. Typical spray parameters for low alloyed steel coating are given in Table 1.

During the deposition of the coating the temperature of the cylinder block is maintained at 80 to 120°C without active cooling. This temperature is acceptable for all types of AlSi-cast alloys for engine blocks to avoid modification of the microstructure and distortion.

5. COATING FINISHING

After the coating disposition, the coatings are finished by honing using diamond tools. It is important to adapt the finishing specification and honing parameter to the sprayed coating. Specifically, the honing with cross line design must be avoided on sprayed coating. This is due to the effect on the oil consumption. The residual porosity of the coating (about 2%) gives after the honing a suitable topography to keep a residual lubricant in the micro-cavities. The cross line design increases the amount of residual oil and the consumption increases. Surface roughness of Ra below 0.3 μm can be obtained after the diamond honing of most metallic plasma sprayed coating. A non-destructive testing operation after the machining can be recommended. Potential NDT processes were tested and modified for this application. A hundred

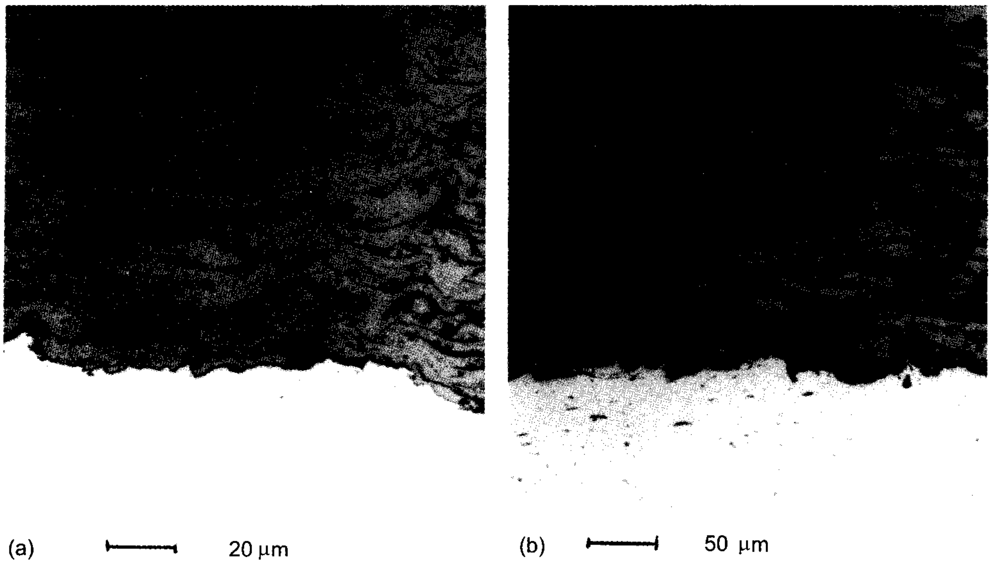

Figure 3. Typical internal coating sprayed on AlSi cast alloy.
(a) Low alloyed carbon steel with built solid lubricant ($HV_{0.3}$=400)
(b) Composite metal ceramic ($HV_{0.3}$=530)

percent control of the coating is possible in a short time. This fact allows the deposition of the plasma coatings for cylinder bores in a manufacturing line.

6. MATERIAL USED AND COATING PROPERTIES

Different types of material can be used for the cylinder bore in engine blocks. Some experience exist using metallic alloys, metal-metal composites, metal-solid lubricant composites and metal-ceramic composites. For the metallic alloys (mainly, low alloy carbon steel) and the metal-metal composites the following typical characteristics are measured on coatings sprayed in cylinder bore of 75 to 100 mm internal diameter.

- Residual porosity < 2% typical
- Oxide content < 2% typical
- Microhardness $HV_{0.3}$ 350-650. Hardness depends on the material. The lower limit is determined by coating performances, the upper limit is given by the machinability costs of the coating
- Bond strength on AlSi cast alloy 40-60 MPa
- Bond strength on lamellar gray cast iron 50-70 MPa
- Typical thickness used: as sprayed 120-250 μm, after machining=70-170 μm

During the coating deposition the formation of iron oxides FeO and Fe_3O_4 can be controlled. These types of

Table 2. Summary of the laboratory and field test engine with plasma sprayed coatings.

Region or country	Category of material	Type of engine (fuel)	Status
Europe	Composite metal-metal*	Petrol fuel 4 cylinders Diesel 4 cylinders	Successfully long test in testing. Production introduction in 2000
Switzerland	Composite metal-metal*	Boxer-Engine, 4 cylinders for aircraft	Successfully test, now in series production since 1996
Europe and Japan	Low alloyed carbon steel	Test engine 4 cylinders	First tests are successful
USA	Steel and solid lubricant*	V-8-engine, Gasoline	Successful in field-test to 200'000 km
Europe	Composite metal and ceramic*	Petrol fuel 4 cylinders and Diesel engines	First tests show positive results, especially for Diesel

*Proprietary material of SULZER METCO or others oxides also have a function of solid lubricant. However the formation of Fe_2O_3 must be avoid regarding the abrasive effect of this type of oxide.

The minimum value of 30 MPa bond strength is also obtained without problems. Figure 3 show typical microstructures of a low alloyed carbon steel coating and composite sprayed using the plasma process in a cylinder bore of 80 mm diameter.

7. COATING PERFORMANCE IN ENGINES

Plasma sprayed coating were deposited and tested in several types of engines. Coatings on the following material categories were successfully tested in engines according to the conditions shown in Table 2.

In 1996 the first introduction in series production of plasma sprayed engine cylinder bore was done for an Aircraft Boxer-Engine of 120 kW power. This engine is a four cylinders design with a bore diameter of 100 mm, a stroke of 84 mm and a 2.63 liter capacity. The nominal speed of the engine is 4'500 RPM. This engine was developed by MDB Aerospace Corp. in Switzerland.

After two years of testing the decision was taken to go into production with the plasma sprayed coatings. SUZLER METCO, Switzerland, is responsible for the deposition of the plasma coating. The use of a plasma coating in the engine block of the airplane proves the technical capability of this spraying technology.

In the automotive industry it was demonstrated that the plasma coating can contribute to decrease significantly the coefficient of friction between piston ring and cylinder liner (20 to 30%). Significantly higher wear resistance in comparison with cast iron was obtained. Depending of the coating material the wear resistance is increased from a factor 3 to 10.

8. ECONOMIC ASPECT

The coating costs are strongly depending on the material price and on the required coating thickness. High powder feed rates (to 120 g/min.) and high deposition efficiency (> 80%) allows short spray time and low consumption of powder material. For the coating of cylinder bores of 80 mm diameter and length of 120 mm, the process time can be less than 60 sec. Depending on the powder, the spraying cost for a bore will be USD 2-4. These costs are significantly lower than the galvanic process.

9. OUTLOOK

Pilot equipment is already working in the European and Japanese automotive industry on the industrial introduction of the plasma sprayed technology for the coating of engine cylinder bores. The technology of internal plasma spraying with a rotating device deposits a wear resistant coating onto the cylinder bores of engine blocks for internal combustion engines. Based on the cylinder bore tribological requirements, powder selection together with the plasma process can result in specific coating solutions. Furthermore the costs of the coating are competitive compared with galvanic processes and cast iron sleeves. Plasma spraying presents a real alternative for this application and will continue to gain importance. The introduction in series in the automotive industry is expected already for this year in Europe.

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REFERENCES

Ayrault-Costil, S., Montavon, G., Barbezat, G. and Coddet, C. Thermal spray deposition of a copper coating on aluminum using the PROTAL process Proceeding *ITSC* 98, Nice, 1409-1413.

Barbezat, Keller, S. and Wegner, K. H. (1995). ROTA-PLASMA Applications in the Automotive Industry *ITSC* 95, Kobe, 9-13.

Barbezat (1996). Neue entwicklungen zum innenbeschichten, Schweissen und Schneiden **48**, *Heft 2*, 127-131.

Barbezat, Keller, S. and Wegner, K. H. (1996). Innenbeschichtungen für zylinderkurbelgehäuse proceeding *TS* 96, Essen, 114-117.

Barbezat, G. and Wuest, G. (1998). Advantages for automotive industry of plasma spray coating of AlSi cast alloy cylinder bores london, *Surface Engineering*, **14**, **2**, 113-116.

Byrnes and Kramer, M. (1994). Method and apparatus for the application of thermal spray coating onto aluminum engine cylinder bores in Proc. *NTSC*, Boston, USA, 39.

Byrnes and Kramer, M. (1997). Method and apparatus for the application of thermal spray coating onto aluminum engine cylinder bores, *ASM/ESD Meeting*, Romulus.

McCune (1995). Thermal spraying of cylinder bore surfaces for aluminum engine blocks, *Welding Journal*, 41-47.

Nakagawa, Kawakami, K. and Kudoh, T. (1994). Trends in automotive application of thermal spray technology in Japan in Proc. *NTSC*, Boston, USA.

Rao, Kabat, D. M., Rose, R., Yeager, D., Brandt, R. and Leong, D. Y. (1997). Performance of plasma spray coated bore 4.6 L V 8 aluminum block engines in dynamometer and fleet vehicle durabitity tests, *SAE*

Paper 970008.

Rao, Kabat, D. M., Cikaneth, H. A., Facriari, C. A. and Wuest, G. (1997). Material systems for cylinder bore applications - Plasma spray technology, *SAE Paper* 970023.

Smith (1991). Plasma spray processing, Proc. 2nd Plasma-Technik Symp. Lucerne, **1**, Plasma-Technik, 17-38.

Wuest, Barbezat, G. and Keller, S. (1997). The key advantages of the plasma-powder spray process for the thermal spray coating of cylinder bores in automotive industry *SAE* Int. Congress, Detroit.