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Coating Bores of Light Metal Engine Blocks with a Nanocomposite Material using the Plasma Transferred Wire Arc Thermal Spray Process

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Engine blocks of modern passenger car engines are generally made of light metal alloys, mostly hypoeutectic AlSi-alloys. Due to their low hardness, these alloys do not meet the tribological requirements of the system cylinder running surface—piston rings—lubricating oil. In order to provide a suitable cylinder running surface, nowadays cylinder liners made of gray cast iron are pressed in or cast into the engine block. A newer approach is to apply thermal spray coatings onto the cylinder bore walls. Due to the geometric conditions, the coatings are applied with specifically designed internal diameter thermal spray systems. With these processes a broad variety of feedstock can be applied, whereas mostly low-alloyed carbon steel feedstock is being used for this application. In the context of this work, an iron-based wire feedstock has been developed, which leads to a nanocrystalline coating. The application of this material was carried out with the Plasma Transferred Wire Arc system. AlMgSi0.5 liners were used as substrates. The coating microstructure and the properties of the coatings were analyzed.

Keywords automotive industry, engine block, nanocrystalline coatings, Plasma Transferred Wire Arc

1. Introduction

Two of the most important objectives of the automotive industry in the near future are the reduction of emissions and the reduction of fuel consumption. Both objectives depend on lowering not only the engine's weight but also the frictional resistance within the engine. Decreasing the engine's weight is obtained by the use of light-metal alloys. Gray cast iron, which was once the standard material in the production of engine blocks, is now often replaced by, mostly hypoeutectic, AlSi-alloys. Engine blocks made of those alloys save up to 50% in weight compared to those made of gray cast iron (Ref 1). The mechanical properties such as Young's modulus, tensile strength, and hardness of aluminum-based alloys used for engine blocks are significantly lower than those for gray cast iron. Particularly due to the low hardness, hypoeutectic AlSi-alloys (AlSi8Cu3: 115-135 HB (Ref 1)) do not meet the tribological requirements in the contact area between the piston ring and the cylinder bore wall.

Due to the low wear resistance of these aluminum alloys, the surface in this contact area has to be modified or replaced. Generally the material on the surface is replaced by pressed in or cast in cylinder liners made of gray cast iron. Gray cast iron has a sufficient hardness, and the embedded graphite lamellas serve as a solid lubricant, especially in the bottom and top dead center where the piston speed is near zero (mixed friction). Along with the high costs and an increase of the engines weight and size, the use of cylinder liners exhibits further problems. The different thermal expansion coefficients of gray cast iron and the engine block material can cause a deformation of the liner and also local heat transfer problems (heat pockets) if the liner disengages from the engine block. The deformation of the liner leads to an increased oil and fuel consumption, blowby, and increased emissions.

One of the options to avoid cast iron liners is for the engine block to be made of a hypereutectic AlSi-alloy (e.g., AlSi17Cu4Mg). The good tribological properties are provided by primarily separated silicon, characterized by very small (20-70 µm) and hard crystallites. In this case, iron or chrome plated piston rings are required. Another disadvantage that has to be considered is the machining of these engine blocks, because of the Si-crystallites hardness.

Another possibility to produce AlSi cylinder running surfaces lies in the local enrichment of the hypoeutectic

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alloy with silicon. Therefore highly porous, powder metallurgically produced silicon liners are cast in the engine block.

A further approach to create a surface on the engine bore characterized by the necessary requirements is to deposit a layer of a suitable material onto the wall of the bore. Coatings can be deposited by electroplating, e.g., nickel with dispersed SiC particles, or by thermal spraying.

An option that is becoming increasingly popular is using a thermal spray process to apply a hard wear resistant surface on the cylinder bore. This option has the advantages of low cost (depending on the process it can be less expensive than cast iron liners), high compatibility, and the standard advantages associated with eliminating the cast iron liners.

The presented investigations are part of the joint project ''Nano-crystalline composite coatings for cylinder bores with nano-structured surface and wear forecast for highly loaded gasoline and diesel engines—NaCoLab,'' promoted by the German Federal Ministry for education and research in the range of the program ''Nano-mobil.'' The objective of the research project is to comply with all requirements in order to produce engine blocks of aluminum-silicon alloys with thermally sprayed cylinder running surfaces.

2. Thermal Spraying of Cylinder Bores

The coating of bore walls by thermal spraying requires specifically designed thermal spray systems. In order to enable the application of thermally sprayed coatings onto cylinder bore walls, the gun head's dimensions have to be small compared to the bore. Typically the diameters of cylinder bores in modern passenger car engines are smaller than 100 mm. In order to avoid having the engine block rotated, the gun head has to rotate coaxially to the bore.

At present, at least four thermal spray systems with this configuration are either commercially available or under research, whereas three of them use wire as feedstock while the fourth one uses powder feedstock.

RotaPlasma™: The RotaPlasma™ process, developed by Sulzer Metco, is a rotating powder fed atmospheric plasma spray system, which is in serial production with Volkswagen AG (Ref 2).

Twin Wire Arc: The rotating Twin Wire Arc System (RTWA), developed by Daimler AG, is in serial production with AMG.

HVOF: General Motors has developed a HVOF (High Velocity Oxygen Fuel) system which uses wire feedstock.

PTWA: The PTWA (Plasma Transferred Wire Arc) process was developed by Flame-Spray Industries and the Ford Motor Company. The plasma generator or gun head consists of a tungsten cathode, an air-cooled pilot nozzle made of copper, and an electrically conductive consumable wire which is the anode (Fig. 1). The head is mounted to a rotating spindle, which rotates with up to 600 rpm. The wire is fed perpendicularly to the center orifice of the nozzle. The plasma gas is introduced through tangential boreholes situated in the cathode holder (not shown in the figure) to ensure a vortex is created. To start the process, a

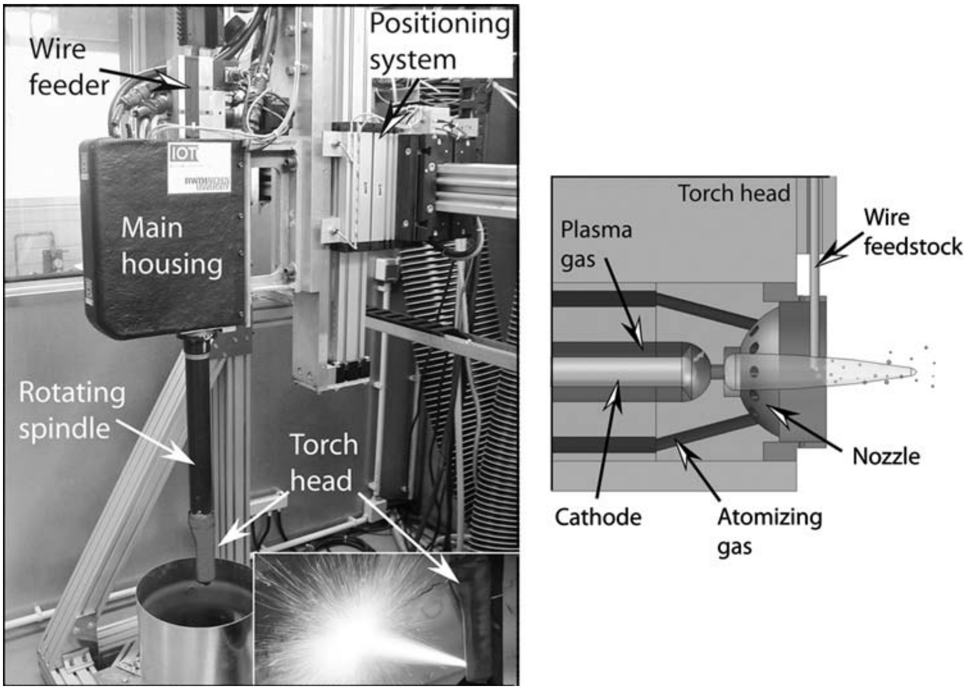

Fig. 1 Picture of the PTWA system, as it is installed at the Surface Engineering Institute (left), and a schematic of the PTWA process (right)

high voltage discharge is initiated, which ionizes and dissociates the gas mixture between the cathode and the nozzle. Due to a constricting orifice in the pilot nozzle the plasma is forced to exit the nozzle at supersonic velocity. The elongated plasma is transferred to the consumable anode, the wire, completing the electrical circuit. A constant current power supply maintains the plasma from the cathode to the wire with an arc voltage of 100-120 V and a current of 60-100 amps. This melts the tip of the wire and then the high-pressure plasma gas together with the atomizing gas strips the molten particles from the end of the wire (Ref 3). Thereby a jet of finely atomized particles is created, which is accelerated toward the substrate at high speed. The atomizing gas can be any noncombustible gas. In this work, a mixture of argon and hydrogen is used as the plasma gas and compressed air is used to atomize and accelerate the molten particles. The system is suitable to coat cylinder bores with a diameter of 35-360 mm. Due to the high speed of the spray particles of 100-130 m/s, dense coatings with a porosity of less than 2% can be applied with the PTWA system. The particle temperature reaches a value of approximately 2100 °C.

In this project, all three wire-based systems mentioned above are under evaluation. In the framework of the project two PTWA systems are employed at GTV Verschleiss-Schutz GmbH (Fig. 2) and at the Surface Engineering Institute of RWTH Aachen University.

The process chain in the production of coated cylinder bores consists of four steps. First is machining the cylinder bore to a certain diameter and then machining the surface to be coated as mentioned later, so the coating is able to adhere. Next steps are the thermal spraying and the honing of the coated bore to receive a surface that meets the tribological requirements. The thickness of the coating after the honing operation for most applications is typically 100-150 μm. Because of the roughness of the coating and the required machining allowance, the thickness as sprayed is typically 200-300 μm. It depends on the feedstock and also on the thermal spray process.

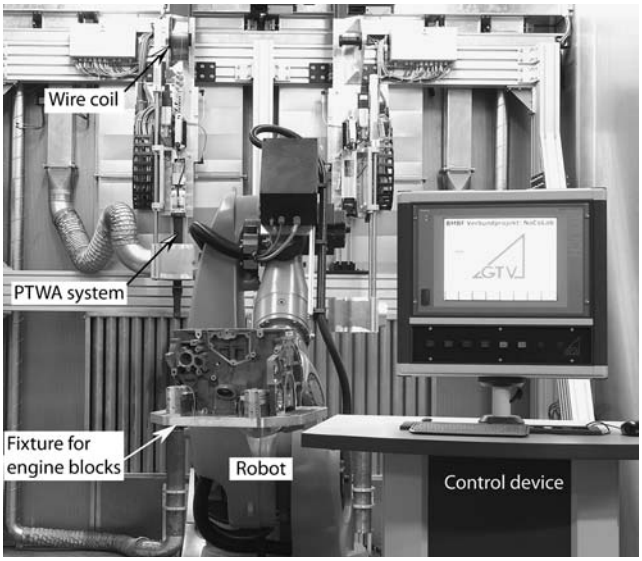

Fig. 2 PTWA system at GTV Verschleiss-Schutz GmbH

3. Pretreatment of the Substrates

The standard surface roughening process for the thermal spray industry is grit blasting. For the cylinder bore applications, grit may remain within the many internal passages of the engine block, which can come loose during operation and later cause engine breakdowns. Another roughening possibility lies in the high-pressure water jet blasting process, where water is used with a pressure of up to 300 MPa and accelerated toward the substrate surface (Ref 4). Due to its high kinetic energy, the water jet partially removes the surface and leaves a finely structured topography, characterized by the required undercuts (Fig. 3). The topography leads to high bond strengths of up to 50 MPa. However, this process requires expensive high-pressure water pumps.

Another surface preparation technology is the Ni/Al-Flux process developed by the Ford Motor Company, which also leads to high bond strengths. In this process Nocolok™ flux is applied onto the nonroughened surface of the aluminum bore. Thermal energy, e.g., by a thermal spray process, activates the flux agent, which then strips the oxide layer from the aluminum. Best results can be reached with a bond coating made of nickel and aluminum and a concentration of 95% nickel (Ref 5).

The need for a substrate pretreatment process which enables high bond strengths and can be easily integrated into the process chain, has led to different mechanical roughening processes (MRP). One process was developed by the Institute of Machine Tools and Production Technology of Braunschweig University (IWF) within the framework of the "NaCoLab" project. With this fine boring process a tool with one or two geometrically defined cutting edges is used to bring different topographies into

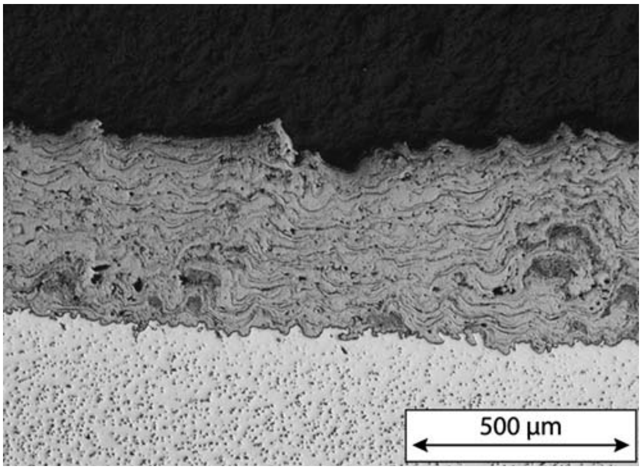

Fig. 3 Micrograph of a water jet blasted and steel coated substrate

the substrate. With this MRP process, the overlay of the rotary motion and the axial infeed of the tool lead to a helix, similar to thread cutting. The process was developed as a lube oil free process, which means that no additional cleaning steps are required prior to coating.

Early attempts of a mechanically roughened surface (liner made from EN AW 6060) led to a bond strength of 40 MPa, which is significantly higher than the recommended value of 30 MPa (Ref 6). A micrograph of such sample is given in Fig. 4. In order to further improve mechanical interlocking between coating and substrate, the ''dove tail'' like profile was developed (Fig. 5). Figure 6 compares the bond strengths of PTWA-sprayed 0.82% C-steel coatings sprayed onto substrates, which were roughened with the three processes mentioned above. For coatings applied onto a surface roughened with the ''dove tail'' like profile, the highest bond strengths of up to 58 MPa could be measured.

Measurement of the bond strength was carried out with a PAThandy™ pull off adhesion tester, DFD Instruments, Kristiansand, Norway. Compared to the established testing method in accordance with ASTM C 633 or DIN EN 582 it is possible to measure the bond strength directly on coated parts such as the curved surface of a bore. Therefore a suitable test element (dolly) with a curvature of the test element is fitted to the curvature of the coated part and a diameter of 8.16 mm is glued onto the coating. In the second step all the coating at the edge of the test element has to be cut to the substrate to define a specific area for the adhesion test. This was carried out by laser cutting. The function of the testing head is shown in Fig. 7. With a palm held pump pressure is applied onto the four jack cylinders, which pull the test element off the coating. Via the ratio of the diameters of the test element and the cylinder in the pump along with the pressure the bond strength can be determined.

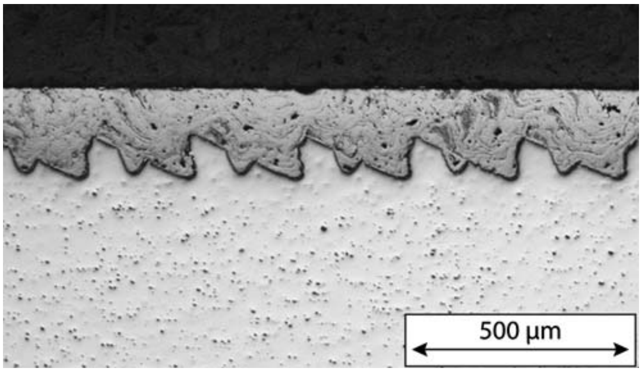

Fig. 4 Micrograph of a mechanically roughened and steel coated substrate

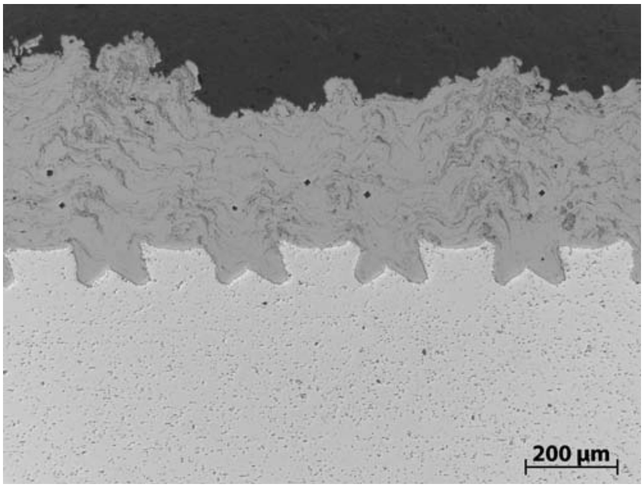

Fig. 5 Micrograph of a ''dove tail'' roughened and steel coated substrate

4. Surface Building Materials

In this work, two materials systems are under research. As reference material low-alloyed carbon steels are used as feedstock. These steels contain 0.1-0.82 wt.% carbon.

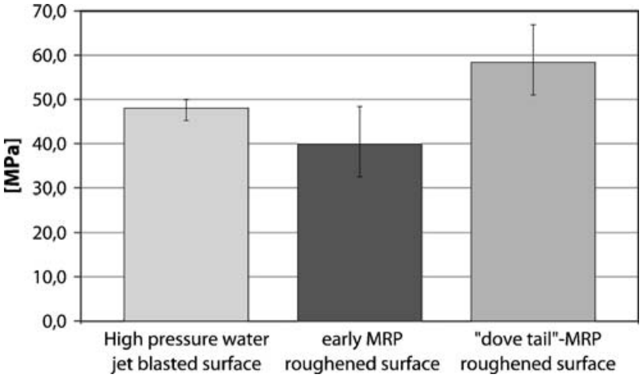

Fig. 6 Bond strength of PTWA-sprayed 0.82% C steel coatings on aluminum EN AW 6060 substrates

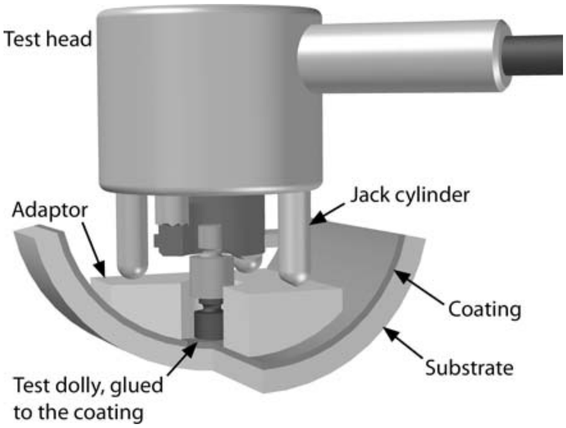

Fig. 7 Schematic of the PAThandy testing head

However, special iron-based alloys were developed in the "NaCoLab" project by the company DURUM GmbH, Willich, Germany. The objective of this work was to develop an iron-based feedstock, which, when processed by thermal spraying, forms wear resistant coatings, characterized by embedded nanoscale boridic precipitations.

All materials were sprayed onto liners made from EN AW 6060 (AlMgSi0.5) with an inner diameter of 83.3 mm and a height of 120 mm. The substrates were mechanically roughened with the "dove tail" like profile. Cross sections of the coatings were produced to evaluate the microstructure. To gain further information on the coating, especially on the size of the precipitations, transmission electron microscopy (TEM) investigations were carried out by the Institut fuer Produkt Engineering of Duisburg Essen University, Duisburg, Germany. The microhardness was determined for all coatings.

Thermally sprayed coatings in general contain a certain amount of porosity. For most applications the presence of pores is disadvantageous. For this specific application though, it was found that the pores can have a positive effect on the frictional behavior of the coating when they are machined open by the following honing process (Ref 7). The open pores at the functional surface of the cylinder bore work as microcavities, which are able to store a certain amount of oil in addition to the oil storage capacities of the honing grooves. This additional oil storage capacity improves the frictional behavior of the surface (Fig. 8). The oil storage capacities of some coatings were analyzed. The recommended oil storage capacities for RTWA sprayed C-steel coatings are between 0.050-0.070 mm^3/cm^2 for the pores and 0.014-0.018 mm^3/cm^2 for the honing topography (honing grooves) (Ref 8). For PTWA-sprayed coatings, these values have to be seen as reference values since the coating structure differs from the coating structure of RTWA-sprayed C-steel coatings in regard to the content of oxides.

Carbon Steel-Coatings: When low carbon steel is used with the PTWA thermal spray process and compressed air is used as the atomizing gas, the iron in the alloy reacts with the oxygen of the atomizing gas and forms FeO (wuestite), a high temperature oxide, which, due to the high cooling rates, is frozen at room temperature. Wuestite is a hard, self-lubricating oxide phase that is responsible for the excellent exhibited tribological properties of these Fe/FeO-coatings, especially in both dead centers. These oxides are significantly harder than the iron matrix (430 HV 0.3 compared to 260 HV 0.3; 0.1% C-steel as feedstock). Wuestite also works as a self-lubricating material, similar to the graphite lamellas in gray cast iron. Wuestite has a cubic closed packed structure; due to its crystallographic shearplane it acts as a low shear strength, lubricious oxide (Ref 9). Depending on the thermal spray process and the parameters chosen, the amount of iron oxides varies between 20 and 40%, determined by optical image analysis.

Typical spray parameters for producing steel coatings are given in Table 1. To produce a coating with approximately 300 μm in thickness, 16 passes are required, whereas the material throughput is 4 kg/h.

Figure 9 shows a micrograph of a PTWA thermal spray coating made from 0.82% C steel. The micrograph shows some porosity within the coating, and some finely distributed wuestite. The hardness of these coatings is significantly higher than that for the 0.1% C coatings. The values are between 550 and 620 HV 0.1. The coating was produced with optimized coating parameters. It was found that an increase in the revolution speed from 400 to 600 min^{-1} leads to a better distribution of the oxides within the coating.

The second materials system in this study is an iron-based flux-cored wire feedstock called SUNA. Due to the high amount of alloying elements (approx. 25 wt.%) the feedstock was developed as a cored wire (Fig. 10). Main alloying elements are Cr, W, and 1.9-5 wt.% B. The sheaths of the different SUNA wires were made from Fe and FeCr, respectively.

The first developments of these feedstocks, called SUNA 2 and 3, were made from coarse (grain size −350 μm) crushed powders in an iron sheath with a high content of boron (5 wt.%). The coatings made from this

Table 1 Typical spray parameters for C-steel

Ar, slpm	H_2, slpm	Current, A	Wire feed rate, m/s	Air, slpm	Revolution speed, 1/min
67	29	65	0.072	1200	400

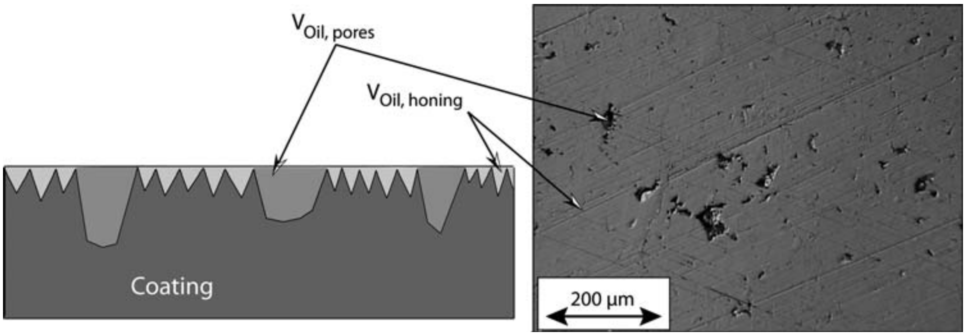

Fig. 8 Schematic of the different oil storage capacities of a thermally sprayed and honed coating (left), fax film-picture of a honed surface (right)

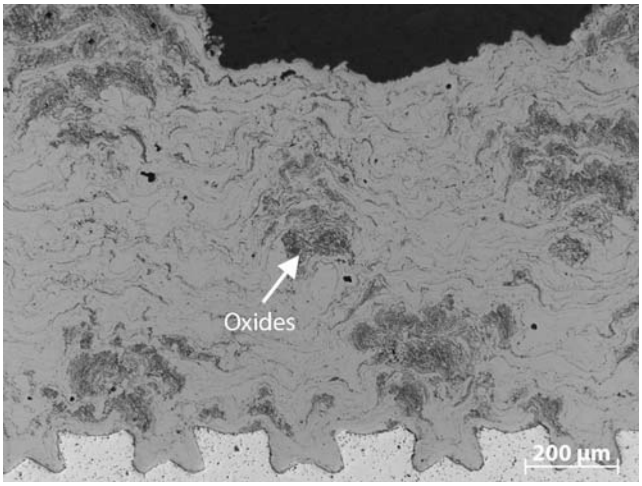

Fig. 9 Micrograph of a 0.82% C-steel coating applied with the PTWA system. In the figure, the oxide phases appear darker than the Fe matrix

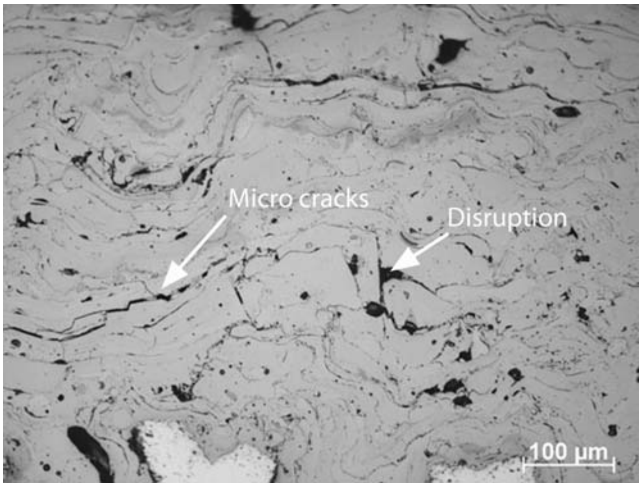

Fig. 10 Micrograph of a coating made from early SUNA 3 wire (Hardness 1200 HV 0.1)

feedstock show a very high hardness of 1200 HV 0.1 but also numerous microcracks and disruptions as shown in Fig. 10. One sample was honed to determine the oil storage capacities caused by the honing grooves and the machined open pores. It was shown that because of the brittle behavior many particles quarried out and left behind a surface with the oil storage capacities being too high, which does not meet the requirements of a cylinder running surface.

For the second batch (SUNA 6) the content of boron was lowered to 1.9 wt.%, which led to dense coatings free of microcracks. A cross section of such a coating is given in Fig. 11. The oil storage capacities of the honed surface were within the required range. Some unmolten particles and semi-molten pieces of the sheath were found within the coatings. Figure 12 shows two TEM bright field pictures of this coating. The picture on the left hand side indicates a predominantly amorphous matrix, whereas the picture to the right shows nanoscale (Fe, Cr)$_{23}$B$_6$ precipitations in an amorphous matrix. The oil storage capacities of this coating lay within the recommended range. The spray parameters for processing this feedstock are given in Table 2.

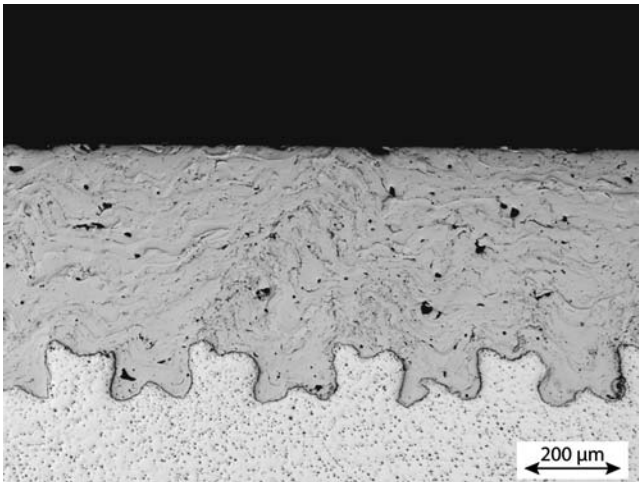

Fig. 11 Honed coating made from SUNA 6 wire

To produce more homogeneous coatings, with the next batch (SUNA 6-3) the powder filler made of crushed material was replaced by a mixture of gas atomized and crushed powders of a smaller grain size distribution (−180 µm, +45 µm). Because of the lowered grain size, the wire feed rate could be increased by approx. 40% compared to the parameters given in Table 2, all other parameters remaining identical. Figure 13 gives a micrograph of a SUNA 6-3 coating with some semi-fused sheath material embedded. The bright field picture and the diffraction pattern, given in Fig. 14, show that the precipitations are nanoscale. Two phases were found: M$_x$B$_y$ and M$_3$O$_4$ (M = metal, B = boron, O = oxygen). The analysis of the precise composition of both phases is subject to current investigations. The SUNA 6-3 feedstock was already successfully applied onto the bore walls of an engine block (Ford Zetec 1.4l).

Finally, the iron sheath (SUNA 6-5) was substituted with a FeCr sheath to further improve the process stability and avoid the inclusion of semi-molten sheath material. For the PTWA process, a well-straightened wire is essential for a stable process since the torch head rotates around the wire. With a not-well-straightened wire the distance between the wire tip (the anode) and the cathode fluctuates, and hence the process stability decreases. The hardness of these coatings lies within the same range as SUNA 6 coatings. Compared to the coatings made of SUNA 6 and 6-3 the homogeneity of the coatings was further improved, as shown in Fig. 15. From the latter three materials crack free coatings could be produced, even if thick coatings of 600 µm were produced.

The results of the determination of the oil storage capacities for SUNA 3, 6, and 6-5 coatings are given in Fig. 16.

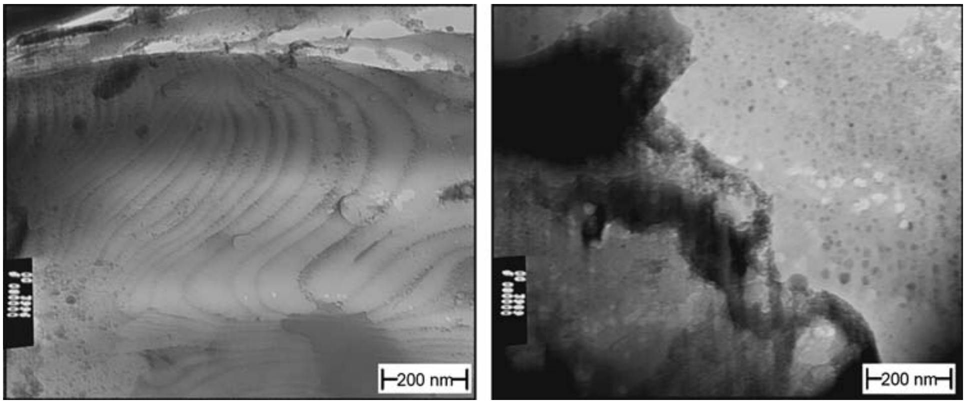

Fig. 12 TEM bright field pictures of a PTWA-sprayed SUNA 6 coating. In the picture to the left an amorphous structure is shown while the picture on the right hand side shows nanoscale precipitations

Table 2 Spray parameters for processing SUNA 6 wire with the PTWA process

Ar, slpm	H_2, slpm	Current, A	Wire feed rate, m/s	Air, slpm	Revolution speed, 1/min
70	10	85	0.072	1100	600

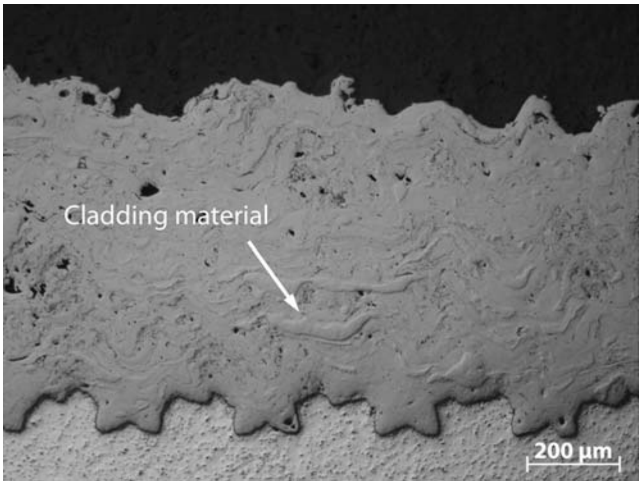

Fig. 13 SUNA 6-3 coating with some sheath material embedded

Besides test liners, two Ford Zetec in-line 1.4 l engines were coated with the reference material 0.1% C-steel and the SUNA 6-3 feedstock. Friction tests were carried out with a stripped down engine for the 0.1% C steel coating. The stripped down engine consists of:

1. crank case,
2. crank shaft,
3. bearings,
4. pistons and piston rings,
5. bedplate/bearing bracket,
6. radial shaft seals, and
7. cylinder head (depending on the strip level).

Thereby the engine is driven by an electric motor. The torque required to rotate the crankshaft with the pistons is

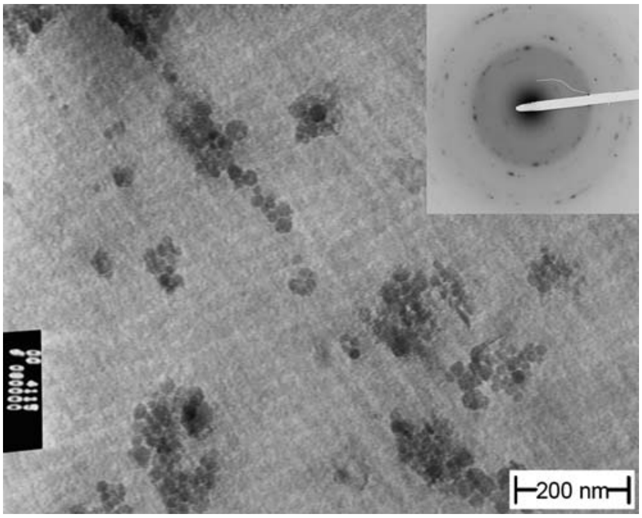

Fig. 14 TEM bright field picture and diffraction pattern of a SUNA 6-3 coating

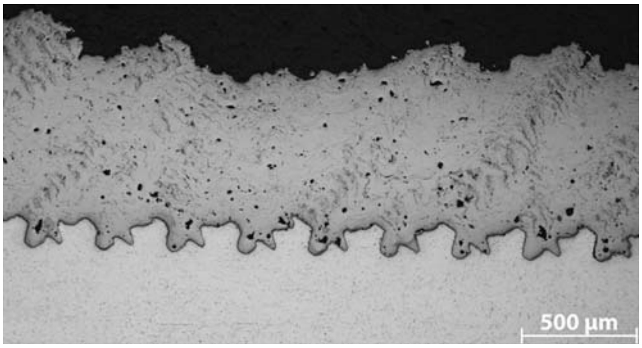

Fig. 15 Micrograph of a SUNA 6-5 coating

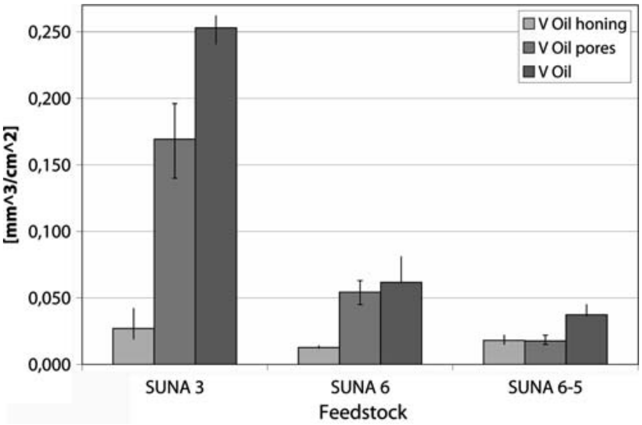

Fig. 16 Oil storage capacities of coatings made from different SUNA wires

recorded. The test can be carried out with or without the cylinder head. For the engine including the cylinder head, the friction was determined to be 6.8% below the values measured for the standard engine with liners made from gray cast iron. Without the cylinder head, the friction was 14.1% lower compared to the standard engine. Testing of the SUNA 6-3 coated engine is subject to current investigations.

Furthermore, in order to evaluate the SUNA feedstocks with regard to their tribological behavior, at the moment honed coatings are being tested on a reciprocating and on a rotating sliding wear tester against nitrided and also against electroplated, alumina reinforced chromium coated (CKS) piston rings. Intermediate results show no measurable wear of the cylinder running surface.

5. Summary and Outlook

Thermal spraying provides a sophisticated and economic technical solution for the application of a high performance wear resistant coating for new aluminum engine blocks. Different process alternatives have been developed in recent years. Latest process development is focused on wire-based feedstock materials to meet automotive industries requirements with respect to costs and process stability. The PTWA (Plasma Transferred Wire Arc) process provides a wear resistant surface with very high quality and reliability. The novel spray processes in combination with new materials and substrate pretreatment concepts are currently undergoing systematic testing and evaluation with very encouraging results. Present results also show very promising characteristics for mechanical pretreatment technologies. Furthermore for more advanced applications it is also possible to apply iron-based coatings with a nanocrystalline structure. With the success seen on new production applications, PTWA has a proven ability to help meet the goals of the automotive industry over the next years in a reduction of CO_2 emissions.

Acknowledgment

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