ABSTRACT

Rising fuel prices and more stringent vehicle emissions requirements are increasing the pressure on engine manufacturers to utilize technologies to increase efficiency and reduce emissions. As a result, interest in cylinder surface coatings has risen considerably in the past few years. Among these are SUMEBore® coatings from Sulzer Metco. These coatings are applied by a powder-based air plasma spray (APS) process. The APS process is very flexible, and can process materials which wire-based methods cannot, particularly metal matrix composites and pure ceramics. Applications range from small 2-stroke engines, motorcycles, and lightweight passenger car engines, up to high-speed diesel truck engines and medium-speed diesel engines.

The compositions of the coatings can be tailored to the specific challenges in an engine, e.g. excessive abrasive wear, scuffing, corrosion caused by adulterated fuel, improved heat transfer from the combustion chamber into the water jacket, etc. A number of engines have been tested successfully. Most of them exhibited significant reductions in lube oil consumption (LOC), reduced fuel consumption, very low wear rates and corrosion resistance on the liner surfaces. This coating solution has been commercialized in various markets. It has proven to be suitable for mass production on both new engine blocks and liners, and for repair of worn-out parts. Such coatings will continue to play an important role when it comes to reductions of weight and emissions in internal combustion engines. An example of such a coating solution will be outlined. It has been carried out in collaboration with BRP Powertrain in Austria on a 1.5L 3-cylinder aluminium engine and together with the adjustment of the ring package and the piston a reduction of 35% in LOC was achieved. This engine will go into production in September 2012 with limited numbers coated in the Sulzer Metco Wohlen facility in Switzerland, until an engineered coating system is ready on site to start large series production. More details on the engine performance and design changes made to the cast aluminium block in order to take full advantage of the coating on the cylinder running surfaces is presented in the paper from Zorn et al. [1].

INTRODUCTION

Over the past years, the demands in the field of internal combustion engines have increased continuously. The reasons are manifold. Often, we see the reduction of CO₂ emissions on top of the list. Reducing weight, minimizing friction, reducing consumption of fuel and oil, optimizing the combustion process, and ensuring the long term stability of the initial engine performance are all part of achieving this overall goal. In addition to these demands, engine developers are facing additional challenges with adulterated fuels in emerging markets, hybridization of cars and in-engine reduction of emissions with exhaust gas recirculation (EGR), although the latter is so far mainly an issue in commercial vehicles and large diesel engines. Some of these engine developments give rise to corrosion and wear issues on the cylinder surfaces.

Internal combustion (IC) engines still have a large potential for further improvement, and significant development activities are ongoing in the areas of turbocharging, engine...
Along with the optimization of other engine components, the cylinder running surface often gets into the focus of engine designers. Honing structures are being optimized on existing, proven cylinder surfaces such as cast iron blocks and sleeves, hypereutectic aluminum alloys (Alusil), and on various galvanic coatings (e.g. Nikasil). In parallel, the direct coating of cylinder running surfaces with the application of thermal spray processes has become more and more important. Applying a coating directly to the cylinder surfaces in aluminum engine blocks can eliminate the need for cast iron sleeves. This can significantly reduce the weight of the engine block, leads to improved heat transfer from the combustion chamber into the water jacket and can - if required - give corrosion protection of the running surface.

Apart from the atmospheric plasma spray (APS) technology, which has been applied in mass production over the past ten years, other thermal spray processes found its way into niche applications in various market segments. The twin wire arc spray (TWAS) and the plasma transferred wire arc (PTWA) processes are the most important of these alternative thermal spray processes used for cylinder surface coating applications. The capability of the APS process for mass production has been amply proven; it has been used to coat more than 2.5 million passenger car cylinder bores over the past 10 years and the developments in the various markets have been continuously reported [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. Recent developments in this area include the industrialization of the process and obtaining the series-production readiness in various additional market segments (including recreational and commercial vehicles, power generation, marine propulsion, and rail), as well as the provision of suitable coating materials to cope with the different challenges in these market segments.

**PROCESS OVERVIEW**

The whole APS cylinder surface coating process, except for the cleaning/washing step, is portrayed schematically in Figure 1 on an aluminum engine block. The process flow is identical for coating of liners that are typically made of cast iron or steel.

A rotating plasma torch (RotaPlasma) is used to apply the coating to cylinder surfaces in engine blocks. Powdered material is brought into the plasma plume with a carrier gas. The particles melt, are accelerated, and hit the surface to build up the coating layer.

**Preparation and Surface Activation**

Before the coating is applied, the bore diameter has to be oversized to accommodate the coating. The oversize is determined by the target coating thickness after final machining (honing). This pre-machining can be carried out by means of line boring, single point drilling, honing, or other processes. An arithmetic roughness average $R_a < 4 \mu m$ is required after pre-machining. Thereafter the part has to be thoroughly cleaned to remove any oil and grease and residues from the machining process from the surface. This is typically done in a dedicated washing machine. The specified surface tension after cleaning and drying is about $36 \text{mN/m}$ in the area where the coating will be applied. The cleanliness can easily be checked on the part using a test fluid of defined surface tension [31]. A clean surface is necessary to guarantee the adhesion of the coating.

The next step in the coating process is the so-called activation of the surface. This step consists of a roughening of the substrate surface to increase the surface area and produce a structure which facilitates the mechanical interlocking of the coating with the substrate. Since the adhesion of the coating is not due to a metallurgical bonding with the substrate, as would be the case for a weld overlay coating, the adhesion of the coating is dependent on this roughening. The activation (roughening) of the surface can be accomplished by a number...
of methods. Contrary to widespread perception, APS coatings can be applied to all different kinds of activated surfaces, not only grit blasted surfaces. Activated surfaces generated with the most commonly used activation processes and an APS coating deposited onto these surfaces are shown in Figure 2.

All of the activation processes shown in Figure 2 have found applications with thermal spray processes on cylinder bore surfaces. The dovetail profile shown at the bottom of Figure 2 was developed by the Braunschweig University of Technology [32]. In general, the profiles created with machining produce an undercut, either by cutting only, or by a combination of cutting and plastic deformation as described in [33]. Which of the activation processes will be applied in a project is determined in close collaboration with the customer. A number of factors need to be considered in the selection of the process. Table 1 gives an overview of the three processes, with pros and cons.

As can be seen from the table, not every surface activation process is well-suited for every substrate material and engine block design. In case of cast iron surfaces, only grit blasting with corundum (Al$_2$O$_3$) is applied today.

Grit blasting can be applied to all different substrate materials. For very high hardness materials, the grit could be SiC. In contrast to the high pressure waterjet activation process, grit blast activation does not enlarge any casting pores that may be present on the cylinder surface. This will allow a larger acceptable pore size in the casting if grit blast activation is used, which will increase the casting yield and therefore reduce the costs.

Mechanical activation may not be feasible in a specific engine design due to geometrical constraints. For example, if the length of the honing recess does not allow the complete tool length to exit the cylinder bore, the profile cannot be completely cut to the very bottom of the bore. Depending on the profile and the method of creating the undercut (cutting only or cutting and plastic deformation), a minimum of up to 9mm of honing recess is necessary. This is not available in all existing block designs, and the current trend in engine design
clearly goes towards minimizing the honing recess. In some engine designs, the bearing blocks protrude fairly far into the bore at the bottom, which may limit the selection of the coating gun. If such a geometrical constraint necessitates the use of a coating gun that sprays at a 20-30° downwards angle (as is the case in the W-type Volkswagen engines), it may be difficult to completely fill a symmetrical profile like the dovetail shown in Figure 2 with coating materials. Parts of the profile could shade off the arriving liquid particles of the coating material and prevent coverage.

With both the high pressure waterjet and the mechanical roughening processes, only the cylinder surface is activated. Chamfers at the top or the bottom of the bores, the honing recess, the top face of the bearing block and other surfaces are not activated. Therefore, overspray (“straying” material particles that are not directed towards the cylinder surface to be coated), which cannot be prevented, has to be completely removed after the coating process, as it will not adhere to surfaces which have not been activated. With the grit blast activation method, all of the above-mentioned critical areas that may be hit by overspray can easily be activated prior to coating application (together with the activation of the cylinder surface), which will lead to good adhesion of any overspray in these areas so that it does not have to be removed. This is a big advantage of the grit blast activation. The risk, however, of leaving entrapped grit particles in the block after the process has to be taken seriously, and appropriate masking techniques and thorough washing of the block have to be guaranteed. Volkswagen in Salzgitter has proven the controllability of the grit blast activation method in large series production on an L5 and a V10 engine block.

For the selection of an activation process it may be important whether or not the pre-machining of the engine block and the coating application will be done at the same site. The activation should be done more or less immediately before the coating application to minimize the risk of surface contamination between the activation and the application of the coating. In case of mechanical activation, this can mean that an additional cutting machine has to be provided at the coating site, if the pre-machining and coating are geographically separated. The consequence is that the engine block has to be mounted again, just for the activation.

From the point of view of the necessary investment the mechanical activation has an advantage, if the activation can be done on an existing machine. High pressure waterjet equipment and its cost of operation are most likely the most expensive solution. Figure 3 shows cylinder bores that have been activated with grit blasting. On the right side, a surface with casting defects (pores) can be seen. Oil that had been entrapped during the pre-machining leaks out and is clearly visible on the activated surface.

### APS COATING MATERIALS AND PROCESSES

The use of powder based materials to build up the coating allows great flexibility in the choice of the material. Requirements for corrosion resistance, low friction, and low oil consumption can be met with appropriate material compositions, which can be varied and adjusted over a wide range. As can be seen in Table 2, the range of materials starts with a low alloyed carbon steel (XPT512), which has been used to coat more than 2 million cylinder bores. The column “HV0.3” shows typical hardness values of the materials, measured on the coating.

The addition of a ceramic such as Al₂O₃/ZrO₂ generally does not increase the hardness, which is deliberate, but it will increase the scuffing and wear resistance. If carbides are blended with the alloyed powder the hardness could increase significantly. However, the size of the carbides has to be chosen carefully, in order not to be abrasive to the piston rings. Such carbides are typically in the size range of 2μm or smaller.

For racing applications, molybdenum-containing materials are the most common, as molybdenum acts like a solid lubricant and can improve the scuffing resistance.

In case of high abrasive wear on the cylinder surface, the materials can be blended with ceramics; this class of materials is called metal matrix composites (MMC). An example of such a material is F2056, the composition and hardness of which are shown in Table 2.

If there is a need for corrosion resistant cylinder surfaces, the basis of the MMC may be a 14Cr-2Mo steel (XPT627); when blended with ceramics, it is called F2071. This material has become the standard material in diesel engines with high EGR rates.

In some applications, it has been found that 14% chromium is not sufficient to guarantee the corrosion resistance. In this case, a superferritic matrix with 28Cr-4Mo (F4375) is used, which, when blended with ceramic, is designated F2220.

Should there be a requirement for coatings with higher hardness, materials with a high content of hard phases are available. These include F5122 and F2186, both of which contain chromium carbide. In some cases, even pure oxide ceramics are applied, as can be seen in Table 2.

As all of these materials are powder based, there is almost no limitation if it comes to mixing and blending powders to create new customized materials. For example, various carbides can be added to corrosion-resistant matrices in order to produce a coating which is both hard and corrosion resistant. The powder based approach also makes it easy to
Table 1. Comparison of the three most commonly applied activation processes for automotive thermal spray applications on cylinder surfaces.

<table>
<thead>
<tr>
<th>Method of surface activation prior to coating application</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Grit blasting (with Al₂O₃)                                | • In mass production for almost 10 years  
• Suitable for all substrate materials  
• Large processing window  
• Activation of areas in the block where overspray from coating application is possible (good adhesion of overspray) | • Dedicated equipment necessary  
• Cleaning with pressurized air necessary after activation  
• Consumption of pressurized air and grit material  
• Risk of grit particle contamination of any openings in the block  
• Grit particles remaining entrapped in the surface | |
| High-pressure waterjet (without abrasives)               | • No contamination of block with abrasive particles  
• Higher bond strength of coating  
• Experience in series production (Daimler and BMW)  
• Cleaning of the surface during activation | • Dedicated equipment necessary  
• Need for vacuum drying to reduce cycle time  
• Only suitable for lightweight materials  
• Small processing window (pressure and standoff distance of nozzle)  
• Opens up casting defects like pores  
• Only areas perpendicular to waterjet activated  
• High casting quality required (porosity, segregation)  
• 100% visual inspection of all activated surfaces required after activation  
• Patent-protected pressure ranges (license cost) | |
| Mechanical roughening                                    | • No contamination of block with abrasive particles  
• No separate equipment necessary if it can be done as part of the pre-machining of the block  
• Very high bond strength of coating | • Quality control of activated surfaces remains an open issue  
• Cleaning of the activated surface may be necessary  
• At this point, only suitable for lightweight alloys (prohibitive wear rate on tool for cast iron)  
• Lifetime of tooling not yet determined in detail  
• No activation of chamfers and honing recess  
• Experience only with small series production  
• Interrupted cut can be critical (e.g. ventilation holes, lower end of bore)  
• Complete filling of the open profile volume with coating material is difficult  
• Long honing recess as complete tool has to exit the bore to guarantee complete profile to the bottom of the bore | |
blend in solid lubricants, such as MoS$_2$, WS$_2$, or ZnO. In principle, all powders suited for plasma spraying can be processed.

Figure 4 shows metallographically prepared microstructures of some of the coatings shown in Table 2. All of these coatings exhibit porosity in the range of 1 - 3% by volume. This is one of the main characteristics of APS coatings, and plays an important role in their functionality on the cylinder running surfaces of IC engines.

As indicated above, APS coatings can be applied with a rotating plasma torch. Alternatively, if the parts are rotationally symmetrical (liners, some single cylinders), the part can be rotated while the plasma torch will only travel up and down on a single axis during the coating application. Different torches are used depending on the size of the bores. The SM F210 gun is typically used for bore diameters up to 150 mm, including passenger cars, race engines, recreational vehicles, and some commercial vehicles. For bores sizes in the range of 40 - 60mm, the SM F300 and SM F3 plasma guns are used. For larger bore sizes, such as 2-stroke and 4-stroke medium-speed diesel engines and gas compressors, the best choice is the iPro90, which can achieve powder feed rates of up to 250g/min. Bores with diameters above 500mm may be coated with the TriplexPro plasma gun, with powder feed rates of up to 500g/min.

### Table 2. Some of the most commonly-used APS coating materials.

<table>
<thead>
<tr>
<th>Alloying Elements of the Powder</th>
<th>Blended into the Powder</th>
<th>HV$_{0.3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Mn</td>
<td>Cr</td>
</tr>
<tr>
<td>XPT512</td>
<td>1.0 - 1.3</td>
<td>1.4 - 1.6</td>
</tr>
<tr>
<td>F4301</td>
<td>1.0 - 1.3</td>
<td>1.4 - 1.6</td>
</tr>
<tr>
<td>F4334</td>
<td>1.0 - 1.3</td>
<td>1.4 - 1.6</td>
</tr>
<tr>
<td>F2056</td>
<td>1.0 - 1.3</td>
<td>1.4 - 1.6</td>
</tr>
<tr>
<td>XPT627</td>
<td>0.4 - 0.5</td>
<td>0.4 - 0.8</td>
</tr>
<tr>
<td>F2071</td>
<td>0.4 - 0.5</td>
<td>0.4 - 0.8</td>
</tr>
<tr>
<td>F4375</td>
<td>–</td>
<td>0.5 max.</td>
</tr>
<tr>
<td>F2220</td>
<td>–</td>
<td>0.5 max.</td>
</tr>
<tr>
<td>F5122</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>F2186</td>
<td>composition of F5122 with the addition of 20 wt.% Mo</td>
<td>–</td>
</tr>
<tr>
<td>F6250</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>F6397</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
feed rates of up to 500g/min. Three torches can be seen in Figure 5: the SM F300 in the 40mm bore of a single cylinder engine, the SM F210 in the 81mm bore of an aluminium engine block, and the iPro90 gun in an EMD 16-710 G3 cylinder liner for a diesel locomotive application.

A typical coating thickness after final machining (honing) is in the range of 120 - 130μm for passenger and high performance car applications. For heavy-duty diesel engines, the target coating thickness is around 150μm. Including the honing allowance, the coating thickness in the “as sprayed” condition is around 230 - 280μm. Typical surface roughness

Figure 4. Typical microstructures of some commonly-used APS coating materials for cylinder surfaces
values after coating application are $R_z \sim 50 \mu m$, which is very smooth if compared to wire sprayed surfaces.

The APS coating technology can also be applied for the remanufacturing of worn-out parts. If necessary, a coating thickness in excess of 1mm can be achieved, depending on the bore size and the coating material. This is an important feature of the coating solution, as it allows remanufacturing options formerly not available: for example, bringing cylinder bores back to original size (e.g. vintage cars). This is attractive for many engine types, because it requires only a single size of piston and rings, a single size of cylinder head sealing device, and simplifies the logistics significantly.

Final Machining of the Coating (Honing)

The performance requirements for a honed cylinder surface are high, and will further increase as the injection and combustion pressures increase, and even lower friction coefficients, greater corrosion resistance, and lower wear rates are targeted. Recent results indicate that the surface, apart from having the suitable chemical composition, should exhibit small and homogeneously distributed open pores in order to take the full benefit of a plasma coated cylinder surface. The final machining of the plasma coating is a very important step which is carried out by honing with diamond ledges. The final surface has a so-called “mirror finish,” without a plateau honing pattern. Over the past few years, the recommended specification for the honed, plasma coated surfaces has been refined, based on engine tests with measurements of reduced lube oil consumption (LOC) and fuel-oil consumption (FOC). Table 3 shows the recommended roughness specification of the honed surface.

<table>
<thead>
<tr>
<th></th>
<th>Re</th>
<th>Rz</th>
<th>Rk</th>
<th>Rpk</th>
<th>Rw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra</td>
<td>0.15–0.35 μm</td>
<td>&lt; 5 μm</td>
<td>&lt; 0.3 μm</td>
<td>0.07–0.16 μm</td>
<td>0.5–2.0 μm</td>
</tr>
</tbody>
</table>

A honed plasma coated surface can be seen in Figure 6 (left) in the scanning electron microscope (SEM). It reveals one of the main characteristics of this type of coatings: open porosity. This porosity retains the oil in the surface. It is also the reason why the surface can be honed to a mirror finish and will not scuff as a similarly-polished cast iron bore does. It is important to perform the honing in such a way that the pores are properly opened, have deburred edges and do not contain any debris from the honing process. Figure 6 (right) shows a mirror finished surface of a 200mm diameter cylinder liner with an APS coating (F2071).

APPLICATIONS AND INDUSTRIALIZATION

The application of thermal spray technology in the mass production of cylinder bore coatings requires a combination of know-how from different areas, both from the industrializing partner and from the user. Casting technology, cleaning, machining, thermal spray processes, honing, and engine design are a few of the most important areas. For the supplier of the coating equipment, fast on-site support and access to all of the technology partners involved in the coating application process (e.g. cleaning, machining and honing) are additional challenges that require the appropriate infrastructure and resources. In the following section, an
example of an industrialization project of Sulzer Metco’s APS coating equipment is highlighted.

Development Project with BRP Powertrain in Austria

A development project has been carried out in close collaboration with BRP Powertrain Austria over the past 2 years. The engine that was used as a technology demonstrator has 3 cylinders and specific power output of 126 kW/L. The current version of this product on the market is equipped with cast-in cast iron sleeves. For the next generation of this engine, it is absolutely essential to significantly reduce the LOC in order to conform to the tightening emission regulations in the respective market segment (recreational vehicle). The reduction of the LOC was therefore the prime development target. The start of production for this engine will be in September 2012 with an APS coated cylinder bore, directly applied to the aluminum surface.

The application of an APS plasma coating in this engine block required significant design changes, particularly to reestablish the necessary stiffness of the open deck bores after eliminating the cast iron sleeve. In addition, the management of the heat flux from the combustion chamber into the water jacket had to be addressed, as the system changed fundamentally by eliminating the cast iron sleeve. The optimization of the system included changes to the piston and the piston rings in order to take full advantage of the APS plasma coating. The final coating solution, which was developed together with the OEM, will lead to an engine block which is completely free of overspray. An important contribution came from the honing company NAGEL, which provided support to develop and install a robust process for the final machining (honning) to achieve a very smooth, mirror finish of the plasma spray coating. In Figure 7, a metallographic section of the coating at the final stage of the development is shown in the “as sprayed” condition (material: XPT512). Figure 8 shows the roughness profile after honing, and Table 4 shows the relevant roughness values of this profile and Figure 9 shows a picture of the aluminium engine block.

The following coating specification for the final coating was used:

- **corrosion resistance** on the level of cast iron (as the engine is currently on the market with cast iron sleeves and does not have any corrosion issues. In addition there is experience with this specific coating applied in series production in a V6 aluminium outboard engine from Yamaha Motors in Japan)
- **porosity** 1-3%, measured with image analysis on a metallographic section as shown above
- **hardness** 300-500 HV\(_{0.3}\), as an average out of 10 measurements on a metallographic section
- **bond strength** >30MPa, determined according to the standard ASTM C633
- **max. temperature** \(T_{\text{max}}\) of the aluminium engine block was allowed to be 200°C during the coating application

![Figure 6. Left: Scanning electron micrograph of honed surface with open porosity for oil retention. Right: mirror finished surface of a 200mm diameter cylinder liner with F2071 APS coating.](image)
Table 4. Roughness values for the honed XPT512 surface profile shown in Figure 9.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R_a$</th>
<th>$R_z$</th>
<th>$R_k$</th>
<th>$R_{pk}$</th>
<th>$R_{vk}$</th>
<th>Mr$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values in μm</td>
<td>0.129</td>
<td>3.84</td>
<td>0.14</td>
<td>0.07</td>
<td>0.8</td>
<td>84%</td>
</tr>
</tbody>
</table>

Figure 7. Metallographic section of the XPT512 APS coating applied to the aluminum cylinder bore surface (as sprayed).

Figure 8. Typical roughness profile of the honed XPT512 APS coated cylinder surface.

Mr$_2$ represents the lower limit of the core roughness profile (in the Abbott-Firestone curve).

A number of 350 hour runs on the test bed and in vehicles showed a reduction of the LOC of 35% in comparison to the existing cast-in cast iron solution. An additional observation was that the APS coated cylinder surfaces did not exhibit measurable wear after the above mentioned test programs. This is in line with earlier investigations on a plasma coated diesel engine, which exhibited a radial wear of the coating in the order of 1μm over a test period of 300h [34].

More details about the specific engine tests performed are given in the paper from Zorn et al. from BRP Powertrain [1].

CONCLUSIONS

From the evidence presented in this paper, it can be seen that the APS cylinder bore coating solution is both versatile and robust, even in automotive mass production. It has emerged, especially over the past few years, as a leading-edge choice of Original Equipment Manufacturers (OEMs) for both new and re-manufactured cylinder blocks and liners. As a proven and robust product capable of withstanding the rigors of high speed and highly automated industrial production processes, this technology has become a preferred solution for many engine professionals. A broad base of materials extends the solution capability of this system into all types of reciprocating engines, no matter what the application or design parameters of the engine are. The optimization of the cylinder running surface coated with a porous APS coating with an adjusted ring package and piston geometry led to an improvement of the LOC in a high performance engine of BRP Powertrain of 35% compared to the current engine in the market that uses a cast iron sleeve. The changes to the piston rings and the piston geometry were specifically made to take full advantage of the mirror finished, porous APS cylinder running surface coating. BRP Powertrain will continue this development together with Sulzer Metco and apply the learnings from this technology demonstrator to a number of additional engine types in the future.

A study that was recently completed in Germany compared the friction of coated cylinder running surfaces with cast iron surfaces in a floating liner test engine. Under full load conditions of the engine the APS coating showed a reduction in friction of over 20% compared to the cast iron baseline [35].

REFERENCES


34. Sauerwein, U., “Zylinderlaufflächen für Aluminium-Dieselmotoren”, MTZ 2002-06


ABBRÉVIATIONS

APS - Air Plasma Spray
EGR - Exhaust Gas Recirculation
FOC - Fuel Oil Consumption
IC - Internal Combustion
LOC - Lube Oil Consumption
MMC - Metal Matrix Composite
OEM - Original Equipment Manufacturer
PTWA - Plasma Transferred Wire Arc
SEM - Scanning Electron Microscope
SOP - Start of Production
TWAS - Twin Wire Arc Spray

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