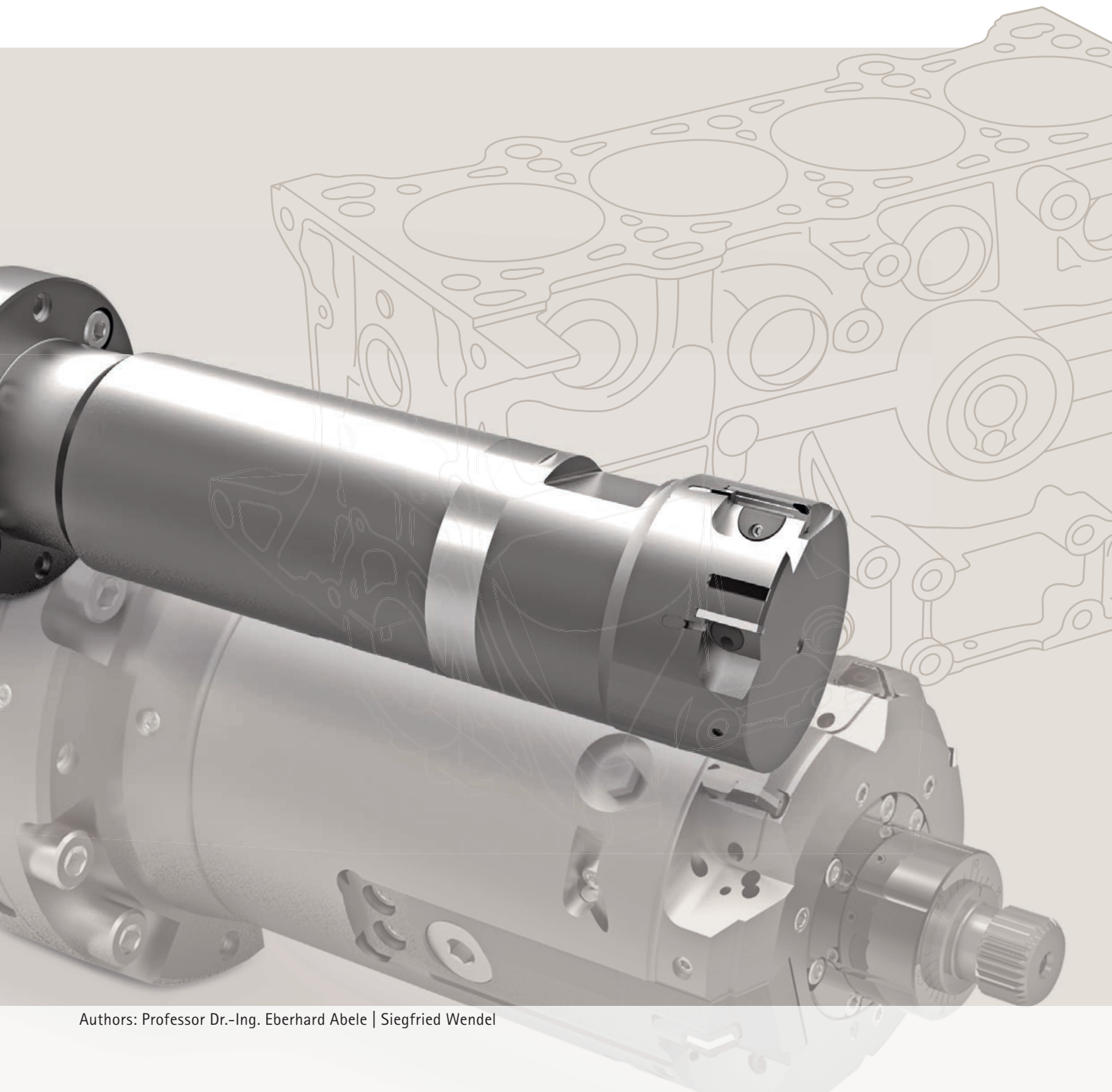




# TECHNOLOGY REPORT

05 | Processing thermally sprayed coatings



Authors: Professor Dr.-Ing. Eberhard Abele | Siegfried Wendel

## Motivation

### Motivation

With the aim of achieving European and international climate targets, the upper limits for emissions in the passenger car sector have been further reduced. This is resulting in a drive for innovation in engine development and manufacture, aimed at efficient design in internal combustion engines and enhancing their efficiency levels. To achieve these objectives, all of the available potentials for improvement must be exploited, from weight savings throughout the vehicle and reducing friction in the drive train through to more efficient combustion. Even reducing the weight of the vehicle by just 100 kg results in an 8.5 g/km CO<sub>2</sub> reduction in emissions, corresponding to around 0.3 litres of petrol per 100 km. Assuming the life cycle of the vehicle to cover a distance of 150,000 km, this then amounts to 450 litres. In pursuit of more efficient combustion, in recent years the trend has been towards highly-supercharged engines of low cubic capacity and fewer cylinders – frequently referred to as ‘downsizing’. The concomitant requirements imposed on the internal combustion engine like an increased combustion pressure combined with generally higher temperatures call for new construction

materials [1]. With – as pointed out above – weight savings being called for at the same time, greater use is being made of aluminium materials. At the same time, component design is being optimised for minimum material volume and minimum piston bore spacing, with the thickness of the material between the individual cylinders representing an important factor here.

One possible way of satisfying the requirement for minimum component volume and the reduction of friction between the cylinder line surface and the piston ring is the use of a thermally sprayed surface applied to the cylinder line surface. As this does away with the cylinder sleeve currently in use, savings in both construction space and weight can be achieved. However, the direct application of any such coating calls for special pre-processing to ensure that the coating to be applied adheres adequately. In the past this was normally undertaken by means of very time-consuming blasting technology.

In order to enhance productivity in this area, MAPAL offers a solution involving mechanical activation of the surface. This fine boring technology makes it possible to pre-process and activate the cylinder bore on the same

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machine. A special tool design creates fine undercuts on the surface and this can considerably increase the adhesion of the coating.

The coating process is normally followed by a two-stage honing process which creates the required surface, consisting of striae for oil adhesion and plateaus to provide the contact ratio. Here, too, MAPAL offers a system with a geometrically-defined cutting edge which replaces the rough honing process with a fine-boring process. If both

of these technologies are used, it becomes possible to increase manufacturing productivity while also improving the functionality of the component.

Below we present the main coating procedures in the field of cylinder line surfacing, along with the trends in engine construction. We also look at the technologies indicated above to provide an insight into how they function and the potentials they hold.

## Motivation

## Trends in engine design

Due to the higher stresses imposed on the cylinder line surface, the use of lightweight aluminium alloys for crankcases calls for special solutions, as these surfaces do not normally offer adequate tribological properties in respect of friction and wear. To meet these requirements there are three different construction types available for the aluminium crankcase:

- heterogeneous construction type
- monolithic construction type
- quasi-monolithic construction type

In the heterogeneous crankcase construction type, the cast-iron cylinder sleeves are inserted or cast into the aluminium crankcase [2]. A monolithic construction type involves doing away with cylinder sleeves entirely and is only possible with the use of special alloys (hyper-eutectic Al-Si alloys with hard silicon crystals), and these also impose high demands on the machining process. Similarly to the monolithic construction type, the quasi-monolithic construction type does away with cylinder sleeves, while at the same time fulfilling the requirements for the cylinder line surface, even when use is made of conventional (hypo-eutectic) aluminium alloys for the crankcase. This is achieved by coating the cylinder line surface and also by means of local material engineering. The preferred construction type is derived from the performance requirements on the engine. So in today's passenger car sector, due to the relatively low distances covered and the need for replaceability

falling away as a result, the cylinder sleeves are cast in (heterogeneous construction type). This heterogeneous crankcase construction type guarantees excellent heat dispersal out of the cylinder chamber [2]. The roughened sleeves are inserted into a mould and have molten aluminium alloy cast around them. The sleeves are then fine bored and honed. This honing represents a last important mechanical machining step in the processing and has been irreplaceable. With the superimposition of a rotary and a translational movement of the tool during honing, a network of criss-crossing striae is created in the cylinder line surface, as required for generating the lubricating film. Once the sleeves have been honed, they end up with a wall thickness of up to 4 millimetres. The material used for cylinder sleeves is predominantly lamellar graphite cast iron (GJL) or for higher stresses vermicular graphite cast iron (GJV) [2]. Use is also made of coated or uncoated aluminium alloys and simple construction steels. Using sleeves provides the benefits of low costs and a high degree of resistance to wear. However, adopting this approach diverges from the original intentions of reducing weight and achieving a more compact construction. This explains why greater use is being made of the quasi-monolithic construction type which combines the good tribological properties of a cylinder sleeve and the possibility of a considerable saving in weight. The coating processes applied in this connection are presented below.

## Trends in engine design

1 Cf. „The EU Directive on Reducing CO<sub>2</sub>-emissions from Passenger Cars“

2 Cf. „Volkswagen Sustainability Report 2013“

## Coating processes

### Coating processes

As a result of high production costs and high substrate temperatures, CVD and PVD processes cannot be considered for serial applications [3]. Despite a very wide range of variants and low substrate temperatures, due to the long cycle times, high costs and poor environmental compatibility involved, even galvanic processes (e.g. Nikasil) are increasingly being replaced by thermal

processes [3]. Accordingly, the trend in the coating of cylinder line surfaces is heading clearly in the direction of thermal spray processes. The functional principle for the thermal spray process is described in greater detail below. Fig. 1 provides an overview of the current coating processes.

Coating process		
Thermal Spraying	Galvanic process	Others
Wire Arc Spraying (WAS)	NIKASIL	Physical Vapour Deposition (PVD)
Atmospheric Plasma Spraying (APS)	CROMAL	Chemical Vapour Deposition (CVD)
Plasma Transferred Wire Arc (PTWA)		
High Velocity Oxygen-Fuel Flame Spraying (HVOF)		

Fig. 1: Overview of coating processes

### Wire Arc Spraying (WAS)

#### Wire Arc Spraying (WAS)

Wire arc spraying is already used in serial production by major automobile manufacturers such as Daimler and BMW [4, 5]. In this process two wires under electrical tension are fed into the spray gun. An electric arc is created where the wires come together in the front part of the spray gun. This arc completely melts the wires and the molten particles are propelled forward by means of a nebulising gas (air, nitrogen or argon) at high speed, onto the surface to be coated [6]. Almost all electricity-conducting wires can be melted and sprayed in this way. It is also possible to use flux-cored wire to create a variety of alloys or for the application of hard materials (carbides).

The flexibility of this process is also evident in that it can be applied irrespective of the manufacturing process used for the crankcase. This means that die-cast, chill-cast or sand-cast crankcases can be coated by means of wire arc spraying. The application rates for WAS in general (not specifically for cylinder line coating) are relatively high in comparison with other thermal spraying processes and lie in the range of 6 to 8 kg/h [6]. The achievable wall thicknesses for cylinder bore surface coating are up to 0.3 mm, depending on the individual user [7]. Fig. 2 presents the wire arc spraying process.

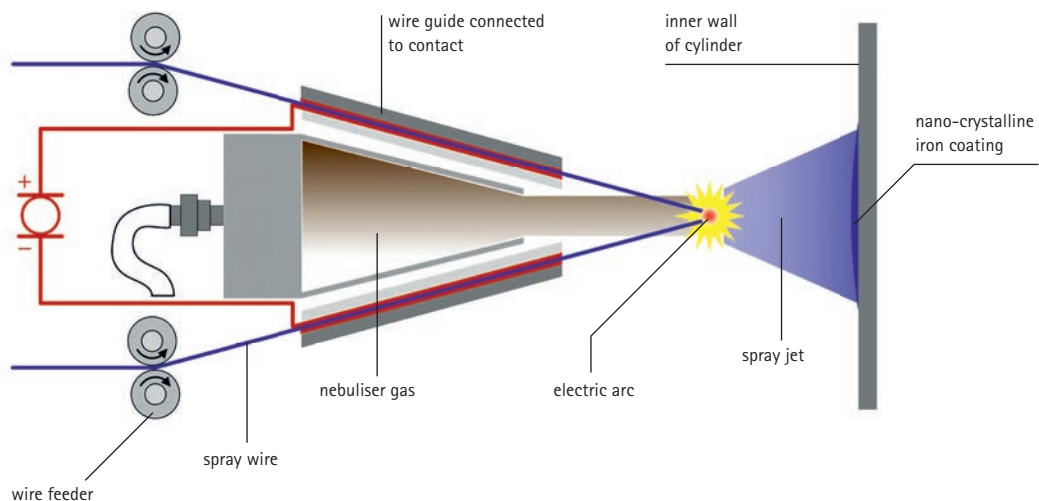


Fig. 2: Wire arc spraying (WAS), own representation with reference to [9]

### Atmospheric Plasma Spraying (APS)

This process makes use of a rotating plasma burner for coating the cylinder line surface. It has been developed by Sulzer Metco [8]. The coating unit produced under the RotaPlasma name and the overall cylinder line surface coating package labelled SUMEBore are already in use in the serial production of both VW and Bugatti, and consist of cleaning, surface activation and honing process [8, 9]. In this process, within the plasma burner there is a bundled plasma spray generated at high speed. A material in powder form is directed to the outlet side of the burner, where it is melted and sprayed onto the surface for coating (Fig.

3). The plasma spray is created by directing the gases (argon, nitrogen, helium, hydrogen or mixtures of these) through a permanently burning electric arc. The supply of materials in the form of powder and plasma temperatures of up to 20,000 °C permit a high degree of flexibility in the choice of materials [10, 11]. With this technology it is possible to spray the widest range of materials, from low-alloy carbon steels and composite metal-matrix materials through to purely ceramic materials. Typical coating thicknesses with SUMEBore found in the passenger car sector are 0.12 millimetres [8].

Atmospheric Plasma Spraying (APS)

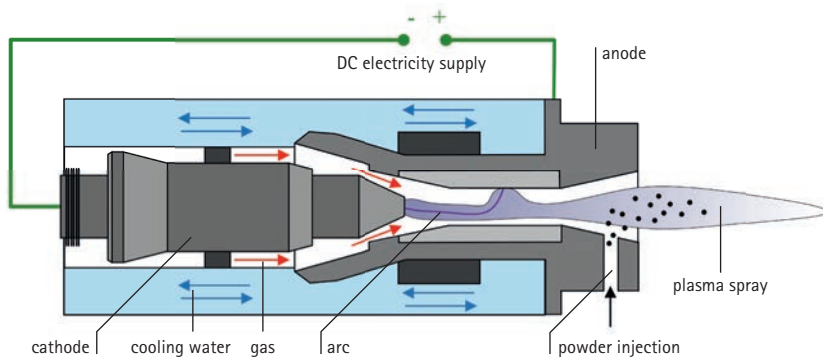


Fig. 3: Atmospheric plasma spraying, own representation with reference to Sulzer Metco

### Plasma Transferred Wire Arc (PTWA)

Plasma Transferred Wire Arc was originally developed by Flame-Spray Industries in collaboration with Ford and is also a process used for cylinder line surface coating in the industry today. Honsel AG and GTV market this process commercially and have it in serial production use at Ford and Nissan [3, 9]. In the vicinity of the plasma outlet there is a spraying additive material in the form of a wire directed to the side towards the plasma spray. The argon and hydrogen gas flow is directed along the wolfram cathode at high speed. The plasma is generated by means of a high-voltage discharge and then

carried over to the wire, with the electric circuit being completed by the wire serving as the anode. The wire is resistance-heated by a strong current (65-90 Amps) and melted and nebulised under the impact of the plasma spray. The plasma burner thus created is now applied to a rotating spindle and can be used for coating cylinder line surfaces [9]. Honsel AG's PTWA process can be used irrespective of the casting process used for the aluminium cylinder crankcase [3]. Application rates are 4 kg/h [13]. After honing, the coating applied is 0.15 millimetres thick.

Plasma Transferred Wire Arc (PTWA)

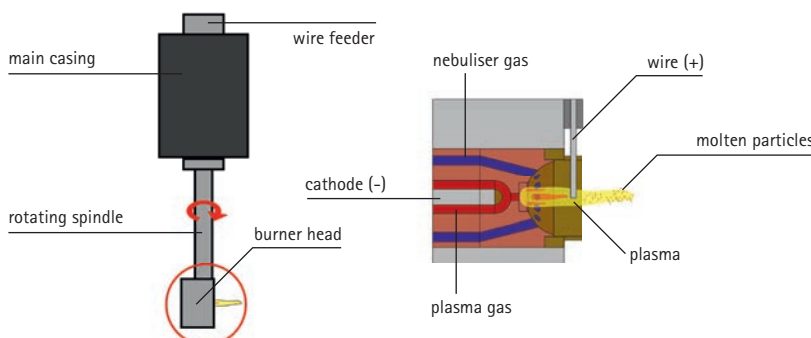


Fig. 4: Plasma Transferred Wire Arc (PTWA), own representation with reference to [9]

### High Velocity Oxygen-Fuel Flame Spraying (HVOF)

## High Velocity Oxygen-Fuel Flame Spraying (HVOF)

In the high velocity oxygen-fuel flame spraying process, a material in powder form is injected into a flame comprised of propane, propene, acetylene, hydrogen or natural gas and liquid flammable materials such as kerosene. Characteristic features of this process are temperatures of 2,500–3,200 °C and very high speeds in the gas flow after the expansion jet of up to 2,000 m/s (making it the highest value of all of the thermal spraying processes) [10, 11, 14]. The high kinetic energy of the particles results in a dense structure of low porosity. Conversely, the thermal energy of the powder particles remains comparatively low, with a beneficial effect on coating properties and reducing the transfer of heat over to the substrate. The procedure is also characterised by the very high

binding forces and a very high degree of hardness in the coating applied [10]. According to Sulzer Metco AG, however, due to the dependence on the temperature of the flame and the flammable material used, and due to the small clearance from the substrate during the coating process, the cylinder block may be overheated despite the low thermal energy of the powder particles. As far as the choice of the spray additive material in powder form is concerned, the highest degree of flexibility is provided. With HVOF it is possible for very thin coatings of high quality to be obtained [15]. However, this process is currently in the development stage and has not as yet seen use in serial production in the field of cylinder line surface coating [3].

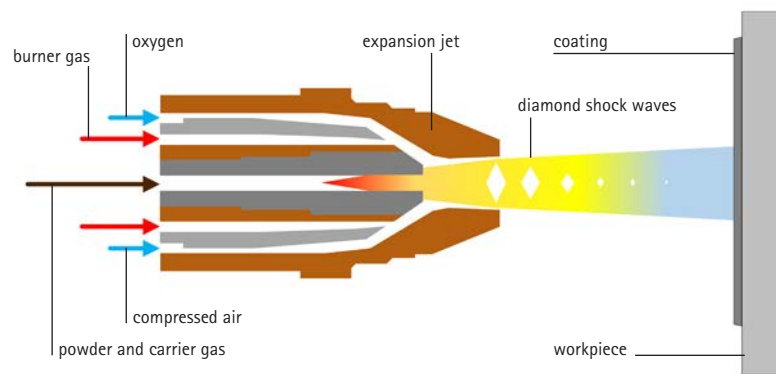


Fig. 5: High Velocity Oxygen-Fuel Flame Spraying (HVOF), own representation with reference to [10]

## Pre-processing the surface for coating

### Pre-processing the surface for coating

Before the coating can be applied, the surface for coating must be activated in a roughening process. This is a necessary precondition if the sprayed particles are to adhere to the cylinder line surface. There are numerous processes available for surface activation, each with its own specific advantages and disadvantages:

- corundum blasting
- high-pressure water blasting
- mechanical activation
- chemical activation
- roughening the surface with a laser

In the past, corundum blasting has been the process most frequently used in the industry. Conversely, high-pressure water blasting is sometimes used in combination with wire arc spraying, although it is regarded as very expensive and associated with high plant and operating costs [12]. One significant disadvantage of chemical treatment is disposing of liquid materials. Mechanical activation involving a geometrically-defined cutting edge has important advantages over other procedures. Fig. 6 shows the characteristic surface structures for the current processes. Here, mechanical activation is the only process to generate a geometrically-defined surface.

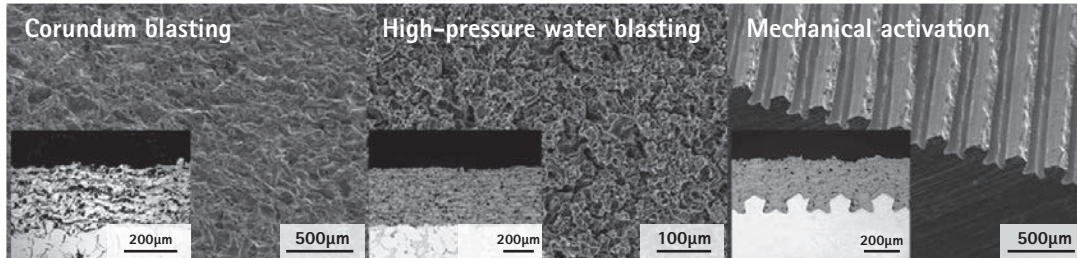


Fig. 6: Surface activation processes. Source: [12]

Mechanical activation is assigned to the fine boring process group, and as such can be undertaken in the machining centre in the same workpiece clamping arrangement as the preceding fine boring [16]. Mechanical activation allows the roughening process to be integrated in serial production, with comparatively short cycle times. At the same time, unlike water or corundum blasting, a higher degree of process reliability is achieved from the use of geometrically-defined cutting edges with energy efficiency and environmental compatibility also being improved. The influence of changing material properties is also minimised with the use of geometrically-defined cutting edges. This process calls for visual checking for breaks in the cutting edge and tool wear. Nevertheless, this does guarantee the required quality of the machining at the same time.

Processes and tools for mechanical surface roughening for the subsequent thermal spraying are offered by a number of suppliers. While the tools display differences in their construction, in the basic way they work and in the topology of the surface they produce they are similar. These tools create a profile with grooves, fluting and undercuts, as what is termed a dovetail structure over the surface for coating and in this way produce the ideal conditions for the coating sprayed to adhere.

At the Institut für Werkzeugmaschinen und Fertigungstechnik (IWF – Institute for Machine Tools and Manufacturing Technology) of the Technical University of Brunswick, a process for the mechanical activation of surfaces with a geometrically defined cutting edge has also been developed and patented. With this tool it is also possible to produce a dovetail shaped surface structure. The tool takes the form of a conventional cutting plate with a poly-crystalline diamond (PCD) insert soldered in place. For its part, the PCD insert consists of two individual cutting edges facing in opposite directions, put in place by an erosion process (cf. Fig. 7)

[16]. Fine turning of the cylinder bore is undertaken first using a separate tool in an upstream work step. With the superimposed machining by the two individual cutting edges on the tool developed, at a constant feed the typical dovetail surface structure with undercuts is created. In the course of adhesion studies an optimum cutting depth of 100 µm was calculated, with a minimum cutting depth of 75 µm being required for adequate adhesion. At the optimum cutting depth an adhesion value of 60 MPa is obtained [16]. Depending on the length of the cylinder bore and the aluminium alloy, the machining time is 10 to 20 seconds. When compared with conventional blasting processes, this still represents a considerable improvement [16].

Pre-processing the surface for coating

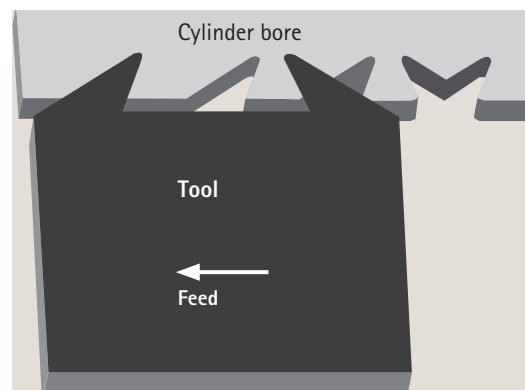


Fig 7: Creating the roughening profile with the insert drilling tool. Source: [16]

### Pre-processing the surface for coating

The MAPAL tool concept carries out the roughening process in one operation. First, the cylinder diameter is fine urned. A right-angled profile is then created with a comb-cutter, before the right-angled profile is flattened with a spherical cutting edge, thus producing an undercut. Fig. 8 shows the roughening tool with two cutting edges (1 and 2) and a spherical cutting edge (3). The structure of the surface (depth, groove width and undercut angle) can be flexibly adapted to the respective coating process through the choice of tool and the settings for the process parameters, such as feed (cf. Fig. 9). At the same time, the profile depth can be varied within the range 70–120  $\mu\text{m}$  and the distance between grooves in the range 0.3–0.45 millimetres. Poly-crystalline

diamond (PCD) is used as the cutting material. The cycle time with this process is between 7.5 and 11 seconds. By way of comparison, high-pressure water blasting normally requires 30–40 seconds. The quality of the structure created is ensured in that the cutting edges are measured before and after machining and offset against the tracking or machine data. Having acquired a licence on a basic patent for the mechanical roughening of cylinder line surfaces prior to thermal spraying, MAPAL is also in a position to offer its customers reliable solutions from both technical and legal points of view. The basic patent provides protection for both grooves and thread-like profiles with undercuts.



Fig. 8: Roughening tool. Source: MAPAL

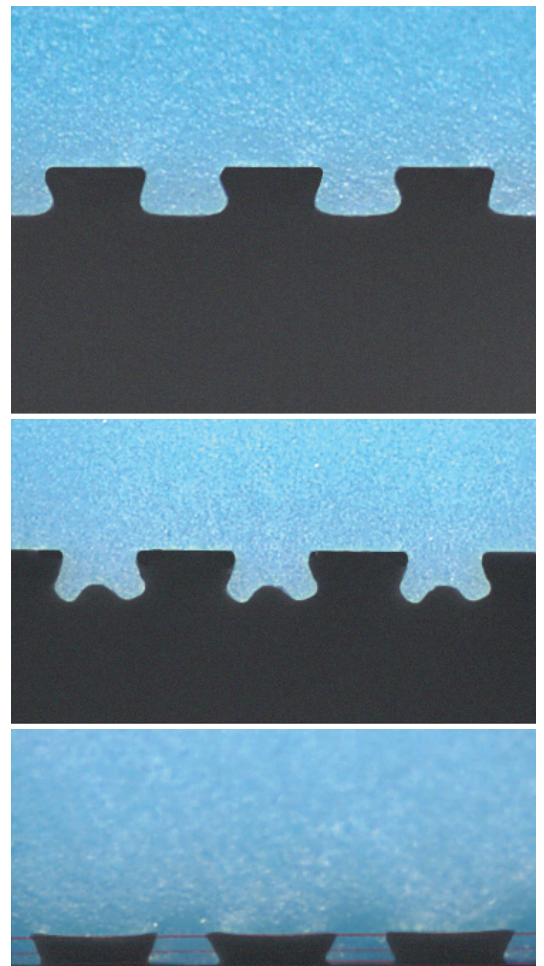


Fig. 9: Roughening profile. Source: MAPAL



## Post-processing thermally sprayed coatings

On completion of the coating process, the cylinder bore surface is finished by honing. To obtain the optimum results, the parameters for the honing process must be adjusted for the specific coating technology in use. This step in the process is of particular importance as the essential properties of the coating are determined by this honing. Micropores created by the thermal spraying must not be sealed in the process, but must instead be exposed by the honing process [8]. These pores are essential as they serve as oil reservoirs and have a crucial role to play in determining tribological properties. As such, they represent the counterpart to the striae on the conventional cylinder line surface.

In order to obtain the desired cylinder line surface structure consisting of plateaus with an extremely high contact ratio and with individual striae for oil adhesion, the classic honing process normally consists of pre-honing

and finish honing (fine honing). In the first instance, pre-honing creates a rough surface with striae and peaks. These peaks are then flattened out by the fine honing, thus obtaining a plateau structure. While to date there are no alternatives to fine honing being offered, pre-honing can be replaced by fine boring. For this, MAPAL offers a tool for rough turning with a geometrically-defined cutting edge and fitted with PcBN cutting edges (Fig. 10). The ideal process parameters for the use of the tool are highly dependent on the coating process used. The tool also features a wear-compensation system and a coolant-controlled actuating mechanism. When used in combination with a wear-compensation system and with five or six cutting edges, with such a tool it is possible to process some 1,000 to 1,500 bores and still adhere to the cycle times required by the industry.

[Post-processing thermally sprayed coatings](#)

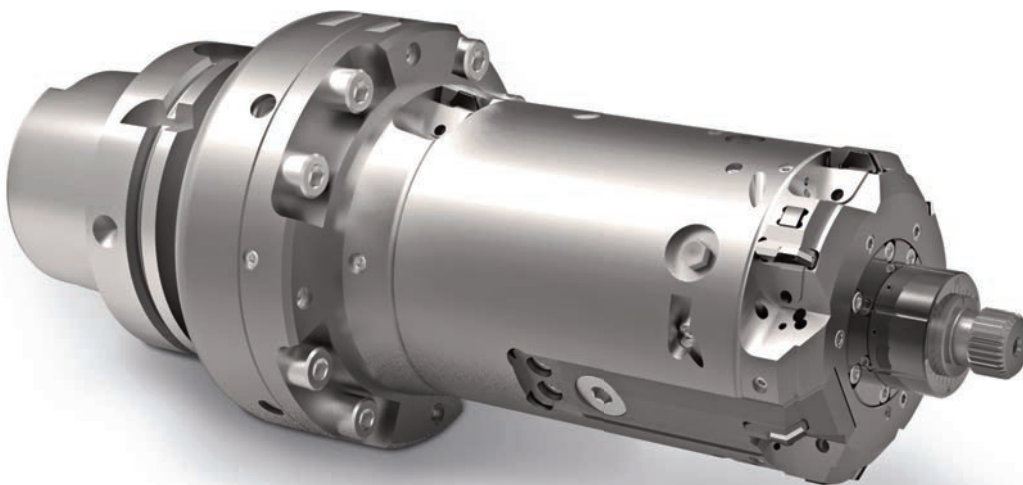


Fig. 10: MAPAL actuating tool

## Advantages of thermally sprayed coatings

With the use of thermally sprayed coatings in the past, various manufacturers have managed to achieve weight reductions of more than 4 kg per engine with different coating processes [17]. Furthermore, thanks to the micropores in the thermally sprayed coating, improved

tribological properties are obtained, resulting in lower friction values and greater resistance to wear. This has a positive effect on fuel and oil consumption and therefore allows for lower emissions from the vehicles of tomorrow.

[Advantages of thermally sprayed coatings](#)

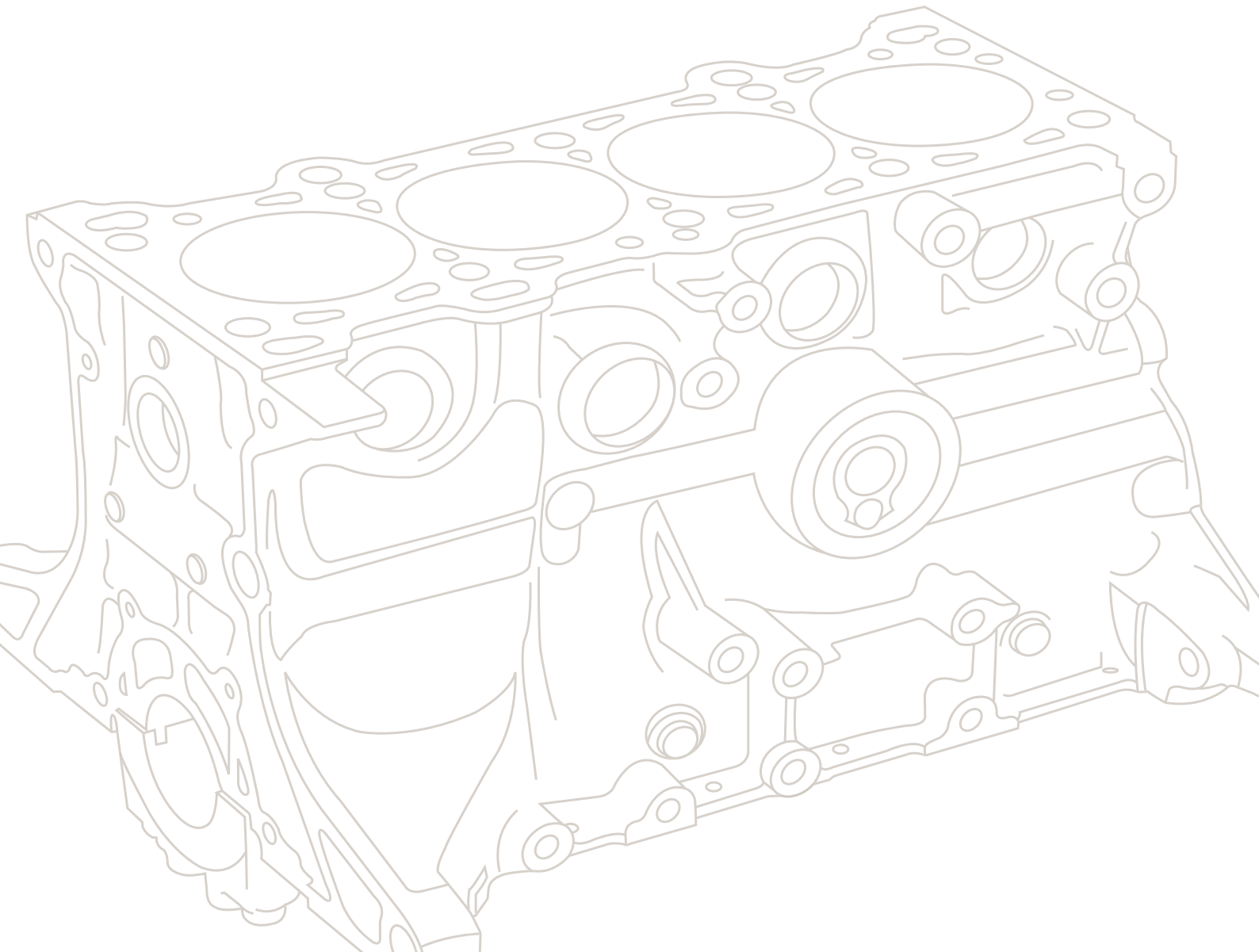
## Summary

### Summary

In order to fulfil international climate targets, automobile manufacturers find themselves confronted with ever more stringent emissions directives. These call for ever more efficient internal combustion engines along with higher demands for performance on the part of customers. These conflicting targets are being addressed by manufacturers with small, highly supercharged engines also offering reduced weight and less friction. New production technologies are essential.

One way of reducing weight is to use thermal spraying for coating the cylinder line surface. Due to the reduced thickness of the coating and with the coating being applied directly to the base material, it is possible for the cylinder bores to be positioned more closely together, thus making the entire engine block smaller and lighter. If this technology is combined with efficient post-processing, it becomes possible for manufacturing times to be cut and the running properties of the engine to be improved.

For this, MAPAL has developed a special technology with geometrically-defined cutting edges which makes it possible both to activate the surface prior to the coating process and also to simplify the post-processing work chain. The surface to be coated is processed in a fine turning process to produce a finely structured surface profile. This special structuring produces undercuts making it possible to ensure optimum adhesion for the coating. With this technology alone, in this production step it has been possible to reduce the main machining time for each cylinder bore by more than 50 %. Furthermore, it has been possible to replace pre-honing with a fine turning process, thus allowing this process step to be undertaken on a conventional machining centre. This successful application of the stated technologies gives rise to enhanced productivity and weight reductions of over 4 kg per engine, along with improved running properties.



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Reading List

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