Advances in high velocity oxygen fuel spraying enhance long term durability in Bosch Rexroth Large Hydraulic Cylinder rods.

From miter gates to casters, from oil rigs to excavation equipment, Bosch Rexroth Large Hydraulic Cylinders are utilized in very demanding, corrosive environments. Both the design and the materials utilized in the creation of these large-scale hydraulic systems have been rigorously engineered to provide superior performance throughout their lifecycle, no matter how harsh the conditions.

One key Large Hydraulic Cylinder component requiring special attention is the most exposed and critical part of the entire hydraulic cylinder: the rod. Typically, a cylinder in use in an offshore application has high demands on corrosion resistance and repairability, while cylinders functioning in a large civil application will have high demands on durability and long term reliability.

This technical paper focuses on the technology Bosch Rexroth has invested in to continuously improve the coating quality, process stability and, ultimately, the performance and durability of the Large Hydraulic Cylinder rods. Specifically, the coating application process called High Velocity Oxygen Fuel (HVOF) spraying is discussed in detail, because how that process has been evolved and improved by Bosch Rexroth has had a significant impact on the quality and longevity of the rod coatings. The topics covered include:

- Overview of HVOF
- Development of coating technologies – Enduroq 2000 and Enduroq 2200
- Coating quality and properties
- Surface preparation—grit blasting
- HVOF Materials:
  - Powder metallurgy and chemical composition
  - Powder production and particle size
- Quality Control
- HVOF Flame
- Prerequisites and applications
- Conclusion

**HVOF overview**

HVOF spraying is a process in which a powdered substance is sprayed on to the surface of the piston rod. The particles are heated by a burning gas mixture of a fuel (e.g., hydrogen, methane) and oxygen. Subsequently, the particles are accelerated to supersonic speeds before they hit the substrate material. During this...
collision the partially molten particles undergo plastic deformation and rapidly solidify to form the typical ‘stacked pancake’ morphology. The HVOF gun is specifically designed for obtaining these high particle speeds.

**Development of coating technologies**
Bosch Rexroth has a long-standing investment in advancing the quality and effectiveness of coating technologies and thermal spraying processes. This includes the introduction of the revolutionary Ceramax coating in the mid 1980s. Since the introduction of this plasma sprayed ceramic coating (Ceramax 1000) it has been continuously improved by optimizing the spraying and finishing parameters.

In the early 2000s, Bosch Rexroth introduced the next-generation Ceramax Engineered Coating, or CEC, family of fully metallic, HVOF sprayed coatings, which became the coating of choice for many applications. After more than two decades, this family of coatings was rebranded by the Enduroq family of HVOF coatings, emphasizing the high levels of enduring durability.

Enduroq 2000 is a single layer coating that provides excellent corrosion protection against regular environmental attacks. For more aggressive application environments (e.g., continued salt water contact), the Enduroq 2200 coating provides an excellent solution; it is a dual layer coating, with the top layer an Enduroq 2000 coating and an extra layer between the substrate and the top layer that provides a corrosion barrier layer that is exceptionally hard to penetrate. The Enduroq 2200 can withstand years of direct contact with salty sea water without any signs of corrosion.

This extra layer has extremely low oxide content and porosity, thus significantly increasing the corrosion resistance of the Enduroq 2200 coating system. Since the top layer is identical to the Enduroq 2000

**Cross section of Enduroq 2200 dual layer coating, depicting strong adhesion with rod metal surface and mechanical interlocking between coating layers.**
coating, the same hardness, wear, and tribological properties, are found on the Enduroq 2200 coating.

**HVOF: Achieving coating properties and quality**

The properties of the Enduroq 2000 and Enduroq 2200 coatings are achieved through the HVOF process, which Bosch Rexroth has worked to refine and improve over many years. There is a dynamic interplay of factors that, through their research and development, has enabled them to continually refine the coating properties.

For example: Due to the buildup mechanism of the coating, there is always a certain amount of porosity and oxidation present. Porosity, for example, can accelerate corrosion; however, the porosity on the surface also acts as small oil pockets which ensures a good tribological surface. A certain degree of oxidation adds to the hardness and wear resistance of the coating; however, it also impedes the corrosion resistance. Balancing these properties has been the focus of Bosch Rexroth’s development efforts, along with strict process control of the HVOF spray coating systems, to ensure consistent high quality coating of Large Hydraulic Cylinder rods.

The superior performance these coatings deliver has been made possible by the significant investment Bosch Rexroth has made to refine every aspect of the HVOF spraying process—from preparing the surface of the cylinder rod prior to HVOF spraying, to the chemical composition of the coatings and ultimately the actual HVOF process.

Grit blasting improves surface preparation

Any coating must have both adhesion—bonding of the coating particles to the substrate—and cohesion, which is bonding between the coating particles—to achieve optimum longevity and protection. Cohesion is optimized by choice of powder and process characteristics.
Adhesion, however, is achieved by a number of mechanisms. In HVOF, due to the size of the particles, adhesion of the coating mostly depends on the mechanical bonding of the coating to the surface.

Mechanical bonding is increased by a higher contact surface area, which can be increased by roughening the surface of the substrate. Bosch Rexroth has invested in refining the controlled and optimized grit blasting process: it provides micro-hooks for mechanical interlocking of the coating particles with the rod surface, which is the most important bonding mechanism, and the all pre-treatment processes are optimized to promote this mechanism.

Recently to improve the purity and stability of the HVOF spray coating, Bosch Rexroth switched from grit blasting using korund (i.e., aluminium oxide) to a special non-korund blasting grit. It was found that the sharp aluminium oxide particles had the potential to be embedded in the substrate and subsequently could cause uneven build-up of the coating during the spraying process, which could potentially reduce the desired levels of spraying adhesion, leading to layer undesired build-up, excess porosity and oxidation in the coating.

The specially-developed non-oxide grit particles do not have this disadvantage, while retaining the desired surface morphology for optimal mechanical interlocking. Another advantage is that with the new blasting grit and blasting process, the rod substrate is cleaner and better prepared to mechanically interlock with the coating, substantially improving the coating adhesion to the substrate.

Since the HVOF process uses high velocity oxygen flame (which obviously can affect the ultimate properties of the coating) it is necessary to take this process into account and compensate for differences in behavior of the metallic constituents in the flame and during coating formation on the substrate. Bosch Rexroth has worked closely with its suppliers on issues such as differences in sublimation, in melting range, in thermal expansion, in shrinkage due to solidification, to continually optimize the composition of coating materials to the HVOF process.

For example: the Enduroq 2000 family of coatings is a relatively hard coating, which means stress in the coating due to thermal expansion or solidification shrinkage could cause detrimental cracks in the coating. In order to reduce these effects the Enduroq 2000 powders were designed with constituents lowering the melting point of the alloy.

**Powder production:** The HVOF powders used at Bosch Rexroth are gas atomized using an inert gas. This provides a spherical powder with the least amount of oxides possible. The spherical shape of the powder gives the best possible flow characteristics, which in turn provides the HVOF gun with a continuous and constant flow of powder which is essential for consistent coating quality.

**Particle size:** The powder particle size is also very important as too small particles will get overheated in the flame, and too large particles will not melt (sufficiently). Overheating of the powder particles might cause the coating to be highly oxidized and porous, thus effectively reducing its corrosion resistance. When the
powder doesn’t melt enough the resulting coating lacks cohesion and adhesion.

Commercially available powders never have just one particle size; they always have a particle size distribution. This distribution is typically defined by a lower and an upper limit, and the amount of powder that is allowed to be outside these limits.

A fully mathematical description of a powder is not possible, but a particle size distribution curve, such as the one presented here, provides an effective method for measuring and controlling this HVOF process variable.

Bosch Rexroth has refined the powder specification by significantly lowering the amount of finer particles, and slightly increasing the amount of courser particles allowed in the powder mixture. This step was taken to improve several coating powder characteristics: lowering the amount of oxidized particles in the layer, reduced tensile stress in the coating, and reduced consumption of consumables like air caps.

Bosch Rexroth has established strict quality testing of powders to ensure specifications are met for chemical composition, shape, particle size distribution, and sprayability. These ensure highly consistent spray coatings, batch to batch, to sustain the integrity of our Large Hydraulic Cylinder performance.

**HVOF process control**

While it is crucial to exert precise control over both surface preparation and coating chemical composition, control of the HVOF flame is the key factor in optimizing coating formation and, ultimately, durability. The flame determines the speed, temperature, direction, and to some extent the chemical composition of the particles added to it.

The combustion parameters, i.e., the absolute and relative fuel and oxygen gas flows, determine the temperature and stoichiometry of the flame, which—together with the flame speed—in its turn determines the temperature and oxidation level of the powder at the point of collision with the substrate. The flame speed is determined by a
complex interaction of combustion parameters including:
- Gas flows and pressures
- Chemical reaction parameters
- Thermal expansion
- The geometry of the burn chamber and air cap.

Bosch Rexroth has made continuous investments into improving all these HVOF parameters; for example, it has been found that the flame has to be optimized to ensure the particles have the optimum speed and temperature combination to create a dense, low oxide containing coating with excellent cohesion and adhesion to the substrate surface.

An important factor controlling this process is the HVOF spraying distance, i.e., the distance from the gun exit to the substrate surface. It is important this distance is well chosen in combination with the other flame parameters, and powder characteristics. Combined with the design of the spraying gun, controlling these factors has been shown to enhance the overall performance of the HVOF process.

Lifecycle care of HVOF coatings
Due to the nature of the HVOF sprayed coatings, a number of steps need to be considered to sustain their durability over the long term. The Enduroq 2000 coating is very impact resistant, so catastrophic impact damage during normal operation is not likely. However, if such damage takes place, repair is difficult when the damage is larger than several millimeters. In such a case, removal of the piston rod and repair in a Rexroth service facility may be necessary.

Repairs smaller than that can be performed on-site by a certified technician under the right environmental circumstances. When the risk of impact damages is quite high, and the application calls for on-site repair methods, the Enduroq 3000 overlay welded coating could be preferred. Alternatively, simply shielding the piston rod from these impacts may also be a viable option.

It has been found that Enduroq 2000 series coatings have low resistance to acid environments. Generally, fresh and salt water have pH levels of 7 or slightly above, so in most civil, offshore, and marine applications this issue is not very significant. However, please be aware of acidic cleaners, or chemical plants upstream the application. The alternative here is also the Enduroq 3000 overlay welded coating, of which the cobalt-based material has an extremely high acid resistance.

Conclusion
The HVOF spraying process, as developed and enhanced by Bosch Rexroth, has led to a more stable and reproducible process, enabling the production of consistently high quality coatings that extend the performance and operational life of the cylinder rods in Rexroth Large Hydraulic Cylinders.

In particular, the HVOF-sprayed Enduroq 2000 and Enduroq 2200 coatings demonstrate excellent properties for use in hydraulic piston rods in many applications. The salt water corrosion resistance of the Enduroq 2200 is very high, and the coating structure makes the coating highly suitable for low friction applications.

Because of the properties mentioned above, the Enduroq 2000 coating has become recognized as an effective solution and alternative to conditions where electrolytically applied hard chromium or nickel-chrome coatings are under-qualified and where the advantage of superior life time expectancy in comparison to the Enduroq 3000 is desired. Any application where occasional exposure to aqueous environments are expected will benefit from the Enduroq 2000 coating, while applications that demand prolonged exposures to aqueous environments, or even in submerged salt water environments, the Enduroq 2200 demonstrates proven properties that make it an ideal option for those settings.