Numerical simulation of plasma spray processes

High-temperature gradients within short distances

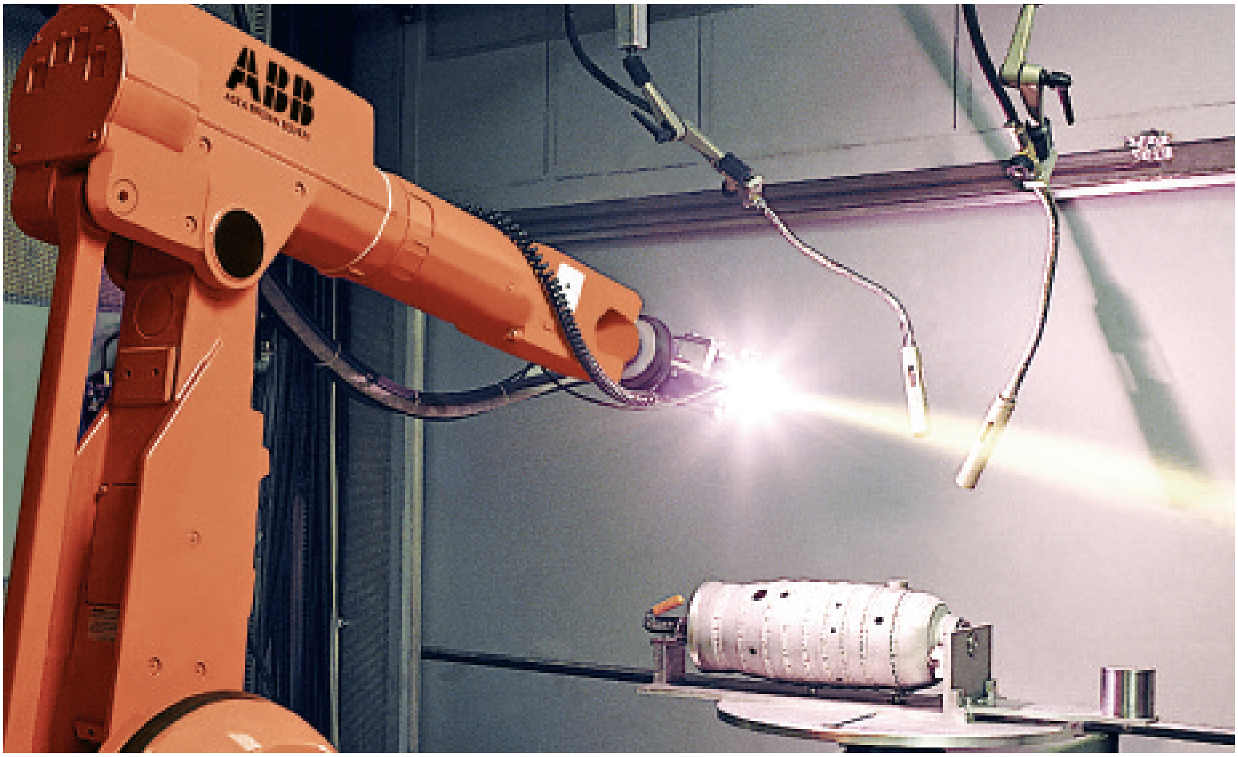
The development of numerical models for the simulation of plasma spray processes at Sulzer Innotec over the last few years has contributed a great deal to the understanding of the physical process in plasma spray guns. Working together with Sulzer Metco, the models have been continually expanded, applied to various spray processes, and validated where possible.

In plasma spray processes, a gas mixture is accelerated in a nozzle. The powder is added radially immediately after the exit from the nozzle and then builds up the layer on the substrate, while the thermal energy necessary to melt the powder is generated by an electric arc within the nozzle 1. In order to be able to depict these complex physical phenomena inside and outside the nozzle on the numerical level, a link between fluid dynamics (Navier-Stokes) and electromagnetism (Maxwell) is necessary. This link is made through the resistance heating in the gas, together with the Lorentz force from the magnetic field and the current, and is known as magneto-hydrodynamics (MHD).

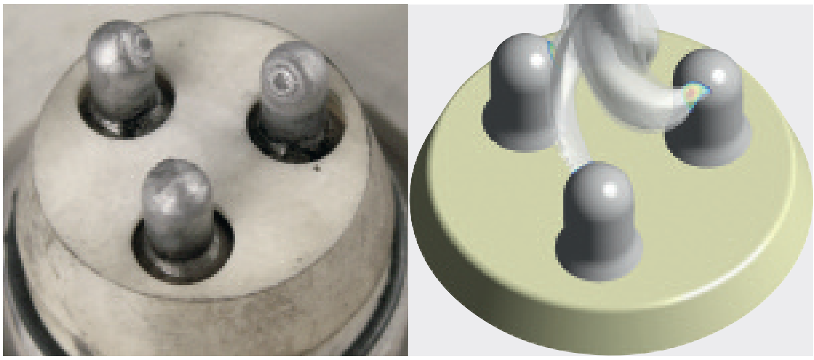
Gas temperatures of 30 000 K

The electrical power that is converted into heat by the arc is typically in the range of 25–130 kW. This results in maximum gas temperatures of up to 30 000 K within the gun. In order to simulate the process, it is therefore essential that the material data of the gas mixture have been correctly determined

1 F4 plasma gun (mounted on an ABB robot) spraying turbine parts.



up to these high temperatures, as the dissociation and ionization of the particles strongly affect the properties of the gases.


[2] The qualitative comparison of the positions of the simulated arc attachment points with the abrasion of the cathode demonstrates the accuracy of the simulation.

Such high power densities naturally also lead to severe stress on the nozzle material, so that cooling of the individual components is essential. This takes place in most processes by means of integrated water circulation. Up to 50% of the electrical power in plasma spray processes is mainly dissipated by radiation from the nozzle material, and is thereby transferred to the cooling water in order to avoid overheating the components. It is consequently very important that the energy loss through the radiation of the arc should be numerically replicated as accurately as possible.

Model validation based on the Triplex*Pro*™-200

The validation of such complex physical phenomena is enormously important. The modeling of the Triplex*Pro*™-200 from Sulzer Metco was selected for the first MHD simulations, as this plasma gun, with its three cathodes, stands out for its high process stability.

Quantitatively, only global variables—such as the electrical power, the heat losses to the cooling water, and the pressure at the inlet—could be measured and compared with the results. As the measurement of the individual variables, such as gas speed, gas temperature, etc., is not possible inside the gun, qualitative comparisons had to be used for the further validation of the simulation results. Qualitative comparisons of this kind are the shape and the positions of the arc attachment on the cathode and the anode [2]. The Triplex*Pro*-200 also has a so-called "consolidation point." This is the position in the chamber where the flow of the individual gas inlets changes into an axial vortex flow. The exact position can be determined by marks on the chamber walls and is compared with the results from the flow simulation.

Despite numerical simplification and some assumptions for the model, very good agreement was achieved between reality and the simulation. In a second round, the model parameters were slightly adjusted and then successfully tested under different process parameters.

Application of the model to the F4 spray gun

The existing simulation model validated on the basis of the Triplex*Pro*-200 was then applied to the F4 spray gun from Sulzer Metco. The aim of this was primarily to optimize the cooling circuit, which required an expansion of the model. The goal was to change the water guidance geometrically so that the stress on the material would not be too great, and nevertheless transfer as little energy as possible to the cooling water. Furthermore, it was also a case of holding the temperatures in the cooling water below boiling point, as this would lead to a drastic local reduction in heat transfer.

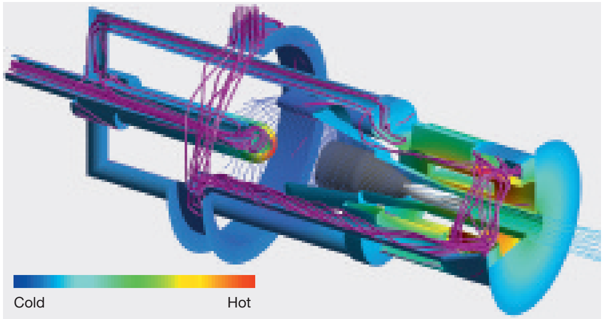
The simulation was divided into two simulation steps due to the physical and geometrical complexity. First, the plasma flow and the resulting heat stress through radiation and convection on the wall of the nozzle were calculated. As the F4 is a single-cathode gun, the flow in the nozzle could no longer be regarded as quasi-stationary. The attachment point of the arc on the anode changes considerably in time in both the axial and the circumferential direction, which is depicted by the saw tooth like curve of the electrical voltage. However, these fluctuations are in the kHz range and, as a good approximation, can be averaged over time in the circumferential and axial direction.

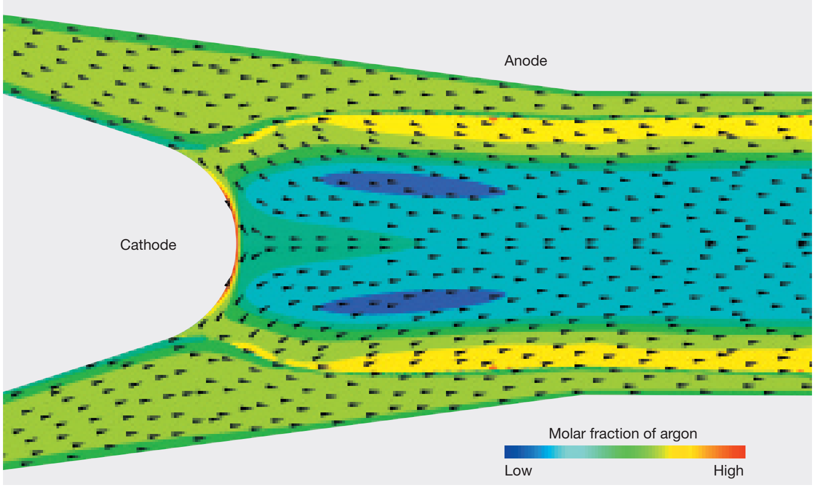
The average thermal stress was then transferred to a further simulation, which took the heat conduction in the material and the flow in the cooling circuit into account. With appropriate variations of the design, the guidance of the cooling water was optimized and the thermal stress of the nozzle material significantly reduced [3].

De-mixing of the plasma gas—a phenomenon of high gradients

In most cases, gas mixtures (e.g., argon-helium) are used as plasma gas. Up to now, the gases have been considered as homogenous mixtures and their properties have been correspondingly weighted. In reality, however, there is a separation of the individual gas components driven by local gradients in the molar fraction, in the temperature, in the pressure, and

[3] The high temperature leads to a high exposure of the material. Therefore, water cooling is needed. The figure shows the streamlines and temperature distribution in the cooling circuit of the F4 gun.





[4] The high temperature gradients lead to a de-mixing of the plasma gas. The figure shows the molar fraction of argon inside a simplified F4 gun.

in the electrical field [4]. This, in turn, results in a spatially dependent, variable composition of the gas and, thereby, to different material properties. With the implementation of the temperature- and pressure-dependent diffusion coefficients, major separation effects could be visualized in the vicinity of the cathode.

Thermal loading of the electrodes

The electrodes of a plasma spray gun are subjected to high thermal loading. At the emission point of the arc on the cathode in particular, enormous temperature gradients arise, as the temperature increases from the surface temperature of the cathode to the plasma temperature in a very short distance. An imbalance of ions and electrons arises in this area in operation [5].

The light electrons diffuse faster in this area of reduced ionization level. Due to this ambipolar diffusion, an additional electrical field arises directly at the cathode, which accelerates the ions in the direction of the cathode. A recombination then takes place close to the cathode, resulting in a release of the ionization energy. At the same time, electrons are emitted by the hot cathode. This has a cooling effect, the so-called thermoemission.

This thermal interaction between the cathode and the plasma gas was studied numerically in a further project. To do this, the simplified, rotationally symmetrical flow around an F4 cathode was selected during operation, as a very fine computational grid is required in the area of the electrode. It was shown that loading was highest at the edge of the emission point, as cooling through thermoemission breaks down almost completely at this point in this border area. The direct qualitative comparison with worn cathodes indicated good agreement with the results obtained from the simulations.

New process for the generation of thermal-barrier coatings

A new process for the generation of thermal-barrier coatings (TBC) is PS-PVD (plasma spray physical vapor deposition). Here, a high-performance O3CP gun is operated in a vacuum chamber at absolute pressures of 1.5 mbar. The powder is added inside the nozzle and is melted in flight, and even evaporated. This vapor condenses again on the relatively cold substrate, thereby forming a columnar layer.

The flow in the vacuum chamber can no longer be replicated using standard CFD methods that are based on continuum mechanics. Therefore the nozzle outlet region has been reduced to a minimum. The focus of this work lays on the investigation of particle behavior from entry into the nozzle to evaporation. Various geometrical variations of powder addition in the nozzle and their influence on particle movement were also investigated.

In-depth process know-how thanks to state-of-the-art simulation methods

The adaptation and expansion of MHD methodology to applications in plasma spray technology in recent years have contributed to a deeper understanding of the physical phenomena in spray processes. The ongoing increase in computing power has helped to satisfy the high demands on the numerical simulation of complex processes. The process knowledge that is generated in this way helps the developers at Sulzer Metco to optimize existing products. The knowledge gained is also utilized in the development of new products.

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[5] Schematic illustration of the physical processes in the sheath region.