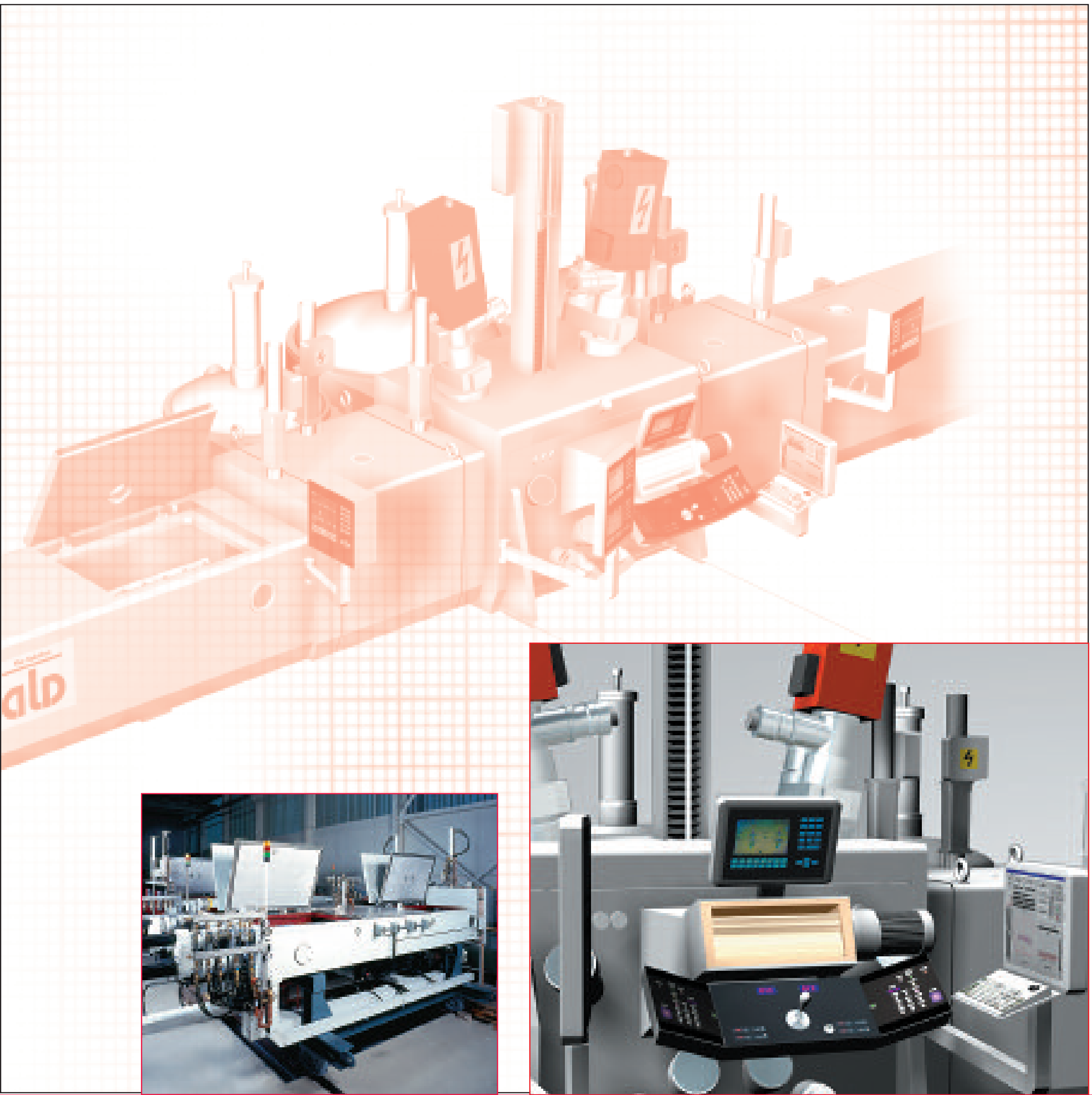


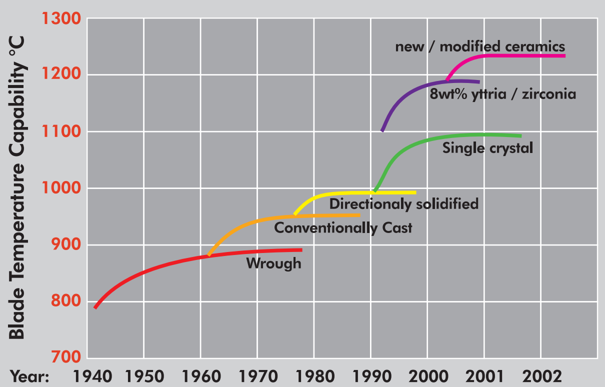
Vacuum TURBINE BLADE COATING

Electron Beam / Physical Vapor Deposition (EB/PVD) of Protective (MCrAlY) and Thermal Barrier Coatings (TBC)

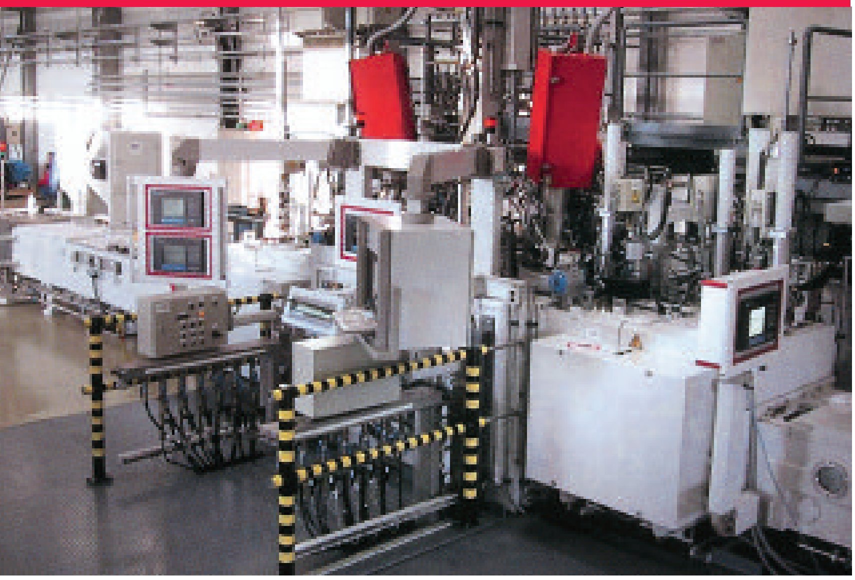
EB/PVD Coating of Turbine Blades and Vanes

Increasingly stringent demands are being imposed on the efficiency of gas turbine engines employed in the aerospace and power generation industries. This is driven by the requirement to reduce consumption of fossil fuels and thus operating cost. The major means for improving turbine efficiency is by increasing operating temperatures in the turbine section of the engines. The materials employed must withstand the higher temperatures as well as mechanical stresses, corrosion, erosion and other severe conditions during operation, while providing extended lifetime as required by the end users. This is an area where EB/PVD coating processes make a significant contribution today.

TBC coated single-crystal blades



Turbine Blade Temperature Capability
Source: Chromalloy UK Ltd.; Materials World March 2000



EB/PVD coater for mass production

Increase of Turbine Efficiency

Turbine components have been continually improved over decades, specifically with respect to temperature resistance. Initially the focus for improvement was as the blade material itself and its temperature capability. Large improvements have been achieved since the sixties by continually refining the casting methods, developing new Ni-base alloys, optimizing component shapes, component dimensions, grain structures and finally by applying special cooling methods to the components. This process continues today, but gains in temperature and effciency have reached the limits set by the laws of physics. Since the seventies, metal base vacuum coatings (e.g. MCrAlY) have been applied to protect the Ni-base alloy component surface against corrosion by hot gas. The success of these coatings marked the starting point for the development of non-metallic coatings with thermal insulation properties. Today these coatings are an integral part of the design of all modern aircraft turbine engines.

Electron beam physical vapor deposition (EB/PVD) is the preferred choice, not only for metal-based corrosion protection coatings, but also for thermal barrier coatings (TBC). EB/PVD coating technology is currently employed, virtually exclusively, for applying thermal barrier coatings onto aircraft engine components.

EB/PVD Coating Applications

Among various vacuum coating methods, electron beam / physical vapor deposition is characterized by the use of a focused high-power electron beam, which melts and evaporates metals as well as ceramics. The high deposition speed results in many cost-effective applications. EB/PVD coatings are used in the field of optical coatings for lenses and filters, in the area of semiconductor manufacture, for the coating of packaging web and many other high-volume applications. A system for coatings of turbine components was first introduced at Leybold-Heraeus in the late sixties.

Modern gas turbine

Coating of Blades and Vanes

Turbine blades and vanes manufactured in accordance with the latest state-of-the-art methods are currently composed of:

- Specially shaped, precision cast, superalloy, single crystal components with cooling air passages;
- A bond coating;
- A diffusion barrier;
- A thermal barrier coating.

Bond coatings are employed in order to protect the superalloy component surface from corrosion caused by hot air and to compensate the different thermal expansions between the superalloy component and the ceramic thermal barrier coating. The bond coating absorbs mechanical stresses between the component and the protective ceramic coating.

Bond coatings are applied in separate manufacturing steps. MCrAlY bond coatings were originally developed with EB/PVD methods. Today low pressure plasma spray (LPPS) is another vacuum process to fabricate such bond coatings. LPPS has the advantage of being a fairly simple method with low cost, especially when larger components such as blades and vanes for power generation turbines are considered. EB/PVD is, however, still the best choice for applying MCrAlY onto the blades and vanes of aircraft engines.

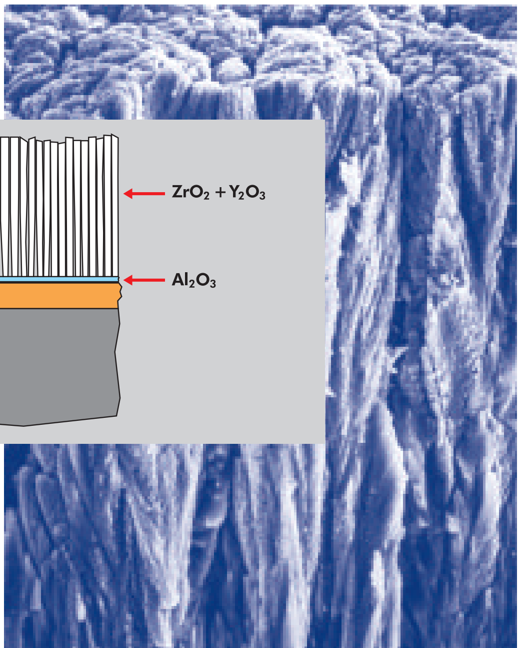
Another bond coating process, Platinum-Aluminide, was developed in order to avoid patent violation when using MCrAlY. In this process, aluminum is applied in a simple

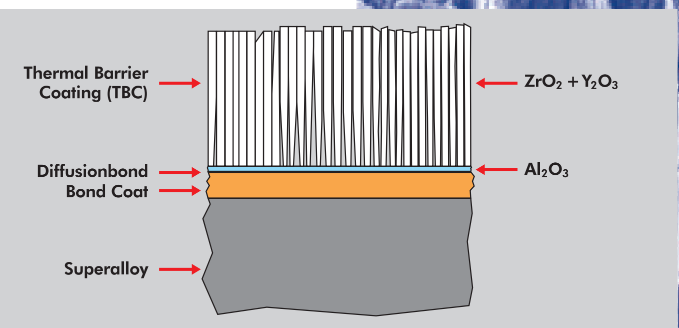
vacuum furnace, platinum in a separate step by electroplating, then a final heat treatment process is utilized in order to create the PtAl coating with required properties.
Both coatings are used today with comparable quality. The use of MCrAlY or PtAl depends on the specification established by the original equipment manufacturer (OEM).

Diffusion barriers are employed between the bond coating and the thermal barrier coating (TBC) for enhanced adhesion between the two layers. The diffusion barrier consists of a thin Al_2O_3 ceramic zone on top of the bond coating. This is an ideal condition for applying TBC. It is created just prior to the TBC coating inside the EB/PVD machine by oxidizing surface aluminum of either the MCrAlY or the PtAl bond coating.

Thermal barrier coatings (TBCs) are employed as the final layer that protects turbine components against high temperatures. The paper-thick coating allows high gas temperatures, which can be 100 to 150°C higher than the melting temperature of the Ni-base superalloy component. Yttria-stabilized ZrO_2 has been proven to be the ideal material for these TBCs. The dendritic structure of the TBC produced with EB/PVD, the firmly anchored roots and the loose tips allow the coating to absorb high mechanical stresses which are induced by the severe, rapidly varying, thermal cycling of aircraft and stationary gas turbine engines.
The EB/PVD method for producing the TBCs has been the exclusive choice in aircraft turbine components from their introduction until today.

An alternative method for TBCs, air plasma spray (APS) has recently been developed. The air plasma spray (APS) method has advantages as well as limitations compared to EB/PVD. Advantages include: atmospheric process and no need for vacuum, relatively low investment in coating equipment, the ability to quickly coat large components and good thermal barrier properties of the coatings. Disadvantages include a pallet structure of the coating which is inferior in terms of bonding and thermal cycling properties, the closing of cooling holes by the powder particles, roughness of the coating which requires the surface to be smoothened after coating and finally the fact that the process is a step by step process. Various OEMs have chosen APS as the preferred TBC coating method for large components of power generation turbine engines. This is due to the simplicity of the process and the comparably low operating cost. Aircraft components from the same OEMs are coated by EB/PVD, due to its superior quality and reliability.





Dendritic structure of a TBC produced by EB/PVD

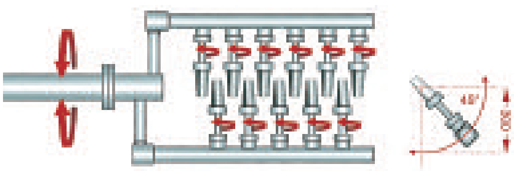
EB/PVD-Production Systems

Coating Machines

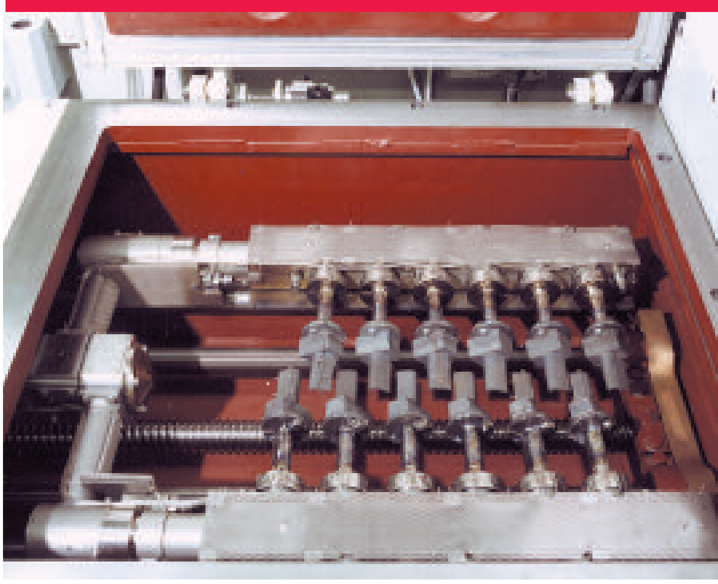
Mass production EB/PVD systems are equipped with one central coating chamber incorporating two electron beam guns and a reservoir of zirconia ceramic for the coating process. Preheating chambers are connected on either side of the coating chamber. Each preheating chamber allows the connection of up to two alternately actuated parts loading chambers. Each loading chamber is equipped with a carrier and drive system for the parts to be coated. This system carries the parts from the loading position to the preheating station and finally to the coating position. In the coating position, parts can be rotated, tilted or both at the same time, matching the part geometries and the specified coating thickness distribution requirement.

Vacuum valves are installed between the coating and heating chambers. This allows the coating of parts loaded from the left side of the machine, while at the same time the next lot of parts is preheated in the right side heating chamber. As soon as the coating process is finished, the left side parts are carried out to the unloading station while the just preheated parts from the right side are moved into the coating chamber for coating. During the coating process, the left side parts are unloaded and replaced by new parts, which are then moved into the preheating position.

The modular design of the EB/PVD coating system offers the possibility to install up to four loading chambers for the highest productivity requirement, two loading chambers for medium-size capacity or even a single loading chamber for pilot production or a small-size capacity requirement as needed by repair and overhaul shops today.

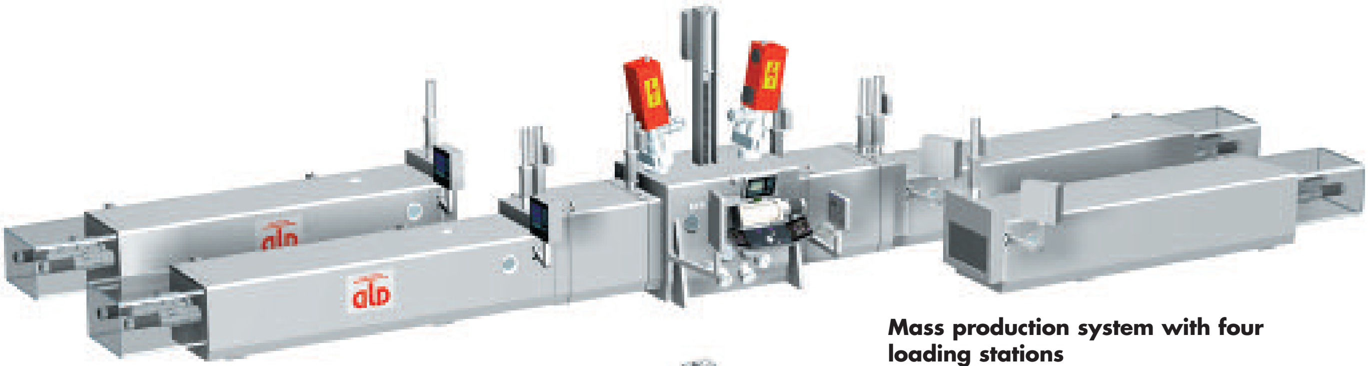


Complex substrate motions ensure a controlled thickness distribution

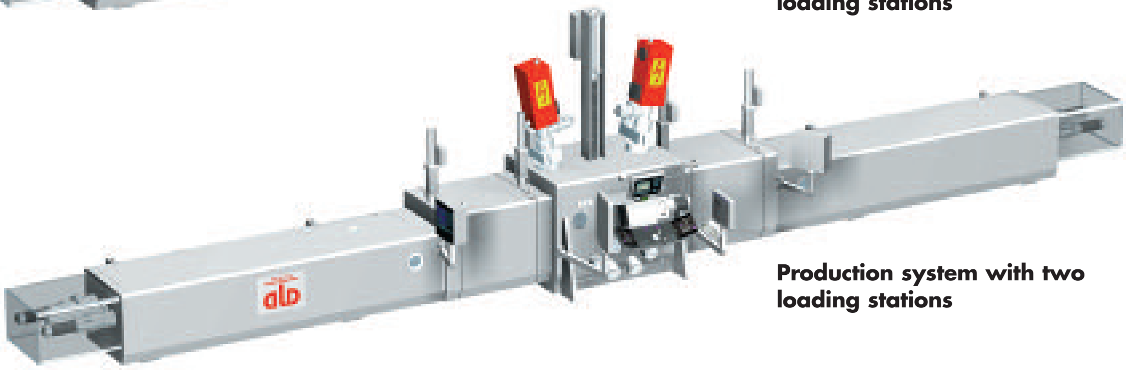


Loading chamber of an EB/PVD system

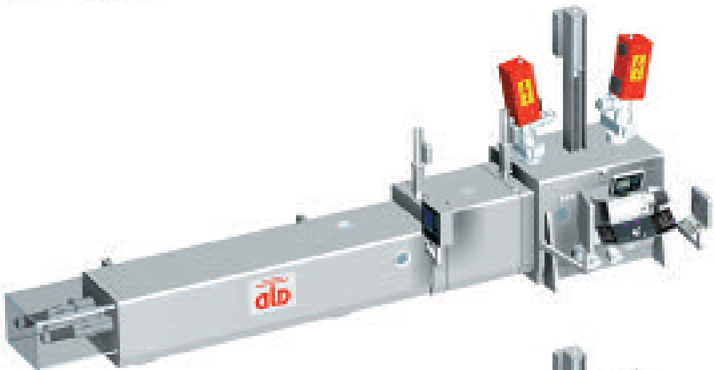
Family of EB/PVD-production systems



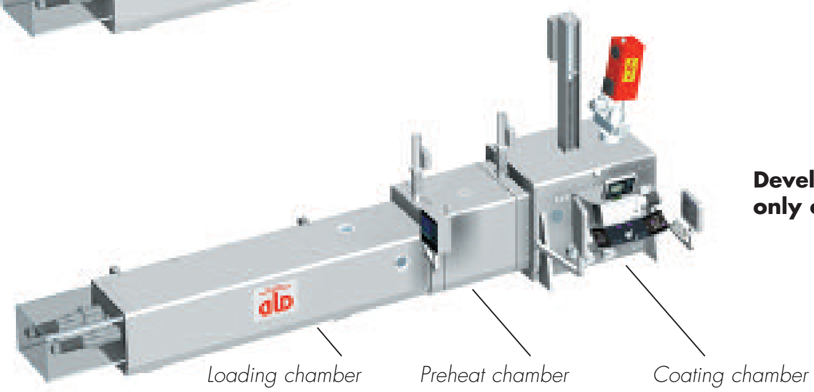
Mass production system with four loading stations



Production system with two loading stations



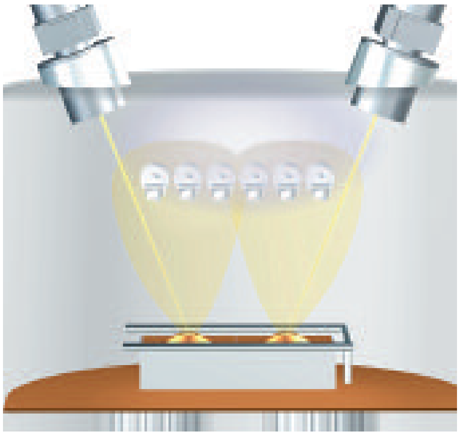
Coater for pilot production and repair coatings



Development coater for R&D with only one EB gun

TBC Process

The diffusion barrier mentioned earlier is created during the preheating process just prior to TBC coating. The major factor determining the quality of the TBC is the process that takes place in the coating chamber. A homogeneous cloud of vapor must be generated. In order to accomplish this, the coating material must be dosed in the right quantity, sufficient reactive gas must be added, the right scanning patterns of the electron beam over the molten material selected and last but not least the parts must be moved inside the vapor cloud in a preprogrammed motion.



Process chamber with EB guns, crucibles and parts to be coated in the vapor cloud

Process Control

The easy-to-use process controllers of ALDs EB/PVD systems provide both optimal and fully reproducible control over parts manipulator and drive motions. Controls for heating, coating, feeding of new material, vacuum system, valves, interlocks, safety and other items are provided at state-of-the-art level of modern production equipment. An ESCOSYS® (electron beam scanning computer system) computer controls the scan of the electron beam over the molten ceramic ingot. Only in the rare event that the coating process departs from its optimum course will operator interaction be required. In this case, a mouse click is all that is needed to make the corrections and return the process to its ideal course. The process is then stabilized by means of preprogrammed algorithms in the ESCOSYS® computer. This type of control system involving infrequent operator intervention, has proven to be the most reliable and most successful means for mastering the EB/PVD coating process and reaching high yield levels.

The main process controller employed allows thorough documentation of all parameters affecting the coating of each individual item involved. From the time components to be coated arrive at the weighing station, before being loaded, until the time they are unloaded and weighed again all stations involved are networked. The course of processing at each and every stage is fully documented for quality-assurance, a must for critical components employed in the aircraft industry. The entire system may be integrated into the operator's host-computer environment.

Future Advances

Opportunities for making further improvements arise when the general designs of components and system operators' manufacturing chains are taken into consideration. Stand-alone processes that are separated today may be combined in the future. This could reduce the complexity, increase the quality, as well as reduce the cost of the end product.
Examples of their applications, such as applying TBC to turbine blades, demonstrates the great potential that EB/PVD coating technology harbors for further improving the efficiency of turbines. Development efforts currently underway are aimed at investigating the deployment of new types of ceramic materials that have even better thermal barrier properties than the material used today. Multilayered coatings and custom-tailored combinations of various ceramics that yield better thermal barriers and exhibit better adhesion to bonding layers are also being discussed.

Operator's cockpit at an EB/PVD-production coater

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