EB-Preheating Technology and Equipment for Thermal Barrier Coating

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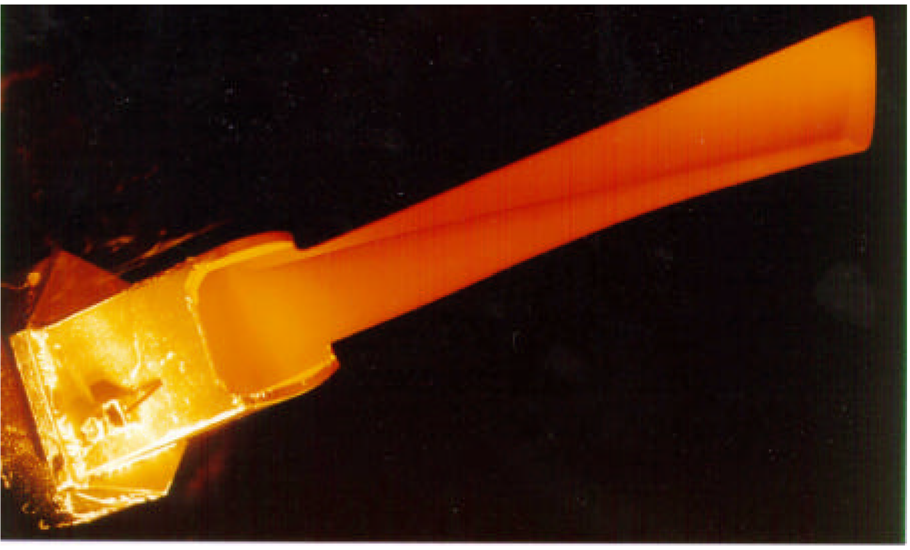
Presentation on the International Conference
on Metallurgical Coatings and Thin Films 2000,
San Diego, USA, April 10-14, 2000



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Deus-ICMCTF00-2A Veröffent.doc, 2000-12-06

Abstract
While EB preheating of gas turbine components has been established in the EB-PVD TBC research community for years, the large-scale industrial application of this advanced preheating technology for production purposes - primarily for industrial gas turbine parts - emerged only two years ago. This conceptual innovation had to be supported by sophisticated solutions in EB gun design as well as beam deflection hard- and software.

A high-precision high-frequency beam deflection system was developed, providing outstanding performance in scanning a 200 x 800 mm^2 wide evaporation field at frequencies above 10 kHz. A fast and completely uniform heating can be achieved by supplying different regions of the heated parts with power densities exactly matched to their mass distribution. A dedicated soft/hardware combination ensures that these optimized power density distributions follow the varying positions and outlines of parts that rotate during the heating cycle.

The prospect of expanding this technology to the more sensitive aircraft engine market is discussed, addressing well-known concerns about reproducibility, stability and traceability of the technological parameters.

1 Introduction

The technology of Electron Beam Physical Vapor Deposition (EB-PVD) of thermal barrier coatings (TBCs) on hot-section turbine parts such as first and second stage blades and vanes always comprises an integral pre-treatment step to ensure optimum chemical and physical conditions for the following – for layer durability most critical - nucleation phase of the applied barrier layer [1,2]. For YSZ-coatings this pretreatment stage usually consists of a preheating process, optionally assisted by plasma treatment or by controlled oxidation.

Several aspects have to be considered for the selection of a preheating technology:

- Quality: The constancy and uniformity of the final preheating temperature determine coating phase nucleation properties and are therefore most critical. The temperature uniformity during the entire heating phase is important for the formation of the thermally grown oxide (TGO) and may be critical for thermal stress sensitive advanced blade materials. Overheating of parts of the blade such as tip or trailing edge must be avoided for obvious reasons.
- Productivity: The productivity of an EB-PVD TBC coating plant is primarily limited by the coating process itself. Pre- and post treatments have to be matched to the deposition time in order to avoid or minimize dead time for the cost intensive coating chamber.

- Quality Assurance: The preheating process must ensure that every single piece of hardware is provably processed within a pre-determined temperature window.
- Cost: Equipment and running cost are investment decision factors.

Two alternative preheating technologies are available on an industrial scale [3], compare fig. 1. The concept of radiation heating has been used in production coaters for years, mainly because of its simplicity and stability. A furnace is held at a stand-by temperature prior to part entry and heated up to target temperature on part entry. The blade temperature rises until it eventually approaches the TC-controlled uniform furnace room temperature. The main disadvantage of this technology is an upper limit of the heating power density which starts to raise productivity issues on two-sting-coaters for first row industrial turbine blades and will definitely get problematic for second row ones. This productivity issue was handled in conventional coaters by grouping up to four sting-heater-aggregates around the coating chamber. A more convenient solution on the basis of radiation preheating was introduced with the VON ARDENNE IN-LINE EB-PVD TBC coater (fig. 2a) installed at ITC in Lomm (NL), where a two-stage cascaded heating system with a quartz lamp preheater in the load lock chamber and a conventional graphite heater in the second heating chamber ensures sufficient heating of first row industrial blades within 30 minutes cycle time [4,5].

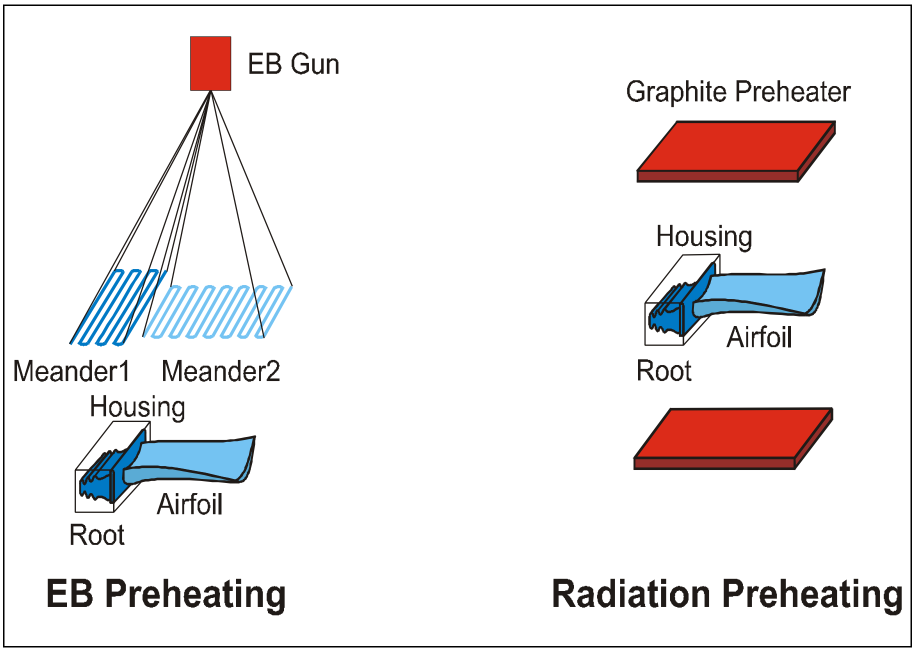
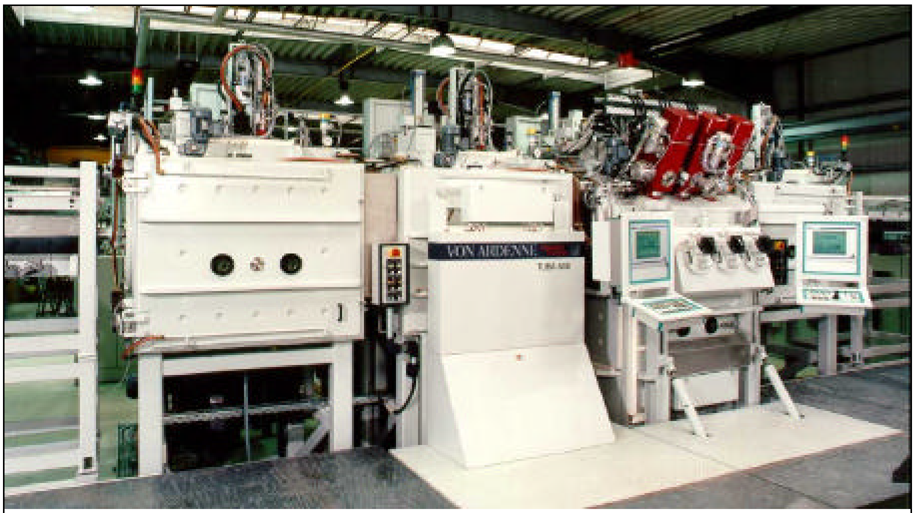


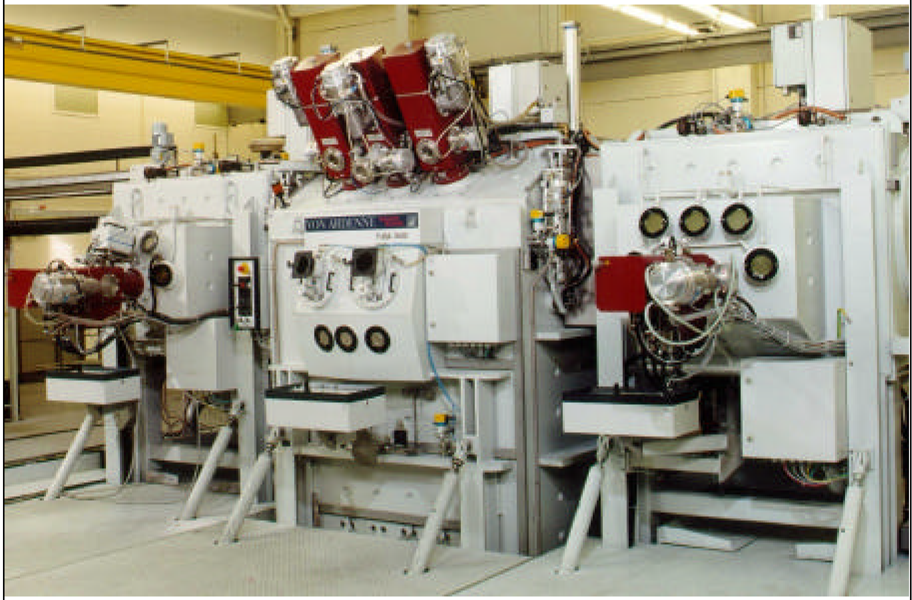
Figure 1

Preheating technologies for turbine components

Electron beam (EB) preheating, on the other hand, is achieved by scanning the part surface with a defocused electron beam in the power range 5...150 kW. It has been used in TBC research plants for years, leaving no doubt about the general applicability of this technology [6]. The strict safety standards of the aircraft industry delayed the introduction of this technology on an industrial scale until 1997/98, when VON ARDENNE ANLAGENTECHNIK developed the first EB-preheated EB-PVD TBC production coater (fig. 2b) and commissioned it to the Siemens company TACR Berlin [7].



a) 4-chamber in-line design with quartz lamp preheater and conventional graphite radiation heater



b) 3-chamber double-sting-trolley design with EB heating systems

Figure 2

State of the art EB-PVD TBC production coaters

2 Preliminary Studies

Radiation preheating provides a steady power density distribution – depending on the current local blade temperature. A surface point of an EB preheated part, on the other hand, experiences power input by periodic flashes on two different time scales – one determined by the repeated scanning of the beam over the exposed area, and the second by the rotation of the parts that are heated from one side only. Beam spot size, scanning frequency and part rotation speed have to be chosen within certain limits that avoid local overheating as consequence of any of those two periodicities.

2.1 Influence of part rotation

The influence of part rotation on the local temperature of a point on the airfoil surface was simulated for different rotational speeds. The temperature fluctuation during one revolution is largest at the end of the preheating process. For a typical industrial part with an airfoil mass per surface area of 43 kg/m^2 (4.3 g/cm^2), this variation is in the size of $\Delta T = 0.94 * \tau$, where ΔT is the total temperature amplitude for an airfoil surface element measured in K and τ is the time needed for one revolution of the blade measured in s. A rotational speed of 30 rpm (τ = 2s) yields the absolutely non-critical temperature amplitude of ΔT = 1.88 K. Aircraft parts with a lower mass per surface area will experience a proportionally higher amplitude.

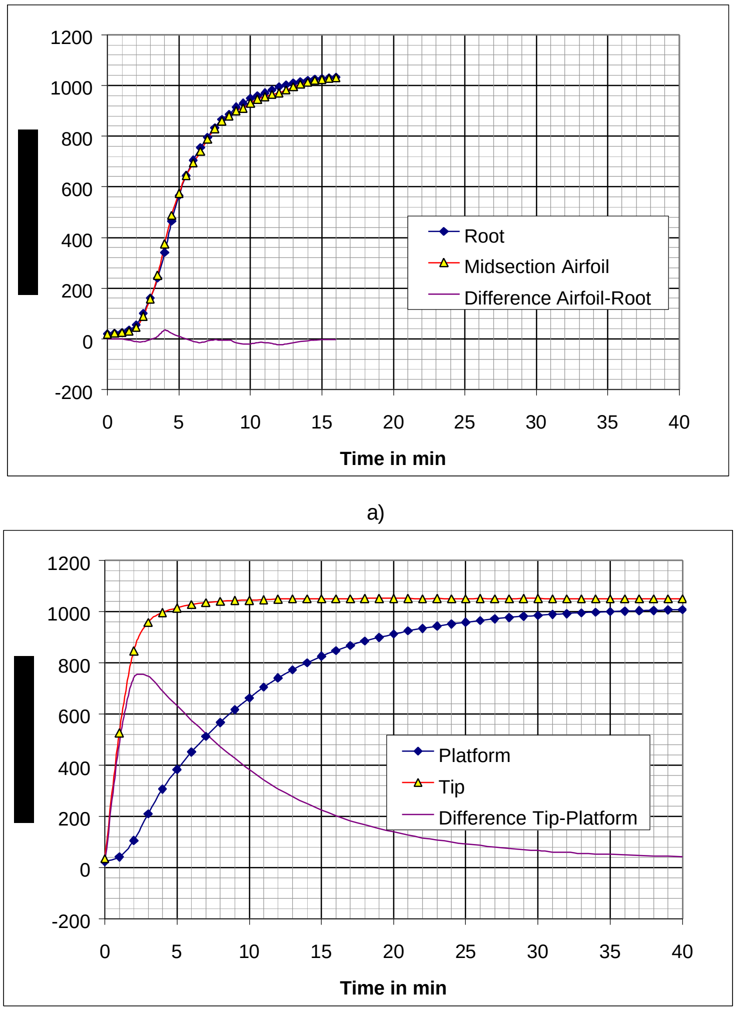
2.2 Influence of spot size and scanning frequency

Due to electron penetration depth, the energy of a 40 kV electron beam is released within a 7 µm thin layer below the surface. Because the scanning spot is much smaller than the totally scanned area, this power input occurs in relatively short flashes. During such a flash, the temperature in the 7 µm-layer raises, until the heat flow to adjacent layers is in equilibrium with the power input. The overheating needed to reach this equilibrium is a function of beam power, spot size, scanning velocity, and material parameters. The height of the temperature peak developed directly below the scanning spot was theoretically estimated. It could be shown that the peak temperature can be widely varied by changing scanning velocity and spot size. For the typical case of a 40 kV - 40 kW - beam scanned at a velocity of 400 m/s over a steel plate, the peak amounts to 14 K, 23 K , and 42 K for beam focus diameters of 0.04 m, 0.03 m and 0.02 m, respectively. This means that the local flash overheating can be easily held below a critical level by defocusing, or – on the other hand – can be used for a controlled overheating of a thin surface layer without affecting the base material.

3 EB Preheating Technology

3.1 Part complexity

A turbine blade or vane consists of the relatively light and hollow airfoil, a complexly shaped aerodynamic structure, that is attached to a massive inner root and optionally to a similar outer root. The roots have a much higher mass per surface area than the airfoil and are covered by a closed housing to protect them from coating. For those two reasons, they react much slower to a uniform heating power input than the airfoil. The heating power needs to be distributed to several heating zones of highly differing power density, if a homogeneous temperature profile during the entire heating phase is desired (fig. 3). The geometrical complexity of the components, which rotate during preheating, requires the continuous adaptation of the heating zones to the varying shape of roots and airfoil, viewed in the gun's perspective (fig. 4).



a)

b)

a) EB-preheating allows a supreme temperature homogeneity during the entire heating phase by precisely controlled power input to different heating zones.

b) Radiation heating requires the double heating time and develops temperature differences as high as 700 K between airfoil tip and platform.

Figure 3
Heating curves for EB heating and radiation heating of an industrial component (mass of approx. 7 kg). Temperatures were measured with thermocouples located in caveats of the components.

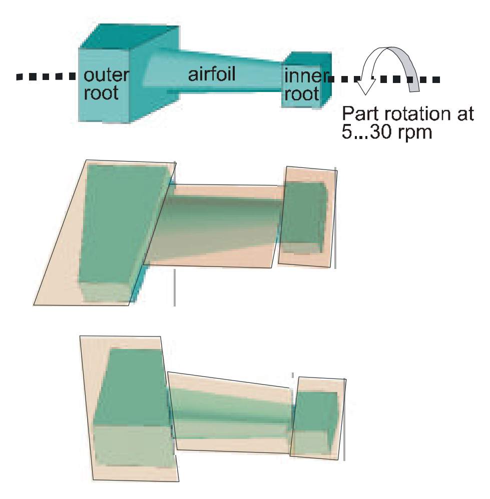


Figure 4
The complexity of the rotating components requires continuous adaptation of the beam scanning patterns directed to the different heating zones for inner and outer root and airfoil.

3.2 Deflection pattern optimization by teach-in

Scanning pattern optimization and adaptation to several component geometries can comfortably be performed utilizing a teach-in mode of the VON ARDENNE BeamGuidance software. Single deflection figures directed to one of the heating zones of one of the processed blades can then be modified by simple joystick and pushbutton commands under direct observation of the interior of the heating chamber through one of the wide-angle viewports (fig. 5). It could be shown that the adaptation of a general parallelogram to each of the heating zones is sufficient to achieve the required temperature homogeneity (fig. 6). This process is repeated for blades resting at a set of different rotational positions. The system is able to store a deflection pattern set every 15° of blade rotation. Production work is usually performed with deflection patterns optimized every 45°, 60°, or 90°.

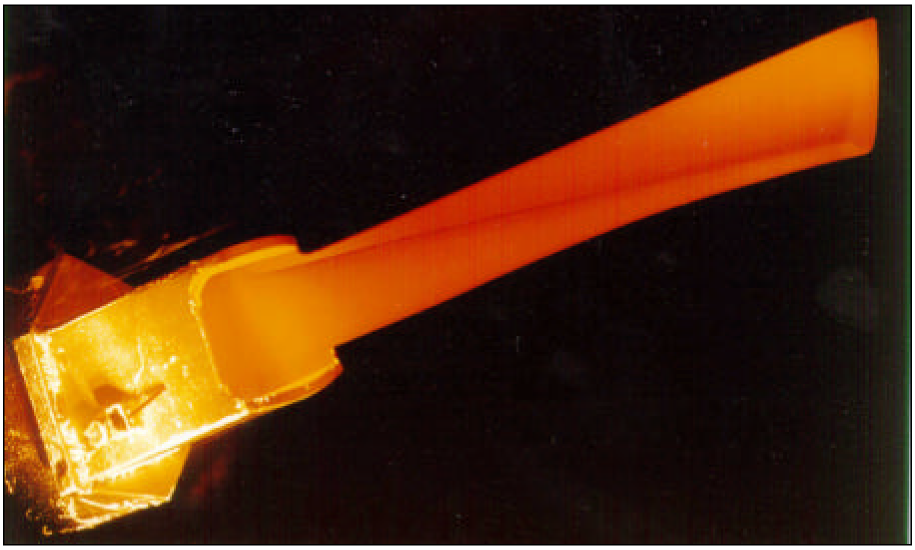


Figure 5
Preheating process observation through one of the wide-angle viewports

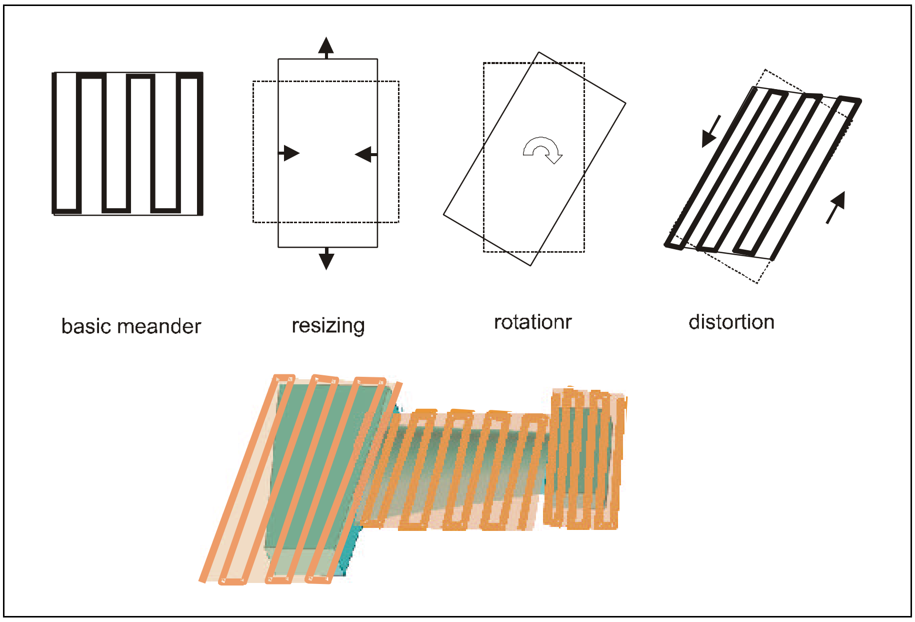


Figure 6
Pattern optimization by teach-in. The basic meander is translated, rotated, resized and distorted to match the heating zone to the part geometry.

3.3 Heating process control

During an actual preheating run, the rotational speed needed to avoid temperature differences due to the one-sided heating and the pattern adaptation every 15° of rotation requires the projection of a new deflection sequence every 0.1 seconds. This task, resembling the projection of a movie, is directly performed by the pattern generating digital signal processor, which is fed with the analog angular position signal for this purpose (fig. 7). The power distribution between the individually heated regions is at the same time varied according to a part-specific recipe which ensures temperature homogeneity during the entire heating process.

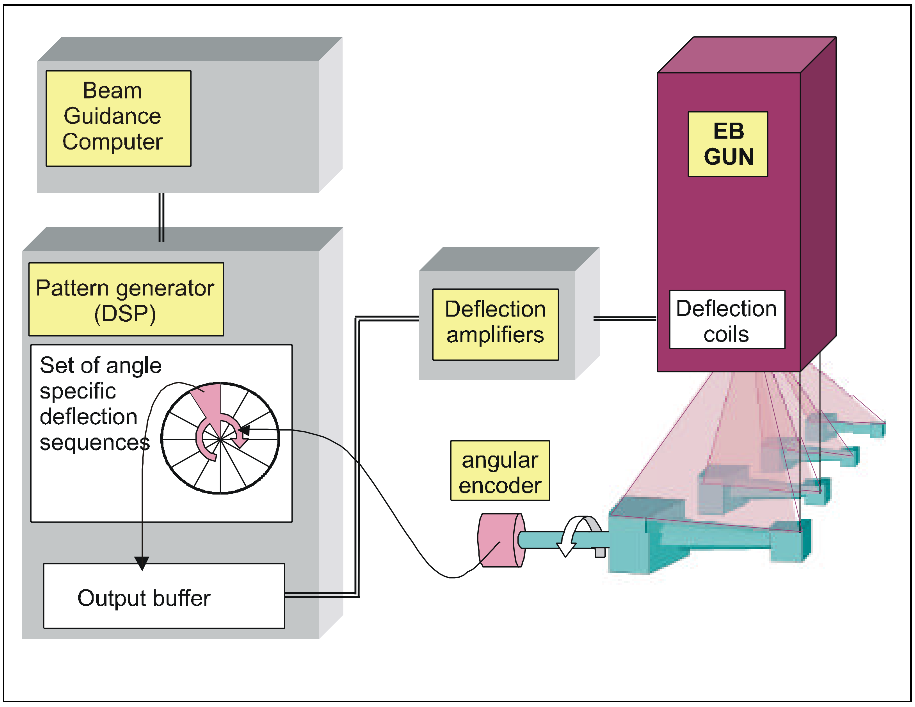


Figure 7
EB deflection system layout: the angular position of the rotating blades is fed into the pattern generating digital signal processor which selects the appropriate angle-optimized deflection pattern sequence.

3.4 Gun and deflection system

For an industrial EB-PVD TBC coater, the airfoils of the processed components are arranged within a typical coating deposition window (guaranteeing the specified uniformity of layer distribution) of 200 x 800 mm^2. Additionally, the roots of the components which have not to be coated, but do require preheating to assure temperature homogeneity, may be positioned outside this deposition window and thus enlarge the necessary scanning area for the preheating gun.

Both the gas load due to outgassing at the beginning, and the gas inlet for controlled TGO formation at the end of the preheating process require chamber pressures in the 0.1...5 Pa range, such that a high acceleration voltage (40 kV) has to be combined with a beam path as short as possible (1.1 m) in order to minimize the gas influence on beam focus and efficiency. The scanning speed requirements for the electron beam combined with the geometrical conditions result in a scanning frequency of 3 kHz (triangular pattern) at a dynamic deflection amplitude of ± 25°. A VON ARDENNE variocathode EB gun [8] equipped with a fast deflection system having a limiting frequency of 10 kHz was combined with deflection electronics optimized for high deflection precision [9]. Deflection amplifiers developed for this application can provide scanning at 10 kHz with an angle-frequency-product of 130000 °Hz in combination with a maximum static deflection angle of ± 29°.

4 Results

The first years of production experience have shown that EB preheating does achieve the desired goals – shorter heating time for large blades in conjunction with excellent temperature homogeneity and controlled TGO formation – within a well-controlled, stable, reliable process in a 24-hours-per-day production schedule. Up to now not a single piece of hardware has been damaged due to preheating problems.

Temperature homogeneity and heating speed of actual production runs do repeat the excellent results of the research plant studies (fig. 8). The total power needed during a heating process depends on the mass and design of the blades processed, and is comparable to the power used by a conventional heater (fig. 9).

Finally, the components coated in the past year do perform well in power plants, a rainbow test comparing EB heated hardware with third party technology is currently in progress.

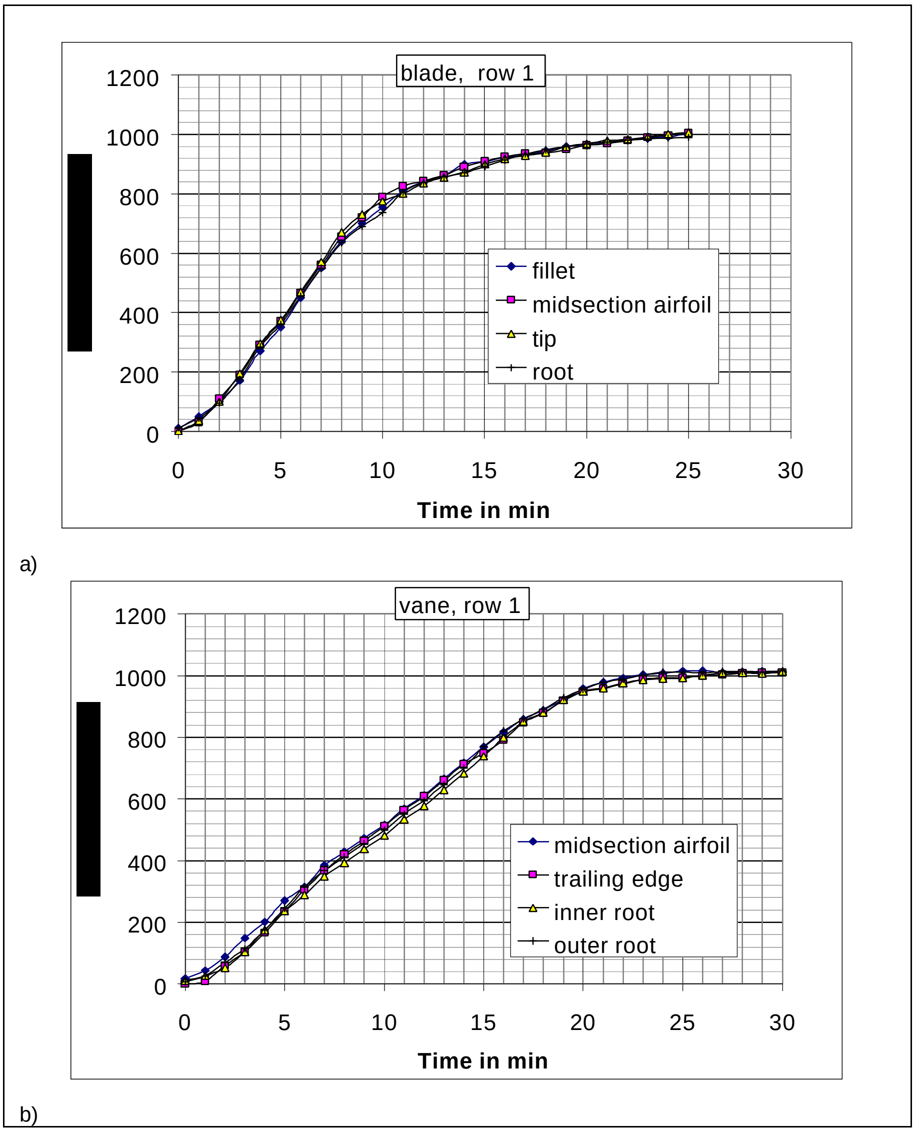


Figure 8

EB heating curves for industrial first row components

(a) blade

(b) vane

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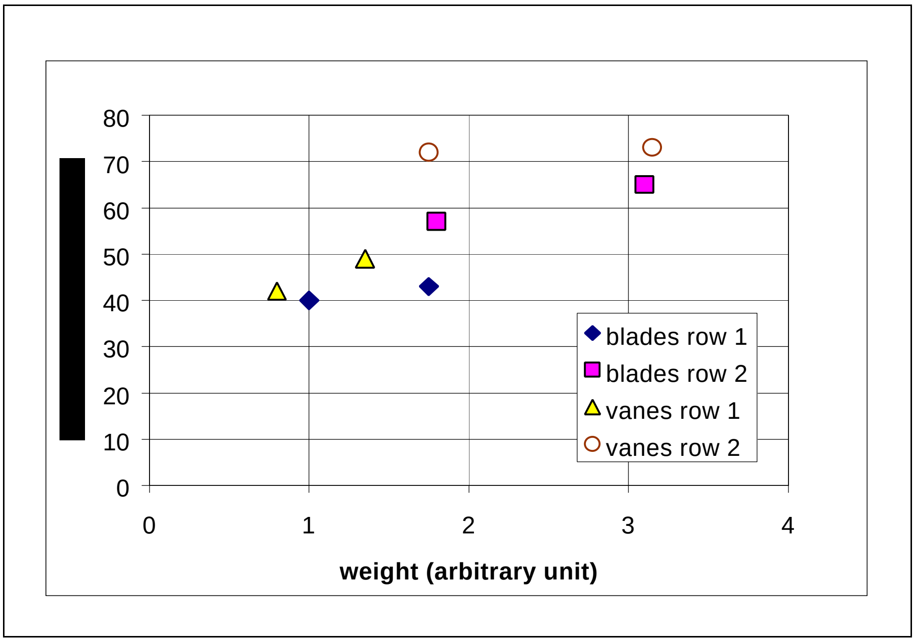

Figure 9
Total heating power for heating a charge of two components of different designs at end of heating phase (heating to approx. 1000°C in 20 min). The required heating power is not uniquely determined by the mass of the components, the actual design and total surface area (including housings) are further factors.

5 Quality Assurance Issues

Temperature profiles of the blades are measured during process development and in reference runs by direct thermocouple measurements in and on blades. Component rotation during preheating is performed in an oscillating mode (e.g. ± 180°) in these cases to allow for TC attachment to the blades. Actual temperatures of the components are set in relation to reference thermocouples placed at specific points in the part carrier, and to the signals of a mechanically scanning high-precision IR camera. In production runs, reference temperatures are logged in conjunction with gun parameters, vacuum conditions, and part movement measurements.
The utilization of an IR-camera combined with a reference black body radiator opens the possibility for precise temperature measurement of the entire blade surface in every production run.

For the highly sensitive aircraft engine industry, additional refined methods of process data acquisition can be applied:

- Gun focus and gun beam offset, which vary within known bounds due to cathode assembly aging, can be measured on-line and corrected automatically using an in-situ beam position and focus measurement system.
- Blade dummies with a more critical mass distribution than the actual can be mounted in the heating chamber and processed by heating patterns more sensitive to beam quality changes than the patterns used for heating the coated hardware. Reference temperatures measured directly in those dummies will be a highly sensitive indicator for any EB-preheating process instabilities.

6 Conclusions

Table 1 compares the two existing preheating technologies in the view of VON ARDENNE, incorporating the experience of installing these concepts in production TBC coaters. It can be concluded that the preheating concept has to be selected in every individual case, carefully weighing advantages and disadvantages.

In general, radiation heating will retain its significance in the field of aircraft engine parts, due to its established acceptance and for legal reasons. EB preheating is expected to enter this market as soon as certification issues are resolved by a pioneering coating manufacturer. There is no doubt about the technical applicability of EB preheating in this sector.

For industrial turbine parts, this pioneering step has been carried out by TACR, showing the formidable future potential of this technique with the prospect of larger blades, higher productivity and advanced TGO formation control. EB preheating will be the technologically preferable choice for mixed aircraft/industrial and pure industrial blade assortments.

Table 1: Comparison of radiation preheating and EB preheating

	radiation preheating	**EB preheating**
Status and Acceptance		
industrial standard for stationary engine parts	established	first coater 1998
industrial standard for aircraft engine parts	established	pilot coaters only
quality assurance	established methods	equivalent methods
Handling		
part technology development	easy	EB pattern optimization
process stability	excellent	excellent
maintenance	virtually none	EB gun (1hr / week)
robustness	delicate graphite elements	robust gun design
TGO formation control		
controlled oxygen inlet during preheating	not possible	up to 5 Pa
temperature homogeneity during entire preheating phase	up to 700 K difference tip-fillet	less than 40 K difference over entire blade
typical 2-sting production coater		
layout	5 vacuum chambers	3 vacuum chambers
required sting length	4.25 m	2.25 m
productivity for aircraft engine parts	45 min cycle time	40 min cycle time
productivity for stationary engine parts	60 min cycle time	45 min cycle time
typical in-line production coater		
layout	4 vacuum chambers	3 vacuum chambers
productivity for aircraft engine parts	20 min cycle time	20 min cycle time
productivity for stationary engine parts	30 min cycle time	25 min cycle time

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