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The technology of Plasma Spray Physical Vapour Deposition

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ABSTRACT

Purpose: The deposition of thermal barrier coatings is currently the most effective means of protecting the surface of aircraft engine turbine blades from the impact of aggressive environment of combustion gases. The new technologies of TBC depositions are required.
Design/methodology/approach: The essential properties of the PS-PVD process have been outlined, as well as recent literature references. In addition, the influence of a set process condition on the properties of the deposited coatings has been described.
Findings: The new plasma-spraying PS-PVD method is a promising technology for the deposition of modern thermal barrier coatings on aircraft engine turbine blades.
Research limitations/implications: The constant progress of engine operating temperatures and increasing pollution restrictions determine the intensive development of heat-resistant coatings, which is directed to new deposition technologies and coating materials.
Practical implications: The article presents a new technology of thermal barrier coating deposition - LPPS Thin Film and Plasma Spray - Physical Vapour Deposition.
Originality/value: The completely new technologies was described in article.
Keywords: Metallic alloys; Corrosion; Technological design; Thin and Thick Coatings; Surface treatment

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1. Introduction

The deposition of thermal barrier coatings is currently the most effective means of protecting the surface of aircraft engine turbine blades from the impact of aggressive environment of combustion gases. The constant progress of engine operating temperatures and increasing pollution restrictions determine the intensive development of heat-resistant coatings, which is directed to new deposition technologies and coating materials. The thermal barrier coatings currently used in industry are made up of at least two layers: the bond coat protecting from corrosive factors such as oxidation, hot corrosion and compensating the differences in the physical properties between the base material and the coating; and the ceramic outer layer. The latter has a function of a thermal barrier and protects the blade from the impact of high temperature. At present, there are basically two coating deposition technologies applied in aerospace industry.

In order to protect the inner combustion chamber, the atmospheric plasma-spraying technology is employed. Both the bond coat built of multi-content MeCrAlY and the ceramic yttrium-oxide-stabilised zirconia outer layer are deposited this way. The obtained coating is characterised by the thickness of the inner layer of approx. 100 µm and the outer layer of approx.

250-500 μm. The APS method is also utilised for depositing coatings on the vane rings of aircraft engines.

On the surface of rotary vanes, especially of initial grades, two combined deposition methods are used. The metallic bond coat is usually obtained by diffusion aluminising or by physical methods such as arc evaporation (Arc-PVD) or, more frequently, electron beam physical vapour deposition (EB-PVD). The outer layer is deposited in the EB-PVD process and its morphology is different from the coatings obtained by plasma-spraying. Furthermore, its thickness is lower (100-200μm) and so is its roughness. The aluminide bond coat, built of β-NiAl phase, is 30-60 μm thick and highly resistant to oxidation thanks to the formation of the aluminium oxide film. The said layers are either obtained by gas phase out of pack method or by the more advanced chemical vapour deposition (CVD) method. Both processes are conducted within retort furnaces, but the major difference between them is the source of active atmosphere. In the out of pack method, the source includes granules containing aluminium enriched with a small amount of halogen activator, which are placed nearby the coated part. In the CVD method, the coating gases are created outside the furnace, in the independent generator, and is a result of a hydrogen chloride reacting with aluminium. The resultant active gas is directed inside the retort furnace and the aluminium deposits itself on the surface of the coated part. Both of the processes described take place in high temperature: 800-1100°C in hydrogen or in argon [1].

Introducing the platinum addition has enabled an increase in the oxidation resistance of aluminide bond coats. The element is added by depositing a 2-10 μm thick film, using galvanic method, followed by diffusion annealing and aluminizing. The obtained coating can either have a single-phase structure, made up of (Ni,Pt)Al phase, or a double-phase structure, including additional PtAl2 phase. At present, other elements are being tested as modifiers for aluminide coatings, which would improve their oxidation resistance. These include palladium - introduced similarly to platinum (galvanically), and hafnium, zircon, silicon, added i.a. in CVD process. The outer ceramic layer is obtained via EB-PVD method and formed as a result of evaporating the ceramic ingot with an electron beam, followed by the deposition of the vapour on the surface of the workpiece, which results in the formation of narrow vertical crystals [2].

The increasing requirements of the aircraft engine manufacturers result in the intensification of investigations into the alternative methods of producing ceramic layers of thermal barrier coatings (TBC). Current research concentrates on two methods. The first one is plasma-enhanced chemical vapour deposition. The enhancement can take the form of using microwave frequency plasma either with metalorganic precursors (low temperature process) or inorganic compounds, e.g. chlorides (high temperature process). In Japan, laser-assisted CVD process has been investigated. The growth rate of the ceramic coating is relatively low in CVD method and ranges from 120-150 μm/h to 300 μm/h. The thermal conductivity and the structure of these coatings are similar to EB-PVD-deposited TBC's (1.5-1.9 W/mK) [3,4].

Another alternative is plasma-spray physical vapour deposition (PS-PVD). This method had been investigated by the manufacturer - Sulzer Metco, by Institute of Energy Research in Julich and in the USA by NASA.

2. Results

2.1. The PS-PVD technology

The presently applied technologies are based on depositing the coating via complete or partial melting of feedstock powder particles, followed by sprinkling them on the workpiece and forming a splat-type coating. In physical vapour deposition processes, the electron-beam vaporised material condensates from the vapour onto the surface, forming a continuous, thin and compact coating. In this way, especially designed coating structures may be created, for instance ceramic thermal barrier coating with a columnar structure, deposited on first grade aircraft engine vanes. This technology, however, is not very cost-effective, as the PVD equipment is extremely expensive (more than a dozen million euro for the commercial scale production device) and has significantly lower deposition rates. As well as his, depositing coatings on more complex-shaped parts such as vane rings of aircraft engines. The PS-PVD technology, developed by Sulzer-Metco and currently investigated by one of European universities as well as by NASA, is a hybrid method. It is a cost-effective plasma-spraying technique, enabling the evaporation of the coating material, which is used as an alternative method of depositing thermal barrier coatings. It is decidedly one of the most prospective technologies for industrial scale applications.

PS-PVD is based on traditional low pressure plasma spraying (LPPS) techniques. The standard LPPS process is conducted at the pressure of 50-200 mbar and enables the deposition of 20 μm-1 mm thick coatings. Lowering the pressure permits the plasma flame to be lengthened from approx. 50 to 500 mm. The thinnest coatings can be obtained via Thin Film technology, which enables the production of a uniform, homogeneous coating (Fig. 1).

In PS-PVD, the chamber pressure is much lower and ranges from 0.5 to 2 mbar, which enables the plasma flame to be lengthened to more than 2 metres, its diameter ranging from 200 to 400 mm. The O3CP modified plasma gun by Sulzer Metco is used to either spray or vaporise the feedstock powders, allowing the coating gas flow to be increased to 200 NLPM (normal litres/minute) and the current intensity to 3000 A. The powder is delivered by a system of 2 or 4 nozzles connected to powder feeders, permitting the deposition of multi-component or gradient coatings. In order to enhance the properties of the deposited coating, the material can be pre-cleaned with a plasma transfer arc or pre-heated with a plasma gun. Although the pressure in the PS-PVD process is a few times higher than in traditional PVD, the high plasma stream velocity (above 2000 m/s) and plasma stream temperature enable the feedstock to be easily vaporised. This, in turn, permits the deposition of coatings even in places which aren't inside the stream [5,7-9].

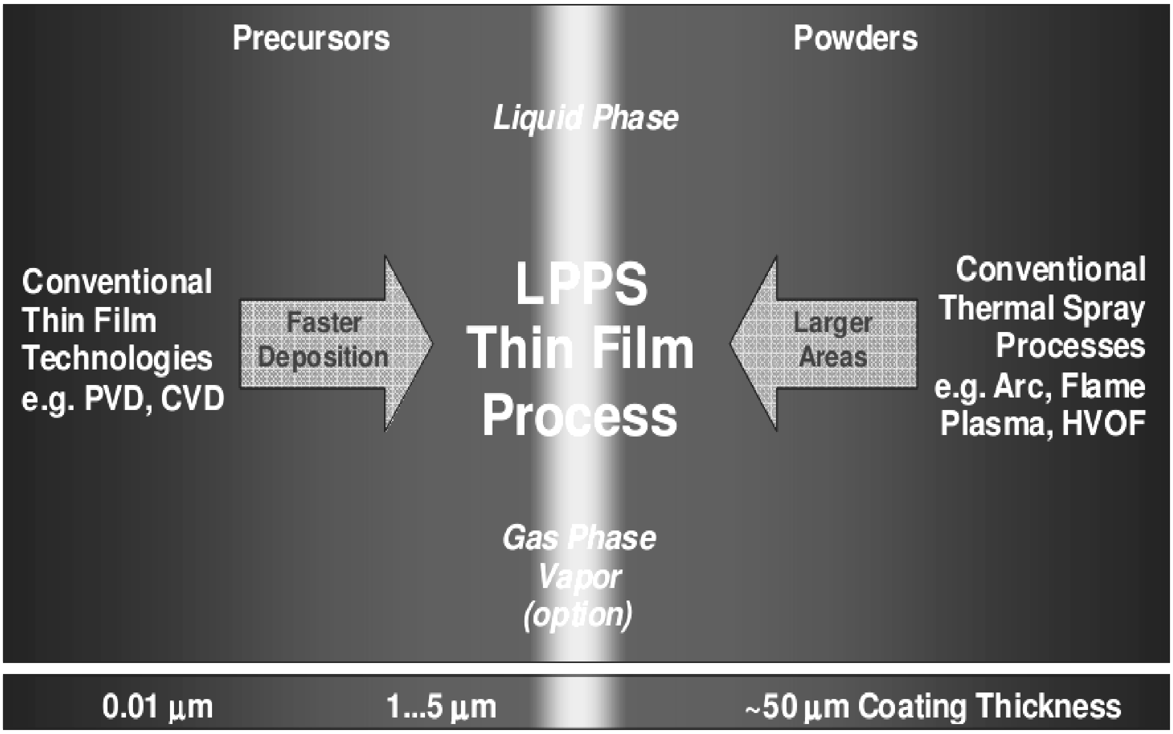

Fig. 1. The distinctive properties of LPPS-Thin Film and PS-PVD processes (Sulzer Metco) [10]

2.2. Depositing of bondcoats by LPPS thin film

In contrast with the PS-PVD deposition of ceramic coatings, in traditional low pressure plasma-spraying (LPPS) the material is partly vaporised, as has been confirmed by optic spectroscopy trials. The microstructure investigation of MeCrAlY coatings deposited via PS-PVD has proven the lack of any oxide inclusions, even without any further heat treatment [7].

2.3. Depositing ceramic coatings with columnar microstructure by PS-PVD

The data concerning parameters for the deposition of thermal barrier coatings by PS-PVD are quite limited and they come, for the main part, from the producer's publications, which are rather scarce.

To deposit TBC with columnar microstructure, low granularity feedstock powders are necessary, which facilitates the vaporisation of the material (Fig. 2). For instance, the typical zirconia powder used for APS/LPPS plasma-spraying has a granularity above 60 µm, while PS-PVD requires the use of powders whose granularity is below 25 µm. The morphology of columnar TBC depends on the process parameters. In order to obtain the columnar structure of the coating, it is necessary to provide low powder feeding ratio, a special selection of plasma-forming gases and a large spraying distance. The substrate temperature during the process ranges from 900 to 1100°C, and its increase facilitates the formation of columnar microstructure. The tests on simple PS-PVD system at the university in Julich have proven that the highest energy level for vaporising the material is needed for the mixture of Ar and He. Using hydrogen requires additional energy to dissociate it. Helium is more adhesive than hydrogen and makes the plasma stream more narrow. The changes in the mixture permit the deposition of a coating whose structure includes 'splat' and vaporised crystals. It has also been confirmed that operating the plasma gun has a smaller impact on the coating morphology. Distance trials with the plasma gun have proven that the feedstock vaporises at distances from 300 to 1200 mm. The deposition occurred on the sides of the sample as well as on its face, even at smallest distances. The crystals grew sideways as well as vertically, and the slope amounted to 10-20°. In addition, the experimental trials have confirmed that applying the classic LPPS process for depositing bond coats may cause the concentration of stress within the coating due to the formation of splats, resulting in its lamination. Further research included trials with coatings deposited by complete vaporisation of the powder with the use of an additional turn in order to prevent the overheating of the substrate. Furthermore, a great impact of sample holder type on the morphology of the coating was observed. It has been proven that the cross-section of the holder should be kept as narrow as possible.

Moreover, there seems to be another essential factor determining the mechanics of the coating growth: the condition of the surface. The preliminary tests have confirmed that R_a cannot exceed 2 µm. Otherwise the crystals grow in various directions rather than vertically, which in turn imposes polishing the surface.

This type of growth results from the privileged development of columnar crystals in higher places. The growth rate of the coating inside the plasma stream is high and amounts to approx. 100 µm/min. However, the application of the coating is difficult due to the possibility of overheating and damage to the substrate material. Therefore, fast movement of the workpiece in relation to the plasma gun is used, which facilitates temperature compensation. During the single swap, the coating growth amounts to 0.1-0.2 µm; hence theoretical coating growth would equal 10-20 µm/min. The obtained results were similar for the producer's prototype device and for the system used in Julich [6,7,10].

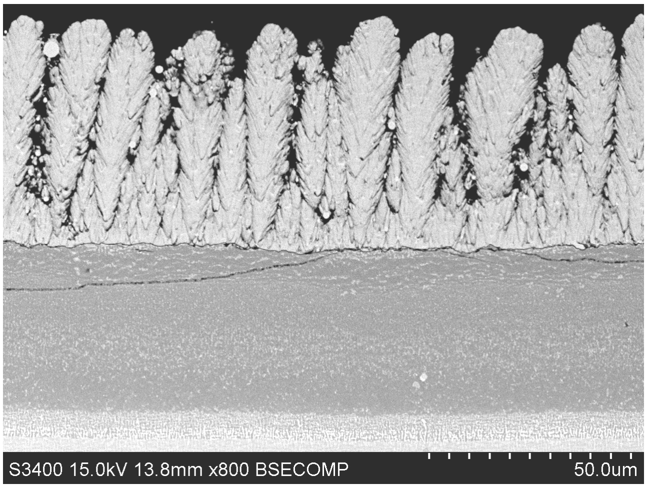

Fig. 2. The microstructure of the ceramic coating obtained by PS-PVD

2.4. The properties of TBC's obtained by PS-PVD

The preliminary optimisation of the process conducted by the producer indicates that the erosion resistance of PS-PVD coatings is lower than EB-PVD coatings, but higher than APS plasma-sprayed coatings. The thermal fatigue of PS-PVD-deposited TBC's with various bond coats is comparable or even better than the thermal fatigue of those deposited by EB-PVD. Tests conducted at 1135°C have confirmed that MeCrAlY bond coats are sensitive to deposition conditions such as overheating. This effect hasn't been observed in Pt-Al diffusion coatings. The thermal conductivity tests have proven its value to be low, amounting to 0.8 W/m K [10].

2.5. Monitoring the PS-PVD process

Traditionally, devices such as Accuraspray and DPV-2000 by Canadian Tecnar or CMOS cameras are used for monitoring plasma-spraying processes, whether atmospheric-pressure or low-pressure. These devices, however, cannot register particle movement and plasma temperature during the powder vaporising process, which is typical for the PS-PVD method. Consequently, optic emission spectrometer (OES) is necessary to measure plasma properties and the degree to which the feedstock is vaporised (Fig. 3). The appearance of zirconia-specific spectrum as well as its intensity allows for such an assessment. Similar measurements have been used for bond coats. However, the identification of aluminium-specific lines proved quite difficult, which was explained by the low aluminium content in the feedstock. In order to measure the substrate temperature, infrared cameras are indispensable, as well aw infrared pyrometers and thermocouples. To assess the performance of powder particles introduced into the plasma stream, fast CCD camera with a telephoto lens [7,9].

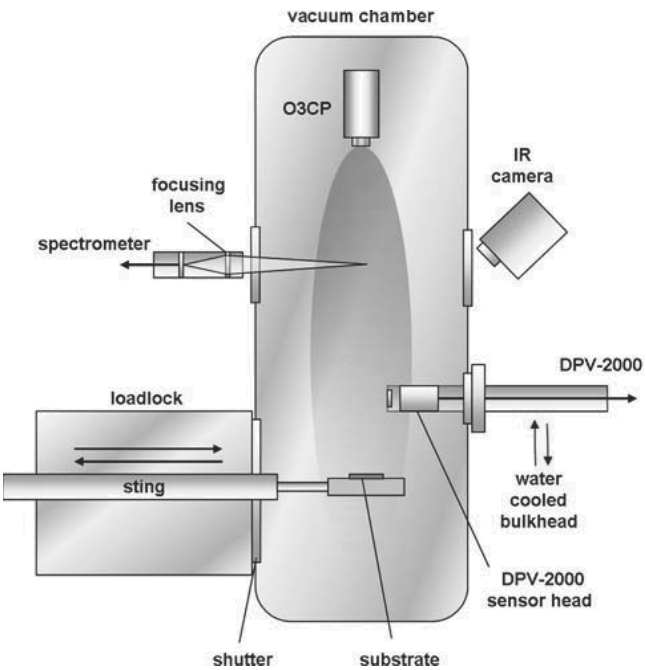

Fig. 3. A diagram of the deposition chamber for the PS-PVD process, showing the placement of monitoring devices (Sulzer-Metco) [10]

3. Conclusions

The PS-PVD technology is a major breakthrough in the development of plasma-spraying processes. It introduces plasma-spraying technologies into the applications where PS-PVD processes used to dominate. The outline presented in this article proves that the literature concerning this technology is still scarce. This fact determines the directions for further investigations into the influence of deposition parameters on the morphology of TBC's. The only available publication in the matter has been prepared by NASA. As well as this, the publications investigating the phenomena occurring during the deposition process are rather limited.

It is essential that new research is done into the matter, so that complex description of the PS-PVD process is obtained.

Thorough analyses of fluid mechanics and of the phenomena occurring in the plasma stream, as well as a description of coating mechanisms are necessary. The currently applied models refer to APS or LPPS plasma spraying, where no powder vaporisation take place. In order to develop new TBC's, it is vital that we understand the processes occurring during their formation.

Acknowledgements

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