Increasing thermal and mechanical properties of thermal barrier coatings by suspension plasma spraying technology

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Abstract. Suspension plasma spraying technology is a promising method to produce advanced thermal barrier coatings using nanopowders. A liquid feeder system is needed to overcome the limitations of nanosized powders spraying – low inertia of the particles. The process is capable of producing coatings with different types of structure – from very dense and compact to columnar with high volume of vertical intercolumnar voids. Consequently, the coating thermal and mechanical properties can be higher than sprayed using conventional technologies.

1. Introduction

For higher gas turbine efficiency and lower emissions, a higher gas flow temperature has played an important role. At the same time, an increase in the operational temperature of turbine blades leads to necessity of the advanced thermal barrier coatings (TBC) and spraying technologies.

Electron beam physical vapor deposition (EB-PVD) and air plasma spraying (APS) are widely used technologies in the area of TBC. Despite of the lower thermal conductivity of APS coatings compared to EB-PVD, the overall performance of EB-PVD coating are better due to the thermal shock tolerance and overall lifetime [1]. The suspension plasma spraying (SPS) is the emerging spray technology that can be used to produce advanced thermal barrier coatings with improved thermal and mechanical properties and lower equipment costs.

This work highlights the recent studies in the field of TBC produced by SPS technology in comparison with conventional APS and EB-PVD technology. The technological features of the process and reachable TBC properties are discussed.

2. Features of the suspension plasma spraying technology

The SPS technology was designed to process the powders consisted of nanometer-sized particles. Since, it is impossible to produce a coating of such fine powders (mainly because of its low inertia) the liquid and ethanol-based suspensions are used in the SPS technology [2]. The process scheme is given in figure 1.

The separate droplets (with size up to several tens of micrometers) of suspension generate because of interaction between the suspension and high temperature plasma flow. Then the liquid phase of droplets vaporizes and powder particles deposit on the substrate. The full or partially agglomeration also occurs during the powder transportation in high temperature flow [3]. Therefore, the finally deposited particles usually has mean diameter up to several micrometers [2, 3].
The equipment for SPS process is almost the same as used in conventional air plasma spraying. However, the liquid feeder system must be used instead of a powder feeder. In addition, different injection systems can be used, as described before in [4]: fluid jet, atomizer and external excitation source (figure 2). Using of the last two allows forming the droplets of nearly constant size, which is very important for process stability.

![Figure 1. Scheme of the SPS process.](image)

Moreover, the relatively low inertia of droplets leads to very high velocity in comparison with the conventional powders with the size of particles is about tens micrometers. In this case, the amount of heat transferred from high temperature flow to droplet can be insufficient to vaporize the liquid [5]. The modern high enthalpy plasma torches should be used to produce the longer plasma jet core: Triplex 210 (Oerlikon Metco), SG-100 (FST) and Axial III (Mettech), for example.

![Figure 2. Injector types for the SPS process [4].](image)

3. SPS coatings characteristics

The wide range of coatings characteristics (thermal conductivity, thermal shock resistance, erosion and sintering resistance, hardness) can be reached using the SPS technology, as well as different TBC structures can be formed. Not only regimen of the spraying process (power, torch speed, spray distance), but the suspension characteristics also can drastically affect the coating structure and properties – viscosity, surface tension, powder/liquid ratio, etc.
There are three major structure types in the area of TBC was described in recent studies (figure 3) of the SPS process [5]: columnar, compact-columnar and compact. The compact structure are similar to the APS one. The columnar structure characterized by vertically elongated voids (between the columns). The compact structure has no vertically voids or cracks and higher overall density.

Studies on the microstructure of TBCs show that the SPS coatings has lower thermal conductivity (in the range about 0.6–1.0 W m$^{-1}$K$^{-1}$) compared to EB-PVD with typical values more than 1.3 Wm$^{-1}$K$^{-1}$ (table 1). The porosity of the EB-PVD coatings is mostly inter-columnar (figure 3d), while the inner part of columns is very dense. In this way, the conductive and radiation contributions to thermal conductivity are rather high [4]. The SPS columnar structure presents a fine-dispersed porosity of columns with that similar inter-columnar porosity (figure 3(c)). Consequently, the SPS coatings with columnar structure have the lower conductive contribution and higher thermal resistance compared to the EB-PVD coatings [6].

Table 1. Thermal conductivity of TBCs [1, 7, 8].

| Technology               | Thermal conductivity (W m$^{-1}$K$^{-1}$) |
|-------------------------|-------------------------------------------|
| EB-PVD                  | 1.3 – 1.8                                 |
| SPS (compact columnar)  | 0.6 – 0.8                                 |
| SPS (columnar)          | 0.8 – 1.1                                 |
| APS                     | 0.8 – 1.0                                 |

The SPS coating with compact columnar structure has even better thermal resistance properties because of its fine-dispersed porosity of columns and suppressed inter-columnar porosity [9]. In this case, both radiation contribution to the thermal conductive mechanism are decreased, compared to the columnar structure of the SPS coatings.

On the contrary, the presence of the voids between columns in thermal barrier coatings structure can drastically improve its thermal cycling resistance because of the strain tolerance. As described in the literature, SPS coatings with columnar structure has better thermal cycling resistance compared to the compact structured coatings. Moreover, the lifetime of the SPS columnar coatings is close to the value of the EB-PVD coatings [10]. The recent studies show that the SPS coatings with columnar
structure appeared to be more resistant to thermal cycling than the EB-PVD coatings (2145 and 1800 cycles to failure respectively) [8]. At the same time, the coatings with compact columnar structure have lower lifetime due to the lack of strain tolerance compared to the SPS coatings with columnar structure, but it still higher than conventional APS ones.

4. Conclusions
The suspension plasma spraying is an emerging technology for obtaining advanced thermal barrier coatings using nanostructured powders. The increased coating characteristics such as low thermal conductivity and high level of thermal cycling resistance can be reached using the SPS technology.

The main advantage of the process is the ability to varying the structure parameters (porosity, vertical cracks and columns density) for obtaining certain properties of the TBCs. In addition, the core components of the SPS system are the same with the conventional APS technology, so the SPS technology can be cost-effective solution compared to the EB-PVD.

This work shows the potential of the SPS technology but it still needs further research. The process required the structure (and thermal resistance, consequently) and the lifetime optimization as well as the suspension parameters stability.

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