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Investigation of the Thermal Protective Coating for the Experimental Flight Test Vehicle within the International HEXAFLY-INT Project

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Abstract

A potential thermal barrier coating, its composition and the method of its application are discussed. The results of dedicated experiments on coated metal samples are elaborated. The possibility of using a coating to protect aerodynamic models at hypersonic speeds from high temperatures is experimentally confirmed.

1. Introduction

Presently, in many countries various concepts of high-speed vehicles for civil passenger transportation are developed for long distances with travel times much less than could be attained on the existing civil aircraft. In framework of the LAPCAT-II European project [1, 2], several high-speed passenger vehicle concepts were studied on the basis of hydrogen fuelled air breathing engines. Aim of this work was to assess the technical feasibility of a high-speed vehicle for civil transportation that could fly to diametrically opposite points (e.g. from Brussels to Sydney) at cruise speeds ranging from Mach number M= 5 to 8. The claimed performances were verified on the basis of simulations and on-ground experiments. The next step is the verification by flight experiment which is one of the main goals of the international coordinated HEXAFLY-INT project.

Due to the high thermal load on the structure, one of the most important issues addressed by the project is the research and technology development for thermal protective coating and its characterisation. According to the computational estimation [3, 4], the outer surface temperature of the vehicle may well exceed 1200 K. This temperature level at the surface substantially exceeds the maximum permissible operating temperature for the metallic alloys used in the construction. To solve this problem, it is necessary to reduce thermal stresses in the structure by applying thermal barrier coatings on titanium, copper and aluminium samples.

2. Thermal barrier coating

In the development of thermal barrier coatings intended to protect titanium plates (BT20), copper (M1) and aluminum (AK4) alloys against high temperature exposure, the technology of high-energy plasma powder spraying is proposed. The essence of the high-energy plasma deposition method consists of heating and melting a powder material by a plasma flow followed by acceleration. On the substrate’s surface, the sputtered material comes in as a dispersed state in the form of fine fused particles, which are fixed once hitting the material. They are then consecutively superimposed one upon another, forming a coating.

The method of high-energy plasma spraying is a modification of the standard gas flame technologies but with high energy characteristics of the plasma flow (V = 2400 m/s, T = 5000 – 10 000 K) [5]. This leads to the heating of the spray particles up to the melting point. Compacted and deposited layers increase the strength of their adhesion to the treated surface. Due to the high energy input to the material being processed, the conditions for the formation of heat-resistant intermetallic and thermobarrier ceramic coatings are realized.

Coating was carried out on a special facility with an original assembly installation of the plasmatron with a rated power of 50-70 kW (Figure 1). Plasma torches are the heart of any plasma plant. They determine the quality of the coatings obtained and the technical and economic parameters of the plasma spraying process. The plasma torch PNK-50 is made of a linear scheme with sectioned inserts and is equipped with a node for annular injection of powder materials with gas dynamic focusing. The structural feature distinguishing it from the commercially available

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plasma torches are the available sectioned inserts which serves fixing the arc length between the cathode and the anode as well as reducing the plasma jet pulsation level [5]. It further allows increasing the length and arc voltage, which provides an increased power of the plasma torch.

Figure 1: Electric arc plasma torches for deposition of metallic, intermetallic and ceramic powder materials

A significant part of the particles, after experiencing a collision, cancels out the radial velocity component and continues along the axis of the jet (Figure 2). The central part of the jet remains unperturbed at the annular input, which indicates an insignificant depth of penetration of cold transporting and focusing gases into it. Therefore, a slight decrease in temperature when feeding the transporting and focusing gases increases the efficiency of particle heating, and, consequently, the quality of the coatings formed. The use of the ring-input unit promotes an increase in the average velocity of the sputtered particles with a certain decrease in the plasma temperature.

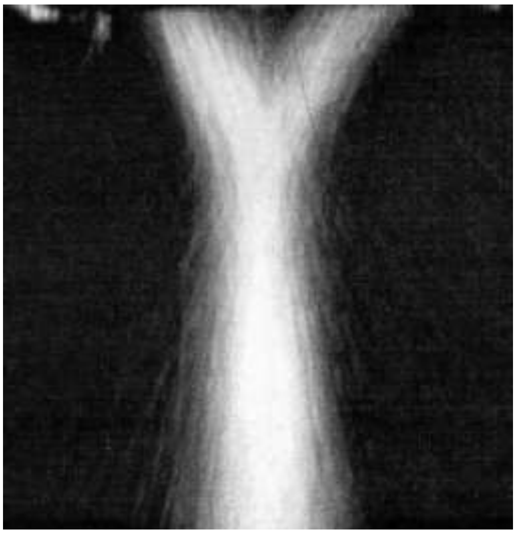

Figure 2: Photo of tracks of powder particles that expire from the radial-circular slot of the input unit

The conducted researches of the developed thermobarrier coating based on zirconium dioxide have shown that this coating has a high density and hardness index with a low porosity value. The obtained complex of mechanical properties is necessary from the point of view of providing such important operational characteristics of the protective coating as heat resistance, erosion resistance and thermal protection efficiency.
As a result of high-energy plasma spraying technology, the developed thermal barrier coating is zirconia (for a heat-resistant sublayer system «Ni - Co - Cr - Al - Y») with a microstructure of nodular type and columnar substructure grains having low porosity (total porosity P = 5%), high densities (6. 8 g/sm^3) and high hardness (HV = 950 kg/mm^2) providing the ingredients to increase the heat resistance and the efficiency of heat shielding the sample surface (Figure 3).

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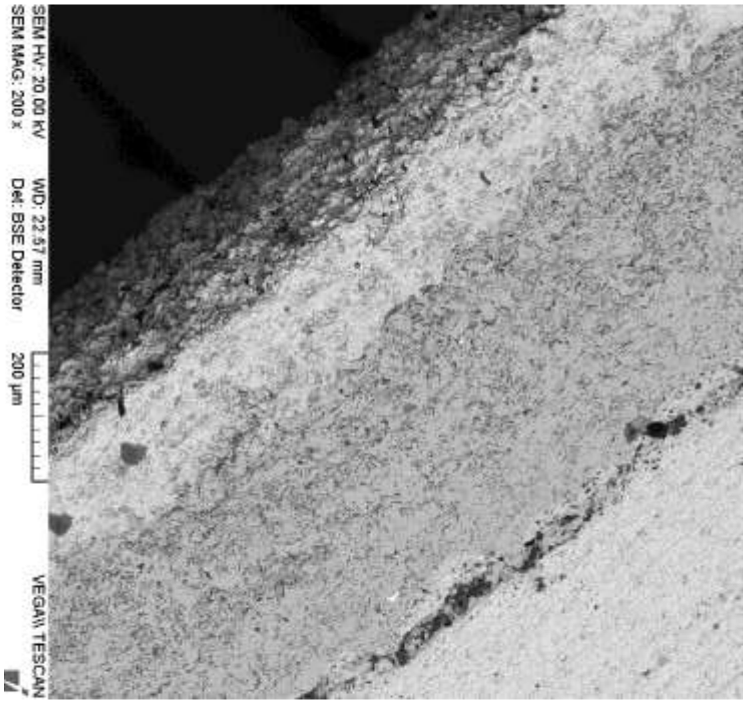

Figure 3: Microstructure of the triple layers thermobarrier coating with ZrO_2

For conducting tests in the facility T-131 of TsAGI, several samples in titanium, copper and aluminium alloy were manufactured and coated with ZrO_2. As an example, Figure 4 shows a titanium sample with thermobarrier coating.

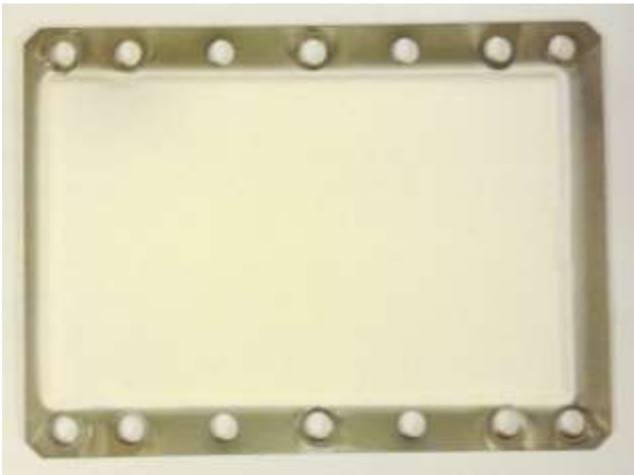

Figure 4: Titanium sample (BT20) with thermobarrier coating based on ZrO_2

3. Description of the experimental facility T-131 of TsAGI

The tests of the metallic samples with thermo barrier coating are carried out in the T-131 facility (Figure 5) which is intended to study:

- Operational processes in ramjet models;
- Various fuels carburation and burning processes in subsonic and supersonic flows;
- Thermal transformations of hydrocarbon fuel;
- Heat-shielding and structural materials;
- High speed air-feed jet engine models in free stream;
- Burning on the outer surfaces of flying vehicles;
- Air-feed jet engine air intakes.

The key component of the facility is a kerosene air heater of the gas-flame type. The air, oxygen and kerosene are supplied into the air heater combustion chamber in an amount needed to create a flow with the predetermined stagnation parameters T_0 and P_0. It is to be noted that the oxygen is supplied into the air heater combustion chamber to replenish the burnt oxygen from air in such a way that the oxygen portion in products of combustion be g_{ox}=0.232. The last requirement is of importance for simulating the atmospheric air when testing combustion processes. Such a manner of compensation provides also the high completeness of kerosene burning.

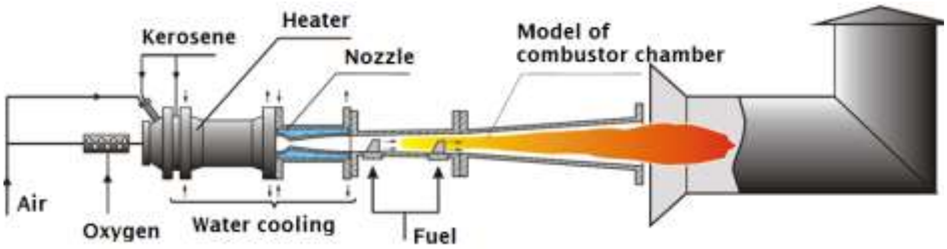

Figure 5: Scheme of the T-131 facility

As a fuel, the air-heater uses the kerosene with the following comparative weigh percentages: 13.4 % of hydrogen and 86.6 % of carbon, with the stoichiometric air ratio as L_0=14.75 and a calorific capacity of 10.250 kcal/kg. The oxygen weight share in air is 0.232. To assure that the oxygen portion in combustion products, produced by the air heater, corresponds to pure air, the flow rates of the kerosene and oxygen supplied to the air heater must be interrelated. There are correlations of components that come in/out of the heater while keeping the accurate oxygen concentration equal to 0.232.

It has to be noted that there is also a possibility to carry out the tests without keeping the oxygen mass portion in the combustion products corresponding to pure air. This widens essentially the range of gas flow composition and parameters at the air heater exit.

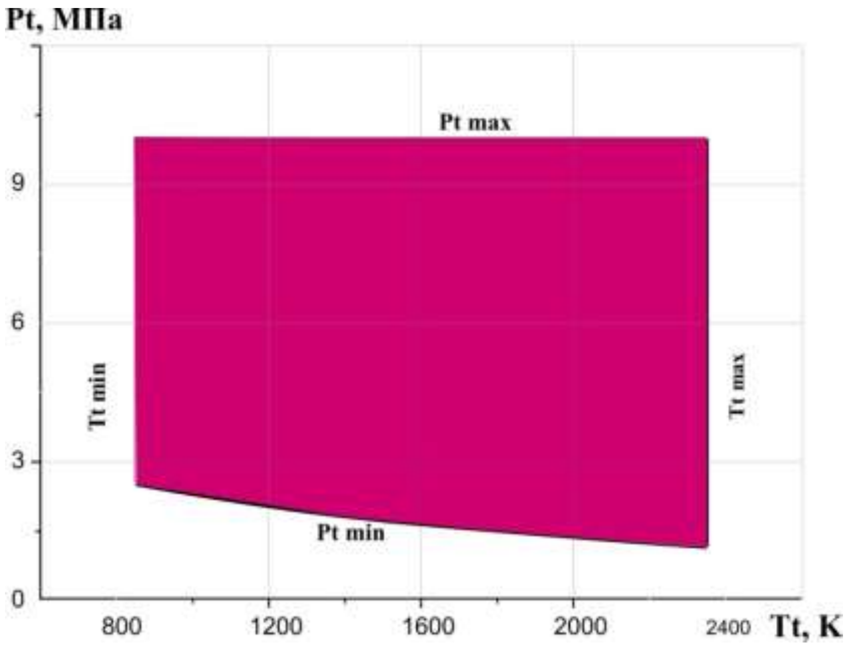

Figure 6: Limitations of the heater’s regimes

The air preheater operates persistently under temperature range of T_0 = 850 – 2350 K and pressures up to 10 MPa. The operational area of the air preheater is given in the Figure 6. The upper operational area boundary conditioned by the pressure p_0 and the temperature T_0 of the air preheater gas is limited nowadays by the p_0 = 10 MPa pressure maximally available in the fuel system. The lower limit is estimated by the minimally possible p_0=0.2 MPa pressure gradient at the fuel injectors, under which the sustainable air preheater operation can be kept. The right boundary (T_0=2350 K) is estimated by the maximal oxygen flow rate of 1.5 kg/s and the left one (T_0=850 K) is determined by the kerosene ignition ranges and combustion stabilization in the air preheater.

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4. Results of samples testing

Tests of samples were held in the T-131 wind tunnel at TsAGI. It is actually a connected-pipe facility consisting of a working chamber made from high heat-resistance material supporting the sample followed by conical funnel stainless steel cooling flow (Figure 7).

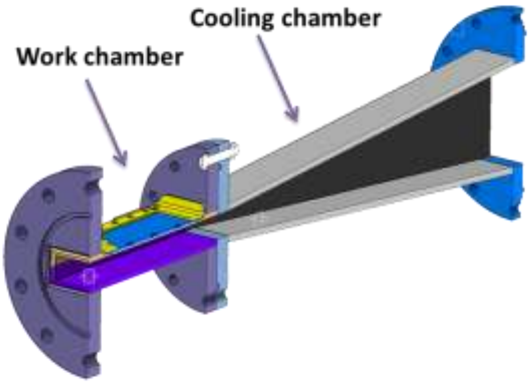

Figure 7: Mock-up for testing samples in WT T-131 TsAGI

All tests were conducted with an aerodynamic nozzle with Mach number M = 3 at the entry of the mock-up and with a total flow temperature of T_0=2000K. Initially short debugging tests were held with a stainless steel plate in order to define static pressure distribution on the sample surface.
Based on these tests, 3 rhenium-tungsten thermocouples were installed with a diameter of 0.35 mm on the sample compartment along with another 10 chromel-alumel (0.3 mm in diameter) thermocouples. The endurance tests for the titanium (VT20) and copper (M1) alloy samples recorded the tests flow parameters of the T-131 along with temperature inside the mock-up and the sample.
Pictures of the mock-up installed in the WT T-131 are shown in Figure 8.

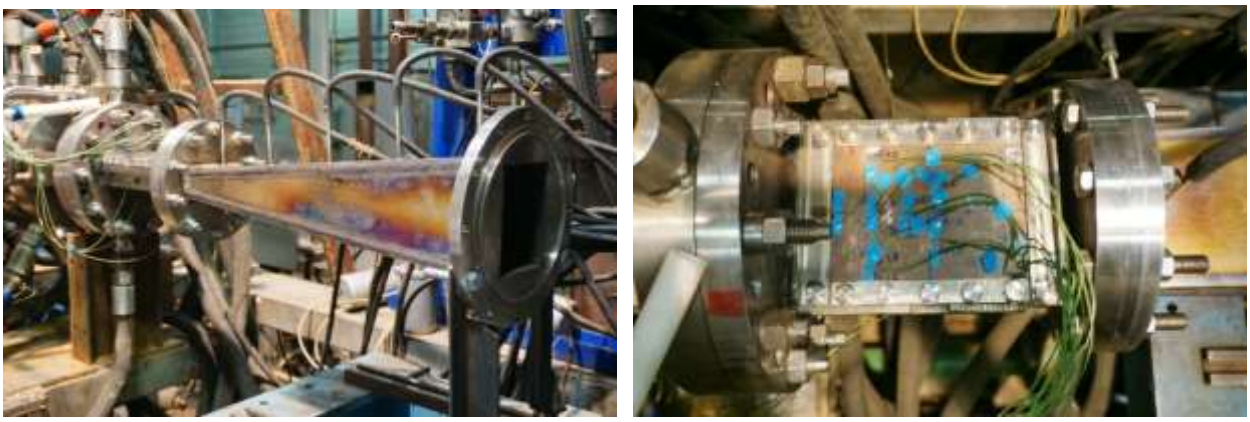

Figure 8: Mock-up in the WT T-131 TsAGI

Main goal of the tests was heating up the samples to the necessary temperature along a predefined temperature gradient. This information will be useful in future thermal analyses of the vehicle. As an example, the temperature distribution in the copper sample during tests is shown in Figure 9.
It should be noted that the metals (both BT20 and M1) were heated to a temperature of 850-900 K. The samples didn’t melt and the thermal barrier coating remained intact. As for the aluminum alloy, it was heated up to 500 K. After this first test coating was fine but during the second test, the thickness of coating was decreased and the sample was damaged due to the high temperature flow inside the mock-up.

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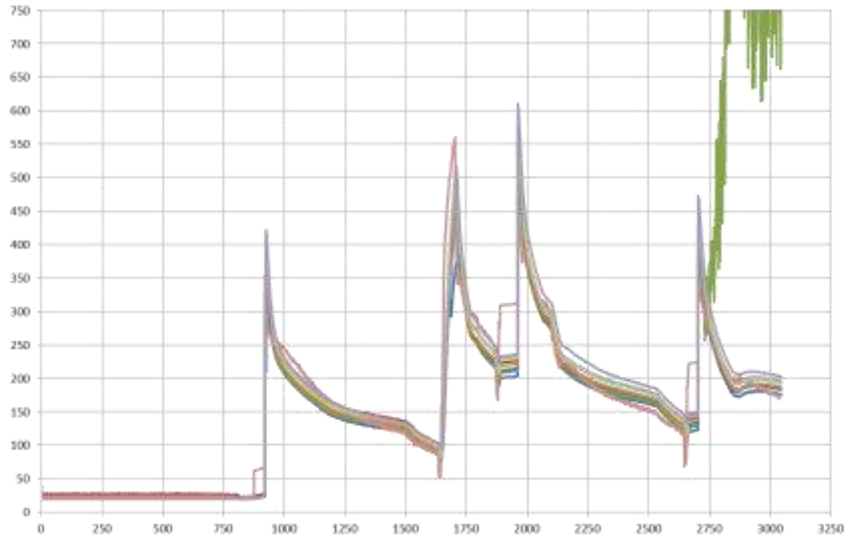

Figure 9: Temperature distribution on the copper sample during test

After the high-temperature bench tests, investigation of the structural-phase state of the thermal barrier coating of zirconia was conducted on the experimental plate of BT20 titanium alloy. The appearance of the plate after the test is shown in Figure 10. To determine the phase composition and microstructure analysis of the coating separated fragments were created by cleavage. X-ray diffraction analysis revealed that the phase composition of the coating on the surface and in the inner layer is virtually identical, and the ZrO_2 has a tetragonal type crystal lattice. The difference is that in the inner layer cover has a small amount of residual phase monoclinic ZrO_2 present in the powder mixture and was preserved after the plasma spraying.

Figure 10: Titanium sample after high-temperature tests (small pieces were separated for analysis)

Investigations were carried out by an electron microscopy to examine the state of the inner layer and outer surface coating of zirconia. Strong differences in the structure were not observed on the outer surface of the coating having a single pore diameter of not more than 3 - 5 microns. Elemental analysis carried out on the cross section of the coating showed that the stoichiometric composition of the coating after exposure to high temperature is maintained, as evidenced by the simultaneous arrangement of zirconium and oxygen lines. It should be noted that the surfaces prefecture layer (thickness ~ 60 micrometers) coating has carbon reflex, part of the combustion products.

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The microstructure of the thermal barrier coating of the coating is shown in Figure 11. The coating consists of a layer thickness of about 1-2 microns. Good columnar grain structure is visible to T- ZrO_2.The transverse dimension of the columns is ~ 200 nm.

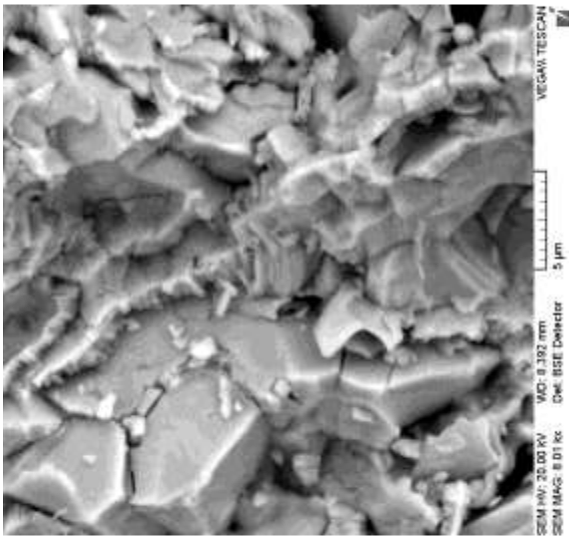

Figure 11: Microstructure of the thermobarrier coating ZrO_2 after tests (X8000)

According to this investigation, it was found that the Zirconia thermal barrier coating retained its stoichiometry, phase composition, surface morphology and an inner columnar grain microstructure T-ZrO_2 after the high-temperature bench testing.

5. Conclusions

The thermobarrier coating of zirconium dioxide formed on the intermetallic sublayer of the "Ni-Co-Cr-Al-Y" system is designed for high-temperature protection of the titanium alloy VT-20, copper alloy M1 and aluminum alloy AK4. The zirconia coating has a microstructure of spheroidal type and a columnar substructure of grains. It has a low porosity (total porosity P = 5%), a high density (ρ = 6.8 g/sm^3) and high hardness (HV = 950 kg/mm^2). Based on the investigation results in the WT T-131 at TsAGI, it was found that after carrying out high-temperature bench tests, the thermal barrier coating of zirconia retained the stoichiometric and phase composition, as well as the surface morphology and the internal columnar microstructure of T-ZrO_2 grains. Therefore, the developed thermal barrier coating technique is recommended for testing on prototypes as a protective coating against high-temperature thermal impact.

Acknowledgements

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