Investigating the radiation-convective heat exchange of a metal-ceramic plate

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Abstract. The paper presents the experimental data on heat exchange during thermo-cyclic interaction of a flame jet with a thermal barrier ceramic coating. Cooling due to radiant heat transfer into the environment allows organizing heat exchange in such a way that when a flow of combustion products with a temperature of 1500 °C flows onto the sample, the temperature on the surface of the TBC does not exceed 1200 °C. The thickness of TGO after 1500 thermal cycles was 9.5 microns

1. Introduction

Thermal barrier coating (TBC) based on Zr and Y oxides is widely used to protect the heat-stressed surfaces of elements of power and propulsion systems. The application of TBC allows increasing the temperature of the gas flow and improving the resource characteristics of the design. In thermal cyclic tests of TBC, the used methods differ both in the ways of organizing the process and in the set of parameters that characterize the intensity of the impact. Often, the «isothermal» ISO14188 standard is taken as the basis for the test procedure, when the sample is placed in the furnace for a fixed time. The ISO14188 standard recommends a heating/cooling rate of ~1.2 K/s for the sample. The resource testing programs developed at CIAM are based on the method of cyclic heating in the flame of a gas burner. In [1], the same approach was used to organize thermocyclic tests. The heating/cooling cycle took 60 seconds. The number of cycles varied from several hundred to 6000. In [2], the TBC system was evaluated using thermal cycling under isothermal conditions and under heat flux conditions. Under isothermal conditions, the TBCs retained their functional parameters for up to 120 hours before the coating completely degraded. Under these conditions, the presence of cracks in the TBC was detected after about 100 hours. The same TBC samples tested under non-zero heat flux conditions degraded in just 8 hours. Under the destruction of TBC, the integrity violation of 30% or more of the coating surface area was assumed.

The resource of the coating is determined by the formation of destructive cracks. There are two stages of crack growth. At the first stage, a gradual growth of thermally grown metal oxide (TGO) occurs at the metal/ceramic interface, mainly consisting of Al\(_2\)O\(_3\). The specific density of this layer differs markedly from the metal and an increase in the stress concentration occurs on the metal roughness elements. After TGO thickness reaches the values of 5–6 microns, the second stage of coating destruction starts, and individual cracks begin to merge, forming larger objects. In some cases, the growth of TGO can lead to local detachment of TBC, which is the beginning of the destruction of
the coating. As a threshold boundary for the beginning of the coating destruction, a TGO thickness of ~10 microns may be taken. It is clear that the formation of cracks that destroy the ceramic coating depends on a complex of reasons. It has been experimentally established that some of these factors are the rate of heating and cooling of the coating and the value of the temperature gradient over the TBC thickness, which depends on the intensity of cooling of the metal at a fixed thermal load.

The TGO growth and the destruction modes are determined by the time spent in the high-temperature state and practically do not depend on the method of influence on the sample. Although there is a noticeable difference in the coating durability for each test method, in the TGO, under conditions of a constant temperature gradient, a crack of 30 microns, and in isothermal conditions, a crack of 55 microns appear. In most isothermal tests with round flat samples, the final destruction occurs at the edge of the sample, while the samples tested under the influence of heat flux are destroyed in the center of the sample, where the flame exposure is maximum. Currently, various semi-empirical approaches have been developed to predict the lifetime of a TBC taking into account specific operating conditions. In [3], a phenomenological method for predicting the service life of a TBC obtained by ZrO$_2$ plasma sputtering with a binding MCrAlY layer is presented. The analytical model [4] uses a two-stage approach to calculate the development of stratification cracks: it is assumed that the initial crack growth is proportional to the thickness of the TGO scale on the binding layer. After exceeding the critical thickness of the TGO, the crack propagation is regulated by the linear elastic fracture mechanics, taking into account the stresses that cause thermal discrepancy and growth of the TGO.

The purpose of this work is to develop a stand and conduct thermocyclic tests of samples of heat-protective coatings using an oxygen/propane flame under conditions of radiation-convective heat exchange.

2. Problem statement

The scheme of the organization of the thermocyclic testing system is shown in Figure 1. In the setup, a gas burner PCT-ZP(M) was used to heat the sample: propane/oxygen/air. The PCT-ZP(M) burner consisted of two coaxially arranged channels (Figure 2). Oxygen was supplied through the central tube. A mixture of propane, oxygen and air was supplied through the annular channel. The flow modes were set using digital gas flow regulators UFPGS-2, Bronkhorst El-Flow, and MKS FlowMeter. The composition and flow characteristics of the reagent flows were selected to ensure the absence of soot particles at the temperature of the combustion products of 1500–1800°C. The diameter of the outlet orifice on the burner section was 6 mm. The distance from the burner to the sample was ~ 90–100 mm. At this distance, the diameter of the free jet impinging on the barrier varied depending on the operating parameters and ranges from 15 to 30 mm. Metal temperature control was carried out using K-type thermocouples, and gas flow was controlled by B-type thermocouple. The analog signal from the temperature sensors was digitized by the Termolab-32 module, coupled with an external ADC/DAC module E14-140. The received code was read by the program via the USB bus and, taking into account the readings of the built-in «cold junction» sensor, it was converted to the current temperature value. To synchronize and record the time series of the measured parameters and the corresponding position of the test sample relative to the high temperature source, the readings of the internal timer of the computer were used. The software control allowed setting the number of cycles, the range and the speed of movements of the holder made of heat-resistant material TZMK-10 with the fixed test sample continuously cooled with air.
Figure 1. Setup diagram. 1 – cylinder-receiver of the cooling system compressor, 2 – gearbox of the cooling system compressor, 3 – filter, 4 – cooling air flow control valve, 5 – pressure gauge, 6 – rotameter, 7 – metal tube, 8 – tube bracket, 9 – programmable logic controller SMSD-4.2, 10 – stepper motor PL57H76-D8, 11 – coupling, 12 – carriage of the linear movement unit, 13 – sample mounting stand, 14 – sample holder, 15 – ceramic pins, 16 – test sample, 17 – infrared pyrometer electronics unit, 18 – optical head of the infrared pyrometer, 19 – camera, 20 – TermoLab32 module, 21– E14-140 converter, 22 – computer, 23 – PR400B gas flow regulators control unit, 24 – PCT-3P(M) propane – oxygen burner, 25 – MKS1179A gas flow regulator, 26 – EL-FLOW gas flow regulator, 27 – UFPGS-2 gas mixture formation unit, 28 – oxygen cylinder, 29 – propane cylinder, 30 – compressor receiver cylinder, 31 – LED floodlight.

In the implemented scheme of thermocyclic tests, high heating/cooling rates in the gas phase of ~12 K/s are used. To control the temperature of the ceramic surface from the torch side, an OPTRIS CT pyrometer model 3MN2-CF4-CB3 was used. An experimental estimate of the surface grayness coefficient of 0.2 was obtained to be consistent with the data of [1]. After a series of N tests, the condition of the coating was photographed. The resistance of the coating to periodic thermal loads and the coating area due to sublayer corrosion or destruction of the ceramic coating was evaluated on the basis of 1500 cycles. The sample was moved to the propane/oxygen flame for 20+55 s. The linear movement speed was 20 mm/s. In this case, the «cold» side was continuously cooled by a stream of air at room temperature. After that, the continuously cooled sample was withdrawn for 40 seconds from the flame zone. The maximum temperatures on the ceramic surface did not exceed 1200°C. Typical thermograms are shown in Figure 3.
3. Results and discussion

Under the conditions of our experiments, the Stark number characterizing the effect of absorption on heat transfer in a translucent medium is

\[ N = \frac{\alpha L}{4\sigma_0 T^4} \ll 1 \] [5].

It is known that for \( N \rightarrow \infty \) the absorption of the radiation flux inside the body may be neglected, the layer is transparent to radiation, and the temperature profile inside it is linear. When \( N \rightarrow 0 \) the thermal conductivity may be neglected, and everything is determined only by radiation. At \( N \approx 0.1 \ldots 0.01 \), both transfer mechanisms work, the nonlinearity of temperature distributions, and temperature distributions are described by an integro-differential equation. Under such conditions, the temperature distribution may become nonlinear [5].

At the temperature of the burner walls, from which the impact jet flows out, and the surrounding surfaces below 1000 °C, cooling into the surrounding space due to radiant heat exchange reduces the surface temperature of the TPC by an amount of about 70–80°C.

Figure 2. Photo of the sample during heating.

Figure 3. Typical thermograms: 1 – gas flow; 2 – temperature at the metal/ceramic interface; 3 – on the cooled side of the metal; 4 – temperature on the «hot» surface of the TBC.

Figure 4. TBC structure after 1500 thermal test cycles, phase 4 – metallic layers, phase 3 – TGO, phase 1 and 2 – ceramic layers.
A detailed analysis of microimages has shown the presence of a transition (interface) layer (phase 3) with an average size of 9.5 microns between phases 2 and 4. The elemental analysis has shown the presence of Zr, Ni, Cr, Al, O in the structure of the layer. To study the uniformity of the application of layer coatings, a transverse section of a composite material sample was also obtained at a distance of 5 mm from the central section. This region is also characterized by the presence of at least 5 layers of different phase composition that almost completely repeats the composition of the central plume. There is no unevenness of coating on the sample.

Cooling due to radiant heat transfer into the environment allows organizing heat exchange in such a way that when a flow of combustion products with a temperature of 1500°C flows onto the sample, the temperature on the surface of the TBC does not exceed 1200°C, and the temperature of the substrate material does not exceed 950-980°C. The thickness of TGO after 1500 thermal cycles was 9.5 microns, while no significant violations of the integrity of the coating were recorded.

References
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