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PHYSICO-MECHANICAL PROPERTIES OF CERAMIC MATERIALS AND COATINGS OBTAINED BY PLASMA SPRAYING: QUALITY MANAGEMENT ASPECTS

V.I. Liubushkin[1], O.B. Zagorodny[2], V.Yu. Bozhanova[3], A.V. Liubushkina[4],
O.Ye. Kononova[5].
[3]Doct. of Econ. Sc., [3]Prof., [5]Doct. of Econ., Assoc.prof.
[1,2,3,4]Ukrainian State University of Science and Technologies Educational and Scientific Institute «Prydniprovska State Academy of Civil Engineering and Architecture», Ukraine
[5] Chief Economist, LLC "BC "MEGA-BUD"

Abstract. *The study aimed to develop high-quality ceramic material powders based on $Al_2O_3 \cdot Cr_2O_3$ and to determine their physico-mechanical properties, as well as the properties of coatings obtained from these powders through plasma spraying. The physico-mechanical properties of the powders were assessed using standard methodologies, including particle shape and size, granulometric distribution, density, flexural strength, elastic modulus, and the coefficient of linear thermal expansion. The study led to the development of high-quality, high-temperature protective materials of the $Al_2O_3 \cdot Cr_2O_3$ and CAS (cobalt alloy + spinel) types, and samples of coatings from these materials were manufactured. New high-quality thermal protection composite materials were developed for the coating of combustion chambers in gas turbine engines, and their physico-mechanical properties were determined. The newly developed high-quality thermal protection composite materials have been used to form shell components through plasma spraying to produce combustion liners for gas turbine engines. These components are undergoing industrial testing at Motor Sich JSC as part of implementing a quality management system.*

Keywords: *Ceramic composite material, plasma spraying, thermal protection coating, combustion chamber, gas turbine engine, quality management.*

The combustion liners of gas turbine engines operate under extreme conditions, including high temperatures ranging from 800 to 1800 °C and high gas flow velocities of up to 50 m/s. These conditions necessitate the development of new materials capable of maintaining operational integrity at elevated temperatures and gas flow speeds while also possessing enhanced physico-mechanical properties. Currently, ceramic composite materials are utilized for this purpose [1-3].

The physical properties of the composite powders included particle shape, size, granulometric distribution, density, and flowability. The particle shape was determined using optical and electron beam microscopy by analyzing projection images. The shape factor is defined as the ratio of the maximum (ℓmax) to the minimum (ℓmin) observed particle dimensions (ℓmax/ℓmin) – was used as a key characteristic. The granulometric composition of the powders was assessed using sieve and microscopic analysis.

In the sieve method, powder granularity was determined through the mechanical separation of a 100 g sample using a set of sieves arranged in a cascading manner. Fractions smaller than 125 μm were analyzed via microscopic examination using transmitted and reflected light with an eyepiece micrometer scale.

Bulk density was measured according to an established standard using a calibrated container, where the powder was poured through a funnel with a 5 mm outlet diameter. The mechanical properties of the ceramic material coatings—including flexural strength σ_{bend}, elastic modulus «E», and coefficient of linear thermal expansion «α») were determined in accordance with DSTU 3716-98 "Ceramics. Method for Determining Flexural Strength." The standard specifies a three-point bending test, where the specimen is freely placed on two supports and subjected to a centrally applied force. The tests were conducted using a Ynstron-TTDM-L type testing machine (Figure 1).

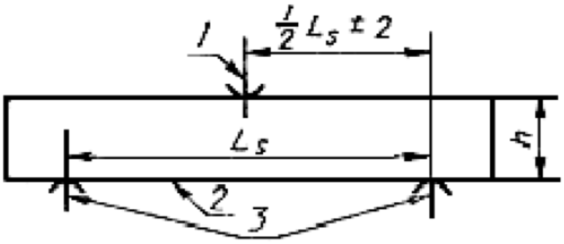

Figure 1 - Three-point bending pattern of sample (B)
1-load bearing support (pressure); 2-surface of the sample, which is working on stretching;
3-pillar that supports the sample.

The parameters of the sample loading pattern when bending are presented in Table 1.

Table 1

Parameters of the sample loading pattern when bending

Loading Scheme	Distance Between Support Rollers, L (mm)	Distance Between Loading Rollers, L/2 (mm)
B	40	20

The sample sizes are presented in Table 2. The elastic modulus was determined according to the standard.

Table 2

Sample sizes for test

Sample Type	Width (mm)	Thickness (mm)	Length (mm)
Bending Strength (σ)	4,0	3,0	50
Type I (for Elastic Modulus Determination)	10	10	30

The bending tests of the samples were conducted using a fixture designed to ensure minimal load eccentricity and experimental safety. The mechanical characteristics E^c, $\sigma^c_{\text{пц}}$, $\sigma^c_{\text{т}}$, were determined based on the autodiagram recorded by the testing machine in force–absolute deformation (P-Δh) coordinates, taking into account the recording scale. The determination of the thermal expansion coefficients for coatings made from experimental $Al_2O_3 \cdot Cr_2O_3$ spinel compositions was carried out in the temperature range of 100°C to 1000°C, with 100°C increments. The tests were performed using an MD-83 dilatometer according to the methodology of the Institute for Problems of Materials Science (IPMS) of the National Academy of Sciences of Ukraine. The sample length changes were recorded using a two-coordinate PDP4-002 potentiometer, while the sample temperature was measured with a KSP4 potentiometer. The calculation of the coefficient of thermal expansion was performed based on the dilatogram, taking into account the thermal expansion coefficient of the quartz system. The powders for plasma spraying were obtained using the sol-gel process.

Results

1. Particle Shape. Measurements showed that the irregularity factor for $Al_2O_3 \cdot Cr_2O_3$ powder ranges from 1.0 to 1.2, indicating a spherical particle shape. In contrast, the composite CAS powder (cobalt alloy + spinel) exhibits an irregularity factor of 2 to 5, with a characteristic fragmented particle shape (Figure 2).

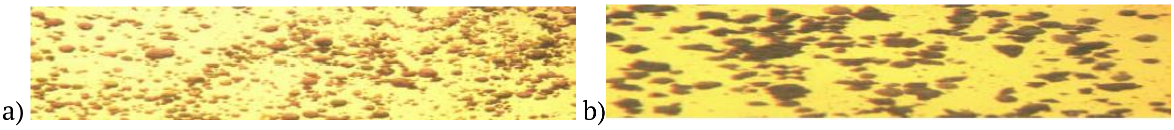

Figure 2 - General appearance of particles of:
a) spinel powder Al2O3·Cr2O3 x100; b) of CAS (cobalt alloy+spinel) x100.

The particle shape of the powders has a decisive impact on their technological properties (powder feeding into the plasma torch), as well as their density, permeability, and strength.

2. Particle Size. Composite powders are polydisperse systems consisting of particles of varying sizes. Depending on the range of particle sizes, the powder is characterized by its granulometric (fractional) composition. Thus, the conducted studies on composite powders of $Al_2O_3{\cdot}Cr_2O_3$ and CAS (cobalt alloy + spinel) revealed that the powders have different geometric shapes: spherical shape is characteristic of the $Al_2O_3{\cdot}Cr_2O_3$ composite, while a fragmented shape is typical for the CAS composite. The results of particle size measurements for the spinel powders and CAS , as well as their size distribution, are presented in Figure 3.

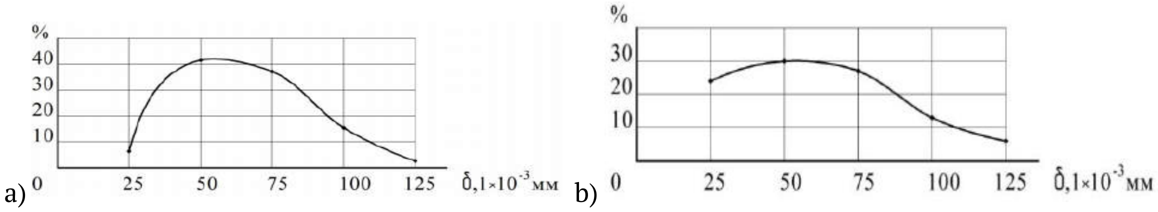

Figure 3 - Graph of particle size distribution for spinel powders, δ – partical size in mkm:
a) Al2O3·Cr2O3, δ – partical size in mkm; b) spinel powders CAS (cobalt alloy+spinel)

The particle size of the powders primarily ranges from 25 to 75 µm. This size range ensures the proper feeding of these powders into the plasma jet and the formation of coatings. The conducted studies on the bulk density and flowability of $Al_2O_3{\cdot}Cr_2O_3$ spinel powders, as well as the composite ПЦПК 63-Н10, show a broad range of possibilities for transporting them from the dispenser to the plasma torch. The physico-mechanical properties of the coatings made from the investigated materials are presented in Table 3.

Table 3

Physical and mechanical properties of sprayed materials

№	Properties	Material Name		
		Spinel powders Al2O3·Cr2 O3,	CAS (cobalt alloy+spinel)	Composite ПЦПК 63-Н10
1	Flexural Strength, σизг, MPa	50/185*1	62,1/195*1	41/110*1
2	Elastic Modulus, E, MPa	150/344*1	161/360*1	60/81,4*1
3	Coefficient of Linear Thermal Expansion «α»·10-6, 1/ºC	8,2*2	9,8*3	10,1*4

Notes to Table 3:

^{*1}- after annealing at 1000°C for 5 hours (denominator), before annealing (numerator);

^{*2}- initial composition: 80% $Al_2O_3 \cdot Cr_2O_3$, measurement in the range of 20°C → 1000°C;

^{*3}- in the temperature range 20°C → 1000°C, plasma spraying;

^{*4}- in the temperature range 20°C → 1000°C; after annealing at 1000°C for 5 hours.

Composite CAS shows superior mechanical characteristics compared to other compositions. The coefficient of linear thermal expansion "α" of the ПЦПК 63-Н10 composition is the highest. According to the data in Table 3, it is evident that annealing the materials enhances the strength properties of the composites by 2-3 times, with the ПЦПК63-Н10 composition showing an increase of only 1.3 times.

Conclusions

1. The studies of the physico-mechanical properties of the developed $Al_2O_3 \cdot Cr_2O_3$ and CAS powders have demonstrated their high quality, owing to their potential application in the formation of plasma coatings. The particle shape and size meet technical requirements, which confirms their compliance with quality standards.

2. Plasma coatings made from $Al_2O_3 \cdot Cr_2O_3$ and CAS powders exhibit high flexural strength, and the coefficient of linear thermal expansion, which approaches that of the base material, allows for improved performance under alternating loads, indicating their high quality.

3. The ceramic material based on spinel and CAS can be recommended for the components of combustion chamber heat shields in gas turbine engines when integrated into the quality management systems of relevant specialized enterprises.

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ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ КЕРАМІЧНИХ МАТЕРІАЛІВ І ПОКРИТТІВ ОТРИМАНИХ ПЛАЗМЕННИМ НАПИЛЕННЯМ: АСПЕКТИ МЕНЕДЖМЕНТУ ЯКОСТІ

Любушкін Валерій, Загородній Олексій, Божанова Вікторія,
Любушкіна Анастасія, Кононова Олександра

Анотація. *Метою досліджень було розробка високоякісних порошків керамічних матеріалів на основі* $Al_2O_3{\cdot}Cr_2O_3$ *з визначенням їх фізико-механічних властивостей, а також властивостей покриттів із цих порошків отриманих плазмовим напиленням. Фізико-механічні властивості порошків визначали по загальновідомим методикам: форма та розміри часток, розподілення по крупності, щільність, границя міцності при згині, модуль пружності, коефіцієнт лінійного теплового розширення. Результати: на основі проведених досліджень отримано якісні високотемпературні захисні матеріали типу* $Al_2O_3{\cdot}Cr_2O_3$ *та КСШ (кобальтовий сплав+шпінель), виготовлені зразки покриттів із цих матеріалів. Наукова новизна: розроблено нові високоякісні термозахисні композиційний матеріали для отримання покриттів камер згоряння газотурбінних двигунів та визначені їх фізико-механічні властивості. Практична цінність: розроблені нові високоякісні термозахисні композиційні матеріали використані для формування коркових деталей плазмовим напиленням при виготовленні жарових труб ГТД, деталі проходять промислові випробовування в умовах ВАТ «Мотор Січ» при впровадженні системи менеджменту якості.*

Ключові слова: *керамічний композитний матеріал, плазмове напилення, теплозахисне покриття, камера згоряння, газотурбінний двигун, менеджмент якості.*