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Additive technology of ceramic turbomachine manufacturing

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Abstract

New nanostructured ceramic powders based on SiC-Si(BN) - Al_2O_3 system for laser sintering were elaborated. Investigations of ceramic material have been conducted. Ceramics obtained by selective laser sintering followed by thermal treatment is 3-5 times less massive than metallic and is sufficiently compact for applications as a constructional material for microturbine production. Microturbine components produced and tested are presented.

Keywords:; nanostructured ceramic;selective laser sintering,;ceramic turbomachine;non-shrinkage cermet.

1. Introduction

Ceramics are considered as the most promising materials for long- term mechanical loading at high temperatures. The main advantages of ceramic materials include their heat resistance, thermal stability, and high compression strength. They, however, have a number of disadvantages: low stability against cracks, impacts and high temperature gradients, and insufficient bending strength. For this reason, new techniques should be applied so as to take advantage of the positive properties of ceramic materials while minimizing the effects of their negative properties. However, the basic problem in application of ceramic materials to gas turbine construction is the difficulty to manufacture components of complex geometry such as those which include internal cavities and orifices of changing curvature. An evident choice for the manufacturing of such components would be to use diamond tools, but they are not effective when manufacturing components of complex geometry, and their use is also time consuming and expensive. An alternative choice would be the laser rapid prototyping technique, preferably selective laser sintering (SLS), widely used when producing metal components of complex geometry from a metal powder. Selective laser sintering of ceramics without binder was first practised by Klocke and Wirtz [1,2] for investment casting shell. The maximum density achieved was 50% of theoretical one and product has been unusable as construction material. Best results were obtained by Y.-C. Hagedorn et al [3] through fully melting (SLM) mixture of Al_2O_3 and ZrO_2 powder under static CO_2 -laser preheating for crack formation prevention. Fully dense parts were produced without post-processing. However, as a consequence of poor surface qualities (Ra =150 µm), the post-processing with a diamond tools is required.

Studies and application of structural ceramic materials (CMC) almost simultaneously began in 1988 in three countries (the USA, Japan, the USSR) in accordance with large-scale governmental programs of creation by 2001-2005. Uncooled

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eco-friendly ceramic gas turbine engine with an initial working fluid temperature of 1350 ° C and an efficiency of 42-46% [4,5].

In the world practice of GTE production, additive technologies (AT) for the manufacture of parts from metal powders have been widely introduced, while the physicochemical and strength properties of the material for the construction of parts, as a rule, practically do not differ from the properties of foundry alloys. AT, developed for technological ceramics, porosity and strength is much worse than analogs (pressing, injection, etc.), since the formation is obtained by melting only the alloy (metal) component of the powder [5]. A metal-ceramic powder free from the above-mentioned drawbacks was created in 2007 on the basis of compositions of the Al-SiC-BN system.

2. Preparation of ceramics and experimental procedure

Nanostructured ceramic powders based on SiC-Si(BN) - Al_2O_3 system for laser sintering were produced by procedure of their manufacturing process which includes mechano-activating ball milling using planetary mills, vacuum calcination, disintegration, and mesh classification. The fraction with the particle size <20µm was finally used in laser sintering, and the average particle diameter as determined by PSD analysis (Horiba LA 950, volume distribution) was ~ 10µm. Selective Laser Sintering (SLS) was done using a Phenix PM-100 machine modified for ceramic powders sintering, and synthesis was made in dried argon at room temperature. A standard 100 W Ytterbium laser was used, and the thickness of the layer calcinated with the laser was ~ 40µm. Samples made for the structural analyses were disks whose diameter was 10 mm and height 3.5 mm. A more detailed report of the procedures used in sample preparation is given in [6]. SEM analysis was performed using a Supra 40 electron microscope and applying standard measurements procedures.

3. Investigation og ceramic material

X-ray tomography is a nondestructive imaging technique in which the three dimensional structure of the sample is reconstructed from two dimensional X-ray projection images [6]. The measured absorption of X-rays is based on the linear absorption coefficients and the thicknesses of the material components along the X-ray paths, which allow us to resolve the distributions of components of different linear absorption coefficients inside the sample. By adjusting the X-ray energy with respect to sample composition and size, the sensitivity of the measurement can be optimized. Also, increasing the number of projection images enhances the quality of the reconstructed three dimensional distribution of linear absorption coefficients. In the tomographic analysis an Xradia MicroCT-400 device was used. The maximum energy of the X-rays was 40 keV, and 1505 projection images of each sample were recorded for the reconstructions. The pixel size in the projections and the reconstructed images was 1.17µm which is close to the maximum resolution that can be reached by conventional X-ray CT scanners. X-ray 3D image of the ceramic fragment is shown in Fig. 1a, which revealed that ceramic structure is closely packed.

Results of the SEM analysis are shown in Fig. 1. Inspection of Fig. 1c indicates the presence of agglomerated objects with typical dimensions of 1 to 20µm which is in accordance with the average particle size of the powder used in the manufacturing, ~ 14µm as well as with the calcinating effect produced by the laser beam with a focus size of <100µm. Obviously, the maximal temperature is achieved in the region near the center of the focus (note that this region is slightly smaller than the area illuminated by the laser beam). This was the reason for the high quality of calcination obtained near the center of the focal point.

Fig.1b demonstrates the nanostructure of the agglomerates. It is evident from Fig.1b that agglomerated particles are formed by pseudo-layers with a typical thickness of 30-50 nm. It is also evident that these layers consist of nanoparticles of similar dimensions. This observation supports the conjecture that the observed layers are monolayers of nanoparticles.

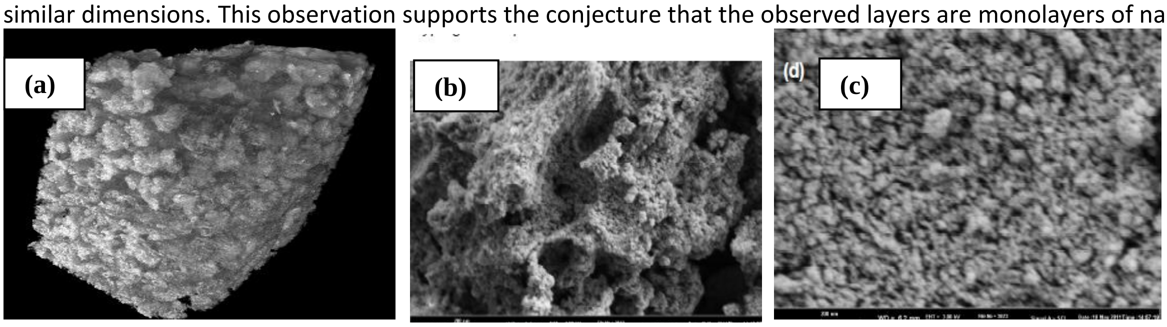


Fig. 1. X-ray 3D image of the ceramic fragment- (a). Volume of the fragment - $0.1mm^3$. SEM examination of the final ceramics structure – (b,c).

The nanoparticles that form the agglomerates have dimensions of 30-50 nm, although larger structures (up to ~ 120 nm) also appear

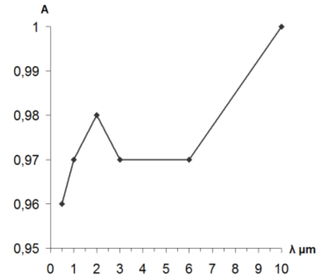


Fig. 2. Spectral absorption of radiation in 40 µm thick ceramic layer.

Investigations of the thin powder layer absorption of the laser radiation in wide spectral region were carried out. Special ditch with 40 µm powder layer was located in spectrophotometers. The absorption in such layer was found to be practically 100% (fig. 2) in spectral region 0,5- 10,6 µm that provides a means for the application of any lasers for sintering.

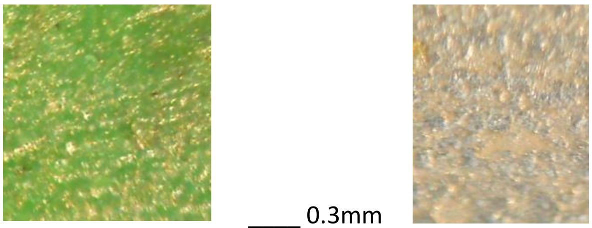


Fig. 3. Cross-sections of ceramic articles

The main characteristics of the ceramic material are presented in Table 1.

Table 1.Main characteristics of the ceramic material

Material	ρ g/cm^3	Thermal expansion K^{-1}	Poisson's ratio μ	E MPa	λ W/mK
Ceramics	2,0	$1{\cdot}10^{-5}$	0,25	$1{\cdot}10^5$	6

The ceramic material produced by selective laser sintering followed by thermal treatment is compact enough for the applications as constructional material .

Constructional ceramics is obtained with subsequent long-term high-temperature synthesis and, in the case of ensuring non-shrinkage, can be used for AT in gas turbine construction. In the scientific centers "Ceramic Engines" them. A.M. Boyko and "Glass and ceramics" since 2006 [4] in the field of development of laser-alloyed CCM.

During this time:

• non-analogous CCMs with a thermal resistance up to 1350 ° C, which do not have shrinkage during fusion, which allow machining in the intermediate stage of manufacturing parts without the use of a diamond tool, as well as the use of technological operations such as diffusion bonding and electroerosion;

• the basis for the scientific design of ceramic parts and devices, high-temperature tract of ceramic gas turbine engine (turbine, combustion chamber, air heater, flues, etc.), manufactured by AT;

• laboratory technological complex, including a research laboratory with high-precision testing facilities, which allows to produce for metallurgical nanostructured powders for selective laser alloying (SLA) with control of their properties at each technological stage.

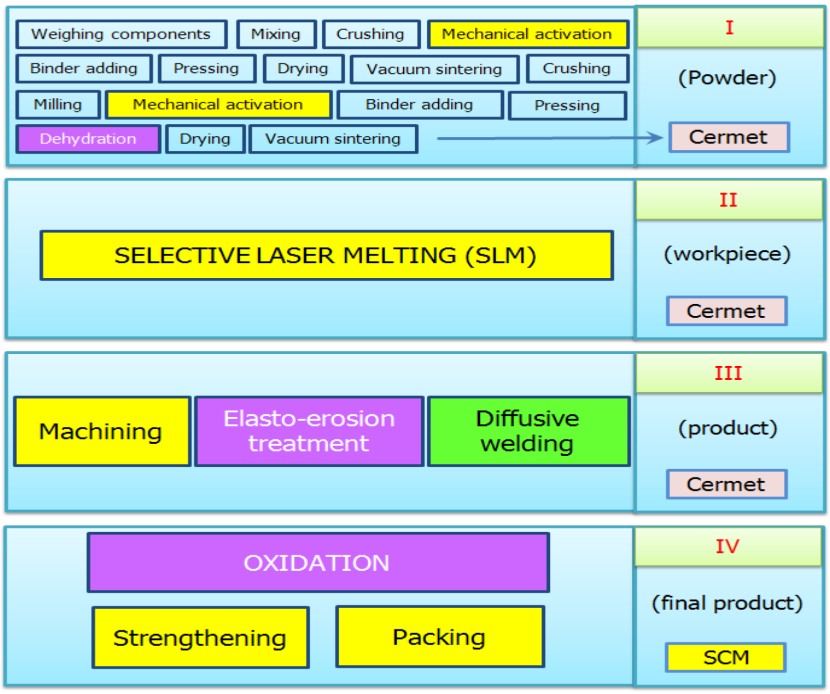


Fig. 4. The technology of manufacturing products from the CMC.

The process of manufacturing ceramic products consists of 4 stages (Figure 4):

- production of a non-shrinkage cermet powder using double mechanical activation;
- the implementation of the SLS - the output of the cermet at the exit;
- if necessary - machining, diffusion welding, electroerosion machining;
- oxidation in the furnace in an oxide atmosphere, hardening and compaction.

4. Design and creation of ceramic turbomachine.

The attainment of a high cycle efficiency of a µGTU (micro gas turbine) depends on many factors: the choice of the basic thermodynamic cycle, aerodynamic and mechanical perfection of nodes, etc. Increase of economic efficiency of a µGTU and reliability can be achieved by applying the following developments and design innovations:

- Non-blades type design of the µGTU allows a fix of rapidly growing negative impact on the efficiency of gas-dynamic leaks and leakages of the working fluid through the gaps between the rotor and stator of turbo machines;

- Ceramic combustion microchamber without separation of it's aerial paths with different laws of radial change spin counter-shifted streams makes it possible to reduce hydraulic losses during the processes of combustion and to eliminate the secondary-emission, resulting in NOx emission less than 5 ppm (at 15% oxygen) .

- Regenerative micro air heater with turbulent sublayer laminar flow along the surface of both sides of the walls of the heat exchange matrix, makes possible decrease of a total resistance of gas and air tracts more than 25% (from 8 to 6% at a recovery of 86%);

- Micro-electro generator, the stator and rotor parts of which are built into the stator and rotor parts of µGTU, so that the electrical efficiency of micro power generator is close to 100%.

The biggest challenges were solved in the creation of the ceramic µGTU:

1. Development of innovative material-laser sintered shrink-proofing ceramics,
2. New technological process with selective laser sintering, which allows reject the diamond processing, diffusion welding.
3. New design concepts, among them tunnel turbine, matrix-ring recuperators, built-in generator. At the same time the creation of more powerful machines may be based on simply combination of a several µGTU into multimodular construction.

5. Micro turbomachine elements produced by SLS and tested

Series of the ceramic μGTU components which were produced by selective laser sintering followed by thermal treatment are presented in the drawings (fig. 3-5)

(a) (b) (c)

Fig. 5. Ceramic parts for high-temperature non-cooled tunneling turbine engine (Ti = 1623 K = 1350 ° C) , rotor speed up to 230,000 1/ min: rotor – (a) , diffuser-(b), nozzle unit – (c).

Ceramic components were manufactured on the progressive technology of the ceramic material processing which includes step of shaping by SLS with cermet formation, step of diffusion joint, electro-erosive and mechanical treatment of the cermet, followed by thermal alloying with minimum shrinkage (<0,1%).

(a) (b) (c)

Fig. 6. Ceramic combustion chamber with uncooled flue pipes and cleaner burning of fuel in the counter-offset swirling jets for multimodular gas turbine engines power up to 32 MW: front device – (a), external flame tube – (b), internal flame tube – (c).

(a) (b) (c)

Fig. 7. Ceramic air heater heats the air entering the combustion chamber to a temperature above 1273 K . Built-in turbo electric generators with an efficiency of up to 99.9%, as the device further performs the role of an upstream stage air heater (a,b). The rotor of the turbo electric generator-(c).

The application of these ceramic components in μGTU's construction allows significantly raise its technical characteristics .

The table 2 shows the comparison [7] of data of the same power plants – metallic μGTU of firm Capstone C30 and multimodular machine of 15 ceramic μGTU F / E-BC2 capacity of 2 kW each of Center Ceramic Engines.

Table 2 . Comparison of multimodular ceramic µGTU with metallic µGTU.

№	Firm	Capstone (C30)	Center ceramic engine	
			F/E-BC2	(F/E-BC2)×15
1	Power, кW; (КПД, %)	30; (28±2)	2;(28±1)	2×15=30; (28±1)
2	Dimensions(L×B×H), или ∅D×L, мм	1900×1344 ×714	∅116×424	(∅116×424)×15
3	Volume, м^3; (mass, кг)	1,823; (578)	0,0045; (6)	0,0045×15=0,0675; (6×15=90)
4	Specific power mass, W/кг; (volumetric, W/l)	62,8; (16,46)	333; (444)	
5	NOx emission, ppm (at 15% O_2)	<9,0	<5,0	

It can be seen that for the same power, efficiency and environmental friendliness multimodular machine 15 F / E-2BC more than 6 times lighter and more than 18 times smaller than designed as a single engine Capstone C30.

Similar comparison [7] (fig 6) between monomodule ceramic GTU with power 16 MW, volume 359 м^3, weight 35,3 т - the curve № 16-35 and multimodule ceramic GTU with volume 202 м^3, weight 20,0 т from 32 µGTU , 500кW each – the curve №1623, shows, that multimodule ceramic GTU not only significantly smaller , but also ensures a constant maximum efficiency at every regime of operation.

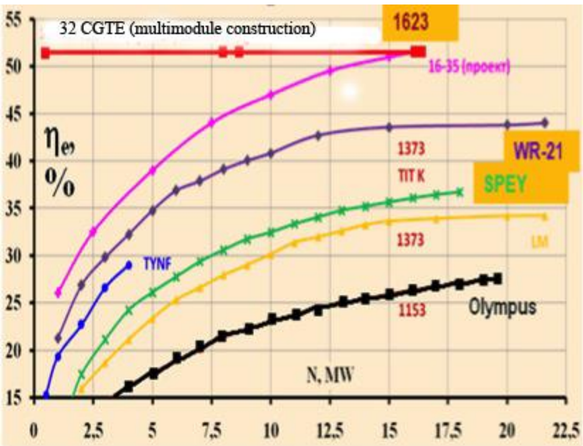
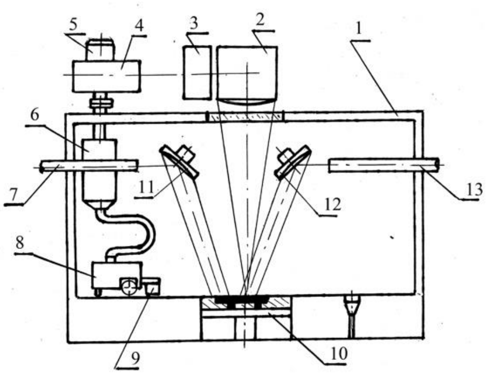


Fig. 8. Efficiency of custom and projected turbomachines.

For sintering ceramic parts for up to 1.5 MW turbomachine a advanced selective laser sintering system based on some patents is designed [8]. The sintering technology implemented on the machine used several sources of concentrated energy flows .Optical monitoring and control is used for sintering turbomachine parts quality [9,10].

6. SLS machine design for ceramic turbine production



Technical parameters of SLS machine :
- size of the workspace – 300x300x600mm
-speed up the manufacture of parts – 50 cm3/h
-scanning speed – 15 m/s
-laser power - 200 W
-mocrowave frequency – 14 GHz
-microwave power – 2 x 2-3 kW
-consumption AC – 8 kW
-gas flow rate Ar (N2) – 2m3/h

Fig. 9. Concept project of SLS machine : 1- technological chamber, 2- laser scanner , 3- optical control system,4-laser, 5 – powder cartridge,6- powder feeding container , 7,13- waveguide, 8- re-coater powder feeding system, 9- 2D-scanner, 10- piston, 11,12 – scanning mirror .

To ensure against the formation of cracks dynamic controlled heating and cooling of the powder surface in two regions is employed using microwave or lamp heating. In these regions selective laser sintering is carried out under temperature control. Precise control of a 3D – body dimensions during the sintering process is effected using 2D-scanner. Laying of the ceramic powder with density 1g/cm^3 is available by a combined system blade-roller. The powder layer is compacted by roller.

7. Conclusion

The development of ceramic μGTU with high temperature level 1800-1850 K in the hot zone of the engine has been made possible through the selective laser sintering of nanostructured ceramics with cermet 3D object formation, technological processing of the cermet, followed by thermal treatment of the 3D object with minimum shrinkage (<0.1%).

New innovative material-laser sintered shrink-proofing ceramics was elaborated which has not need of cooling up to 1623K.

New technological process allows fully reject the diamond processing, diffusion welding and fully automates the manufacturing. New design concepts - tunnel turbine, matrix-ring recuperators, generators were successfully realized. At the same time the creation of more powerful machines may be based on simply combination of several μGTU into multimodular construction.

Ceramic electric μGTU produced by additive laser technology allows:
- increase efficiency
- increase the power density
- eliminate emissions of toxic components of exhaust
- significantly reduce the mass and dimensional characteristic
- ensure continual optimal performance
- simplify management, control and protection
- reduce costs and operating costs.

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