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# EFFICIENCY OF PROCESS OF COATING SPRAYING USING MULTICHAMBER DETONATION UNIT

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A multichamber detonation unit is designed for coating deposition using powder materials. Heating and acceleration of powders is carried out by detonation combustion products of gas mixture of propane, oxygen and air with 20 Hz frequency and more. A difference of multichamber detonation unit is a presence of additional combustion chamber, which rises gas-dynamic parameters of the detonation products and efficiency of spraying process. Effect of unit design peculiarities on gas-dynamic parameters of detonation products was determined. Velocity of detonation products reaches 1520 m/s, detonation wave pressure makes approximately 3.5 MPa. Velocity of the sprayed particles using this unit reaches 1200 m/s. The unit is equipped with a valveless system for gas and powder feeding. This provides reliable operation at high frequency of detonation initiation (up to 50 Hz). A spraying deposition efficiency at that reaches 82 and 67 % for cermet powders and oxide ceramics, respectively. Coatings received at that are characterized with small porosity (< 1 %) and high adhesion to substrate. 13 Ref., 1 Table, 6 Figures.

***Keywords:*** *multichamber detonation unit, velocity and pressure of detonation products, spraying deposition efficiency, velocity and extention of powder jet*

A coating spraying method based on application of processes of detonation combustion of gas mixtures, remains the dynamically developing technological direction from the moment of first patent granting in 1955 [1]. Mastering of this technology was started in Kiev in the 1960s under the leadership of Prof. G.V. Samsonov and at the beginning of the 1980s there were already around tens of modifications of detonation guns for spraying. A vast practical material has been collected from that time. Investigation of physical processes of detonation spraying allowed optimizing the technology and design of the unit and increase coating quality. However, mass application of the detonation technology in the industry was limited by low efficiency, problems of powder dosing and feeding in a pulse jet of the combustion products, relatively low spraying deposition efficiency (SDE) and low safety of detonation units in whole. The perspective direction is development of a valveless detonation unit operating at increased frequencies. For the first time the valveless high-frequency detonation unit (frequency of more than 80 Hz) was created and produced in 1976 [2]. The methods of detonation deposition of coatings and units with continuous feed of the combustible mixture components, gas-dynamic mixture and application of propane, methane and other carbureted hydrogen gases [3] as a combustible gas were developed in the 1976–1980s. A high-frequency pulse detonation gun HFPD [4] can be referred to one of the variants of such class of the units.

Coating material in thermal spraying is formed as a result of interaction of flow of dispersed particles (powder) with treated part material. The key parameters, determining physical-chemical peculiarities of materials' interaction and the possibility of formation of quality coatings, are velocity and temperature of the particles at the moment of collision with a substrate. These parameters determine a nature of contact, namely dynamics of spread of material of the dispersed particle, level of substrate deformation etc. Currently, further development of the high-velocity thermal methods of coating formation is directed on increase of powder kinetic energy at decrease of its temperature. High velocity of the particles at their lower temperature allows carrying out plastic deformation and structuring of the powder material. This provides the possibility of formation of the nanosubmicrocrystalline, dense coating materials, without oxidation and with high parameters of adhesion and cohesion.

The detonation units with nonstationary combustion processes [5] are reasonable to use for getting a high-velocity gas-powder jet. Application of the nonstationary modes of detonation combustion allows significant increase of quality characteristics of the deposited coatings as well as reducing their weight and dimensions of the unit. A mode of overcompressed detonation can be realized, for example, in the convergent channels [6] or at electric discharge of a capacitive storage behind a detonation wave front [7]. Now an important factor is also a level of technology automation. A computerized detonation complex CCDS Dragon [8] can be an example of technological process control. Regardless the achieved success, there are still problems with increase of efficiency of interaction of combustion products' jet and powder particles as well as automation of dosing and rise of dosing accuracy. An important problem is also increase of velocity and pressure of the combustion products and, respectively, a powder jet velocity. It is also necessary to provide complete automation of unit operation and high indices of its reliability and reparability.

An automated multichamber detonation unit (MCDU) [9] was developed for solving these problems. This unit realizes a mode of detonation combustion of the gas mixture in specially profiled chambers. Accumulation of combustion energy from two chambers in a cylindrical barrel provides formation of a high-velocity jet of combustion products, which accelerates and heats sprayed powder. The aim of carried work was investigation of pressure behind the detonation wave front, velocity of detonation products and powder sprayed particles outflow using this unit. A special valveless assembly for dosing and feeding of the powder doses to the barrel was developed to get the high parameters of spraying deposition efficiency (SDE). The dosing assembly includes powder feeder, providing mixing and transporting of gas-powder mixture along pipeline, and gas-dynamic dozing unit. Feeding into these devices provide accurate feeding MCDU barrel portions (doses) of the powder, synchronized with detonation generation frequency (20–50 Hz).

**Equipment and investigation procedure.** *Materials, design peculiarities and principles of MCDU operation.* Investigations, optimizing technological modes and design were carried out on a laboratory experimental prototype of MCDU (Figure 1). Consumption of the combustible mixture components varied in the following ranges, namely 0.6–1.6 m$^3$/h for propane and 3.0–9.0 m$^3$/h for oxygen. The unit has three chambers: *1* — prechamber for initiation of detonation process; *2* — main cylindrical chamber, where development of detonation combustion mode takes place; *3* — annular chamber with slot output into the cylindrical barrel *4*. Annular chamber *3* is used for compression of the combustion products and development of an additional jet, which «support» in the cylindrical barrel *4* the detonation products of main chamber *2*. A dose of powder is fed into the barrel for acceleration and heating. The barrel can have internal diameter 16–20 mm and length 300–520 mm and is selected depending on properties of sprayed powder material. Constriction of working volume of the cylinder chamber of 24 mm diameter to barrel diameter 16 mm provides overcompression of the detonation combustion mode. Further contraction of the combustion products takes place due to annular chamber. Gas-dynamic process of detonation initiation in the annular chamber provides collapse of the combustion products along the barrel axis that dramatically increases their velocity, pressure and density.

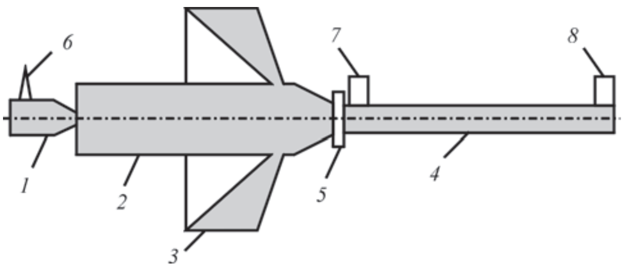

**Figure 1.** Scheme of multichamber detonation unit (see designations in the text)

A dose of powder material is fed ahead a front of the high-velocity combustion products. This dose is fed through annular slot of special gas-dynamic feeder assembly *5*. The size of slot in radial direction is selected experimentally and being the fact of optimizing for specific powder. SDE, determined by weight method, was used as an optimizing parameter. Initiation of the combustion detonation mode for gas mixture was made by car ignition plug *6*. Powder of H.C. Starck: AMPERIT® 740.0 — $Al_2O_3$ (5.6–22.5 μm dispersion) and AMPERIT® 554.074 — WC–Co–Cr(86–10–4 %) 15–45 μm dispersion were used in the experiments

Mode of spraying of $Al_2O_3$ and WC–Co–Cr using MCDU

| Powder<br>Mode | | | $Al_2O_3$ | WC–Co–Cr |
|---|---|---|---|---|
| Pulse repetition rate, Hz | | | 20 | 20 |
| Barrel length/diameter, mm | | | 500/16 | 300/18 |
| Powder consumption | | | 0.7 | 1.4 |
| Gas consumption, m$^3$/h | Chamber 1 | $O_2$ | 4.4 | 3.2 |
| | | Air | 0.14 | 1.6 |
| | | $C_3H_8$ | 0.83 | 0.72 |
| | Chamber 2 | $O_2$ | 4.0 | 3.2 |
| | | Air | 0.25 | 1.4 |
| | | $C_3H_8$ | 0.82 | 0.75 |
| | Transporting gas nitrogen | | 0.9 | 0.9 |
| Specific consumption of propane, m$^3$/kg | | | 2.3 | 1.0 |

on optimizing the design, measurement of velocity of gas-powder jet and coating spraying. Spaying modes are indicated in the Table.

*Procedures for investigation of pressure, velocity of detonation products and powder particles.* Measurement of pressure in the detonation products and velocity of detonation wave were carried out using piezoelectric pressure probes LKh-611, which are calibrated on shock tube with known parameters. The first probe *7* (see Figure 1) was fixed at approximately 60 mm distance form outlet of the annular chamber directly at barrel inlet. The second probe *8* was fixed at the outlet from the barrel. The barrel of 500 mm length and 16 mm diameter was used in the experiments. The distance between the probes' axes is 525 mm. The experiments were carried out using combustible mixture of propane and oxygen in stochiometric proportion. A signal from the probes through a signal converter ADC L-card783 was recorded using Powergraph 3.0 program.

Powder velocity was determined using a device visualizing luminance of heated gas-powder jet. Two fast germanium photodiodes FD287 (time of rise of pulse front 10 ns) with operating spectral range λ = = 0.5–1.7 μm were used as a photodetector. The signal from the probes after amplification came into ADC L-Card783 and was recorded using Powergraph 3.0 program. An amplifier and receiving photodiodes were removed from the detonation unit and the signal from gas-powder jet were supplied to photodetector by means of fiber-optic cables. The axes of the latter were located normal to the gas-powder jet axis. The distance from nozzle section to the axis of measurement system was varied in 40–100 mm range. It is well known fact that density of a radiation flow from the heated gas is much lower than from the powder particles, that allows neglecting radiation of combustion products and register radiation only from the heated powder.

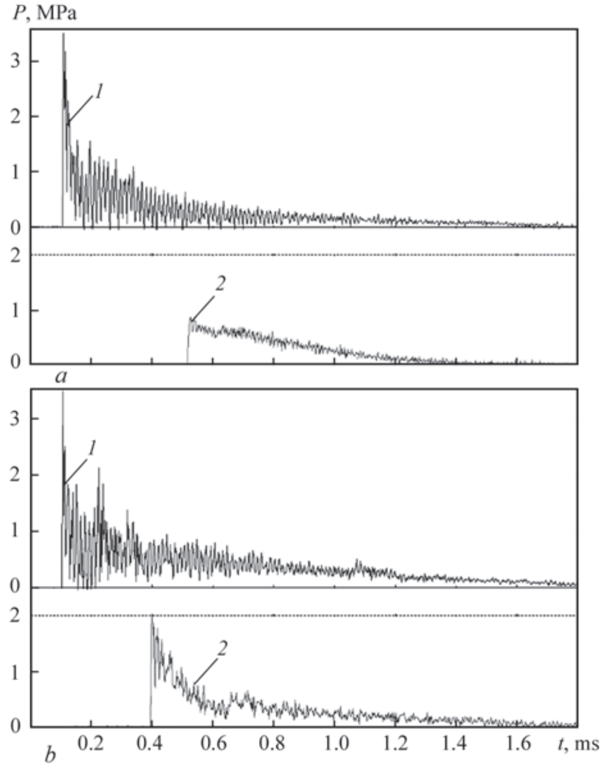

**Figure 2.** Change of pressure $P$ in time: *a* — using one chamber; *b* — with second chamber connected (*1* — at the barrel inlet; *2* — at the outlet)

*Metallographic examinations*. Optical microscope Olympus GX51 and electron scanning microscope Quanta 200 3D equipped with spectrometer of X-ray radiation of PEGASUS system from EDAX Company were used for metallographic examinations and phase analysis of coating microsections. Coating porosity was determined by means of analysis of the microsections, performed by image-processing system. It consists of optical inverted microscope OLYMPUS GX51 and software for image quantitavite analysis. Hardness measurement was carried out using an automated system for microhardness analysis DM-8 by Vickers method at indenter loading 300 g. Adhesion of coating from WC–Co–Cr powder was determined on a glue procedure according to ASTM C633 standard.

**Results of investigations and discussion.** *Pressure and velocity parameters of detonation products.* Determination of velocity of a stationary detonation wave in the unit was carried out at its complete filling with combustible mixture. The combustible mixture was not fed in the annular chamber (see Figure 1).

The experiments showed that time of passing of the detonation wave between the probes makes on average 0.25 ms and velocity is 2100±100 m/s. The value of stationary detonation velocity, corresponding to Chapman-Jouguet conditions, reaches 2450 m/s [10] for oxygen-propane mixture of stochiometric relationship. Received velocity is low due to energy losses during movement in the barrel of 16 mm diameter. Besides, there is a possibility of air admixture in process of chamber filling between the pulses and deviation from stochiometry.

The situation is completely changed, if the detonation unit is filled with the combustible gas mixture to the level of location of the first probe. Such filling of internal volume of the unit with combustible mixture components is used during spraying. At that, the detonation process is finished at the inlet to the barrel, transfer of a detonation wave into shock one takes

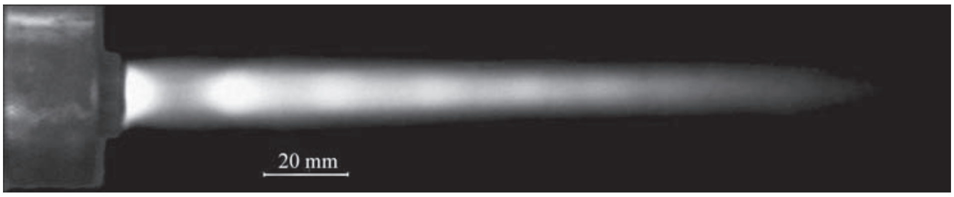

**Figure 3.** Appearance of supersonic pulse jet coming from detonation unit nozzle

place and the latter is developed inside the cylinder barrel. Intensive attenuation of the shock wave takes place due to passing along the barrel when using one chamber (Figure 2, *a*). There is decrease of pressure, velocity and extension of combustion products' zone.

Simultaneous application of the second (annular) chamber allows significantly changing physical parameters behind the shock wave (Figure 2, *b*). The second chamber creates an additional jet, which proceeds by detonation products after the first detonation wave and feed them with energy. The first probe registers formation of the shock wave second front. An amplitude of shock wave at the second probe makes 2.0 MPa, that two times exceeds the indices in using one chamber. Extension of the combustion products flow, having increased pressure at nozzle outlet, is also higher and makes 1.2 ms. An average velocity of shock wave between the probes at that makes 1750 m/s, whereas using one chamber it is 1300 m/s. In order to evaluate the gas velocity behind straight line front of the shock wave, expression [11] is used

$$V = \frac{2}{k+1} D \left( 1 - \frac{c_1^2}{D^2} \right),$$

where $k = 1.3$ is the adiabat; $D$ is the shock wave velocity; $c_1$ is the sound velocity in still environment.

Then estimation of average velocity of the combustion products in the barrel makes 1130 and 1520 m/s using one and two chambers, respectively.

Direct estimation of outflow velocity of the combustion products at barrel outlet is also possible by length of periodic structure wave of a supersonic jet in still environment [12]

$$L = 2.613 r \sqrt{M - 1},$$

where $r$ is the radius of detonation unit nozzle; $M = V/a_0$ is the Mach number; $L$ is the length of periodic structure wave (distance to shock wave); $a_0$ is the local sonic speed in combustion products.

Figure 3 shows an image of supersonic pulse jet at MCDU operation in two chambers with 16 mm diameter barrel. The structure of gas jet is typical for supersonic outflow in underexpanded mode and agrees with explosion nature of detonation unit operation, at which pressure in the chamber significantly exceeds environment pressure.

Based on experiment data ($a_0 \approx 1000$ m/s, $r = 8$ mm, $L \approx 27$ mm), the outflow velocity $V \approx 1600$ m/s is received. This result is correlated with estimation of outflow velocities of the combustion products, given above on the results of experimental investigation of pressure in combustion products and shock wave for 16 mm diameter and 500 mm length barrel.

Carried investigations prove that velocity of the combustion products is significantly increased at the second chamber connection. At that more extended flow of the combustion products is formed in the barrel, having two pressure maxima and higher velocity.

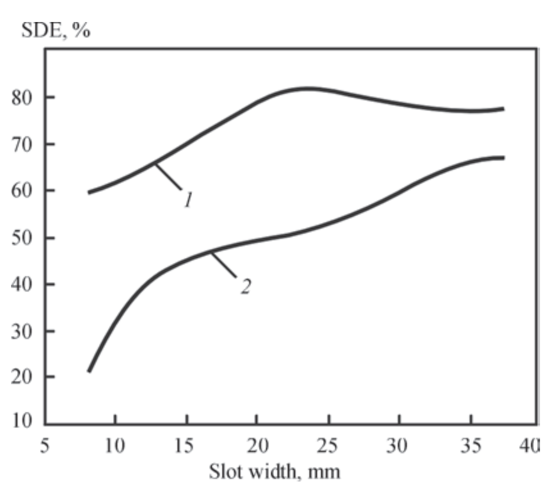

**Figure 4.** Change of SDE depending on width of assembly slot for powder feed: *1* — WC–Co–Cr; *2* — $Al_2O_3$

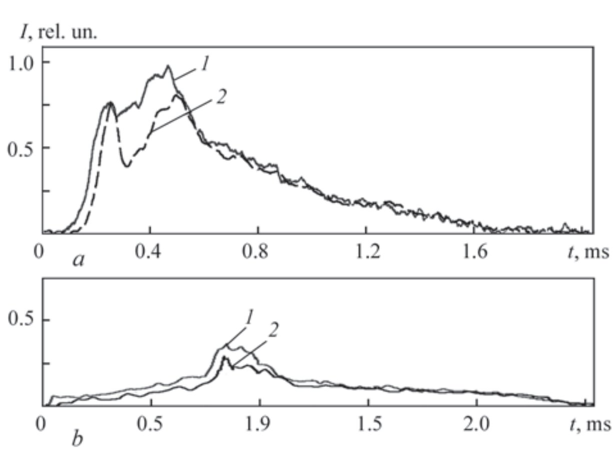

**Figure 5.** Radiation of gas-powder jet of $Al_2O_3$ (*a*) and WC–Co–Cr (*b*) registered using germanium photodiodes FD287: *1* — at 30 mm distance from nozzle section; *2* — at 60 mm distance

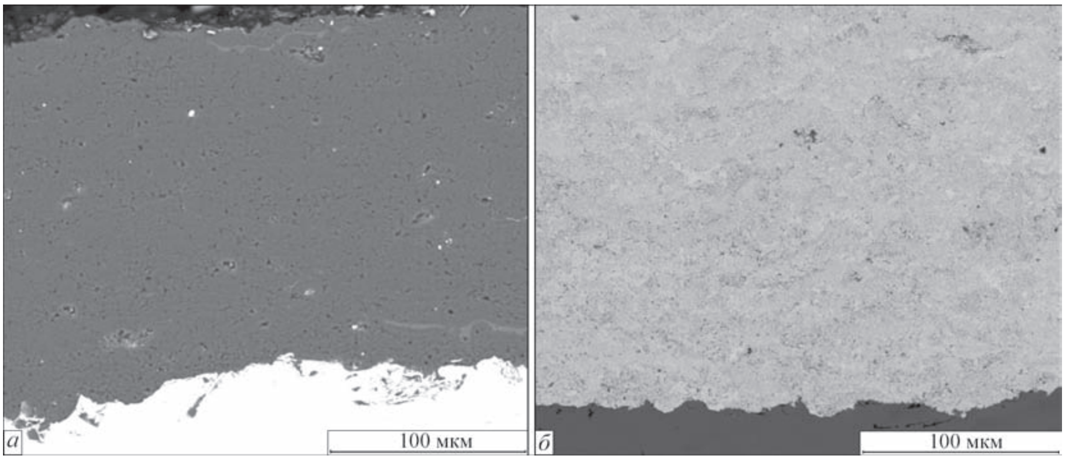

**Figure 6.** Microsection of cross section of specimen with coating of powders: *a* — $Al_2O_3$, dispersion 5.6–22.5 μm; *b* — WC–Co–Cr 86–10–4 %, dispersion 15–45 μm

Such a flow is more effective in powder particle acceleration.

*Optimizing a powder feeder for MCDU*. Taking into account that MCDU works at increased frequencies (20 Hz and more), application of the pulse valve systems for powder feeding, containing moving mechanical parts, is not reasonable from point of view of reliability.

Specially developed assembly for powder feed used in MCDU has a cavity, to which powder is fed from a distantly remote feeder. In the process of spraying the powder comes in the barrel of unit through annular slot during wave discharge. A moment of powder injection in the barrel for the following pulse is determined by slot length in radial direction (slot width). A size spectrum of assemblies for powder feed was manufactured in 5 pcs. amount to get maximum SDE. Figure 4 shows an effect of slot width in SDE for $Al_2O_3$ and WC–Co–Cr. Aluminum oxide has significantly lower density than cermet and, respectively, lower inertia. In order to obtain the maximum SDE in $Al_2O_3$ (67 %) spraying the slot width shall make 37 mm. That for WC–Co–Cr is 23 mm. At that SDE will reach 82 %.

*Velocity parameters of powder in coating deposition*. Visualization of integral radiation of a heated gas-powder jet allows evaluating its dynamics and extension. The velocity of powder jet was determined taking into account time shift of signals from the first and second photoprobes. Figure 5 shows a variation of radiation time from the gas-powder jet at deposition of coatings of $Al_2O_3$ and WC–Co–Cr. The spraying modes are given in the Table. Obtained results were averaged by 20 measurements.

The investigations showed that duration of outflow of the gas-powder jet, containing $Al_2O_3$, makes approximately 1.4 ms. The velocity of jet front at a distance of spraying surface location (up to 60 mm from nozzle section) equals 1000±200 m/s. Such parameters provide spraying of quality coating on solid substrate. For example, Figure 6, *a* shows coating cross-section of given powder, deposited on a sample of low-carbon steel. The investigations showed that the coating has < 1 % porosity. The maximum hardness *HV*0.3–1320±25 was received in coating upper layers. Hardness gradually decreases by approximately 30 % and in the layers, adjacent to the boundary, has the values of *HV*0.3–900±25. Composition of coating material is the following corundum ($\alpha$-$Al_2O_3$) to 47 %; other phases — softer modifications of oxide ($\gamma$ and $\theta$-$Al_2O_3$).

In cerment coating deposition, for example, WC–Co–Cr, the temperature of combustion products was reduced by dilution of the combustible mixture with air (see Table). It is necessary for prevention of the processes of thermal decomposition of higher carbides [13], resulting in decrease of service properties of the coatings. Reduction of powder temperature effects radiation intensity trapped by photodiodes (Figure 5, *b*). Increased content of air in the combustible mixture results in decrease of the detonation product velocity and, respectively, powder outflow velocity. Investigations showed that the average velocity of WC–Co–Cr powder reduces to 550 ± 100 m/s (Figure 5, *b*), that is sufficient for producing coating material with low porosity < 0.7 % (see Figure 6, *b*) and high adhesion (> 80 MPa) to substrate.

## Conclusions

1. High-frequency (more than 20 Hz) valveless multichamber detonation unit was developed. It allows generating pulse jets of the combustion products,

having two pressure maxima (3.5 and 2.0 MPa) due to energy cumulation from cylinder and annular combustion chambers.

2. Application of double-chamber design provided increase of velocity of the detonation combustion products by 35–40 %, that, respectively, rises velocities of powder material. For example, velocity for $Al_2O_3$ powder of 5.6–22.5 μm dispersion made 1200 m/s.

3. A gas-dynamic powder dosing assembly was created. It provides accurate feeding of powder portion before detonation initiation that increased SDE to 82 % for cerment and 67 % for aluminum oxide.

4. High efficiency of spraying process using MCDU is proved by the example of investigation of two types of coating materials — cermet WC–Co–Cr and ceramics $Al_2O_3$. The coatings are dense (porosity less than 1 %), having high adhesion to the base (more than 80 MPa). Formation of 1 kg of material of cermet and ceramics coating required 1.0 and 2.3 $m^3$ of propane, respectively, that is 2 times less than in known detonation units.

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