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DEVELOPMENT OF DETONATION GAS SPRAYING TECHNOLOGY OF COATINGS AT THE E.O. PATON ELECTRIC WELDING INSTITUTE OF THE NASU (OVERVIEW)

O.V. Kolisnichenko[1], **V.M. Korzhyk**[1], **P.D. Stukhlyak**[2], **A.I. Kildiy**[1], **R. Tovbin**[3], **M. Shynlov**[3], **V. Mudrichenko**[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Paton Research Institute of Welding Technologies in Zhejiang Province:
PRC, Zhejiang Province, Hangzhou City, Xiaoshan District, St. Shixing Beilu 857, office. 426
[3]Sputtek Inc. 110 Share Road, Vaughan, Ontario, Canada, L4L 8P4

ABSTRACT

Despite the fact that the detonation gas spraying method is a high-tech process that allows high-quality coatings deposition on products, it has some disadvantages that may limit its widespread use in industry, compared to other thermal coating methods. Such disadvantages include increased safety requirements, low productivity and reliability of structures. However, the use of the latest component base, accumulated technological experience, modern research in the field of detonation processes, and new approaches to the design of detonation units allow us to hope that the detonation gas method will become widespread along with such methods as plasma or High Velocity Oxygen Fuel spraying. The paper shows the leading role of Ukrainian scientists and engineers in the development and implementation of detonation gas spraying of coatings. Particular attention is paid to the work carried out at the E.O. Paton Electric Welding Institute of the NAS of Ukraine. The concepts and development stages of design from classic detonation guns to valveless multi-chamber guns operating at high frequencies are shown. Automated industrial complexes have been created on their base with application of modern components and equipment that allow effective use of the advantages of detonation gas spraying.

KEYWORDS: detonation, coatings, detonation gas unit, valveless design, combustion chamber, production area

INTRODUCTION

High fuel combustion velocity, supersonic velocity of the process, high temperature and higher pressure of combustion products determine the fields of technical application of gas detonation. One of the first most important and currently well-developed accompanying processes for gas detonation is deposition of wear-resistant, thermal protection, corrosion-resistant and other kinds of powder coatings on the surface of various purpose parts. The essence of the method consists in heating and transportation of powder particles to the surface being sprayed using gas detonation.

Development of detonation spraying method is promising in the context of peculiarities, characteristic only for this technology, compared to other numerous thermal coating methods. The cyclic nature of the process, effectiveness of application of the energy of combustion of a flammable mixture, relative simplicity of detonation unit design, etc., allow implementation of the main advantages of detonation spraying method, namely:

● at the same quantity of sprayed powder, the loss of the components of the flammable gas mixture will be smaller at application of detonation combustion mode, compared to deflagration mode;

● detonation spraying units do not require any costly cooling systems;

● low energy consumption. The detonation gun consumes 100 kW, that is sufficient to generate a spark, instead of, for instance, thousands Ws for plasma spraying units;

● detonation complexes can use a standard inexpensive gas feed system with standard hoses, where the pressure in the lines is not higher than 0.3 MPa. In systems of high-velocity oxy-fuel (HVOF) it can be 1 MPa and higher;

● possibility of performing more complex tasks, for instance spraying of coatings without product overheating. The sprayed object is heated up to a temperature not higher than 250 °C, which allows avoiding thermal deformations of different parts, or applying coatings on thin-walled products.

However, the most important point is that when choosing the detonation spraying method, the determinant factor is the quality of the produced coatings, namely:

● high density (porosity < 1 %), due to higher particle velocity;

● increased wear resistance due to harder and stronger coatings;

● higher hardness due to less decomposition of the carbide phases at spraying of metal ceramic coatings;

● improved corrosion protection, due to reduction of through-thickness porosity;

● higher strength of adhesion to the base and increased cohesion strength of the coating;

● lower oxide content due to a shorter time of flight and heating by the products of the spraying powder combustion;

● preservation of the powder chemical composition due to shortening of the time of staying at a high temperature;

● low level of residual stresses;

● lower roughness of the sprayed surface due to a higher impact velocity and smaller particle size of the powder.

A high value of the jet kinetic energy relative to the thermal component kinetic energy make this method better for such applications as spraying wear resistant coatings from metal ceramics, where lower process temperatures prevent decarbonization, and high velocities create practically poreless coatings in a state with minimal residual stresses, making them less prone to cracking.

DEVELOPMENT OF TECHNOLOGICAL DETONATION-GAS SPRAYING UNITS

The question of application of detonation to obtain useful work in energy installations was first raised by Ya.B. Zeldovich in 1940. According to his paper "On the question of energy use of detonation combustion" [1] the thermodynamic effectiveness of detonation units is much higher than the efficiency of units with deflagration combustion of fuel. This is due to the fact that the detonation products have smaller entropy, compared to the products of regular burning, and at isentropic expansion a large portion of chemical energy goes into useful work. As a result, use of the detonation gun will be somewhat more cost-effective, compared to HVOF.

The detonation gas unit for spraying was first developed and patented in the USA by "Union Carbide Corp" in 1955 [2]. The initial stage of studying the method and development of the units for its realization is described in detail in [3, 4]. Creation of this invention was related to investigation of acetylene detonation to look for safe methods of its storage and transportation, conducted at the end of 1940s by Linde Company. Investigation results showed for the first time that the destructive force of gas detonation can be used to perform useful work. The researchers' efforts were aimed at development of the process of deposition of a layer of hard coatings with improved properties, compared to coatings, produced by other spraying methods. This technology, known as Detonation Gun process, became the base of commercial-industrial activities of Linde Division. Development of the method and first unit for detonation gas spraying ensured creation of top quality products. The firm established a wide network of specialized plants for deposition and processing of coatings, located in Japan, Germany and Canada, Great Britain and Switzerland, and for a long time maintained a monopoly for the unique technology.

Many of the advantages of detonation spraying were obvious for specialists immediately after appearance of the first information about the new technology. However, no one was able to reach this level of properties by other methods, although such attempts were made by numerous researchers in many countries of the world. Such a situation was explained in many ways by the monopoly of Praxair Company (former name is Union Carbide Corporation) and no possibility to purchase its equipment.

In 1960s the work on mastering the technology of detonation gas spraying began at the Institute for Problems of Materials of AS of the Ukr.SSR under the leadership of academician G.V. Samsonov [5, 6]. At this moment there was practically no information about the physical fundamentals of the process, and numerous publications in Western media were mostly of promotional nature. Investigations also began at Dnipropetrovsk Chemico-Technological (O.D. Kornev, V.I. Shynkarenko and oth.), metallurgical (T.P. Shmyrjova, G.M. Vorobjov) Institutes, Voroshilovgrad Mechanical Engineering Institute (Yu.O. Kharlamov, B.L. Ryaboshapko and oth.), PA "Kyivarmatura" (O.I. Zverev, V.I. Shesternenkov), CDB "Leninska Kuznya" (Kyiv), E.O. Paton Electric Welding Institute of AS of the Ukr.SSR (Kyiv), OJSC "Motor-Sich" (Zaporizhzhya) and at other organizations. Later on Kharkiv Aviation Institute, Research Institute of Mechanical Engineering Technology (Kharkiv), G.V. Karpenko Physico-Mechanical Institute (Lviv) joined the research. Investigations were focused on studying the stationary gas detonation processes. Gas dynamic parameters of the spraying process were studied, assessment of the energy state of sprayed material particles and clarification of the mechanism of coating layer formation were performed.

The coating deposition processes was performed using detonation units, which included: a combustion chamber in the form of a cylindrical barrel, gas-distribution device, ignition system, powder doser and system of unit control by the specified cyclogram.

For unit operation, oxygen was used as oxidizer, and acetylene was the flammable gas . This way the first local detonation gas units (DGU) appeared: first experimental samples "Soyuz" and "Blyskavka", and then the first production GDU — ""Dnipro" (IMP of AS of the Ukr.SSR), etc. In 1990s the detonation gas units ADM-2 and ADM-4 were created with the participation of specialists of IMP of AS of the Ukr.SSR.

Despite the fact that all the traditional detonation units are designed by the same principle, they differ by the method of introducing the spraying material: axial or radial feed, by the method of feeding the combustible mixture: chambers of direct or preliminary mixing; by the method of detonation initiation: direct or forechamber ignition.

DEVELOPMENT OF THE TECHNOLOGY OF DETONATION SPRAYING AT PWI

Investigations of the process of detonation-gas spraying began to be conducted at PWI since 1980s under the leadership of E.A. Astakhov [7–10]. Taking into account the main postulates of gas detonation theory, a complex of theoretical and experimental investigations were conducted as to selection and development of optimal designs of DGU components. The requirements to the unit main components and gas distribution and control systems, and the main principles of development of detonation equipment were defined. Allowing for powder characteristics and properties (density, dispersity, specific surface, bulk mass, gas permeability, etc.), powder feeders for DGU were developed, which operate with the firing rate of 1–8 Hz. The influence of the method of powder injection (transverse, axial, pulsed, continuous) on ensuring a stable density of the gas-powder mixture along the barrel length was studied. A comprehensive investigation of coatings from different powders was performed. DGU designs developed at the Institute for Problems of Materials of AS of the Ukr.SSR were taken as the base. The work related to mastering detonation spraying of coatings by industry was conducted at the same time. PWI and the Institute of Superhard Materials of the NAS of Ukraine developed units of "Perun" series, and SPA "Orgtekhavtomatizatsia" (Simferopol, Ukraine) mastered their pilot-production. The units have sufficiently different design and operating conditions, but most of the unit components were unified. It allowed producing equipment components in different block combinations. Automated detonation complex (ADC) "Perun-C" [11] is one of the characteristic representatives of this class of units. It has the following fundamental technological capabilities:

- operation of the developed equipment is possible at application of different working gases (propane-butane or hydrogen can be used as fuel, alongside acetylene), and it is allowed to use both nitrogen and compressed air transportation of powder, blowing the coil and barrel, and dilution of explosive mixture;
- control of the properties of sprayed coatings due to the change of spayed particles temperature and velocity in a broad range at the moment of coating layer formation and influence on the degree of their oxidation and change of the chemical and phase composition;
- spraying of a coating on large surfaces with minimal allowance for treatment, which is provided by stable operation of the doser (change of the injected powder dose during operation is not more than 8%) and application of a computer program for unit movement;
- fitting of the unit with two independently controlled powder feeders, which provide a transition from the mode of detonation-abrasive treatment to the mode of coating deposition without switching off the unit; performance of the process of abrasive treatment and spraying in one cycle; spraying a two-component coating without preliminary preparation of powder mixtures and adjustment of their percentage.

Similar to all classical detonation units, "Perun-C" complex uses a cylindrical barrel of a constant diameter for realization of the mode of stationary detonation and further heating and acceleration of the powder. Similar to the majority of the known DGU, electromechanical valves are used in the unit for periodical feeding of the combustible mixture and powder material. Figure 1 shows the design of "Perun-C" detonation gun. Pulsed-axial powder feed through assembly *1* by a preset cyclogram for each pulse is realized in the unit. Combustible hydrocarbon gas and oxygen are fed under pressure of 1.2 atm by supply line *2*, located inside the cooling jacket *3*. After filling of cylindrical barrel *4* up to the set level with the combustible mixture, its ignition by spark plug *5* is performed. It results in heating and acceleration of powder portion already fed into the barrel. Then the detonation unit is blown with nitrogen or air by a preset cyclogram supplied under the pressure of 3 atm. Higher pressure allows blocking the lines of flammable gas and oxygen during the unit blowing and using an electromechanical valve only in the blowing gas line.

"Perun-S" detonation unit is a highly-productive stationary complex, the effectiveness of industrial application of which was manifested particularly at mass and large-scale fabrication of coated products. Technical characteristics of "Perun-S" complex are given below.

Parameter	Value
Frequency of working cycles, Hz	3.3– 6.6
Coating area per cycle, mm^2	320
Coating thickness per cycle, μm	3–10

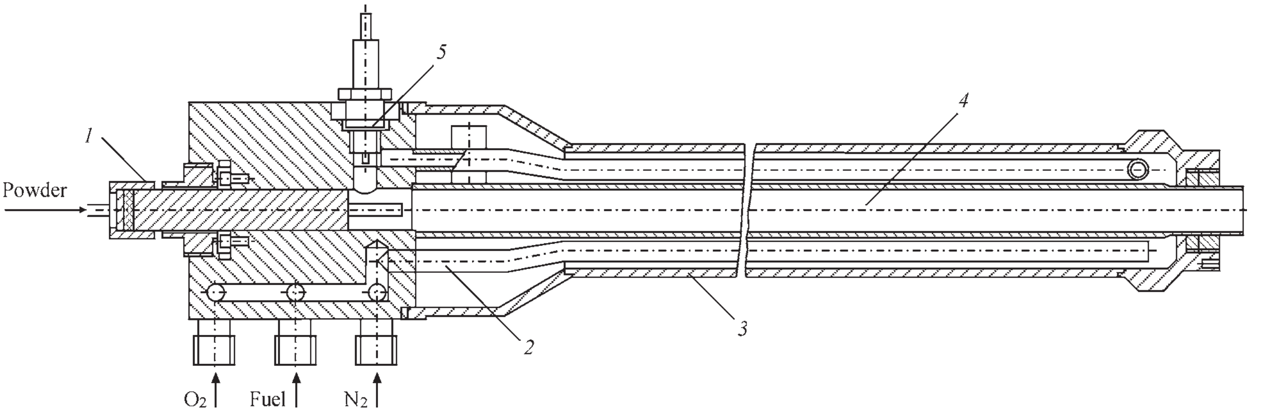

Figure 1. Perun-C detonation gun

Powder spraying productivity, kg/h	1–3
Powder utilization coefficient, %	30–60
Working gas flow rates, m^3/h:	
acetylene	0.65–1.20
propane-butane	0.6–1.1
hydrogen	2.0–3.6
oxygen	1.3–4.0
nitrogen	4.6–5.2
compressed air	4.6–5.2
Power, kW	2
Supply voltage, V	220, 380
Frequency, Hz	50
Three-coordinate manipulator movement range, m:	
right–left	1.6
forward–backward	0.85
upward–downward	0.20

As shown by practice, electromagnetic valves are operating with success in units with up to ten Hz frequency of detonation wave generation in gas mixtures. At operation at higher frequencies, however, the valve system creates great difficulties. Now, increase of DGU operating frequency allows improving the efficiency and coefficient of powder utilization. As a result, in parallel with studying detonation spraying in DGU classical designs, in order to increase process efficiency, work on designing valveless detonation units, as well as investigation of the possibilities of using nonstationary overcompressed detonation for coating deposition began at PWI under the leadership of Yu.M. Tyurin [12–17].

Figure 2 shows a drawing of one of the first variants of valveless detonation devices. Use of fore-chamber *4* allows initiation of gas mixture detonation by car spark plug *7*. When leaving holes *5* uniformly distributed around a circle, detonation is developing mainly in the main volume *6* of the detonation unit. Diameter of barrel *1* is smaller than that of the adjacent combustion chamber. It allows realizing an over-compressed detonation mode. Powder was fed radially into the barrel by pulsed powder feeder *2*. The device had water cooling *3*.

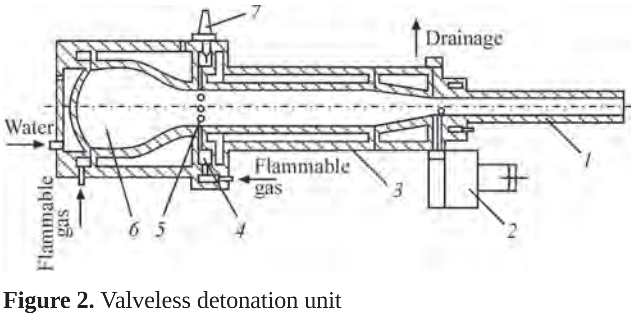

Figure 2. Valveless detonation unit

Despite a large number of experimental designs of valveless DGU developed at PWI, their operation is based on the same principle. Operation of valveless units in the pulsed mode is realized due to gas-dynamic processes in fuel and oxidizer supply lines, which result in interruption with a certain frequency of fuel and oxidizer supply into the detonation combustion chamber (DCC) and prevention of uncontrolled ignition of a new portion of combustible mixture by the combustion products from the previous cycle. The process proper consists in the following. A combustible mixture forms in the chamber. Mixture ignition leads to appearance of a detonation wave (DW) and, hence, to increased pressure in the DCC. At the moment, when the pressure in DCC begins to exceed the pressure in the supply lines, which usually is not higher than 300 kPa, flowing of the combustion products into the respective lines takes place. This way, supply of fresh fuel and oxidizer into DCC is interrupted. In other words, the “gas-dynamic valve” is closed. The detonation products are cooled, when moving in the gas lines. For stable operation and prevention of self-ignition the supply line length and diameter are selected experimentally. After DW has left the combustion chamber, a rarefaction wave starts propagating inside the latter towards the detonation product flow. Having reached the fuel and oxidizer supply lines, it propagates through the channels, and after some time, the pressure in the combustion products decreases, causing a reverse gas motion in the supply lines. Thus, “gas-dynamic valves” are opened. The backflow of the already cooled combustion products into the chamber begins. It is similar to the process of chamber blowing with inert gas, which takes place at operation of valve detonation systems. This is followed by DCC filling by a new gas mixture. Here, the cooled combustion products are located between the combustible mixture and hot combustion products, the temperature of which exceeds that of combustible mixture self-ignition, thus preventing ignition of the supplied fresh gas mixture. DCC filling is followed by the next detonation initiation and the cycle is repeated. The period of time during which the DCC is again filled with fresh mixture after combustible mixture ignition includes the total time of: deflagration transition into detonation; DW propagation into DCC; outflowing of the combustion products from DCC into the ambient space; outflowing of the cooled combustion products from the fuel and oxidizer supply lines into the DCC; and DCC filling with the combustible mixture.

In the general case, the maximal frequency of the unit operation depends on combustion chamber length, its diameter, length of fuel and oxidizer supply lines, their diameter, pressure in them, kind of fuel and oxidizer and their proportion. Knowing all these parameters, it is possible to assess the limit frequency of DCC operation. Modern valveless DU for coating spray-deposition, allow operating with up to 100 Hz and higher frequency. Note for instance, the device design, using high-frequency pulsed detonation (HFPD) process [18, 19]. A number of detonation units were developed on their base which allow deposition of sound coatings with a high efficiency. In particular, HFPD-PK 200 modification of Aerostar Coatings (Spain) for deposition of metal powders, oxides and metal ceramics proved itself well [20]. At present in the market of thermal spraying equipment the Tecnalia Center of applied research and technological development (Spain) proposes HFPDneo system, which provides increased productivity and possibility of operation, using various combustible gas mixtures in a broad frequency range (up to 100 Hz and higher). Investigations and practical results in the field of creation of pulse detonation engines were the impetus for development of new generation valveless detonation guns, operating at high frequency. As an example, we should note the developments of Hiroshima University [21]. The high-frequency detonation gun developed by them allows deposition of coatings with the frequency of 150 Hz [22]. Stable operation of the detonation gun in this case is ensured due to feeding the combustible mixture in the mode of detonation chamber blowing by inert gas or in the mode of blowing by vapours of the injected liquid [23]. Work on increasing the frequency, optimization of combustible mixture feeding and designs of detonation chambers of this class of devices is going on.

Controlled reliable ignition of detonation in the combustion chamber should be regarded as one of the main problems, associated with development of units, using the detonation phenomenon. In technical terms, of greatest interest when designing detonation units used for coating spray-deposition, is the initial ignition of the combustible mixture by a weaker energy source with the possibility of further realization of combustion transition into detonation (CTD). A method of initiation of accelerated CTD often used for this purpose is detonation formation as a result of flame acceleration in a separate channel (forechamber) and its guiding into the main volume of the combustion chamber.

Special attention should be paid to this assembly during design. The authors developed several forechamber designs which allows implementation of the detonation combustion mode in connected DCC of different geometry. As an example, Figure 3 shows a drawing of the working laboratory set up with air cooling of DCC. To avoid overheating, the maximal detonation frequency in the considered DGU is not higher than 12 Hz. The flammable gas (propane in this case) is supplied through nozzle *1* into forechamber *2*. Small-diameter holes are drilled in the nozzle for fuel gas feeding in the radial direction. Oxidizer (oxygen or a mixture of oxygen with air) is fed radially along a tangent to the internal cylindrical surface of

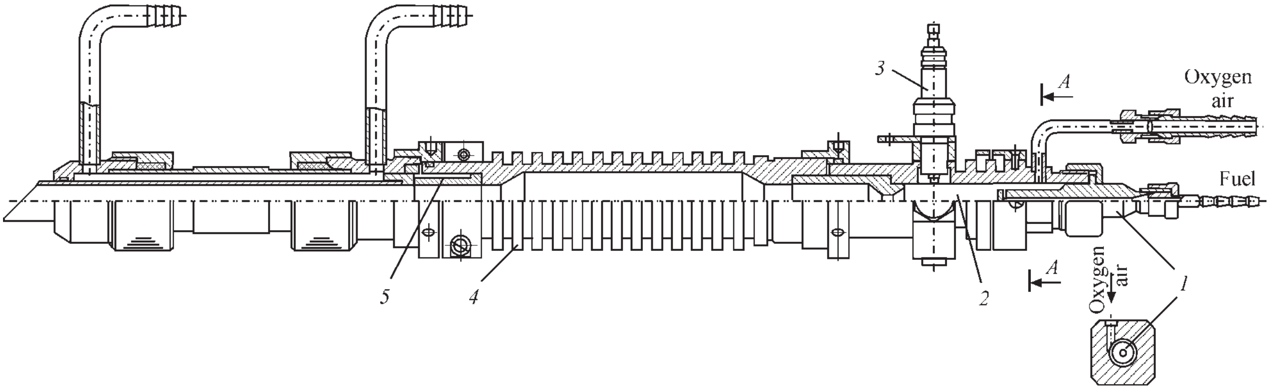

Figure 3. Valveless detonation unit with cylindrical forechamber

the forechamber, thus imparting an angular velocity to this flow. Such feeding of the combustible mixture components allows performing their uniform mixing. Spark plug *3* is located closer to the forechamber outlet. In order to create the conditions for detonation, the forechamber has a narrowing at the end. After ignition and detonation the shock wave front leaves the forechamber and detonation propagates in the adjacent DCC *4*. In this design the overcompression mode is realized at DCC outlet due to narrowing of the chamber cross-sectional area (30 mm diameter) to that of the cylindrical barrel (16 mm diameter) at 35° angle of inclination of the formed cone. As the overcompressed wave transforms into stationary Champan–Jouguet (ChJ) DW at the distance of several calibres in the cylindrical barrel, for effective acceleration and heating of the powder, it is desirable to feed it at the beginning of the barrel cylindrical part, whish is exactly what was realized in the considered design. Powder, which is heated and accelerated by the gas region with increased velocity head, is radially fed through special assembly *5*, directly at the beginning of the barrel.

In DCC of a variable cross-section the degree of DW overcompression α is determined by the following ratio: $\alpha = D_*/D_{ChJ}$, where D_* and D_{ChJ} are the velocities of overcompressed DW and ChJ detonation, respectively. As shown by calculations [24], already a slight increase of DW velocity leads to an abrupt increase of such characteristics of detonation products as pressure p_*, density ρ_*, mass velocity u_* Although the rise of detonation product temperature is partially compensated by dissociation processes, it is still noticeable. Therefore, overcompressed DWs can be the source of pulsed flows of the detonation products with parameters, noticeably exceeding those, which can be obtained at ChJ detonation that is exactly what determines the area of their possible application at powder coating deposition by the gas detonation method.

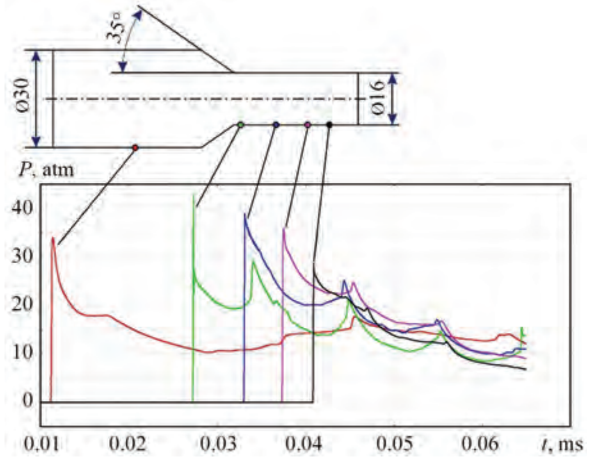

Figure 4. Numerical modeling of time distribution of pressure on the walls of detonation combustion chamber and barrel at different distance from the narrowing

The estimate of pressure and density at the overcompressed DW front and velocity of detonation products, depending on the degree of overcompression can be derived from the ratios given in [25]. For DCC of the detonation gun shown in Figure 3, the overcompression degree α = 1.043. At application of a combustible mixture with molar ratio of the components (oxygen to propane), equal to 4.2, which contains 5 % nitrogen, the ChJ detonation parameters will be approximately as follows: D_{ChJ} = 2400 m/s, p_{ChJ} = 34 atm, ρ_{ChJ} = 2.59 kg/m^3, u_{ChJ} = 1100 m/s. Then, in this unit, in keeping with dependencies from [25] the following maximal parameters can be achieved due to overcompression: p_* = 47 atm, ρ_* = 3.62 kg/m^3, u_* = 1470 m/s. Here, dynamic head of overcompressed detonation products $\rho_* u_*^2/2$ *w*ill be 2.5 times higher than that of ChJ detonation.

Evaluation calculations are in agreement with numerical modeling of the detonation process in the considered DCC, performed using ANSYS program package.

Figure 4 shows time distribution of pressure on DCC walls and in the barrel. In DCC the detonation parameters correspond to ChJ parameters. The overcompressed detonation region, after which the detonation again changes to stationary ChJ, is located in the narrowing zone and at the distance of approximately two calibers directly in the barrel.

Multisection chambers can also be used in the detonation units, in order to ensure effective energy exchange and the required transformations in the initial powder material. Therefore, development of valveless DGU at PWI is currently focused on designing and studying the multichamber structures. At present, a series of laboratory multichamber units for detonation spraying have been developed. In this type of units, DW propagates in cylindrical and in annular combustion chambers, which enclose them, that ensures multiple reflection of the wave from the walls, their collision and combining into one jet of combustion products. As a result, an essential difference of this type of unit, is that a combination of the energy of the process of combustible mixture detonation from several, specially profiled detonation chambers, is realized. This ensures formation of a jet of the combustion products, having a high velocity and temperature, which allows effectively spraying different powder materials, using a combustible mixture based on hydrocarbon flammable gas.

Figure 5 shows a drawing of one of the experimental samples of a multichamber detonation unit (MCDU). In MCDU the design of forechamber *1* for

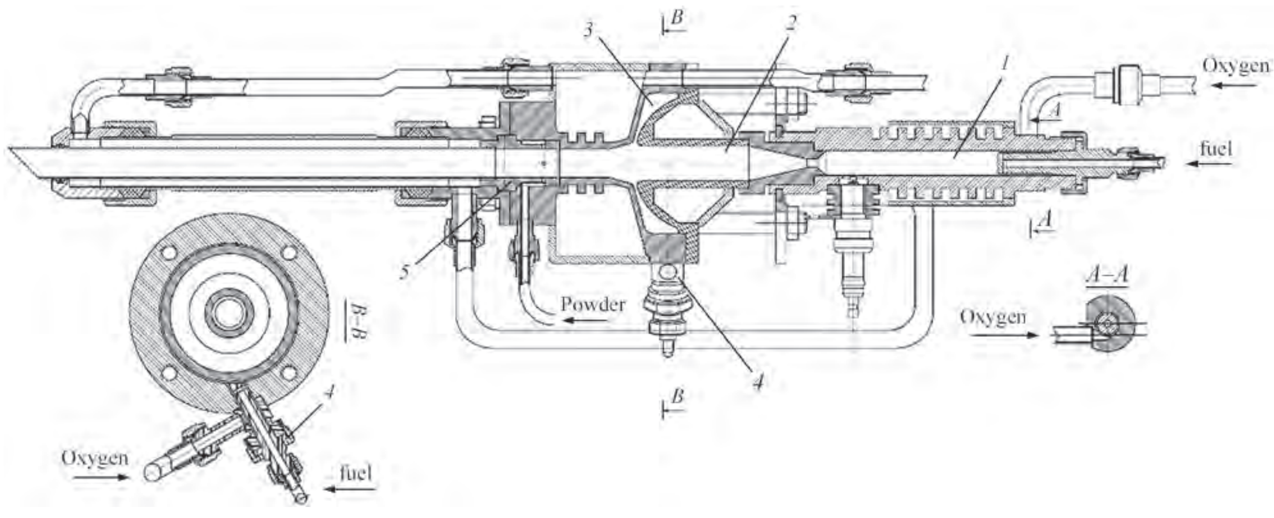

Figure 5. Multichamber detonation unit

detonation initiation was left unchanged, similar to DGU, shown in Figure 3. Propane-butane, propylene, methane, ethylene, and propylene-propane-methylaceneal (MAF) can be used as flammable gas. Oxygen or a mixture of oxygen with air is used as an oxidizer. The degree of combustible mixture dilution by air both depends on the properties of the sprayed powder, and is selected experimentally based on multifactorial experiment planning.

Flammable gas is fed through the nozzle into forechamber *1* of a similar design, as that of DGU, shown in Figure 3. The spark plug is located at the forechamber outlet. Main cylindrical detonation chamber *2* is filled with combustible mixture after forechamber filling. Annular DCC *3* is located around the cylindrical DCC. The annular chamber volume filling is performed through mixer *4*. Feeding the combustible mixture components into the mixer and their mixing are organized as in the forechamber. The spraying powder is fed into DU barrel radially through cylindrical insert *5* with holes uniformly drilled in a circle. There are no electric valves either in the gas or powder supply lines. The unit operates “quasicontinuously” at the frequency of 20 Hz and higher, that ensures the possibility of using standard devices and components for feeding powders and gases. Continuous feed of powder and combustible mixture simplifies the design and lowers the equipment cost, improves the reliability of its operation, and application of hydrocarbon fuel (except for acetylene) ensures the safety and efficiency of the technology.

Flow rates of the combustible mixture components can vary in the following range, m^3/h: 0.8–2.0 of propane, 5–10 of oxygen and 0–5 of air. The detonation combustion mode develops in main cylindrical chamber *2*. Annular chamber *3* with slot exit into the cylindrical barrel is used for compression of the combustion products and creation of an additional jet, which “back up” the detonation products in the cylindrical barrel from the main chamber. A dose of powder is fed into the barrel for acceleration and heating. The barrel can have an inner diameter of 16–20 mm, and length of 300–520 mm, and it is selected, depending on the properties of the sprayed powder material. Narrowing of the working volume of the cylindrical chamber of 26 mm diameter to barrel diameter of 16 mm ensures overcompression of detonation combustion mode. Further compression of the combustion products occurs owing to the annular chamber. Gas-dynamic process of detonation initiation in the annular chamber ensures collapse of combustion products along the barrel axis, which significantly increases their velocity, pressure and density. MCDU allows stretching the detonation products along the barrel length and thus enlarging the heating and acceleration zone, and, hence, also the time of the powder portion staying in this zone. This has a positive effect on material utilization coefficient.

EXPERIENCE OF DEVELOPMENT OF PRODUCTION AREAS OF DETONATION GAS SPRAYING

PWI staff developed several MCDU designs for coating deposition, and the best of them, in addition to scientific-laboratory experiments, have passed industrial trials. Figure 6 shows one of the modifications of such guns.

MCDU main parameters are given below.

Parameter	Value
Overall dimensions (300 mm barrel length), m	0.8×0.2×0.15
Weight, kg	15
Consumed power (ignition system), W	< 100
Total volume of combustion chambers, cm^3	150
Barrel diameter, mm	16–18
Frequency of pulse generation, Hz	10–30
System of powder feed and combustible	

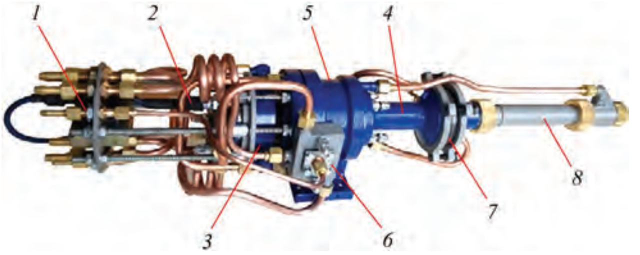

Figure 6. Multichamber detonation unit for coating spray-deposition: *1* — assembly of combustible mixture component feeding; *2* — spark plug; *3* — forechamber; *4* — main DCC; *5* — annular DCC of the mixture; *6* — gas mixer; *7* — powder feeding assembly; *8* — barrel

mixture supply . . . . .Valveless
Pressure in gas lines, atm 1.2–3.0
Used fuel . . . . .LPG, propylene, MAF, methane
LPG flow rate, m^3/h 1.0–1.6
Oxygen flow rate, m^3/h 5.0–8.5
Air flow rate, m^3/h. 0.3–3.5
Coolant flow rate (water), l/min 7
Productivity, kg/h:
ceramics 0.5–1.0
cermet 1.0–2.0
metal 1.0–3.0
Powder utilization coefficient, %:
ceramics 40–60
cermet 70–80
metal 70–90

The production areas for MCDU were set up mostly using standard equipment, widely applied for other thermal spraying methods. As regards the cost of the detonation unit proper, it is usually low, owing to relatively small production expenses and low material consumption. As a result, the cost of the detonation gun is equal to a tiny portion of the overall capital expenditures for the area and its infrastructure. Thus, in the feasibility study for establishing the production area the main attention was focused on the level of equipment automation and quality of its components.

Small dimensions of the spraying unit, low pressure (up to 0.3 MPa) in the gas supply lines and continuous feeding of the components of the flammable gas mixture and powders provide the conditions for technological manipulation at application of standard automated units and robots. Here, it is possible to use standard boxes and noise neutralization systems, as well as powders feeder, gas cylinder systems of gas feeding, control panels and systems of control of spraying technology and coating quality.

The detonation spraying section (Figure 7) consists of three parts:

I — Operator's room for control and monitoring of the technological process.

II — Soundproof shelter, where the gun is installed on a manipulator, and coating deposition proper is performed.

III — Gas compartment accommodating the oxygen manifold, nitrogen and propane-butane cylinders, as well as compressor and cooling block.

A technological section for detonation spraying of metal wear-resistant coatings based on tungsten carbide on product surface was established in 2016 at Sputtek Advanced Coating Technologies Company (GTA, Ontario, Canada). Its main component is MCDU installed horizontally on a stationary bedplate and robotic manipulator for movement of sprayed products relative to the detonation unit nozzle. A programmed controller allows performing deposition of coatings of the specified thickness on parts of both flat and cylindrical shape. An integral part of technological equipment is a soundproof room of 36 m^3 volume, which allows lowering the noise level to 90 dB and lower. A high-efficient exhaust ventilation system (up to 200 and higher m^3/min) is envisaged, in order to lower the dust level in the working zone. Figure 8 shows the soundproof block with the control panel and operator's console. Process monitoring is performed remotely, using TV cameras. The system of supplying such gases as nitrogen, propane-butane mixture and oxygen, incorporates the required regulators of pressure, stop valves and a set of fire barriers. The technological section is fitted with equipment for part preparation for the spraying process, as well as quality control (surface roughness, coating thickness and its adhesion).

An important factor of technology development now is the degree of its automation. A robotic complex

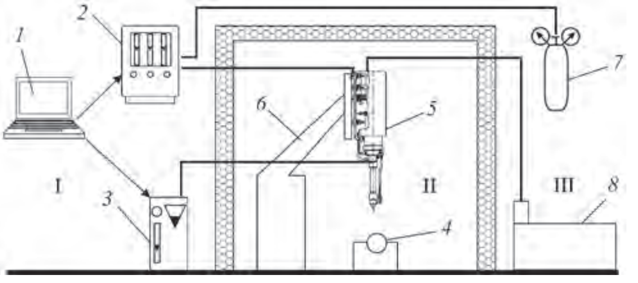

Figure 7. Scheme of detonation spraying area: *1* — system of technological process control and monitoring; *2* — low-pressure gas panel for feeding oxygen, propane-butane and air; *3* — powder feeder; *4* — sprayed product; *5* — multichamber detonation unit; *6* — manipulator; *7* — gas manifold; *8* — dealer

with an intelligent control system (Figure 9) for detonation gas spraying with realization of cumulative energy effect in the mulitchamber unit, manufactured at the production facilities of "Scientific and Production Center PLAZER" LTD (Kyiv) can be an example of complete automation of the process. The soundproof box (overall dimensions of 6540×6280×5200 mm) was developed, proceeding from the requirements of sanitary norms. The room is explosion-proof, and its sound insulation allows lowering the noise level in the operator work zone to the level of ~90 dB. In order to clean the air from combustion products, aerosols and micropowders, the ventilation installation is fitted with cyclone apparatus of the capacity of not less than 9000 m^3/h and mechanical filter. The gun proper is installed on a programmable anthropomorphous 6-axis robot for unit movement along a preset trajectory or in the manual mode by operator's commands from the remote panel of the control system. The following components are located outside the soundproof box: modules of the programmed system of automated control of the equipment and technology (including: cabinet for gas preparation and gas flow rate control;

Figure 8. Section for detonation spraying of coatings

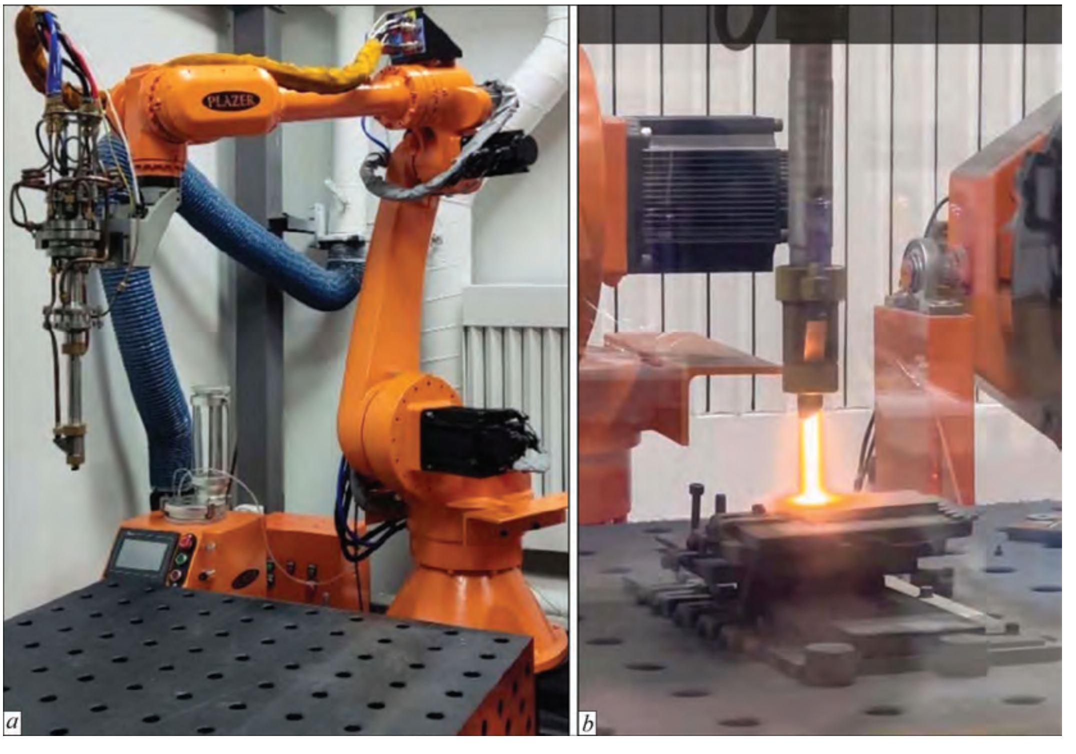

Figure 9. Robotic equipment (*a*) and process (*b*) of detonation gas spraying with realization of cumulative energy effect in MCDU, production of which was set up at "Scientific and Production Center "PLAZER" LTD. (Kyiv)

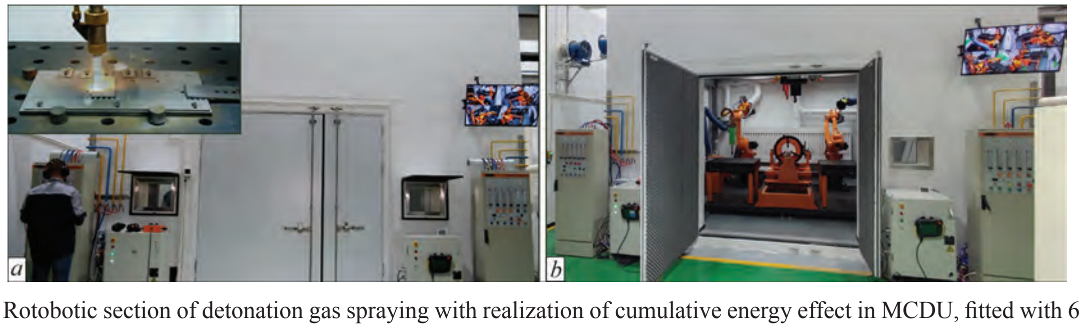

Figure 10. Rotobotic section of detonation gas spraying with realization of cumulative energy effect in MCDU, fitted with 6 axis robot with maximal arm range of 2238 mm and two-axis manipulator for rotation of the sprayed parts

mobile panel of the control system with PLC controller and CCTV module monitor; display of the module for remote measurement of the part temperature; controller of spraying robot); block of MCDU forced autonomous cooling, integrated with automatic control system; cylinder manifold. In order to avoid emergency situations, special attention was given to development of a safety system. Figure 10 shows an example of such a robotic section, set up at the Paton Research Institute of Welding Technologies in Zhejiang Province (PRC).

Application of such automated complexes allows performing operator training in a short time and introducing the technology and equipment in production.

CONCLUSIONS

The paper provides information about the work on development of detonation gas spraying technology, conducted at PWI. Traditional DGU of "Perun" class and coatings produced in them, were studied in detail by the Institute staff, beginning from 1980s. Despite the fact that acetylene is the best studied fuel, convenient for detonation combustion, and acetylene-oxygen explosive mixtures feature the highest temperature and high dynamic head of detonation products, use of acetylene requires compliance with increased safety measures. Now, application of a safer combustible mixture based on methane, propane-butane or MAF allowed the developers significantly enhancing the capabilities at detonation gun design and considering the possibility of using valveless systems, operating at higher frequencies. This way, it became possible to increase system reliability, efficiency and productivity of the process. Operation in the pulsed mode of valveless DGU, developed by PWI staff, is ensured due to gas-dynamic processes in the fuel and oxidizer supply lines. This principle is ever more often used when designing the detonation guns also in other research organizations.

At present the possibility of using nonstationary overcompressed detonation for coating deposition is actively studied. All these problems were addressed by PWI staff also when designing MCDU. Unlike the traditional detonation units for coating deposition, in MCDU an overcompressed mode of detonation combustion of flammable gas mixtures and valveless supply of combustible mixture and powder are used. More over, application of cumulative energy in specially profiled chambers enables creation of a multifrontal flow of detonation combustion products, which ensures enhanced influence on the dispersed particles of sprayed material. This significantly enhances the effectiveness of energy transfer and ensures its saving. Burning of combustible mixtures in specialized chambers provides wide possibilities for controlling the velocity, temperature and composition of combustion products, which allows creating technological conditions for spraying, which are realized, for instance, by such technologies as Cold Spray, HVAF or HVOF. The high frequency of combustion initiation (20 Hz and higher) will ensure quasicontinuous flow of the combustion products, that allows using this technology for coating deposition on product surfaces at the level with known HVOF, HVAF and Cold Spray spraying processes. The technology based on MCDU has several advantages, compared to the high-velocity thermal methods, which are widely applied. High-quality coatings are produced at much lower material and energy expenditures, and easy selection of spraying parameters ensures a wide range of coating properties. The unit design allows working with a high efficiency and reliability using various hydrocarbon mixtures in a broad range of adjustment of the combustion product temperature. The unit is safely operating with different fuel, for instance, propane, propane-butane, propylene, MAF and natural gas. Low pressure infrastructure is used for gas supply. Automated system of control (monitoring) of the process and modular concept allow easily integrating the technology with the already available material and technical base for thermal spraying in the enterprises.

The concept of development of valveless, multichamber detonation guns operating at frequencies of 20 Hz and higher, has high potential in terms of improvement of the effectiveness of coating deposition method proper. At present PWI is actively conducting work on studying the process and introduction of the already available unit designs for their practical application in different industries.

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ORCID

O.V. Kolisnichenko: 0000-0003-4507-9050,
V.M. Korzhyk: 0000-0001-9106-8593,
P.D. Stukhlyak: 0000-0001-9067-5543,
A.I. Kildiy: 0000-0001-8133-8705,
M. Shynlov: 0009-0003-2679-9850,
V. Mudrichenko: 0009-0005-8311-2685

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

O.V. Kolisnichenko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: okolis@i.ua

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