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Design concepts of gaseous detonation guns for thermal spraying

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Summary. Presented a structural analysis of gaseous detonation guns for spraying powder coatings and the possible variants of their operational cycle. The basic principles for the design of high detonation-gas plants for spraying powder coatings, including the concept of a valveless devices, are formulated.
Key words. Gaseous detonation, coating deposition, operational cycle.

INTRODUCTION

In spite of competing processes (chemical vapor deposition (CVD), physical vapor deposition (PVD), etc.) and certain drawbacks, thermal spray process sales are increasing regularly (almost by 10% per year since 1990 [6]). The growth will probably continue, because spraying techniques are relatively harmless to the environment and the full potential of thermal spraying as an alternative to more conventional coating techniques (e.g., hard chromium) for processing "multimaterials" or for free forming and repairs is still undiscovered. However, this development could be enhanced with increased quality of coatings and process reliability. It demands improved process understanding and on-line control with a real time closed-loop control. Decades of research and development in thermal spray (TS) processes have exposed that higher performance and lifetime coatings can be produced if the feedstock particles are accelerated to a high velocity and heated prior to impact on the substrate to be coated [4, 13, 27].

Almost in parallel to plasma spraying, Union Carbide (now Praxair Surface Technologies, Inc., Indianapolis. IN) marketed the trademarked D-Gun producing premium coatings, especially metallic and cermet ones, which have long been the goal of all other coating processes, i.e., higher density, improved corrosion barrier, higher hardness, better wear resistance, higher bonding and cohesive strength, almost no oxidation, thicker coatings, and smoother as-sprayed surfaces. However, the detonation gun (D-Gun) process was available only as a service [12].

Historically, the two fundamental modes of combustion, namely flame and detonation, have found a wide variety of applications in human activities. It is a slow flame that has been extensively utilized in propulsion, power engineering, material science, and chemical technology, while detonations were used basically for military purposes. As the knowledge in detonation physics and chemistry is continuously advancing, one inevitably arrives at the time when this knowledge is to be used for constructive purposes as well to help humanity at large. Detonation is a very attractive phenomenon from the viewpoint of the thermodynamic efficiency of chemical energy conversion into thermal and kinetic energy. Once this advantage of detonation is capitalized properly, considerable benefits are expected to be achieved in terms of fuel consumption, manufacturing and operational costs, pollutant emissions, etc. [1, 3, 20].

For a long time, D-Gun technology has been the reference standard in producing metallic and cermet coatings. However, as it was available only as a service, no research work was published on the process. With the transformations that occurred in the former USSR, Russian equipment and literature on the subject became available in the mid 1990s [19].

Gas detonation can be used to generate thrust in engines, to induce force or destruction actions on objects located both inside and outside the device, to heat and accelerate condensed particles, to rapidly burn the fuel, etc. [19].

The development of detonation spraying is accompanied by broadening its industrial use [16]: deposition of coatings on aircraft engines and parts, jigs and fixtures [2], strengthening of cumulative punches [8, 9], improvement of wear resistance of work items re-adjustable dies [15], creation of a new metal-working tools [17], hardening of abrasive wheels, balancing of rotor systems [18], improvement of resistance to abrasion [21], etc.

There are many different D-Gun designs [14,23,24,28]. Unfortunately, the available literature contains no reliable data on the reliability of these devices and the comparative analysis of their structural characteristics.

Compared to HVOF or plasma spray processes, much work, some of which is in progress, is necessary to better understand the phenomena of the D-gun process [10, 11].

The aim of this work is to develop the basic principles of structural analysis and synthesis of structures of high efficiency detonation-gas plants for spraying of powder coatings.

BASIC PRINCIPLES OF GASEOUS DETONATION GUNS

The detonation-spraying technique is cyclic. In a D-Gun, detonation is initiated in a tube that serves as the combustor. The detonation wave rapidly traverses the chamber resulting in a nearly constant-volume heat addition process that produces a high pressure in the combustor and provides the formation of high velocity impulse flow, which used for powder heating and acceleration. A typical duty cycle of detonation-gas spraying of coatings and its main parameters are shown in Fig. 1.

To facilitate the description and analysis of basic physicochemical phenomena involved in the working cycle, nine principal steps will be considered: (1) filling the detonation gun barrel with a fresh charge of combustible gas mixture (GF), (2) powder doze feeding into DC (barrel) (PF), (3) creation of “phlegmatizing gas plug” between ignition point and gas mixer (GP), (4) ignition of gas mixture (Ig), (5) DC purging of residual gases (Pr), (6) deflagration to detonation transition (DDT), (7) impulse burn-out of the fresh charge (B), (8) interaction of the powder particles with an impulse flow of combustion products and two phase outflow from barrel (AP), (9) interaction of the gas-powder stream with the substrate and single layer coating formation (CF).

In the most general case the gaseous detonation gun (GDG), as an auto-oscillatory system, has a block diagram shown in Fig.1. The oscillatory system can also be represented as a sequence of systems of the GDG itself and of the environment receiving the powder being processed (the product being coated, cooling chamber, etc.). The behavior (state) of the environment may affect parameters of the working cycle because of the effect of feedbacks on the controllers and actuators. Growing pressure to improve the performance of D-Guns, as of IC engines, has resulted in development of improved control systems [5].

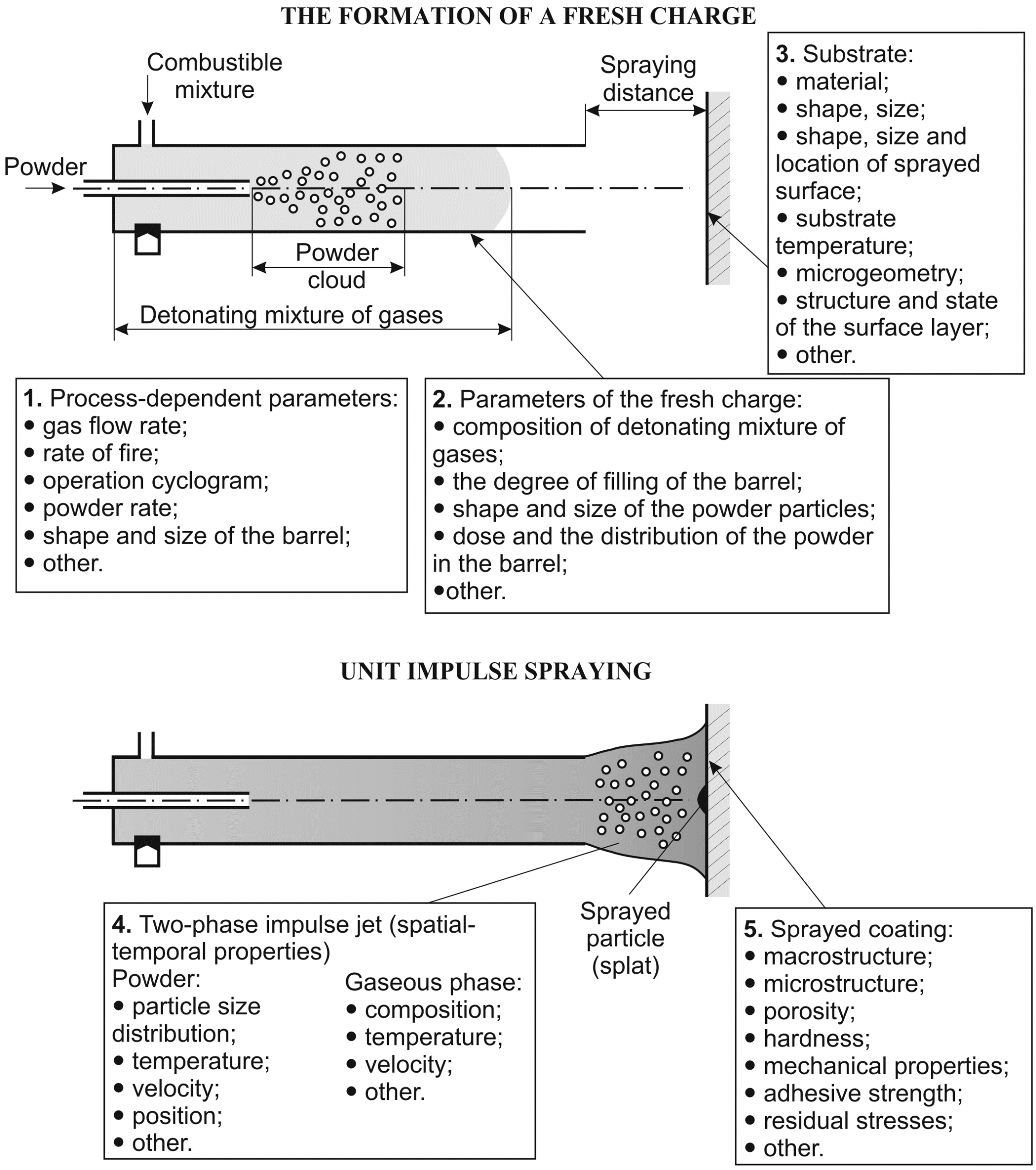

Fig. 1. A typical duty cycle of detonation-gas spraying and its main parameters

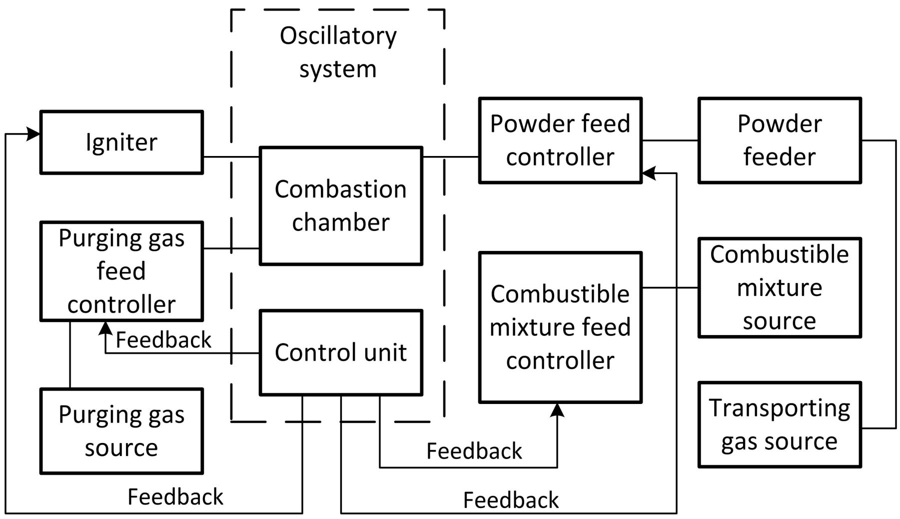

Fig. 2. Block diagram of gaseous detonation gun for thermal spraying

The steps of an impulse burn-out of the combustible mixture and formation of an impulse heterogeneous stream are governing steps and depend greatly on the quality of barrel filling. Repetition of cycles causes the fresh charge to contain a certain amount of combustion products and powder from the preceding spraying cycle. The gases and powder, on the one hand, reduce the mass of a fresh charge and, on the other hand, adversely affect the processes of burn-out and formation of an impulse heterogeneous stream themselves. It is therefore natural to attempt to reduce the fraction of residual gases and powder in a fresh charge. Also the flow of a working medium (purging gas, fresh combustible mixture or gas suspension of the initial powder) has a limited time to overcome the resistance of inlet paths, to contact heated surfaces etc. All this changes the density of the working medium and hence also the mass of charge capable of filling a barrel of predetermined dimensions, the degree of barrel filling, the spatial distribution of fresh charge components in the barrel. The barrel-filling processes have been poorly studied.

After the barrel has been filled, an ignition source operates, installed in the combustion chamber, or in an ignition chamber or in the combustible mixture feed piping. The mixture ignites, a flame front emerges, and burn-out of the combustible mixture occurs accompanied by progressive acceleration of the flame until a stationary detonation mode arises. The flow field around spark plug impacts the spark discharge in spark ignited D-Guns. Ignition resulting from spark discharge between spark plug electrodes is a crucial factor which strongly influences the combustion process [22]. As a consequence the flow field around the spark plug significantly affects D-Gun work repeatability and toxic components concentration in exhaust gases.

The pressure in the barrel during combustion rises and burn-out and is accompanied by ejection of incandescent combustion products jointly with suspended powder particles through the open end of the barrel [25]. After the discharge, the pressure in the barrel first drops below atmospheric pressure (because of the inertia of the flow) and then equalizes. The combustion chamber is again filled with a fresh charge, and the process is repeated. Thus, vibration burning with discontinuous oscillations (relaxation or non-resonance burning) occurs in the barrel.

The regularities in the burn-out of the combustible mixture and in the outflow of combustion products from the barrel are the scientific fundamentals to be considered in an efficient development of spray-coating production processes [26]. However, this step of the working cycle has not yet been studied sufficiently. The most urgent issues for further investigations should include the following: the effect of design characteristics and the geometric configuration of the barrel, ignition chamber and other pre-barrel spaces on the development and conditions of the combustible mixture burn-out, outflow of detonation products and heat exchange with the barrel walls, the composition and properties of combustion products and their change during mixture burn-out and gas outflow from the barrel, the optimization of the design characteristics of detonation-spraying plants to provide the most efficient conditions of combustible mixture burn-out and subsequent interaction of combustion products with the powder.

OPERATIONAL CYCLE OF GASEOUS DETONATION GUNS

A specific feature of operation of gaseous detonation gun (GDG) consists in periodical sustained oscillations of the pressure, velocity, temperature, and acceleration, which arise inside the barrel and other structural elements of the GDG. The oscillations are not caused by external periodical effects and therefore belong to auto-oscillations. Like any auto-oscillatory system, the GDG consists of the following main elements: energy source (a container or line with a gaseous or liquid energy carrier and oxidant), oscillatory system of a varying complexity (including the combustion chamber and control unit) with a definite dynamic characteristic, device controlling the energy input from the source into the oscillatory system in both the amount and the rate (the metered amount of energy defines the work accomplished by the GDG per a working cycle, while the rate, along with other system parameters, defines the frequency or cyclicity of GDG operation, the cycle energy and the GDG operation frequency will define its power). A feedback providing the control of the energy input (amount and rate) from the source into the oscillatory-system exists between this system and the control device [7]. Because of a specific nature of the production processes accomplished, the GDG are also fitted with a source of the powder material processed (powder feeder), a device controlling the powder feed into the combustion chamber in the amount, rate, and time (the metered amount of powder will define the output and the useful work performed by the GDG per a working cycle, the feed rate and time interval, the spatial arrangement of powder in a fresh charge and the nature of its interaction with combustion products), a combustible mixture igniter, compressed gas sources for the powder feed and combustion chamber purging (cleaning), a feedback exists between the oscillatory system and the powder feed controller, the igniter (it provides for controlling the time between the combustion chamber filling and the combustible mixture ignition) and the purging gas controller, (provides for the control of the amount and rate of purging gas feed into the combustion chamber).

The conditions of processing powder materials are governed by the thermal, velocity, and chemical relaxation of particles in a high-temperature two-phase pulsed stream generated at every working cycle of the GDG. The relaxation of particles is conditioned by the parameters of the entire system under consideration and depends not only on the energy of a single pulse and the parameters of the high-temperature gaseous medium, but also on the spatial arrangement of a fresh gas charge and a single dose (metered amount) of powder.

The traditional structure of the operating cycle of the GDG (version 1) can be represented as a sequential method of performing its individual steps:

$$\begin{gathered}\boxed{GF} \to \boxed{PF} \to \boxed{GP} \to \boxed{Ig} \to \boxed{\mathrm{Pr}} \to \\ \to \boxed{DDT} \to \boxed{B} \to \boxed{AP} \to \boxed{CF}\end{gathered}. \qquad (1)$$

Elements *GF, PF, GP, Ig* and *Pr* belong to the so-called preparatory ones, and elements *DDT, B, AP,* and *CF* to independent ones which do not depend on the GDG control system. Functions of elements *GF, PF*, and *Ig* are clear from the essence of the DCP as an auto-oscillatory system, while element *GP* is aimed at providing a localization of the burn-out of combustible mixture in the combustion chamber and preventing flashbacks into the GDG actuators and energy source. Independent elements *DDT, B, AP,* and *CF* of the working cycle are separated for convenience of the analysis and organization of the control of processes proceeding at a pulsed burn-out of the combustible mixture.

Varying the parameters of the preparatory elements of the working cycle and the design features of the GDG, predominantly of the combustion chamber, provides a means for controlling the independent (self-proceeding) elements of the working cycle and thereby, e.g., the coating formation processes.

The operating frequency of a given GDG is $f = 1/t_c$, where t_c – operation cycle duration, $t_{c1} = \sum_{i=1}^{i=k} t_i$, is composed of characteristic time intervals of steps of operation cycle. For this case i = 9. The gas and powder filling and exhaust/purging processes tend to be the longest duration.

A *version* 2 represents a common combination in time of the processes of filling the combustion chamber with a fresh mixture and feeding the powder:

$$\begin{gathered}\frac{\boxed{GF}}{\boxed{PF}} \to \boxed{GP} \to \boxed{Ig} \to \boxed{\mathrm{Pr}} \to \\ \to \boxed{DDT} \to \boxed{B} \to \boxed{AP} \to \boxed{CF}\end{gathered}. \qquad (2)$$

In this case operation cycle duration will be $t_{c2} = t_1 + t_3 + t_4 + ... + t_9$, that is will be shorter as a result of combining of gas and powder filling.

We will now consider the specific features of other versions of the GDG working cycle structure.

Version 3. When powder feed actuators are present, a command from the control system arrives after the delivery (or even execution) of the command for initiating the combustion:

$$\begin{array}{l} \boxed{GF}\to\boxed{GP}\to\boxed{Ig}\to\boxed{PF} \\ \qquad\qquad\quad\;\downarrow \\ \qquad\qquad\quad\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \end{array}. \tag{3}$$

In this case for given GDG operation cycle duration $t_{c2} = t_{c3}$. However, the time of operation of the pulse feeder of powder should be matched with the flame propagation time and with the period of its pre-detonation acceleration. In view of a considerable lag of powder feed devices, ignition and combustion chambers should be connected by passages providing for a delay of combustible mixture ignition in the barrel, sufficient for introducing the powder. Another way consists in using a direct combustion process for the powder feed.

Version 4. The powder feed is effected by the gaseous mixture combustion products in the detonation mode:

$$\begin{array}{l} \boxed{GF}\to\boxed{GP}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \\ \qquad\qquad\qquad\qquad\qquad\;\downarrow \\ \qquad\qquad\qquad\qquad\qquad\boxed{PF} \end{array}. \tag{4}$$

Version 5. Differs from the preceding one by the use of burnout products in the pre-detonation mode:

$$\begin{array}{l} \boxed{GF}\to\boxed{GP}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \\ \qquad\qquad\qquad\qquad\;\downarrow \\ \qquad\qquad\qquad\qquad\boxed{PF} \end{array}. \tag{5}$$

Version 6. Elimination of the combustion chamber "locking" is attained by means of special design features of the GDG, with the aid of hard-to-ignite combustible gases and at a relatively low frequency of GDG operation, which ensures cooling of the combustion products before filling of the combustion chamber:

$$\frac{\boxed{GF}}{\boxed{PF}}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF}. \tag{6}$$

Version 7. Differs from the preceding one in that the powder feed is carried out similarly to version 3:

$$\begin{array}{l} \boxed{GF}\to\boxed{Ig}\to\boxed{PF} \\ \qquad\quad\;\downarrow \\ \qquad\quad\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to CF \end{array}. \tag{7}$$

Version 8. Differs from version 6 by a sequential filling of the combustion chamber with a fresh mixture and in the powder feed method:

$$\begin{array}{l} \boxed{GF}\to\boxed{PF}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to \\ \to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \end{array}. \tag{8}$$

Versions 9 and 10 are combinations of the specific features of structure 4 and 6, 5 and 6 respectively:

$$\begin{array}{l} \boxed{GF}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \\ \qquad\qquad\qquad\quad\;\downarrow \\ \qquad\qquad\qquad\quad\boxed{PF} \end{array}. \tag{9}$$

$$\begin{array}{l} \boxed{GF}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{DDT}\to\boxed{B}\to\boxed{AP}\to\boxed{CF} \\ \qquad\qquad\quad\;\downarrow \\ \qquad\qquad\quad\boxed{PF} \end{array}. \tag{10}$$

Subsequent versions are derivatives from preceding ones and differ by a restriction of the combustible mixture burn-out by the pre-detonation mode: 11 corresponds to 1, 12, to 2, 13, to 3, 14, to 5, 15, to 6, 16, to 7, 17, to 8:

$$\begin{array}{l} \boxed{GF}\to\boxed{PF}\to\boxed{GP}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to \\ \to\boxed{B}\to\boxed{AP}\to\boxed{CF} \end{array}. \tag{11}$$

$$\frac{\boxed{GF}}{\boxed{PF}}\to\boxed{GP}\to\boxed{Ig}\to\boxed{\mathrm{Pr}}\to\boxed{B}\to\boxed{AP}\to\boxed{CF}. \tag{12}$$

$$\begin{array}{l} \boxed{GF}\to\boxed{GP}\to\boxed{Ig}\to\boxed{PF} \\ \qquad\qquad\quad\;\downarrow \\ \qquad\qquad\quad\boxed{\mathrm{Pr}}\to\boxed{B}\to\boxed{AP}\to CF \end{array}. \tag{13}$$

$$\begin{array}{l}\boxed{GF} \to \boxed{GP} \to \boxed{Ig} \to \boxed{\Pr} \to \boxed{B} \to \boxed{AP} \to \boxed{CF} \\ \qquad\qquad\qquad\quad\;\; \downarrow \\ \qquad\qquad\qquad\quad \boxed{PF}\end{array} . \quad (14)$$

$$\frac{\boxed{GF}}{\boxed{PF}} \to \boxed{Ig} \to \boxed{\Pr} \to \boxed{B} \to \boxed{AP} \to \boxed{CF} . \quad (15)$$

$$\begin{array}{l}\boxed{GF} \to \boxed{Ig} \to \boxed{\Pr} \to \boxed{B} \to \boxed{AP} \to \boxed{CF} \\ \qquad\qquad\quad\;\; \downarrow \\ \qquad\qquad\quad \boxed{PF}\end{array} . \quad (16)$$

$$\boxed{GF} \to \boxed{PF} \to \boxed{Ig} \to \boxed{\Pr} \to \boxed{B} \to \boxed{AP} \to \boxed{CF} . \quad (17)$$

Purging for removing residual gases is not considered since it is in fact combined with filling the combustion chamber with the combustible mixture.

The above-described features of the working cycle can be implemented in more numerous design versions of the GDG, but the working cycle of any of them consists of the above-considered elements. Their analysis will make it possible to create a scientific basis for calculating and designing the processes proceeding in the GDG. Comparing and evaluating different versions of the working cycle structure are possible only at a joint analysis of their design features and physical principles of GDG operation.

The sequence of accomplishing individual elements of the working cycle is given by the GDG operation cyclogram. The plants are of two types: with an adjustable (changes can be made, when required, in the cycle duration and operation of its individual elements as well as in the time intervals between them) and non-adjustable (rigid) cyclogram of the working cycle. The former type of cyclograms is typical for general-purpose GDG intended for depositing coatings of various types and on various products (having different service functions, shapes, sizes, arrangement of surfaces being coated). The latter type of cyclograms, which makes possible the use of simpler and more reliable control systems, is more preferable for special and specialized GDG.

The regularities of implementing the independent elements of the working cycle are primarily determined by the design features of ignition and combustion chambers, properties of the combustible mixture, and parameters of filling with a fresh combustible mixture and powder. Only a partial automation of the GDG control, associated with the execution of the working cycle, has been attained at present. The operator, however, has to interfere all the time with the GDG operation control at its starting (sequential feed of individual working gases and powder, switching-on of the ignition and actuation of protective devices to protect the surface to be sprayed until the plant reaches the working conditions, gaining of the working conditions by the plant, feed of the part being coated, monitoring the spraying process on instruments and visually) as well as with the spraying process when intolerable deviations from the parameters occur. The production process quality therefore depends to a great extent on the operator's skill.

D-GUN DESIGN CONCEPTS

The permanent efforts are directed to the achievement of the highest quality of coatings and productivity of GDS at lowest possible cost. This may be achieved:

Firstly: by better understanding of patterns of relationship of DGS operation cycle, by better understanding of gaseous detonation products interaction with processed powder, by search of methods for powder particles behavior control at impulse jet, by better understanding of impulse jet-substrate and particle-substrate interaction,

Secondly: by continuous improvement of process technology of DGS on basis of system approach and better understanding of materials interaction in process of coating formation, by full control of all parameters involved in the GDS, by adequate GDS process simulation and optimization of all working conditions,

Thirdly: by development of the fully adaptive systems for GDS and the process monitoring devices.

In order to use propagating detonations for processing of powder materials and realize the D-guns advantages, a number of challenging fundamental and engineering problems has yet to be solved. These problems deal basically with low cost achievement and control of successive detonations in a gaseous detonation device. To ensure rapid development of a detonation wave within a short cycle time, one needs to apply (1) efficient fuel injection and oxidizer supply systems to provide fast and nearly homogeneous mixing of the components in the detonation chamber (DC), (2) efficient powder injection and supply systems to provide mixing of powder with gas mixture and controllable location into DC, (3) low energy source for detonation initiation to provide fast and reliable detonation onset [20], (4) cooling technique for rapid, preferably recuperative, heat removal from the walls of detonation chamber (DC) to ensure stable operation and avoid premature ignition of gaseous mixture leading to detonation failure, (5) geometry of the combustion chamber to promote detonation initiation and propagation at lowest possible pressure loss and to ensure high operation frequency and control of powder heating and acceleration, and (6) control methodology that allows for adaptive, active control of the operation process to ensure optimal performance at variable processing conditions, while maintaining margin of stability of repetitive two phase impulse jets. In addition to the fundamental issues dealing with the processes in the DC, there are other issues such as (7) efficient integration of DC with inlets and nozzles to provide high performance. The other problem is noise. Therefore, the equipment for detonation-gas spraying should be placed in soundproof booths. It is promising additional reduction of noise by suppressing the noise themselves detonation-gas guns, including the use of devices for active noise reduction.

To date it are created manifold gaseous detonation guns (DG) which differ by mode of functioning (principle of operation) and embodiment. Therefore it is urgent question of estimation of technological capabilities, as advantages and shortages of different variants of DG and development of justified recommendations for their industrial application. For DG classification the next attributes are used: 1. types of fuel and oxidant, 2. typical mode of gas mixture burning, 3. type and design philosophy of barrel (configurations of transverse and longitudinal sections, microgeometry of barrel surface, type of cooling, attitude position), 4. type, location and operation mode of ignition generator, 5. technique of predetonation distance control, 6. peculiarities of gaseous exchange at barrel, 7. technique for gas mixture preparation and flow rate control, 8. initial gas mixture pressure at barrel, 9. technique for localization of gas mixture burning at barrel, 10. technique and point of powder injection into barrel, 11. ambient medium of spraying, and others.

Valved D-Gun concept implies the use of mechanical or electromagnetic valves to ensure a controlled (periodic) inward flow rate of fuel-oxidizer mixture into the DC, to prevent detonations or shocks from moving outwards from the DC through the inlet, and to provide a sufficient time for mixing of fuel with air. Several designs with mechanical or electromagnetic valves are available in literature. These types of D-Guns are in industrial use.

Valveles D-Guns concepts imply continuous or intermittent supply of propellants (fuel and oxidizer) to the DC without using mechanical valves.

Predetonator concept implies the use of a two-step detonation initiation process in the DC, namely, the use of an additional, highly sensitive reactive mixture contained in a tube of small diameter and readily detonated by a source of low energy, and transmitting the obtained detonation wave into the larger-diameter DC containing considerably less sensitive reactive mixture. The small-diameter tube is referred to as predetonator.

Enchanced deflagration to detonation transition (DDT) concept implies the use of various passive means to promote DDT and obtain a detonation wave in the main DC with the working mixture ignited by a low-energy source.

Stratified-charge concept implies controlled injection of propellants into the D-Gun DC aimed at formation of the explosive charge with variable spatial sensitivity to detonation. Stratified explosive charge can be obtained by proper timing of fuel and/or oxidizer valves, by controlled distributed injection of fuel and/or oxidizer along the DC, or by various geometrical means creating a proper vertical structures in the barrel, or use of multipoint gas injection systems.

Multibarrel schemes allow one to control the relative time of detonation products outflow, operation frequency, and productivity of gaseous detonation spraying. Most of the D-Guns schemes can be readily extended to multibarrel configurations. In addition to the study of single-barrel D-Gun system performance, much effort was made to investigate the intricate combustion and gasdynamic processes in multibarrel pulse detonation combustors.

CONCLUSIONS

1. Enhancement of operational efficiency of detonation-gas spraying technology can achieved only through the establishment of applicable reliable equipment.

2. The permanent efforts are directed to the achievement of the highest quality of coatings and productivity of gaseous detonation spraying at lowest possible cost. First of all, this may be achieved by better understanding of patterns of relationship of DGS operation cycle, by better understanding of gaseous detonation products interaction with processed powder, by search of methods for powder particles behavior control at impulse jet, and by better understanding of impulse jet-substrate and particle-substrate interaction.

3. Continuous improvement of process technology of D-Gun spraying could be done using system approach and better understanding of materials interaction in process of coating formation, by full control of all parameters involved in the GDS, by adequate GDS process simulation and optimization of all working conditions, and by development of the fully adaptive systems for GDS and the process monitoring devices.

REFERENCES

1. **Bazhenova T. V., Golub V. V., 2003.:** Use of Gas Detonation in a Controlled Frequency Mode (Review), Combustion, Explosion, and Shock Waves, Vol. 39, No.4, 365-381. (in Russian).
2. **Boguslaev V.O., Dolmatov A.I., Zhemanyuk P.D., et.al., 1996.:** Detonation coating of aircraft engines and parts, jigs and fixtures, followed by magnetic abrasive treatment, Zaporozhye: Deca, 366. (in Russian).
3. **Desbordes D., Daniau E., Zitoun R, 2001.:** Pulsed detonation propulsion: key issues, High-Speed Deflagration and Detonation. Fundamental and Control, G. Roy, S. Frolov, D. Netzer, A. Borisov (eds.), ELEX-KM Publ., Moscow, 177-192.
4. **Dolmatov A.I., Markovich S.E., 2007.:** Automation problems and prospects of development of processes of detonation-gas spraying of protective coatings, Aerospace engineering and technology, №11 (47), 52-61. (in Russian).
5. **Dziubinski M., Czarnigowski J., 2011.:** Modelling and verification failures of a combustion engine injection system, TEKA Commission of Motorization and Power Industry in Agriculture, Vol. 11c, 300-305.
6. **Fauchais P., Vardelle A., Dussoubs B., 2001.:** Quo Vadis Thermal Spraying?, J. Therm. Spray Technol., Vol. 10, N1, 44-66.
7. **Gavrylenko T.P., Kiryakin A.L., Nikolaev Yu.A., Ulianitsky V.Y., 2006.:** Automated set detonation "Ob" for deposition of powder coatings, Modern automation technology, №4, 47-52. (in Russian).
8. **Kalashnikov V.V., Demoretskii D.A., Nenashev M.V., Trokhin O.V., Rogojin P.V., et.al., 2011.:** The detonation method and technology of multilayer facing charges of cumulative punches, Herald of the Samara State Technical University. Ser.: Technics, N3, 213-219. (in Russian).
9. **Kalashnikov V.V., Demoretskii D.A., Nenashev M.V., Trokhin O.V., 2012.:** Explosive technology development for oil and gas industry, Electronic scientific journal « Oil and Gas Business », № 4. (in Russian).
10. **Kharlamov M.Y., 2003.:** Optimization of process parameters of detonation-gas spraying based on genetic algorithm, Herald of the V.Dahl East Ukrainian National University, № 11, 163-170. (in Russian).
11. **Kharlamov M.Y., 2007.:** Formation and the expiry of the pulse-powder mixture from the barrel a detonation coating plants, Herald of the V.Dahl East Ukrainian National University, № 11, part 1, 207-214. (in Russian).

12. **Kharlamov Y.A., 1987.:** Detonation Spraying of Protective Coatings, Materials Science and Engineering, Vol. 93, 1-37.
13. **Kharlamov Y.A., Kharlamov M.Y., 2011.:** Gas detonation spraying jets, Lugansk, The East-Ukrainian National University named after V.Dahl, 260. (in Russian).
14. **Ladan E.P., Ladan I.E., Zarmaev A.A., Kalinichenko V.P., 2012.:** Technological equipment for the application of detonation coatings, Bulletin of the Academy of Sciences of the Chechen Republic, № 1 (16), 76-84. (in Russian).
15. **Movshovich I.Ya., Chernayu Yu.A., Ischenko G.I., 2012.**: Effect of physical and mechanical characteristics of the detonation coatings on the wear resistance of work items re-adjustable dies, Forging and stamping production. Materials processing by pressure, № 10, 6-11. (in Russian).
16. **Nenashev M.V., Ganigin S.Yu., Zhuravlev A.N., Djakonov A.S., Belokorovkin S.A., Karjakin D.J., 2011.:** Perspective technologies, properties and applications of detonation coatings, Herald of the Sergei Korolev Samara State Aerospace University, № 3, Part 1, 197-203. (in Russian).
17. **Nenashev M.V., Ibatullin I.D., Utyankin A.V., Zhuravlev A.N., Usachev V.V., Karjakin D.J., Djakonov A.S., 2011.:** Application of detonation coatings to create a new metal-working tools, Herald of the Sergei Korolev Samara State Aerospace University, № 3, Part 1, 204-210. (in Russian).
18. **Nenashev M.V., Ibatullin I.D., Zhuravlev A.N., Ganigin S.Yu., Usachyov V.V., Karjakin D.J., Djakonov A.S., Paklev V.R ., Rahimova A.V., 2011.:** Application of detonation coverings in technology of mechanical engineering, Proceedings of the Samara Scientific Center of the Russian Academy of Sciences, Vol. 13, №4(3), 830-834. (in Russian).
19. **Nikolaev Yu. A., Vasil'ev A. A., Ul'yanitskii B. Yu., 2003.:** Gas Detonation and its Application in Engineering and Technologies (Review), Combustion, Explosion, and Shock Waves, Vol. 39, No. 4, 382-410. (in Russian).
20. **Roy G.D., Frolov S.M., Borisov A.A., Netzer D.W., 2004.:** Pulse detonation propulsion: challenges, current status, and future perspective, Progress in Energy and Combustion Science, Vol. 30, Issue 6, 545–672.
21. **Sirovatka V.L., 2011.:** Study of resistance to abrasion of the detonation coating from mechanically alloyed powders Ti-Al-B, Friction and wear, Vol. 32, N 2, 131-135. (in Russian).
22. **Sosnowski M., 2011.:** Computational domain discretization and its impact on flow field around the spark plug in SI engine, TEKA Commission of Motorization and Power Industry in Agriculture, Vol. 11c, 300-305.
23. **Tyurin Y.N., Pogrebnjak A.D., 1999.:** Advances in the development of detonation technologies and equipment for coating deposition, Surface and Coatings Technology, Vol. 111, Issues 2–3, 269-275.
24. **Tyurin Y.N., Pogrebnjak A.D., Kolisnichenko O.V., 2009.:** Comparative analysis of an efficiency of cumulative-detonation and HVOF devices, which are applied for gas-thermal deposition of coatings, Physical Surface Engineering, vol. 7, No. 1-2, 39-45. (in Russian).
25. **Ulshin V.A., Kharlamov M.Y., 2005.:** Optimization of the parameters of detonation-gas spraying using a genetic algorithm, Automatic welding, № 2, 32-37. (in Russian).
26. **Ulshin V.A., Kharlamov M.Y., Borisov Y.S., Astakhov E.A., 2006.:** The dynamics of the motion and heating the powder at detonation spraying of coatings, Automatic welding, № 9, 37-43. (in Russian).
27. **Ulyanitskiy V.Yu., Nenashev M.V., Kalashnikov V.V., Ibatullin I.D., Ganigin S.Yu., Yakunin K.P., Rogozhin P.V., A.A. Shtertser A.A., 2010.:** Experience of research and application the technology of detonation coverings coating, Proceedings of the Samara Scientific Center of the Russian Academy of Sciences, Vol. 12, №1(2), 569-575. (in Russian).
28. **Ul'yanitskii B. Yu., Zlobin S., Muders C., Xi Jang, Shtertser A., Veselov S., 2012.:** Computer Controlled Detonation Spraying of WC/Co coatings containing MoS2 solid lubricant, Surface & Coatings Technology, Vol. 206, Issue 23, 4763-4770.

ПРИНЦИПЫ КОНСТРУИРОВАНИЯ ДЕТОНАЦИОННО-ГАЗОВЫХ УСТАНОВОК ДЛЯ НАПЫЛЕНИЯ ПОКРЫТИЙ

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Аннотация. Представлен структурный анализ детонационно-газовых установок для напыления порошковых покрытий и проанализированы возможные варианты их рабочего цикла. Сформулированы основные принципы конструирования высокоэффективных детонационно-газовых установок для напыления порошковых покрытий, в том числе концепции создания бесклапанных устройств.

Ключевые слова. Газовая детонация, осаждение покрытий, рабочий цикл.