and properties. Such properties of materials may support at nanostructure level, for example, the effects of high-temperature superconductivity or «structure» memory.

In the whole the government program of supporting the development of this direction is required for SH-synthesis industrialization.

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AUTOMATED EXPERIMENTAL COMPLEX FOR RESEARCH AND CONTROL OF DETONATION STREAM AT PARTICLE SPRAYING

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The opportunity of application of image input system to PC on the basis of PZS with electronic shutter and exposition time 35,5 mks in structure of complex of optical control of particle spraying detonation stream characteristics on installation «Katun-M» has been shown. The results of inspection of particle speeds by the length of their tracks on image, dynamics of gas fuse formation at the initial moment of stream occurrence on section of installation shaft and root angle of the stream are given.

Search for the ways of intensifying the process of coating the surface and automated control of the process requires the development of the bases of detonation spraying technologies. The most important stage of detonation spraying process is propagation of detonation wave (DW) in detonation set shank and interaction of powder with DW and high-speed gas flow of combustion products. The analysis of physical phenomena at this stage allows approaching more substantiated to selection of spraying modes. The examination of literary sources shows that occurrence of detonation spraying processes was studied both experimentally and theoretically. Inspite of significant amount of issues devoted to detonation coating there are almost no theoretical and experimental investigations of two-phase flow dynamics, course of two-phase flow occurring at output from the channel to submerged space and its interaction with the barrier (substrate where the powder is coated) that allows determining process energy parameters. The comparative analysis of some characteristics and processes of binding materials coated by gas-thermal coating on the basis of works [1–3] confirms the advantages of detonation-gas coatings among which high cohesive strength with sprayed surface and low porosity may be singled out.

The process of spraying differs in pronounced non-stationarity the level of which influences significantly the selection of technological parameters of equipment. Examination of domestic and foreign issues gives the information on technology of detonation coating far from being complete. There are considerable divergences in values of spraying parameters in the modes of obtaining coatings from one and the same material. It can be explained by the fact that detonation spraying represents complex multiparameter process. Separate experimental one-way dependences given in a number of issues are made for some concrete conditions of spraying or at certain equipment therefore, they do not always correctly and fully reflect regularities inherent to the studied process. Besides, the given references are difficult to be applied at changing conditions and equipment. The analysis of laws peculiar to the process of detonation coating should precede the selection of technology and equipment [2].

M.Kh. Shorshorov and Yu.A. Kharlamov [3] put forward the concept of coating formation at detonation spraying. It considers dislocations as active centers within which chemical interaction is implemented. The authors put forward the suppossition according to which the increase of pressure in contact zone results in intensification of plastic deformation of substrate or a particle of sprayed material and increase of dislocation pressure and as a result of this intensification of interaction processes between the material of coating and base. Taking into account the intensity of plastic deformation of substarte at calculation of cohesive strength does not conflict with kinetic concepts as plastic deformation is the thermoactivated process. It should be noted that mechanism of coating formation at detonation spraying technique is under development, the given data are based on the results of phenomenological analysis simplify obviously physicochemical nature and require deeper research. The development of optimal technological processes of spraying should be carried out taking into account efficent ratio between the rate and temperature of sprayed particle.

The characteristic distinguishing detonation-gas spraying from all other known gas-thermal types of coating is presence of DW. The phenomenon of detonation in gases represents propagation of combustion wave at certain speed for each combustible mixture about 1...4 km/s [4]. Gas detonation was discovered in 1881–1890 in connection with methane explosions in coal mines. Berthelot, Viemm, Mallerot Le Chatelier et al. studied detonation. In former USSR K.I. Schelkin, Ya.B. Zeldovich, R.I. Soloukhin, S.M. Kogarko, B.V. Voitsekhovskii et al. carried out fundamental researches.

By the results of experimental researches it was stated [5–8] that:

1. Velocity of detonation propagation in pipes depends on mixture composition, changes from 1000 to 4000 m/s; exceeds several times velocity of sound in these mixtures at usual temperatures and pressures and it is constant for this mixture.
2. Detonation velocity depends slightly on pipe material.
3. Detonation velocity depends slightly on change of initial temperature of gas mixture.
4. Detonation velocity increases at rise of mixture initial pressure.
5. There is optimal ratio of components for each gas mixture at which detonation velocity achieves its maximum value.

According to the theory of hydrodynamics [7, 9] detonation is conditioned by motion of shock wave (SW) in reacting gas mixture. If in SW front the amplitude is greater than a certain value then the wave at its propagation is capable of exciting intensive chemical reaction occurring according to Arrenius law outside the front. Thus, DW propagation is conditioned by motion of SW front, region of chemical reaction and products of detonation which have a volume considerably exceeding the volume of the initial combustible. At present there are many works (review is carried out in [10]) which are based on numerical simulation of instability and occurrence of DW cellular structures. For the case of detonation combustion of propane-butane mixture with oxygen in stoichiometric ration in the device «Katun-M» the generated volume of products of the reaction exceeds the original volume in 100 times. High pressures occurring at explosion and effect of operation fulfillment conditioned by them could not be achieved if chemical reaction of explosive transformation accompanied by formation of large amount of gaseous explosion products. These products being in very squeezed state at instant of explosion are those physical agents at expansion of which potential energy of explosive materials transfers very quickly into mechanical work or kinetic energy of moving gases.

Experimental device of detonation gas spraying (DDGS) «Katun-M» is intended for coating powder materials on working surfaces of various items for attaching to them qualitatively new properties in comparison with the original material. Propane-butane-oxygen mixture is used as detonating composition. The device is in isolated, ventilated box for protecting operator from SW influence and prevention of probable emergency situations connected with possibility of self-ignition of combustible gases. Consumption of actuation gases amounts at average shot frequency of 4 Hz not more than: propane butane mixture 2...3,5; oxygen 10...12; compressed air 10...15 m^3/h.

Detonation-gas device «Katun M» (Fig. 1) consists of the following main nodes: evaporation unit consisting of forehearth – 1 and (shock tube) shank 3; 2 is the ignition system (combustible mixture igniter); 4 is the powder feeder; and control unit – 7, including gas-distributing station, cooling system of shank and other heated elements of the device construction, system of localization of combustible mixture burning in the device shank as well as manipulators [2].

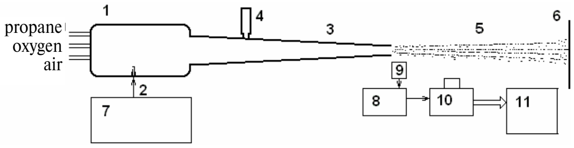

Fig. 1. *Diagram of experimental complex of high-speed video filming and control of spatial parameters of detonation flow at spraying particles on the basis of DDGS «Katun M»*

Control unit allows specifying a number of cycles in the given series of spraying as wellas supports start and finish of operation of the whole experimental-diagnostic «Katun M». Operation of manipulators set in the box of detonation spraying are controlled through the system of remote control from the control unit for changing geometric position of a detail at spraying.

Destination of the shank consists in directing and concentration of energy of combustion agent explosion to the strengthened detail. The distinctive feature of construction of the shank of the device «Katun M» is a conical form of inner cavity with angle of backing-off 4°. It allowed decreasing shank length to 550 mm. In this case diameter of outlet hole amounted to 20 mm. There is a cylindrical section with the length of 50 mm in output part of the shank for stabilizing gas jet. The shank is fixed at forehearth. The forehearth is the device used for DW formation. Presence of forehearth supports high level of homogeneity of gas mixture supplied into inner cavities of the device that supports in its turn stabilization of detonation flow in shank part of the device. Gas outflow from forehearth space into the shank is implemented through the Laval nozzle. Filling with combustible mixture and blasting of inner cavities of the device is implemented directly through the forehearth. Detonation is initiated by electric-spark discharge in a spark plug set on lateral surface of forehearth. To implement one spraying cycle the combustible mixture fills completely the forehearth and a part of shank of detonation device through the Laval nozzle.

The cooling system serves for protecting forehearth, shank and other parts of the device from thermal effect of working gases. For cooling there are input and output channels in forehearth supporting circulation of cooling liquid; in this case channels are connected directly to cooling channels of shank part of the device.

Powder is supplied into the flow by radial method in the plane perpendicular to flow direction. For this purpose there are 9 holes situated at 100 mm from each other on lateral surface of the shank. As a result, it is possible to control the depth of charging powder material into the shank of the device by setting a dispenser into one of them. The sprayed powder material is put in dispenser bin. Powder material is transported into detonation flow by a transporting agent; compressed air came at pressure 150...200 kPa serves as this agent. The consumption of sprayed material is defined by changing the volume under the bin outlet hole. Locking needle is used for preventing penetration of detonation product dispenser into inner channels and their negative influence on powder material. The needle opens owing to pneumatic actuator by a signal from control unit. The dispenser is universal and may be used for various powder materials with particle size from ~0 to 200 mkm.

Gas-distribution station supports preparation, supply and control of combustible mixture consumption, it supports as well shank blasting with inert gas (air) before a regular shot. Gas mixture is supplied directly to the device forehearth.

Technical features of the device «Katun M»: working gas consumption – oxygen – 6 m^3/h, propane-butane – 1,5 m^3/h, compressed air – 12 m^3/h, water consumption – 0,25 m^3/h, power consumption – 3 kW, capacity – 0,2...1,0 m^2/h.

Experimental examination of development process and structure of pulse unsteady flow of sprayed particles in gas jet represent the important scientific and technical task [6, 8, 11, 12]. In Altai scientific innovation center of powder technologies at I.I. Polzunov Altai STU the digital high-speed system of image entrance VS-CTT-285/X/E-2001/M, produced by «NPK Videoscan», Moscow is applied for diagnostics and control of coating at the device «Katun M». The main technical features of the system: image ratio is 1360×1024; pixel dimension (mkm) is 6,45×6,45; CCD matrix dimension (mm) is 6,6×8,8, electronic shutter; storage time $T_{\text{нак}}$ (exposure) – 35,5 mks – 132 s±0,07 ns; ADC is 10 (8) discharges, external synchronization mode is provided. The system provides application of different lens and light filter set up. The experimental images given below are obtained when using lens Gelios-44M.

At occurrence of the flame at the output from the shank – 3 (Fig. 1), recorded by photosensor – 9, the clocking unit – 8 produces a pulse according to which the image of sprayed particle flow – 5 from digital video camera – 10 is transferred to computer – 11 for further processing. In the clocking unit – 8 there is a possibility to delay the pulse of video camera – 10 relative to the moment of flame occurrence at the output from the shank – 3 discretely by 10 microsecond from 0 to 5 s.

The system of image entrance VS-CTT-285/X/E-2001/M was applied in several directions of experimental examinations in composition of the complex of high-speed video filming and control of spatial parameters of detonation flow at particle spraying. When filming the process of escape of gaseous detonation products from the device shank without sprayed particles the jumps of compacting the escaping gas at certain periodicity which has the dependence on time of gas flow development were recorded. The first jump of compacting is at a distance of two calibers (40 mm) from the section of the device shank. In delay time of the start of electronic shutter of the system VS-CTT-285 relative to the moment of fame occurrence at the section of the shank of the device $T_{\text{зад}}$=2 ms 4–5 gas compacting are observed. The first one is at a distance of two calibers from the shank section the next ones are uniformly arranged at a distance 100...120 mm. In $T_{\text{зад}}$=4 ms up to 10 compactions are observed; then at time $T_{\text{зад}}$ more than 4 mks no gas compactions are observed though gas continues escaping. The example of imaging the flow without the particles – $T_{\text{нак}}$=35,5 mks, $T_{\text{зад}}$=4 ms is given in Fig. 2. On the left luminescence starts at shank section, on the right there is a substrate 45° inclined to flow axis.

Taking many images of detonation flow it is ascertained that at fixed time T of flow development the amount of gas compactions and their space arrangement retains. It allows determining coordinates of compaction maximums by radiation intensity and trying to use them later for checking the results of any numerical simulation of DW motion. Rather higher brightness of powder flying particles in comparison with brightness of gas without powder particles and insignificant (almost absent) influence of gas compactions on change of particle paths is noted.

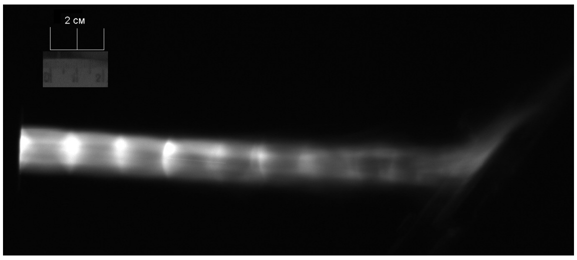

Fig. 2. *Experimental image of gas flow without particles at DDGS «Katun M» ($T_{\text{нак}}$=35,5 microsecond, $T_{\text{зад}}$=4 ms)*

The next direction of using the system of image entrance became studying gas block at the initial moment of gas glow escape from the shank of DDGS «Katun M», existing T=0,2...1 ms from the moment of flame escape from the device shank. Then the block stops existing dissolving in space round the formed «tunnel» in gas medium of ambient air at rest. The flow of sprayed particles is then developed along the «tunnel». The example of gas block ($T_{нак}$=35,5 mks, $T_{зад}$=0,5 ms) is given in Fig. 3. The character of bend of luminous area in flow front – gas block and curl of outer shell in a trace out of flow front is seen from the image. Brightness of gas block luminescence depends on the amount of combustible mixture pumped into DDGS. Tracks of powder particles rather scattered relative to flow axis are seen before the flow front. It is conditioned by high concentration of gas in luminescence centre. The image is obtained without applying light filters, brightness overload of camera CCD-element is observed below by the section of DDGS shank and at particle collapse with substrate (from the experimental images which are not given in this work) that indicates maximal quantity of radiant energy emitted in these regions.

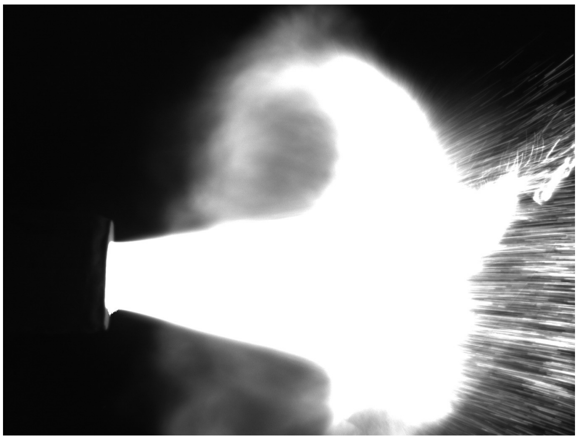

Fig. 3. *Experimental image of gas block ($T_{нак}$=35,5 microsecond, $T_{зад}$=0,5 ms)*

Knowing the scale of image the speed of particles in the flow was determined by particle track length and exposure time $T_{экс}$=35,5 microsecond; it amounted at an average to more than 400 m/s for the time T=1...5 ms in each 500 microsecond. The example of imaging flow particle track at calculated speed is given in Fig. 4. From scientific literature [13] it is known that particles may start reacting to each other just in DDGS shank and follow each other as a result of detonation cell occurrence. Calculating track length it is supposed in this work that one particle leaves track. Thickness of some tracks in the image is larger than diameter of used powder particle that may be explained by parallax of camera optical system. Some tracks have periodically repeated brightness pulsation that is explained by particle axial rotation, parallel flow axis conditioned by particle form factor. The statement given above is of hypothetical character and should be further investigated.

The value of particle average speed in the flow by the time of spraying cycle is given in Fig. 5. Measurements were carried out by particle track length subject to assumption noted above. Each point was calculated as an average value by three – five tracks in the image. It is seen from the diagram that at the beginning of spraying cycle speeds increase to 400 m/s to T=1 ms, at T from 1 to 4,5 ms they practically retain their value about 400 m/s and after T=4,5 ms at the end of spraying cycle they decrease.

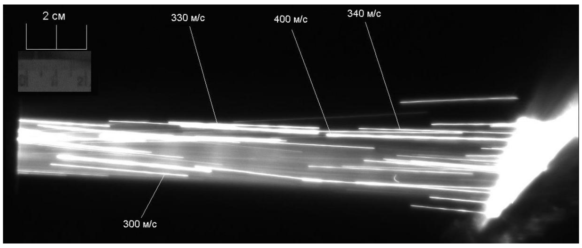

Fig. 4. *The example of imaging particle tracks ($T_{нак}$=35,5 microsecond, $T_{зад}$=4 ms)*

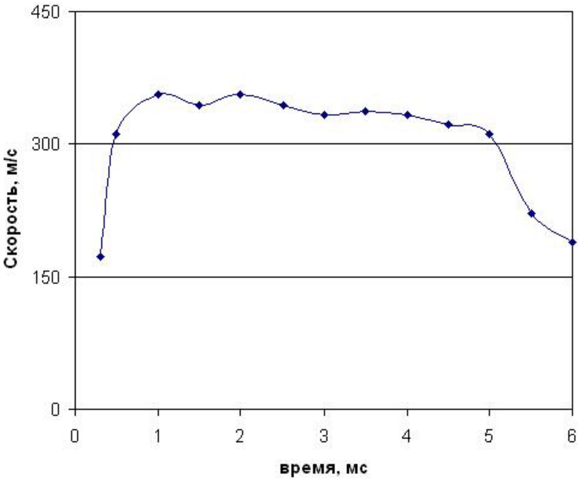

Fig. 5. *The value of particle average speed in the flow by the time of spraying cycle*
Время, мс – Time, ms; скорость, м/с – speed, m/s

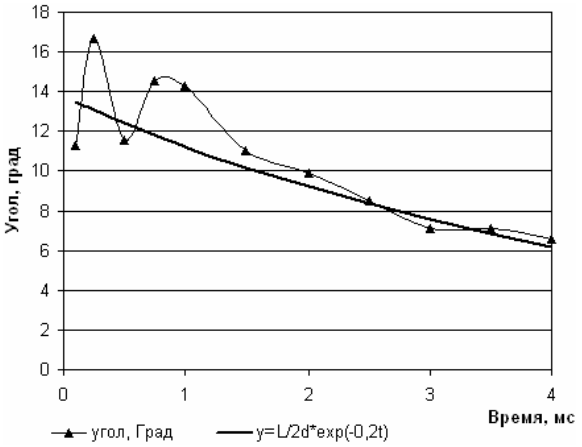

Fig. 6. *Dependence of flow root angle on time of its development*

Defining the width of the flow at a distance of 100 mm from shank section at each image for T=0...5 ms in each 500 microsecond the root angle of particle flow change of which in time is given in Fig. 6 was calculated. For DDGS «Katun M» the dependence of root angle α was obtained empirically:

$$\alpha = \frac{L}{2d}\exp(-0,2t),$$

where L is the length of gun shank, d is the diameter of shank output section, t is the time of flow development.

The first maximum in Fig. 6 at time T=0,3 ms is conditioned by the presence of compact gas block at the initial point of time scattering particles in the direction normal to flow axis. The second maximum at T=1...1,2 ms has smoother character in comparison with the first one and it is explained by maximal particle concentration in the flow in the very noted time point.

The results given in the work are obtained at DDGS «Katun M» and they should be applied carefully for the devices with another geometry of forehearth, shank and dispenser.

The developed experimental complex of visual investigation of particle flow parameters at detonation coating allows controlling in real time scale speed of flow particles and root angle. Application of the system of image entrance into computer VS-CTT-285/X/E-2001/M gives an opportunity of developing methods of control and particle luminance temperature on substrate and in the flow in real time mode [14].

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