The combustion of Al–CuO powder mixture under shock wave initiation of the reaction

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Abstract. The results of experiments on monitoring of manifestations of chemical transformation of Al–CuO powder mixture as a result of shock loading are given. Speeds of shift and expansion of chemical transformation area in free space are determined. The data about structure of combustion area of are received. The temperature of combustion area is measured. The duration of chemical transformation is determined.

1. Introduction
In a present time a researches of a new ways of obtaining energy systems with advance energy release speeds, including methods of colloid chemistry and mechanochemistry are actively conducted (see the review [1]). The purpose of the researches consists in solving the technological problem—development of scientific bases for technology of obtaining energy nanomaterials of the new generation, and solving of fundamental problem–study of patterns of chemical reactions at various ways of initiation. In particular, shock loading of reactive powder mixtures is followed by processes of mechanical activation, dynamic deformation of components particles and initiation of chemical transformation between them [2]. The implementation of these processes is connected with dissipation of shock loading energy and occurs, as a rule, for submicrosecond times. The duration of subsequent chemical transformation is defined by both initial parameters of components, and the pattern of external conditions change. Among mixtures, capable to chemical interaction between components with allocation of thermal energy up to 4 kJ/g, of particular interest is the high-density mixture of aluminum and copper oxide powders [3]. This article presents the results and characteristics of the process of shock initiation and chemical transformation of components of Al–CuO mixture in the specific experimental conditions.

2. The experimental assembly
The object of research were the pressed pellets from mechanoactivated mixture of aluminum and the copper oxide micron powders mixed in a stoichiometric proportion are used. As a result of mechanoactivation the ignition temperature decreases and the contact surface of components are significantly increases. The relative density of pellets had values 0.70–0.85. Shock initiation
of a pellet was performed under detonation of HE (High-Explosive) charge in a steel cover with a diameter of 8 mm, see figure 1. The steel cover contained two cylindrical elements. The first element played a piston role (steel) and thermal protection of the second element against hot products of a detonation. The pressed pellet was a second element. The steel cover was fixed coaxially with a nozzle (diameter 5.5 or 8 mm) on a 2.5 mm thick steel plate. The ratio of mass of a HE charge, the piston and a pellet kept constant: 1 : 1 : 1. The mass of a HE charge in all experiments constituted 1 g, density of a charge 1.15 g/cm$^3$. The calculated densities of a charge chemical energy was 5 kJ/g, the energy of pressed pellets was 4 kJ/g.

3. Process and parameters of loading
To evaluate the values of loading parameters the known steel Hugoniot's and an unloading isentropes of detonation products are used. After HE charge detonation a pellet is loaded via a steel piston with shock wave pressure of 14–20 GPa. Pellet components gain mass speeds of 700–800 m/s. Uncertainty of values is caused by heterogeneous character of powder mixture structure and residual porosity of a pellet. Distinction in structure and properties of pellet components leads to the relative shift and plastic deformation of their particles. Focal heating of a pellet is a consequence of these processes. In points of the maximum heat localization there is a reaction initiation. Duration of loading is estimated at 6–8 $\mu$s. Parameters of experimental assembly and loading in combine determines an energy flow through the tablet at 100 MW. The results of previous experiments [4] allowed to estimate energy values of dissipative processes in a pellet of 10–20 J, and heating temperatures in the thermal emission centers of 550–850 K.

4. Experimental results
In experiments the measurement of parameters of chemical transformation as result of shock loading is made: speed, volume, brightness, duration, conductivity, dynamics and structure of light emission area.

4.1. Results of loading
After detonation of charge there was a destruction of a steel cover in the location of a charge and shock loading of a pellet. In the location of pellet the cover destruction didn’t occur, but its deformation in the form of diameter increasing reached 10%. Shock loading and primary initiation of chemical interaction comes to the end with dispersating of a pellet in unloading waves on a nozzle of assembly. The typical nozzle (diameter 5.5 mm) deformations are given in figure 2 (in section). In the lack of chemical transformation, deformation has obviously shock and wave character, see figure 2(a). In presence of chemical transformation in pellet the nozzle deformation has plastic character with traces of thermal influence, see figure 2(b).

The subsequent process of chemical transformation occurs with formation of dynamic light emission area outside assembly, see figure 3. Eight pellets with different density have been initiated at the same time in this experiment. Duration of shooting is 2000 $\mu$s.
Figure 2. The photos of a nozzle deformation after shock loading of a pellet in cases of lack or presence of chemical transformation.

Figure 3. Photos of light emission area dynamics with chemical transformation. Exposition of images is 50–100 ns. Interval between shots is 150 µs.

The initial geometry of light emission area has the expressed jet kernel with the skirt extending behind. After a while the back border of area comes off a nozzle. In general the light emission area extends in time and moves from a nozzle with some changes in form. Quite a long time light emission has homogeneous character. At the same time there are some photos of light emission from separate points.

4.2. The flow dynamics
Expansion of light emission area occurs both in longitudinal and in cross directions with average speed 35 mm²/µs. Initial speed of a frontal part of area makes 800 m/s, see figure 4(a). For the following 1000 µs the speed of a frontal part decreases to 500 m/s. Subsequently the speed of a frontal part changes a little, see the x–t chart in figure 4(b). The initial speed of cross expansion of light emission area can reach 200 m/s in diameter. Final diameter of area does not exceed ten diameters of a nozzle.

4.3. The flow structure
The light emission area homogeneity implies plasma nature of products of chemical transformation. For refining of plasma conductivity in a light emission area on a flow way placed wire electrodes with potential difference of 200 V/cm. The oscillograms of conductivity current along and across the flow are shown on figure 5. The form of conductivity current impulses allows to assume inclusion a variable resistance in a measuring circuit. Change of resistance is caused, first of all, by increasing of contact area of electrodes with plasma. The brightness temperature of product cloud was determined by pyrometric measurements. Depending on the time of preliminary mechanochemical activation of the mixture the temperature varied from 2500 to 3400 K. The maximum temperature obtained for samples of the mixtures activated in the vibration ball mill for 8 min.

At the same time, the focal character of initiation and dispersating of a pellet in a expansion shock wave assume the discrete maintenance of the formed stream. For specification of this assumption photography of an inert stream in the passing light is carried out. The inert stream
Figure 4. (a) Speed of a frontal part of the light emission area. (b) The $x$–$t$ graph a head part of the light emission area shift.

Figure 5. Oscillograms of conductivity current along and across the flow. The triangular superstructure shows an impulse under short circuit of electrodes.

was received at shock loading of the pressed pellets from non-reacting powders. Such pellets was made from copper oxide powder only or from a copper oxide and lithium fluoride non-interacting powders. Photos of inert streams under dispergating pellets from copper oxide are provided on figure 6.

The lower flow is formed by a pellet weighing 2 g in lack of steel piston in assembly. The upper flow is formed of a pellet weighing 1 g at presence of piston (mass 1 g). Speeds of a frontal parts of both flows were almost identical 430 m/s. It specifies that the speed of a flow is determined, first of all, by HE charge power and the mass loaded, but not by the content of a pellet. The longitudinal size of a flow increases over time. Also a flow transparency changes. It specifies that the flow has discrete structure indeed. Moreover, arbitrary distribution of particles on weight under dispergating a pellet in unloading wave sets them different speeds that leads to forming of an extended flow.

The similar picture is observed when comparing of the reacting flows (Al–CuO mixture) and non-reacting (LiF–CuO mixture) flows. The flows are received in identical experimental assemblies. Photos at figure 7 show that speeds of frontal parts for inert and glowing flows are approximate equal (480–490 m/s). The proximity of speed values for these flows demonstrates
Figure 6. Photos of inert streams in the passing light under dispersing pellets from copper oxide.

Figure 7. The dynamics of reacting (the lower) and non-reacting (the upper) streams (the interval between frames is 350 µs).

Figure 8. Photos of penetration of the reacting flow through a thin tin foil (interval is 100 µs).

that allocation of energy under chemical transformation does not influence dynamics of a flow, and is directed, therefore, on increase of internal energy of reaction products. Back part of an inert flow is displaced with a speed 40 m/s. It confirms a conclusion about the longitudinal distribution of inert particles of a flow by speed. The rough estimate of a flow kinetic energy gives value 50 J.

As for the reacting flow, its back part is displaced from a nozzle slightly. The glowing of the front of reacting flow begins to decrease in cross section approximately through 1 ms. It can occur both due to burnout and braking of the smallest and easy particles. The additional evidence of radial distribution of particles is the photos of penetration of the reacting flow through a thin foil, see figure 8.

Photos show a cut-off of a peripheral part of flow that is possible at decreasing of particles density with increasing in distance from an axis. It demonstrates radial distribution of particles density in flow. The big density of particles on an axis of flow provides their penetration through a foil, and then the light emission area is expanding again. Thus, chemical reaction continues behind an obstacle.

Figure 9 shows influence traces of axial and peripheral area of reacting flow on a thin foils, placed at distance 100 and 200 mm from a nozzle. Destruction of a foil occurs due to the greater stagnation pressure because of greater particles density on a flow axis, see figure 9(a). The size
of bulk of traces on the foil’s periphery does not exceed 1 mm, see figure 9(b). On a tin foil with a low melting temperature (320 °C) damages have melt traces. The initial microsize particles can not leave such traces. Therefore, it is possible to claim that the reacting flow is formed by rather large clusters with the chemical interaction centers of initial components, surrounded by a radiating plasma cloud of reaction products.

5. **Duration of chemical transformation**

By estimates the initiation of chemical interaction in Al–CuO mixture is performed in the range of 6–8 µs between the beginning of shock loading and the subsequent unloading of the pressed pellet. Combustion of the dispersed and accelerated material of a pellet occurs during 5 ms. Chemical reaction is shown in the form of a luminescence (radiation). The analysis of the received results allows to make assumptions about the nature of reaction under shock initiation and scattering of products:

- initiation of reaction occurs in the separate centers on contact surfaces of particles of Al and CuO under passing a shock wave through the mixture;
- under the scattering in a unloading wave there is a dispergating of reacting mixture in the form of hot reaction products clusters;
- between fragments of the dispersed mixture the reaction extends due to scattering of hot clusters through air gaps. Duration of chemical transformation established on light duration does not testify to its completeness completion during scattering. However, analysis of the
condensed particles collected on substrates shows formation of end reaction products—Cu and Al₂O₃.

6. Conclusions
Shock loading leads to the focal initiation of chemical interaction and dispergating of pressed pellet on clusters, accelerated in unloading waves on a nozzle of experimental assembly. The basic process of chemical transformation happens outside assembly with formation of dynamic area of reacting components surrounded with a cloud of the radiating plasma of reaction products. The initiating factor of chemical reaction in a flow is the scattering clusters transferring primary centers of chemical reaction. Chemical energy of reaction between pellet components passes, generally, into an internal energy of reaction products.

References
[1] Dreizin E L 2009 Prog. Energy Combust. Sci. 35 141–67
[2] Batsanov S S 1986 Russ. Chem. Rev. 55 297–315
[3] Monk I, Schoenitz M, Jacob R J, Dreizin E L and Zachariah M R 2017 Combust. Sci. Technol. 189 555–74
[4] Ananev S Yu, Dolgoborodov A Yu, Shiray A A and Yankovsky B D 2016 J. Phys.: Conf. Ser. 774 012069