COMBUSTION OF CONDENSED SUBSTANCES
REINFORCED BY ELEMENTS
WITH THE SHAPE MEMORY EFFECT

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This paper reports the results of an experimental study of unsteady processes during combustion in a half-closed volume of model condensed-material samples reinforced by elements with the shape memory effect (titanium nickelide). It is shown that the thermal and mechanical action of the elements on the combustion process makes it possible to broaden considerably the range of control of the condensed-system burning rate as compared with the well-known technique (use of wires or plates with a high heat conductivity).

One promising method of controlling the burning rate of condensed substances is the use of heat-conducting elements. These elements are made, as a rule, of metals with a high heat conductivity (copper, magnesium, or silver wires, plates, or tubes, which reinforce a sample either randomly or in an orderly fashion). The well-known theoretical dependences, which are corroborated by experimental data, describe adequately the change in the burning rate of compositions reinforced by elements with various orientations relative to the combustion-wave front and make it possible to predict the gas-evolution law [1-6]. For homogeneous systems the thermal effect of heat-conducting elements on the combustion wave is described in terms of the Zeldovich theory. In a first approximation the increase in the burning rate is proportional to the square root of the heat conductivity and to the part of the volume occupied by the elements in the specimen. Bakhman and Lobanov [3, 4], using an approximate model of flame propagation along an infinite metal wire, derived an expression for the effectiveness of the action of the wire on the combustion process:

\[ z = \frac{u}{u_0} = \frac{A\sqrt{\lambda_m}}{(u_0d)^{1-m/2}} \left( \frac{\rho_m c_m + \frac{4\lambda_k}{u_0d}}{\rho_m c_m + \frac{4\lambda_k}{u_0d}} \right)^{-1/2}. \]  

Here \( u_0 \) and \( u \) are the burning rates of the starting and reinforced specimens, respectively; \( d, \lambda_m, \rho_m, \text{ and } c_m \) are the diameter, heat conductivity, density, and heat capacity, respectively; \( \lambda_k \) is the heat conductivity of the starting condensed substance; \( k \) and \( m \) are constants in the relation for the heat transport from the gaseous combustion products to the wire \( Nu = k Re^m; \Theta = (T_{mel} - T_0)/(T_s - T_0) \), where \( T_{mel} \) is the melting point of the wire; \( T_0 \) is the initial temperature; \( T_s \) is the surface temperature of the burning specimen;

\[ A = \frac{2}{T_s - T_0} \left[ k \lambda_g \left( \frac{\rho_k}{\eta_g} \right)^m \left( T_{mel} - T_s \right) \left( T_g - \frac{T_{mel} + T_s}{2} \right) \right]^{1/2}, \]

\( \lambda_g, \eta_g, \text{ and } T_g \) are the heat conductivity, dynamic viscosity, and temperature of combustion product, respectively; the subscript \( g \) refers to gaseous combustion products.

According to (1) and the experimental data of [4], for copper wires, \( z = 2.5-3.5 \).

Below we present the results of an experimental study of unsteady processes involved in the combustion of specimens of a model composition reinforced by heat-conducting elements made of titanium nickelide, an alloy with the shape memory effect.
At present, a number of alloys are known in which, with a change in temperature, a reversible martensitic transition occurs, resulting in the shape memorization effect [7-9]. One property of these alloys is the ability to restore the initial shape on heating to a certain temperature $T_\text{a}$. Thus, a wire made of a given alloy, when heated in a combustion wave, straightens out, assuming its initial shape.

The limiting rupture stress for typical composites does not exceed 0.5–1.0 MPa [10]. The force developed to restore the shape in TN-1 alloy amounts to ~ 100–400 MPa [7]. Thus, a heat-conducting element is capable of deforming and destroying adjacent layers of a condensed substance. Owing to this, during combustion of reinforced specimens, an increase in the burning rate can be due not only to the thermal but also to the mechanical action of the heat-conducting element on adjacent layers in the specimen.

The processes of reinforced-specimen combustion were studied experimentally using both metal-free and metallized (with 10% aluminum powder) model compositions based on ammonium perchlorate and a butyl rubber combustible binder. In the experiments, use was made of end-combustion specimens 40 mm in diameter and 40–50 mm in length reinforced along the lateral surface by a non-combustible coating. The experimental setup is shown schematically in Fig. 1. A tested specimen 2 is fixed to the top cover 1 of the body 4, and the free end of the specimen is in the combustion chamber 3. The combustion products are removed through a nozzle 8. The combustion chamber is furnished with a pressure release unit 6 (breaking membrane 7), a pressure gauge 5 of the LKh-412 type, and an igniter.

Cylindrical, plate-like and spiral elements made of titanium nickelide (TN-1 alloy) and, in some experiments, bars made of copper and graphite were pressed into the specimens. The main thermal characteristics of TN-1 alloy and of the traditional reinforcing materials are presented in Table 1.

The geometric characteristics of the elements used in the experiments are given in Table 2. The linear dimensions of the specimen’s arch above the heat-conducting elements as well as the orientation of the elements and the quality of pressing were checked by means of x-ray photographs (Fig. 2) and used in processing of the experimental results.

The program of experiments included the following stages:
   — examination of specimens extinguished in air;
   — study of end burning regimes for metal-free and metallized compositions;
   — investigation of unsteady combustion processes due to the heat effect of bar-shaped titanium-nickelide elements and also of copper and graphite reinforcing bars;
   — investigation of unsteady combustion processes caused by the thermal and mechanical effects of spiral and plate-like reinforcing elements made of titanium nickelide.

The experimental data on the mechanism of action of elements with the shape memory effect were obtained for specimens extinguished in air and in the combustion chamber by the pressure-release method.