The effect of various factors on the strength and ignition of the used Ni-Al system

S A Seropyan, I V Saikov, V G Salamatov and M I Alymov
Merzhanov Institute of Structural Macrokinetics and Materials Science Russian Academy of Sciences, 8 Academician Osipyan str., Chernogolovka, Moscow Region, 142432, Russia

Abstract. The aim of this work was to obtain structural reactive materials from high-energy mixtures. The effect of various additives on the parameters of the burning rate and the ignition temperature was studied. The object of the study was a powder mixture based on nickel and aluminum in a stoichiometric ratio with a particle size of less than 50 microns. Boron and tungsten fibers were used as reinforcing and energy elements. Mixtures of powders were compacted to a relative density of 0.7 and 0.8. Specimens were made in the form of a parallelepiped. The strength of the samples was studied using three-point bending. It was possible to increase the initial strength of the samples by 9 times when reinforced with tungsten fibers.

1. Introduction
Reactive materials (RM) – a new class of energy materials, characterized by high density and energy intensity, low sensitivity under normal conditions and the ability to intensive chemical reactions in conditions of high speed impact and/or explosive loading. [1]. Reactive materials are of scientific interest because of their unique combustion characteristics. They consist of two or more components, are inert under normal conditions and insensitive to friction, heat, fuses and detonator [2-5].

Energetic structural materials (ESMs) have many potential military applications due to their unique functions [3]. Reactive materials (RM), consisting of two or more non-explosive solid components capable of releasing stored energy at the right time [6-7].

The creation and testing of reactive materials that combining a required set of physico-mechanical characteristics and high energy release are associated with a number of physicochemical limitations and technological difficulties. Such research, as a rule, are purely experimental and are distinguished by the complexity of studying fast-acting physicochemical processes directly in the process of explosive loading of the reaction mixture, which is characterized by high rates of deformation, pressures and temperatures [1, 3]. One way to achieve the desired properties is to disperse the components as shown in Work [8-9].

The aim of this work is the formation of metal reactive materials with high structural strength. The reactivity of a mixture of powders is determined by their composition, contact area between particles, temperature, speed and method of applying external pressure, the ratio of volumetric and shear components of the deformation, the state of the surface of the particles (the presence of oxide films) and other factors.

The subject of the study was a mixture of Ni and Al based powders. Studies were carried out on compact samples in the form of parallelepiped with relative density from 0.7 to 0.8. Samples reinforced with tungsten wire and boron fibers were also made. A pressing problem is the development of methods for consolidating reactive materials that preserve the strength and reactivity of the compositions.
2. Experimental methods

The powders of aluminum brand ASD-1 and nickel brand PNE-1 were used. The particle size of the powder did not exceed 50 microns. Using the ISMAN-THERMO program, the adiabatic temperature of combustion was calculated for this mixture at various ratios of nickel and aluminum, and a graph of the dependence of the temperature of combustion on the mass content of nickel was constructed. The maximum burning temperature corresponds to the equiatomic composition of the powder with 68.5 wt. % Ni and 31.5 wt. % Al amounts to 1912 K. Of the works [10-11] it is known that this mixture is successfully initiated by the shock wave. The mixing was carried out in a «Turbula» type with the ratio of the mass of powder to steel balls 1:5 with a rotation speed of 20 rpm for 12 hours. In addition to the two-component composition, the samples were reinforced with tungsten and boron fibers. Pressing pressure for obtaining samples with a density of 0.7 and 0.8 of the theoretically possible was about 4 and 8 MPa, respectively. Samples were subjected to heat treatment (HT) in the appropriate modes. The strength of the compacts (20×5×5 mm) was determined using three point bending on Instron 1195 equipment according to GOST 25282-93.

To study the process of ignition, pellets with a diameter of 3 mm and a thickness of 0.3–1 mm were compressed. The experiments were carried out in argon at atmospheric pressure in a reactor, the main details of which are shown in Figure 1. The reactor was sealed with a lid with a quartz viewing window. The heater was a strip of graphite cardboard with a width of 5–6 mm and a length of 20–25 mm, through which electric current was passed from the battery. The current was controlled by a rheostat. A crucible of boron nitride with a flat thermocouple welded from thermocouple wires WRe5/WRe20 with an initial diameter of 100 μm rolled to a thickness of 15–20 μm was placed on the heater. The test sample was placed directly on the thermocouple. The sample was heated by convective and radiative heat flux from the crucible. The sample temperature signal through an analog-to-digital convertor (ADC) was recorded on a computer. [11].

HT was carried out in an oven in air. The processing temperature varied from 300 to 550 °C, and the exposure time varied from 1 to 3 hours. The change in phase composition was determined using a DRON-3 diffractometer. The start of the combustion wave was carried out using a heated spiral. The burning rate was measured by video.

3. Results

Figure 2 shows the samples after testing for three-point bending. The nature of the destruction for unreinforced and reinforced samples is completely different from each other. Unreinforced samples break brittle. Samples reinforced with boron and tungsten fibers are destroyed in steps: after cracking of the powder matrix, further destruction occurs as the fibers are pulled out or torn.

Figure 3 shows the dependence of the strength of compacts from the Ni-Al system on the density and type of reinforcement. The initial strength of Ni-Al samples at a relative density of 0.8 was 35 MPa; with the implantation of tungsten fibers, the strength increased to 115 MPa, which is comparable to the strength of cast aluminum.

![Figure 1](image_url). Image of the main reactor details for ignition studies
Figure 2. Unreinforced samples after destruction (1,2) Boron fiber reinforced samples after destruction (3, 4), tungsten fiber reinforced samples after destruction (5, 6): 1,3,5 – before heat treatment; 2,4,6 – after heat treatment

Figure 3. Strength of compacts depending on density and type of reinforcement

The effect of heat treatment on the mechanical properties of compacts was also investigated and are shown in Table 1.

Table 1. Strength of compacts after heat treatment and various types of reinforcement

| Reinforcement type          | Unreinforced | Boron fibers | Tungsten fibers |
|----------------------------|--------------|--------------|-----------------|
| Temperature, °C             | 300 400 500  | 400 500      | 400             |
| Bending strength σ, MPa     |              |              |                 |
| 1 hour HT                   | 13 47 92 90  | 42 70        | 93              |
| 2 hours HT                  | 22 54 82 99  | 44 80        | 99              |
| 3 hours HT                  | 20 44 68 101 | 40 58        | 112             |

Heat treatment has a double effect on the strength characteristics of samples. An increase or decrease in the strength of samples after heat treatment can be associated with a change in their phase composition. As can be seen from the diffraction pattern (figure 4), at a temperature of 400 °C, nickel
oxide appeared. A further increase in temperature to 550 °C led to the formation of intermetallic compounds (Ni$_2$Al$_3$, NiAl$_3$), which led to a strength of 90–100 MPa.

![Figure 4. X-ray diffraction patterns of samples after heat treatment at 1 hour](image)

The ignition temperature of the heat-treated samples was determined and a dependency graph showing the effect of the heat treatment modes on the ignition temperature was plotted (figure 5).

![Figure 5. Ignition temperature after heat treatment](image)

The burning rate was measured for different types of samples (table 2). The burning rate of samples with a relative density of 0.7 and 0.8 did not differ.

**Table 2. Burning rate depending on the type of reinforcement of the samples**

| Reinforcement type | Unreinforced | Boron fibers | Tungsten fibers |
|--------------------|--------------|--------------|-----------------|
| Burning rate, mm/s | 60           | 30           | 70              |

4. Conclusions
The strength of compacts increases with increasing density. Reinforcement of samples with boron and tungsten fibers increases the strength of the reactive materials. Boron fibers increase the strength by a factor of 1.6 compared to non-reinforced specimens. Reinforcement with tungsten fibers increases the strength by 4 times compared to non-reinforced. The reason for this effect is explained by the
The temperature of ignition of samples after heat treatment: at 400 °C and 1 hour – 1.9 times and 44 MPa; at 500 °C and 2 hours – 3.5 times and 80 MPa. The samples reinforced with tungsten fibers before HT had an average strength of 60 MPa after heat treatment: at 400 °C and 3 hours – 1.8 times and 112 MPa. The temperature of ignition of samples after HT at similar heating rates ranged from 720 to 980 °C depending on time and holding temperature. HT in air reduces the reactivity in the Ni-Al system due to the growth of the oxide film and partial synthesis of the components.

The burning rate of unreinforced samples was 60 mm/s. The burning rate of samples reinforced with boron fibers was 30 mm/s, and samples reinforced with tungsten fibers 70 mm/s.

Acknowledgments
The study was carried out within the framework of a major project on basic scientific research in priority areas determined by the Presidium of the Russian Academy of Sciences (KP No. 22) “Promising physical and chemical technologies of special purpose”.

References
[1] Imkhovik N A, Svidinsky A V, A. S. Smirnov A S and Yashin V B 2017 Foreign involvements of new high-density reactive materials for different advanced munitions Combustion and Explosion, 10 (1) 93–101
[2] Witbeck B, Sink J and Spearot D E 2018 Influence of vacancy defect concentration on the combustion of reactive Ni/Al nanolaminates. Journal of Applied Physics 124 (4), 045105.
[3] Xiong W, Zhang X, Tan M, Liu C, and Wu X 2016 The Energy Release Characteristics of Shock-Induced Chemical Reaction of Al/Ni Composites. The Journal of Physical Chemistry. C 120 (43) 24551–24559
[4] Wu J, Fang X, Gao Z, Wang H, Huang J, Wu S and Li Y 2018 Investigation on Mechanical Properties and Reaction Characteristics of Al-PTFE Composites with Different Al Particle Size. Advances in Materials Science and Engineering 2018 1–10
[5] Xu F Y, Zheng Y F, Yu Q B, Zhang X P and Wang H F 2017 Damage effects of aluminum plate by reactive material projectile impact. International Journal of Impact Engineering. 104 38–44
[6] Wang L, Liu J, Li S and Zhang, X 2016 Investigation on reaction energy, mechanical behavior and impact insensitivity of W–PTFE–Al composites with different W percentage. Materials & Design 92 397–404
[7] Sun M., Li C, Zhang X, Hu X, Hu X and Liu Y 2018 Reactivity and Penetration Performance Ni-Al and Cu-Ni-Al Mixtures as Shaped Charge Liner Materials. Materials 11 (11) 2267
[8] Hastings D L and Dreizin, E L 2017 Reactive Structural Materials: Preparation and Characterization. Advanced Engineering Materials 20 (3) 1700631
[9] Mukasyan A S, Rogachev A S and Aruna S T 2015 Combustion synthesis in nanostructured reactive systems, Adv. Powder Technol. 26 (3) 954–976
[10] Saikov I V, Alymov M I, Vadchenko S G and Kovalev I D 2017 Investigation of shock-wave initiation in metal- teflon powder mixtures. Letters on materials 7 (4) 465–468
[11] Vadchenko S G, Alymov M I and Saikov I V 2018 Ignition of Some Powder Mixtures of Metals with Teflon. Inorganic Materials: Applied Research 9 (3) 517–522