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# Influence of aluminum on the characteristics of detonating emulsion explosives

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**Abstract.** The influence of aluminum on the detonation and electrical characteristics of an explosive has been studied experimentally. Comparison of the data obtained by different methods allowed us to formulate conclusions about the course of the chemical reaction of the emulsion explosive with aluminum.

## 1. Introduction

Emulsion explosives (EMX) are the most common industrial explosives. EMX are used for explosion welding, stamping and for mass explosions on rock workings. Possessing a number of advantages (environmental friendliness, safety, the ease of fabrication), EMX has not yet exhausted the optimization possibilities [1], dictated by a number of requirements - increase in power and throwing ability. The addition of aluminum in EMX helps achieve this goal.

Despite wide application of aluminized EMX, the effect of aluminum on the detonation characteristics of EMX has not been completely studied. In [2] pressure and temperature profiles were obtained for EMX with various aluminum contents. On the basis of these profiles it was concluded that aluminum reacts behind the Chapman-Jouguet plane.

As it was found in the work [1], the use of polymeric microballoons with an ultrathin wall filled with isobutane is optimal for the sensitization of emulsion. Addition of aluminum to an emulsion matrix leads to increase of the detonation parameters.

In this paper, we compared our experimental data with those known from the literature. Matching of pressure, temperature and electrical conductivity profiles allowed us to suggest the course of reactions of detonation products with aluminum, which differs from the one proposed in [2].

## 2. Experimental data

### 2.1. The compositions studied

Emulsion was chosen as the base of the explosive composition. It consists of an aqueous solution of ammonia and sodium nitrate, industrial oil and emulsifier. The density of pure emulsion is 1.41 g/cm<sup>3</sup>. "Expancel" polymeric microballoons with a density of 0.024 g/cm<sup>3</sup> were used as a sensitizer. Aluminum powder PAP-2 was added into the EMX. The powder particles have the shape of flakes with an average thickness of 0.25 ÷ 0.5 μm, and the average linear size was 20 ÷ 30 μm.

Six explosive compositions were studied. Three of them were based on EMX with a density of 0.52 g/cm<sup>3</sup> (numbers from 1 to 3 in Table 1) and three on the basis of EMX with a density of 0.97 g/cm<sup>3</sup> (numbers from 4 to 6 in Table 1). The compositions were prepared by adding aluminum powder to EMX in an amount of 0%, 10% and 20% above the emulsion weight.



**Table 1.** The parameters of mixtures of different compositions of EMX

No	composition	$\alpha$ emulsion	$\alpha$ expancel	$\alpha$ , PAP-2	$\rho_{\text{theor}}$ , g/cm <sup>3</sup>	$\rho_{\text{measured}}$ , g/cm <sup>3</sup>	D, km/s
1	0.52* +0%Al	0.97	0.03	0	0.52	0.53	3.17
2	0.52* +10%Al	0.882	0.03	0.091	0.56	0.56	3.17
3	0.52* +20%Al	0.808	0.025	0.167	0.60	0.62	3.42
4	0.97* +0%Al	0.992	0.008	0	0.97	0.97	4.92
5	0.97* +10%Al	0.902	0.007	0.091	1.03	1.01	4.99
6	0.97* +20%Al	0.826	0.007	0.167	1.09	1.03	4.83
$\alpha$ – mass concentration							
* - base emulsion explosive density							

### 2.2. Detonation velocity

Detonation velocity of the compositions was measured in a copper tube (inner diameter of 22 mm and 230 mm long. The results are presented in Table 1. The accuracy of determining the detonation velocity was about 5%.

It is seen that the addition of an aluminum powder practically does not affect the detonation velocity. It is believed that chemical reactions of aluminum added to individual high explosives (for example, cyclotrimethylene-trinitramine RDX) occur after the Chapman – Jouguet point. So, remaining inert in the reaction zone, aluminum powder only reduces the detonation velocity, and this is observed in the experiments. For EMX, the situation is different, which may indicate a partial reaction of aluminum before the Chapman – Jouguet point.

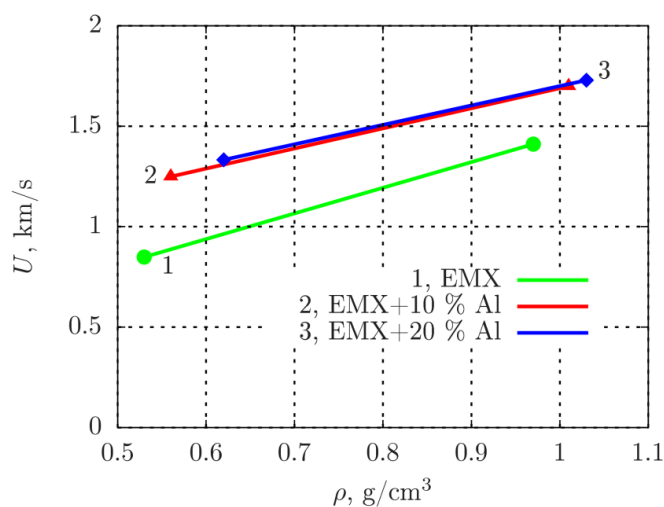
### 2.3. Throwing ability.

To study the throwing ability of the EMX, it was placed in a copper tube with an internal diameter of 22 mm, a wall thickness of 1 mm, and a length of 230 mm (similar to [3]). The tube was annealed at a temperature of 700 ° C. The process of detonation was recorded using pulsed X-ray diagnostics. The radial velocity of the copper shell was determined from the angle of its expansion and the known detonation velocity. Estimated accuracy of radial velocity determination was 10 %.

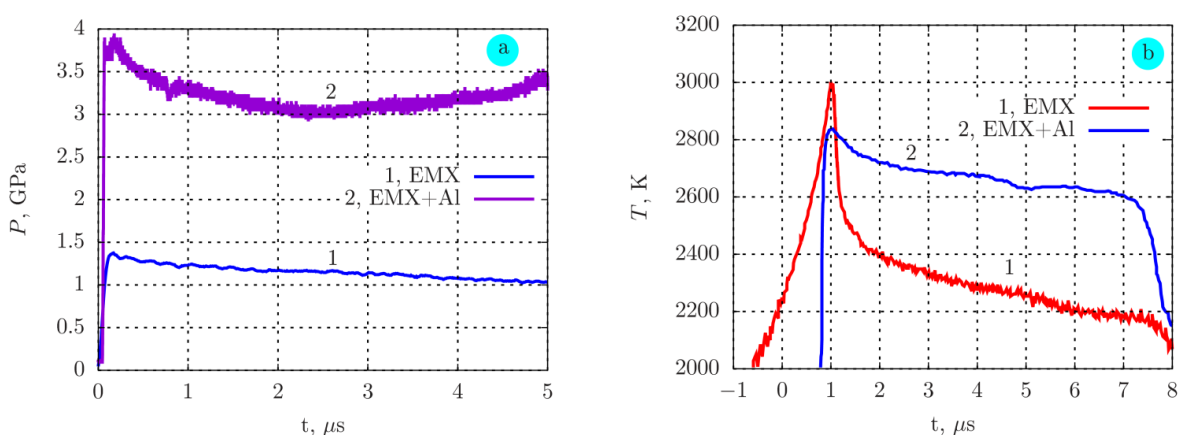
It was found that the shell velocity increased substantially for 10 % aluminum. When adding more aluminum (up to 20 %), the shell velocity increased insignificantly (see Fig. 1).

### 2.4. Results of temperature and pressure measurements

The pressure and temperature profiles were measured for explosive compositions similar to those in formulations 1 and 3 of table 1. The experimental setup was as follows: the EMX charge was placed in a thick-walled steel tube with an internal diameter of 57 mm and height of 160 mm. The charge was initiated by the plane wave generator. The pressure was measured in the 15 mm thick PMMA barrier using a PVDF gage. The luminescence profile was measured using the optical fibers located on the assembly axis under the barrier of PMMA. The PVDF gage was slightly displaced from the axis, to avoid interference with the optical measurement.



**Figure 1.** Radial velocity of the copper shell. The numbers on the graph correspond to the mass content of aluminum.



**Figure 2.** The pressure (a) and temperature (b) profiles for the EMX / PMMA boundary for formulations 1 and 3 of the Table 1.

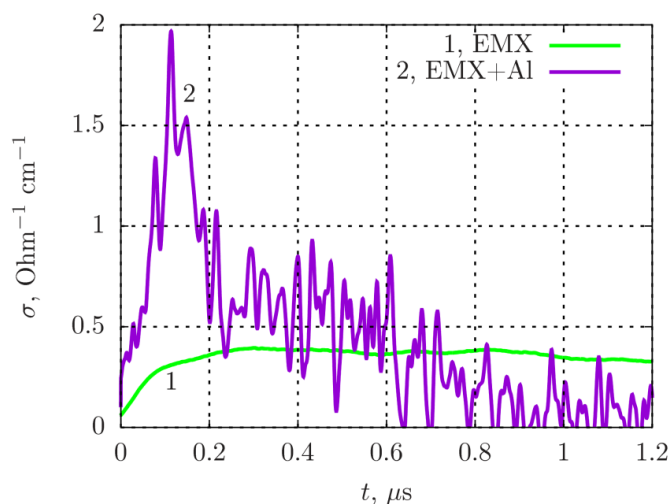
The pressure profiles are shown in Fig. 2.a. Analysis of these profiles shows that the Chapman-Jouguet pressure in pure EMX is equal to 0.92 GPa, and in EMX with 20 % Al the pressure increases to 2.42 GPa. Moreover, in the latter case the high pressure lasts longer.

Figure 2, b shows the temperature profiles obtained in the experiments. In the experiment with pure EMX, a monotonic increase of radiation intensity is observed when the detonation front approaches the PMMA barrier. This increase is due to the partial transparency of the EMX. The maximum intensity of the radiation corresponds to the detonation wave arrival to the PMMA barrier. The maximum value of 2800 K is the temperature of the "hot spots". After that, the intensity of the luminescence drops sharply. At the assumed Chapman-Jouguet point, the temperature is equal to 2250 K. The temperature profile for aluminized EMX has a different form. There is no smooth increase in the signal, since due to the addition of aluminum powder, the explosive becomes opaque. The temperature of the "hot spots" in this case does not change, but the signal drop is much slower. The temperature at the Chapman-Jouguet point is approximately 2750 K and remains approximately constant for at least 6  $\mu$ s.

### 2.5. Profiles of electrical conductivity at the detonation of EMX and EMX + Al

Experimental study of electrical characteristics was carried out using a high-resolution scheme developed earlier [4,5]. The high explosives initially are dielectrics with electrical conductivity under  $10^{-13}$

$\text{Ohm}^{-1}\text{cm}^{-1}$ . The emulsion of EMX has an electrical conductivity of the order of  $10^{-8}\text{Ohm}^{-1}\text{cm}^{-1}$ , so it may be formally classified as dielectric. But initial resistance of the EMX charge with aluminium may become essential for our dynamic experiments. Therefore measurements of the conductivity of EMX with aluminium in a static state were carried out. The following values of the electrical conductivity were obtained: for the composition with 10 % of aluminium,  $\sigma = (1.9 \div 8.8) \cdot 10^{-8}\text{Ohm}^{-1}\text{cm}^{-1}$  (this is close to the electrical conductivity of a pure emulsion [6,7]), while for 20 % aluminium  $\sigma = 6 \cdot 10^{-5}\text{Ohm}^{-1}\text{cm}^{-1}$ . These conductivities are low, presumably due to the surface oxidation of the Al particles, though the oxide films may be partially damaged at high concentration of aluminium.



**Figure 3.** The profile of conductivity during detonation, line 1 - data for EMX with glass microballoons, 2 - EMX with polymeric microballoons and addition of 10 % aluminium.

Figure 3 shows the electrical conductivity during the detonation of EMX with glass microballoons (line EMX) and EMX with polymeric microballoons and addition of 10 % aluminium (line EMX+Al).

The electrical conductivity of EMX after reaching a maximum remains constant. The profile of the electrical conductivity in EMX + aluminium is quite different. One can see the pronounced conductivity peak lasting 200 ns. Duration of this peak is close to that of the region of high temperature (see Fig. 2, b, EMX). Thus, the addition of aluminium makes the chemical reaction zone visible.

The appearance of the peak on the electrical conductivity profile for EMX with aluminium is due to the following factors. The formulation of EMX is determined by the optimal fuel/oxidant ratio with an oxygen balance close to zero. Nitrates, which are part of EMX, contain oxygen in large quantities, that is sufficient for oxidation of fuel (paraffin, oil, emulsifier) whose mass fraction in the emulsion is about 0.06. The fuel contains carbon, about 80% of its mass. Earlier it was shown [8,9] that the electrical conductivity in detonating explosives is determined by the carbon, if its mass fraction is greater than 0.15. This quantity is sufficient for contact conductivity through the carbon structures in the reaction zone [10]. In EMX, the content of neither carbon, nor aluminium, is too low for contact conductivity. But the addition of metal flakes promotes the formation of a conducting grid consisting of aluminium and carbon particles. Carbon creates bridges between metallic inclusions, which are destroyed by oxidation at the end of the reaction zone. Thus, the addition of aluminium makes the reaction zone on the conductivity profile visible. After 200 ns (Fig. 3), the electrical conductivity of about  $0.5\text{Ohm}^{-1}\text{cm}^{-1}$  slightly differs from the value found for the pure composition, which confirms the conclusions above.

Measurements of the total resistance of the EMX charge demonstrated that the virtually constant electrical conductivity of about  $0.25\text{Ohm}^{-1}\text{cm}^{-1}$  exists for at least  $5\mu\text{s}$  after the detonation front. We interpret this as a result of continued chemical reactions of the detonation products with aluminium, which is confirmed by the results of pressure and temperature measurements (Fig. 2, b).

#### 4. Conclusion

Aluminum chemically interacts with the detonation products during the time of measurement. In the region of the ZND peak, the contribution of the energy from these reactions is sufficient to maintain high values of the detonation parameters.

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