Hazard Assessment of Heat-Resistant Igniting Composition and Parameters of its Initiation Mechanism under Conditions of Mechanical Effects

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Abstract

The article contains the results of research of the mechanism of heat-resistant igniting composition initiation from the perspective of deformation processes in the circumstances of short-term mechanical effects (shock, friction) and depending on different factors (ratio of h/d, layer thickness, speed of shock load, composition dispersity, value of roller displacement and surface roughness). We identified the peculiarities and studied the deformation processes taking place in pre-explosive period. Herewith, we showed that the mechanical impact on the composition layer result in emergence of several zones on it, which are determined by the irregular distribution of pressure and various deformation processes, from elastic to elastic-brittle. We found that among the dangerous factors in the mechanical methods of processing of the studied composition, the main ones are the terms of localization of the elastic flow at hitting under the ball and friction at the surface denudation. As a result, we developed recommendations to improve explosion and fire safety of the technology of perspective energy-consuming substance processing and substantiated the conditions of its safe application as the initiating charge in the blasting cap design.

Keywords: Deformation Processes, Heat-Resistant Igniting Composition, Impulse Friction, Initiating Charge, Initiation Mechanism, Safety, Shock

1. Introduction

The problem of security in the development of modern initiating devices is always up to date. In recent years, more and more researches are conducted on the development of industrial detonators of high reliability of operation, protected from electrostatic charges, in the circumstances of relatively high earth stray currents and electromagnetic waves, safe to use in mines with gas and dust hazards1. Determining the possibility of safe use of explosives and recommending on elimination of hazardous conditions from the technological process, as well as on the rules of safe handling is interconnected with the processes of deformation occurring in the substance charge at external mechanical impacts, initiating mechanism and, accordingly, sensitivity3. The performance of the initiating devices first of all depends on the physical, chemical and explosive properties of the primary explosives used3. The key role in this is played by the substance responsible for both the reception of the initial pulse and for the energy transfer to the next item of the initiating circuit. Besides, the response time is also essential4. In the design of the industrial electrical detonator, the igniting composition is the substance. Improvement of the overall safety of the product can be achieved by using Heat-Resistant Igniter Compositions (hereinafter – HRIC) for the electric igniters with low values of safe current, minimum operating current and non-explosive method for their generation.

This article studies the issues of security of one of these promising materials based on lead rhodanide. Preliminary tests of the Blasting Cap (BC) as the initiating charge

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showed the ability of the HRIC to initiate detonation of the high explosive charge. There was a question regarding the possible application of HIC as the initiator and primarily regarding the safety of its application in more severe conditions. Particularly, these conditions involve shock and shock-shear (impulse friction) loads. Therefore, the article's objective was to study the HIC initiation mechanism under mechanical impacts, develop recommendations to improve the safety of processing technologies and its application as the initiating charge. It is known that the mechanism of initiation of a number of explosives by mechanical action is of complex nature and is attributable to a variety of deformations occurring in the starting moment of initiation and at the subsequent stages of the propagation in the charge.

The article contains recommendations aimed at exclusion of hazardous conditions. To develop them, it is necessary to understand the charge initiation mechanism and carry out a system analysis of cause-and-effect relationships between the affecting factors. Such factors include the typical mechanical impact on the charge of Explosive Material (EM); the deformation processes in the sample; the shock and friction sensitivity of the substances at tests. This determines the safety during the technological processing operations and failure-free operation in the finished product at the stage of its application.

### 2. Methods

#### 2.1 Shock Tests

To define the shock sensitivity, we performed HIC study using the drop test rig K-44-I. Figure 1 shows the dependence of the frequency on the impact energy.

As the practical implementation of the theoretical concepts regarding the occurrence of heat source, the method of assessment of shock sensitivity with minimum impact energy ($E_{min}$) with account of the fire (explosion) propagation was used.

$E_{min}$ values were defined at optimum ratios of the minimum (critical) diameter of the contact area of the ball and the layer thickness ($H/d$). The analysis of the shock sensitivity failures showed the results that were expected, on the one hand, and surprising, on the other. With an increase in the shock energy and ball penetration in the composition layer, the spherical contact surface increased. That is the ball could be considered as the striker or roller of different diameters.

During the striker ball penetration in the HIC layer, a number of effective deformation processes with various ratios $P = f(H/d)$ took place, where $P$ is the critical pressure meeting hazardous conditions. A similar dependence can be presumed for elastic-brittle fracture and with regard to the shock energy: $E_{min} = f(H/d)$.

![Figure 1. Shock sensitivity on the drop test rig K-44-I.](image-url)
Figure 2 shows the dependence of the ball contact area diameter on the shock energy and corresponding frequency.

![Figure 2](image.png)

**Figure 2.** Ball contact area diameter versus shock energy and corresponding HIC initiation frequency.

Figure 3 shows the generalized scheme of samples deformation when tested on the drop test rig K-44-I, where A is the initial position; B – after ~ 400 msec after the load weight touches the ball; C – after ~ 600 msec; D – after ~ 650 msec.

In the beginning, the ball deforms the charge. Then through the thin trial sample layer, it reaches the cup bottom and deforms it forming a dimple and actually causing initiation or failure of the charge. In the result of the experiments, it was stated that with small impact energy (up to 0.11 J), HIC explosive transformation occurs as a result of the mechanism of destruction and effluence in free space between the ball surface and the cup side walls during the initial period of the ball movement, which just starts to deform the charge layer (~400 msec after the load weight touches the ball). At the average impact energy (up to 0.22 J), the explosive transformation is initiated at the moment of cup deformation (~600 msec after the load weight touches the ball), that is the initiation occurs in the end of loading. The flow of the charge layer of critical thickness at a high speed and with increasing resistance

![Figure 3](image.png)

**Figure 3.** Scheme of processes taking place in pre-explosive area during shock:
1 – cup; 2 – HIC trial sample; 3 – ball; F and F1 – ball travel and rebound direction; a – gap width between the ball surface and cup bottom; b – base diameter of the ball contact area and critical deformation zone; c – forge depth; d – forge diameter; e – ball rebound height.
from the narrow gap between the ball and the formed dimple at the cup bottom causes trial sample heating up to the critical temperature of inflammation.

Figure 4 shows the typical situation of the charge and cup states after the shock tests if there is no explosion.

Figure 5. Overall picture of common processes of HIC initiation under shock conditions on drop test rig K-44-I: 1 – support roller of the drop test rig K-44-I; 2 – cup with the HIC trial sample; 3 – ball; 4 – load weight; 5 – flash outflow in the gap between the striker and cup walls.

Figure 5 shows the image received using high-speed photographic recording at the end of the loading process, cup deformation and start of load weight rebound in the single exposure mode.

Figure 6. Overall picture of common processes of occurrence and propagation of HIC explosive transformation close to the upper limit and higher: 1 – support roller of the drop test rig K-44-I; 2 – cup with the HIC trial sample; 3 – striker ball; 4 – load weight; 5 – occurrence and propagation of explosive transformation in the form of flashes at the moment of ball rebound; 6 – initiation process development.

During tests at the upper limit level (0.29 J), the full actuation of test samples in the form of explosive burning occurs. Fire propagation occurs in the dust air suspended
solid of fine-dispersed HIC particles, which are formed during their breaking off from the charge and cup surface. Figure 6 shows the image received as the result of high-speed photographic recording of dust air cloud generation process, in which the burning is being spread at the stage of load weight and ball rebound.

The image was received in the single exposure mode with the shutter lag 650 msec, synchronization at load weight's touch of the ball striker and exposure time 10 msec. Forced lighting was not used. Light emission of dust air cloud was detected that testifies burning propagation in it.

3. Results

3.1 Shock Tests Depending on Different Factors

The study results of HIC shock sensitivity depending on different factors are provided below:

Figure 7 shows the safe energy maximum $E_{\text{max}} = 0.05\ J$ when $H/d = 3$ and also the initiating shock energy minimum $E_{\text{min}} = 0.11\ J$ when $H/d = 4.6$.

![Figure 7. Shock energy with optimal ratios H/d.](image)

At the increase of $H/d$ and decrease of the layer thickness below critical (0.2 mm), flashes occur when the energy of mechanical impulse is increased (0.11…0.45) J, however, no process development is observed. At the $H/d$ decrease, the energy required for charge destruction also decreases (0.14…0.08) J, but no explosion occurs. Here, it is required to supply higher energy (0.14…0.45) J consumed for optimal layer thickness formation.

The dependence of the initiating shock energy on the trail sample thickness is shown in Figure 8, which evidences that the required energy decreases at the thickness increase. After the maximum sensitivity value is reached, we can observe the energy increase and accordingly, hazard decrease.

![Figure 8. Initiating shock energy versus layer thickness.](image)

Dependence of the initiating shock energy on the layer thickness and also the presence of the energy minimum at different $H/d$ ratios is the result of two deformation processes responsible for initiation - the brittle structural fracture and plastic deformation.

Change in the test conditions encourages one process transformation in the other.

The results of experiments aimed to define the dependence of HIC initiation frequency close to the lower limit on the shock load speed at $H/d = 3$ showed that with similar impact energy (0.05 J), the shock speed (0.4 m/s and 0.7 m/s) does not influence the frequency.

Simulation of a hazardous production situation related to the initiation of dust air mixtures from fine-dispersed EM particles was performed at bulk and combined charges tests. In the result, the most hazardous conditions were revealed - the decrease in the minimum energy of initiating shock was detected (0.08…0.05) J in case if adding the filling to the composition of the combined HIC charge.

3.2 Friction Tests

To consider the possibility to use HIC as the initiator and primarily to solve the issue regarding safety of its usage in more severe conditions, we included in the task of the present survey the qualitative study of regularities related to the peculiarities of deformation of the charges of the substance under study and the mechanism of its initiation in the process of impulse friction. A detailed study of the HIC processing technological procedure parameters allows concluding that friction as a source of local heat areas generation and their heating up to critical temperatures plays an important role and is the integral mechanism occurring and taking part in many deformation processes - elastic, brittle or plastic.
For detailed investigations and study of the HIC initiation mechanism under shock shear impact, we used the standard drop test rig K-44-III\textsuperscript{16}.

Figure 9 shows the dependence of frequency on the HIC application pressure during friction on the drop test rig K-44-III.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Friction sensitivity on the drop test rig K-44-III.}
\end{figure}

The study of the wide range of test pressures was determined by the necessity to determine the dynamics of changes in the structure of pre-explosive area from the perspective of deformation processes that were studied by the residual layer image received after tests with different pressure application.

In the process of shock shear, the upper roller shift was accompanied by pressure redistribution in the thin substance layer. From the shear side, one could observe a sudden drop (discharge) in pressure (for 150-200 msec) to 40-60\% of the initial test pressure. Herewith, there was denudation of the substance layer by the friction surface for the value of the upper roller shift with respect to lower one (1.5 mm). On the opposite side from the shock impact, the pressure increased due to its distribution on the reducing end surface of the roller.

Such complicated mechanical influence on the thin layer led to the formation of several areas determined by the uneven pressure distribution and different deformation processes.

Figure 10 provides a generalized scheme of the residual picture of sample deformation after the tests including the processes that took place at the pre-explosive stage at friction in the load and discharge areas, which shows the high- and low-speed deformation modes, such as: damage area formation and high-speed jet generation\textsuperscript{11,17,18}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Generalized scheme of processes taking place at the pre-explosive stage: A – load area, B – discharge area, 1 – lower roller; 2 – fracture area; 3 – front separating areas of sample partial fracture; 4 (L) – burnout area; δ – burnout depth; 5 – incomplete sample fracture area; 6 – front separating fracture areas and the intact part of the sample; 7 – area of the intact sample; 8 – boundary of the intact sample from jet generation; 9 – jet generation area, a – area width; 10 – upper roller.}
\end{figure}

Investigation of the pre-explosive stage showed that initiation occurred on the fracture surface in the discharge area and spread into the compressed layer. This process was preceded by a shear structure, which could be observed before the front of the chemical reaction and facilitated its propagation in the deformed area. Besides, flashes occurred in the dimple close to the side surface of the roller, in the chemical reaction source area as per the “jet” mechanism.

The residual picture of the chemical reaction front occurring in the discharge area and partially propagating into the compressed layer is presented on Figure 11. Uneven distribution of the layer’s movement speeds caused local deformation and initiation of samples.

High-speed jet generation in the arising dimple close to the side surface of the roller in the load area occurred during HIC particles breaking off from the layer. The residual picture is presented on Figure 12.
The processes of deformation and HIC initiation in the shock friction conditions were studied experimentally by means of speed photographic recording. In the result of the study, we obtained the general picture of the processes occurring during shock shear tests and determined the shear speed of the upper roller and particle movement (jet generation from the dispersed product).

Image recording was performed during the shear of the upper roller, the high-speed jet generation in the load area and its motion in the multiple exposure per frame mode; the shutter lag was in 1,200 \( \mu \text{s} \) after the load weight touch of studs; the exposure time – 20 \( \mu \text{s} \); the number of exposures was 5 per frame at the interval of 1,000 \( \mu \text{s} \). The results are provided in Figure 13.

During a thorough study of the obtained image, we discovered traces (tracks) left in the medium by moving particles of the dispersed product during generation and spread of the jet. In Figure 13, the extension lines show the following values of movement for a particular time interval:

\[
l_1 = 1.2 \text{ mm} \quad \text{«track-1», the value of movement of an HIC particle for 20 \( \mu \text{s} \); accordingly, the movement speed of the HIC particle (jet generation from the dispersed substance) was } V = 60 \text{ m/s}.\]

\[
l_2 = 0.6 \text{ mm} \quad \text{«track-2», the value of movement of an HIC particle for 20 \( \mu \text{s} \); accordingly, the movement speed of the HIC particle was } V = 30 \text{ m/s}.\]

The movement speeds of different substances at a shock on the drop test rig were measured by\(^{19}\) and can have values exceeding 100 m/s. The speed of the chemical

Figure 11. Typical picture of chemical reaction front occurrence:
1 – lower roller; 2 – upper roller displacement direction;
3 – fracture surface;
4 – uneven front of chemical; reaction; 5 – plasticized sample part.

Figure 12. Typical picture of high-speed jet generation:
1 – joint sleeve; 2 – upper roller displacement direction;
3 – lower roller; 4 – sample disruptions; 5 – emission of dispersed product; 6 – high speed jet; 7 – front separating partial sample damage zones; 8 – fracture surface.

Figure 13. General picture of the high-speed jet generation in the process of the composition deformation in case of failure on the drop test rig K-44-III:
1 – joint sleeve; 2 – lower roller; 3 – upper roller; 4 – support roller of the drop test rig’s test unit; 5 – shock stud; 6 – discharge area; 7 – load area; 8 – local damage with emission of the dispersed product.
reaction is higher than the speed of particles expansion during the jet generation in the load area. Therefore, initiation of fine-dispersed HIC particles occurs in the moving stream in the form of the dust air mixture in the unconfined area of the drop test rig K-44-III.

To prove the above-mentioned, we performed experiments close to the upper limit of sensitivity with image recording during shear of the upper roller, occurrence of explosive transformation in the discharge area and its penetration into the thin compressed layer in the mode of multiple exposure per frame\textsuperscript{20}. The parameters were: the shutter lag – in 400 $\mu$s after the load weight touch of the stud; the exposure time – 15 $\mu$s, the number of exposures – 10 per frame at the interval of 45 $\mu$s. The tests were carried out in the following conditions: $P_{\text{shock}} = 280$ MPa; $V = 3.2$ m/s; $m = 0.02$ g. The results are presented in Figure 14.

Figure 14. General picture of occurrence and propagation of the HIC explosive transformation on the drop test rig K-44-III:
1 – joint sleeve; 2 – lower roller; 3 – upper roller; 4 – support roller of the drop test rig’s test unit; 5 – shock stud 6 – discharge area; 7 – load area; 8 – initiation of fine-dispersed particles in the form of dust air mixture.

3.3 Friction Tests Depending on Different Factors

The determination of the most hazardous dominating deformation process, as well as its occurrence limits depending on different conditions are no less important for justification of the HIC safe processing modes. For this, it is required to perform comprehensive consideration of all peculiar features of the mechanism of occurrence and propagation of explosive transformation of the substance under study\textsuperscript{21}.

The results of the study of HIC friction sensitivity depending on various factors are provided below.

The influence of the roller shift value on the frequency is shown in Figure 15.

Figure 15. GInitiation frequency versus roller shift value.

We determined the influence of the roller shift value (0.3...1.5) mm – occurrence of source areas happens most of all not at the moment of the shear start but during denudation of the friction surface. The mechanism of external friction and local damage in discharge area prevails.

The influence of the shear speed on the frequency is presented in Figure 16.

Figure 16. Initiation frequency versus roller shear speed.

With the increase of speed (1.5...3.4) m/s and the shear energy (3.8...8.8) J, the explosion frequency increases rapidly. The initiation occurs also by the mechanism of external friction and because of the high intensity of the deformation processes.

The influence of the layer thickness on the minimum initiation pressure is shown in Figure 17.

The increase in the thickness of the test charges layer (0.015...0.15) mm leads to the decrease in the minimum
initiation pressure up to the lower limit (75 MPa), then to the layer pressing-out from beneath the rollers during shear. Herewith, for initiation one should apply higher application pressure (90...110) MPa; in this case one can observe transition from external friction to plastic or brittle bulk failure\(^\text{22}\).

Figure 17. Initiation pressure versus layer thickness.

Implementation of the mechanism of external friction and shear for different charge thicknesses and roller surfaces showed that during friction with standard rollers, HIC shows high hazard level owing to the layer shear caused by roughness with formation of the friction surface inside the charge\(^\text{23,24}\).

4. Discussion

The results indicate an ambiguous HRIC initiation mechanism, which is determined by the influence of various factors of tests and is manifested, depending on the conditions of the mechanical impulse application. The above phenomena occurring in the HRIC charge at a mechanical impact and causing its explosive transformations are currently explained in terms of the locally thermal initiation theory.

At a strike impact, the temperature in local areas rises due to the destruction and the concomitant external friction of the striker ball on the deformable medium and the internal friction of certain parts and particles of the HRIC on each other at their certain displacement due to the in homogeneity of the structure of the charge formed by compressing in a cup. The amount of emitted heat will depend on how quickly the HRIC charge can absorb the shock energy. A sufficient speed of the shock absorption is provided for by the properties of deformation and medium's resistance. Thus, depending on the applied energy of the shock, the deformation processes caused by it, their nature and intensity, several different and at the same time effective initiation mechanisms manifest themselves, each with its own peculiar features.

The experimental data on the one hand indicate a lack of effectiveness and a low probability of HRIC initiating at the first stage of deformation in the free space between the spherical surface of the striker ball and the cylindrical walls of the cup. On the other hand, at a slight increase in the impact energy, the deformation processes that give rise to local heating dramatically change their nature and intensity, thereby qualitatively prejudicing the probability of initiation.

During the shock shear (friction) test depending on the parameters of the mechanical impact - the pressure and shear rate - the nature of the explosive transformation of the studied composition changes. We observed flames, smoke, a sharp sound and the residues of the composition evidenced its incomplete burnout. As the contact pressure and shear rate increased, the explosion frequency, completeness of burnout and sound level also increased. Such a change in the relative degree of hazard at the lower and upper limits of the explosion frequency can be explained by the different degree of manifestation of the most effective deformation processes: external friction, shear in the explosive material and volume fracture. Thus, the two observed kinds of explosive transformation in the form of low sound flares and full-toned explosions are attributable to the local initiation of the composition in the depression wave front and the possibility of its penetration in the thin compressed layer that is under increasing pressure.

Initiation of explosive transformation of the HRIC occurs also in the decompression area in the process of localized deformation of the thin layer on the exposed surface of friction. The process of propagation of the explosive transformation from the decompression area to the composition contracting under increasing pressure can be facilitated by the degree of deformation (fracture) of the layer when the compression pressure and energy (speed) of the impact increase.

5. Conclusion

In the production of explosives, the risk is considered as a quantitative characteristic of a hazard that can be
characterized by sensitivity to mechanical impacts (shock, friction). Justification of the solution of practical problems of explosion and fire safety of the existing and newly developed technological processes of manufacture and processing of explosive materials resides in the detailed understanding of the mechanism of their initiation under concrete conditions of external influences. Investigation of the features of the mechanism of explosives initiation by mechanical impact is necessary to calculate the safest modes during industrial processing of the HRIC. At the same time, there are certain dependencies between the physical and mechanical properties of the substance and the deformation processes proceeding under the load impact.

The study of the peculiarities of the explosive materials initiation mechanism under mechanical impacts is required for calculation of safe modes during the HIC processing in the production.

Hazardous factors in HIC mechanical procedures will be the conditions of plastic flow localization at the shock under the ball and at the friction during surface denudation. Above all, the hazard increases drastically if there is filling with fine-dispersed particles in the test unit, as well as during formation of the friction surface inside the charge.

The number of performed experiments allows stating that if the process conditions corresponding to the procedures of initiating substances pressing in the Blasting Cap (BC) shell are complied with, there is danger of local emergencies occurrence with HIC as the initiating charge\(^2\). The recommendations to exclude hazardous conditions and to ensure process and operational safety include the experimentally defined safe and minimum parameters of HIC initiation depending on various factors.

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