EFFECT OF STORAGE CONDITIONS ON THE VIABILITY OF AMMUNITION

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Abstract

The ammunition during its lifecycle is affected by climatic conditions in parallel with induced environs resulted from its operational use. Its safety and serviceability may be limited by an unacceptable level of degradation of components and materials, which subsequently results in a critical failure. This failure becomes a limiting factor of its operational life Identification of these processes enables appropriate predictions and assessment of the lifecycle period.

Keywords: failure, degradation, lifecycle, mathematical simulation, ammunition.

1 Introduction

Ammunition should resist influencing of wide range of effects of environments without becoming a dangerous or useless for handling, storage and transportation, at the same time it must operate in a defined way. It may mean, that the ammunition is loaded with the most extreme climate environs concurrently with evoked environs resulted from its operational use. Safety or usability of ammunition can be limited by an unacceptable level of degradation of components or of materials after having been exposed to standard operational environs or to certain extreme conditions. Degradation of ammunition components and materials during their standard operational use consequently activates a critical failure, which becomes a limiting factor of its life-cycle. Such kind of failure may be a development of cracks in energy materials or of the ammunition cover. Identification of these processes enables an assessment of the adequate life-cycle period.

2 Mechanisms of degradations, categories of the failure kinds

Ammunition constructions contain a wide range of materials. They involve mainly energy materials, metals, plastic materials, rubbers, glues and composite materials. Wrappage is also important, which must provide a protection against rough handling and affects of environments, against influence of mechanical and climatic conditions during entire life-cycle including a newly projected period. Materials, used during ammunition design, can be deteriorated in various ways. They can be immediate or progressive, reversible or irreversible. The failure kinds can be classified in 3 categories, namely thermal (chemical), mechanical and thermo-mechanical.

2.1 Thermal (chemical) kinds of failures

These kinds of failures can be defined as changes generated in chemical substances resulting in deterioration of safety or of functional features. Some explosive substances are instable by their nature and they are subject to decay at the temperature of the environs. Speed of decay reaction changes depending on a temperature and sometimes on other factors (e.g. air humidity). Examples of chemical kinds of failures include decay reaction of propellants (e. g. energy materials) as well as a degradation effect of solar radiation on natural and synthetic, organic materials (e.g. rubbers and plastic materials).

For the chemical reactions the temperature dependence is defined by activation energy. A modified Arrhenius speed equation defines a relation between speeds of the reaction at different temperatures:

$$F = \frac{k_1}{k_2} = e^{\frac{E}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (1)$$

Where F = factor of the reaction acceleration

k_1, k_2 = speed constant at T1 and T2 temperatures ($m^3.mol^{-1}.s^{-1}$)

T_1 = test temperature (K)
T_2 = reference temperature (K)
E = activation energy ($J.mol^{-1}$)
R = general gas constant (8,314 $J.mol^{-1}.K^{-1}$)

Several thermal (chemical) degradation processes occur during ageing process of the ammunition. In assessment of the construction it is stated a kind of failure, that may occur. A process leading to each cause of the failure rise is a sequence of chemical reactions.

$$A + B \xrightarrow{E_1} C; \qquad C + D \xrightarrow{E_2} E; \qquad E + F \xrightarrow{E_3} G$$

Where E_n represents activation energy for n-step of the reaction sequence. Each sequence will include a step, controlling its total speed. Activation energy for this step is to be measured or to be preliminary calculated for each prospective kind of failure. The lowest activation energy is then uses in the Arrhenius speed equation to define F factor representing a minimum ratio between period of accelerated daily temperature cycles and a lifecycle.

Calculations become more complicated if the ammunition is exposed to the changing temperatures depending on daily climatic cycles (STANAG 2895) it is necessary to calculate a weighted average temperature for a cycle and particular activation energy for a crucial step. Each step represents the most demanding conditions of storage in a given climatic zone. The maximum temperature of the storage temperature cycle is the air temperature that will be exceeded in a short time non-ventilated field storehouse, exposed to a direct solar radiation in the warmest part of the area for a period of 7 up to 8 hours per year. This cycle can be used for an acceleration of standard processes of a chemical degradation by an effect of higher temperatures in comparison with a cycle that the ammunition is exposed to during the most part of year.

Cold environs have no significant effect on chemical kinds of failures, as decrease of temperature decreases a speed of physical-and-chemical processes. The exception is phase changes and crystallization of amorphous substances (e.g. rubber).

As reference temperature (T_2) is considered an average value obtained from really measured data at storage conditions. If such information is not available, T_2 is chosen based on an average annual temperature calculated from STANAG 2895 for a given climatic zone.

T_1, T_2 and E values have a significant influence on the calculated F values because on the exponential nature of the equation. Influence of various values of the activation energy on the reaction acceleration factor for given values of T_1 (60 °C) and T_2 (20 °C) are stated in the Table 1. In Table 2 there are listed the changes of F value for particular activation energies, if the test temperature remains 60 °C, but a reference temperature changes. Introduction of accurate values in the Arrhenius equation is decisive for obtaining of a real prognosis of the life-cycle based on tests of an accelerated ageing process.

Table 1 *Factors of speed acceleration for different activation energies*

E activation energy (kJ . mol^{-1})	**Reaction acceleration factor F**	**Approximate life-cycle at 20 °C for 15 weeks at 60 °C (year)**
50	11,9	3
60	19,3	5
70	31,1	9
75	40,2	12
80	51,1	15
90	84,5	24
100	139,4	40

Table 2 Reaction acceleration factors at 60 °C and various temperatures for activation energy 70 kJ . mol^{-1}

T_2 temperature (°C)	**Reaction acceleration factor F**	**Life-cycle period at T_2 for 15 weeks at 60 °C (year)**
20	31,4	9
25	19,3	6
30	12,4	4
35	7,9	2

Activation energies for explosive systems range from 40 up to 200 $kJ.mol^{-1}$. They include a thermal decay of the explosive materials of the first class and pseudo-monomolecular reactions represented by an interaction of humidity with pyrotechnical composite substance. When penetration and a subsequent reaction of the humidity represent a reason of failure, E value will depend on a speed of diffusion through a seal.

Table 3 *Activation energy for a speed of steps of some reasons of a failure rise.*

Reason of the failure rise	**Activation energy (kJ . mol^{-1})**
Diffusion of humidity through a seal e.t.c.	70
Migration of the propellant plastificator	50 – 75
Rubber ageing	85 – 95
Thermal decay of explosives	150 – 200
Thermal decay of fulminating compositions	90 – 120
Rise of cracks in propellants in gas rising	100

Some useful values of activation energies are listed in Table 3. For ammunition materials the reactions having low activation energy advance at 20 °C faster than reactions with higher temperatures. Also very allied materials, as propellant of a given kind can show significant variations in values of activation energy and it is needed to pay them maximum attention.

The Berthelot´ s rule can be used for a prognosis of a safe life-cycle of the propellant. Measuring of the stabilizator consumption at different temperatures provides data enabling to graphically illustrate a relation between temperature (T) and time logarithm (log t) for different consumption of the stabilizer. If the result is in form of a line, then the process is governed by the Berthelot ´s rule, expressed in the form:

$$T = -\frac{1}{a}\log t + \frac{1}{a}\left(\log c - b\right) \qquad (2)$$

where a = factor, characterizing material being tested (J . m^3.mol^{-2})
b = factor, characterizing material being tested (m^3.mol^{-1})
c = stabilizator concentration (mol.m^{-3})

Gradient of the lines can be defined by γ10 factor representing an increase of a reaction speed at a changing temperature by 10 °C. The above mentioned equation can be rewritten as follows:

$$\frac{t_1}{t_2} = \gamma_{10}^{\frac{T_2 - T_1}{10}} \Rightarrow D_x = \frac{\alpha_x \gamma_{10}^{\frac{T_2 - T_1}{10}}}{365} \qquad (3)$$

where α_x = period in days needed to reach x% decrease in contents of the stabilizer at $T2$
γ_{10} = increase of a reaction speed at a changing temperature by 10 °C
D_x = prognosis of a safe life-cycle (in years) at x% decrease of the contents of the stabilizer at T_1

2.2 Mechanical kind of failures

We recognize two major kinds of mechanical failures. The first is a fatigue of material, where cracks appear due to a cyclic load, that then enlarge up to a failure of the part. The second way of the failure rise results from a load exceeding a limit level and breaking a part.

Especially in energy materials the friction (contact) failure can rise due to movements in a place of a reciprocal contact, resulting in two kinds of problems: decrease of material and warming. Decrease of material is able to activate structural attenuation or a release of matched surfaces. Existence of friction under such conditions for exposed surface can lead to a development of hot nuclei with a subsequent inflammation or an explosion. Alike a generation of explosive material occurs in form of dust with a higher sensitivity that is of an original compact material and with a hazardous condition. Penetration of dust into the particle of ammunition, where a squeezing of material may occur, often leads to its ignition and to a reverse penetration of flame to an explosive charge.

We recognize these two kinds of mechanical failures:

Fragile crack - it occurs in a moment, when a force creating a crack on its top (peak) becomes greater than a value of strength. A crack quickly enlarges.

Fatigue of material - in a cyclical loading the defects may be increasing up to a moment, when a pre-determined size of crack is achieved, that is considered as a failure of the part.

Plastic crash - it occurs, when a crack size is sufficient in order the remaining binding forces of the cracked part are not more able to resist to a rising strain having been developed during life-cycle.

A failure due to leakage - failure condition of the protecting container, when its safety and usability is endangered by a rise of a through pass from inside outwards.

Corrosion, erosion, fatigue of material due to corrosion, corrosion due to strains - it occurs resulting effects by factors from inner environs, that themselves may activate a failure (e.g. corrosion) or to contribute to a defect of another kind.

Warp - it occurs when a total surface and position of defects at a used load results in an overload of a limit of the resistance of the part.

Creeping - it is a slow stable enlargement of a macroscopic crack. It is an interaction between creeping and fatigue of material; with absence of experimental data it is very difficult to indicate a structural integrity.

Failure caused by initial defects - initial defects can cause a concentration of tensions, resulting in an accelerated or more probable rise of failure due to defects in these areas.

Wear - a wear is a surface phenomenon of a progressive decrease of material and reduction of dimensions during a time period.

There can occur other kinds of failures that are a combination of above mentioned kinds.

a) Material fatigue

To activate a fatigue of material, it is necessary to have such cyclical load that contains a traction part. Cumulative damage increases on a micro-structural level that may result in a rise and spread of crack. An appropriate way to describe a fatigue of material is a use of S-N curve, where S is amplitude of the used strain around zero-based mean strain (expressed in MPa) and N is a number of cycles until the failure rises. For many materials (e.g. metals) the S-N curve can be described in a following relation:

$$N.S^b = C \qquad (4)$$

where b and C parameters characterizing material. In addition there exists a limiting value of the strain amplitude, under which no recordable fatigue of material occurs.

If a mean strain increases from a usual zero value, the curve falls on a lower level of strain. For a fatigue of material a smaller number of cycles are needed with a particular strain.

S-N curve in such a case can be standardized using the Goodman chart.

Prognosis of the life-cycle in loading with different amplitudes of strain can be realized through the Miner’s hypothesis, which simply counts up proportional parts of the life-cycle at different amplitudes of strain, up to gaining 1. Damage of material *di* during application *ni* of strain semi-cycles with an amplitude *si* is given by a relation (meaning of symbols is similar as in a previous text):

$$d_i = \frac{n_i . s_i^b}{2C} \qquad (5)$$

This approach is mostly realized using the special Rainflow software aiming to count up a cumulative damage. The ammunition is produced from plenty of different materials, and therefore knowledge about strains (elements concentrating strain) is needed for a full use of this method at a given point in a dynamic load. It can be calculated using a method of final elements for a prognosis of a time flow of strains following a dynamic (or thermal) Load of ammunition.

The mentioned method represents an improvement of a classic method applying Miner´s hypothesis for assessment of a fatigue of material for soft steel based on a total input mean quadratic value of acceleration. It is used to compare a relative rate of effects of different environments, which are used in testing and a real environment. We start from a supposition, that actions activated in the ammunition are similar during testing. The following relation is used:

$$\frac{t_1}{t_2} = \left(\frac{R_1}{R_2} \right)^{2,5} \qquad (6)$$

where t = time (s)

R = demandingness of the test expressed in a structural density of acceleration (m^2.s^{-4})

Applications of simulated impulses must be performed in a real time.

b) Mechanics of a fracture

Mechanics of crack is based on a previous existence of a crack, found either by measuring or by a supposition. Equivalent of strain amplitude $\Delta\sigma$ in the mechanics of a fracture is ΔK a range of factors of the strain intensity. A factor of the strain intensity depends on a used strain, on geometry and a size of a crack and it is considered as a parameter for a description of an increase of the crack due to a fatigue of material. Speed of growth of the crack that has risen by a cyclical loading is a function of ΔK, K_{max} and K_{min}.

For many materials, as e.g. metals at low ΔK, it is an obvious limiting value, hereunder no increase of cracks occur. A linear change of the speed of growth of the crack is valid for intermediate values of ΔK in accordance with the Paris rule:

$$d_a / dN = C.\Delta K^m \qquad (6)$$

where a = length of a crack (m)

N = number of loading cycles (1)
ΔK = an amplitude of the factor of the strain intensity (kJ . m^2)
C , m = constants for a given material.

There is a fast rise of failure at higher values of ΔK, because Kmax approaches to a fracture ductility of the material KIC. The length of the crack is designated as a critical size of the crack on reaching this condition. Knowledge about behavior of material, from a point of view of its fatigue and fracture features, enables to elaborate a concept of the tolerances of defects for some mechanical and thermo-mechanical loads by strains. The existing cracks are being monitored and a life-cycle until a failure is preliminary defined based on a monitored loading cycle. This concept is usually supported by a model using a method of final elements.

2.3 Thermo-mechanical kind of failures

It concerns mechanical strains in materials resulted from thermal effects and resulting in a mechanical failure. Changes of temperature in a system containing substances with different thermal features, with a thermal conductivity and factors of a thermal dilatability create strain in materials (and especially in welds). Coefficient of metal dilatability is much lower that coefficient of plastic materials and rubbers. It is necessary to take into account such risen problems for rocket engines, especially in junctions between a propellant charge, a cartridge and a chamber body or between a charge and an inhibitor in case of free charges. Such failures lead to a catastrophic functional failure. The effects of an uneven thermal dilatability and contraction of materials in the ammunition, that lead to dimensional changes, may cause e.g. a rise of cracks in explosive charges or defects of seals, and so to enable a penetration of humidity to the charges with all consequences or precipitation of components of energy material would appear. For TNT major explosive charges a rise of cracks is more critical if a charge is glued on an inner wall of the missile body and so its volume shrinkage is limited during cooling. All these phenomena will gradate due to fast changes of temperatures, e.g. at a sudden change of elevation above sea-level in air transportation.

Generally, a thermal load is minimized by using materials with similar factors of thermal expansion and a high thermal conductivity (thermal conductivity divided by a specific heat and density product). Quantitative acceleration of degradation caused by thermal-and-mechanical effects, which already have been listed, is difficult to obtain. Testing at a larger range of temperatures, than it is supposed to be in operation, leads to increase of demandingness and to a faster identification of kinds of failures, but it is not certain, that these failures would occur in real conditions.

Similarly an increase of speed of changes in temperature increases a testing loading, but it may lead to similar conclusions. During testing the ageing process, therefore, if possible, such overrun of temperature or a speed of their changes should not occur.

3 Conclusion

Failures, especially in energy materials can lead to catastrophic events. Therefore every methodology, aiming to present a proof, that the ammunition is safe and useable, requires an identification of potential critical failures and their activation energies. Mathematical simulation of the behavior of ammunition in processes with climatic affects and resulted environs will enable a significant decrease of number of practical tests, and therefore costs and time in programs of assessment of its life-cycle.

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