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Possibility of the Use of Different Types of Materials in Passive Ventilation Systems of Munitions

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Abstract. The paper presents different types of insensitive munition used in military equipment, especially in western countries. Tests of this munition, their parameters, e.g. fast and slow heating, bullet, fragment and shaped charge jet impact and sympathetic reaction are described. The characteristics of shape-memory materials like alloys and polymers are presented. Behaviour of shape-memory alloy is explained by example of TiNi al-loys during mechanical or thermal loading, and martensitic transformation into austen-ite during unloading. Material parameters of the TiNi alloys, their testing and mathematical equations are shown. Venting systems used in the explosive reactive armour cassettes are presented. Different examples of materials, including shape-memory materials in munition, are demonstrated.
Keywords: ventilation system in munition, insensitive munition, shape-memory alloy, shape-memory polymer, stress-induced martensitic transformation, TiNi alloy

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1. INTRODUCTION

Application of technological advances in the design of military explosives makes possible development of munitions termed „Insensitive Munitions" (IM), less dangerous than previous weapons when subjected to accidental and combat stimuli.

The term „munitions" used hereinafter refers to bombs, shells, warheads, rocket motors, torpedoes, missiles or any similar devices, containing gun or rocket propellant and explosive, other energetic material or pyrotechnic device, enclosed within a casing.

The insensitive munition is characterized by effectiveness in designed application and less sensitiveness to extreme factors, as heat, shock or impact. Introduction of IM into service, aimed to enhance the survivability of logistic and tactical combat systems, improves safety to personnel, increases efficiency of transport, storage, and handling of munitions reducing their effective cost. The idea is included in the NATO HQ guidance [1] which concerns all non-nuclear munitions (including reactive armours ERA (*Explosive Reactive Armour*) [2-4]). The IM safety and suitability for service is assessed following NATO Standardisation Agreement (STANAG) 4297:2001 „Guidance on the Assessment of the Safety and Suitability for Service of Munitions for NATO Armed Forces – AOP-15". For testing the STANAG 4123:1995 „Methods to Determine and Classify Hazards of Ammunition" is applicable, which specifies minimum standards to be observed when determining classification of military ammunition and explosives for storage and transport purposes.

Mainly two types of shape memory materials are applied into the insensitive munitions:

1. shape memory alloys (SMAs);
2. shape memory polymers (SMPs).

The examples of typical sensitive munitions initiated by fire, causing next their explosion and further ships destruction are the HMS Sheffield in the Falklands War and the USS Forrestal in the Vietnam War, in both cases resulted in large casualties, loss of platforms, systems and munitions.

2. TESTS FOR INSENSITIVE MUNITIONS

The NATO HQ guidance [1] recommends for IM the assessment following an internationally agreed baseline range for each threat, defined in Table 1. Its purpose is to help interoperability and facilitate modification of life cycle.

Blast, overpressure, fragment spray and heat produced by the munitions as a consequence of stimuli generated by a threat or combination of threats, are considered as the IM response. Under some conditions a very rapid release of chemical energy, for example in projectiles, can cause deflagration, thermal explosion or detonation of the munitions.

Table 1. Threat and baseline threat range

Threat	Requirement	Baseline threat range
Magazine/store fire or aircraft/vehicle fuel fire (Fast Heating)	No response more severe than Type V (Burning)	Average temperature between 550ºC and 850ºC until all munitions reactions completed 550ºC reached within 30 s from ignition.
Fire in an adjacent magazine, store or vehicle (Slow Heating)	No response more severe than Type V (Burning)	Between 1÷30ºC per hour heating rate from ambient temperature.
Small arms attack (Bullet Impact)	No response more severe than Type V (Burning)	From one to three 12.7 mm AP round, velocity 400÷850 m/s.
Fragmenting munitions attack (Fragment Impact)	No response more severe than Type V (Burning)	Steel fragment from 15 g with velocity up to 2600 m/s and 65 g with velocity up to 2200 m/s.
Shaped charge weapon attack (Shaped Charge Jet Impact)	No response more severe than Type III (Explosion)	Shaped charge calibre up to 85 mm.
Most severe reaction of same munition in a magazine, store, aircraft or vehicle (Sympathetic Reaction)	No propagation of reaction more severe than Type III (Explosion)	Detonation of donor in appropriate configuration.

The tests are described as follows [1]:

1. **Fast Heating (Fast Cook-Off)** – represents a munition completely engulfed in a hydrocarbon fuel fire such as that resulting from an aircraft crash, on a ship or road transport accident (typically fast heating is represented by fires with temperatures exceeding 800°C, lasting up to 20 minutes).
2. **Slow Heating (Slow Cook-Off)** – represents heating of a munition by a remote heat source such as a fire in an adjacent compartment or building (constant heating rate of 3.3°C/h until the munition reacts). The simplified and detailed protocols for the above testes are given in [1].
3. **Assessment of bullet/fragment impact –** reaction of a munition to the bullet/ fragment impact stimulus occurring as a result of direct shock initiation or ignition of damaged energetic material, when the bullet passes through or lodges in the material. Typically the stimuli are represented by:
   - Bullet Impact – a 12.7 mm AP bullet impacting at (850±20) m/s.
   - Fragment Impact – a single 18.6 g steel fragment with a right-circular cylindrical body and a conical nose.

3. THE SHAPE MEMORY ALLOYS (SMAs)

They are characterized by thermo-mechanic and super elastic (SE) properties, and ability to recover permanent shape and dimensions. The functional properties of SMAs are based on the exothermic martensitic transformation (MT) which is sensitive to differences of temperature and stress, and to their hysteresis, therefore deformation properties are complex [4, 5].

The possible effects for the SMA are: shape memory and pseudo elasticity, since the phase transformation can be induced by mechanical or thermal loading. The SMA deformation at a temperature below the austenitic start temperature (A_s) and the induced residual strain is completely removed after the unloading and the subsequent heating above the SMA austenitic finish temperature (A_f). The pseudo elasticity occurs when the SMA is loaded at temperatures above the SMA austenitic finish temperature (A_f) with an inelastic strain generation and it recovers its initial state during the unloading [5÷8].

The examples of shape memory alloys, used in the housing industry, automobile, aircraft and space industries, biomedicine (as biocompatible materials – stents, guide wires and orthodontic braces) are: NiTi – Nitinol, FeNiAl, CuAl, CuZnAl, CuAlNi, CuNiAlZnMn, which are able to memorize their initial size and shape.

4. THE SHAPE MEMORY POLYMERS (SMPs)

The examples of shape memory polymers (SMPs) are: a partially cured resin, thermoplastics, and fully cured thermo-set systems, among which the latter are preferred. This is because of changing properties with every cycle as the partially cured resins continue to cure during operation, and „creeping" (gradually „forgetting" memory shape overtime) of the thermoplastic SMPs.

For the SMP composites the fibrous material such as carbon nano-fibres, carbon fibre, spandex, chopped fibre, random fibre mat, fabric of any material, continuous fibre, fibreglass, or other type of textile fabric compatible with the SMP resin can be used. Their weaves such as flat, two or three dimensional patterns, influence on the strength of the SMP composite, which may consist of one or more fibrous material layers in combination with a shape memory polymer. The fibrous material can be impregnated with the shape memory polymer or embedded within it.

5. EXAMPLE OF A TEST FOR THE SHAPE MEMORY ALLOYS (SMA)

The SMA samples are mechanically loaded on Instron 5867 testing machine at 25°C, above the A_f temperature (Table 1), demonstrating their pseudo-elastic behaviour [5].

The samples of 160 × 10 × 0.38 mm, belt shape, are cut from the TiNi SMA (50.5 at.% Ni) strip. In order to provide proper functioning of the loading system, combined of the TiNi sample, a mechanical extensometer and the clamps of the testing machine, the samples are placed in a holder [5].

Verification of the measuring system is carried out by the use of a laser extensometer, allowing measurement of the sample strain independently of the influence of the testing machine. The results of the obtained stress and strain are presented in Fig. 1.

Table 2. Parameters of the tested SMA made of TiNi [5]

Parameter	Value	Parameter	Value
E_A, GPa	59.2	ν	0.41
E_M, GPa	45	h, W m^{-2} K^{-1}	6.5
$\alpha_{A,M}$, K^{-1}	1.1 × 10^{-5}	c_p, J kg^{-1} K^{-1}	460
$\rho\Delta s_0^{(A,M)}$, MPa K^{-1}	-0.378	ρ, g cm^{-3}	6.29

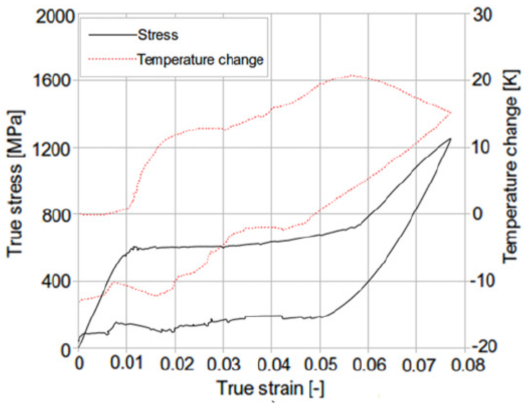

Fig. 1. Stress versus strain and temperature versus strain for TiNi, tension at strain rate 10^{-3} s^{-1}

They relate to the current cross section of the test sample, obtaining the so called true stress and true strain values (1).

$$\sigma_{\text{true}} = \frac{(l_0+\Delta l)F}{l_0 S_0}, \quad \varepsilon_{\text{true}} = \ln\frac{l_0+\Delta l}{l_0} \tag{1}$$

where: l_0 – the length of the sample prior loading, Δl – elongation of the sample, S_0 – the area of the sample cross section, F – the applied force.

6. SHAPE MEMORY MATERIALS IN AMMUNITION

Various parts of ammunition, especially insensitive type, e.g. in projectiles, include systems of ventilation for protection from explosion in case of fire on the battlefield, in magazines or during transport.

Road or railway transport of ammunition (grenades, projectiles, rockets, bombs, reactive armours, etc.) is endangered by its ignition or explosion in case a vehicle or a lorry fells over, collides with an obstacle, catches fire and it takes the transported cargo, or in case of terrorist attack (firing, a bomb trap, etc.).

In such cases, one of the ways to protect the ammunition is the use of less sensitive explosives and ventilation systems capable to reduce pressure inside the ammunition housing.

Among the ventilation systems (executive systems) there are the following ones:

1. vents in the explosive of a projectile or a booster, in a propellant of a rocket motor, in a powder contained in the cartridge, etc.;
2. elements offloading completely or only reducing stress (e.g. in a detonator/fuse, in a shell of the projectile, etc.);
3. fragile metal or plastic connections (in a detonator/fuse, in a shell of the projectile, etc., in a rocket motor);
4. closures and/or mechanical sealing or resulting from melting of a special easy-meltable material;
5. elements causing displacement of a primer, detonator/fuse, etc.;
6. shape memory materials.

Considering the way of reaction, the ventilation systems are divided into passive and reactive ones.

In the passive ventilation systems, the opening or creating vents occurs as a result of chemical reactions in solids. Physical reaction resulting in the force which makes the vents open, can also occur in special materials, like the shape memory materials.

In the active ventilation systems the high energetic material (or other) is initiated and within milliseconds, at high speed, makes the elements closing vents open. This results from weakening or movement of the closure elements vents, which makes the case of the projectile, rocket motor, missile shells, etc., unseal or open.

Such chemical reaction needs relatively large mass of high energetic material, which limits volume of the proper energetic material, e.g. explosive in the projectile, propellant in the rocket motor, gunpowder in the cartridge, etc. The unsealing or opening of the projectile case, rocket motor, missile shell etc., runs relatively softly and causes separation of the sealing/closing elements at the time the pressure arises inside the ammunition.

With the intention of Slow Heating decreasing, the transition temperature must be higher than the highest temperature occurred in normal service, which may typically be within (50-110)ºC. It depends on the conditions of storage and service, but must be below the lowest temperature at which slow heating can occur. For some classes of propellants the cook-off temperature can be as low as 125ºC, but well over 200ºC for some pyrotechnic compositions.

Examples of the shape memory materials application for various types of the munitions are presented in Figs. 2-7 [9, 10].

The rocket propellant charge in casing, as the example of the SMA use for insensitive munition, is presented in [9]. A temperature responsive extended annulus of shape memory alloy connector 4 which has an internal thread 3 (Fig. 2) for connection of separate components 1, la of a munition casing or other structure (rocket motor casing), comprises an integral operative part 3 for locking engagement with an integral co-operating part 2, 2a (external threads) of at least one of the components. Either or both of the operative parts or co-operating part is/are made of a shape memory alloy (SMA) such that at a first temperature the operative part and co-operative part are engaged, and at a second temperature the parts are released.

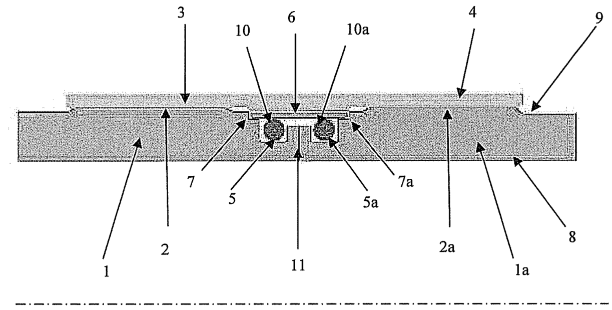

Fig. 2. A partial cross section through a connection device:
1 – separate components; 2, 2a – an integral co-operating part (external threads);
3 – connection casing (munition or rocket motor); 4 – connector with an internal thread;
5, 5a – channels; 6 – SMA metal insert; 7, 7a – stepped shoulders; 8 – metal latch;
9 – external surface; 10, 10a – o-ring seals; 11 – interface [9]

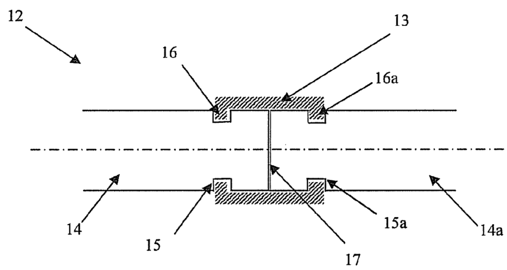

Fig. 3. A partial cross section through a connection device having one or more lugs or alternatively a raised annulus:
12 – connected unit; 13 – SMA connection sleeve; 14, 14a – joined members;
15, 15a – recesses; 16, 16a – annular projections; 17 – interface [9]

In the event of a thermal hazard, e.g. a fire, the connector and overwound munitions casing allow any build-up of pressure within a casing to be released quickly thus preventing an explosive reaction of a munition.

Figure 2 [9] shows a connection device having an internal thread in conjunction with two sections of a rocket motor casing which possess complementary external threads, and Fig. 3 presents another type of connection device in use to join together two pipes or columns which possess complementary recesses [9].

Respective stepped shoulders (7, 7a), formed on the outside of the casing sections, make the reinforcement of the interface (11) between the two rocket motor sections (1, 1a). The shoulders (7, 7a) are seated against a metal insert (6), which can be of SMA or any material capable of providing mechanical support, and the insert may be independent from the connector (4) or integral with it. Two o-ring seals (10, 10a), located in the channels (5, 5a) in the casing sections guarantee proper gas sealing during normal operation.

The connector (4) deforms itself by shrinking along its axis plane causing the internal thread (3) to move against and to break the two rocket motor sections external threads (2, 2a). The two rocket motor sections will separate and allow the pressure inside the rocket motor to decrease. It is prepared when a predetermined temperature of (4) is reached. The connector (4) simply expands so as to disengage threads 3 and 2, 2a, respectively, again allowing the motor sections to separate.

At the interface (17), two joined members (14, 14a) are cylindrical and they can be solid or hollow (Fig. 3).

The connection sleeve (13) has annular projections (16, l6a) which are located into proper recesses (15, l5a). The connected unit 12 can contain a part of an oil rig or other structure which is desired to disassemble in the future. Connecting sleeve 13 is made from an SMA which is shrunken onto the elements. This sleeve is heated to a predetermined temperature it will expand sufficiently to separate the elements (14, 14a). The sleeve 13 can be activated by cooling, which would be more appropriate for any structure exposed to a fire hazard.

In order to decrease the effect of slow cook-off an alternative mode of the SMAs use can be applicable in case of motor tubes or launch tubes. A collar is made of solid SMA and placed around the outside of the motor casing or launch tube.

A solid collar can be made up of a plurality of windings of an SMA wire. The windings contract when the SMA passes through its transition temperature range to a sufficient degree to cause the motor tube or launch tube to rupture.

The example of the SMP use in insensitive munition is presented in Figs. 4-7 [10].

After reaching the transition temperature (T_g) by the SMP pressurized material releases containment to prevent ignition or explosion of hazardous material. The seal, made of the SMP or SMP composite, at normal temperatures is deformed and protects the contents of the container.

In case the temperature of the SMP (or SMP composite) is higher than T_g, the SMP returns to its memory shape in a controlled geometry – instead of melting. The venting of the container is after returning the SMP to its memory shape. A simplified mechanism with the failsafe SMP-actuated pressure venting system in IM is presented in Fig. 4 [10].

When a threshold temperature is reached the SMP (or SMP composite) hand 2 and the end section 4 is able to detach from the main body 6 (Fig. 4). A ring (or band) of SMP (or SMP composite) hand 2 ensures the seal between the end section 4, and main body 6. This ring attached to metal latches 8 allows or disallows containment (Fig. 5) [10].

In case of the SMP (or SMP composite) band 10 reaches its transition temperature (T_g), the SMP returns to its memory shape which is smaller than its deformed shape (Fig. 6) [10]. This provides the means for releasing containment of the pressurized material to prevent ignition (or explosion) of hazardous material by retracting the metal latches 8. The tension of the SMP (or SMP composite) band, at normal temperatures, keeps the metal latches of the mechanism in contact with the lip 14, of the main body 6, maintaining seal to protect the IM. The container is vented when the SMP (or SMP composite) band 12 returns to its memory shape causing the metal latches 8, to retract from the lip 14 (of the main body 6), unseal the end section 4 from the body of the container (Fig. 7) [10].

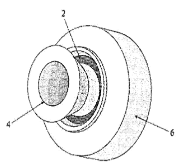

Fig. 4. One embodiment of an IM compliant mechanism [10]

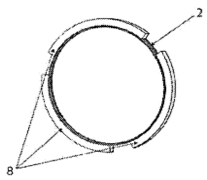

Fig. 5. The shape memory polymer ring and metal latches used in the embodiment of the IM compliant mechanism [10]

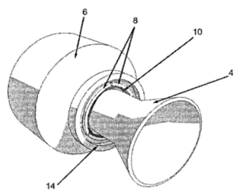

Fig. 6. The first embodiment with the SMP ring partially retracted from the IM [10]

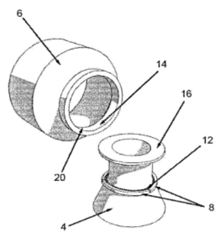

Fig. 7. The fully retracted SMP ring which has caused the two parts to the IM compliant mechanism to become separated [10]

2 – SMP or SMP composite hand; 4 – end section; 6 – the main body; 8 – metal latches; 12 – SMP or SMP composite band; 14 – the lip; 16 – the second lip; 20 – hole

The main body 6, has a hole 20, through which the end section 4, has a second lip, 16 (the second lip 16 has a diameter slightly less than the diameter of the hole 20).

Different types of insensitive munitions with SMA and SMP are manufactured in Picatiny Arsenal Dover [11].

7. REACTIVE CASSETTES WITH THE VENTILATION

The example of the using Polish insensitive ammunition with ventilation are ERAWA-1 and ERAWA-2 explosive reactive cassettes [12÷14] which are assembled on Polish (PT-91 Hard) and Malaysian' tanks.

According to present requirements ERAWA-1 and ERAWA-2 cassettes should be safe and not to detonate [2, 3]:

1. after falling from height of 12 m on hard and stiff foundation (steel or concrete),
2. after firing from small-calibre armour piercing incendiary (API) bullets,
3. after hitting with hand grenade and mortar fragments,
4. as a result of burning petrol on them (Fig. 8, 9),
5. as a result of burning napalm on them (Fig. 10, 11),
6. as a result of burning of incendiary agents, producing temperatures about 3000ºC, on them (Fig. 12, 13).

Testing of the resistance to detonation during firing of cassettes was carried out for different kinds of small-calibre API bullets. For this purpose there were used for this purpose: 7.62 mm rounds, with BZ and B-32 bullet fired from 7.62 mm PK; 12.7 mm rounds with B-32 bullet, fired from 12.7 mm HMG and 14.5 mm rounds with B-32 bullet and MDZ, fired from 14.5 mm HMG KPW.

None from usual bullets mentioned above, incendiary or detonating-incendiary, such as MDZ, (containing pentryt), caused detonation of explosive material in cassette. Cassettes were only penetrated, and frontal metal part of cassette was partly destroyed with 12.7 mm and 14.5 mm bullets. However, destroying of cassettes with 7.62 mm API bullets type of B-32 was so little that these cassettes could be fired several times.

From 82 mm mortar projectile sides at the distance 0.5 m and at front of it at the distance 0.1 m, ERAWA-1 cassettes were placed. After detonation of projectile, surfaces of cassette had indents made by fragments of projectile even without disarrangement of their structure, and protective ability of cassettes did not change.

The ERAWA-1 cassettes are tested according to Slow Heating (Slow Cook-Off – [1]). However, at the battle field these cassettes can be exposed to higher (not constant) heating rate than 3.3°C/h.

The ERAWA-1 cassette was placed in the middle of a container with petrol (Fig. 8) and time of petrol burning accounted for t = 5÷10 min.

Influence of such a thermal impulse caused only destruction of lacquer coat of a cassette (Fig. 9) and did not have any influence on diminishing the protective ability of a cassette.

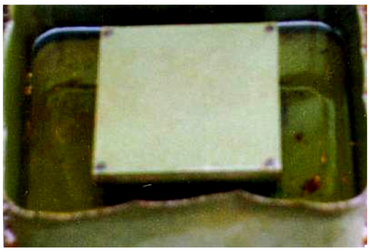

Fig. 8. Test of ERAWA-1 cassette resistance to detonation and destruction during burning petrol around it

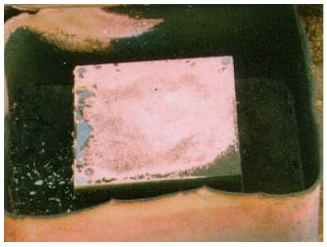

Fig. 9. ERAWA-1 cassette after combustion of petrol around it

The ERAWA-1 cassette was placed in the middle of a container with napalm (Fig. 10), and time of burning it accounted for 5÷10 min. As a result of strong warming of the cassette, lacquer coat of the cassette was destroyed (Fig. 11) and small quantity of explosive trickled from the cassette. However, after carrying out a test of protective ability of such a cassette (Fig. 12), the value *PC* slightly decreased – only by 5%, in relation to a cassette not exposed to impact of such a thermal impulse.

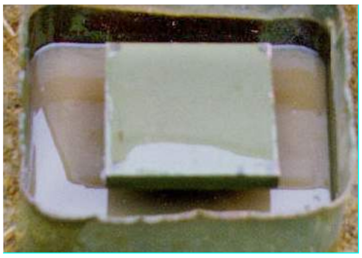

Fig. 10. Test of ERAWA-1 cassette resistance to detonation and destruction during burning napalm on it and around it

Fig. 11. ERAWA-1 cassette after combustion of napalm on it and around it

Fig. 12. Test of protective ability of ERAWA-1 cassette (after burning napalm on it) by PG-7 shape charge head (of RPG-7 grenade launcher ($\propto = 60^{o}$)

On a surface of the ERAWA-1 cassette ZAB-2.5 incendiary bomb was placed (Fig. 13), on which burning thermite produced a temperature 3000ºC, causing overheating of a cassette casing (Fig. 14) and inflammation of explosive material, however, it did not detonate.

1 2 3

Fig. 13. Test of ERAWA-1 cassette resistance to detonation and destruction:
1 – before, 2 – during, 3 – after burning ZAB-2.5 incendiary bomb containing thermite (3000ºC) on it

1 2 3 4 5

Fig. 14. Test of ERAWA-1 cassette resistance to detonation and destruction:
1 – before, 2-4 – during, 5 – after burning napalm bomb on it

The same all tests mentioned above were also carried out with the use of ERAWA-2 cassettes. Non-transferring detonation from hit cassette on neighbouring cassette is the condition for using ERAWA-1 and ERAWA-2 cassettes.

All results confirm that ERAWA-1 and ERAWA-2 cassettes contain insensitive explosive and their behaviour while burning around petrol, napalm up to thermite (generates 3000ºC temperature) is proper – without detonation because the specific venting system allows trickle small quantity of explosive.

8. CONCLUSIONS

The described above possibilities of the use of shape memory materials in projectiles can be summarized as follows:

1. With the use of the NATO procedures STANAG 4297, 4123, etc., Slow Cook-Off, Fast Cook-Off and bullet/fragment impact, insensitive ammunition can be precisely tested.
2. Shape memory materials are very important for application in insensitive ammunition in order to protect from initiation during its burning, impact of fragments and penetration with a shaped charge jet.

3. Casing of special construction, filled with propellant or high explosive (with pyrotechnic devices), combined with smart memory alloys (SMAs) or smart memory polymers (SMPs) can be classified as „insensitive ammunition”, e.g. shells or projectiles (guns, mortars), rocket motors, bombs, torpedo, missile, explosive reactive armours, etc.
4. SMAs or SMPs used as a ring or wire intended to shrink on heating, which have memory imparted by stretching, can be implemented in the rocket motors, bombs, torpedo, missiles, etc.
5. Connection means can be made with the shape metal alloy Cu-Al-Zn, Cu-Al-Ni, Cu-Ni-Al-Zn-Mn and Ti-Ni.
6. The NiTi type of SMAs tested in Polish conditions is suitable for application in the insensitive munition type 120 mm and 125 mm tank or 60÷120 mm mortar projectiles.
7. The container venting device can be made as metal latches, a lip, a ring etc. For this purpose the shape memory polymer or shape memory polymer composite can be used, e.g. based on styrene, epoxy, cyanate ester, polyurethane, maleimide, and siloxane, thermoset resin, etc.
8. Various fibrous materials, like carbon nano-fibres, carbon fibre, spandex, chopped fibre, random fibre mat, fabric of any material, continuous fibre, fiberglass, or other type of textile fabric are used for the purpose of insensitive munition.
9. A fibrous material can be used in the shape memory polymer as a layer or impregnated with the shape memory polymer.
10. ERAWA-1 cassettes that contain insensitive explosive do not detonate after firing from small-calibre weapon, after hitting with hand grenades and mortar fragments and after falling from height of 12 m on hard and stiff foundation (steel or concrete).
11. ERAWA-1 cassettes do not detonate in result of burning petrol, napalm, incendiary agents, producing temperatures about 3000^{o}C on them. It is due to their specific venting systems, so the pressure inside them decreases, because small quantity of explosive material trickled from the cassettes and it allows not detonating them.

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