Energetic Material/Systems Prognostics

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SUMMARY & CONCLUSIONS

The US military and weapons industries require their weapon systems to be reliable. As inexpensive miniaturized sensors and affordable simulation tools have become available, the prognostics method has begun to attract the attention of engineers seeking a new way to increase and optimize system reliability. This paper presents the tools currently available and being developed for prognostics of military energetic systems. Key elements of the study were assessments of available energetic material models, as well as current and future sensors for monitoring the health of energetic systems. A roadmap for developing prognostic methodologies is proposed.

1 INTRODUCTION

Military energetic systems have unique and demanding reliability and safety requirements. Use of such systems in combat situations calls for a high degree of confidence. An added element of concern from a reliability standpoint is the issue of safety associated with energetic materials. For example, US Navy systems are often stored right next to personnel living quarters when deployed on board ship. In other cases, these systems are often subjected to harsh conditions in storage, handling, transit, and actual use (see Figure 1). The US military and weapons industries are looking at applying prognostics to maximize system reliability.

Prognostic methods are used to predict the end of life or failure of a system in order to minimize the cost associated with under-predicting or over-predicting system failures. This is accomplished by sensor-based persistent health monitoring and use of modeling and simulation tools to predict performance degradation or failure based on monitored system data. For any physical system, deterioration leading to the end of life can be attributed to usage and/or the environmental stresses imposed on the system.

In the traditional approach, often it is assumed that deterioration can be correlated with age. This simplified model of predicting the end of life of a system is shown in Figure 2 [2]. The model predicts the end of life based on an assumed rate of deterioration. However, the problem with this approach is that elapsed time may not necessarily be the best indicator of system usage or environmental stress. Depending on the usage and environmental conditions, the rate of deterioration may be quite different over time, as shown in Figures 3 and 4 [2].

![Figure 2. Model prediction of system deterioration [2]](image)

![Figure 3. Conservative prediction of system failure [2]](image)

As shown in Figure 3, if the assumed rate is overly conservative and the system is discarded at the time of predicted failure, the remaining usable life of the system may be wasted. In the case of the US Air Force ballistic missile
fleets, this can be as much as 50% of the life cycle cost [3]. If, on the other hand, the assumed rate is excessively optimistic, as shown in Figure 4, the system may fail sooner than predicted and could lead to significant unexpected costs or risks.

![Figure 4. Optimistic prediction of system failure [2]](image)

In summary, the flaw in using simple models, such as the elapsed time as the indicator of system failure, is that these measures are not directly correlated with system deterioration. The ideal way to predict system failure is by directly measuring the progression of deterioration. Currently, development efforts are underway to make such measurements via small embedded sensors. In many cases, however, direct measurement methods are not possible. An alternative way to determine deterioration is by measuring stress conditions, and then employing a physics-of-failure (PoF) model to correlate deterioration with the stress conditions imposed on the system.

In the case of military energetic systems, usage may not be a good indicator, since the actual usage time is very short. Instead, energetic system deterioration arises chiefly from stresses induced by environmental conditions experienced during storage, handling, and transit. Such loads include thermal; mechanical (vibration, shock); environmental (humidity); and chemical (presence of contaminants) factors. The extent and rate of product degradation depend upon the nature, magnitude, and duration of exposure to such loads.

The following sections discuss models and measuring techniques applicable to military energetic systems.

### 2 ENERGETIC MATERIAL MODEL

There are, broadly, two classes of energetic materials for military use: explosives and propellants. In the first class, RDX, TNT, HMX, and plasticized explosives such as polymer bonded explosives (PBX) varieties are some of the most common energetic materials used in the current US military inventory. In the second class are liquid and solid propellants. For the majority of military weapons systems, solid rocket motors (SRM) are the preferred and more commonly used form. A large number of US military systems, including submarine-launched ballistic missiles (SLBMs), use solid composite propellants. In this study, only the solid forms of explosives and propellants are considered, due to their ubiquity in military use. We also make no distinctions between explosives and propellants, since their chemical formulation, material structure, chemical properties, and mechanical properties can be considered similar.

A key step in estimating the remaining life of energetic materials is understanding the nature and causes of their failures. Various modes of failures could lead to termination of the usable life. One such example is a significant departure of ignition sensitivity from nominal values. Higher sensitivity in energetic materials may result in autocatalytic ignition or ignition due to minor mechanical or thermal stimuli. Lower sensitivity would result in performance failures such as non-ignition when the system is intentionally initiated. Another mode of failure is the formation of structural flaws in propellants. A crack in rocket propellant grains can increase the burn surface area and cause the rocket motor chamber pressure to rise until the motor ruptures. Debonding of propellant material from the rocket motor casing may lead to similar results. These failures are mostly the result of material deterioration due to exposure to adverse environments.

#### 2.1 Empirical Models

To predict possible failure, micro-mechanical property models and chemistry models describing pristine energetic material baseline characteristics must be formulated and extended to describe energetic material behavior changes over time due to environmental stresses. For mechanical property models, the aging models predict changes in the modulus of elasticity, relaxation modulus, and material strength. Current efforts rely on empirical data obtained from energetic material samples taken by periodically sampling aged materials from stored weapon systems or from samples produced by accelerated aging processes [4, 5, 6, 7]. Collection of such data is expensive and difficult, in addition to presenting hazards associated with handling live materials. Each new formulation requires distinct collections of test data for developing empirical models.

#### 2.2 Physics-based Models

An alternative approach to developing aging models is by using physics-based methods. Some work has been done in developing models using the molecular dynamics (MD) approach in recent years [8]. Despite the seemingly abundant computational power currently available, quantum mechanics descriptions of atomic interactions are too expensive and impractical to be utilized in MD at this time. Instead, these studies have employed approximation methods that can describe chemical reactions in a computationally efficient way [9, 10, 11].

Numerically modeling PBX materials presents challenges because they are visco-elastic particulate composites, unlike molecular solid explosives such as TNT or RDX. These composites contain high-volume fractions of particles, as shown in Figure 5, and accordingly, the modulus contrast between the particles and the binders is extremely high. To overcome these difficulties Banerjee and Adams [12] developed micromechanics-based methods using simple numerical homogenization techniques. Their approach included the Generalized Method of Cells (GMC) and the Recursive Cell Method (RCM). However, comparison of RCM predictions with experimental data showed limited agreement.
Some of these developmental efforts include diaphragm based methods that have not yet been used on any deployed systems. These methods have been demonstrated on subscale articles, but these developments provide embedded sensors for energetic materials, and there have been demonstrations on subscale articles. The FEM analysis using the material strength obtained from the aging model can predict when failure would occur. An example of this approach is a model developed for the US Navy’s Standard Missile Program [4].

The next step is integrating these aging models into an assembled structural model of a warhead or a rocket motor, using structural analysis techniques such as the finite element method (FEM). Structural models are generated for each system and the projected environmental loads are applied to the model to identify failure locations, such as stress concentration points. The FEM analysis using the material strength obtained from the aging model can predict when failure would occur. An example of this approach is a model developed for the US Navy’s Standard Missile Program [4].

The loading mode considered in this model is stress induced by thermal contraction of the propellant when it is restrained within a rigid rocket motor casing. From field environmental temperature history, a stress history for each of the peak load regions of the propellant is derived. Using the cumulative damage function, a damage history is derived from which a prediction of time of failure is made. To deal with uncertainties associated with the variability of propellant mechanical properties and the variability of the temperature history of each stored propellant, a stochastic analysis of the cumulative damage process was conceived. This model has been tested using sample rocket motors drawn from a deployed missile fleet and samples of freshly constructed motors that had undergone accelerated aging. The model predicted trend consistent with the test results but with significant uncertainties.

2.3 Structural Models

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3 SENSORS FOR ENERGETIC SYSTEMS

Current methods of monitoring the health of energetic systems are X-ray imaging, X-ray CT, eddy-current, and ultrasound scanning. These methods are used mostly for quality control by manufacturers during the production process, and are seldom used once the system has been fielded. Moreover, for military energetic systems, it is usually impractical to use these methods in the field. For health monitoring in the field, deployable or portable sensors are needed.

3.1 In-situ Sensors

Key advantage of embedded sensors is that they provide direct measurements. Thus, by continuous monitoring of those parts posing a higher failure risk, these sensors can provide inputs for preventive actions. Efforts are under way to develop embedded sensors for energetic materials, and there have been demonstrations on subscale articles, but these methods have not yet been used on any deployed systems. Some of these developmental efforts include diaphragm based bond-line sensors for correlating pressure measurements to strain measurements, and fiber-optic sensors using Bragg-grating technology for measuring strain [14]. Actual implementation of fiber Bragg-grating sensor is being considered for some future systems [15].

There are some limitations with the application of embedded sensors in energetics, due to concerns about the effects sensors may have on energetic materials. In the case of propellants, the concerns include what effect embedded power and data lines may have on the burning characteristics of the propellant and the possible perturbation of the motor strain field by the sensors themselves. Would sensors cause a greater risk of crack formation due to their presence in the propellant grain? In the case of explosives, the concern is that the sensor electronics or power supply may set off the explosives. To minimize these effects, energetic systems must be designed and manufactured with sensors in mind from the beginning.

3.2 External Sensors

To avoid the risks associated with embedded sensors, external sensors can be mounted at a standoff from the energetic materials. In this case, another layer of modeling is necessary to bridge the differences of the parameters being measured and the parameters of interest in situ. For example, energetic material temperature can be monitored from the exterior temperature of the weapon’s carrying case, but a heat-transfer model is needed to correlate the temperatures measured on the carrying case and the energetic material. External sensors and surveillance systems are under development for related applications. The US Navy’s Advanced Technology Ordinance Surveillance (ATOS) program is being developed as a demonstration of health monitoring and inventory control of field-stored personnel protective equipment [1]. Miniaturized and self-powered radio frequency identification (RFID) sensors are being placed on storage crates to log environmental data, and the information gathered is relayed to a control location for processing and assessment of equipment health. This system can be adapted to health monitoring of energetic systems, such as stored munitions. With a system composed of external thermal sensors and a corresponding temperature-history/deterioration model, it would be possible to predict the remaining life of stored munitions.

One of the potential future sensors for energetic material chemical deterioration monitoring is the multifunctional optoelectronic (OE) MEMS sensors shown in Figure 7 [16]. The multifunctional OE-MEMS requires low energy input, thus posing very little risk of setting off energetic materials, even if it is utilized as an embedded sensor. Due to its small size and projected low cost, it is anticipated to be a desirable option for health monitoring of energetic materials.

3.3 Canary for Energetic Material

A “canary-containing” packet may be developed that can be externally attached to weapons casings, receiving environmental loadings nearly identical to those the casings...
experience. If the canary material is configured to deteriorate at a slightly faster rate than the energetic material [17], noting the failures of the canary can lead to predictions of the impending failure of the energetic material. This concept is attractive, since it would predict impending failure in a direct manner and could be applied to legacy systems. The canaries can be designed such that they would remain attached to the system being monitored, but could easily be detached when the system is used.

![Multifunctional OE-MEMS Sensor](image)

Figure 7. Multifunctional OE-MEMS Sensor [16]

One of the key challenges of this concept is developing canary materials that exhibit behaviors similar to those of the energetic material itself. The environmental loading conditions on the energetic material are dependent on how the material is encased in the system. Thus the container packet needs to provide interface conditions similar to those of the canary material, as well as those of the casing of the energetic material.

4 A STRATEGY FOR DEVELOPING ENERGETIC SYSTEM PROGNOSTICS

The dominant method of developing material aging models is through empirical means. Testing of samples from various stages of the aging process is needed to ensure reliable failure prediction with these models. Although it may produce reasonably accurate predictions, the process is very expensive because it needs to be repeated for each new formulation. An alternative is the development of physics-based models. With user-provided specifics regarding the formulations and structures of energetic materials, physics-based models may provide accurate predictions for material properties and their deterioration processes. Only a small amount of sample testing over the aging period may be needed to calibrate the models for accurate predictions. Developing mesoscale models with algorithms, such as RCM, may enable the construction of reasonably accurate models applicable even to composite formulations, such as aluminized propellants or PBX-type explosives. Although it may be costly to develop such a model at first, its applicability could be extended to different formulations. Thus the formulation of each model may be affordable in the end. Unlike empirical approaches, physics-based models can provide an entire suite of material characteristics, including mechanical and chemical properties and property changes over time. Thus the models can provide additional insight into the aging process of energetic materials, leading to the development of new types of sensors more directly tied to the deterioration process. Physics-based models may also be able to suggest more accurate methods of the accelerated aging process for sample testing.

In situ sensors are desirable for prognostic systems, since they provide direct measurements of the parameters of interest. However, the influence of the in-situ sensors on the energetic material being monitored should be minimal, though this can be difficult to achieve in practice. As an example, it may be desirable to place strain sensors at stress concentration points to directly measure any indications of incipient material failures; however, placing the sensors near these locations may initiate failures far earlier than would normally occur if the sensors were not present. Consequently, current development of in-situ sensors focuses on miniaturizing the sensors so their influence on energetic materials is minimal.

For short-term development of surveillance sensors, it may be more expedient to focus on external sensors in lieu of embedded sensors. If environmental load parameters, such as ambient temperature-time history or shock induced acceleration of casing can be correlated with the material deterioration model, external sensors can provide sufficient information to estimate the remaining life of the energetic material. For this approach to be practical, a deterioration model needs to be developed. Some deterioration models have been developed from an empirical approach, but most of these models are yet to be validated. Unlike the models, there are commercial off the shelf (COTS) sensors suitable for environmental stress monitoring of energetic systems.

A more immediate payoff can be realized from the development of energetic materials canaries. Although it may be a challenge to find suitable surrogate material to be used as canaries, there are various inert formulations, with similar mechanical properties as energetic materials, in use in the military. Similar loading conditions in the canary packet structure can also be provided by using the information generated from the model structural analyses to identify stress concentration points. Unlike the external or embedded sensor approach, canaries require no additional decision-making algorithms for failure predictions. A direct indication of failure in the canary material would provide an early warning of impending failure of the actual material.

5 CONCLUSION

The U.S. Navy’s first objective, as noted in the Chief of Naval Operations’ “Navy Strategic Plan” [18], is designing a cost effective military capability approach. In this cost-conscious environment, U.S. military and weapon industries need to find ways to make the current energetic systems more cost effective and dependable. The method of prognostics applied to energetic systems can lead to substantial savings in replacement costs as well as providing highly reliable products. According to this review, the tools to implement prognostics are mostly in development at this stage. Continuous health monitoring and instantaneous remaining life prediction is not yet possible for military ordinance systems. As summarized in the previous section, significant investment needs to be made to develop validated models and un-intrusive embedded sensors for making energetic system prognostics a reality.
REFERENCES


BIOGRAPHIES

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