Observation in Ballistic Evaluation Motor Static Firing: Cracking in Graphite Nozzle

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ABSTRACT

Ballistic Evaluation Motor (BEM) is the representative of large size rocket motor and is static tested to evaluate the ballistic parameters such as burning rate, specific impulse, thrust etc. In the solid-rocket propulsion studies, rocket nozzle erosion has been a critical issue when the motor is operated at high temperature and pressure. The throat area of the nozzle undergoes the extreme heat transfer, thereby decreasing the thrust and causing severe performance reduction of the propulsion system. Shear and normal forces on the nozzle surface, surface temperature, chamber pressure, and heat transfer to the wall, particle impacts, chemical kinetics, and surface melting are considered primary factors of nozzle erosion. One of the Observations in Ballistic Evaluation Motor Static firing is Graphite Nozzle Cracking. Speciality grade Graphite is used in all sections of small test nozzles. The reason behind the cracking in BEM-1 is Graphite used is relatively brittle and the thermally induced stress cracked the material. Furthermore Graphite does not crack clean. The crack propagated through the material lead to spot erosion. In the case of BEM-1, at two places local spots were observed radially from the throat region where high temperature, high velocity gas flows occurs wherein decrease in pressure (undulations) is observed in Chamber pressure – time trace. Due to this localized nozzle cracking, throat area has increased which reduced chamber pressure and caused performance reduction in the propulsion parameters. In BEM-2, eliminated this problem; thereby performance parameters were obtained as expected which revealed (no undulations) in chamber pressure – time trace.

Keywords: Ballistic; Graphite; cracking; erosion

NOMENCLATURE

r_b = burning rate
r_{TOT} = burning rate by thickness/time method
w_b = web thickness
t_b = burning time
a = empirical constant

p = chamber pressure
n = burning rate exponent
A_t = area of throat
A_b = burn surface area of propellant
ρ_p = density of propellant
C_d = coefficient of discharge through throat

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1. INTRODUCTION

Propellants for solid rocket motors (SRM) can broadly be divided into two categories: homogenous (double-base) propellants composed of fuel and oxidizer present in the same molecule, or heterogeneous (composite) propellants[2] composed of a fuel and oxidizer blend. Oxidizer particle size and shape has a significant impact on the burning rate, with smaller particles having larger surface area for a given volume and therefore higher burning rate. Oxidizer crystals and fuel particles are encased in a polymeric binder. Other ingredients such as burning rate modifiers, plasticizers, curing agents and additives can be included in the blend to modify the regression rate, physical properties, and manufacturability.

Solid Rocket Motors have been attracting attention world over as solid propellants become more energetic in pursuit for increased performance and it is overriding power behind most of the missile programmes. Before the final launch of motors, the small rocket motors are fired with known parameters in order to outline performance prediction. The performance prediction can be done with ballistic evaluation of grain. The ballistic properties calculation is mainly governed by the propellant burning rate.

The burning rate of propellant depends on a number of parameters: on the propellant composition that is fuel to oxidizer ratio, particle size of components (oxidizer and fuel), flow velocity, temperature and mostly on pressure. The burning rate is usually measured in the conditions where operating pressure and initial temperature are constant; the data generated at operating conditions represent the propellant burning rate.The solid propellant, commonly called the grain, is cast directly into the motor case or cartridge in a configuration that is chosen to give the desired thrust versus time behaviour.
Ballistic Evaluation Motor (BEM) is a small size solid rocket motor which is the representative of large size solid rocket motor for ballistic properties evaluation. BEM is produced with same propellant composition[6] with similar procedures of processing in small scale as large motor will be produced. BEM is static tested to evaluate the ballistic properties of the propellant formulation.

The main objectives of the BEM static test includes - to qualify the formulation by evaluating the ballistics properties of propellant,by verifying the properties against the mission specifications, to evaluate ballistics properties for large size solid rocket motors, to evaluate ballistics properties for long term storage, to generate data for various formulations of propellant composition ('n' value determination). The fundamental method for determination of burn rate is TOT method; average web thickness (w_b)/burning time (t_b). The average web thickness of grain measured before the performance of motor and burning time can be determined from the pressure-versus-time trace after the motor firing.

The material used for nozzle throat insert [8] is Speciality grade Graphite.These are relatively inexpensive materials formed by extrusion. Due to its high temperature capabilities, graphite is an excellent material for rocket nozzles, especially for hot burning propellants. Two drawbacks are graphite's relatively low strength and brittle nature.

The performance of Ballistic Evaluation Motor also depends on nozzle design[5]. A solid rocket motor nozzle is a carefully shaped aft portion of the thrust chamber that controls the expansion of the exhaust products so that the energy forms produced in the combustion chamber are efficiently converted to kinetic energy, thereby imparting thrust to the vehicle. This is achieved by designing the necessary nozzle geometric profile; the familiar rocket motor nozzle is convergent – divergent nozzle. This nozzle is subjected to very high pressures, and rapid, dense gas flow at high temperatures. A nozzle must be fabricated from a material that will be capable of withstanding such conditions of structural and thermal loading[4]. Furthermore, nozzles for propellant consist of nothing more than a nozzle shape machined from a rod of graphite held in a metallic nozzle holder.

2. EXPERIMENTAL SETUP

To evaluate the ballistic parameters of different propellant composition, BEMs are cast and static tested. BEMs are static tested in the horizontal configuration using swing bench type test stand.

2.1 Propellant Ingredients and Sample

Oxidizer used in the present work is obtained from known source. The oxidizer particles are subjected to grinding in an Air Classifying Mill to reduce the size. The micro-Al used is obtained from the known source. The binder used is a polymeric binder cured by a curator, with addition of plasticizer. These propellants contain apart from oxidizer & fuel other ingredients also to manufacture propellant.

2.2 Burn-Rate Measurement

The steady burn rate pressure dependence of Ammonium Perchlorate (AP)-based composite propellants is fitted by the Vieille-St.Robert law[1] (Eq.1), if working pressure of rocket motor is below 2000 psi (138 bar) and for a given initial temperature.

$$r_b = ap^n \qquad (1)$$

The performance of the formulation was evaluated by static testing star-shaped Ballistic Evaluation Motor[10]. The BEM used were star grain configuration. Both ends of the propellant grain were inhibited for allowing radial burning only. The burn rate is obtained dividing the grain web thickness by the burning time (Eq. 2).

r_b=web thickness / burning time (2)

3. EXPERIMENT

The main objective of small scale motors[7] is to measure burning rate in a motor environment by saving time and money during the actual motor development. Before the experiment to measure the burning rate of a particular propellant, the propellant web has to be determined. A measured web thickness is preferred over a thickness taken from a drawing. Propellant web is measured at 10 places and arithmetically averaged. The motor action time follows from the pressure time trace, which starts at the beginning of motor operation, and ends at the end of motor operation. The burning time is determined from this trace as the period from the moment that all propellant is considered burning till the moment the web is considered consumed.

The propellant grain has a progressive surface spread, because it has star shape and is inhibited at both ends. The propellant grain is placed into the combustion chamber and all necessary components are assembled for testing. However, the thermo chemical erosion caused by high heat fluxes from the combustion product gases during motor firings will incur decrease of the specific impulse, downgrading overall thrust performance[14]. Therefore, to gain a fundamental understanding of how different combustion gaseous products will react with the graphite nozzle materials[9] at particular motor operating conditions, it is imperative to know the thermo physical properties of the Speciality Grade Graphite in order to integrate these data into numerical or experimental studies.

Typically, small ballistic evaluation Motors are radial burners having a sharp tail-off, short burning duration (2-10s) to minimize heat losses and nozzle erosion, small grain web thickness to minimize thermal shrinkage, conical nozzle geometry with 15° ± 0.5° half angle of divergence and no flow separation. The motor nozzle size, A_t is estimated from the burning rate, r_b, based on the mass conservation equation (Eq. 3).

$$A_t = \frac{A_b r_b \rho_p}{C_d p} \qquad (3)$$

Burning rate is based on propellant thickness and the burning time as shown in Fig. 1 and is referred to as the thickness/time (TOT) method.

r_{TOT} = web thickness/ burning time

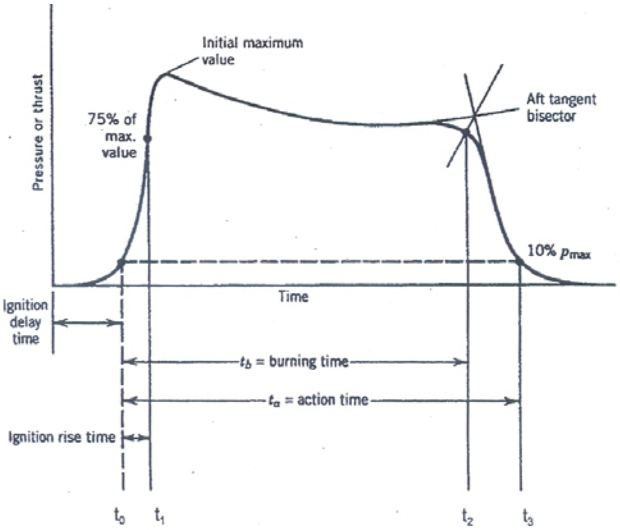


Figure 1. Burning Times.

Time Point	Variant
Beginning of motor operation	t_0
Beginning of burning	t_1
Ending of burning	t_2
Ending of motor operation	t_3

3.1 Tangent Bisector Method:

Defining burning time using the Tangent Bisector Method[11] as shown in Fig. 2 begins with the identification of the start of burning (typically t_1 is taken at the first point 10% Pmax point). The end of burning is determined in an effort to minimize the effect of the tail off integral. However, the method neglects tail off burning, which is the part of the web that continues burning after the anticipated end of burn[15]. This method usually defines a point in time that represents an arbitrary web burn out point and not the actual burn out point. This method may be more difficult to implement in software, however, the maximum intercept approximation of web bisector is relatively to program.

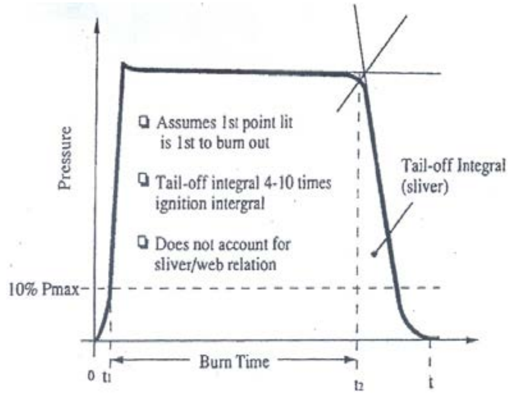
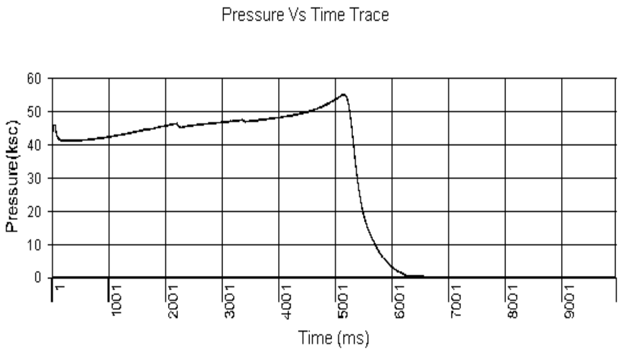


Figure 2. Tangent Bisector Method.

In our experimental study, two sets of BEMs [BEM - 1 & BEM - 2] were static tested with same chemical formulation. BEMs were conditioned for ensuring homogenous temperature throughout the surface of the BEM. The first BEM is denoted as BEM - 1 suffered Nozzle cracking at two places as shown in Fig. 4 and second BEM is denoted as BEM - 2 suffered no cracking as shown in Fig. 7.



. Figure 3. Pressure vs Time Trace of Cracked Nozzle

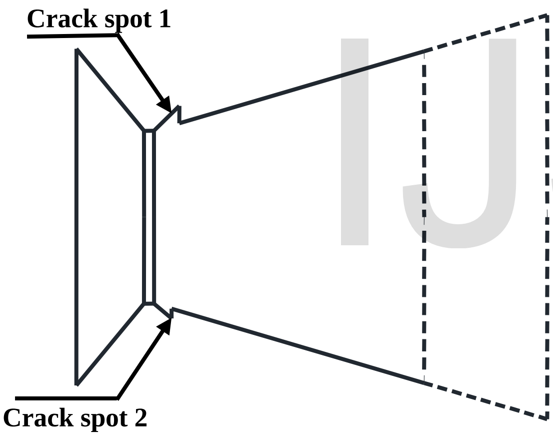


Figure 4. Cracked Nozzle.

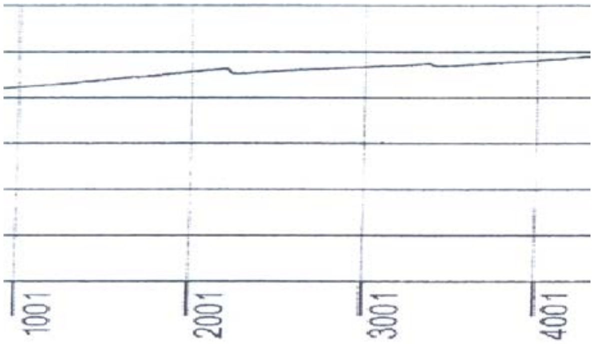


Figure 5. Enlarged View from Pressure Vs Time Trace At Location Where Spot Erosion Occured.

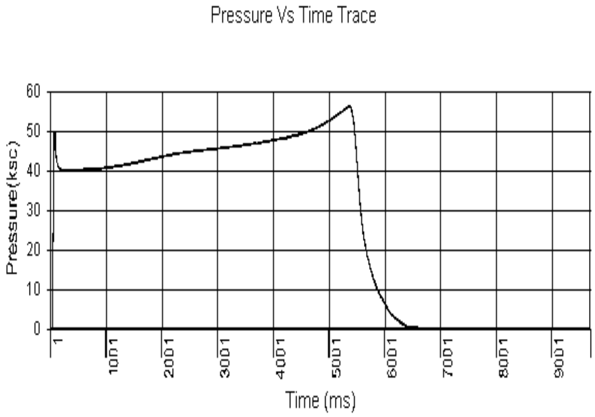


Figure 6. Pressure vs Time Trace of Noncracked Nozzle.

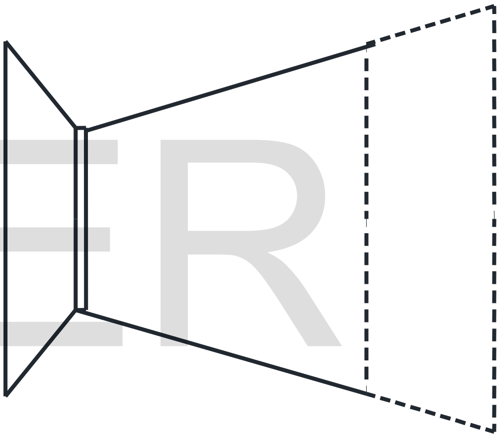


Figure 7. Non cracked Nozzle.

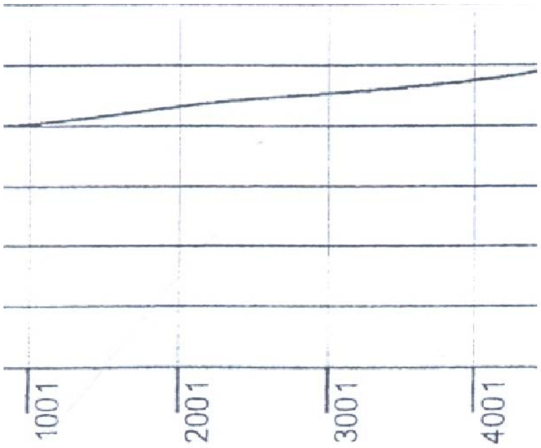


Figure 8. Enlarged View from Pressure vs Time Trace without Spot Erosion.

The main requirement of a solid-propellant rocket nozzle is to retain dimensional integrity. Degradation occurs by erosion of the exposed internal surface or by cracking. Cracking is usually thermally induced and could result in the loss of large fragments of the nozzle. It was found in this investigation that in BEM - 1, fragments of graphite particle has been observed i.e., two spots similar to triangle in shape because of that throat diameter of nozzle has increased as compared to BEM - 2 which results in decrease in chamber pressure and burn time for BEM - 1.

4. RESULTS AND DISCUSSIONS

Nozzle cracking occurred at two places in the static test firing of BEM - 1. The reason behind the cracking is that graphite used was relatively brittle, and the thermally induced stress cracked the material. Furthermore, graphite often does not crack cleanly[13]. These cracks tend to propagate through the materials, resulting in severe fracturing that usually leads to ejection. In BEM - 1 test, the graphite has cracked and has not been ejected; found fragments of graphite pieces circumferentially eroded from the throat region. To eliminate this problem, in subsequent static test firing (BEM - 2) ensured suitable graphite block with nozzle holder.

The two spots in the nozzle of BEM - 1 represent more or less triangular shape. After investigation, % increase in area of BEM – 1(cracked nozzle) is 2.3% compare to % increase in area of BEM – 2 (non-cracked nozzle) which is 1.03%. Therefore on comparison of above two areas with cracking and without cracking there is increase in cross section of throat area by nearly equal to 1.23%. The increase in area causes decrease in chamber pressure and burn time of propellant and is seen from experimental data there is also reduction in thrust and specific impulse.

With above data it is difficult to predict the exact performance with nozzle cracking. Hence for predicting performance of a given solid rocket motor there should be no cracking in the graphite nozzle. Fig 9 shows meshed model of Cracked nozzle. Variation of mesh pattern[12] is observed because of the crack, hence mesh is redefined at the cracked portion to induce accurate pressure plot. Fig 10 shows meshed model of Non cracked Nozzle. Normal mesh pattern is observed.

Because of the crack, throat portion is under the influence of less pressure (Light Green) as seen in Fig. 11. Non cracked Nozzle has regular pressure distribution pattern (yellow) at the throat region when compared to cracked nozzle as seen in Fig 12.

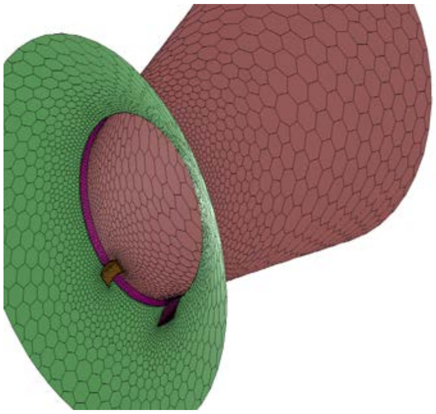


Figure 9. Meshed Model of Cracked Nozzle.

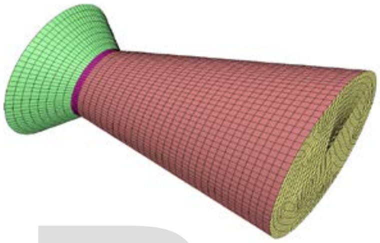


Figure10. Meshed Model of Non cracked Nozzle.

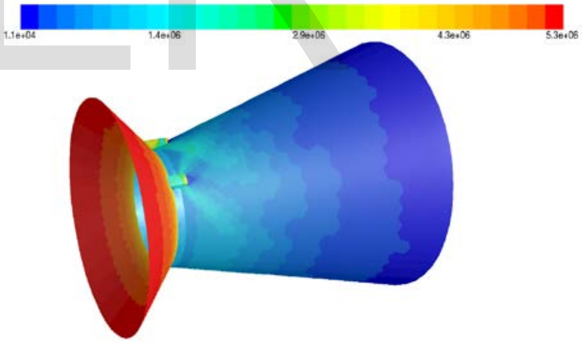


Figure 11. Pressure Distribution in Cracked Nozzle.

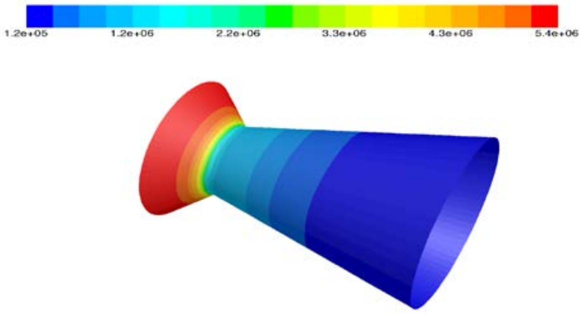


Figure 12. Pressure Distribution in Non cracked Nozzle.

5. CONCLUSIONS

Analysis of graphite to predict cracking is imperfect, the lack of accurate high-temperature properties, and the wide variation in the material from piece to piece and within pieces, and the lack of well-established failure criterias to identify the cause. The percentage increase in throat area caused performance variation; this results in decrease in all the performance parameters of the cracked nozzle. The present study shows nozzle cracking plays a significant role in predicting the performance of solid rocket motor.

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