Desirability and Assessment of Mechanical Strength Characteristics of Solid Propellant for Use in Multi Barrel Rocket Launcher

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Abstract—**Solid fuel is the first choice to propel the rockets for the area weapon Multi Barrel Rocket Launcher (MBRL) due to ease of design, manufacturing, handling, packaging, transportability and deployability. It also has the capability of prolonged storage without noticeable degradation of its quality. It is also quite safe and does not pose safety hazards. Tactically it suits the requirement of very fast response time and generates high thrust for small duration. Composite modified double base propellant (CMDB) is preferred in MBRL due to wide range of favorable mechanical properties including superior strain capability. Properties of composite propellant may be tailor made by changing the compositions and compound rate. Various failure modes of this propellant are found to be thermal cycling, handling and transport vibrations, ignition shock and pressure loading, launch and flight acceleration, flight maneuver, high speed maneuver, environmental condition etc. All these causes unsymmetrical stress distribution and may lead to failure. Bond strength within the propellant and between the propellant and inhibitor material is very important parameter to control mechanical failure. For safe design the bond strength should be more than the ultimate tensile strength of the propellant. This criterion is satisfied in the present case for the CMDB propellant of MBRL.**

Index Terms—**Composite modified double base propellant, debonding, load-Elongation plot and MBRL.**

I. INTRODUCTION

Solid propellant is the first choice to propel rockets of Multi Barrel Rocket Launcher (MBRL) primarily due to its ease of handling, transportability quick response time, and deployability. Its manufacturing process is also safe and simple. A solid propellant is a monopropellant fuel, a single mixture of several chemicals i.e. the oxidizing agent and the reducing agent or fuel. This fuel combined with oxidizer is in its solid state; called grain. Its shape can be designed to provide best burning characteristics. The variables determining grain related performance are core surface area and specific impulse. Solid propellant ammunitions [1] are basically supplied in 'ready for use' condition. All such ammunitions except small arms ammunition are just needed to be armed by inserting the igniter which is kept separately for safety. During the service life, solid propellant grain is subjected to many stress-inducing environments.

The desirable qualities of military propellants need to match with that of ammunitions. It should have simple design and easy to manufacture. In addition to high thrust generation capability, the propellant must also retain its usefulness even on prolonged storage and deployment in field condition. It should have negligible toxicity/health hazards to the troops. Transportation and handling should be easy with minimum response time. The viscoelastic nature of the propellant causes a strong load-rate and temperature dependence of mechanical properties. Besides a natural decrease of physical propellant parameters in unloaded conditions, called chemical aging, there is also mechanical properties degradation, referred to as cumulative damage. Temperature variations during storage are found to be the main reason for the propellant strain and stress leading to decreasing quality [2]. To transport solid propellant ammunition it is packaged in palates and transported by road, rail, sea or air. Drill of handling the weapon and ammunition is taught to the troops and rehearsed umpteenth time. However, rough handling cannot be ruled out due to human error [3] and battle stress. So it should remain mechanically stable enough to withstand the shocks and vibration during transportation and rough handling to avoid accidental cook off.

For use in MBRL composite rocket propellants have acquired greater significance because of advantage of wide range of favorable mechanical properties including superior strain capability compared to homogeneous propellants (Nitrocellulose (NC) and Nitroglycerine (NG) based propellants). Also composite propellant is preferred [4] due to its main advantage of low vulnerability and high specific impulse. Properties of composite propellant may be tailor made by changing the compositions and compound rate and by optimizing grain geometry design. The composite propellant is composed of one binder (typically, Polybutadiene or glycidyle azide), one oxidizer (typically ammonium perchlorate (AP), chemically NH_4ClO_4) and one fuel (Al, Zr or Mg). With aluminized propellant a large fraction of exhaust consists of liquid or solid particles which accelerate with expanding gas but do not contribute to the thermodynamic process [5]. Major disadvantage of composite propellant is its low specific heat value. This problem is resolved by mixing NC and NG (both have high specific heat) making it Composite Modified Double Base (CMDB) propellant [6]. CMDB being a composite material unavoidable are the many interfaces between materials of differing physical and chemical properties. Hence there is a requirement of the structure of adequate strength to transfer or distribute stress when subjected to, for example, thermal and mechanical loading, that will help determine performance and failure criteria [7]. If the materials on each side of the interface are also chemically complex (as is the case with solid propellants), then other issues such as surface

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segregation, diffusion, solubility, and reactivity of chemical constituents also affect the interfacial region and aging of overall system. To launch the rockets of MBRL, CMDB propellant which is viscoelastic in nature required to have adequate mechanical strength [8] to withstand stresses produced due to various loading conditions, changes in environmental condition, transportation and handling. Severe stress and extreme environmental conditions cause damage in terms of initiation and propagation of crack, separation at polymer interface, debonding etc. Prolonged storage also changes mechanical properties (tensile strength, modulus and percentage elongation). Change in temperature brings significant change in the tensile strength, percentage elongation, and elastic modulus. It was observed [9] that for each class of propellant, as temperature reduces, propellant becomes hard. Extruded double-base propellants show less percentage elongation (around 1%) at reduced temperature (223 K) probably due to brittleness. Intense heating by frictional sliding between the faces of a closed crack during unstable growth can form a hot spot, causing localized melting, ignition and fast burn of the material adjacent to the crack. Opening and growth of a closed crack due to the pressure of burnt gases inside the crack and interactions of adjacent cracks can lead to violent reaction, with detonation as a possible consequence [10]. Hence, an accurate estimation of stress and strain response needs to be evaluated along with shear modulus which is a very important parameter for viscoelastic material.

This paper analyses desirable mechanical characteristics of solid propellant for MBRL application. Various models and methods available for assessment of mechanical characteristics of such propellants have also been discussed.

II. RECENT ADVANCES

Mechanical properties of CMDB propellant depend on its ingredients [11]. Its tensile strength and elongation at moderate temperature decrease significantly with decrease of NC (12% N) content. The experiments by Fenglei H *et-al* [12] showed that the fracture of AP is essential for crack growth. A simplified dynamic brittle fracture model is presented. Comparison of numerical and experimental results shows that this new model describes the spallation of solid propellant successfully. Plihal B *et-al* [13] developed a technique for the complex evaluation of a modified Brinell test for determining some of the mechanical properties of solid propellant. The basis for the approach is the time-dependent impression made by a ball into the propellant material under the action of a constant load, and the subsequent recovery when the load is removed. The calculation methodology is supported by the measurement of some viscoelastic characteristics of representative solid propellants. Lindsey G H [14] carried out a fracture characterization of critical stress intensity factor including extensive dewetting experiments for a composite propellant. The fracture study has been subdivided into three parts: a fracture criterion is developed for stress fields producing mixed mode crack propagation by drawing a comparison with fracture in uncracked geometries; a means for predicting crack growth and velocity have been developed strictly on the basis of stress intensity factors. Kenneth W B Jr *et-al* [15] developed an analytical method for the treatment of fracture behaviors in composite propellants using non-linear fracture mechanics. In addition, a non-linear strain energy function was also investigated by the team. Study and experiments by Han Wang *et-al* [16] observed that particle sizes of AP have influences on the mechanical properties of the propellant. AP with smaller particle size is helpful to improve the tensile strength of the propellant, while AP with bigger granularity is conducive to the improvement of the propellant elongation. Xupeng Wang *et-al* [17] reported that mechanical strength of CMDB propellant with HTPB binder can be improved to a high level by adding chain extender and crosslinking agents. In characterizing fracture behavior of this propellant, linear elastic and linear viscoelastic fracture mechanics have met with some success. Schapery R A [18] reviewed recent work in the area, first for continuous crack growth and then for fracture initiation. A tentative nonlinear model for crack growth and failure is proposed. Approximate generalization to nonlinear elastic behavior, microcracking and its effect on overall mechanical response of a solid propellant has also been considered. Gazonas G A [19] modeled nonlinear viscoelastic mechanical response of a conventional tank gun using a “modified superposition integral” that incorporates the effects of microstructural fracture damage. Because of the viscoelastic nature of the polymer material constituting solid propellant grain, an accurate estimation of the stress and strain response is essential for structural integrity evaluation of the grains. Cantey D E [20] reported investigation of viscoelastic and failure properties of highly filled PBAA and PBAN propellants as a function of solids loading. Study of the relationship between crack propagation velocity and propellant physical characteristics are brought out. Thermomechanical response to sustained cyclic inertial loading was done experimentally, and the results were found to be in agreement with theoretical result. Chyuan S W [21] simulated the material and geometrical nonlinearities, a step-by-step finite element model accompanied by concepts of time–temperature shift principle, reduced integration and thermorheologically simple material assumption. Results show that the material nonlinear effect is important for structural integrity of solid propellant grains under higher surrounding temperature, and the differences between linear and nonlinear analysis results become more and more predominant as temperature increases. The effect of material nonlinearity is more predominant as compared to the effect of geometrical nonlinearity. Xu Chang Li *et-al* [22] studied the relationship between microscopic structure and mechanical properties of HTPB propellant. The experimental result indicated that the mechanical properties of a propellant are closely related to its microscopic structure state. The structural integrity of propellant is mainly influenced by the bond effect of the interface between binder and solid particles, solid particle’s shape, size and its distribution, the content of binder matrix, etc. Ying Wang *et-al* [23] studied the mechanical properties of single-chamber dual thrust grain on the interface of the two propellant grains. Results show that the interfacial mechanical properties are close to that of cast propellant. Chang J Dick *et-al* [24] demonstrated a testing technique for measuring the modulus of elasticity of propellant grains having low-modulus. The technique is simple and offers substantial advantages over the traditional dog bone testing method. More importantly, a biaxial stress field can be established in the test specimen to simulate conditions encountered during pressurization of solid propellant having nonlinear and viscoelastic property. It is concluded that, for nonlinear and viscoelastic material, results obtained through the uniaxial stress data of dog bone tests do not provide material characteristics under biaxial strain conditions.

Poisson's ratio is one of the most important factors that have the effect on the accuracy of the stress analysis of the solid propellant grain. It's value depends on the composition of the grains. It is often assumed, however, that the propellant is incompressible. Therefore Poisson's ratio takes the value of 0.5, especially at low strain levels. Poisson's ratio is evaluated experimentally by photographic method in National Aerospace Laboratory, Japan [25] at the room temperature and at the strain rate of 0.03 per min. Test results show that Poisson's ratio of the propellant has a value of 0.47+0.01 at the strain level up to 10%, and then the ratio decreases gradually because of the dewetting phenomena. Kohsetsu Y [26] proposed a simplified method for generating a structural vibration model of a solid-rocket motor. Here Poisson's ratio of solid propellant was taken as 0.5 considering it incompressible. Subsequently the ratio found to be less than 0.5. Chyuan SW [27], [28] carried out an investigation on solid propellant grains considering the effect of Poisson's ratio variation under ignition pressurization. In order to simulate the time–temperature-dependent behaviour of viscoelastic polymer materials for a range of Poisson's ratio values, the concepts of a time–temperature shift principle and reduced integration were used. In addition, eight different Poisson's ratio values from 0.47 to 0.4999 were assumed and compared using the finite element method. However, this assumption has not been agreed by Shekhar H *et-al* [29]. The team observed that numerical value of slope for variation of Poisson's ratio with strain almost doubles after dewetting. Composite propellants behave as compressible material in most of the regions and near-failure region or at higher strains. Poisson's ratio under various strain rates have been analysed and found to be close to 0.25. The team also reported that [30] shear modulus is one of the most important mechanical parameters of viscoelastic materials, and it is widely used in 3-dimensional stress and strain calculation and strength analysis, but it is very difficult to be obtained directly from the experiment. Considering ill effects of stress in solid propellant, Milos P [31] in his paper presented a specific methodology minimizing stress and strain without compromising its performance. The experiment has been conducted in a star shape solid propellant. Kai Deng *et-al* [32] discussed a new method to study the viscoelastic properties of solid propellant. He carried out the feasibility study and process of shear relaxation experiments at different temperature and obtained shear modulus. Bohua Z [33] analyzed Poisson's ratio of modified double base propellant in the concept and meaning of elastic and viscoelastic material. The integral equation between the tensile stress relaxation modulus, volume relaxation modulus and viscoelastic Poisson's ratio are derived. A method of calculation for the numeric integral for solving Poisson's ratio is obtained. The results are publisher in the [34] paper is of practical significance to grain structural integrity analysis and computation of solid rocket engines.

The importance of crack propagation in solid rocket motors is widely recognized. When cracks occur, the stresses near the crack tip will be redistributed according to nonlinear material behavior. This significantly alters the performance of the rocket. Jung G D *et-al* [35] developed a three dimensional nonlinear viscoelastic constitutive model the validity of which is extended to three-dimensional cases. Large deformation, dewetting and cyclic loading effects are treated as the main sources of nonlinear behavior of the solid propellant. Viscoelastic dewetting criteria is used and the softening of the solid propellant due to dewetting is treated by the modulus decrease. The nonlinearities during cyclic loading are accounted for by the functions of the octahedral shear strain measure. The constitutive equation is implemented into a finite element code for the analysis of propellant grains. However, the processes of crack propagation and branching in burning solid propellants are not as yet well understood [36]. It is important to know whether the flaw, which can take form as a crack or fracture (a volume between two propellant surfaces) or a debond (a volume between propellant and liner), will propagate or simply burn out after it ignites. Miller T C [37] suggested that engineers responsible for predicting solid rocket motor performance and ensuring reliability know that during manufacture, transport, and storage, cracks may appear in the propellant that threaten this reliability. Structural analysis shows the critical loads for the cracked motor, and testing of specimens determines the tendency of the material toward crack growth initiation, as well as subsequent growth rates. The measurement of crack growth rates in propellant is complicated by nonhomogeneity of the microstructure and by time-dependent behavior. The crack growth is affected by local microstructure, so that growth does not increase uniformly with load. Instead, the crack growth is sporadic, reacting to local stresses and strains in the microstructure; crack growth may even stop at some points during the test. Also, the high ductility of the viscoelastic matrix causes large dimensional changes, resulting in crack tip blunting and damage zones near the crack tip that deviate from the mathematical ideal of an infinitely sharp, well-defined crack. Another source of difficulties is that material properties often vary among specimens because of trouble maintaining uniformity during processing of large grains, resulting in high statistical scatter in measurements when compared with other materials. Moore J C [38] evaluated stress relaxation test data for the structural analysis of propellants and other polymer materials used for liners, insulators, inhibitors and seals. The stress relaxation data is examined and a new mathematical structural model is proposed which has wide application to structural analysis of viscoelastic materials. Hood C *et–al* [39] made predictive analysis of whether the crack will propagate, and to what extent it will propagate, can be made by calculating the pressure distribution inside the burning flaw and then the resultant stress/strain field generated in the solid propellant. The work described focused on studying the gas dynamic behavior inside a simulated solid propellant flaw using a computational fluid dynamics approach. In this effort, a finite-volume, density-based Navier-Stokes solver called Loci-CHEM was used by the team. The code replicated experimental results with reasonable accuracy and showed little sensitivity to grid resolution and gas properties assumptions. Work of Knauss W G [40] addressed the failure behavior of propellant through crack propagation. The objective of the study was to develop the means for measuring large deformation fields around the tips of stationary or slowly moving cracks, to develop realistic data for comparison with improved analytical results, and to initiate a new computational approach for stress analysis of cracks at and near interfaces, which can draw on the expanding capabilities of parallel processing. Important results are strain nonhomogeneities are much more pronounced than hitherto anticipated. They are associated with the granular microstructure and are characterized by spatial variations on the sub-millimeter size scale. These strain nonhomogeneities dominate the deformation field around a crack tip and control the fracture process. The author [41] also reported results of research addressing the failure behavior of bonded materials at and near the interface in support of structural integrity methodology of the failure response of solid propellant rocket motors under storage and operating conditions. Experiments determined the propagation of a crack away from an interface and established the direction and onset of crack propagation. It is concluded that a true fracture problem is a mix between small and large deformation formulations. These formulations depend on how large the growth steps of crack propagation are relative to the size of a small zone of nonlinear material response around the crack tip vis-a-vis the region of relatively small strain farther from the crack tip. Post D *et-al* [42] suggested that the near tip behavior of crack**s** in solid propellant material during opening and extension of the crack needs to be quantified experimentally. Hertzler C M [43] conducted experimental study on propagating crack in a viscoelastic material. By applying an extension of the 'correspondence principle' the stress and displacement at the crack tip were found as functions of the crack tip stress intensity factor. Fracture characterization was then performed by experimentally relating the crack tip stress intensity factor to the crack velocity. The theory was applied successfully to solid propellant fracture tests. Development of crack found to influence combustion process.

Kuo K K *et-al* [44] presented a study report establishing that the ignition front propagates from the entrance of the crack to the tip. However, under rapid chamber pressurization rates (100,000 atm/s or higher), the tip region of the crack was observed to ignite before the arrival of the convective ignition front. A theoretical model has been developed to explain the tip ignition phenomena. The model considers: a one-dimensional transient heat conduction equation for the solid phase; and one-dimensional, unsteady mass and energy conservation equations for the gas phase near the crack tip. Both experimental and theoretical results indicate that the ignition delay time decreases as the pressurization rate is increased. Ju F D *et-al* [45] investigated mechanism for solid propellant hazard. That mechanism is a consequence of friction from a running antiplane crack propagating in its own plane. When a continuum that contains a crack is subjected to an applied load at some oblique angle to the face of the crack, then the load may be resolved into a shear stress and a normal stress. The normal stress causes friction at the crack surface that resists further growth of the crack while the shear stress provides the driving force for crack growth. It follows that for given crack characteristics and given load, the kinematics of the crack depends on the crack orientation with respect to the load. Continuous displacement in the antiplane direction will occur provided the shear stress is sufficient to cause the crack growth. Under the conditions of continuous crack growth the friction energy will depend upon the normal pressure. There may be combinations of applied load and crack orientations, which will lead to a deflagration to detonation transition (DDT) of the propellant. Kim K [46] made selective calculations for burning in cracks of solid rocket motor propellants. The possibility of obtaining pressures high enough to cause a shock-to-detonation transition (SDT) in propellant grains is examined. Variables affecting the crack combustion process which were selected for study are: crack shape; location; surface roughness; propellant deformation; ignition criterion; and burning rate. The variables are evaluated and ordered in groups of relative importance. Results suggest that SDT should not occur in propellants unless the granulation of the grain is severe enough to provide large burning surface area.

Present day high energy propellants are often more frangible than their predecessors and physical properties are now found, in many cases, to exert an inordinate effect on combustion. New failure modes are believed to be able to contribute to DDT. Prentice J L [47] presents a study report to reduce the problem of convective combustion in porous charges and other grain defects to its ultimate simplicity (viz., the single pore), and then proceeds to reconstruct the more complicated geometrical and combustion situations leading to the porous bed or highly cracked (i.e., spider web) propellant. Flashdown (one of the more dramatic types of convective combustion), may be defined as runaway combustion rates (and pressure) associated with flame propagation into grain defects such as ducts, fissures, annuli, pores, etc. This type of anomalous combustion leads to flame spreading rates many orders of magnitude greater than normal. Pressures and pressurization rates exceeding design limits are common where such phenomena occur. Local damage near the crack tip in a solid propellant under a constant strain rate at room temperature, using pre-cracked biaxial strip specimens has been investigated by Liu C T [48]. The results indicated that, on a macroscale, the material can be considered a continuum, and plane strain fracture toughness may not exist for it. In the highly strained region at the crack tip, material may be damaged and voids may develop and the crack can grow by the coalescence of the voids with the crack tip. The crack-damage interaction is a contributing factor to the fluctuation of the crack growth behavior. It is experimentally found that crack tip blunting occurs during the loading process, and that crack growth consists of a blunt-growth-blunt phenomenon that appears to be highly non linear. The author investigated [49] the change of microstructure and the formation of cracks in a solid propellant under an incremental strain loading condition using digital radiography x-ray techniques. Experimental findings revealed that the degree of nonhomogeneity of the material's microstructure and the number of non-propagating cracks increased as the applied strain was increased. The author [50] also reported the results of research addressing cumulative damage and crack growth behavior in a solid propellant and interfacial fracture of bi-material bonded systems. The program's basic approach involves a blend of analytical and experimental studies. In general, mechanisms and mechanics involved in cohesive fracture in the solid propellant and adhesive fracture in the bi-material bonded systems are emphasized. The results of both analytical and experimental analyses are evaluated and discussed. Investigation of the local behavior near the crack tip and the crack growth behavior in a composite solid propellant containing hard particles in a rubbery matrix, under various loading conditions was done [51]. In the study, three temperatures (347 K, 295 K and 219 K) and two crosshead speeds (2.54 mm/min and 12.7 mm/min) are considered. Experimental results reveal that the local behavior (blunting, voiding, coalescing and growing) are the same, differing only in a quantitative sense. Crack growth occurs through a blunt-growth-blunt-growth mechanism of extension which is highly nonlinear. Experimental results also reveal that the effect of crosshead speed on crack behavior is considered small relative to that of temperature.

Yeu Cherng Lu *et-al* [52] reported formulation of transient combustion processes inside a solid-propellant crack cavity and proposed to solve it numerically. Parametric study investigating the effect of several physical properties on the initiation of fracture was also carried out. It was found that, fracture initiation is very sensitive to the magnitude of pressure exponent of the propellant burning rate. To estimate the initial crack propagation angle, Zhi Shi-jun *et-al* [53] reported use of maximum tangential stress criterion and the maximum energy release rate criterion. J integral criterion (J_{Ic}) has also been introduced to estimate the initiation of crack propagation. Results show that, the initial crack propagation angle can be calculated more accurately, considering the crack tip shape's influence. Fracture process of solid propellant can be effectively simulated with multiple expanded step circulation calculation method and cohesive element. Abdelaziz M N *et-al* [54] proposed an experimental method for fracture characterization of solid propellants. Regarding non linear behavior of such material, investigation is kept restricted to high loading rate conditions and J_{Ic} fracture criterion is computed. Results are then analysed and special attention is given to validity of Linear Elastic Fracture Mechanics (LEFM) assumptions in this case. Fracture tests on solid propellants have been performed under three ranges of loading rate leading to fracture toughness results in terms of J_{Ic} and $\tilde{J}c$ (Andrews' parameter). Using two different specimen shapes, finite size effects have been pointed out (considering SENT sample) when dealing with Andrews' theory and a modified equation, taking into account the specimen compliance, is proposed [55]. The importance of fracture criteria in the failure assessment of solid propellant grains is described by Rao B N [56]. Computation of the crack tip stress intensity factor and the development of the crack growth rate equation through fracture properties essential for fracture analysis are also brought out. Rao S *et-al* presented test results [57] of compact tension (CT) specimens for fracture toughness evaluation of nitramine (in extruded and slurry cast conditions) and composite solid propellants. For notched strength evaluation of cracked configurations, failure assessment diagram is generated utilizing the inherent flaw model. The team reported that testing of the specimens needs specialized facilities to avoid open-up the crack even before commencement of actual test. Therefore, a non-contacting type extensometer was employed. Fracture toughness of the extruded nitramine propellant is found to be higher, compared to those of slurry cast nitramine and composite propellants. Rao A S *et-al* [58] made an attempt to correlate the fracture data of center crack tension specimens made of nitramine and HTPB-based propellant materials. The analysis results from the well-known inherent flaw model as well as in the stress fracture models are found to be in good agreement with test results. The study confirms the applicability of the above fracture models to solid propellant materials having relatively low stiffness and strength. These models have been proposed for use [59] to generate a failure assessment diagram to predict notch strength. Since the notched strength estimates of composite/solid propellant tensile specimens are close to the test results, any one of them has been recommended to be utilized while evaluating the notched tensile strength of specimens.

Kalaycioglu B *et-al* carried out a study [60] in which three-dimensional modeling of extrusion forming of a double base solid rocket propellant is performed on a commercially available finite element analysis program. Considering the contact effects and the time dependent viscous and plastic behaviour, the solid propellant is assumed to obey the large deformation elasto-viscoplastic material response during direct extrusion process. The deformed shape, hydrostatic pressure, contact stress, equivalent stress, total strain values are determined from the simulation in order to get insight into the mechanical extremity that the propellant has undergone during processing. Papakaliatakis G [61] studied the stress and displacement fields in the problem of the fracture of an orthogonal plate made of a solid propellant containing only a crack or a crack and a circular hole or a crack and a circular steel inclusion. The specimens are subjected to a uniform displacement along its upper and lower faces. The solid propellant was simulated as a hyperelastic material with constitutive behavior described by the Ogden strain energy potential. A nonlinear finite-deformation analysis was performed based on the finite-element code. A very detailed analysis of the stress field in the vicinity of the crack tip was undertaken [62]. The results of stress analysis were coupled with the strain energy density theory to predict the initiation of crack growth as a function of the distance of the crack tip from the hole or the inclusion and the normal distance of the hole or the inclusion center from the crack axis.

Xu F *et-al* [63] proposed a general 3-D nonlinear macroscopic constitutive law that models microstructural damage evolution upon straining through continuous void formation and growth. The law addresses the viscous deformation rate within the framework of additive decomposition of the deformation rate and the concept of back stress is used to improve the model performance in stress relaxation. Experimental data from the standard relaxation and uniaxial tension tests are used to calibrate the model parameters in the case of a high elongation solid propellant. The model is used to predict the response of the material under more complex loading paths and to investigate the effect of crack tip damage on the mechanical behavior of a compact tension fracture specimen. Sih G C [64], [65] assessed the time dependent nonhomogeneous deformation and possible failure modes. Only initial properties of the materials were used to determine the evolution of nonequilibrium response. The isoenergy density theory that accounts for internal heat generation and energy dissipation effects has been used. Results of the experiments are presented in two parts. In Part 1, equal stress rates are applied in both the longitudinal and transverse direction while Part II different stress rates in these two directions are applied. At approximately one second after loading, a slanted but straight macrocrack occurs in the rubber next to the interface. This initial crack was found to become unstable at eight seconds and was estimated to be close to the adhesive/rubber interface. The onset of fracture depended directly on the load transient behavior.

Traditionally, the transient analysis of solid propellant grains subjected to ignition pressurization loading was not considered, and quasi-elastic–static analysis was widely adopted for structural integrity because the analytical task gets simplified. To experiment the dynamic response of solid propellant Chyuan S W [66] simulated a transient finite element model, accompanied by concepts of time–temperature shift principle, reduced integration and simple material assumption thermorheologically. For studying the dynamic response, diverse ignition pressurization loading cases were used and investigated. Results show that the dynamic effect is important for structural integrity of solid propellant grains under ignition pressurization loading. From the work of quasi-elastic–static and transient analyses, the dynamic analysis highlighted several areas of interest and a more accurate and reasonable result could be obtained for the engineer.

A statistical approach has been developed to model a multiple-shock experiment by Mulford *et-al* [67] to examine the dynamic response of brittle materials by superimposing the effects of a myriad of microcracks. The superimposing included opening, shear, growth and coalescence, taking as a starting point the well-established theory of penny-shaped cracks. The effects of crack orientation and temperature dependence of viscosity of the melt on the response have been examined. Numerical results confirmed the theoretical finding by Zuo Q H *et-al* [68] that crack orientation has a significant effect on brittle behavior, especially under compressive loading where interfacial friction plays an important role. With a reasonable choice of crack orientation and a temperature-dependent viscosity obtained from molecular dynamics calculations, the calculated particle velocities compare well with those measured using embedded velocity gauges.

The burning rate of a solid propellant is affected by its initial temperature. Michael T *et-al* [69] expressed the sensitivity of burning rate to propellant temperature in the form of two different temperature coefficients. The one coefficient describes the effect of temperature on the burning rate in a constant pressure environment, while the other describes the effect of temperature on the pressure (i.e. thrust) of a solid rocket motor. It has been assumed in past derivations that the two coefficients could be related quite simply for the situation in which all of the temperature effects were lumped into a variation of a single constant. However, that assumption is claimed to be incorrect by the team.

With aging, mechanical properties of solid propellant degrade. Manfred A B *et-al* [70] found that ageing mechanisms of composite propellants are: after-curing, chain rupture by mechanical overload during temperature cycling, oxidative hardening together with loss in strain capability, oxidative chain scissioning, dewetting between particulate fillers (especially AP) and binder matrix. The accelerated ageing range was between 333 K and 363 K with ageing times adjusted to a thermal equivalent load of 15 to 20 years at 298 K was considered. The investigations revealed distinct changes in the shape of the loss factor curve. Detailed analysis of the shape of the loss factor showed that three parts of molecular rearrangement types can be identified during the total transition of the material from energy-elastic to the entropy-elastic state. The results showed a complex change in soluble or extractable polymeric binder part. Both cross-linking and to some part also chain scissioning occur, which could be recognized by the changes of the molar mass distribution functions of the extractable binder part. Kishore K *et-al* [71] studied ageing behaviour of AP propellant leading to ballistic. It follows a zero-order kinetic law. Ageing behaviour leading to change in burning rate in the temperature range of 333–473 K was found to remain the same. The dependence of the change of the average thermal decomposition (TD) rate at 500 K and 530 K on the change in burning rate for the propellant aged at 373 K in air suggests that the slow TD of the propellant is the cause of ageing. The safe-life at 300 K in air has been calculated in the study as a function of the rate of change. Shekhar H [72] reported variation in various mechanical properties with time. For composite propellant, tensile strength increases where as percentage elongation reduces. Initial modulus is also found to decrease with time. To determine the effects of aging of a solid propellant Yildirim H C *et-al* [73] used finite element method. The results of the experiment can also be used to estimate the service life of the motor. The analyses are performed for both newly manufactured and aged propellants. Thermal and pressure loadings occurring during the shipping, storing and firing are considered to be the most critical in determining long-term behavior of the motor. Maximum hoop strain at the surface of the propellant and bond stresses at the interface between the liner and the insulator are evaluated as indicators of cracking in the propellant grain and debonding at the liner–insulator interface. Suceska M *et-al* [74] carried out work to evaluate the mechanical changes of composite solid propellants induced by natural ageing due to storage up to 35 years. The mechanical and viscoelastic properties were tested using a dynamic mechanical analyzer, a uniaxial tensile and compression tester, and a notch toughness tester. The results have shown that the changes of the studied mechanical and viscoelastic properties are evident, although the results of the tests are rather scattered (as a consequence of measuring uncertainty, different ageing histories of propellants, etc.) or changes of some properties are not too pronounced. Along with these tests, the stabilizer content determination and proving ground ballistic tests were also done. Baron D T *et-al* [75] performed uniaxial tension tests using a strain rate of 0.04./min on rectangular smooth and single edge-notched specimens of varying thicknesses for a composite solid propellant. Stress, strain, crack growth, crack growth rate and crack growth resistance data are obtained. Methods of calculation are explained for the crack growth rate and the Mode 1 stress intensity factor. A model is developed for the crack stable growth rate as a function of the stress intensity factor.

Zalewski R *et-al* [76] attempted to the experimental analysis of viscous effects and characteristic for homogeneous solid rocket fuels. Research schedule involved destructive tensile tests with various strain rates. Three different values of strain rates have been taken into consideration. Based on obtained results, authors confirm the viscoplastic behavior of studied materials. Acquired results are the base for the further investigations of physical properties of homogeneous solid propellants. Liu C T *et-al* [77] predicted the initial crack length near the edge of the hole in solid propellant specimens using micro-macromechanical approach. The approach was based on a simplified micromechanical model, damage mechanics at the micro-level, and finite element analysis at the macro-level. Micromechanical and macromechanical analyses were conducted in tandem. The developed technique together with a mechanistic criterion was used to predict the initial crack length in high stress regions. The criterion was based on the instability of the damaged material just ahead of the crack tip. Durelli A J *et-al* [78] proposed experimental stress analysis method and dealt with three-dimensional photoelastic determination of stresses in a split cylinder bonded to a case. The loading of the model is due to restrained shrinkage. The results obtained would be important data in designing solid propellant grains. Shekhar H *et-al* [79] proposed Maxwell fluid model for viscoelastic modeling of case-bonded composite propellants to generate stress strain curve. With developed formulations, complete stress-strain curve is generated even for those strain rates at which actual testing is not possible in uniaxial tensile testing. Zalewski R *et-al* [80] revealed basic response of solid rocket fuels to different working conditions such as variable strain rates or temperature. Experimental data acquired during experimental tests is a base for development of a suitable constitutive model for homogeneous solid propellants. The work is devoted to modeling of nonlinear properties of solid propellants. In particular, the influence of temperature and strain rate parameters variations is discussed.

Lancelle D *et-al* [81] proposed two steps method to test mechanical properties. In the first step, different samples of the propellant grains are tested under high acceleration and analyzed by a visual check. In the second step, onboard electronics mounted on the piston are developed to collect the data of the strain and the deformation of the composite/fuel grain and to directly measure the acceleration. With this electronically enhanced specimen, another test is carried out, and measurement data are acquired. The main issues in service life prediction of solid rocket motors are the lack of a fundamental understanding of crack growth behavior under service loading conditions and a reliable methodology to predict crack growth. The main technical challenges are microstructural effects on damage initiation and evolution, large and time dependent deformation, short crack and stress raiser interaction, and multi-layer structures with time-dependent material properties and property gradients. Liu C T [82] studied nonlinear viscoelasticity, fracture mechanics, experimental mechanics, damage mechanics, nondestructive testing and evaluation, and numerical modeling techniques of solid propellant. These research studies address a number of important subjects such as cumulative damage and crack growth behavior in solid propellants [83], statistical nature of crack growth, and bonded interface failure.

III. PROPELLANT FAILURE MODES

A CMDB propellant with HTBP binder which is suitable to propel the rockets of MBRL above 200 mm calibre has been considered to analyze likely failure modes. Compositions and properties of the propellant [84] are as under:

1) Composition

(i)	AP	66 ± 1%
(ii)	Al	19 ± 1%
(iii)	$Fe_2 O_3$	2 ± 1%
(iv)	HTPB	13 ± 1%

2) Physical Properties

(i)	Tensile Strength	> 10 kg/cm^2
(ii)	% Elongation	>10
(iii)	Density	> 1.76 gm/cc

3) Thermal Properties

(i)	Calorific Value	1500 kcal/gm
(ii)	Burning Rate at 27^0 C	10 ± 0.3 mm/sec

Main cause of mechanical failure of solid propellant is initiation and propagation of crack. Likely causes of mechanical failure of solid propellant can be broadly categorized into six modes.

A. *Thermal Cycling*

This occurs during storage and transportation when the ambient temperature changes.

B. *Handling and Transport Vibration*

Shock and vibration up to 5- 30g may be generated due to improper handling and during road transport at 5- 300 Hz (may go up to 5 - 2500 Hz for air transportation).

C. *Ignition shock and Pressure Loading*

With end burning grain severe axial pressure differential is experienced.

D. *Launch, flight acceleration*

Axial inertial load is experienced and shear stress is developed at bond line during launch and in flight acceleration.

E. *Flight Maneuver*

High speed maneuver during flight of rocket causes unsymmetrical stress distribution.

F. Environmental Condition

Free stand grains are assembled at 300 K. During its storage and deployment at sub zero temperature, the grains contract and severe compressive stress is developed. Debonding between inhibition and propellant takes place if difference of thermal coefficient of expansion of two materials is more and bond strength is weak.

IV. MECHANICAL STRENGTH

There are primarily two objectives of using inhibitor with propellant [85]. It ensures no burning of the inhibited area and thus leads to controlled burning (end burning, internal burning or external burning) as per requirement. It also protects the rocket casing which otherwise would have exposed to hot propellant gases. Hence bond strength within the propellant and between the propellant and inhibitor material is very important parameter to control mechanical failure. Here mechanical strength of the propellant has been analysed in terms of bond strength and tensile strength using INSTRON Universal Testing Machine [86].

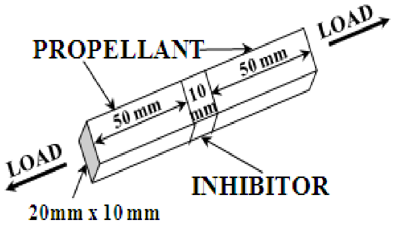

Fig. 1. Bond strength test specimen.

A. Bond Strength

A sample of CMDB propellant (size 50mm x 20mm x 10mm) duly inhibited and cured at the central position as shown in Fig. 1 is considered. Breaking load of 228 N is applied during the test.

Sample Calculation

Bond Strength = Breaking Load/Cross Sectional Area

= 228 N / 200 mm^2

= 1.14 MPa

B. Tensile Strength

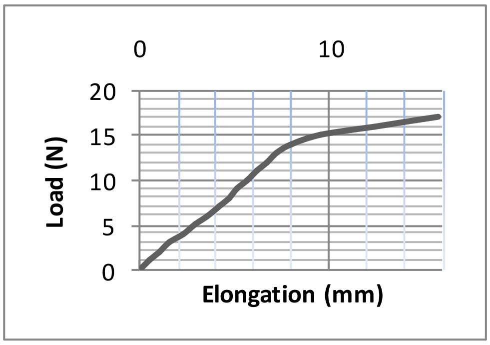

Fig. 2. Load elongation plot.

A dog bone shape CMDB propellant sample as per ASTM specification (cross sectional area of 24.098 mm^2) is considered with initial length 45mm. Axial load 0 – 17 N is applied to the specimen in universal testing machine and elongation against each load is noted. Elastic limit is observed up to the load of 13 N at 7.26 mm elongation. Hence elastic modulus is calculated at this load. Ultimate load is observed at 17.7 N when necking commences. So ultimate tensile strength is calculated at 17.7 N load. The Load-Elongation curve is plotted for calculation of elastic modulus and ultimate tensile strength. The same is given in Fig. 2.

Sample Calculation

Elastic Modulus [87] = Engg Stress/Engg Strain

Engg Stress = 13/24.098 = 0.539464 MPa

Engg Strain = 7.26/45 = 0.161333

Elastic Modulus = 0.539464 / 0.161333 = 3.3438 MPa

Ultimate Tensile Strength (UTS)

= Ultimate load/Initial cross-sectional area

= 17.7/24.098 = 0.7345 MPa

C. Analysis and Discussion

If the failure occurs at the interface of the inhibitor and propellant, the failure is termed as adhesive failure. Such failure indicates poor bond strength and is not expected. For safe design the bond strength should be more than the ultimate tensile strength of the propellant to avid failure (called cohesive failure). This is because various parameters are designed based on UTS. Any strength beyond UTS will not be the cause of failure. Here, the bond strength is 1.14 MPa where as the propellant UTS is 0.7345 MPa. Hence the bond strength is 55.2 % more than UTS ensuring no failure due to debonding.

V. CONCLUSION

Tacticians always demands for maximum damage of the target when the rocket is launched. One way of achieving it is by improving the internal ballistic performance. However, reliability, service life, operating temperature, requirements of handling, transportation and storage is also important parameters for its desired performance. In the world literature there is still insufficient information about typical mechanical features for considered materials used as propellant as well as various components of rockets. This may be because of secrecy due to military intelligence and security of the respective countries. Hence, universal standards for carrying out typical strength experiments have not yet been fully elaborated for this type of materials. Such problems as quasi-static strain range for solid propellants or so called scale effect are still not yet standardized. It is emphasized that the model parameters are descriptors of individual phase constitutive response and criticality conditions for particle decohesion which can systematically be determined through experiment. The interface between a soft and a hard material is vulnerable to debonding because of the prevailing high stress gradient that could be further aggravated under dynamic transient conditions. Such a situation is common in a solid-fuel rocket motor where unstable debonding could be triggered from the initiation of a macrocrack near the interface.

The transition from a survival state to a failure state requires knowledge of how the nonlinear, dissipative and nonhomogeneous effects of the dissimilar material interface would interact with load. For safe design and to ensure no failure due to debonding adequate bond strength is necessary. It is observed that bond strength should be more than the UTS of the propellant material for safe design of rocket. This criterion is satisfied in the present case for the CMDB propellant. This is one of the reasons that this propellant is considered globally for the potent area weapon Multi Barrel Rocket Launcher. CMDB is the most suitable propellant for MBRL as it suits the military requirements brought out earlier. It also provides better solid loading performance thus easy to manufacture. Various desirable physical and chemical properties of this propellant can be tailor made by altering the quantities of various ingredients including the binder. It provides good and wide range of burn rate together with stable combustion. It meets the requirements physical properties for military applications. Raw materials of the ingredients are easily available locally thus making CMDB as one the most economically viable solid propellants for MBRL.

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