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Technical Advisor
Space and Missile Propulsion Division

Crack Growth Data Collection and Reduction Methodology Survey

T. C. Miller
Air Force Research Laboratory

April 18, 2001

1 Introduction

Engineers responsible for predicting solid rocket motor performance and ensuring reliability know that during manufacture, transport, and storage of motors, cracks may appear in the propellant that threaten this reliability. When they discover cracks, engineers use fracture mechanics principles to assess the crack stability. 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 inhomogeneity of the microstructure and by time-dependent behavior. The local microstructure affects the crack growth, 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 rocket grains, resulting in high statistical scatter in measurements compared with other materials.

Inhomogeneity of microstructure, large deformations, and lot variations contribute to a large amount of scatter in crack measurements. This scatter is also manifested in the growth rates, which are time derivatives of the growth data. Some scatter in the growth rate data is inherent because it is a measurement of true variability in the instantaneous crack growth speed. However, the experimental method and the method of determining the time derivatives affect the variability. Researchers have tried to get the best possible results by using various specimen geometries, measurement procedures, and analysis techniques. This study examines the state of the art in propellant crack growth measurement and analysis so that subsequent efforts can improve the uniformity of the process between government and industry groups. This will result in better predictions of growth rates in structures, giving higher reliability and cost savings to industry and government participants. ^{this} The survey incorporates information obtained through communications with JANNAF members involved in these activities and summarizes their experiences.

2 Crack Size Measurement Methods

2.1 Specimen Geometries and Test Procedures

One common factor in most of the test methods was the use of constant strain rates, [1, 2, 3, 4, 5, 6] This may be a result of the use of screw-driven testing machines designed for constant displacement rate tests. Many test procedures also employ thin specimens, although no standard specimen geometry exists. The use of thin specimens helps ensure that the crack growth measurements, which are generally made on the specimen surfaces, represent the actual crack size (thicker specimens might have nonuniform crack fronts).

The most common specimen geometry is shown in Fig. 1a, and is often called the biaxial test specimen.[3, 5] The reason for the frequent use of this specimen geometry is that the lateral constraint imposed by the material on either side of the crack produces an approximately biaxial stress condition (i.e., σ_{xx} and σ_{yy} are about equal), simulating conditions that may be experienced in the actual solid rocket motor. One significant problem noted by several researchers is that the use of a centrally located crack gives two crack tips that initiate at slightly different times and grow at different speeds.[3, 5] Engineers may measure either the total crack length or the two half-crack lengths. The difference in propagation speeds at the two crack tips could be due to problems with the test setup (for example, a small misalignment of the specimen in the load path), but is also caused by the material inhomogeneity. There is no way to distinguish between the two causes. The uneven crack growth then results in an asymmetrical geometry that makes analysis difficult. These complications are not present when edge cracked specimens are used, but the advantage of near biaxial constraint is then lost. Specimens with a single crack tip, such as the single edge notched tension specimen (see Fig. 1b) have been used, but introduce another complication.[6] This is that as the crack growth proceeds the specimen halves rotate with respect to their initial orientation. This rotation can be prevented with special fixtures (e.g., Fig. 1c), but the fixtures themselves, in providing additional constraint, may induce inaccuracies in the load measurements, especially at the low load levels experienced in solid rocket propellant tests.

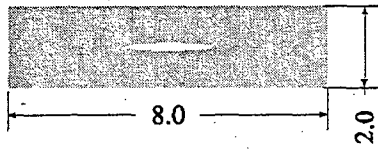
Other specimen geometries^{face} used and are based on subscale motors, but are specific to the particular motor in question and so may not be useful as an industry standard.[2] It seems that researchers use the biaxial specimens the most, but were uncomfortable with the dual crack tips, and were open to specimen geometries that avoided this complication.[3, 5]

2.2 Measurement of Crack Size

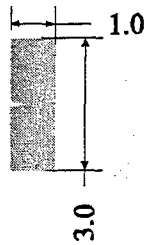
Given the lack of uniformity in specimen geometry choices, it is not surprising that engineers use several ways to measure the crack size. Characteristics common to most programs were the use of surface measurements and the indirect measurement of this crack size through videotape (or film) equipment.[1, 2, 3, 4, 5, 6] Researchers generally used video cameras to record the images of the crack growing on the surface of the specimen during the test. Later, after the test, they measured the images of the cracks, scaling the measurements by some reference length in the image. This method of measuring the crack size has several advantages: it is simple and requires no specialized equipment. There are several disadvantages, however. One difficulty is that to measure the crack size from the videotape, the entire crack must be visible in the field of view, limiting the magnification and reducing the maximum resolution of the measurements. Additionally, researchers also need to measure crack sizes during high strain rate tests of short duration (less than one second), and the use of conventional video equipment is not feasible because of the limited time resolution (thirty frames per second). The use of high speed film or videotape equipment solves this problem, but may not be available to many researchers because of equipment costs. Another drawback is that investigators must make the measurements manually, which introduces subjectivity into the process, and makes the process laborious and time intensive.

Engineers either measured the videotape images directly from a television screen or monitor or downloaded them as image files onto a computer and measured them with imaging software. It is not known which of these procedures is more accurate, but there are not any substantial differences in cost or convenience. Another surface measurement technique was the use of a transparent plastic sheet with grid lines, which was placed over the specimen before testing as a ruler for crack size measurement.[4]

Two of the methods reported were not surface measurements. One researcher reported both methods and has used them in subscale motor tests.[2] During such a test, crack growth is complicated by the geometry, and the use of thin specimens is not possible. Both measurement methods (the use of colored dyes and the use of a card inserted into the crack mouth) required access to the mouth of the crack during the test, and were manual procedures that limited the number of measurements that could be taken during a test. These methods would not be feasible during high speed tests, either, due to time required to take the measurements.



a) Biaxial Test Specimen



b) Single Edge Notched Tension Specimen



c) Displacement Control Fixture

Figure 1: Specimens and Fixtures Used in Propellant Fracture Testing

However, both methods could measure crack sizes without direct observations of the specimen surface, and should be considered useful in subscale tests. The colored dyes were used in subscale motor measurements, and a set of three dyes was used, so that only three measurements could be obtained. The other technique involved inserting a thin card into the mouth of the crack until resistance was felt. The depth to which the card had been inserted was used to infer the crack depth. This method would not measure a non-planar crack face well, so the use of dyes would give a better understanding of the cross-sectional profile, but the card method could be used repeatedly during a test.

2.3 Time Increments for Measuring Crack Size

For the most part, researchers did not report any typical time increment for sampling crack size. However, as one researcher showed, an optimal time interval does exist for any given set of data.[1] This depends, of course, on the rate at which the loads are applied. Using the optimal time interval minimizes the error for any given data set. In general, engineers used constant time intervals during the measurement process.

3 Method of Determining Crack Speed

Most of the researchers interviewed used the crack size vs. time measurements to deduce crack speed.[1, 3, 4, 5, 6] In one case, the crack size vs. time was used to determine the crack length at any particular time in a motor, and crack speed was never an issue.[2] Otherwise, the consensus was to determine crack speed and to relate crack speed to a fracture parameter such as K , the stress intensity factor, through a power law:[1, 3, 4, 5, 6]

$$\frac{da}{dt} = CK^m \quad (1)$$

Here a is the crack size, t is time, K is the stress intensity factor, and C and m are parameters that depend on the material (they may also depend on other environmental parameters, such as temperature). Because of this, we need to calculate the crack speed from experiments so that the power law parameters can be found. However, it is worth noting that the power law predicts monotonically increasing crack speed with increasing loads, a situation realized in the aggregate data but not in any individual instance, because the crack speed varies due to inhomogeneity of the propellant (as discussed above). Although the power law does not capture the sporadic nature of the crack growth, it is useful as a prediction tool because it models the overall response of the propellant crack behavior with respect to loads.[1]

The most popular method for determining crack speeds from crack size data is the secant method.[1, 3, 4, 5] Crack speed is taken from two successive measurements as the ratio of change in crack size to the time increment:[4]

$$\left. \frac{da}{dt} \right|_{t=t_i} = \frac{a_{i+1} - a_i}{t_{i+1} - t_i} \quad (2)$$

Here crack size has been measured at many points in time and the crack speed at the i th point in time is based on crack size measurements at times $t = t_{i+1}$ and $t = t_i$. Advantages of this method are simplicity and ease of use and disadvantages are more scatter introduced into the crack speed measurements (for example, if no crack growth takes place between two successive measurements, a crack speed of zero is calculated). One slight modification was the "modified secant method," which assigns a crack speed to each point in time as the average of the two slopes on either side of the point:[4]

$$\left. \frac{da}{dt} \right|_{t=t_i} = \frac{1}{2} \left[\frac{a_i - a_{i-1}}{t_i - t_{i-1}} + \frac{a_{i+1} - a_i}{t_{i+1} - t_i} \right] \quad (3)$$

These two methods could be called "secant methods." Other methods, which could be called "polynomial methods," are more complicated but smooth the data more (although at the cost of reducing the true variabilities due to material inhomogeneities). These include the "incremental polynomial method" (also called the "spline fitting method") and the "total polynomial method." [4] With the incremental polynomial method, a third order polynomial is fit incrementally to different subsets of the crack size data with continuity requirements for first and second derivatives at the data points. The total polynomial method uses a single polynomial for each test, and has its coefficients determined through a least-squares procedure. The order of the polynomial is determined by examining the variances manifested by different orders.

4 Potential Sources of Error

When asked what the most likely sources of error were, researchers cited various possibilities. One common difficulty was the presence of two crack tips in the biaxial test specimen. [3, 5] Another source of concern was the accurate measurement of boundary conditions and loads. [3] The third set of possible error sources involved the measurement method itself; the crack sizes were difficult to measure because of the lack of a well-defined crack tip, there was concern that the surface measurements did not accurately characterize the crack size, actual crack speed variability made crack speed determination difficult, and there was the possibility of parallax [3] in measurements taken through sight windows in environmental chambers. The presence of dual crack tips is a feature of the specimen geometry, and some problems with measurements are difficulties caused by the measurement technique itself. With sporadic crack growth, the difficulties are an inherent part of the phenomenon of crack growth in a viscoelastic ductile material, and it is unlikely that the problems can be easily surmounted. Improvements, when possible, are left to the efforts of future researchers working in close collaboration with each other.

5 Summary and Conclusions

Cracks may form during manufacturing, storage, and use of solid rocket motors, and require researchers to derive predictions for crack growth. Processing difficulties, material inhomogeneity, and large scale deformations introduce complications into the determination of crack speeds, and measurement procedures have tried to compensate for these difficulties. Experimental procedures usually employ screw-driven testing machines and constant strain rates with thin specimens and crack sizes measured from the surface of the specimens. The biaxial test specimen was popular due to the similarity of the constraint to that of the actual solid rocket motor, but caused difficulties due to the presence of two crack tips. Other specimens have also been employed that have single crack tips, and analog or subscale test specimens have been used. Crack measurements were mostly surface measurements and were commonly taken after the test using stored video (or film) images. Other measurement aids included plastic grids mounted over the specimen, colored dyes sprayed into the crack mouth, and cards inserted into the crack. The consensus was that the measurement of crack sizes using videotape was the best overall method, and was accurate for thin specimens. One main difficulty was the laboriousness of the method, which does not lend itself to easy automation.

When analog test motors were being used as actual test specimens, crack speeds were not measured, but in all other cases the crack speed was an important measurement, since it could be related to loads through fracture parameters such as K . The crack speeds were determined from the crack size vs. time data using derivative approximations, the most common of which was the secant method, although researchers also used polynomial methods. Minor variations in these two classes of methods may offer some improvements and were preferred by some researchers. The secant method was the easier of the methods to use. Regarding time intervals used during the testing process, the investigator's judgment was commonly used, although other guidelines for time interval selection have been established. [1]

Possible sources of error fall into three categories: the presence of two crack tips in biaxial test specimens,

the use of idealized boundary conditions in fracture parameter calculations, and difficulties measuring the crack size accurately given that the crack tip is sometimes poorly defined and the interior of the crack front is not visible. Having surveyed the methods and procedures followed by researchers, it may be easier to arrive at a consensus as to the best method. Hopefully, this document will serve some collaborative effort to improve the measurement procedures. Also, having noted the common procedures and their pitfalls, future researchers can avoid some of these problems. The resulting improvements in crack tip measurement procedures should improve industry practice and accuracy in predictions, resulting in cost savings from improved confidence in crack growth predictions in solid rocket motors.

6 Acknowledgments

This report was written with the input from colleagues in both industry and government. As it is largely a summary of their experiences, it could not have been written without them, and their help is greatly appreciated.

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