Dynamic Finite Element Analysis of Solid Propellant Impact Test

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The objective of this dynamic finite element analysis (with the computer code DYNA) was to better understand the mechanism of the initiation of ignition in the drop weight impact test of rocket motor composite solid propellant. The analysis showed that the shear stresses in the solid propellant are concentrated at the upper and lower propellant surfaces just inside the edge of the propellant sample. These shear bands are caused by friction stresses at the sliding interfaces between the propellant, drop weight, and anvil. The friction stresses generate localized heat concentrations as the propellant extrudes radially. Thus, there is high concentration of heat energy at the shear-band locations where the compressive stresses are low. Three sources of energy contribute to the hot spots at these critical locations: 1) frictional energy, 2) distortional energy, and 3) ammonium perchlorate crystal fracture. Frictional energy alone is sufficient to ignite the solid propellant. These analytically predicted hot spots are in agreement with experimental results that show that ignition occurs in the high shear stress bands near the edge of the specimen and not in the high compressive stress region at the center of the specimen.

Introduction

THE drop weight impact sensitivity test is a small-scale laboratory test for investigating the mechanical initiation of ignition in rocket motor composite solid propellant. The test uses a drop weight machine in which a metal weight falls a measured distance, guided by vertical rods, and impacts on a propellant sample that is on a metal anvil. A typical test setup is illustrated in Fig. 1. Typical sample dimensions are 0.25-in. diam and 0.015-in. thickness. A drop weight of 4.4 lb falling 13 in. will cause ignition in composite solid propellant at about 100–120 μs from initial impact.

An energetic material such as solid propellant will ignite when subjected to an impact stimulus, even though the total energy transferred to the material is insufficient to raise the bulk temperature of the material to its ignition threshold. This phenomenon has led to the postulate that small regions of high-energy density, or hot spots, are formed due to some mechanism by which the energy of the stimulus is localized.

There is a wide body of literature covering hot spots and energy localization and some key papers are discussed in the following. One of the earliest papers was by Bowden and Gurton[1] and showed in experimental work the formation of hot spots in solid explosives. Afanas'ev et al.[2] proposed a mechanism of hot spot formation in solid explosives by the release of energy along slip surfaces formed at the onset of mechanical failure. Field, Heavens, and Winter[3,4] observed the impact initiation of ignition in explosives and postulated that hot spots result from locally obstructed plastic flow. Frey[5] and Boyle et al.[6] studied explosive ignition by impact loading and suggested that rapid shear can cause ignition when it is localized in narrow zones (shear bands). Such bands can form at sliding interfaces. Starkenberg et al.[7,8] formulated the void collapse model leading to ignition of explosives by rapid compression of a gas layer. Coffey et al.[9-14] examined the mechanism of hot spot generation in crystalline energetic materials and postulated that the movement of dislocations is one means by which shear deformation occurs. Coffey found that ignition initiation is not at the geometric center of an impact specimen but at the edge where hot spots are generated by high-rate shear deformation.

It is now generally accepted that a number of mechanisms can create hot spots: 1) void collapse with shock heating, 2) void collapse with plastic heating, 3) shear cracking, 4) shear banding, and 5) shear banding with friction stress at sliding interface. Void collapse models do not fit solid propellant materials because these materials are mixed and processed in a vacuum. The number of voids is, therefore, insignificant. Shear cracking, shear banding, and friction stresses are more likely to be the ignition mechanisms with solid propellants.

One approach to understanding the mechanism of drop weight impact ignition of solid propellant is to perform a dynamic finite element analysis to determine the stress, strain, and energy distributions throughout the propellant sample. Of special interest are the local shear and compressive stresses and the frictional heat energy generated at the sliding propellant surfaces.

Test Considerations

Careful consideration must be given to the hardware and sensors used in the instrumented impact tester. Photodetectors have been used routinely to record ignition initiation. Sensors such as accelerometers, strain gauges, and force transducers were employed by Coffey and DeVost[13] to measure the

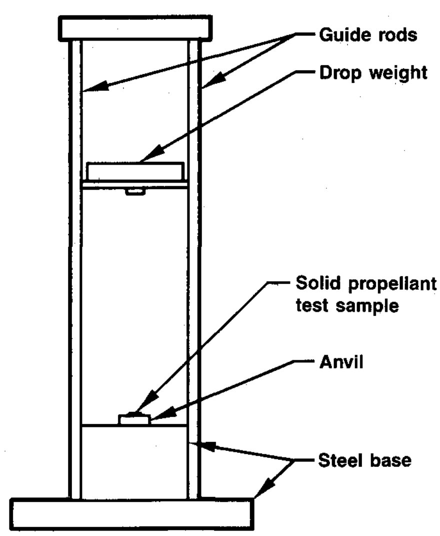

Fig. 1 Schematic of typical drop weight impact tester.

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amount of energy transmitted to the test specimens. Experience has shown the accelerometer to be the most effective sensor. Accelerometer data is typically recorded on a high-speed oscilloscope, which has the ability to store traces in memory and integrate the area under the acceleration-time curves. The oscilloscope is typically triggered by a photodiode and the total test time is approximately 100–120 μs for solid propellants.

Finite Element Analysis

A dynamic finite analysis was performed to compute the response of a solid propellant sample during the drop weight impact test. The propellant stress-strain curve input into the analysis was approximated from a PBAN solid propellant high-rate tensile test conducted at Chemical Systems Division (CSD). As shown in Fig. 2, the values of Young's modulus and the plastic modulus fit the test data reasonably well. The computer analysis results can be synthesized into graphical representations of the compressive and shear responses and deformation of the propellant during the impact test.

Computer Code

The computer code DYNA was chosen for this effort. DYNA is an explicit hydrodynamic finite element code developed at the Lawrence Livermore National Laboratory,[15] Livermore, California, for analyzing the large deformation in the dynamic and hydrodynamic response of inelastic solids. DYNA has a contact-impact algorithm that permits gaps and sliding with friction along material interfaces. These slide lines permit arbitrary zoning along interfaces and gaps in the initial configuration. Input files for DYNA were generated by the preprocessor MAZE. The postprocessor ORION was used to read the binary plot files that DYNA generated and to plot contours, time histories, and deformed shapes. All computations were conducted on a VAX 8800 with typical run time of approximately 1 CPU h.

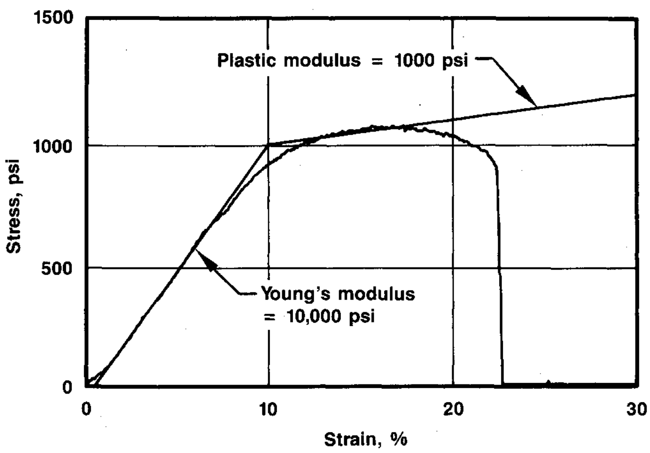

Fig. 2 Propellant stress-strain curve.

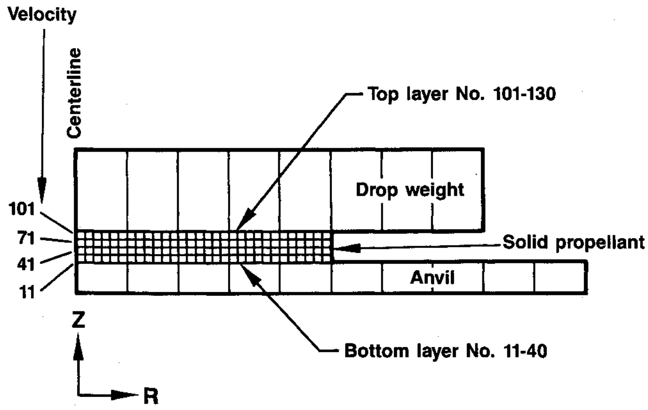

Fig. 3 Axisymmetric finite element model with propellant element numbering sequence.

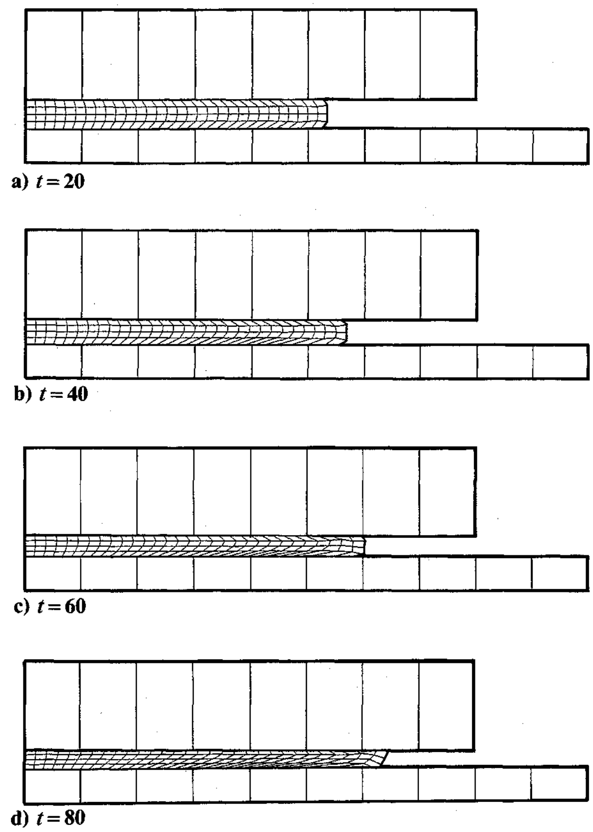

Fig. 4 Deformation at various time t from initial impact in microseconds (friction = 0.5).

Computer Model

Because of the symmetry of the geometry and loading, a two-dimensional axisymmetric model was constructed with DYNA2D for the analysis. The propellant was modeled as an isotropic elastic-plastic material (material 3 in DYNA2D). Young's modulus, Poisson's ratio (0.499), the yield stress, plastic modulus, and a hardening parameter (1.0) were input as the propellant material properties. The stress-strain curve for the propellant was approximated from a solid propellant high-rate tensile test already shown in Fig. 2.

The model assumed an anvil on a rigid base and a drop weight with a simplified configuration, as shown in Fig. 3. The drop weight velocity was assumed to be 100 in./s at initial impact, based on a drop height of 13 in. The two material interfaces (between the weight and the propellant and between the anvil and the propellant) were modeled as sliding interfaces with contact and friction. The friction coefficient was assumed to be 0.2 and 0.5, respectively, in two separate analyses. The undeformed finite element grid in Fig. 3 identifies the numbering sequence of the propellant elements used in the later plots of stress distributions in the propellant. The solid propellant was modeled by four layers of elements numbered 11–130.

When the drop weight hits the solid propellant sample, the propellant deforms such that the thickness decreases and the diameter increases. The deformed shapes at 20–80 μs from initial impact are plotted in Figs. 4. The propellant can be seen to extrude radially as time progresses. The deformed grids look reasonable and show that the top surface, where impact occurs, extrudes in the radial direction slightly more than the bottom surface of the sample. The compressive stress in each propellant element layer varies significantly from the central

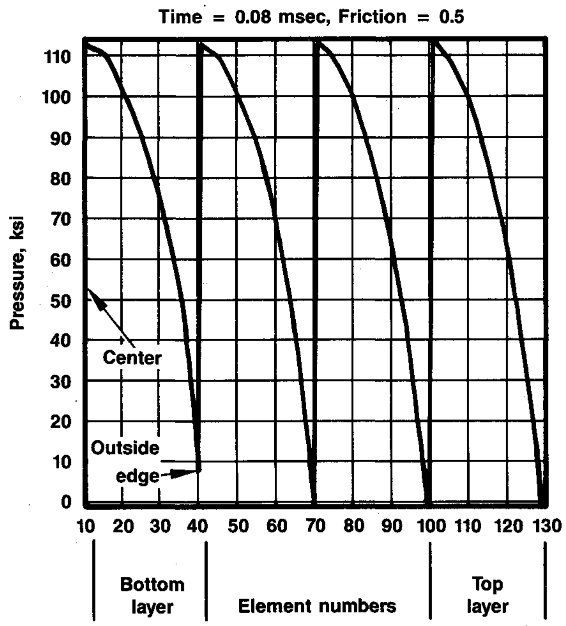

Fig. 5 Pressure distribution from center of propellant to edge.

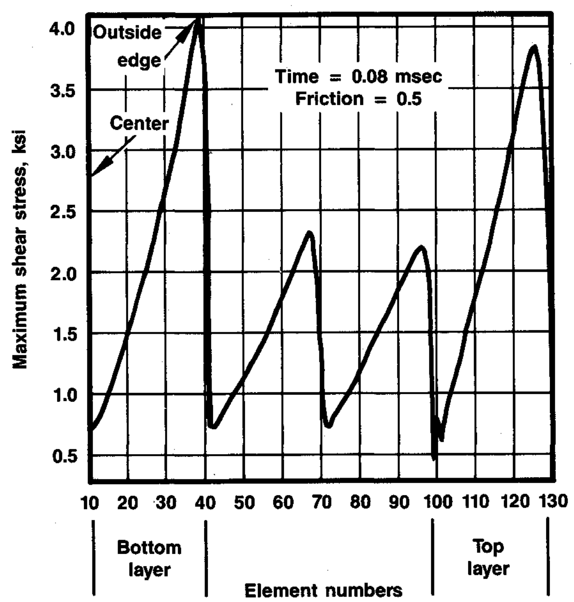

Fig. 6 Maximum shear stress distribution from center of propellant to edge.

part of the sample to the edge. Figure 5 shows the pressure peaking near the center of each of the four element layers and tapering off to near zero at the edge of the propellant sample. This decrease in compressive stress at the edge is consistent for all four layers of solid propellant elements. The peak pressure at the center is approximately 1.1×10^5 psi. The shear stress in the solid propellant is zero at the center and peaks near the edge. Figure 6 shows the maximum shear stress peaks near the edge of the bottom element layer and also near the edge of the top element layer. The maximum shear stress is approximately 4×10^3 psi at the lower and upper surfaces near the edge and reaches approximately 2×10^3 psi at the two central layers of elements near the edge. The von Mises stress and the RZ-shear stress in Figs. 7 and 8 have the same peak stress locations as the maximum shear stress. The peak von Mises stress is about 7×10^3 psi near the bottom surface edge. The RZ-shear stress is about 4×10^3 psi near the bottom surface edge and about 3.2×10^3 psi near the upper surface edge. These plots are all for an interface friction coefficient of 0.5. The stress distributions for the lower friction coefficient of 0.2 are similar in shape, but the peak shear stresses are lower, as shown in Table 1.

Frictional Energy Discussion

The peak RZ-shear stresses, located at the upper and lower propellant surfaces just inside the edge of the propellant sample, are very high. These shear bands, caused by friction stresses at the sliding interfaces between the propellant and metal, generate heat as the propellant extrudes radially. The heat generated by friction at any point at the upper and lower propellant surfaces is given by

$$Q = \int \tau V \, dt$$

where τ is the RZ-shear stress, V the radial velocity of propellant, and t the time. Fig. 9 shows the peak RZ-shear stress at the lower propellant surface vs time, and Fig. 10 shows the radial velocity of the propellant at this location vs time. At the peak RZ-shear stress location at the lower propellant surface

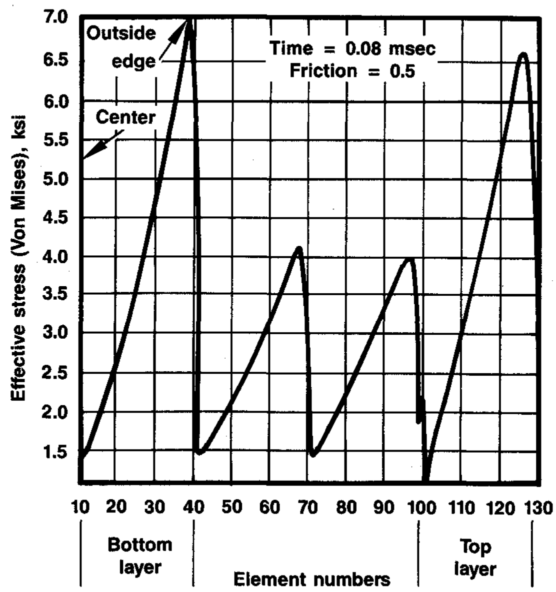

Fig. 7 Von Mises stress distribution from center of propellant to edge.

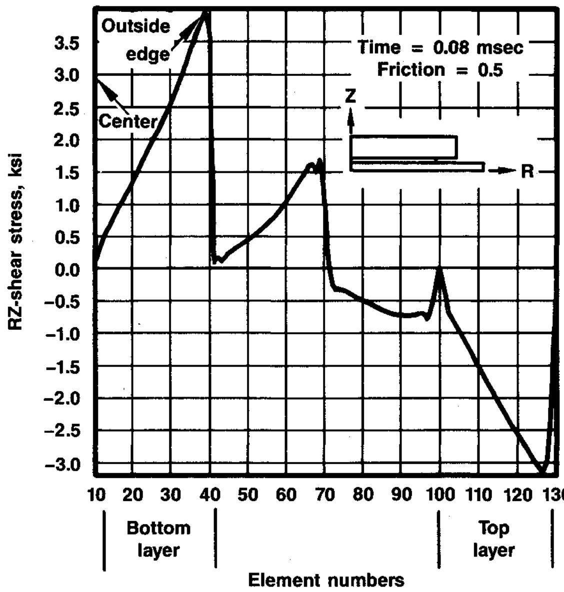

Fig. 8 RZ-shear stress distribution from center of propellant to edge.

Table 1 Comparison of peak shear stresses for different friction coefficients (at 80 μs)

Coefficient of friction	Peak RZ-shear stress, ksi
0.2	3.0
0.5	4.0

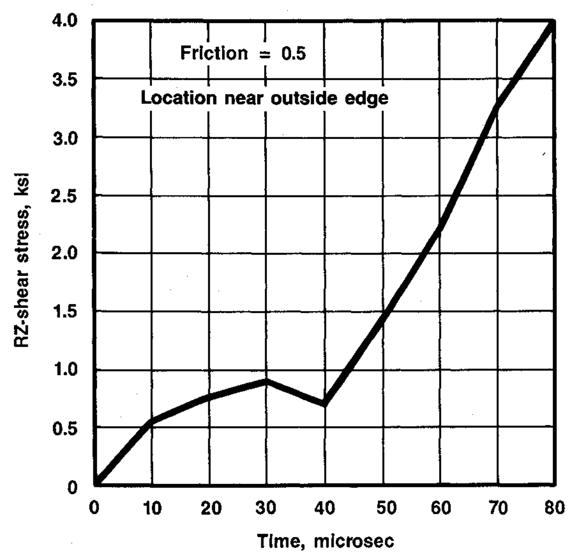

Fig. 9 Peak RZ-shear stress at lower propellant surface vs time from initial impact.

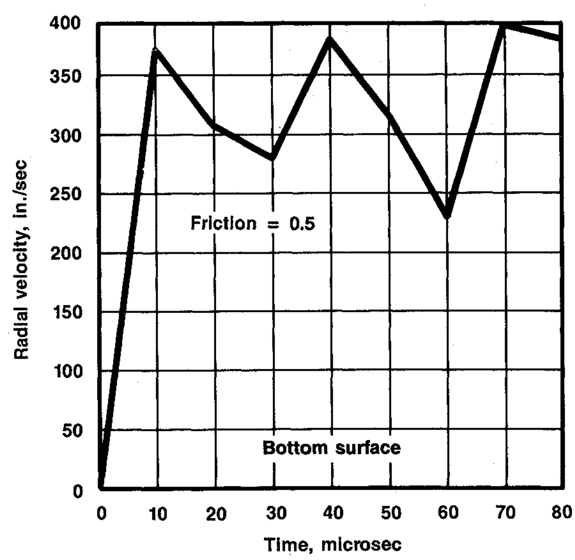

Fig. 10 Radial velocity at peak RZ-shear stress locations vs time from initial impact.

at 80 μs from initial impact, Q can be computed from Figs. 9 and 10 to be approximately 5.1×10^{-3} Btu/in.^{2}

Precise distribution of this heat energy requires a heat transfer analysis. However, for a preliminary estimate, assume that half of the heat energy goes to the drop weight and anvil and that the other half is evenly distributed throughout a 0.001-in.-thick layer of the propellant (which is 0.0078 in. thick at 80 μs). The propellant is 90% solid particles and 10% polymer and is an excellent insulator. Any heat generated at the sliding surface in the microsecond time range will not be able to penetrate the specimen, but will be localized on the surface only. The smallest filler particle of ammonium perchlorate is approximately 0.001 in. thick. If the surface heat stays within the first insulated particle layer, it cannot penetrate more than 0.001 in. deep. Then, the heat energy distributed to the propellant at the peak RZ-shear stress locations at 80 μs is approximately 2.6 Btu/in.^{3} In impact tests, ignition occurs in the 100–120-μs time range. If the peak RZ-shear stress and radial velocity in Figs. 9 and 10 are linearly extrapolated to 120 μs from initial impact, the heat energy distributed to the propellant at the peak RZ-shear stress locations is approximately 7.1 Btu/in.^{3} That is about equal to the energy required to initiate propellant ignition according to autoignition experiments.[16]

The dynamic analysis shows that there is high concentration of heat energy at the upper and lower propellant surfaces just inside the edge of the propellant sample. The heat energy is sufficient to start ignition at these shear-band locations, as illustrated in Fig. 11. This was confirmed at CSD by observing many impact samples of PBAN and HTPB solid propellants. A typical sample is presented in Fig. 12. Ignition occurred near the edge, not at the center. The sample ignited at the edge, and the ignition extinguished by itself before the rest of the sample burned. Many solid propellant samples experienced this partial ignition. Ignition was detected by three photodiode sensors located around the sample and also by the burned region of the propellant and the blackened region on the anvil where the propellant was partially consumed.

Discussion of Results

Frey[5] and Boyle et al.[6] suggested that rapid shear can cause ignition in solid explosives when it is localized in narrow zones

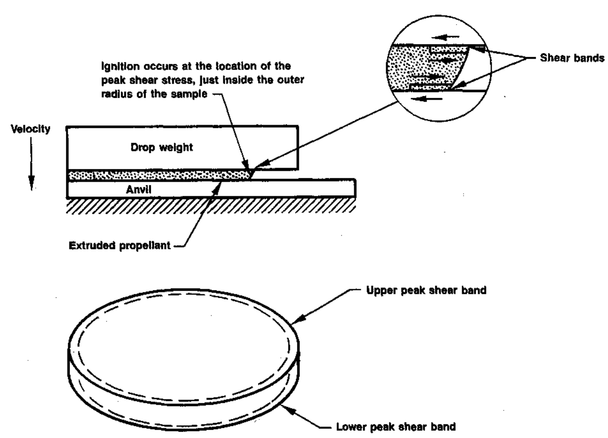

Fig. 11 Location of ignition initiation.

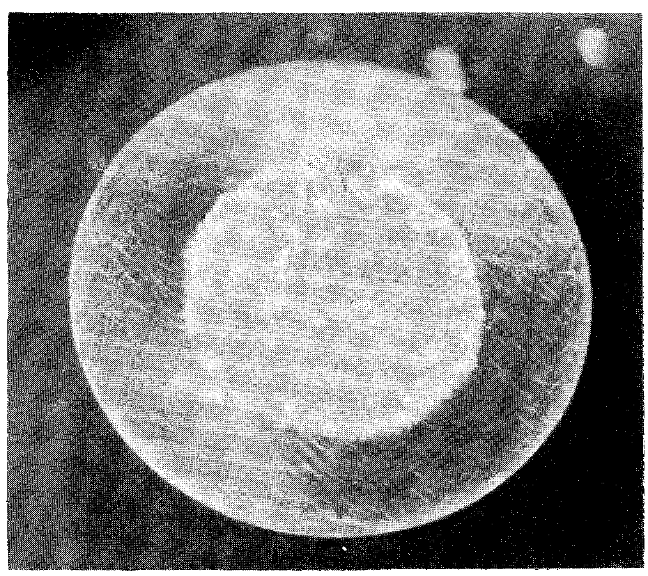

Fig. 12 Solid propellant sample after ignition and partial consumption.

called shear bands and such bands can form at sliding interfaces. They also indicated that ignition initiation depends on both pressure and shear velocity. In the analysis conducted at CSD and presented here, the friction coefficient at the interface of the propellant and metal was assumed to be constant. The friction stress in the analysis then depends on pressure and the frictional heat energy depends on both pressure and shear velocity. Our analysis shows that, at the center of the specimen, the pressure is high but the radial velocity is zero, therefore, the frictional heat energy is zero. At the edge, the radial velocity is high but the pressure is zero, and so the frictional energy is again zero. Close to the edge of the specimen, a combination of pressure and high shear velocity produces the peak frictional energy that is sufficient to start ignition. Ignition initiation occurs near the edge, not at the center and not at the edge, because it depends on both pressure and shear velocity as shown by Frey.

However, the friction coefficient may also vary with temperature, shear velocity, and the melting point of the propellant, as pointed out by Frey. We modeled these variables by changing the friction coefficient in the analysis from 0.5 to 0.2 but the results only changed by 25%, which would not alter the results of the analysis that sufficient frictional heat is available to ignite the solid propellant.

Another source of heat input in the peak shear stress regions is the fracture of the ammonium perchlorate particles. Coffey[11,12] postulated that, in a drop weight impact test of a propellant, shear is the principle process of the localized heating that may eventually culminate in ignition. He believed that this shear is localized within the crystals of the propellant. This localization is to be found in the shear bands that occur naturally in crystalline solids as they undergo shear deformation. The basic mechanism of plastic deformation in crystalline solids is the creation and motion of dislocations. The rapid movement of these dislocations generates high local temperature within the shear bands that can be sufficient to cause ignition.

The PBAN propellant in the drop weight impact test is actually highly filled with ammonium perchlorate crystals, which are randomly scattered in the propellant. This microscopic effect was not modeled in the analysis. In the high shear bands at the interface of propellant and metal, the high shear stresses may be sufficient to fracture the ammonium perchlorate crystals and create dislocations in the crystals. The rapid movement of the dislocations will generate additional heat that will contribute to the initiation of ignition.

The finite element analysis shows that the shear stresses in the propellant are concentrated near the edge of the specimen at the contact surfaces of the weight and anvil. Ignition is predicted to initiate at these shear-band locations. Partially consumed samples at CSD verify that solid propellants do ignite at these surfaces near the edge. Three sources of energy contribute to the hot spots near the edge: 1) frictional energy concentration, 2) distortional energy concentration, and 3) ammonium perchlorate crystal fracture in the critical contact surfaces. Our analysis shows that frictional energy alone is sufficient to ignite the propellant.

Conclusion

Our analysis shows that during impact the central area of the propellant specimen is in a highly compressed condition that forces the outermost region of the specimen to flow outward because it is only constrained by friction in this direction. During this flow process, the shear stresses in the propellant are concentrated near the edge of the specimen at the contact surfaces of the weight and anvil. These shear bands, caused by friction stresses at the sliding interfaces between the propellant and metal, generate heat as the propellant extrudes radially. Thus, there is high concentration of frictional heat energy at the upper and lower propellant surfaces just inside the edge of the propellant sample. The heat energy is sufficient to start ignition at these shear band locations. These analytic predictions are in agreement with the experimental results observed by CSD. Our analysis and experiments show that ignition does not occur in the highly compressed central region but rather occurs in the high shear stress regions at the contact surfaces near the edge of the specimen where compressive stresses are low.

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