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SURVEY AND ASSESSMENT OF FRAGMENTATION MATERIALS/CONCEPTS

June 1976

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FRANKFORD ARSENAL U.S. ARMY ARMAMENT COMMAND PHILADELPHIA, PENNSYLVANIA 19137

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A survey of the materials and concepts which have been developed for natural and controlled fragmentation munitions was conducted. The scope of the review considered all calibers of H.E. munitions and test items, but was limited to those items which rely upon the fragmentation of the casing material for their primary source of lethal fragments. The review considered efforts ranging from basic research to product improvement. The compiled information was assessed in terms of the applicability for

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improving H.E. large caliber shell. Deficiencies in the existing data base for the selection of materials for naturally fragmenting artillery shell were identified. Limitations to the application of controlled fragmentation techniques were also identified. Recommendations for future work were made on the basis of these deficiencies and limitations. An extensive bibliography and associated keyword index is included so that this document may serve as a useful reference work.

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INTRODUCTION

This report is a survey of the past and present efforts in the areas of materials and concepts of explosive fragmentation effects. It is based upon information obtained from three primary sources: (1) Personal contacts by visit or telephone with individuals engaged in fragmentation studies; (2) An examination of R&T Workunit Summaries (DD Form 1498) and Report Bibliographies compiled by the Defense Documentation Center (DDC); and (3) A review of published reports. The reports examined were limited to those obtained from the personnel contacted, those identified from the Report Bibliographies and procured through DDC, and those available at the Frankford Arsenal library.

Fragmenting munitions are explosive munitions which depend upon the dispersion of metal fragments to provide a significant portion of their lethal effectiveness. Next to direct blast effects, fragmentation represents perhaps the most widely employed destructive mechanism for both personnel and materiel targets. Fragmentation effects are incorporated to some extent into nearly all types of weapons ranging from hand grenades and mines through artillery and rockets to aerial bombs and long range missiles. The only notable exceptions appear to be in small arms weapons ranging from 5.56mm to .60 caliber.

The selection of materials for unitary fragmenting munitions involves many limiting considerations. They include: (1) terminal ballistic requirements, (2) launch strength requirements, (3) the adverse pre-launch handling and storage requirements, (4) the capability of detecting critical flaws subsequent to processing, (5) the manufacturing and processing capability to satisfy the volume demand, and (6) the availability of chemical constituents for a particular composition, especially during a period of mobilization. A candidate material for near-future application must be assessed in terms of current suitability for all of these factors. Materials (or concepts) proposed for later usage might not be subject to identical limiting considerations, since technological advances might alter the present requirements.

The fragmentation requirements imposed upon various munitions vary greatly depending upon the size of the weapon and the target to be defeated. Primarily, these requirements relate to the size (mass), velocity and distribution of fragments being dispersed from the munition. The desired fragment sizes can range from as small as two grains to defeat personnel to something on the order of hundreds of grains to defeat targets such as trucks and armored vehicles.

Materials to be used in high fragmentation artillery projectiles required to defeat personnel and soft materiel targets must meet several unique and, to some extent, conflicting requirements. The major problem involved in optimizing material selection is related to the combined requirements of having sufficient toughness to withstand severe handling and launch stresses and yet provide a preponderance of fragments which are small in size relative to the wall thickness of the projectile. Unfortunately, the material parameters which promote increased fragmentation also lead to generally lower toughness. As a result, some of the materials now available may not be suitable in terms of combined fragmentation and material safety requirements for projectiles currently in development or those contemplated for future systems.

There are two general approaches available for seeking improved lethality in unitary fragmentation projectiles. One is to enhance the natural fragmentation characteristics of their materials and the other is to design for controlled fragmentation.* The natural fragmentation of an explosively loaded casing is largely dependent upon the dynamic properties and microstructure of the material. Invariably an exponential fragment number-fragment mass distribution (Mott relationship) is closely obeyed. The mechanism of controlled fragmentation relies, ideally, upon predictable crack nucleation and propagation of a casing during explosive expansion. Hypothetically, this is facilitated by the introduction of macroscopic discontinuities into the casing to promote fracture along preferred paths. The intent is to negate the natural fragmentation distribution through the production of discrete fragments.

The scope of this survey considers all calibers of H.E. munitions or test items but is limited to those which rely upon the fragmentation of the casing material for their primary source of lethal fragments. This includes munitions which employ design features such as scored or engraved shell bodies but does not include fragmentation munitions whose lethality is achieved by the dispersion of preformed fragments. The review considers studies ranging from basic research to product improvement.

The intent of the survey is to review past and current efforts concerned with improved fragmenting materials or concepts. Existing data gaps will be identified and discussed. Recommendations for future work will be made on the basis of an assessment of the information collected as applicable to large caliber projectiles.

In lieu of specific citations for authors, agencies, or contractors within the body of the text, descriptive keywords have been listed with each reference in the bibliography. It is anticipated that these keywords will provide the reader with a brief, albeit disconnected, synopsis for each entry. In addition, the bibliography is appended by a Bibliographical Keyword Index which is intended to serve as a useful literature-search tool.

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* In this survey these approaches specifically exclude consideration of ICM (submunitions) or preformed fragments.

RESULTS

Natural Fragmentation

During World War II and for several years after the war's end, theoretical treatments of natural fragmentation and associated effects were conducted in the U.S. and in Britain. They are still considered generally valid today.

Combat casualty surveys from World War I to the present time have indicated that primary wounding of personnel was attributable to H.E. munition fragments. However, the U.S. made little effort until the late stages of the Korean conflict to develop materials with increased lethal effectiveness over that of the plain carbon steels used until that time. In contrast, the enemy used cast iron mortar shell with devastating effect during that engagement. In fact, the Soviet Union had been examining cast iron for shell during World War II.

From 1952 through the mid-1960's the U.S. Army devoted considerable effort to research and development of cast irons for improved antipersonnel fragmentation effectiveness. Due to limited strength they were approved only for use in mortars and rockets.

During the Vietnam conflict it became clear that increased munition lethality would be a significant asset. Consequently, a broad materials program was initiated by the military services in the mid-1960's to develop cost effective large caliber ammunition with considerably better natural fragmentation characteristics than the conventional plain carbon steels. The ability to fabricate and process candidate materials into sound projectiles at high production rates is an important requirement which must be satisfied. Toward achieving these goals, an extensive amount of work was done in this area by FA, PA and AMMRC under production engineering efforts relating specifically to the development of high fragmentation of 105mm and 155mm artillery projectiles. The materials studied included HF-1, PR-2, 9260, 1095, 1340 and 52100 steels subjected to a variety of thermal and mechanical treatments. The Navy also investigated most of these materials as well as a graphitic steel (06 steel) for use in a 5"/54 projectile. All of these alloys can be processed into a condition which provides significantly better fragmentation effectiveness than the mild or medium carbon steels presently used in large caliber projectiles. Upon assessing the results of these studies HF-1 steel was selected by the Army and 06 steel by the Navy for more extensive testing.

HF-1 steel in a quenched and tempered (Q&T) condition is currently being used by the Army for the 155mm M549 RAP warhead. It is also the primary candidate for Army use in the 155mm XM708 projectile, the 8 inch XM650 RAP warhead, the 8 inch XM711 projectile, and the 8 inch XM762 projectile. It is also being considered by the Navy for use in a HI-FRAG 5"/54 projectile because 06 steel could not satisfy the necessary safety standards.

During this same time period IITRI, as a contractor to the Air Force, investigated the effects of temper embrittlement upon the fragmentation of plain or low alloy moderate carbon steels containing impurity level additions of phosphorus. It was demonstrated that a substantial increase in the fragment yield over that afforded by the base material in the forged condition could be achieved by temper embrittlement. The degree of enhancement was shown to be related to both the phsophorus content and the specific thermal treatment. The material/treatment was recommended for general application to Air Force bomb designs.

The use of powdered metal compacts for improved fragmentation was introduced during the latter 1960's. Data from limited studies at FA, AMMRC, and BRL indicate that proper processing of the compacts can provide excellent fragmentation effectiveness against personnel. In general, the strengths and ductilities of pressed and sintered powder metallurgy compacts are too low for serious consideration as artillery projectile materials. It has been shown, however, that many powder metallurgy compacts can be either hot or cold worked to provide further densification and improved mechanical properties.

Recently completed studies at FA were of a more basic nature, concentrating on the mechanisms of fracture during fragmentation. Part of the effort at FA was included in a Cooperative Program with the Australian Department of Defence. The latter agency has performed fundamental fragmentation studies over the past nine years in attempts to relate fracture mechanisms to metallurgical, processing, and geometrical variables. The major findings of the cooperative effort were: (1) The microstructural changes produced by cold work and stress relief affect the fragmentation of spheroidized 1340 steel; (2) Geometric scaling/fragmentation relationships are not general, as commonly supposed, but have a complex dependence upon the material chenistry and condition; and (3) A dynamic material property measurable in the laboratory is related to the fragmentation performance of brittle materials.

Research studies at PA concerned with the influence of materials properties, geometries, and explosive fillers upon fragmentation mechanisms have recently been concluded. Data were accumulated using two highly specialized experimental techniques. One involved arresting the expansion of explosively loaded cylinders before separation into fragments had occurred. The second employed high speed photography of cylinder expansion from detonation until fragmentation. The materials studied included 1018, 4340, Bearcat, PR-2, and HF-1 steels. Cylinders 5" long with 2" ID and thicknesses ranging from 1/8" to 1/2" were used. The charges included Baratol, TNT, Comp B, HMX 9404 and Octal. The dynamic fracture processes were statistically deduced from post-mortem visual and microscopic examinations. The following generalizations, dependent upon material and geometry, were made: (1) The number of fractures is proportional to the expansion velocity of the cylinder as predicted by the Mott theory; (2) The depth of radial tensile cracking is a function of the explosive; and (3) The fragment length-to-width ratio is independent of explosive.

Several years ago BRL investigated the influences of explosive parameters on the natural fragmentation of steel cylinders. Variations were made in the explosive filler type, the charge-to-mass ratio (C/M), and the cylinder material (one metallurgical condition each of 1020 and HF-1 steels). For the small cylinders tested, it was determined that the fragment size distribution was sensitive to the explosive filler type and that this sensitivity decreased as C/M increased. However, the 1020 steel was more sensitive in this respect than was the more frangible HF-1 steel. It was found that the average fragment mass decreased as explosive energy increased and the fragment kinetic energy was proportional to the explosive energy.

Both experimental and theoretical studies are in progress at AMMRC to investigate a method to control the form of a shock wave induced in a fragmenting munition. The concept involves spallation during the radial expansion of concentric cylinders, and it has been studied with both one and two-demensional wave propagation codes (KO and HEMP). Actual tests were used to show fragmentation details such as size, shape and initial velocities, along with fragment recovery for determination of Mott parameters. The agreement between theoretical and experimental results has been quite satisfying and presently more calculations are being run and tests are being planned to continue optimization studies, to explore new material behavior, and to increase the understanding of fragmentation behavior.

Limited fracture toughness evaluations of potential fragmentation materials were performed at AMMRC in the late 1960's. Correlations between K_{IC} and a fragmentation parameter were not found. Comprehensive dynamic fracture toughness/stress analyses over an expected temperature range of application of the projectile have been performed only over the past several years at FA, PA, and NWL. Limited data have been obtained to date but the work is continuing. One of the significant aspects of the above work was that the results assisted in a decision to reject the use of isothermally heat treated HF-1 steel for the 155mm M107 projectile.

There is in existence a Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) which provides guidance for the preparation and updating of Joint Munitions Effectiveness Manuels (JMEM). These manuals represent an extensive compilation of data in the area of weapons characteristics, target vulnerability, delivery accuracy and effectiveness methodology. Although the manuals include extensive compilations of fragmentation data and effectiveness information useful in pointing out the strength and weaknesses of existing munitions, it provides essentially no guidance as to what is being done or what should be done to overcome the deficiencies. An index to the specialized manuals is entered in the bibliography.

Controlled Fragmentation

A number of techniques have been used in an attempt to achieve controlled fragmentation. The more successful of these can be described as falling into two general categories: mechanical notching and metallurgical notching. These techniques, as applied to hollow cylinders or munitions fabricated from wrought materials, are described below.

Mechanical notching refers to the introduction of physical discontinuities (slots, grooves, V-notches) into the inner or outer surface of the item to be fragmented. A feature common to all of the mechanical notching studies to date has been the use of periodic notch patterns applied to produce through-thickness fractures which would yield fragments as thick as the wall of the test item at fracture but of limited lateral size. Other factors which have been examined to varying degrees are material type and strength, explosive filler type, charge-to-mass ratio, and notch location, depth, profile, and pattern configuration.

Metallurgical notching refers to the introduction of structural discontinuities at either surface wherein the material in the notch is more brittle than the adjacent material. Phase transformed (case hardened) notches may be effected by laser beams, electron beams, carburizing, nitriding, or aluminizing. In the few studies to date in which this technique has been used only the effect of external notches on controlled through-thickness has been considered.

Either of the above techniques could be applied to multi-layered tubes or stacked rings. The fragmentation of such configurations could approximate that achieved by exploding a cannister containing preformed fragments.

Studies of controlled fragmentation techniques for enhanced lethality preceded efforts to improve materials for greater natural fragmentation effectiveness. Early research was done by the British in World War II on grooved ring bombs. Also, canister projectiles, cylindrical sheet metal cans filled with small steel shot (preforms) set in a resin matrix, were used quite effectively in jungle warfare during World War II. However, with the exception of hand grenades, pre-scored or pre-engraved projectile bodies for achieving controlled fragmentation were not being produced at that time.

Shortly after World War II, BRL began to experiment with controlled fragmentation using stacked grooved rings surrounding an explosive core. Other concepts investigated at BRL until the mid-1950's involved the use of notched and unnotched spiral wire casings, cylinders containing fluted bore liners, and multi-walled cylinders. The casing material was moderate carbon steel in each instance. Various wall thicknesses and heat-treated conditions were involved. In each case the predominant mode of failure extended through the casing wall. The degree of control of notched casings was dependent on the material condition and notch spacing. The multi-walled casings and those with fluted liners yielded natural fragmentation distributions, i.e., control was not effected, but the number of fragments increased approximately proportional to the number of layers.

In the late 1960's and early 1970's, PA used (1) a dual-stranded helical coil or (2) a grooved liner insert, in contact with a projectile bore surface. The concept was to produce a shaped charge "cutting" jet action delineated at the bore surface by the insert design. Although referred to as controlled fragmentation, the only effect was to provide a somewhat greater increase in the number of fragments obtained from the same projectile without the insert.

The most extensive work using mechanical notching was performed at the Naval Weapons Center in the late 1950's and again in the late 1960's. Although several higher strength alloy steels were subjected to control techniques in these studies, research efforts were concentrated largely on plain carbon AISI 1010 or 1020 steel since application to bomblets and bombs with low strength requirements was the desired objective. On the basis of statistical groupings of fragments recovered from explosive tests on plain carbon steel cylinders, it was concluded that (1) greater control resulted with internal notches than with external and (2) a significant increase in fragmentation effectiveness could be achieved over that of the natural mode. The technique was studied using test items ranging in size from 1 3/8" O.D., thin-walled bomblets to 2000-lb, thick walled bombs. Proportionately fewer design fragments were obtained with the less ductile, higher strength alloy steels. This reduced control effect was attributed to the overriding influence of the natural fragmentation modes of the materials which promoted additional fracture paths to those produced by the design grid. As a consequence, some of the fragments recovered were smaller than the design size. The proportion of these smaller fragments increased markedly (at the expense of the discrete, design fragments) with increasing casing strength.

IITRI also conducted an investigation (1973), under contract to the U.S. Air Force, using mechanical notching techniques. Cylinders of temper embrittled AISI 1040 steel containing phosphorous with a tensile strength of 140-150 psi were notched and fragmented. It was concluded that the degree of control attained was greater with external notches than with internal notches. These results were recently (1974) applied to a modular bomb design for controlled anti-materiel effectiveness.

The Materials Research Laboratories (MRL) (formerly titled the Defence Standards Laboratories (DSL)) of the Department of Defence of the Commonwealth of Australia have also been studying (1973 to present) the influence of mechanical notches on mild steel cylindrical bomblet warheads over a range of relatively high hardnesses. They were successful in using external notches for controlling the fragmentation to produce a high yield of fragments which were large for the warhead size, provided the notching details were appropriately matched to the natural fragmentation characteristics of steel. Post mortem metallographic examinations of recovered fragments indicated that deformation and fracture could strongly depend upon the influences of hardness and notch configuration or shock wave interactions. A greater latitude in control by external notching could be achieved by filling the notches with epoxy, for example, to reduce the shock mismatch. Nevertheless, a complex interplay between geometric and material factors exists and must be considered in the application of external notching. Recently a parallel fundamental study was initiated at MRL using internal notches in the same material. Early results indicated that quite different fractures occur with the internal notching but further experiments must be performed before explanations can be offered.

In 1972 Honeywell, Inc. developed a proprietary selective case hardening method (metallurgical notching) for controlling fragmentation. External carbonitrided grid patterns were introduced onto quenched and tempered AISI 4130 steel 25mm shells. A certain degree of control was attained, but a size-distribution of small fragments (natural fragmentation) was also produced.

The Naval Weapons Laboratories (NWL) and MRL have passed test items through an electron beam (1970's) to produce hard brittle zones in a given pattern. NWL fragmented a variety of sizes of AISI 1050, 1047, 1061, 1340, 4340, and 9260 steels containing electron beam scored (EBS) zones. Good through thickness control was achieved but, except for relatively small test items, resultant fragment sizes were larger than required for artillery terminal effectiveness against personnel or soft targets. (MRL found similar results in a quenched and tempered mild steel.) Some of the NWL EBS rounds were successfully gun-launched.

The fragmentation of grooved multi-layered powdered metal compacts are currently being evaluated by Eglin AFB and NWL for artillery-sized projectiles. Also, NWL is investigating the potential of casting steel in a mold which contains an inert honeycomb-gridwork to obtain pre-designed rhombohedral fragments. The data for all of these tasks is sparse but work is continuing.

AMMRC has suggested a scale-model study using a selective embrittlement technique similar to that used by Honeywell, inc. The ultimate objective of the proposed study would be to produce controlled fragmentation of artillery shell for the defeat of personnel and soft material targets.

Although a review of natural or controlled fragmentation studies of foreign origin was essentially limited to Australian and British work, one document in the Bibliography is, in itself, a review of foreign controlled fragmentation applications. It includes work of both Free and Communist Bloc nations. The data are classified but many of the methods are similar to those discussed in this section. The report being referred to is No. 230 in the Bibliography entitled "Improved Conventional Munitions (Current and Projected) - Foreign".

DISCUSSION

Natural Fragmentation

Fragmentation and material property requirements for a number of existing and future artillery projectiles cannot be satisfied by conventional plain carbon steels. Either higher carbon or alloy steels are logical choices.

Significant efforts in research, development, and engineering have resulted in a number of excellent wrought, cast, and powder metal iron-based materials which provide a range of fragmentation properties. Although the cast and powder metal materials will not likely have the required strength for many applications, the wrought materials should provide sufficient possibilities for satisfying most needs. However, for each projectile, the candidate materials must be evaluated for specific safety and reliability.

In the material studies since the mid-1960's, there has been a general lack of conformity in fragmentation testing. In particular, test specimen sizes, charge-to-mass (C/M) ratios, explosive filler type and fragment recovery methods commonly varied from installation to installation. Each of these variations uniquely affects the fragmentation behavior, and the combined effects are apparently dependent upon the specific dynamic properties of any given material and its metallurgical condition. Consequently, reliable comparisons or predictions of the fragmentation performance of candidate materials for a particular munition often cannot be made from existing data. Further experimentation is required to provide a more generally applicable data base for confident material selection.

The major data gaps to be filled are the fragmentation performance-fracture toughness for a specific material/condition/geometry. As an example, although temper embrittled phosphorus bearing steels have shown excellent fragmentation potential, they have not been evaluated with respect to fracture toughness. However, they show sufficient promise in most aspects to warrant more detailed study for specific application to artillery projectiles. Similar efforts can probably be suggested from the presently incomplete data bank depending upon the particular projectile requirements. Although the task may be difficult, it is believed possible.

Controlled Fragmentation

It is expected that the implementation of controlled fragmentation concepts for large caliber shell represents a longer range effort than the development and acceptance of improved naturally fragmenting materials. This prospect is based upon the supposition that new or improved technologies must be developed to inspect and test controlled fragmentation projectiles for safety and reliability. Further, the feasibility of obtaining improved lethality against personnel or soft-targets with unit-body large caliber projectiles using controlled fragmentation techniques has not yet been demonstrated.

The technique of notching can, to a degree, provide a means of eliminating the size distribution of fragments produced by explosive loading. The method, as applied thus far, has been confined to yielding control fragments of sizes determined by geometric boundaries (e.g., casing surfaces). The result has been a disproportionately high number of fragments of one or several predetermined discrete (control) sizes which are, however, large compared to those which would be produced by fragmenting an identical test item made from an appropriately processed high fragmenting steel. In regard to large caliber shell, the feasibility of success with this technique to defeat personnel and soft materiel targets relies upon the ability to control other than through-thickness fracture. That is, controlled breakup within the casing wall (internal breakup) must be achieved to yield the relatively small fragments required for terminal effectiveness.

The best control has been achieved using internal notches in ductile steels which tend to naturally fragment by shear failure. It is believed that this control derives from the isolation of the shear failures to the notches as a result of dynamic stress concentrations at the notches. In the relatively more brittle steels, the competition between the material's natural metallurgical stress concentrators and the design discontinuities reduces the absolute control attainable. Also, the tendency for more brittle materials to crack branch will likely interfere with the control process.

CONCLUSIONS

1. Significantly improved fragmentation materials have been developed empirically.

2. The fragmentation behavior of a casing is sensitive to its chemical composition, its metallurgical structure, its geometric configuration, and to the particular explosive filler type used.

3. Fragmentation data have been obtained for many steels from tests on hollow cylinders and munitions of one or more sizes exploded by various explosive mixtures. In many instances, however, there are data gaps which do not permit the direct comparisons necessary for selecting the best candidate materials for a specific application. Generally, these gaps cannot be bridged by extrapolation because the fragmentation of each material/microstructure scale uniquely.

4. The assessment of the acceptibility of materials for the manufacture of high fragmentation artillery projectiles will require extensive fracture toughness testing.

5. The development of the predictive capability needed to assure improved materials for naturally fragmenting munitions must await the

identification of the fracture mechanisms/material/structure relationships from which fragmentation derives.

6. Reliable inspection procedures for projectiles designed for controlled fragmentation will be difficult to develop.

GENERAL RECOMMENDATIONS

1. Compile computerized banks of existing data and data to be acquired in the future from parallel fragmentation-material property tests for the purpose of establishing an efficient retrieval system from which candidate materials for H.E. fragmenting munitions can be selected.

2. Determine the feasibility of applying controlled fragmentation techniques to large caliber shell specifically intended to defeat personnel and soft materiel targets.

3. Perform basic research on explosive fracture mechanisms as related to material structure, properties, and geometry in order to permit an interpretive expansion of the data banks.

4. Make comparisons of the fragmentation performance of materials only from tests performed with (1) one or several casing geometries designed with dimensions comparable to the end items being considered and (2) a common explosive filler.

FOREWORD TO BIBLIOGRAPHY

It is intended that the bibliography, of itself, should serve as a useful reference source. Toward that end, its construction is described below.

Reference Groupings: Single Subject. These works are listed under five major headings: Army, Navy, Air Force, Other U.S., and Foreign. Each major division is sub-divided alphabetically into component agencies. The listing under each agency is in inverse chronological order.

General Reference Sources. These citations are multi-subject compilations which include texts, plans, symposia proceedings, and reviews, and they are also entered in inverse chronological order.

Author/Affiliation: In some instances the authors do not have a direct affiliation with the agency indicated but are contractor personnel who performed the work.

AD Numbers: Documents available from DDC are assigned a retrieval number. References which have been so identified in this listing parenthetically include the retrieval number which is prefixed by the letters AD. An addendum listing those which have not been so identified is being compiled.

Keyword Descriptions: Many of the keywords used are self-descriptive. Keywords which have been applied as broad descriptors are defined below:

Additive - A chemical constituent which has been accidentally or purposely added to steel in a small quantity.

Explosive - An explosive type, pressure, or energy.

Geometrical Effect - The effect due to variations in dimensions or discontinuity configurations in the casing.

Processing - The intentional thermal, mechanical, and/or chemical treatment to the casing from the steel making stage to round assembly.

Reliability - The consistency of performance and the material integrity throughout the life cycle of the munition.

Bibliographical Keyword Index: In this index the relevant reference numbers of the bibliography are collectively listed with most keywords. This will permit the construction of specific bibliographies according to topic from which efficient literature searches can be conducted.

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AMMRC

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* Denotes report which includes controlled fragmentation concepts.

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20.	R. Fitzpatrick, "Methodology for Evaluating Candidate Shell Material in Pit Fragmentation Tests", Internal Report, November 1967, (U).	Cylinder, fragment distribution, geometrical effect, processing
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22.	G. A. Bruggeman, "Attenuation of Fragment Velocities Due to the Deformation Resistance of the Casing", AMRA TR-66-33, October 1966, (U).	Theory, velocity (fragment)
23.	E. N. Kinas, "Development of Alternate Cast Fragmentation Materials for the 2.75" M151 Rocket Warhead", AMRA TR-66-32, October 1966, (C).	Additive, cast material, cylinder, fragment distribution, mechanical properties, processing
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31.	G. A. Higbee, "Personnel Lethal Area Estimates for Several Improved 105MM Fragmentation Artillery Projectiles", AMSAA TM-160, December 1972, (C).	Alloy steel, arena test, explosive, fragment distribution
32.	C. K. Kimber Jr., "Product Improvement Test of Projectile 105MM M1E2, HE, AISI-1340 Steel, APG MT-3994 (AD 889 882L), December 1971, (U).	Alloy steel, artillery, fragment distribution, processing, reliability

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35.	A. M. Dietrich, Jr., "Fragmentation Behavior of Ferrous-Base Powder Metal Casings", BRL MR-2048, August 1970, (C).	Cylinder, flash x-ray, fragment distribution, mechanical properties, metallography, processing, stress analysis
36.	W. W. Clifford, Jr., J. B. Harmon and D. A. Wenner, "Lethal Area Estimates for Fragmenting Infantry Munitions", AMSAA-TM-63 (AD 510 972L), April 1970, (C).	Lethality
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45.	"Product Improvement Test of Projectile, 105MM, M1E2 (Fragmentation Phase)", APG FR-B-15666 (AD 508 612L), 1969, (C).	Artillery, flash x-ray, fragment distribution, mechanical properties, processing, velocity (fragment)
46.	C. Smith, "Product Improvement Test of Projectile, 8-inch, HE, M106 (Comp B Filled) (Safety Certification Phase)", APG MT-3122 (AD 849 078L), 1969, (U).	Artillery, reliability
47.	F. M. Mahan, "Engineering Test of Projectile 155MM, M109", DPS-2652 (AD 395 762L), 1968, (S).	Artillery, reliability
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53.	D. J. Waldon and K. A. Meyers, "Lethal Area Estimates for Various Fragmenting Shell", BRL MR-1483, June 1963, (C).	Artillery, carbon steel, cast material, explosive, lethality, mortar
54.*	C. J. Brown, "Fragmentation Characteristics of Mauler Warheads Employing High Density Fragments", BRL MR-1398, April 1962, (S).	High density material, processing, spall, velocity (fragment)
55.	M. A. Famiglietti and C. J. Brown, "Comparitive Fragmentation Effects of Pearlitic Malleable and Nodular Graphitic (Ductile Iron) Cast Shell and Forged Steel Shell for the 105MM Howitzer", BRL R-1119, November 1960, (U).	Arena test, artillery, cast material, fragment distribution, lethality, velocity (fragment)

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59.	J. R. Windle, "Anti-Personnel Lethalities of the 105MM M1, 155MM M107, and 8 Inch M106 Howitzer Shell, BRL TN-1125, May 1957, (U).	Artillery, lethality
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61.*	C. L. Grabarek, "Comparative Fragmentation Tests of Single and Multi-Walled Cylindrical Warheads", BRL R-928, January 1955, (U).	Carbon steel, cylinder fragment distribution, geometrical effect, velocity (fragment)
62.*	F. A. Weymouth, "Fragmentation Characteristics of Experimental Ring Type Shell Made of a Series of Fully Quenched Steels, BRL MR-864, January 1955, (U).	Arena test, carbon steel, cylinder, fragment distribution, processing, velocity (fragment)
63.*	S. Sewell, "Effect of End Confinement and Shell Length on Spatial Distribution and Velocity of Fragments", BRL MR-862, January 1955, (U).	Arena test, carbon steel, cylinder, fragment distribution, geometrical effect, velocity (fragment)
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97.	E. N. Clark and I. P. Juriaco, "Mechanics of Fragmentation of Cylinders", Internal Report, September 1973, (U).	Alloy steel, carbon steel, cylinder, explosive, flash x-ray, fracture analysis, mechanical properties, processing, theory, velocity (fragment)
98.*	O. Frazier, "Use of Hi Density Metals in Fragmenting Munitions", PA TR-4548 (AD 526 920L), July 1973, (C).	Geometrical effect, high density material, processing
99.	D. Nathan, R. Webster and G. Gaydos, "A Systems Effectiveness Analysis of the M1 Shell Load w/Five Explosives", PA TR-4501 (AD 525 780L). January 1973, (C).	Arena test, artillery, explosive, fragment distribution, lethality, velocity (fragment)
100.	H. Chanin, "A Production Cost Estimating Relationship for Gun Fired High Explosive Artillery Warheads", PA TR-2056 (AD 906 460L), October 1972, (U).	Artillery, processing
101.	C. J. Gardner, "Sensitivity Analysis of Parameters used in Optimization Methodology for Naturally Fragmenting Munitions", PA TM-1996, (AD 515 140L), March 1971, (C).	Alloy steel, arena test, carbon steel, cast material, lethality, mortar
102.	R. D. Webster, "A Fragmentation and Lethality Evaluation of 4.2-Inch Mortar Projectiles in the Fragmentation Material Program", PA TR-4146 (AD 512 994), October 1970, (C).	Alloy steel, arena test, carbon steel, fragment distribution, lethality, mortar, processing, velocity (fragment)
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105.	W. Griffel, "Geometry of Fragmentation Test Arenas and Determination of Zone Factors", PA TR-4102 (AD 876 065), July 1970, (U).	Arena test, fragment distribution, lethality
106.	G. M. Gaydos and W. Griffel, "A Lethality Evaluation of the 105MM M1 Shell Loaded with Various Explosive Fillers", PA TR-4087 (AD 510 747L), June 1970, (C).	Artillery, explosive, lethality
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124.	R. Weil, A. Bornemann and C. Chandler, "Fragmentation of Steel", PA TR-3255, November 1965, (U).	Carbon steel, cylinder, geometrical effect, grain boundary embrittlement, mechanical properties
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135.	M. Kasper, "Effectiveness of Area Fire Weapons", NOLTR 68-28 (AD 390 611) February 1968, (C).	Artillery, cannon caliber, lethality, mortar
136.	A. D. Solem, "Explosives Comparison for Fragmentation Effectiveness", NOLWO R-2933 (AD 40 095), August 1953, (C).	Carbon steel, cylinder explosive, fragment distribution, velocity (fragment)

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255.	E. E. Banks, "Metallographic Features of Explosively Produced Spall Fractures in a Low-Carbon Steel", Journal of the Iron and Steel Institute, Vol 206, p. 1022, October 1968, (U).	Carbon steel, fractography, fracture analysis, metallography, spall, strain rate effect
256.	E. E. Banks, "Fracture and Fragmentation in Shock Loading of Metals", The Journal of the Australian Institute of Metals, Vol 13, No. 1, p. 39, February 1968, (U).	Fracture analysis, spall, theory
257.	E. E. Banks, "The Ductility of Metals under Explosive Loading Conditions", Journal of the Institute of Metals, Vol 96, p. 375, 1968, (U).	Alloy steel, carbon steel, cylinder, flash x-ray, fracture analysis, geometrical effect, strain rate effect, velocity (fragment)
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259.	K. E. Puttick, "The Shear Component of Ductile Fracture", Phil. Mag., Vol 5, p. 759, July 1960, (U).	Adiabatic shear, theory
260.	N. F. Mott, "Fragmentation of Shell Cases", Proc. Roy. Soc. (London), Series A189, p. 300, 1947.	Cylinder, fracture analysis, fragment distribution, theory
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NOTE: There are four keywords (cylinder, fragment distribution, geometrical effect, and processing) each of which would require more than 80 separate bibliographical citations. In the interest of brevity, only the number of citations for each major performing activity are listed for these four keywords.

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ARMY

AMMRC	Army Materials and Mechanics Research Center, Watertown, MA
ARMCOM	Army Armaments Command, Rock Island, IL
AMSAA	Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD
APG	Aberdeen Proving Ground, Aberdeen, MD
BRL	Ballistics Research Laboratories, Aberdeen Proving Ground, MD
FA	Frankford Arsenal, Philadelphia, PA
PA	Picatinny Arsenal, Dover, NJ

NAVY

NOL	Naval Ordnance Laboratory, White Oak, Silver Spring, MD
NWC	Naval Weapons Center, China Lake, CA
NWL	Naval Weapons Laboratory, Dahlgren, VA

AIR FORCE

ADTC	Armament Development and Test Center, Eglin Air Force Base, FL
AFATL	Air Force Armament Laboratory, Eglin Air Force Base, FL

OTHER

NMAB	National Materials Advisory Board, National Academy of Sciences, Washington, DC

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