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FRACTOGRAPHIC ANALYSES OF DENSIFIED CERAMICS AND GLASS-CERAMICS BALLISTICALLY IMPACTED BY CALIBER .30 M2 PROJECTILES

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Technical Report by

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ABSTRACT

Utilizing low magnifications, fractographic analyses have been conducted on low-temperature densified ceramics and glass-ceramics ballistically impacted by caliber .30 M2 projectiles. From examinations of fracture-exposed surfaces, the macroscopic sequence of ballistic fracture occurring outside the initial conoid has been determined and found to be qualitatively similar for both material classes and for impact by both BALL and AP projectiles. Observations indicate that a number of imperfections such as irregularities in as-received specimen surfaces and internal macroporosity induce alterations in ballistic crack fronts.

CONTENTS

INTRODUCTION

Utilizing computer codes, the macroscopic fracture sequence of ceramic composite armor impacted by ogive-shaped, hardened steel, small arms projectiles has been recently predicted.[1,2] Principal features of this fracture sequence, which typically is completed within less than 50 microseconds after impact, have been confirmed by employing high-speed cameras with flash X-ray[1,2] and optical[3] techniques. In addition, Fréchette and Cline have employed fractographic analyses at a variety of magnifications, ranging from visual observation to electron microscopy, to confirm the macroscopic fracture sequence and elucidate elements of the microscopic deformation and fracture behavior of ceramics.[4] It is noteworthy that the detailed macroscopic fracture sequence reported by Fréchette and Cline is qualitatively similar for a wide variety of materials, such as steels, single-crystal and polycrystalline aluminas, beryllium oxide, boron carbide, and glasses, impacted by both ogive-shaped and blunt projectiles.

The purpose of the present investigation is to analyze the fracture surfaces of relatively inexpensive and easily fabricated candidate ceramic armor materials following ballistic impact by caliber .30 M2 projectiles in order to determine the macroscopic sequence of fracture and the possible effects of ceramic macrostructure on the ballistic fracture response. Materials employed in this investigation comprise two classes: (1) Cer-Vit glass-ceramic compositions, C-101, C-117, and C-126, obtained from Owens-Illinois Development Center, Toledo, Ohio; and (2) impregnated and low-temperature densified alumina, silicon carbide, and silicon carbide-silicon nitride ceramics obtained from Kaman Nuclear, Colorado Springs, Colorado.* Ballistic results obtained for these materials form the subject of a separate report (AMMRC TR 70-19).

EXPERIMENTAL

Glass-ceramic ballistic specimens, approximately 1/3-inch thick by 6 inches in diameter, and densified ceramic ballistic specimens, approximately 1/3-inch thick by 6 inches square with rounded corners, were individually mounted on 12" x 12" x 1/4" Doron plates. These composite armor specimens were tested by impact with caliber .30 BALL M2 and AP M2 projectiles at the AMMRC ballistic range, utilizing testing techniques specified elsewhere.[5] Subsequent to ballistic impact, individual specimens were observed under low magnifications, below 5X, in order to determine the macroscopic fracture sequences and to examine topographical features of particular interest. Macrophotographs taken of typical fracture patterns and fracture pattern anomalies are displayed and discussed in the following section.

RESULTS AND DISCUSSION

Macroscopic fracture patterns and general fracture sequences (Figures 1 and 2) for both material classes are qualitatively similar to those reported by Fréchette and Cline.[4] In the present study, several different methods to retain

*Compositional and processing details for these materials are proprietary.

intact portions of the ceramics nearest the ballistic impacts were unsuccessful; hence, elements of the initial sequences within the fracture conoids could not be determined. These methods included using a styrofoam-lined box containing an approximately 1-1/2-inch-diameter central hole through which both V_{50}-range and low-velocity projectiles were shot and utilization of several layers of masking tape to hold fragments in place.

Even though portions from fracture conoids could not be employed to reconstruct the initial fracture sequences, it is obvious that ballistic energy absorption is greatest near the axis of impact. In all cases, fragments become larger in size on proceeding radially from the impact axis to the periphery of the impacted specimens.

Initial radial cracks having included angles between 30° and 45° occur prior to circumferential cracks. This sequence is particularly evident in Figures 1b and 2d and is determined from the discontinuity of circumferential cracks at intersections with radial cracks. However, subsequent radial cracks are also initiated after circumferential cracking has commenced. This behavior is inferred from the continuity of circumferential cracks at intersections with radial cracks and may be observed in Figures 1c and 2a. Late-time front face spallation is frequently observed to occur toward the periphery (Figures 1a, 1c, 2d, and 2e) and is generally initiated at the intersection of radial and circumferential cracks. The peripheral fracture domain size and distribution is indicative of the relative amounts of ballistic energy absorbed by the ceramic for varying projectile velocities as depicted in Figures 1a, 1b, 2d, and 2e where projectile velocities were greater for Figures 1b and 2d.

Particularly evident, moreover, is the corrugated nature of many fracture-exposed surfaces which for a given specimen lie on several planes approximately perpendicular to the impact axis (Figures 1b and 2a). It is reasonable to correlate qualitatively the distance between such parallel fracture planes with both the axial stress generated by projectile impact and the dynamic tensile strength of the target ceramic. The corrugated topography of the fracture surface is postulated to arise from modulation of the local axial stress by the radial and circumferential stress components, with the corrugation wavelength indicative of stress wave reverberations. The corrugations are less prominent for the densified ceramics than for the glass-ceramics. It is thought that the greater porosity present in the former materials, resulting in greater stress wave attenuation and perhaps finer scale fracture, might be responsible.

Macroscopic irregularities in the surface topography of the as-received densified ceramic specimens are observed to have a profound influence on crack propagation. Both forming features (Figure 2c) and scribed identification marks (Figures 2a, 2b, and 2e) induce preferential crack propagation. Furthermore, as depicted in Figure 2a, internal macroporosity alters the direction of the fracture path within the densified ceramic. It is evident that the fracture path has changed direction in order to intersect each pore near its center. This result would suggest that porosity, acting as regions of stress concentration, might degrade ballistic performance by enhancing ceramic fracture during ballistic impact. Edge effects due to specimen geometry are also evident for the densified ceramics. Initial radial cracks in square tiles seek out the tile corners (Figure 2e) rather than spreading randomly from the center of impact.

However, the relative importance of edge effects occurring outside the fracture conoid for degrading ballistic performance is not known at present.

CONCLUSIONS

1. Following ballistic impact, initial radial cracks having 30° to 45° included angles precede circumferential cracks in the ceramics that were investigated. Secondary radial cracks having smaller (5° to 10°) included angles are initiated subsequent to circumferential cracking.

2. The ballistic fracture path frequently follows topographical irregularities in the front surface of the ceramic face plate.

3. Internal macroporosity, and possibly other internal defects, induces a local alteration of the fracture path. For the macroporosity observed in the present study, the fracture path is induced to intersect the pores.

4. Ceramic tiles for ballistic evaluation that are either 6 inches in diameter or 6 inches square insufficiently wide to eliminate edge effects during ballistic fracture, particularly when ballistic impacts are off-center.

RECOMMENDATIONS

Based upon observations during the present investigation, a number of recommendations are suggested for continuing research in this area:

1. Further fractographic analyses of these materials on a microscale are suggested. Some points of interest are possible correlation of the relative amount of total ballistic energy absorption with microtopography for each portion of the fracture sequence, study of the effects of increasing the percentage of crystalline phase in glass-ceramics on fracture behavior, examination of densified ceramics for preferential ballistic fracture at the matrix-impregnant interface, and study of fracture-exposed surfaces near porosity to determine whether porosity inhibits, increases, or does not alter the velocity of the crack front.

2. Improvements in the materials utilized for ballistic testing are desirable. Ceramic tiles for ballistic testing should have surfaces as free of irregularities as possible, and ballistic testing of new and existing materials should be performed, whenever possible, with circular tiles having a minimum diameter of at least 8 inches in order to minimize edge effects during fracture following off-center impact. Further study is necessary to assess the importance of edge effects in degrading ballistic performance.

ACKNOWLEDGMENTS

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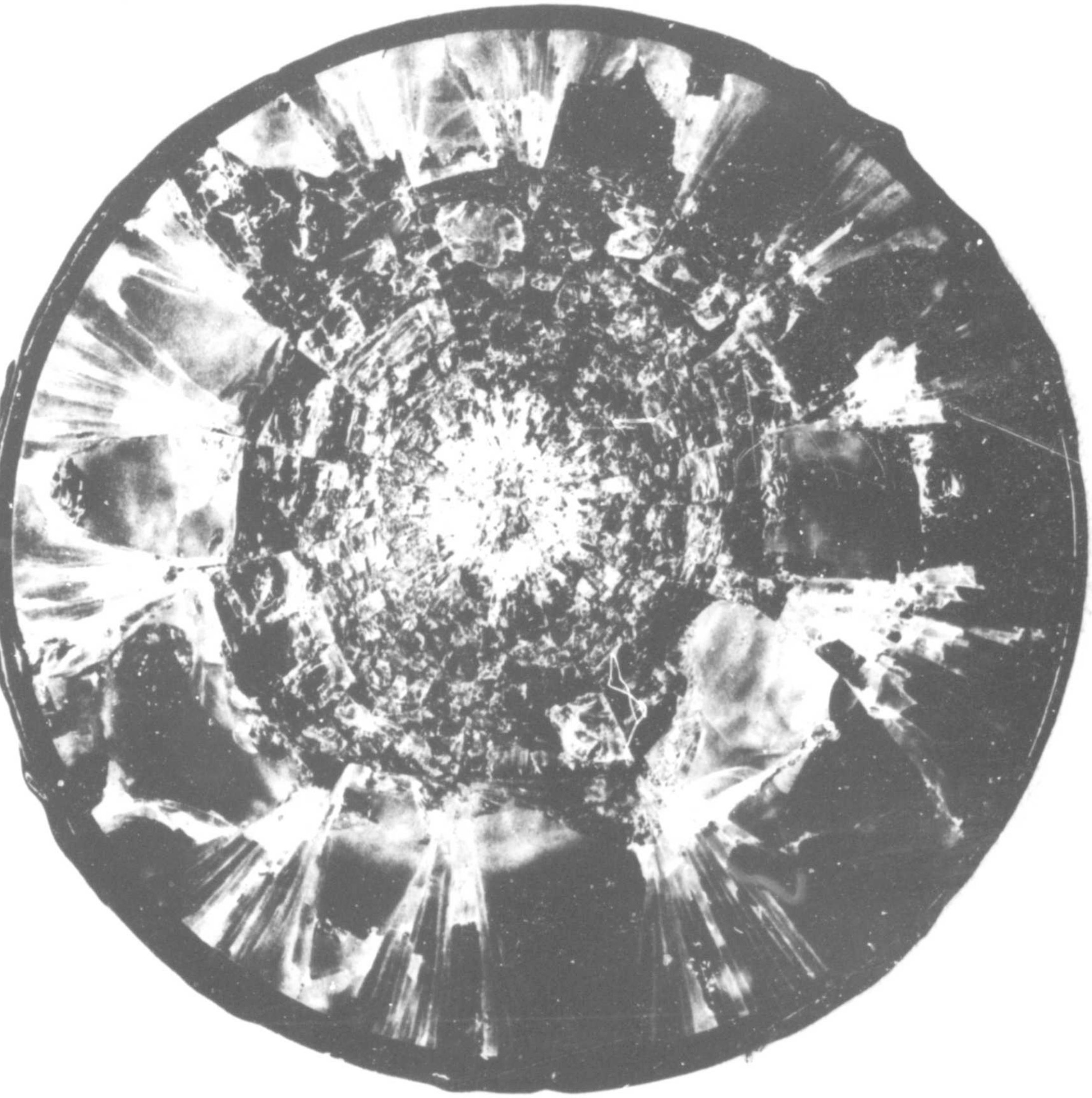
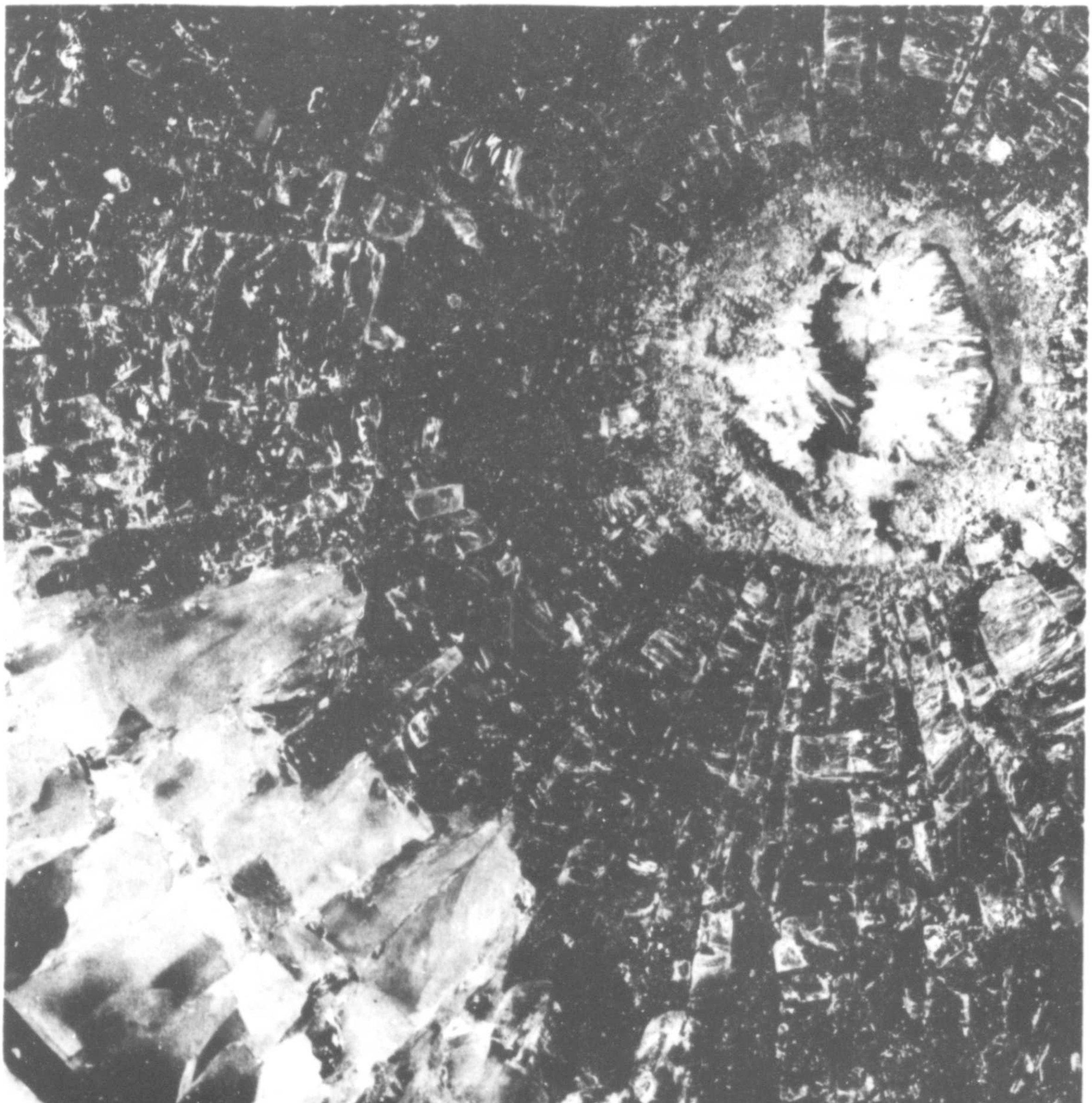


C101 (AP) Mag. 1X

Figure 1a. FRACTURE PATTERNS OF GLASS-CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

19-066-268/AMC-70



C101 (BALL) Mag. 2X

Figure 1b. FRACTURE PATTERNS OF GLASS-CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

19-066-271/AMC-70

C117 (BALL) Mag. 1X

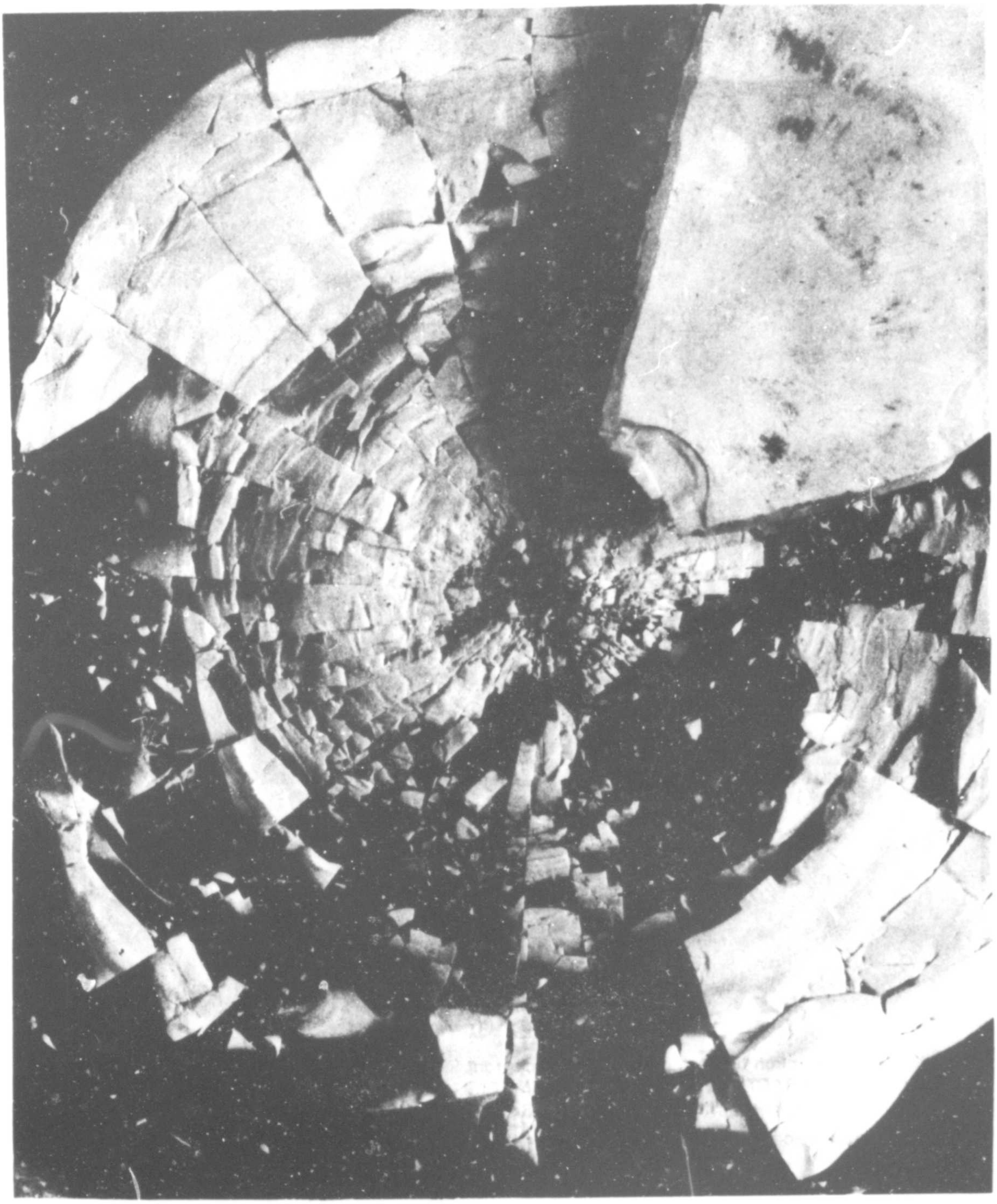
Figure 1c. FRACTURE PATTERNS OF GLASS-CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

19-066-264/AMC-70

C126 (BALL) Mag. 2X

Figure 1d. FRACTURE PATTERNS OF GLASS-CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

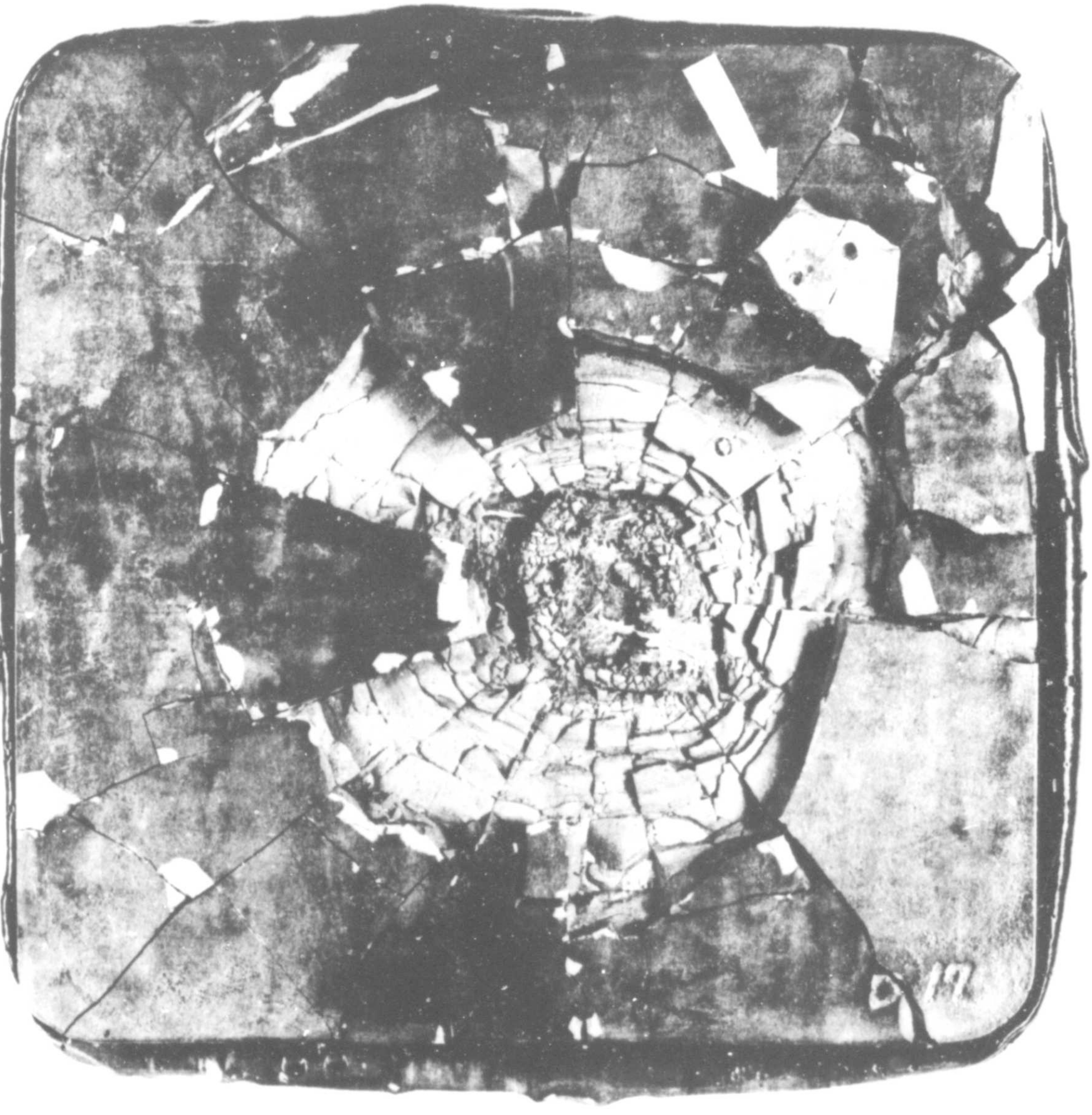
19-066-267/AMC-70



C126 (AP) Mag. 2X

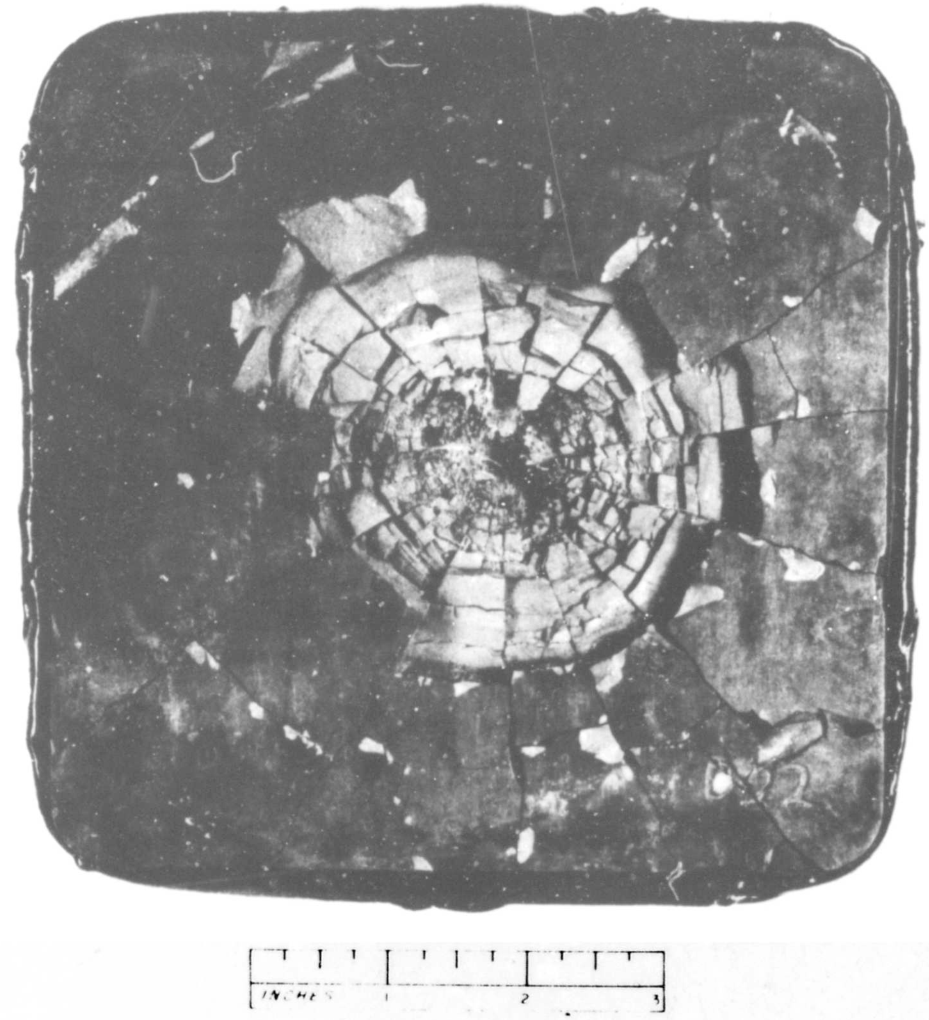
Figure 1e. FRACTURE PATTERNS OF GLASS-CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

19-066-269/AMC-70



Interaction between porosity and crack front in densified silicon carbide. (BALL)
Figure 2a. FRACTURE PATTERNS OF DENSIFIED CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

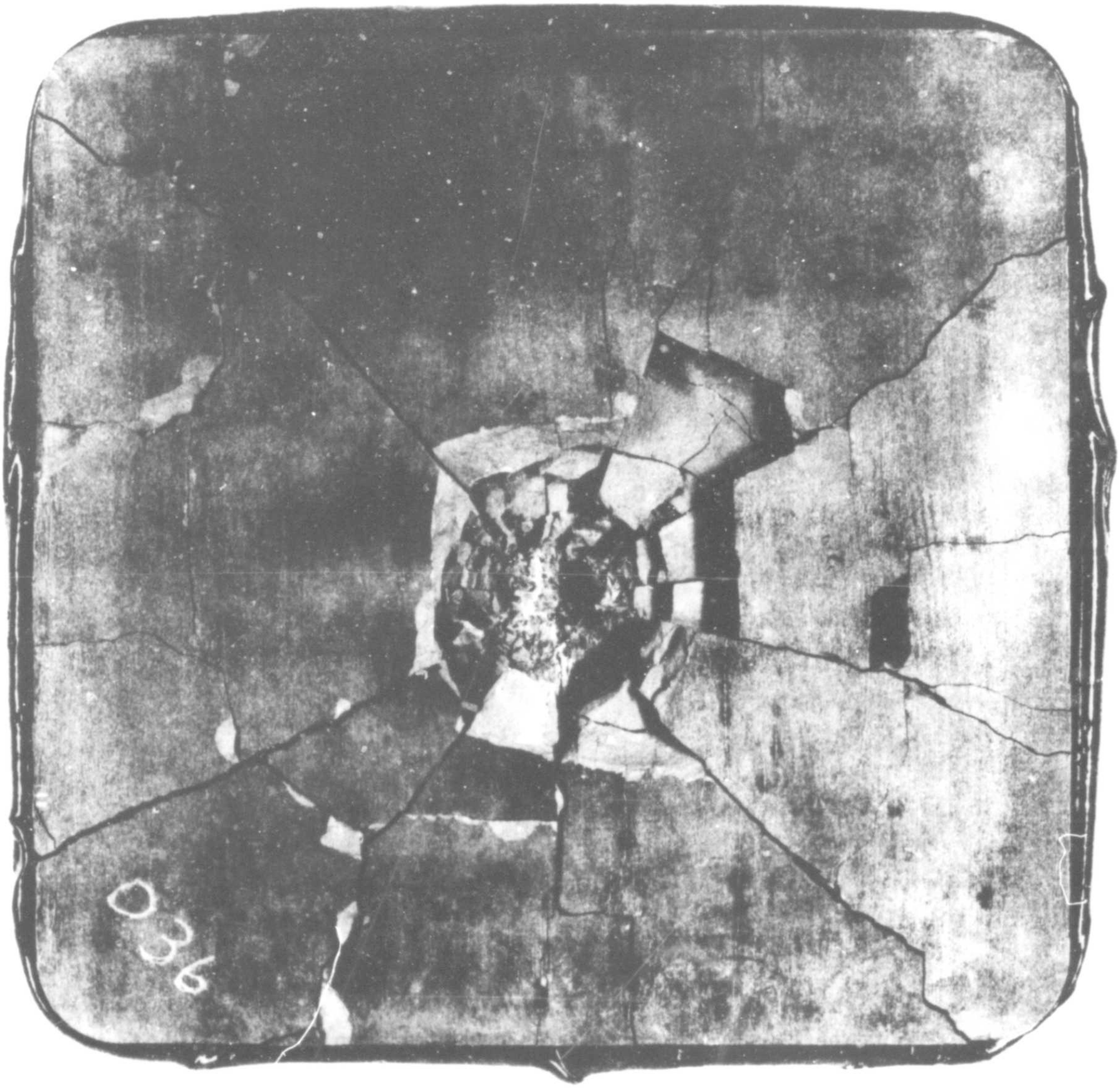
19-066-270/AMC-70



Fracture through surface imperfection in densified silicon carbide. (BALL)

Figure 2b. FRACTURE PATTERNS OF DENSIFIED CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

19-066-263/AMC-70



Fracture through surface imperfection in densified aluminum oxide (BALL)

Figure 2c. FRACTURE PATTERNS OF DENSIFIED CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

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Rearmost portion of fracture conoid for densified silicon carbide - silicon nitride. (BALL)

Figure 2d. FRACTURE PATTERNS OF DENSIFIED CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

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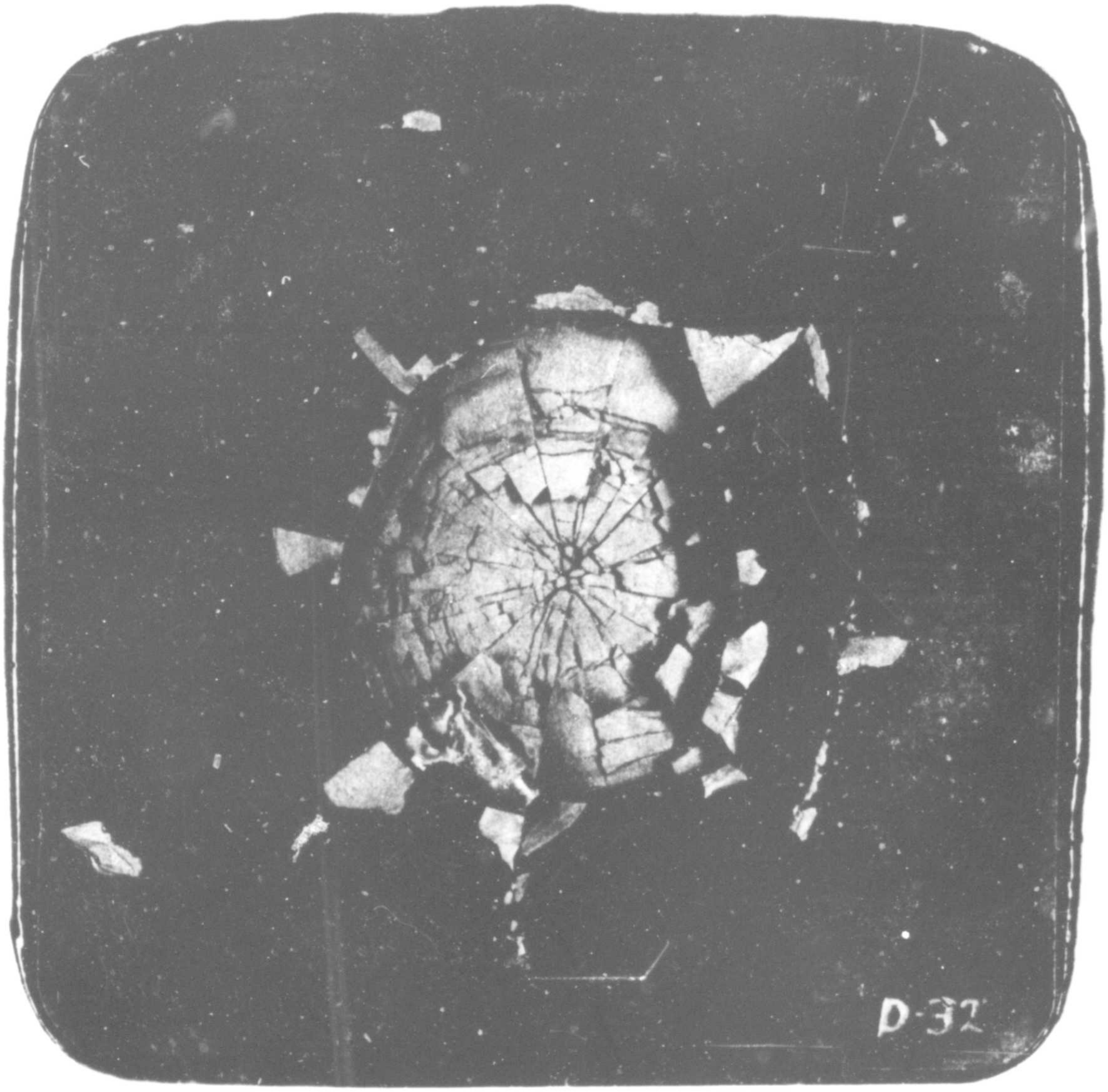

Prominent front-face spallation in fracture for densified silicon carbide - silicon nitride (AP)

Figure 2e. FRACTURE PATTERNS OF DENSIFIED CERAMICS FOLLOWING BALLISTIC IMPACT BY CALIBER .30 M2 PROJECTILES

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Ceramics						
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Lightweight armor						
Devitrified glass						