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EXPLORATORY STUDIES WITH LARGE-GRAINED MATERIALS IN TERMINAL BALLISTIC RESEARCH

by

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for the
Research Department

ABSTRACT. A technique for the preparation of polycrystalline forms of copper with grain sizes in excess of 25 mm makes it feasible to prepare targets for ballistic test in which the deformation of the perforation processes occurs within a few crystal grains or even within a single grain. A description of the process of target preparation is presented, some crystallographic aspects of penetration studies are discussed, and data from tests in which missiles impacted against targets at velocities from 0.6 to 3.6 km/sec are presented.

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FOREWORD

The material in this report represents part of a continuing applied research program in support of explosive ordnance problems at the Naval Weapons Center. This report on preliminary findings of the study is released at the working level and is still subject to modification.

These studies were supported by funds under the Naval Air Systems Command Task Assignment A35-350-004/216-1/F008-08-06, and were conducted by George D. Marshall, Professor of Metallurgy at the Naval Postgraduate School, Monterey, California.

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INTRODUCTION

The materials of the most common interest in terminal ballistic studies are polycrystalline metals with grain size very small compared to the crater dimensions. A technique for the preparation of polycrystalline forms of copper with grain sizes in excess of 25 mm makes it feasible to prepare targets for ballistic test in which the deformation of the perforation processes occurs within a few crystal grains or even within a single grain. The following describes an initial investigation of the potentialities of this process in terminal ballistic research. A description of the process of target preparation is presented, some crystallographic aspects of penetration studies are discussed, and data from tests in which missiles impacted against targets at velocities from 0.6 to 3.6 km/sec are presented. Conclusions are given on the use of this technique in terminal ballistic research.

CRYSTALLOGRAPHIC AND MICROSTRUCTURAL ASPECTS OF TERMINAL BALLISTIC STUDIES

The ultimate objective of penetration studies is to correlate dynamic deformations and failure to physical and mechanical properties of the media. Thus, typically an attempt is made to relate perforation diameter or residual projectile velocity to the impact velocity and material parameters such as the hardness, density, and elastic constants. An understanding of the behavior of the target material at the microstructural level is not usually a primary concern. However, it is not necessarily obvious whether the deformations and fracture of a perforating impact should simply be correlated to empirically determined material properties, or if a deeper correlation can be made to crystallographic type or to natural reaction of some microstructural component to the transient stress conditions. The possible relevance of crystallographic and microstructural aspects of material behavior can be seen by considering each of these in more detail.

CRYSTALLOGRAPHIC ASPECTS

Two classes of materials that are of military interest are steels in various types and conditions and alloys of aluminum. These materials are sensibly homogeneous and isotropic and are characterized by macroscopic parameters such as the density, elastic constants and yield values; however, some of the distinctive characteristics of individual materials can be correlated to their crystallographic type. Thus, steel in the pearlitic or martensitic categories has characteristics related to the brittle-ductile nature of body-centered cubic metals in general, while austenitic steels and aluminum alloys represent the tough and ductile behavior of face-centered cubic metals.

MICROSTRUCTURAL ASPECTS

Engineering materials are rarely homogeneous isotropic media at the microscopic level. A typical microstructure consists of polyhedral grains of a metallic phase and a variety of smaller particles of a separate metallic phase or phases. Nonmetallic particles such as oxide impurities as well as voids, and fissures may also be present. Manufacturing controls determine the sizes, shapes, and distribution of the grains and particles, some of which are too small to be observed by optical microscopy. The distribution of the sizes and shapes of grains and the crystallographic characteristics of the grains are among the factors that determine the gross properties of the material. To these factors must be added the effects of work hardening, balanced elastic stress patterns (sometimes called locked-in stress), and the potential for physical or chemical change associated with metastable equilibria.

In the last analysis, deformation of any crystalline material must be considered in terms of dislocation movement and interaction. To be considered plastic, the material must permit glissile displacement of dislocations within the individual grains even though local stress-strain relations may preclude the realization of the expected flow process. Brittleness, on the other hand, characterizes the inadequacy of dislocation movement to provide for displacement in response to applied stress. Fracture, rather than flow, occurs readily in brittle materials, especially under complex stress conditions and at high strain rates. The body-centered cubic metals undergo a transition from ductile to brittle behavior as the temperature is lowered. Thus temperature, strain rate, and stress pattern all participate in the phenomenon of low-temperature brittle fracture and it is not strange that this aspect of material behavior is poorly understood.

IMPLICATIONS IN TERMINAL BALLISTICS

Engineering materials at the microscopic level must be regarded as a complex mixture of brittle and ductile substances, further complicated by the individual anisotropies and random orientations of the various components of the microstructure.

Ideally, it would be desirable to study the response of each component and of each cluster or arrangement of elemental particles to the conditions encountered in penetration mechanics in the same way that the

the macroscopic behavior of the entity is studied. In this way the contribution of the anisotropic unit to the substantially isotropic whole could be evaluated more precisely. One problem with such a procedure is the difficulty of preparing material of adequate purity, homogeneity, and cleanliness. A second problem is that of producing crystals free of structural defects. These two problems are somewhat interrelated.

Structural defects, including solute atoms, dislocations, free surfaces and interfaces, dispersed clusters, and coherent (martensitic) fragments or domains determine the resistance of crystals to plastic deformation under stress and serve to characterize the material as brittle or ductile with respect to the conditions of loading. It is recognized that many of these defects cannot be avoided entirely, but some of them may be reduced to a relatively low level by judicious selection of the material. The effects of grain boundaries and interfaces may be minimized through use of large single crystals or aggregates of very large grains.

EXPERIMENTAL PROCEDURE

For the exploratory experiments described herein copper has been selected in spite of the fact that this material is not of major interest as a barrier to missile penetration. It has strength characteristics inferior to steel and cannot compete with aluminum in high strength/weight applications. However, like aluminum, nickel and austenitic steel, it has the face-centered cubic crystal structure so that the distribution of stress and strain, the flow and fracture pattern, and the work-hardening characteristics should be comparable. At the same time, copper of acceptable purity is obtainable commercially without premium. It is virtually free of interstitial impurities and the substitutional solute content is comfortably low.[1] The most common commercial grade contains a small, virtually insoluble, oxide residue. Very large grains can be grown by any of several techniques.

TARGET PREPARATION

The copper targets used for this study were treated by a method suggested by Cook and Macquarie[2] to produce the large grains desired. In

[1] ASTM spec. B5-43, for commercial grade E.T.P. copper, calls for 99.90% by weight of copper, silver being counted as copper. Silver seldom exceeds 8 oz per ton (about 0.03%) and oxygen, as cuprous oxide, is about 0.04%. Thus, the solute atom content should be less than 900 ppm.

[2] Maurice Cook and C. Macquarie, AIME Technical Publication No. 974 dated September 1938.

contrast to the strain-anneal methods used to prepare large crystals of many common metals, this method makes use of very heavy reduction by rolling to produce a strongly oriented fiber pattern in the cold-worked metal. In practice, reduction in thickness exceeding 95% of the initial thickness is required. The initial thickness of this target material was limited to 1.100 inches by the capacity of the rolling equipment available so that the finished thickness was 0.055 inch. This is somewhat thinner than targets used in comparable tests of conventional material.

The very large grains develop as the result of the phenomenon of secondary recrystallization and grain growth occurring at temperatures above about 950°C. A few grains from the primary recrystallization process are so oriented as to grow rapidly in directions paralleling the plate surface. The less favored grains are, of course, absorbed in the process.

The crystallographic orientations of the preferred grains are strikingly similar as evidenced by the occurrence of numerous twin interfaces all pointing in closely related directions. The type of preferred orientation or fiber structure assumed by the large grains has been the object of extensive study and will not be considered further here.

Heat treatment of the severely deformed material was performed in conventional laboratory-type equipment. To prevent excessive scaling, the plates were wrapped in copper foil and were quenched from the furnace. Previous experience had indicated that reducing or neutral conditions in the furnace atmosphere interfered with the grain coarsening process. The foil oxidized rapidly at 950 to 1000°C but protected the specimen material adequately for anneals of short duration. Additional thicknesses of foil could have been used for longer times, but foils of other metals were avoided to preclude accidental contamination. Thirty minutes at temperature was adequate for the intended purpose.

The plates were cleaned by immersion in hot 20% sulfuric acid followed by etching in cold 50% nitric acid. The resulting grain structure may be seen in Fig. 1 and 2.

In addition to occasional small twinned regions, there is a more or less uniform dispersion of fine particles of cuprous oxide through the coarse grains. A control target annealed at 450°C developed an average grain size of approximately 0.012 mm.

MEASUREMENT PROCEDURE

Targets were 4-inch-square plates of the prepared material. Missiles employed were either steel spheres or small cylinders of aluminum alloy. The shots were fired at the high-velocity missile research facility of

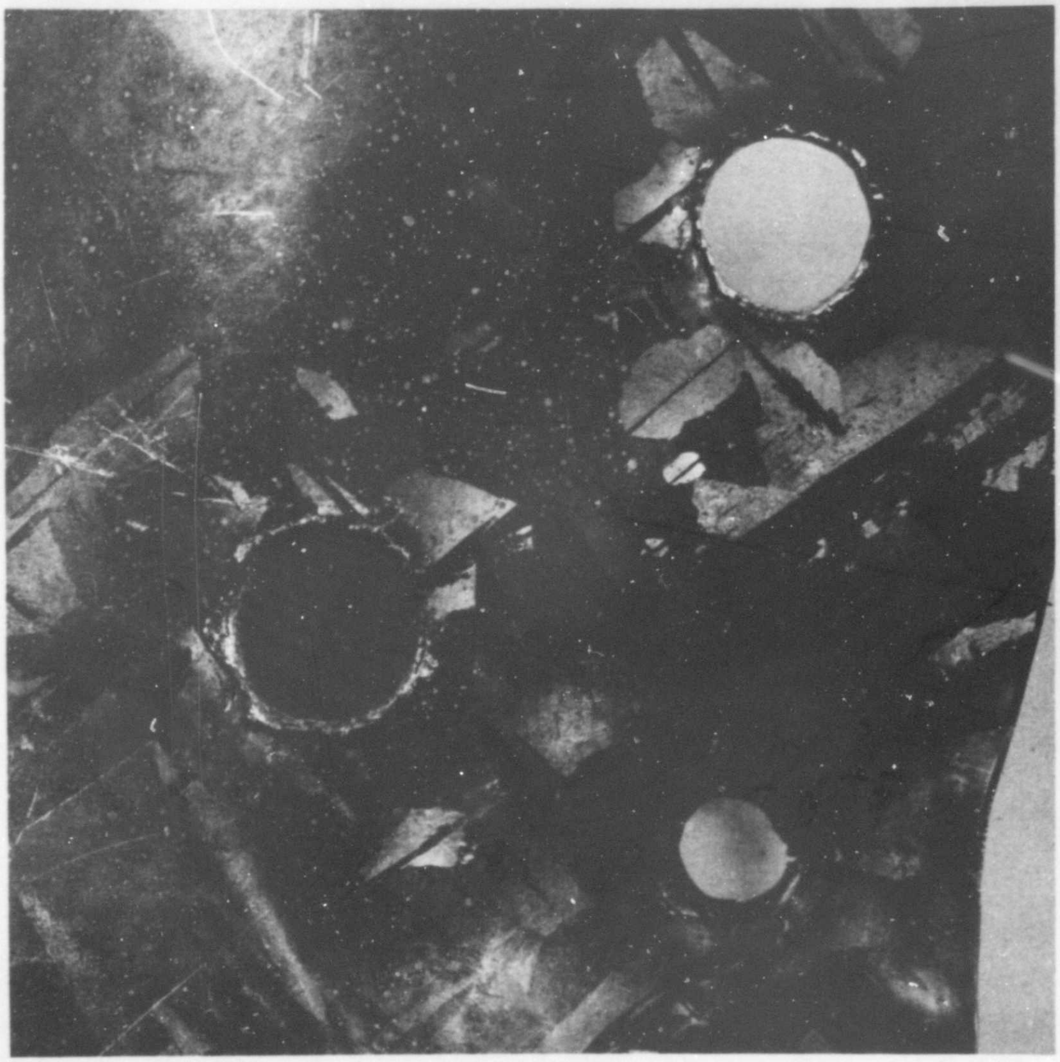


FIG. 1. Target Perforated by Aluminum Alloy Cylinders. The coarse-grained structure of the target material is apparent. 1-3/4X.

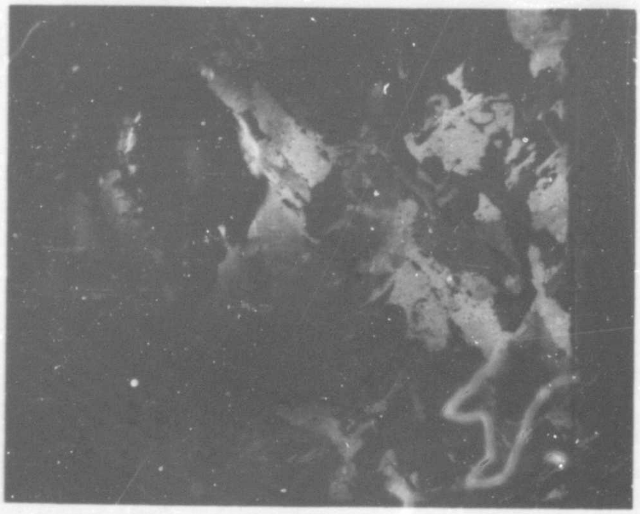


FIG. 2. Target Perforated by Steel Spheres. The large perforation was caused by the sabot in the final shot of the series.

this Center, using the powder gun at velocities of 0.6 to 3.6 km/sec. The gun was readily boresighted on selected target areas, preferably individual large grains. Firing conditions and subsequent measurements are given in Table 1.

TABLE 1. Firing Data

Series	Missile	Velocity, km/sec	Hole diam., in.	Remarks
1a	Al cylinder[a]	3.6	0.5625	Fig. 1
1b	Do.	1.8	0.50	Fig. 1
1c	Do.	0.6	....[b]	Fig. 1
2a	Steel sphere[c]	3.6	0.32	Fig. 2
2b	Do.	3.3	0.31	Fig. 2
2c	Do.	3.0	0.29-0.30	Fig. 2
2d	Do.	2.7	0.29-0.28	Fig. 2
2e	Do.	1.9	0.24-0.25	Fig. 2
2f	Do.	1.3	....[c]	Fig. 2

[a] Cylinder, 0.025-in. diam., 0.3125-in. long, weighing 0.7 g of 2024 aluminum.

[b] The sabot did not separate from the missile at this velocity but passed through the stopper to impinge on the target with the missile.

[c] Steel sphere, 0.125-in. diam.

For purposes of comparison, similar firings were conducted on conventional fine-grained copper annealed to a grain size of 0.012 mm, and on severely cold-worked copper, 95% reduction. Results of these tests are reported in Table 2.

TABLE 2. Firing Data

Series	Target	Missile	Velocity km/sec	Crater diam. in.
3a	Annealed[a]	Steel sphere[b]	3.6[c]	0.47
3b	Do.	Do.	3.3[c]	double crater
3c	Do.	Do.	3.0[c]	0.46
3d	Do.	Do.	2.7[c]	0.43
3e	Do.	Do.	...	0.38
4a	Do.	Steel sphere[d]	3.5	0.32
4b	Do.	Do.	3.2[c]	0.30
4c	Do.	Do.	2.8	0.29
4d	Do.	Do.	2.7	0.275
5a	Hard[e]	Do.	3.6	0.28
5b	Do.	Do.	3.2	0.266
5c	Do.	Do.	2.8[c]	0.26
5d	Do.	Do.	2.1	0.23

[a] Annealed electrolytic tough pitch (E.T.P.) copper, grain size 0.012 mm, Rockwell F-42.

[b] Steel sphere, 0.025-in. diam.--velocity not measured but estimated from similar firings.

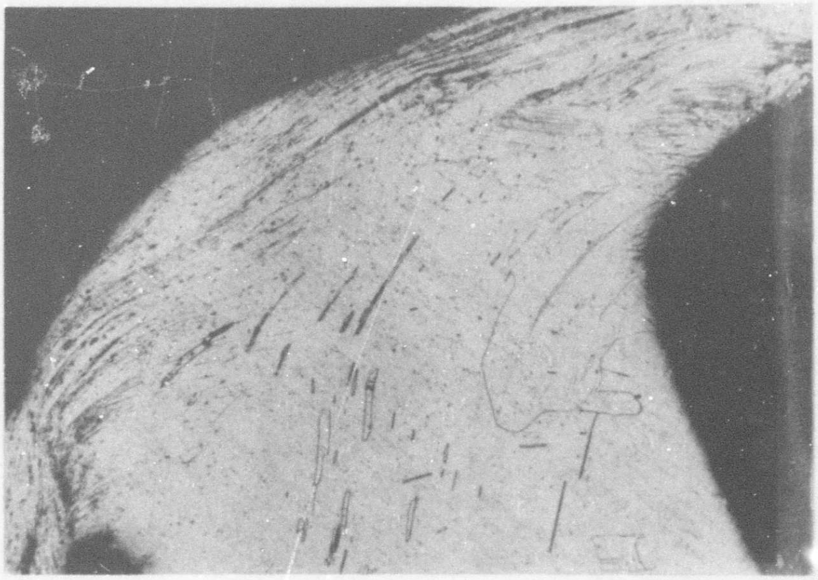
[c] Estimated from similar firing.

[d] Steel sphere, 0.125-in. diam.

[e] Hard worked E.T.P. copper (95% reduction), Rockwell F-97.

Cross sections for microscopic examination were prepared of several of the perforations. These are presented as Fig. 3(a) to 8(a). It will be noted that the flow pattern of metal in relation to the hole is not clearly delineated since there are few visible structural details present to decorate the pattern.

In order to delineate the extent and pattern of plastic deformation associated with the penetration, part of each area containing a crater was heated to 450°C to recrystallize the work-hardened metal. The recrystallized areas, Fig. 3(b) to 8(b) give a sensitive indication of the extent of deformation in excess of the critical deformation required for copper. Copper deformed in tension will recrystallize if the deformation exceeds approximately 0.8% elongation in a gage length of 4 inches. This procedure has the advantage of presenting the entire deformation pattern in graphic form.



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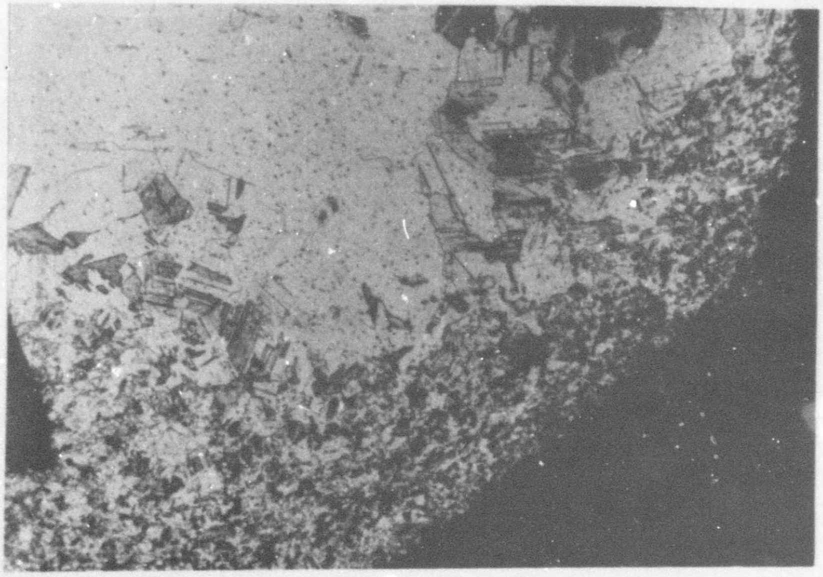
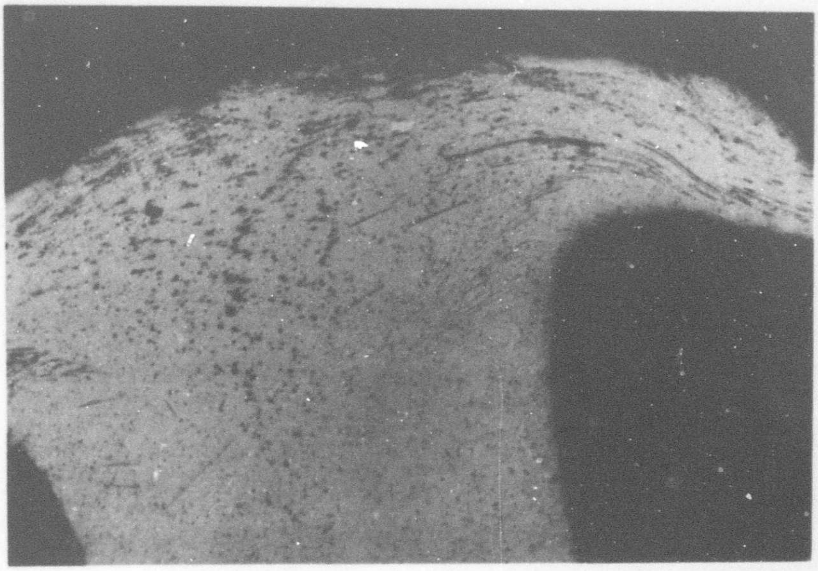


(b)

FIG. 3. Microstructure of Target Perforated by an Aluminum Alloy Cylinder. (a) Before heat treatment (b) after anneal. 50X. In this and following illustrations, the entrance surface is at the left.



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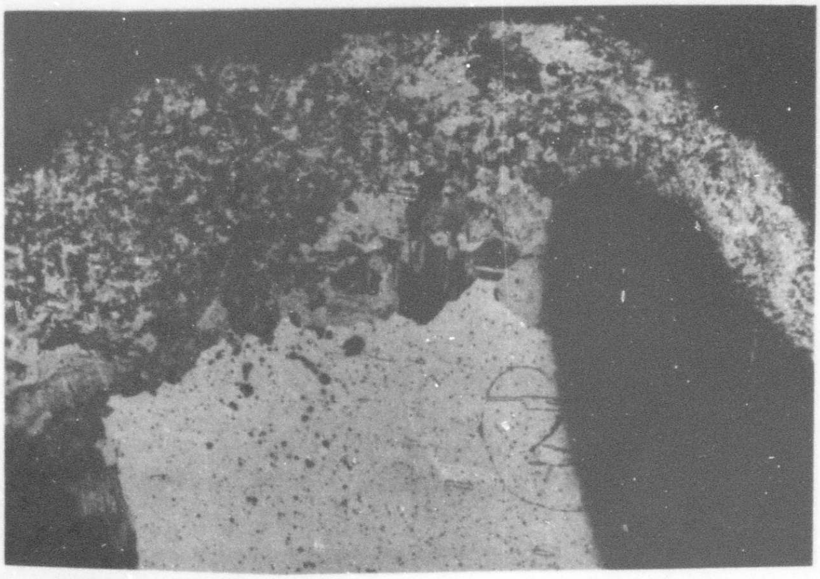

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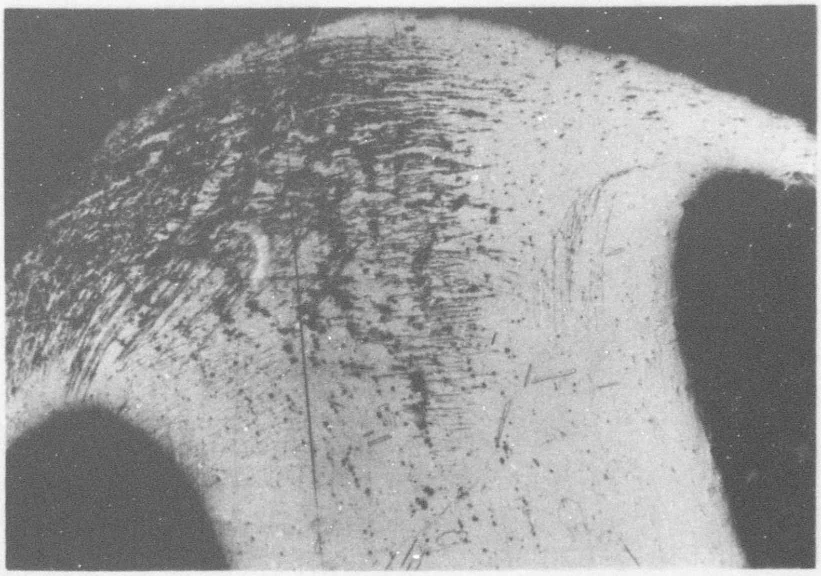
FIG. 4. Microstructure of Target at Perforation 1, Series 2. (a) Before heat treatment, (b) after anneal. 50X.



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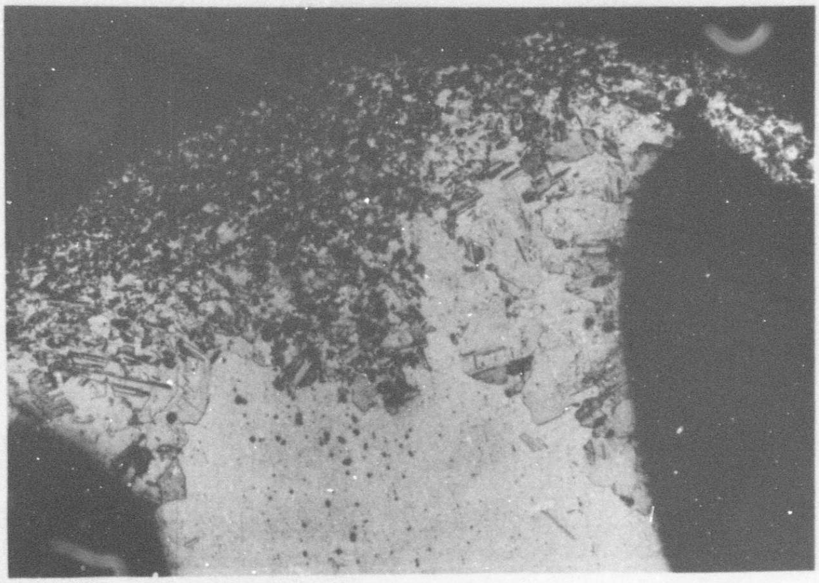

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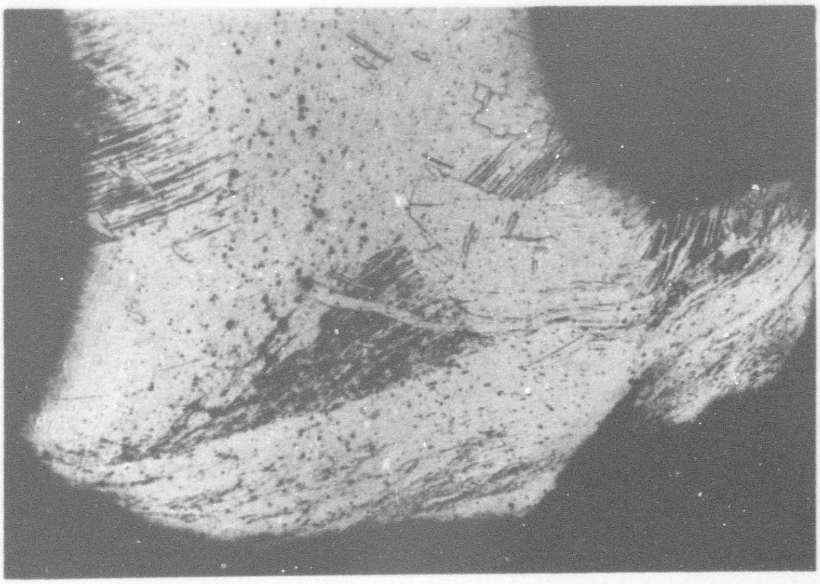
FIG. 5. Microstructure of Target at Perforation 2, Series 2. (a) Before heat treatment, (b) after anneal. 50X.



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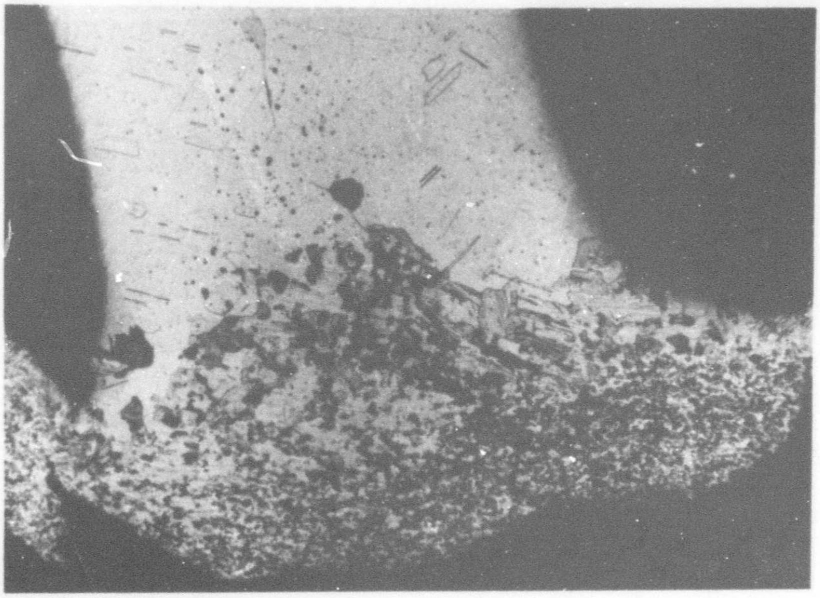
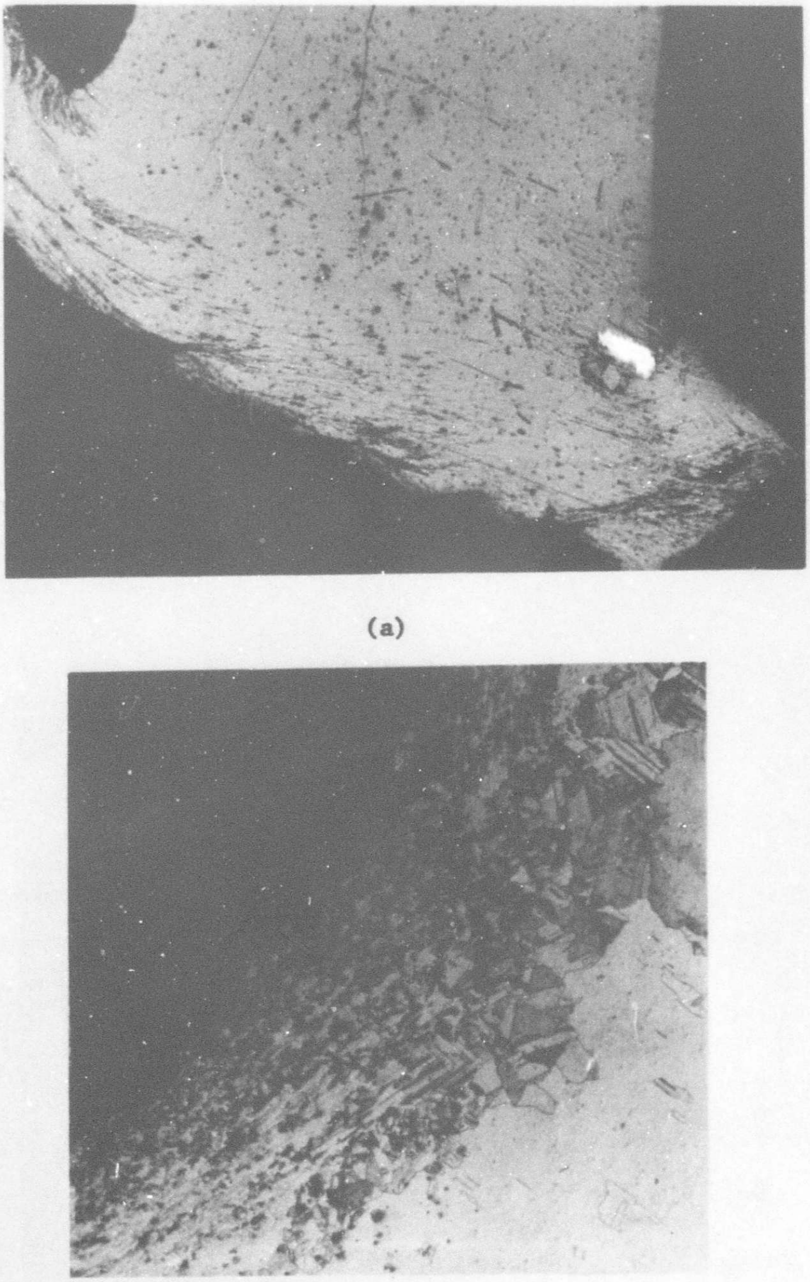


(b)

FIG. 6. Microstructure of Target at Perforation 3, Series 2. (a) Before heat treatment, (b) after anneal. 50X.

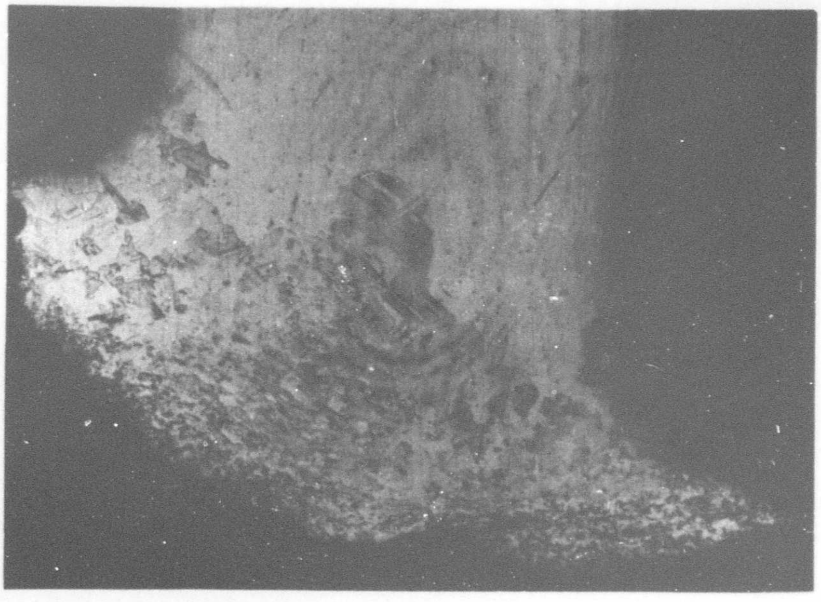


(a)

(b)

FIG. 7. Microstructure of Target at Perforation 4, Series 2. (a) Before heat treatment, (b) after anneal. Note: (b) is tangent to the crater. 50X.

(a)



(b)

FIG. 8. Microstructure of Target at Perforation 5, Series 2. (a) Before heat treatment, (b) after anneal. 50X.

DISCUSSION OF RESULTS

DEFORMATIONS

Examination of the external features of the craters for both the large-grained and the small-grained materials show few significant differences. The holes in the large-grained materials tend to be slightly distorted as would be expected for the plastically anisotropic crystals. The cross sections of the perforation craters are shown in Fig. 3-10. These all show the typical shape of a high-velocity perforation with a lip on both the entrance and exit side. As is typical of ductile materials, the lip on the entrance side is intact except for the work-hardened sample of Fig. 10.

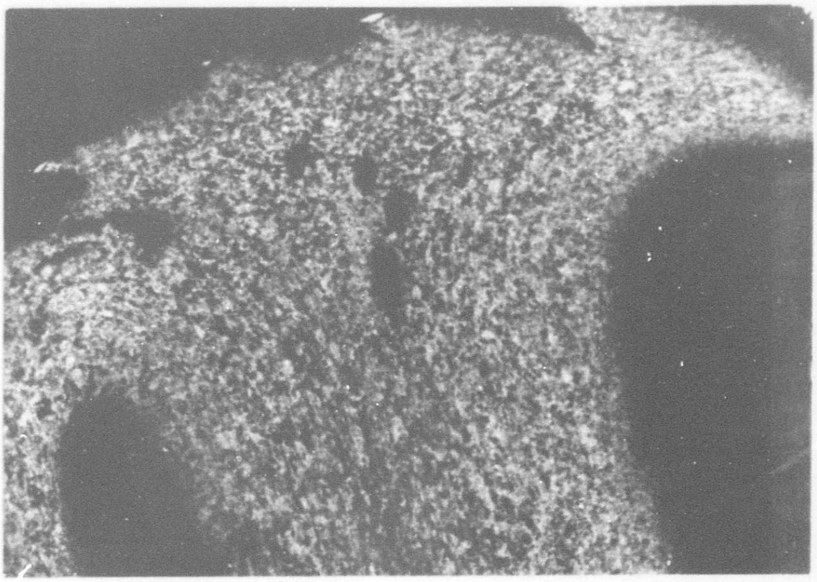
The crater diameter is a very simple measurement that indicated quantitatively the response of the targets to the impact. The crater diameters, Fig. 11, appear to bear a substantially linear relation to the muzzle velocity of the projectile at speeds well above the ballistic limit. There is no significant difference in crater diameter between fine-grained and coarse-grained targets. The work-hardened target yielded craters significantly smaller than those made by the same size projectile in annealed targets.

The cylindrical aluminum alloy projectile caused craters considerably larger than those made by steel spheres of the same diameter. The distribution of metal flow in Fig. 3 indicates maximum distortion at the entrance surface. This is consistent with the low density and high flow capability of the aluminum that would permit substantial flattening at impact and expenditure of energy at the forward surface of the target. Some tumbling of the cylinder may have occurred that would enlarge the impact area.

By contrast, the steel spheres appear to exert a greater effect in the later stages of penetration as illustrated by Fig. 5(b), 6(b), and 8(b). This would be consistent with the greater elasticity and higher hardness of the steel and the fact that there could be no tumbling to cause distortion.

It may be observed that deformation of these targets is entirely in the plastic mode, a characteristic of the majority of face-centered cubic metals. It is clear that this material is not suitable for the study of the interplay of brittle and ductile modes in the perforation process. Such a comparison could be made on targets of iron alloys amenable to the formation of large crystals. Some iron-silicon alloys used for electrical purposes can be obtained with this characteristic.

The smaller crater size in the work-hardened material may be attributed to the greater rigidity of this target. Thus, catastropic shear is preceded by a smaller amount of deformation.



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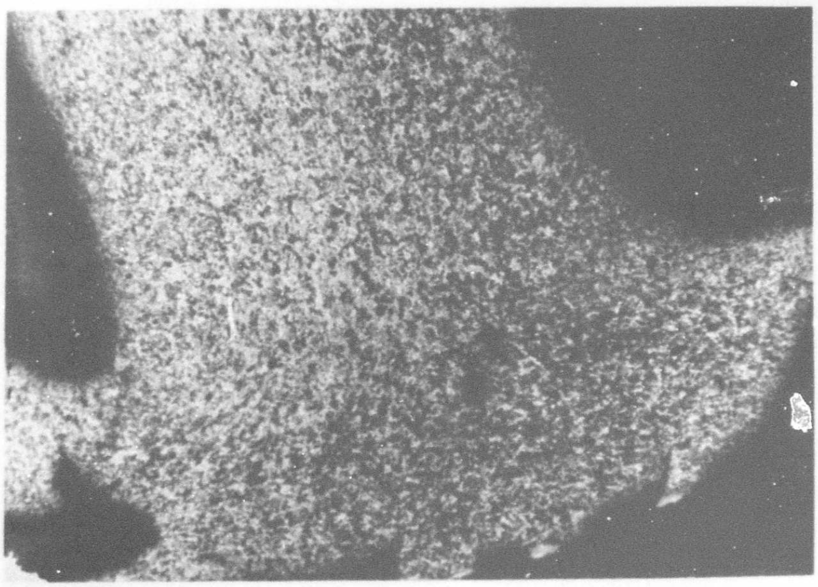
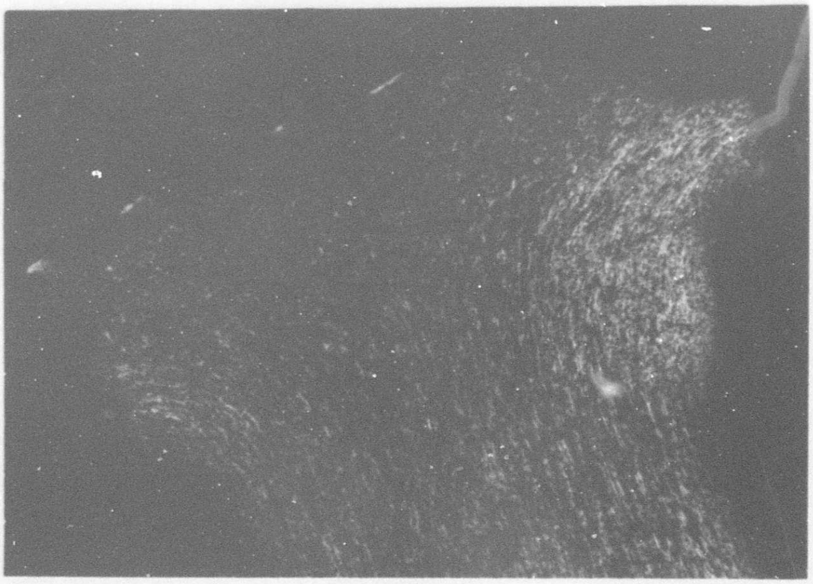


(b)

FIG. 9. Microstructure of Conventional Annealed Target at Perforation. (a) Section parallel to rolling direction, (b) section transverse to rolling direction. 50X.



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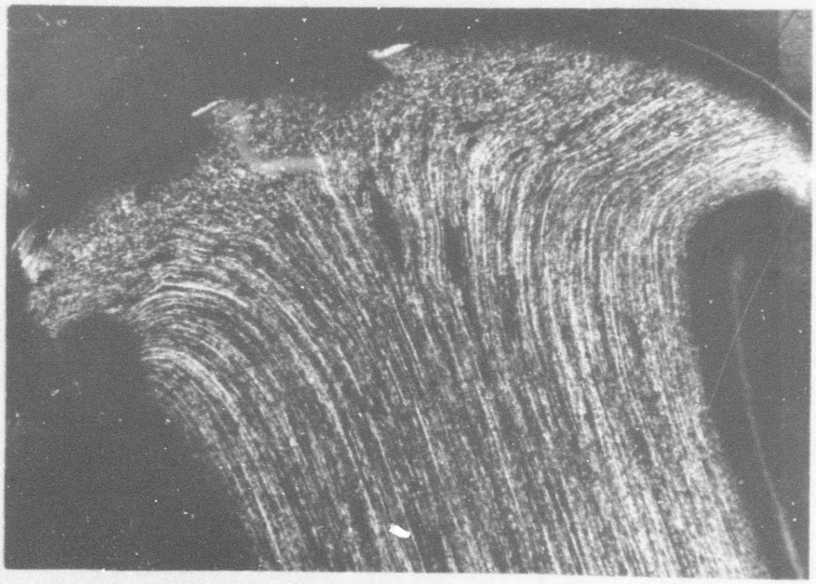

(b)

FIG. 10. Microstructure of Severely Cold-Worked Target. (a) Section parallel to rolling direction, (b) section transverse to rolling direction. 50X.

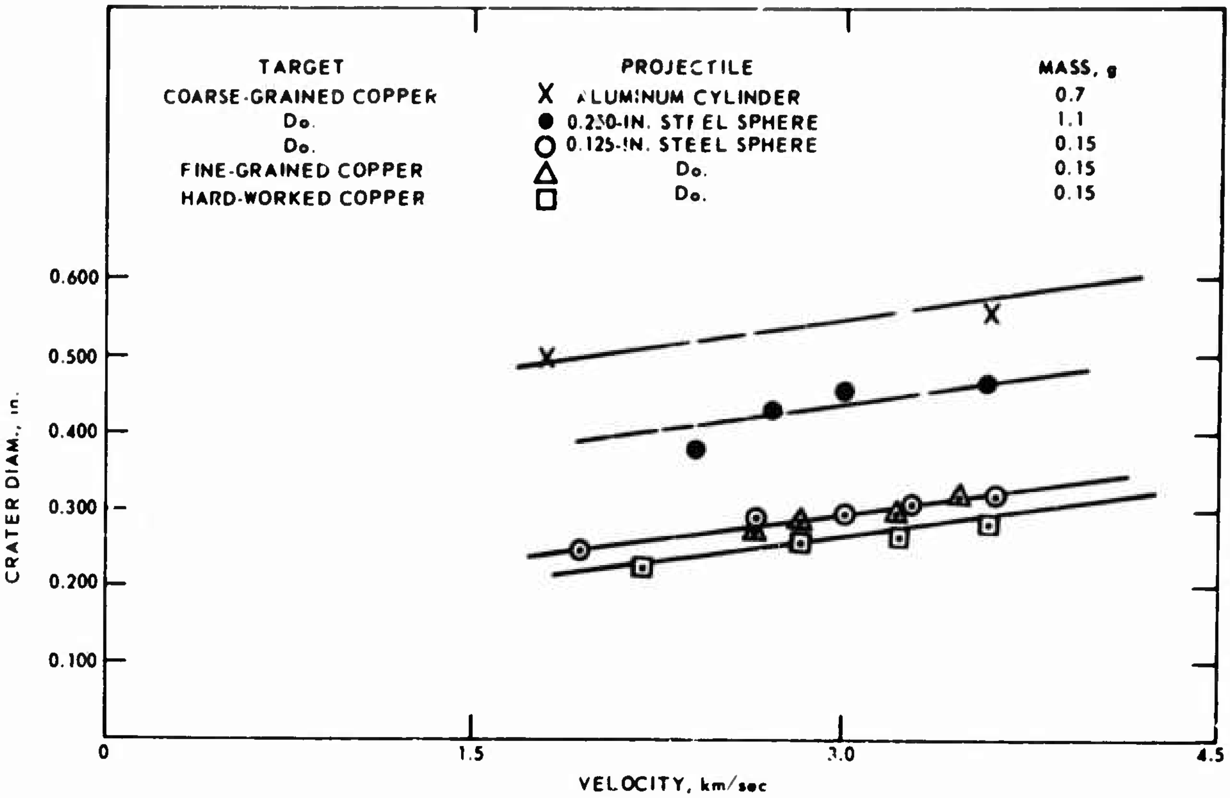

FIG. 11. Perforation Data.

Figures 9 and 10 illustrate the flow patterns at typical craters in annealed and in work-hardened material. Participation of the rolling fiber in the perforation process is clearly indicated. As would be expected, the relationship is more evident in the work-hardened than in the annealed target and more pronounced in the longitudinal than in the transverse direction.

FRACTURES

One area of rather marked differences in the response of the large-grained and the small-grained materials is in fracture behavior. Whereas in the coarse-grained targets, Fig. 3-8, the disseminated oxide particles appear to have very little effect on the fracture pattern, it is clear that the combination of oxide and grain fiber in the conventional material cannot be ignored. There are obviously more fractures and voids in the small-grained materials and the fractures tend to follow the grain fiber. The fracture behavior in this material is significantly different from the behavior that is typical of steels and aluminum but the response of the material does indicate the potential importance of microstructural aspects in the processes of fragment formation during perforation.

CONCLUSIONS

A procedure has been described and some experimental results shown for the application of large-grained, essentially monocrystalline material as the target for certain types of ballistic testing. The kinds of specialized information that may be obtained has been indicated. It is considered that the investigation of essentially single-crystal materials offers a useful means of supplementing information obtained using more conventional materials.

The information forthcoming relates primarily to the behavior of material at the microscopic level. Individual crystals may be expected to behave anisotropically so that deformation may be related to crystal orientation and crystal type. Solid forms known to have brittle-ductile relations should be tested in comparison with forms consistently ductile.

It is suggested that further application be made of single-crystal techniques in high-velocity deformation studies. Temperature- and strain-rate effects may be studied, and spalling and scabbing behavior observed in homogeneous media, relatively free from mechanical defects, grain and phase boundaries, and interfaces. Among other unique characteristics of very coarse-grained materials is the possibility of unusual behavior of shaped-charge liners made of this material.

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13. ABSTRACT

A technique for the preparation of polycrystalline forms of copper with grain sizes in excess of 25 mm makes it feasible to prepare targets for ballistic test in which the deformation of the perforation processes occurs within a few crystal grains or even within a single grain. A description of the process of target preparation is presented, some crystallographic aspects of penetration studies are discussed, and data from tests in which missiles impacted against targets at velocities from 0.6 to 3.6 km/sec are presented.

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13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

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