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BALLISTIC PERFORATION OF OFHC Cu AND 7039Al TARGETS:

A MICROSTRUCTURAL AND HYDROCODE STUDY

by

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Be not afraid of greatness:
some men are born great,
some achieve greatness,
and some have greatness thrust upon them.

- Shakespeare

Dedicated to my sister Cindy;
may she one day discover the greatness within her.

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Family, love and God are truly the key to great happiness in life.

Christine Kennedy

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ABSTRACT

This research involves an effort to study and compare the residual microstructures and dynamic behavior of two metallic targets of finite thicknesses, namely OFHC (oxygen-free high-conductivity) copper and 7039 aluminum, subjected to ballistic impact and perforation by a tungsten heavy alloy (WHA) projectile. Also included in this work is an attempt to validate mathematical modelling of experimental results through the use of a computer hydrocode, AUTODYN-2D, which allows for the simulation of ballistic penetration/perforation events and possible differentiation of fundamental mechanisms through validation strategies. These targets represent two very different FCC materials. The 7039 aluminum is extremely hard in contrast to a softer, ductile copper. The "failure" mechanisms appear to be different on a macroscopic scale, but may be similar on a microscopic scale.

A preliminary investigation of the residual penetration channels in these two targets revealed significant microstructural differences. In the 7039 aluminum target there is a limited extent of microstructural deformation seen through optical microscopy, though numerous shear bands are observed near the channel wall and at the spalled region. Observations of the OHFC target, on the other hand, show a narrow region of recrystallized grains adjacent to the crater wall, beyond which is an extensive area of microband clusters. Similar features have been observed previously in connection with hypervelocity impact cratering in copper.

This investigation will attempt to provide clues to the fundamental issues involved in the differing dynamic behavior of the two FCC materials. A detailed analysis of microstructures and their evolution will be conducted through metallography and transmission electron microscopy. Microhardness measurements will be performed to correlate the results of ballistic computer simulations through residual stress and hardness profiles. Computational modeling will be used to simulate the impact behavior of the two target materials and will be corroborated by experimental results to establish a validation of perforation geometry and residual stress mappings which can be related to actual residual hardness maps constructed experimentally.

This study is an attempt to correlate microstructural issues with computer simulations and especially validation of these simulations to improve predictive models and general ballistic and hypervelocity perforation behavior in metal targets.

STATEMENT OF THE PROBLEM

In studies involving penetration and perforation of metal targets by long rod projectiles, detailed microstructural analyses performed through transmission electron microscopy (TEM) are generally absent or. An analysis of this nature is imperative to the understanding of fundamental issues involved in the dynamic behavior of metal and alloy targets.

The two target materials chosen for this investigation, OFHC copper and 7039Al, exhibit considerably different failure phenomena. Though both are FCC, the initial and residual microstructures of the two target materials are markedly dissimilar. In a recent study by Huang et al. [1], optical microscopy observations of the initial microstructures of 7039 Al revealed heavy deformation (a result of manufacture processing) with an extremely small grain structure and heavy precipitation rendering the material relatively hard (140 VHN) in contrast to the copper. Shear bands were prominent in the residual microstructure, and there were very limited deformation-induced microstructural changes extending away from the penetration channel wall. OFHC copper, on the other hand, exhibited a relatively simple, equiaxed grain structure initially, while perforation of the material by a projectile resulted in a rather extensive microstructural evolution extending from the channel wall into the target.

A systematic and thorough analysis, utilizing optical and transmission electron microscopy, as well as microhardness testing, may lead to the identification of the particular mechanisms involved in the differing dynamic behavior of the two materials.

In the simplest case, these behaviors include a rather "brittle-like" failure for the aluminum alloy in contrast to a classical ductile failure for the copper. Moreover, validation of a computer hydrocode, AUTODYN-2D, via comparisons of stress profile maps between simulated and experimental results will serve to improve the predictive capability and usefulness of ballistic simulations.

Reference:

1. W. Huang, L. E. Murr, C.-S. Niou, N. L. Rupert, F. I. Grace and S. J. Bless, 16th International Symposium on Ballistics, Ballistics '96:

JUSTIFICATION OF IMPORTANCE

With the emerging threat of improved kinetic energy penetrator materials technology, a need arises for the development of more effective armors (target materials). Yet in order to improve upon the effectiveness of modern metal armors, it first becomes necessary to gain a better understanding of the material's behavior under such rigorous dynamic (impact) conditions, characteristic of extreme strains and extreme strain rates.

Advances in theoretical penetration mechanics have produced a large body of knowledge about penetration and perforation, yet certain aspects of the process have not been adequately addressed. This includes the nature of target deformation in terms of changes in microstructure of the material [1]. In a recent study of the impact of a tungsten projectile into both an RHA (rolled homogeneous armor) and a titanium alloy (Ti-6Al-4V) target, the experimental results revealed significant differences in penetration characteristics [2], with a higher efficiency of the Ti alloy against the projectile. This fundamental difference was shown to be reflected in significantly different residual microstructures associated with the perforated channel wall by Huang et al. [3], whose work has become one of the first efforts to systematically observe and compare residual target microstructures associated with ballistic penetration/perforation phenomena.

Computational modelling of ballistic impact is currently an active field of endeavor [4] and can serve as a cost-efficient tool for providing realistic results from the simulation of ballistic events. The validation of existing computer codes and their

associated simulations of dynamic events, through the incorporation of material response (such as hardness as it relates to specific microstructure), can greatly improve the predictive capability and usefulness of these mathematical models.

This study attempts to shed more light on the microstructural issues associated with ballistic impact and in particular to pinpoint the differing mechanisms of penetration-related failure occurring in OFHC copper and 7039 aluminum. Computer simulations will be performed using a hydrocode (AUTODYN-2D) in an attempt to mathematically replicate the behavior of the target materials seen in the experimental evidence, and to use the intrinsic issues embedded in the corresponding constitutive equations to elucidate the mechanisms of rod penetration and target failure.

References:

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3. W. Huang, L. E. Murr, C.-S. Niou, N. L. Rupert, F. I. Grace and S. J. Bless, 16th International Symposium on Ballistics, Ballistics '96 :

4. G. T. Camacho and M. Ortiz, *Comput. Methods Appl. Mech. Engrg.*, **142**, 1997, p269

MATERIALS SCIENCE AND ENGINEERING STATEMENT

In the most simplistic terms, materials are atoms that have been joined in the solid state, and the bulk properties of a material are determined by its atomic architecture. One group of materials in particular, metals, is the primary structural material of technology. Its principal use in military applications include a variety of armors (tank armor, body armor, etc.) as well as high-velocity projectiles. The defeat of structures through projectiles is of great importance, likewise the mechanisms by which armor can protect these structures is equally important [1]. Ballistic impact research, therefore, involves the parallel efforts of both armor improvement and armor defeat. Hence it becomes necessary to fully understand the behavior of metals under such high-velocity, high-strain-rate impact conditions.

It is the purpose of this research to elucidate the mechanisms by which dynamic deformation occurs in the ballistic perforation of two materials, 7039 aluminum and oxygen-free, high conductivity (OFHC) copper. A comparison of the two residual targets, both perforated by an identical tungsten-alloy sub-scale projectile, reveals distinct differences in crater geometry and features, as well as differences in deformation-induced microstructures at the crater edge. This contrast in behavior, as well as the underlying mechanisms involved, may be attributed in part to the dissimilarities in properties between the two materials, though both share a face-centered cubic crystal structure. The aluminum alloy possesses higher yield strength (0.48 GPa) and hardness (140 VHN)

compared to that of copper (yield stress is 0.27 GPa, hardness is ≈80 VHN), though its density (2.9 g/cm^3) is roughly a third of that of copper (8.9 g/cm^3).

In concurrence with the experimental portion of this study, numerical simulations will be performed in an attempt to replicate experimental results. Validation of the hydrocode, AUTODYN, will occur through the comparison of simulated stress profiles to experimental microhardness profiles by the empirical relationship $\sigma_y = H / 3$. Therefore, residual stress maps ($f(\sigma_y)$) are simply and linearly related to residual hardness maps ($f(H)$).

Reference:

1. M. A. Meyers, Dynamic Behavior of Materials, John-Wiley & Sons, Inc., New York, 1994

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