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The Role of Grain Size and Microstructure on the Shock Response of Metals (Summary Technical Report, Oct 2018–Sep 2020)

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**Billy C Hornbuckle, Scott A Turnage, John D Clayton,
Kristopher A Darling, Anit K Giri, and Cyril Williams**
*Weapons and Materials Research Directorate,
DEVCOM Army Research Laboratory*

S Dean
Sandia National Laboratories

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ORCID ID: Scott Turnage, 0000-0001-9375-903X

14. ABSTRACT

For the first time a bulk nanocrystalline material, an alloy of nanocrystalline (NC) copper (Cu)-3at.%–tantalum (Ta), has been successfully shock-compressed from approximately 8 to 45 GPa using conventional and laser shock. Mechanical hardness and transmission electron microscopy results provide evidence that this material can resist high defect accumulation and damage as compared with other known materials reported in the open literature. This behavior is attributed to the stabilized grains and grain boundaries that act as stable sinks, analogous to a NC metal's known ability to absorb radiation damage, thereby providing a mechanism of resistance that neutralizes further deformation-induced defects. This represents an important material science discovery. Spall experiments revealed that through proper microstructural design and manipulation it is possible to increase the inherent spall strength of NC Cu–Ta alloys to a value that is 300% higher than conventional coarse-grain polycrystalline Cu. These results are startling as the spall strength of these NC Cu–Ta alloys is approaching the theoretical strength of Cu single crystals. These new results could pave the way for designing the next leap-ahead spall-resistant materials to enhance Soldier protection.

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Contents

List of Figures

Executive Summary

Under a collaborative 6.1 research endeavor to study the role of grain size and microstructure on shock response of nanocrystalline metals, an alloy of nanocrystalline (NC) copper (Cu)-3at.%–tantalum (Ta), designated Cu3-Ta, was shock-compressed from approximately 8 to 45 GPa using conventional and laser shock experiments. This is the first time a bulk NC material has been successfully shock-compressed to stable high-stress Hugoniot states. Mechanical hardness and transmission electron microscopy results provide evidence this material can resist high defect accumulation and damage as compared with other known materials reported in the open literature. This behavior is attributed to the stabilized grains and grain boundaries that act as stable sinks, analogous to an NC metal's known ability to absorb radiation damage, thereby providing a mechanism of resistance that neutralizes further deformation-induced defects. This represents an important material science discovery. In that, if a material's microstructure is preserved to the length scale of nanometers through certain stabilization mechanisms, then the material's behavior will be anomalous in nature. These results indicate stabilized NC materials provide a new frontier for fundamental discovery where opportunities exist that go beyond the perceived mechanical and functional limits of NC metals.

The first in the scientific community to investigate such materials under extreme dynamic conditions, the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) is positioned to make leap-ahead scientific and technological discoveries. Spall experiments revealed that through proper microstructural design and manipulation it is possible to increase the inherent spall strength of NC Cu–Ta alloys to a value that is 300% higher than conventional coarse-grain polycrystalline Cu. The latter is used as a benchmark material for understanding the mechanisms of spallation. These results are startling as the spall strength of these NC Cu–Ta alloys is approaching the theoretical strength of Cu single crystals. These new results could pave the way for designing the next leap-ahead spall-resistant materials to enhance Soldier protection.

1. Introduction

The microstructures of materials typically undergo significant changes during dynamic extreme conditions such as shock loading, causing failure when higher shock pressures are reached. However, preservation of microstructural and mechanical integrity during shock loading are essential in situations involving Army protection systems and vehicles.

1.1 Program Objectives

The purpose of this research is to advance the state of the art in the characterization, modeling, and development of Army-relevant materials under dynamic extreme conditions. Particular emphasis is placed on the fundamental understanding of the deformation and failure mechanisms active in nanocrystalline (NC) materials under high strain rates (10^4 to 10^8 s^{-1}). The ultimate goal is to further understand how such materials behave during terminal ballistic interactions, which will enable the design and development of robust materials to support Army core functions. Research involving the development of new materials that exhibit novel behavior (e.g., strain rate or temperature insensitivity) as a function of reduced grain size is the main focus of this study with specific emphasis on mitigating failure. Preliminary studies at the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) suggest the stabilized bulk NC materials can absorb high energy loads more efficiently than other known materials because of their microstructure and length scales, which can alter the nucleation and mobility of dislocations and how they interact with phonons. This research developed an in-depth fundamental knowledge of such microstructures and their evolution through ex situ (end state) and in situ (real time) shock-compression studies to help us understand the origin of such behavior and how to harness these materials for improved terminal ballistic applications.

1.2 Current State of the Art

Structural metals often experience high deformation rates such as in vehicle crashes, projectile impact, and shock loading, resulting in strain rates ranging from 10^4 to 10^8 s^{-1}. It is generally accepted that metals show a dramatic upturn in flow stress as a function of strain rate between 10^3 and 10^4 s^{-1}. Recent work at the DEVCOM Army Research Laboratory[1] has uncovered a divergent behavior, wherein the long-established assumption of phonon drag leading to flow-stress increase was found to break down in NC copper–tantalum (Cu–Ta) alloy. Such behavior has never been reported before and suggests this nanostructured material can absorb high energy loads more efficiently than other known materials prior to failing. Recent, atomistic modeling of phonon-drag mechanisms suggest microstructural length scale and spacing alter the formation of phonons and their interaction with dislocations and generated damage.[2] Currently, it is unclear whether the compressive wave during shock loading will play a critical role in defining the types of interfaces (free surfaces and coherent) formed during damage accumulation at strain rates of 10^5 to 10^8 s^{-1} in nanostructured alloys. However, developing an in-depth understanding of the material's microstructure, its real-time evolution with damage, and the corresponding effects/interactions with phonons studied through ex situ and in situ shock experiments will help us understand the behavior of NC Cu–Ta at the fundamental level. This knowledge can be directly passed on to alternative systems for improved terminal-ballistics applications. To the best of the authors' knowledge, not a single publication exists on the experimental shock response of bulk NC metals (grain size <100 nm in all 3 dimensions) and sample sizes >1 cm in 3 dimensions. This is due to the complexities involved in consolidating NC metals because of their poor thermal stability. This research combines two areas of ARL Weapons and Materials Research Directorate's world-renowned expertise, shock-compression science and bulk NC metals synthesis, to comprehensively study the deformation behavior of bulk NC materials.

1.3 Shock Compression

At its basis, shock-compression science has been used to probe, understand, and manipulate the behavior of materials under some of the most extreme conditions on earth. Shock compression of condensed matter has been used to understand microstructural changes and deformation response in a wide variety of materials, which are subjected to potentially catastrophic events including high-speed automobile and aircraft collisions, explosions/detonations, armor penetration, meteor impacts, interstellar dust–dust collisions, and inertial confinement fusion. Consequently, when conventional coarse-grained polycrystalline metals are subjected to shock loading, their microstructure evolves into a very nonequilibrium, highly defected state. A coarse-grain equiaxed microstructure can evolve into high concentrations of heterogeneous defects, such as microbands, dense dislocation-cell structures, voids, regions of amorphous structures, and cracks, leaving the former microstructural state incomparable to the final state. In coarse-grained polycrystalline materials, this rearrangement of the microstructure can lead to significant increase in the residual hardness (as much as 100%) and reduction in the ductility, which can result in failure of the ductile material in a brittle manner. Defect generation and hardening are potentially the origins of spallation in armor materials. Spallation is a process in which two strong decompression or rarefaction waves collide and in the process generate a tensile region in the material. If the tensile stresses developed in the material are greater than the threshold required for void/crack nucleation, growth, and coalescence, then the material will fail. Spallation can generate fragments and these fragments can act as secondary projectiles causing significant injuries and even death.

Recent advances in stabilizing NC alloys at ARL are allowing investigations of the alloys' true mechanical response (i.e., in the absence of grain growth). This microstructural stabilization has revealed drastic deviations from the expected mechanical response under various extreme conditions.[1,3,4–6] In a series of papers recently published,[1,3,4–6] ARL researchers have shown that bulk NC Cu–Ta alloys with the appropriate stabilization exhibit extreme creep resistance, radiation immunity, high conductivity, and so on. Unlike in conventional materials where flow stress increases exponentially at strain rates exceeding approximately 10^3 s^{-1}, resulting in brittle failure, in NC Cu–Ta we discovered the flow stress remains practically unchanged as a function of strain rate up to 10^5 s^{-1}. Previously, these extreme loading conditions were unattainable in NC materials due to thermal and mechanical instability of their microstructures; thus, these anomalies have never been observed in any other material. This discovery may possibly lead to the development of shock-resistant materials that may also be spall resistant. Such materials have great potential for use as armor and will have immense benefit to Soldiers.

1.4 Shock Experiments

Here, we report the details of the first comprehensive ex situ shock experiments of a chemically optimized and microstructurally stable bulk NC Cu-3at.% –Ta alloy designated NC-Cu-3Ta.[*] In this research, we performed conventional shock-recovery experiments using flyer plates, which are accelerated to high velocities—projectile impact velocities of 0.400 and 0.678 km/s, which correspond to shock stresses of 8 and 15 GPa, respectively—using a 105-mm-diameter gas gun. Also, laser shock experiments were conducted at impact velocities of 0.8, 1.9, and 2.4 km/s corresponding to approximately 9, 24, and 34 GPa shock stresses, respectively.

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[*] This report describes efforts conducted within the framework of research Task 61102.AA7.04, "High Deformation Rate Materials", and Task 61102.AA7.10, "Protection Sciences", performed primarily within ARL's Weapons and Materials Research Directorate under the leadership of principle investigators Drs Anit Giri and Cyril Williams.

In the following sections we present results of the studies performed on NC-Cu-3Ta using 1) conventional shock-recovery experiments and 2) laser shock experiments. Conventional gas-gun shock-recovery experiments have been instrumental in understanding the structure-property relationships in metals when shocked to a high-stress Hugoniot state.[7,8] Laser-driven flyer plates represent a low-cost, high-throughput method to induce high shock stresses in a target for short durations, on the order of nanosecond.[9] Since the pulse duration between the two methods are significantly different, the results are presented separately.

2. Conventional Shock-Recovery Experiments

The material for this study was processed through mechanically alloyed powders using a multipass high-temperature equal channel angular extrusion (ECAE) at 700 °C. Complete details of the powder processing and consolidation efforts can be found in several journal articles.[3,8,9] Primary microstructural analysis of the as-consolidated test samples using transmission electron microscopy (TEM) indicates the extruded microstructure for this alloy has an average grain size of 87 ± 15 nm with Ta-based nanoclusters having an average diameter of 3.2 ± 0.9 nm. These Ta-based nanoclusters are observed to exist within the Cu matrix and along grain boundaries. To evaluate microstructural evolution and deformation mechanisms under extreme conditions, the NC-Cu-3Ta samples were shock-compressed, released, and recovered following the procedure outlined in Srinivasan et al.[6] for conventional shock recovery. Two samples were shock-compressed to approximately 8 and 15 GPa, respectively. After the material is plastically deformed, it is then released back to ambient conditions. Following soft recovery, the samples were analyzed using TEM and precession electron diffraction (PED) as well as hardness mapping.

2.1 Microstructure and Mechanical Response after Conventional Shock Loading

The residual structure-property relationships in shock-compressed samples were probed through TEM and hardness measurements. Figure 1a shows negligible changes in the residual hardness across the through-thickness direction between the as-received material and samples shock-compressed to approximately 8 and 15 GPa, respectively, through conventional shock-recovery experiments in NC-Cu-3Ta. Such behavior is anomalous for metals and metallic alloys shock-compressed to such high stresses. For instance, as shown in Fig. 1b the residual hardness in pure Cu and brass is found to increase by factors of two and three, respectively. However, the NC-Cu-3Ta alloy (i.e., 97% Cu) did not exhibit any significant change. To the best of the authors' knowledge, this type of behavior has never been reported before in the open literature for any structural materials.

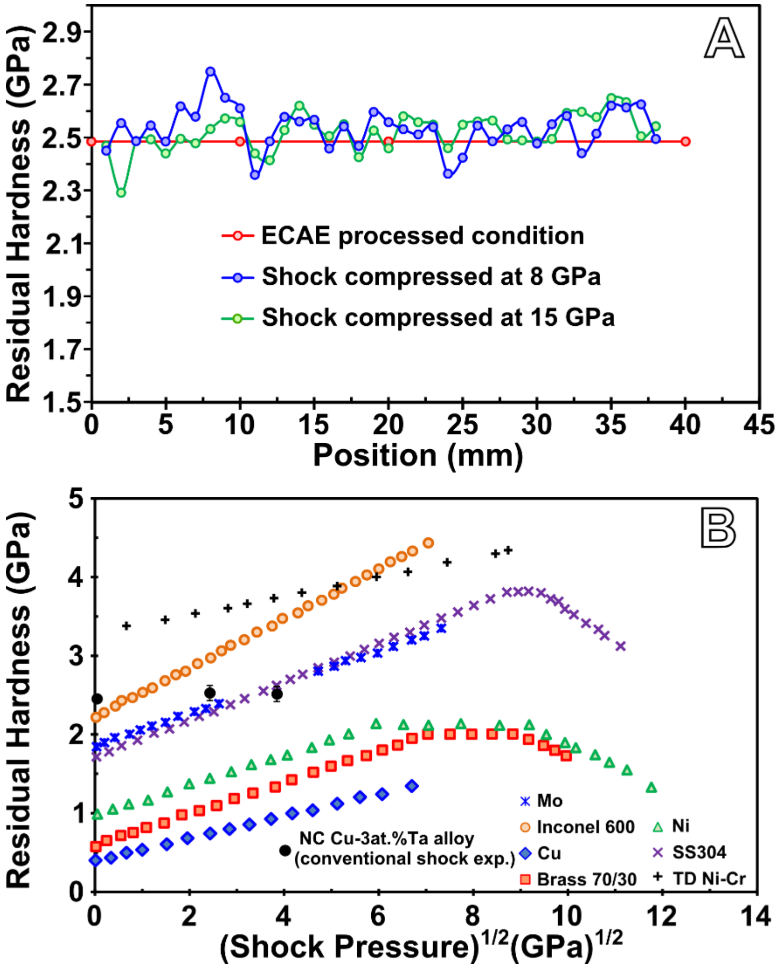

Fig. 1 **Postdeformed mechanical behavior of NC-Cu-3Ta and its comparison with advanced structural alloys: (a) hardness of as-received NC-Cu-3Ta sample compared with residual hardness of the samples shock-compressed to ~ 8 and 15 GPa, respectively, using conventional shock recovery; (b) residual hardness as function of (shock pressure/stress)$^{1/2}$ for several important metals and metallic alloys (adapted from Williams)**[7]

In general, during shock loading evidence of plastic deformation is usually revealed in the residual substructure. The residual substructure may consist of extremely high concentrations of lattice defects such as vacancy clusters, dislocation cells/networks, stacking faults, deformation twins, and so on. The generation of these defects will lead to significant increases in the postshock hardness. However, for the bulk NC-Cu-3Ta alloy shown in Fig. 2, we observed no significant change in the residual substructures among the different shock stresses despite undergoing severe deformation. The bright-field scanning tunneling electron microscopy (BF-

STEM) images shown in Figs. 2a–c represent low magnification of the as-received material shock-compressed to approximately 8 and 15 GPa, respectively.

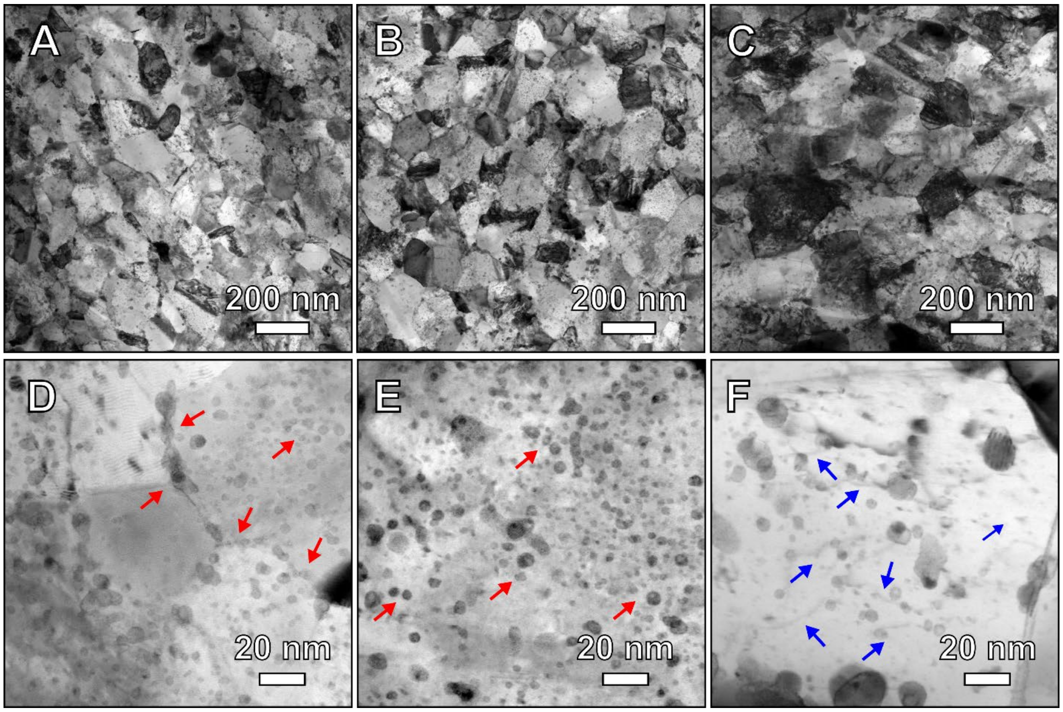

Fig. 2 BF-STEM characterization of microstructural evolutions acquired for as-received and shock-compressed bulk NC-Cu-3Ta alloy: (a–c) low magnification of as-received shock compressed to approximately 8 and 15 GPa, respectively; (d–f) higher magnification of as-received and various shock-compressed samples; red arrows indicate Ta nanoclusters, blue arrows highlight dislocation interaction with Ta nanocluster

Similarly, Figs. 2d–f represent a higher magnification of the as-received material and shock-compressed samples. The slight difference between the microstructures shown in Figs. 2d and e is attributed to the Ta particles pinning the grain boundary in Fig. 2d, whereas Fig. 2e shows a more homogenous distribution of the Ta particles within the grain interior. The TEM images do not reveal significant signs of localized plastic deformation (i.e., dislocation subcell formation and/or extensive twinning activities) except in the case of extreme shock stresses (e.g., Fig. 2f) where dislocations are pinned by nanoclusters. This lack of dislocation activity does correlate to the insignificant hardness increase observed in the postdeformed samples (Fig. 1). Through complex modeling it has been shown the grain boundaries in NC metals can absorb dislocations and other defects during active deformation.[10] Nevertheless, as mechanical testing becomes more extreme, as in high strain-rate and shock loading, unstabilized NC metals will undergo drastic coarsening and begin to function as conventional coarse-grain metals by storing high concentrations of lattice defects within the grain interior. In other words, the absence of grain growth and microstructural evolution in NC-Cu-3Ta signals the stabilized grains and grain boundaries act as stable sinks and persist, thereby annihilating deformation-induced defects during shock compression. Further, no cracking or voids were observed at the grain boundaries or at Cu–Ta interfaces. Overall, the microstructural characterization of NC-Cu-3Ta shown in Fig. 2 supports the earlier observation of negligible postshock residual-hardness increase despite undergoing plastic deformation.

2.2 Orientation-Imaging Map (OIM) of Samples

To evaluate the influence of the extreme stress jump on the textural changes (grain-boundary sliding and grain-rotation processes), precession diffraction measurements were performed in various regions. The OIM in Fig. 3 shows a high degree of randomness in the orientation relationships among the Cu grains in the as-received and the full-release states with a similar texture index. In addition, only a marginal change in the average grain size was observed between the as-received sample and the shock-recovered samples. This is true even for the approximately 15-GPa sample, where the vast majority of the microstructure remains relatively uncoarsened. An important takeaway from these results is that although there may be a small change in the average grain size, no significant changes in the material's residual-hardness value were observed. The observations made on recovered shock-compressed NC-Cu-3Ta specimens clearly indicate the important role of Ta nanoclusters on the structural stability as well as strength of these alloys. These results also allude to the fact the small change in average grain size following shock compression and release is indeed negligible. Therefore, the overall lack of microstructure and texture evolution in this bulk NC-Cu-3Ta alloy is atypical for metals and metallic alloys shock compressed to approximately 15 GPa and is deemed anomalous. In fact, NC pure Cu is a good example of this, whereby its microstructure is so unstable that it is known to coarsen over time even under ambient laboratory temperature/pressure, and under deformation this instability is extremely exacerbated.[5,8]

Based on the analyses of the residual microstructure of NC-Cu-3Ta it is apparent no increase in dislocation density and mechanical twinning is observed; that is, the stabilized NC alloys likely exhibit an unprecedented ability to resist high defect (such as dislocation) accumulation and damage. In contrast, most polycrystalline Cu shocked as low as 5 GPa show significant increase in the dislocation density as well as postdeformed residual hardness.[11] Here, the thermomechanically stabilized grain boundaries and cluster interfaces persist and continue to operate as sinks to absorb the deformation defects such as dislocations. Such inherent behavior or properties are unlikely to be observed in unstabilized NC metals. In general, the accumulation of defects during shock compression can lead to potential void-nucleation sites such as vacancies and vacancy clusters,[12] which can be detrimental to spall failure. Therefore, the ability to maintain a lower defect concentration under shock compression provides an archetype from which materials can be developed that go against conventional theory. That is, smaller grain sizes may then prove to yield higher spall strengths as compared with coarser-grained alloys. To confirm this hypothesis, spall experiments were performed on the NC samples. The spall strength of this NC-Cu-3%Ta alloy was determined to be approximately 2.40, 1.87, and 1.98 GPa at peak shock stresses of 4.5, 9.4, and 44.3, respectively.[7] The maximum value of 2.40 GPa is 300% the value of polycrystalline Cu (0.8 GPa). We achieved a high value of spall strength in an NC material and it is approaching the value of a single crystal, which is free of defect. It was thought previously the latter was the only possible way to attain high spall strength.

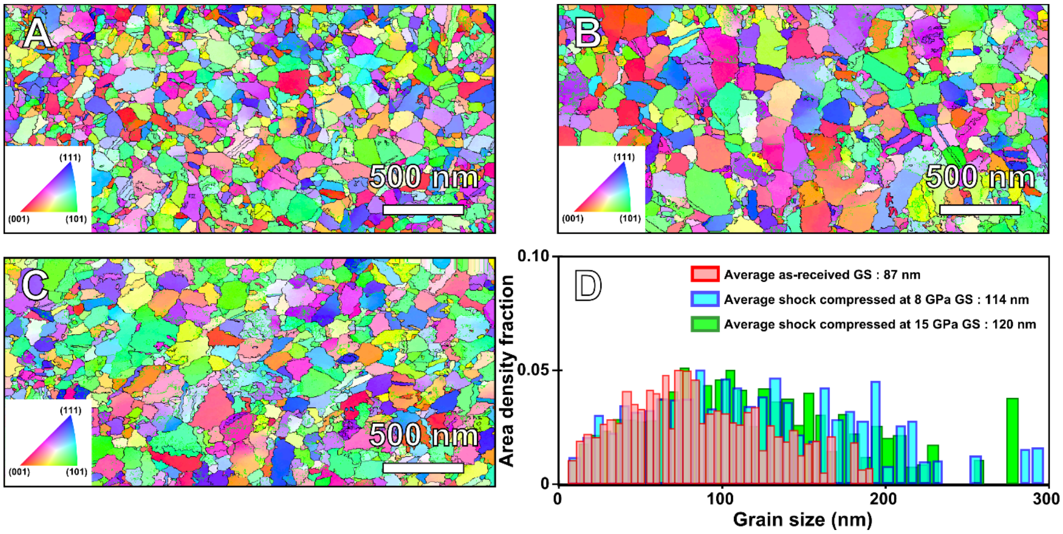

Fig. 3 Microstructural data for as-received and shock-compressed bulk NC-Cu-3Ta alloy using PED microscopy: precession diffraction image of (a) as-received material, (b) material shock-compressed to ~8 GPa, and (c) material shock-compressed to ~15 GPa; (d) distributions indicate nominal increase in Cu grain size with majority of grains remaining in NC regime

3. Laser Shock-Recovery Experiments

NC-Cu-3Ta (at.%) disks were impacted by laser-driven flyer plates at 0.8 km/s (~9-GPa shock stress), 1.9 km/s (~24-GPa shock stress), and 2.4 km/s (~34-GPa shock stress). The experimental details are described in a paper published by the authors of this report.[9]

3.1 Microstructure after Laser Shock Loading

Extensive postimpact analysis was conducted on the laser shock-recovered targets using advanced electron microscopy. Initial STEM analysis of the samples found the flyer plate impact at 2.4 km/s resulted in the formation of microbands roughly 1 µm from the impact surface, as shown in Fig. 4, while the majority of the remaining microstructure remains unaffected by the stress generated during impact. Further, the 2.4 km/s-sample revealed the microbands extend over a micron or two and are discontinuous throughout the microstructure. Fig. 4 shows that the microbands consist of laminar structures, which at first glance appear to be consistent with nanotwins intermixed with microbands. Besides the microbands and a few dislocations, the microstructure is free of damage with no cracking or debonding of interfaces. Furthermore, the insensitivity to shock was also observed in the sample impacted at 0.8 km/s, whereby the entire microstructure remained indistinguishable from the as-received condition.

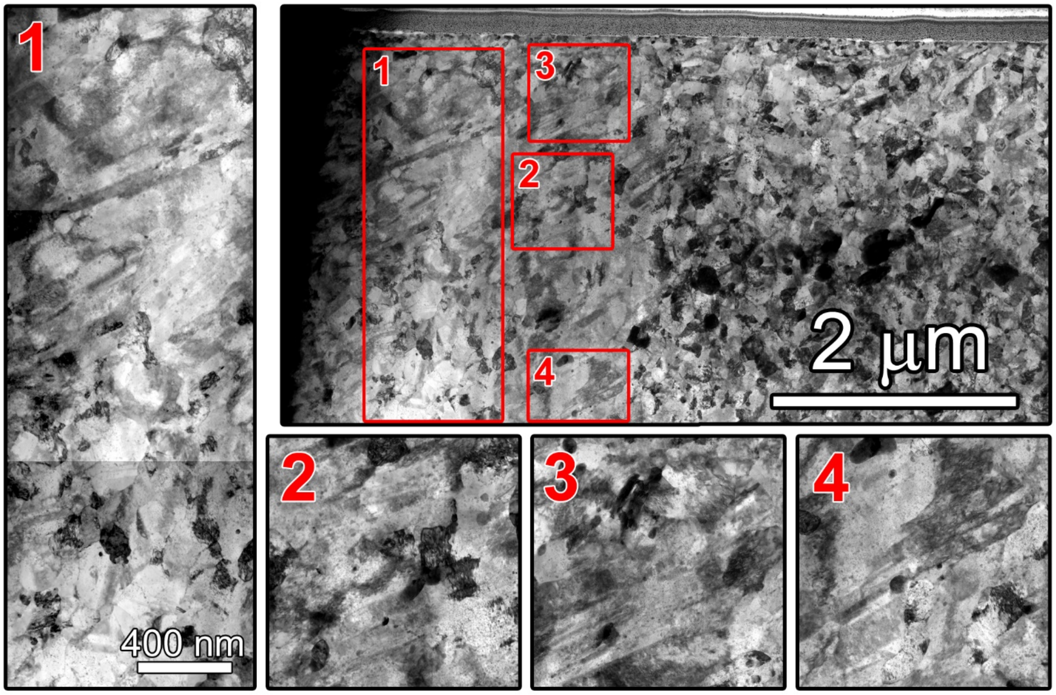

Fig. 4 BF-STEM images providing a closer look at microbanded regions of microstructure after laser-driven flyer-plate shock at 2.4 km/s (34 GPa); microbands occur sporadically in only a few, isolated places throughout the microstructure with average spacing of ~120 nm

A closer look at the undeformed regions of the 2.4-km/s sample reveals the microstructure is very resilient to the extreme stresses generated during shock loading. The shock stresses were calculated to be 9 and 34 GPa for 0.8- and 2.4-km/s impact velocities, respectively. The Cu grain size and size distributions show very little change in either, despite being successfully shock-compressed to a stable high-stress Hugoniot state.[8] The grain size remains equiaxed in shape but increases from 89 ± 41 nm in the as-received state to 179 ± 117 nm after being shock-compressed to 34 GPa, the most extreme case. Such small changes in microstructure are very surprising given the average grain size is less than 200 nm and experienced stresses as high as 34 GPa for which the temperature rises to approximately 526 K.

3.2 Residual Hardness after Laser Shock Loading

To further investigate the stability of the microstructure under such extreme conditions, we probed the residual hardness using a microhardness indenter. The hardness was measured at various locations within the impact crater using a 100-g load, which resulted in an average diagonal length of 13 microns. Given the geometry of Vickers indenters, this equated to an analytical depth of 1.9 microns. Changing the load to probe a range in depth (1 to 3.5 microns) provided consistent results. The average values for the hardness were 2.68, 2.40, and 2.54 GPa at shocked stresses of 9, 24, and 34 GPa, respectively. Figure 5 shows the hardness data for samples acquired from conventional and laser shock experiments. Comparing these values with 2.48 GPa value for as-received condition indicates negligible change in the residual hardness for NC-Cu-3Ta alloy. Overall, the lack of accumulated defect structures such as the formation of cell structures (indicative of high dislocation density) within the microstructure of NC-Cu-3Ta alloys bode reasonably well with the postdeformed hardness measurements.[8]

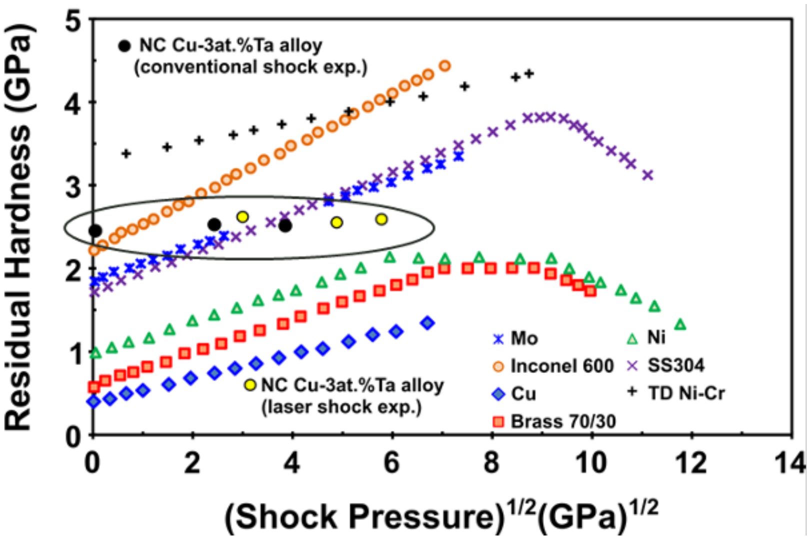

Fig. 5 **Hardness of as-received NC-Cu-3Ta alloy sample compared with residual hardness of samples shock-compressed via conventional and laser shock experiments; residual hardness as function of (shock pressure)$^{1/2}$ for several important metals and metallic alloys (adapted from Williams)[7]**

4. Findings

We have successfully conducted the first-ever shock experiments on a bulk nanocrystalline material. Optimized NC-Cu-3Ta shows extraordinary microstructural stability under extreme conditions for both conventional as well as laser-driven flyer-plate shock experiments. Mechanical hardness and TEM results provide evidence of an unprecedented ability to resist high defect accumulation and damage as compared with other known materials reported in the open literature. This is attributed to the stabilized grain and grain boundaries that act as stable sinks, analogous to NC metals' known ability to absorb radiation damage, thereby providing a mechanism of resistance, neutralizing further deformation induced defects. The spall strength of this NC-Cu-3Ta alloy is found to be 300% of the value of polycrystalline copper. We achieved a very high value of spall strength for this NC material, which has defected structures. The spall strength is approaching the value of a single crystal, which is defect free. It was thought previously the latter was the only possible way to attain high spall strength. This is an important achievement when compare with the spall strength of Cu single crystals. These results indicate that stabilized NC materials provide a new frontier for fundamental discovery where opportunities exist that go beyond the perceived mechanical and functional limits of NC metals. Such metals may have enhanced physical and mechanical properties for mitigating high-velocity impacts and, hence, improved ballistic protection.

5. Recommendations

Preliminary microstructural characterizations of the spalled materials reveal there was no evidence of fracture, damage, voids, and so on; that is, the researchers did not see any detrimental defects that will accelerate spall failure. So, the following questions arise: Why did we not achieve the single-crystal spall-strength value? Where and how did failure initiate? What causes the material to fail before reaching the single crystal spall strength value? Therefore, more shock experiments along with advanced microstructural characterizations are required to address these questions. The fundamental understanding of failure mechanism gained from such experiments will lead to improved spall strength of bulk-stabilized NC materials similar to that of their single crystal counterparts. Also Cu–Ta is a model alloy system and this research must be extended to design other iron- and nickel-based materials, which may have wider application space in terms of temperature and strength.

Payoff and Army Impact

- ARL researchers were the first in the world to develop *bulk* stabilized NC materials.
- Research on this NC-Cu-3Ta alloy has given ARL a leap ahead on how stabilized NC materials behave under extreme dynamic environments at the fundamental level.
- This knowledge will enable ARL researchers to manipulate Army-relevant materials at the microstructural level to exhibit superior mechanical properties at the system level. This will facilitate the development of robust materials for Army protection/lethality systems.
- Due to its high strength and residual hardness, this NC-Cu-3Ta alloy can also be used for wear-resistant gun tubes, improved concrete-busting projectiles, shaped-charge jets, and explosively formed penetrators.
- Developing a fundamental understanding of how materials behave during terminal ballistic interactions will enable better design and improved materials for the Army.
- The spall strength of this NC-Cu-3Ta alloy is found to be 300% of the value of polycrystalline copper, and the knowledge gained in this research could be used to advance spall-resistant alloys for protection systems.

In addition to works cited in the References section of this report, the Bibliography lists other noteworthy publications, presentations, and research findings.

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List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
BF-STEM	bright-field scanning tunneling electron microscopy
Cu	copper
DEVCOM	US Army Combat Capabilities Development Command
ECAE	equal channel angular extrusion
NC	nanocrystalline
OIM	orientation-imaging map
PED	precession electron diffraction
Ta	tantalum
TEM	transmission electron microscopy

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KS FOSTER
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FCDD RLD SM
L BLUM
FCDD RLH
J CHEN
PJ FRANASZCZUK
C LANE
FCDD RLH B
JJ SUMNER
FCDD RLH F
JR GASTON
FCDD RLL
T KINES
FCDD RLL DP
J MCCLURE
FCDD RLR
B HALPERN
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- JD CLAYTON
- S TURNAGE
- C WILLIAMS
- J CAZAMIAS

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- TV SHEPPARD

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- B RICE
- R PESCE-RODRIGUEZ