Influence of shock loading kinetics on the spall response of copper

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Abstract. A suite of plate-impact experiments was designed and conducted to examine the influence of loading kinetics on the spall response of high purity copper samples. The peak compressive stresses (1.5 GPa) and the density of grain boundaries dynamically loaded were held constant for all experiments. The kinetics of the tensile pulses were designed using a hydrodynamic, shock-wave propagation code and experimentally achieved by controlling the geometry of copper impactors and targets. Examination of damage fields shows that the total fraction of damage (voids) increases as the tensile rates decrease. In addition, an accompanying larger plastic dissipation, in the form of grain misorientation measured by means of electron backscatter diffraction, is present in the samples deformed at lower tensile rates. These results suggest a time dependent behaviour of the processes the plastic processes for void growth.

1. Introduction

It has been established that dynamic damage is a complex process strongly influenced by the microstructure but also by the dynamic loading profile or shock wave shape imparted to the specimen [1-6]. The interplay of parameters and mechanisms responsible for damage evolution precludes the assessment of individual contributions from specific material or loading characteristics. To address this problem, a comprehensive study has been undertaken that aims at the determination of the individual contributions of microstructure and loading profile to the mechanisms responsible for damage development. The results corresponding to the effects of microstructure on the deformation mechanisms in high purity copper have recently been reported [7-12]. The main findings can be summarized as follows: (1) damage initiated preferentially at grain boundaries with misorientation angles in the ~10-57° range, while at low angle and special Σ3 boundaries, dynamic failure seems to be mitigated; (2) the mechanisms for damage evolution were dictated by the grain size, which inherently determined the proximity of the nucleated voids; and (3) the previous meso-scopic length scale mechanisms are reflected in the characteristics of the continuum level free surface velocity (FSV) histories. It was found that the re-acceleration slope after the minima provided a direct indicator of the damage kinetics. In this regard, a steep slope was associated with a fast damage growth rate, dominated predominately by coalescence.

Building on the previous observations, in the current work a suite of plate impact experiments have been conducted to individually assess the effects of shock loading profile on the ductile damage evolution of high purity copper in incipient spall experiments. One-dimensional wave propagation...
calculations were performed to shape the tensile pulse. Details to achieve a given tensile profile can be found in Dennis-Koller et al. [11]. The damage fields are characterized by means of optical and electron backscatter diffraction (EBSD) microscopy as well as x-ray micro-tomography. The combination of these experimental techniques leads to a more comprehensive evaluation of the influence of tensile loading profile on the mechanisms responsible for damage evolution in high purity copper.

2. Materials
All targets were prepared from fully annealed, 99.999% pure, oxygen-free high-conductivity (OFHC) copper. As discussed in references [7,11], by modifying the tensile pulse, we alter the rate at which tension is produced within the target material but also, the volume of material sampled in tension. Thus, to isolate the effect of loading kinetics, it is required to control defect density per unit volume for each stress rate. As previous work had established that grain boundaries (GBs) with misorientation angle in the 10-57° range are the microstructural features acting as preferential sites for void nucleation in high purity copper [7-13], we specifically aimed to tailor our microstructures by altering the density of such GBs in our specimens. This was achieved by conducting heat treatments to produce suitable microstructures for our purposes. Representative images, obtained by EBSD measurements, of such microstructures are shown in figure 1. The details on the heat treatments as well as the GB statistics are listed in table 1. The color images show the grain orientation maps, while the accompanying GB maps shows the distribution and total length of GB of interest (colored in red).

![Figure 1](image)

**Figure 1.** Representative micrographs correspond to orientation and grain boundary maps for samples annealed (a) A, (b) D heat treatments.

**Table 1:** Heat treatments parameters to produce each microstructure.

| ID | Heat treatment | GB density (mm/mm²) |
|----|----------------|---------------------|
| A  | 600 / 60       | 37.5 ± 0.9          |
| B  | 700 / 60       | 32.9 ± 1.1          |
| C  | 850 / 60       | 28.0 ± 1.1          |
| D  | 825 / 120      | 22.4 ± 2.5          |

*Note: Only grain boundaries (GB) with misorientation angle in the 10-57° range were considered for the measurements.*

3. Plate impact experiments
Plate impact experiments were conducted using a 40mm bore gas gun. Copper targets were prepared as circular disks 15 mm in diameter and of varying thickness (2-6 mm). The copper samples were press-fit into target assemblies formed by three concentric momentum trapping rings to mitigate...
perturbations from edge release waves. Velocity profiles were obtained using VISAR [14] probes mounted 90° off of the shock direction axis to prevent any subsequent impact of the target with the probe. Further experimental details can be found in references [1-12]. A group of representative experiments conducted under the different loading conditions pursued in this study is listed in table 2. The fifth and last columns list, for each experiment, the size of the area under tension and the tensile stress rate calculated using a hydrodynamic code. For every experimental condition, experiments have been performed between two and three times to test repeatability as well as generate statistically accurate measurements of damage distributions. Additionally, the experiments were conducted at low peak compressive stresses (~1.5 GPa) such that the tensile stresses developed within the target material during the experiment were low enough to cause only incipient or early stages of damage.

Table 2: Parameters for plate-impact experiments.

| Exp. ID | Impactor Thickness (mm) | Impactor Velocity (m/s) | Target Thickness (mm) | Region under Tension ΔX (mm) | Microstructure used in Target | Stress Rate (GPa/μs) |
|---------|-------------------------|-------------------------|-----------------------|------------------------------|-------------------------------|---------------------|
| 1       | 1.0                     | 91                      | 2.0                   | 1.01                         | A                             | 35                  |
| 2       | 1.0                     | 90                      | 3.0                   | 1.18                         | B                             | 27                  |
| 3       | 1.0                     | 90                      | 4.0                   | 1.68                         | D                             | 25                  |
| 4       | 1.5                     | 91                      | 3.0                   | 1.25                         | B                             | 24                  |
| 5       | 1.5                     | 89                      | 4.0                   | 1.39                         | C                             | 22                  |
| 6       | 1.5                     | 91                      | 5.0                   | 1.48                         | C                             | 20                  |
| 7       | 2.5                     | 92                      | 4.0                   | 1.59                         | C                             | 19                  |
| 8       | 2.5                     | 90                      | 5.0                   | 1.66                         | D                             | 18                  |
| 9       | 2.5                     | 92                      | 6.0                   | 1.73                         | D                             | 17                  |

4. Free surface velocity profiles

The free surface velocity (FSV) profiles for the experiments reported herein are shown in figure 2. Comprehensive analyses and discussions on the fine details of free surface velocity traces is currently under preparation and will be reported in due time. Broadly, as signaled by the dotted lines in figure 2, it is observed that the pull-back values, i.e. the difference between the peak velocity and minima, decrease with increasing pulse duration (impactor thickness).

Figure 2. Free Surface Velocity traces using flyers with thickness of (a) 1, (b) 1.5 and (c) 2.5 mm.

Furthermore, for a given pulse duration the pull-back value decreases with increasing target thickness, directly proportional to tensile rate. Exceptions to this trend were experiments using 1mm-thick impactors, i.e. the highest calculated tensile rates. A stochastic behavior rather than a trend is appreciated in the pull-back values. As the magnitude of the pull-back is normally associated with spall strength, i.e. resistance to fracture or damage development, these results suggest that an
increasing amount of damage should be present in samples subjected to lower tensile rates. Results from the examination of damage fields of spalled samples to substantiate this conjecture are presented next.

5. Damage examination

While three different rates for a given pulse duration were conducted, only two conditions for each pulse duration are presented in this manuscript for the purpose of brevity. Optical images of the cross sections are shown in the figure 3. The image on the top shows a typical, bright field, optical micrograph of the cross section of a recovered sample in Exp. 4. The images on the bottom show processed images of the damage fields (red dotted lines) after being converted to 8 bit, binarized, and cleaned using Image J software. These post-processed images pertain to six different experiments. Each image corresponds to the indicated spall experiment. The voids are clearly distinguished as white spots on a black background.

![Figure 3. Top row: bright field optical micrograph of a spalled sample. Rest: processed optical micrographs of damage fields.](image)

The overall damage appears to increase with decreasing tensile stress rate. This confirms our conjecture drawn from FSV measurements. While a scattered damage field is observed in Exp. 1 (35 GPa/μs), void growth is easily observed to increase as the tensile rate decreases in Exps. 3-7. Lastly, a considerable amount of damage in the form of void coalescence is observed for the lowest tensile rate in Exp. 9 (17 GPa/μs), as signaled by the arrows in the micrograph. These images were utilized to perform the quantification of the damage. The damage content, in the form of void area fraction ($V_A$), was measured and the values are plotted in figure 4a. To complement the optical analyses, the results from X-ray micro-tomography measurements are shown in figure 4b. The color is used with the sole purpose of distinguishing between individual voids and has no physical meaning. The plot and images confirm the qualitative trend observed in the optical micrographs: at low tensile stress the damage appears to have reached the coalescence (C) stage. As the tensile stress rate increases to the highest tensile rates examined in this study, damage decreases to the point that void nucleation (N) seems to be the dominant mechanism.
To further examine the damage fields, EBSD misorientation maps of selected experiments are shown in figure 5. These images were taken from areas near the center of the recovered samples. In maps of this type, lattice misorientation within a grain is correlated with plastic dissipation processes, such as dislocation slip [10].

Overall, the deformation and associated damage is observed to change with the tensile rate as follows: for Exps. 1 and 3 mostly incipient damage, in the form of scattered voids, with a moderate amount of plastic dissipation is observed in the misorientation maps. These are the samples deformed at the highest tensile rates in this study. As the tensile rate decreases, an increasing plastic dissipation, in the form of enhanced misorientation development, is observed in Exps. 4-6. As the tensile rate further decreases, the plastic fields allowed for a higher localization around the growing voids with the eventual coalescence into larger voids that seem to be the precursor of a full spall plane in Exp. 9. Overall, the results on the examination of the damage fields presented in this section collectively complement and substantiate the free surface velocity measurements presented in section 4.

6. Conclusions
This work examined the effects of loading kinetics on the early stages of damage evolution in shock loaded Cu samples. More advanced stages of damage are observed in samples that were under the action of slower tensile stress rates. In essence, the kinetics of tensile loading determines the total time under which a region of a sample experienced a state of tension. Because (1) the length scale, in the form of grain boundary density, and (2) as the magnitude of the tensile pulses were strictly kept constant for this set of experiments, time is the sole, or at least predominant, parameter responsible for the development of advanced damage states in the samples. These observations are consistent with a time dependency for the plastic processes that lead to the creation of damage. Finally, extrapolation of this study can be used to bridge the results from a variety of shock loading conditions. For instance, if the tensile stress rate is allowed to increase considerably, the magnitude of the tensile pulse, inherently

Figure 4. (a) Damage vs calculated stress rate, (b) 3D damage fields of indicated experiments. The color is used only to distinguish the voids.

Figure 5. EBSD misorientation maps, the color code indicates the degrees of deformation.
related to the compressive stress magnitude, should also increase considerably to create any observable
damage. Such a case is typically observed in laser driven spall experiments in which incipient damage
is observed in experiments conducted at stresses on the order of 8-10 GPa.

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