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# The Effect of Grain Size on Deformation and Failure of Copper under Dynamic Loading

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## Abstract

In this work, we show experimentally, and using computer modeling that the effect of grain size manifested as an effect on constitutive behavior can have an appreciable effect on the deformation stability of copper deformed in tension under both quasi-static and dynamic loading: an increase in grain size results in greater extents of deformation. In a work previously published by Gourdin and Lassila, the effect of grain size was incorporated into the Mechanical Threshold Stress (MTS) material model applied to OFE copper. Dynamic tensile tests were modeled using a 3-D computer code in which the MTS material model was incorporated. The computer code model accurately predicted the occurrence and growth of necking during dynamic deformation as a function of grain size.

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# **1. INTRODUCTION**

The constitutive behavior of a ductile metal has long been known to control its deformation stability under tensile loading assuming that the deforming body is homogeneous and isotropic [1-4]. A straightforward analysis shows that plastic deformation under uniaxial tensile loading is unstable when the work hardening rate is less than or equal to the flow stress. This is referred to as the instability criterion and represents the point during deformation at which geometric softening due to reduction of the cross sectional area of the sample (assuming constant volume deformation) occurs at a greater rate than work hardening of the deforming material. Under uniaxial tensile loading, instability occurs at the maximum tensile load and, in general, localization of deformation (necking) occurs at this point. The rate of growth of a neck has been shown to be a function of the work hardening behavior and strain rate sensitivity [5-7]. Under dynamic loading inertia effects can retard the growth of instabilities (this effect is geometry dependent; samples with large cross sections being most affected).

Grain size is known to modify constitutive behavior of metals and alloys to various extents. This effect on constitutive behavior can, in turn, have an effect on deformation stability. In the case of copper the effect of grain size on yield and flow stress is appreciable over a wide range of test conditions [8-11]. In a recent work the effect of grain size was incorporated into the Mechanical Threshold Stress (MTS) material model [12]. This development led to analytical studies of the effect of grain size on the strain at which instability occurs under tensile loading, which indicated that increases in the extent of uniform deformation could be expected with increases in grain size at any given strain rate [13].

In this paper the effects of grain size on the stress-strain behavior, deformation stability and necking behavior of copper deformed in tension under quasi-static and dynamic conditions are examined. We present results of computer code modeling of the dynamic tests which utilized the MTS material model with grain size as a model parameter. The computer code model was found to accurately predict the occurrence and growth of necking during dynamic deformation as a function of grain size.

# 2. EXPERIMENTAL AND RESULTS

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Test samples were machined from cold rolled OFE copper bar stock, nominally 99.98% Cu. The test samples were annealed at  $375^{\circ}$  C and  $800^{\circ}$  C for one hour in an argon atmosphere to produce nominal grain sizes of 15 and 120  $\mu$ m respectively. Optical microscopy indicated that the test materials were recrystallized with equiaxed microstructures.

Dynamic and quasi-static testing was performed using 1.00 mm thick tensile samples with a width of 2.54 mm and a gage length of 5.08 mm. This sample geometry was chosen to minimize inertia effects in the dynamic test while still providing a sufficient cross sectional area so that anisotropy due to single crystal effects in the large grain size materials were not appreciable [14]. Quasi-static tensile tests were performed at a nominal strain rate of  $10^{-3}$  s<sup>-1</sup> using a screw driven test machine.

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Results of the quasi-static tests, shown in Figure 1, indicate that the large grain size material had greater extent of deformation prior to the instability strain relative to the small grain size material.

Dynamic testing was performed using the split Hopkinson pressure bar technique (SHPB). The average strain rate was approximately  $5500 \text{ s}^{-1}$  for all of the tests that were performed. Detailed descriptions of the test hardware and data reduction techniques used in this work are given elsewhere [15]. Engineering stress in the sample was measured dynamically by a transmitter bar. A high-speed framing camera, which produces approximately 80 back-lit images, was used to record the deformation of the sample. Engineering strain in the sample as a function of time was calculated using values of relative displacement of the gage marks on the sample taken off the framing camera record. The engineering stress and engineering strain records as functions of time are phased to construct an engineering stress-strain plot as shown in Figure 2 for the 15 and 120  $\mu$ m materials.

The strain at which necking initiates in the dynamic tests was determined visually using the framing camera record. As was the case in the quasi-static test results, the large grain size material produced a greater extent of uniform elongation prior to necking than the small grain size material.

### **3. COMPUTER CODE MODELING OF THE DYNAMIC TESTS**

An explicit arbitrary Lagrange/Eulerian computer code developed at Lawrence Livermore National Laboratory (ALE3D [16]) was used to model the tensile SHPB experiments. The MTS material model, as developed for copper with grain size as a model parameter [12], was incorporated into ALE3D. The computer model of the tensile SHPB experiments included the incident and transmitter bars and detailed meshing of the grips and test sample as shown in Figure 3. The loading input for the computer model of the experiment was a pressure history applied to the end of the incident bar. This pressure history was calculated from the strain history of the incident bar recorded by a strain gage as described in Reference 15. This modeling of the experiment matched, as closely as possible, the actual boundary conditions of the problem.

Output from the computer model consisted of data that could be compared directly to the experimental data: 1.) computer images of the sample at times that could be compared to the framing camera images and 2.) load history of the transmitter bar.

#### 3.1 Comparison of Computer Code and Framing Camera Images.

In Figures 4-a thru 4-d computer images of the test sample are shown along side of corresponding framing camera images for a 15  $\mu$ m grain size copper test sample. (see Fig.4 caption for detailed information). Comparison of the profiles indicates that the computer code model predicted, in general, the deformation and necking of the test sample quite well. This was also found to be the case for the 120  $\mu$ m grain size test sample. The elongation of the test sample as a function of time, based of the relative displacement of the gage marks, was extracted from experiments and

computer code predictions for the 15 and 120  $\mu$ m grain size test samples (shown in Fig. 5). Excellent agreement between the experimental and computer code data is observed.

A qualitative judgment of the time at which necking occurred was performed. The procedure used was simply to the select an image in which there was a perceived inflection in the profile, indicating localized deformation. Necking times were selected by looking at the experimental and computer code data independently (this was done with computer images showing only the profile of the test sample). Good agreement was observed between the selected times at which the experiment and computer model showed necking, for both grain sizes. When the corresponding images that show the occurrence and growth of a neck are compared, it is immediately evident that the location at which necking occurs in the experiments and the computer code predictions is different. Refinements of the meshing in the sample and grips were performed and were found to have an effect on the location of necking (with no effect on the time at which necking occurred or the growth rate of the neck.) It appears that the location of the neck is extremely sensitive to small changes in wave propagation that occur when the meshing is changed.

#### **3.2 Comparison of Stress Measurements**

The computer code output was edited to examine various aspects of the loading of the sample. First, the uniformity of stress in the gage section of the test sample during loading was assessed and was found to be uniform to within about 10% (prior to necking). This suggests that the geometry of the test sample is not having deleterious effects such as end constraints or inertial loading.

The net loading of the test sample in the computer code simulation as a function of time was determined by editing each element through the cross section in the center of the gage section. The result, shown in Fig. 6, was compared with the loading measured by the transmitter bar (experimental and computer code simulation). From Fig. 6 we can conclude that the loading of the test sample is represented reasonably well by the computer code transmitter bar load. However, the experimental transmitter bar load data is in significant variance with the computer data. We believe this is primarily due to deformation which occurs in the grip region of the experimental test sample during testing and various approximations made in the computer code modeling of the grip (no deformation of the test sample outside of the gage section. This resulted in better agreement between the experiment and computer code simulation. However, the load-time data from the experiment still did not have sufficient resolution to determine accurate stress-strain information or the point of maximum load (point of instability).

# 4. CONCLUSIONS

Our study of the effects of grain size on the deformation stability of copper yields the following conclusions:

• An increase in grain size results in greater extents of uniform elongation (and strain to failure) under uniaxial tensile loading at strain rates of 0.001 and 5500 s<sup>-1</sup>.

• The MTS material model, which includes grain size as a material parameter, was incorporated into a computer code which was subsequently used to model the dynamic tensile tests. Excellent agreement between the computer model and the experiments validated the accuracy of the material model and suggests that the variations in mechanical behavior are due solely to the modification of constitutive behavior by changes in grain size.

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Figure 1. Quasi-static tensile test results indicating an increase in the instability strain (strain at maximum load) in the large grain size material relative to the small grain size material. There is also an accompanying increase in total elongation.



**Figure 2.** Dynamic tensile test results. This result is similar to that presented in Figure 1.; an increase in strain to failure is clearly evident. Because of the inaccuracies in the measurement of load in the sample, as discussed in the text, instability strains can not be extracted from this test data.



Figure 3. Computer generated image of the test sample and grip arrangement. There were a total of 20,000 elements used to model the experiment and this resulted in 80,000 degrees of freedom.



Figure 4. Corresponding framing camera and computer generated images of the 15  $\mu$ m grain size test sample: a) sample, b) sample undergoing uniform deformation, c) visible necking, d) sample just prior to failure. The images of the test sample were taken so that the diagonal through the cross section normal to the tensile axis of the test sample was in the optical plane. This resulted in clear images of two opposite edges of the test sample.



Figure 5. Relative displacement of the gage marks during deformation. The grid line that separated the obvious change in mesh size in the gage section of the computer code images corresponds to the gage marks in the experimental test sample, as shown in Fig. 4.



Figure 6. Computer model predictions of the loading history of the test sample compared with the experimentally determined load history (small grain size material). The experimentally determined curve is believed to be grossly in error due to plastic deformation of the test sample in the gripping regions.

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