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Dynamic Fracture of Ductile Materials

The effects of nanostructure upon the dynamic ductile fracture of high purity copper

Sarah Ward[a]*, Christopher Braithwaite[a], Andrew Jardine[a]

[a]*SMF Fracture and Shock Physics Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge, CB3 0HE, UK*

Abstract

Dynamic fracture is a fundamentally important physical process. However, the effect of material nanostructure, including both lattice and grain structure, and their respective defects, on such events is not well understood. Ductile fracture is widely accepted to proceed through the nucleation, growth and coalescence of voids to form a failure plane. The formation of voids at grain boundaries is established, and impurities and secondary phase particles are often found at the centre of these voids suggesting their involvement in the nucleation process. In a pure metal, where impurities are absent, the void nucleation process is unclear, although theories suggest the importance of dislocations and their substructures. Dislocation parameters are underpinned by the plasticity behaviour of the relevant material, which is often highly strain rate dependent, and in the case of copper, is also history dependent. Here, we describe experiments that study the ring fragmentation of OFHC copper, at strain rates around 10^4 s^{-1}. Diagnostics include high speed photography, laser velocimetry, and soft capture of fragments. The number of fragments and strain at fracture was observed to increase with the applied strain rate, suggesting an increase in ductility with rate. The cross-section of the fragments changed significantly during the applied loading, due to interaction of the ring with the driver cylinder, suggesting a strongly tri-axial stress state, where the strain rate is likely to be higher than that which was estimated, based on circumferential expansion from laser velocimetry data. The fracture surfaces displayed macroscale surface topology, and showed evidence of several different fracture mechanisms across the failure plane. The length scales of the fracture surfaces were to the order of tens of microns, and below, suggesting that structures below the grain size of the material are dominating the observed behaviour.

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Keywords: Fracture; ductile; copper; ring; fragmentation.

* Corresponding author. Tel.: +44 (0)1223 337322; fax: +44 (0)1223 363263.
E-mail address: sjw251@cam.ac.uk

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1. Introduction

Dynamic fracture is an important process that is strongly relevant in many real world applications, ranging from crack arrest in engineering structures [1] to the impact of meteorites on structures in space [2]. However, the effects of material micro and nanostructure on these processes are not well understood. Ductile fracture is widely accepted to proceed through the nucleation, growth and coalescence of voids to form a failure plane. Voids have been demonstrated to form at grain boundaries [3]. Impurities and secondary phase particles are often found at the centre of these voids [4], suggesting their involvement in the nucleation process. For pure metals, where impurities and inclusions are absent, the void nucleation process is not well understood, although theories suggest the importance of dislocations and their substructures [5], [6]. Dislocation parameters are underpinned by the plasticity behavior of the relevant material, which is often highly strain rate dependent, and in the case of copper is also history dependent.

Here, we aim to identify the most important microstructural properties of polycrystalline metals that affect crack propagation under tension at high rates. Ductile fracture of OFHC copper is investigated using an expanding ring geometry. The technique produces a well-defined loading state and can achieve a range of high strain rates (10^3 to 10^4 s^{-1}). Conducting such experiments using high purity copper, where the microstructure is thoroughly characterised, enables detailed of the fracture surface length scales with those of the microstructure.

1.1. Dynamic ductile fracture

Ductile materials respond to tensile loading through plastic deformation, and necking. Voids are nucleated when the tensile stress at a point exceeds the threshold stress for void nucleation. A void then grows with the development of a plastic zone around it [7]. Voids coalesce when the shear stress in the connecting ligament between two voids exceeds a critical value. Plastic deformation is governed by the generation and mobility of dislocations within a material, controlled by the starting microstructure of the material, through annealing or cold working, and for the dynamic case, the applied loading. Dislocation mobility is often impeded by microstructural features such as precipitates or grain boundaries.

The distribution of dislocations in an FCC metal can be controlled through annealing [8], cold working [8], [9], and shock loading [10]. The behavior of copper, in a variety of conditions, has previously been studied across a range of strain rates. Copper with a higher dislocation density, due to work hardening [11] or shock loading [12], was found to exhibit similar behavior to fully annealed copper [11], although at larger stresses for a given strain. It was suggested by Jordan et al. [11] that the major numerical differences between stresses achieved at fixed strains in the studies is due to the starting internal structures of the materials, which depend upon cold working, annealing temperature, and annealing time. It was further suggested that the experimental variation within a particular study at a given strain rate may be due to small variations within the internal structure and the strain rate history. It is also important to understand the effects of material condition upon its fracture behavior, and for the dynamic case, to understand the effects of shock loading, known to introduce crystallographic defects at the shock front [13].

In order to examine the effects of strain rate on material properties, it is common to compare the stress at a given strain over a range of different rates [12], [14], [15]. The studies discussed above also investigated the effects of strain rate upon OFHC copper, showing an increase in slope of the stress-strain plots at higher strain rates between 1×10^3 and 2.5×10^4 s^{-1} [14], [15]. Jordan et al. [11] observed an increase in flow stress with strain rate, at around 500 s^{-1}, the as-received copper exhibited similar behavior to the annealed copper, however the upturn was at a higher flow stress. Swegle and Grady [12] conducted a similar study using shock loaded copper, for which a vast upturn in stress was observed at high strain rates (10^5 to 10^7 s^{-1}). The interpretation of the rapid increase in strain rate dependence of flow stress in copper has been the subject of debate, but clearly demonstrates the importance of understanding the relationship between dislocation substructure and strain rate effects.

The effects of microstructural parameters have also been investigated. The yield strength of polycrystalline materials is well known to vary with grain size by the Hall-Petch relationship [16], [17]. Many studies of effects of grain size upon the dynamic tensile fracture properties of copper have reported conflicting results [18], [19]. Christy et al. [18] studied the spall behavior of polycrystalline copper with grain sizes of 20, 90, and 250 μm. The authors observed lower damage in fine-grained copper than larger grain size samples, in agreement with the Hall–Petch relationship that correlates yield strength to grain size. Conflicting results were reported by Minich et al. [19], their