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Ductile failure in polycrystalline OFHC copper

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ABSTRACT

Ductile failure in polycrystalline oxygen-free, high-conductivity copper is explored through uniaxial tension experiments. Specimens obtained through tests interrupted at various stages of deformation and failure evolution are examined through quantitative microscopy to discern the mechanisms of failure and the local strain evolution. The formation of a single rectangular prismatic channel-like cavity, and its subsequent growth as a rectangular cavity, are demonstrated. Fractographic observations are used to suggest that self-similar expansion of the cavity is through an alternating slip mechanism. Local strain levels are estimated from measurements of the change in grain size with deformation and used to indicate that the local values of failure strains are likely to be much larger than that estimated from strains averaged over characteristic specimen dimensions such as the gage length or the specimen diameter.

1. Introduction

Ductile failure in polycrystalline copper has been the subject of numerous investigations over the past century. Failure in this context is understood in the sense described by Orowan (1948): rupture "is a consequence of an instability of plastic deformation and occurs when the deformation becomes localized in a small part of the specimen." Progression of failure from the localized plastic deformation seldom arises from breakage of primary bonds, but from slip along crystallographic planes at the smallest scales and is generally thought to occur by void nucleation and growth at slightly larger scales. It is now well-known, since the early work of Ludwik (1926), that uniaxial tensile specimens of polycrystalline metals fail in the familiar "cup and cone" mode of fracture. Orowan (1948) showed yet another mechanism of failure – based on observations by Tipper of the formation of a polyhedral transverse channel in the neck of an aluminum single crystal specimen, he provided a mechanism of alternating slip for the formation of a crack at the center of the necked specimen. Fig. 1 is a reproduction of the mechanism proposed by Orowan (1948). It is well-known that in plane-strain tension, the deformation localizes along the characteristics (slip lines) of perfect plasticity; these are aligned along lines inclined at 45° with respect to the direction of tension. The rectangular opening occurs where these slip lines intersect; Orowan observed that slip occurs initially along AB and CD with subsequent slip along planes EB and CF. Continuation of such alternating slip events results in an enlargement of the rectangular cavity. Orowan (1948) suggested that failure in polycrystalline materials could also occur by such alternating slip "if the plastic deformation is concentrated in thin zones around planes of maximum shear stress". This suggestion appears to have not been pursued in more recent literature, perhaps due to the lack of experimental observations that carefully outlined conditions under which such a mechanism could be of importance. For example, Rogers (1960) examined ductile failure in OFHC copper with a (fairly large) grain size of about 1 mm; after examination of metallographic sections from uniaxial tests interrupted at various stages of neck growth, he concluded that voids were nucleated both at grain boundaries and in the interior of grains, and accumulated along lines parallel to the direction of tension, at the center of the specimen where the triaxiality was the largest; coalescence of voids resulted in the formation of a central crack. Subsequent growth of this crack occurred by concentration of shear at an angle of 30° to 40° to the tensile axis, nucleation of a large number of voids within this shear zone and their eventual coalescence; this is called the "*void-sheet mechanism*". These void sheets zig-zag across the central segment of the specimen and form the "cup" of the cup-cone fracture. Most importantly, Rogers noted that the final separation (the "cone" part) could evolve by the Orowan mechanism of ductile failure by alternating slip, although he could not rule out cleavage in the highly strained grain.

Puttick (1959, 1960) also explored the basic deformation and failure mechanisms in polycrystalline copper. The material had a grain size of about 50 μm, and contained impurities that were introduced during the rolling process. These specimens developed standard cup-and-cone fractures that began with the formation of a diffuse necking localization. An image of a thickness section is shown in Puttick's paper (see Fig. 1 in Puttick, 1959), identifying voids within the necked region; the average true strain at the narrowest part of the neck can be estimated to be around 0.66. Using

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