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Incipient Spallation Fracture in Light Metals From 3D X-Ray Tomography, 2D Microscopy, and Molecular Dynamics Simulations

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INCIPIENT SPALLATION FRACTURE IN LIGHT METALS FROM 3D X-RAY TOMOGRAPHY, 2D MICROSCOPY, AND MOLECULAR DYNAMICS SIMULATIONS*

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ABSTRACT

The dynamic fracture of ductile metals is known to occur through the nucleation and growth of microscopic voids. As the voids grow, the surrounding metal is plastically deformed to accommodate the change in void volume. In order to gain better insight into void growth, gas gun recovery experiments were used to study incipient spallation fracture in light metals (Al, Cu, V). In addition to in-situ free surface velocity wave-profiles, the recovered samples were first analyzed using 3D X-ray tomography and then sectioned for 2D microscopy. The void size and spatial distribution were determined directly from the X-ray tomography. The single crystal samples show a bimodal distribution of small voids with large (50 -100 micron) well separated voids. The plastically damaged region surrounding the large voids is quantified using optical and electron backscattering microscopy. Microhardness measurements indicate this region to be harder than the surrounding metal. Concurrently, a molecular dynamics model of void nucleation and growth at high strain-rate was developed. The model is consistent with experimental observations, e.g. voids nucleate at the weakest points in the metal such as inclusions and grain boundary junctions. The nature of void growth in a single crystal is sensitive to the crystal structure with initially spherical voids in FCC metals growing into octahedral shapes as observed in experiment. Details of the dislocation mechanisms of void growth will be presented.

1 INTRODUCTION

Direct observations of the three dimensional distribution of voids and the plastically deformed zone surrounding the incipiently grown voids during dynamic fracture experiments are presented. The smaller voids in single crystal experiments tend to show faceted surfaces consistent with previous observations by Stevens [4] while the larger voids tend to be spherical consistent with classical large-scale plasticity. Molecular dynamics modeling of high strain rate void growth reveals a growth mechanism of prismatic loop punching at the void surface.

The dynamic fracture of ductile metals is known to occur through the nucleation and growth of microscopic voids (c.f. McClintock [5]). As the voids grow, the surrounding metal is plastically deformed to accommodate the change in void volume. Continuum models of ductile fracture are based on the evolution of the plastically deformed zone (c.f. Gurson [6]) surrounding the voids. Despite this, little or no direct observation of the three dimensional distribution of voids or the plastically deformed zone for high strain rate dynamic fracture exits. The purpose of this paper is to present observations of the three dimensional distribution of voids and the plastically deformed zone surrounding incipiently grown voids in high strain rate spallation fracture and compare to direct numerical simulations using molecular dynamics. For an overview of spallation fraction, see the review by Curran [7].

2 DISCUSSION

In order to gain better insight into the dynamic fracture process, gas gun recovery experiments were used to study incipient spall fracture in polycrystalline and single crystal aluminum, single crystal vanadium and copper. A two stage light gas gun was used to launch a projectile into a flat target. Shock waves reflecting off the free surfaces interact inside the target to create a state of dynamic tension. The magnitude of the tension is controlled by the impact velocity and the pulse duration is controlled by the thickness of the projectile. We find incipient fracture to occur in aluminum for impact velocities between 150-200m/s for flyers of 1-2mm thickness.

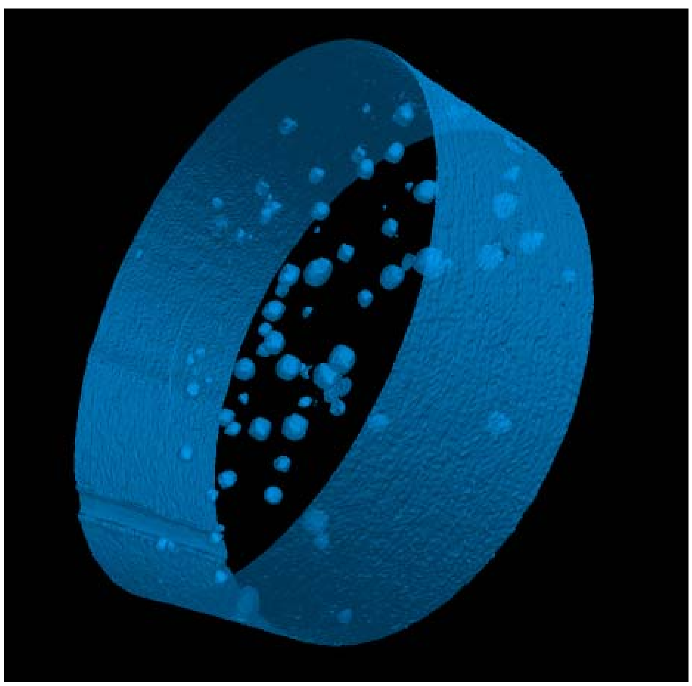

Figure 1. A tomographic reconstruction of the distribution of voids during incipient spallation fracture in single crystal aluminum.

The free surface velocity of the rear surface was measured with an in-situ VISAR concurrently during the recovery experiment. The pullback of the free surface is related to the dynamic strength of the material (c.f. Kanel[8]). The recovered samples were first analyzed using 3D X-ray tomography and then sectioned for 2D microscopy. Void nucleation and growth in the polycrystal samples occurs at grain boundaries with an exponential distribution of void sizes. The void size and spatial distribution are determined directly from the X-ray tomography. The polycrystalline samples show a highly inhomogeneous distribution of porosity inside the material. In repeated experiments, we find additional wave reflections in the VISAR signal to be correlated with regions of high porosity inside the material. These are regions where the initially isolated voids have begun to link up to form a fracture surface. The single crystal samples show a bimodal distribution of small voids with large (50 -100 micron) well separated voids (see Figure 1).

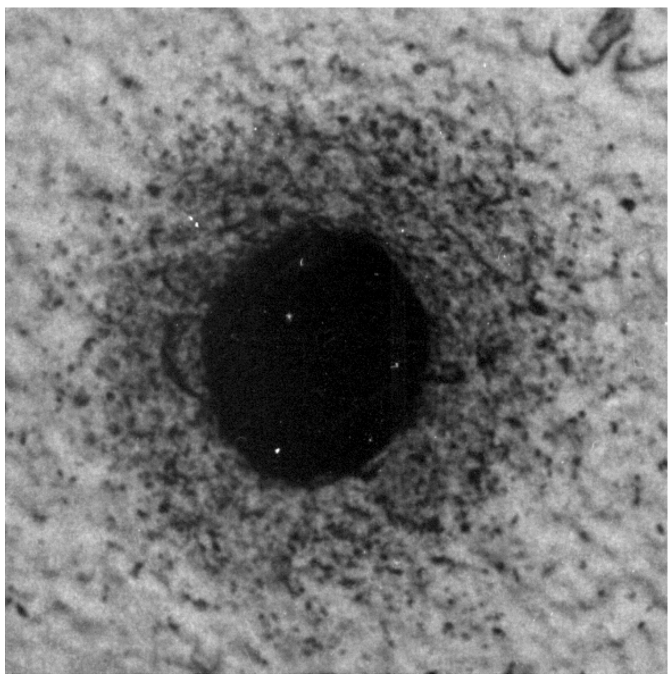

Figure 2. Preferential etching surrounding an incipiently grown void, showing the plastically deformed zone. The void shown is about 80μm in diameter.

The plastically damaged region surrounding the large voids is quantified using optical and electron backscattering (EBS) microscopy. In order to prepare the single crystal samples for EBS microscopy, the surfaces were carefully etched after slicing. As shown in Figure 2, the etching is preferential in region surrounding the voids. We associate this region with the plastically deformed zone. The size of the zone scales reasonably well with classical plasticity analysis. The EBS analysis shows a comparable size region with many microscopic features, for example the region close to the surface of the void contains many small grains suggesting significant recrystallization. Microhardness measurements indicate this region to be harder than the surrounding metal.

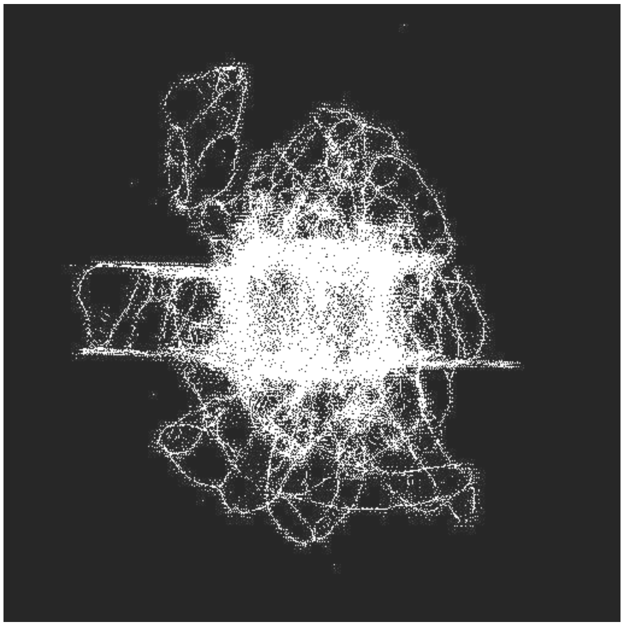

Figure 3. A molecular dymanics simulation of void growth in copper during dynamic fracture, showing the dislocation structure during triaxial loading.

Concurrently, a molecular dynamics model of void nucleation and growth at high strain-rate was developed (c.f. Belak[1]). The model is consistent with experimental observations, e.g. voids nucleate at the weakest points in the metal such as grain boundary junctions. The nature of void growth in a single crystal is sensitive to the crystal structure with initially spherical voids in FCC metals growing into octahedral shapes as observed in experiment. The voids grow through the nucleation and motion of dislocations at the void surface. A model was developed to analyze the dislocation activity during the molecular dynamics simulation (c.f. Rudd[3]). The analysis reveals the mechanism of void growth to be the emission of prismatic dislocation loops (see Figure 3) and the resulting faceted octahedral shape to be a direct reflection of the prismatic nature of the dislocation loops. Recently, the model was extended to study the effect of triaxiality of loading (c.f. Seppälä[2]).

3 ACKNOWLEDGMENT

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