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Determination and interpretation of statistics of spatially resolved waveforms in spalled tantalum from 7 to 13 GPa

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ABSTRACT

A suite of impact experiments was conducted to assess spatial variability in the dynamic properties of tantalum, on length scales of tens of microns to a few millimeters. Two different sample types were used: tantalum processed to yield a uniform refined grain structure (grain size ~20 μm) with a strong axisymmetric {1 1 1} crystallographic texture, and tantalum processed to yield an equiaxial structure with grain size ~42 μm. Impact experiments were conducted loading the samples to stress levels from 6 to 12 GPa, which are well above the Hugoniot Elastic Limit (HEL), then pulling the sample into sufficient tension to produce spall. These stress levels were specifically chosen to investigate the spall behavior of tantalum at levels ranging from the incipient spall stage to significantly above the spall strength, focusing on microstructural phenomena. A recently developed spatially resolved velocity interferometer known as the line-imaging VISAR allowed the point-to-point variability of the spall strength to be determined. Specifically, we have been able to determine *in real time* the nucleation and growth of void defect structures that lead to the eventual spallation or delaminating of the plate. Experiments indicate that the nucleation and growth process is time-dependent and heterogeneous since a time-dependent distribution of defects is measured. This strongly suggests that the spall strength of the material is not a single-valued function. When fitted to Weibull failure statistics, the results indicate a similar mean value and variability for the spall strength of both types of tantalum. The spatial dependence of the material distension of the spalled tantalum is also deduced, in the approximation of uniaxial strain.

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1. Introduction

The dynamic properties of tantalum are of interest for a variety of applications because of the high strength (in tension or spall and in compression), high density, refractory properties, weldability, and high thermal conductivity of this material. However, the strength properties of tantalum and other bcc metals under dynamic deformation are known to be sensitive to texture, microstructure, impurities, strain rate and temperature. There is considerable interest in understanding the deformation behavior of materials and in particular how the initial microstructure of a material affects both its dynamic yield strength (Huang and Asay, 2005) and its spall characteristics (Chen et al., 2006). Here, we describe dynamic studies conducted using impact techniques on smooth bore gas guns at impact velocities in the range of 200–400 m/s.

We have studied two different types of tantalum to evaluate whether the details of microstructure (e.g. grain orientations, aspect ratios, interface impurities, work history) affect (1) the stress levels at which spallation occurs, and (2) the dynamic morphology of the spalled volume. The goal is to be able to measure heterogeneous deformation features in a time-resolved fashion as dynamic compression and tensile rupture of tantalum occurs. The measurements utilize a temporally- and spatially-resolved interferometric diagnostic (line-imaging VISAR) to map out the velocity $v(y,t)$ of all points on a line on the free surface of a sample (Trott et al., 2000). Here, y is a spatial coordinate (position along the line) and t is time. The line-imaging VISAR has recently been used to investigate the granular compression behavior of granular/porous sugar (Trott et al., 2007) and of WHA (Vogler and Clayton, 2008). What is new here is that we are able to deduce the time-dependent void structure produced in the spallation process. In other words, we are directly measuring the nucleation and growth of voids/defects that are responsible for spallation. We have extended an earlier study (Chhabildas et al., 2002) to investigate the effect of peak loading stress and pulse duration on the spallation process. As well, we are able to express statistically variations in the spall strength, with the goal of determining how these failure processes change with time and pulse duration.

2. Phenomenology of spall

Mechanisms for flow and spallation in tantalum have been discussed at some length in the literature. A comprehensive manuscript by Meyer and Aimone (1983) outlines the growth in this field from 1958 to 1982, when many of the main concepts still used to describe spallation phenomena were deduced. Antoun et al. (2003) provide a more recent summary. Spallation is a process of formation and coalescence of voids, together with localized strains ("mixed mode," per Tonks et al., 2006; Henrie et al., 2006), over a volume of finite thickness. An energy balance between increased surface area and associated plastic zones and decreased strain energy constrains the development of voids and fractures (e.g. Grady, 1982). Coalescence of voids affects nucleation rates and local stress fields (e.g. Czarnota et al., 2006). The stress history is generally important for describing spallation behavior (cumulative damage criterion); material processing during the initial loading history must be understood to properly model spallation (e.g. Davison and Stevens, 1973).

In laboratory experiments, spall is often produced by planar impact of a thick sample by a thin impactor, leading to an interaction of release waves that takes the sample into tension. This is diagnosed either by sample recovery or by velocimetry (Fig. 1).

At the stress levels used in the present experiments, the stress waves will separate into a leading wave propagating at approximately the elastic wavespeed and a second wave loading to the final Hugoniot state. Details of the HEL measurements in these experiments are described by Furnish et al. (2007).

From the magnitude of the release at the free-surface (the "pullback" in Fig. 1) prior to the rebound it is possible to calculate the spall strength of the material. The material will support a tensile stress σ_{spall} prior to failure, causing an in-material velocity ("particle velocity") change of $\Delta u_P = -1/2\Delta V_{PB}$, where ΔV_{PB} is the observed free-surface pullback amplitude (the factor of 1/2 is due to the approximate doubling of in-material velocity at the free surface). The relation that is generally used to calculate the spall strength is given by