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Spallation Modeling in Tantalum

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Abstract: A gas gun plate impact spallation experiment has been performed on commercial purity rolled tantalum. The shock pressure achieved was about 7 Gpa. and was sufficient to induce incipient spallation. The particle velocity was measured at the free surface of the spalled plate, and the spalled sample was recovered and examined metallographically using image analysis. The quantitative image analysis results are being used to develop a damage model. The model is micromechanically based and involves novel void growth and coalescence processes. The 1D characteristics code CHARADE has been used in a preliminary simulation of the VISAR free surface particle velocity record. Implications for ductile damage modeling will be discussed.

1. INTRODUCTION

Metallurgical analysis of damage in metals has traditionally involved the qualitative characterization of damage features and general conclusions about the damage process. This approach has yielded valuable information but falls short of the goal of quantitative understanding and modeling. A numerical model that will reproduce damage features and damage evolution requires quantitative information as a basis. Such micromechanically based modeling on the mesoscale deals with the damage process at roughly the grain size length scale and, thus, involves the same damage structures most often examined in classical metallurgical analysis. Hence, adding image analysis of features at the grain size length scale to classical metallurgical analysis would produce the needed quantitative information for mesoscale micromechanical damage modeling.

In a paper by Zurek *et al.* [1], computer image analysis results are presented for a complete cross section through a commercial purity tantalum plate exhibiting incipient spallation. The shock strength was ~7 GPa with 1 μs pulse duration. The cross section, taken using an optical microscope, shows a narrow damage band about 800 microns wide normal to the shock direction. The damage is ductile in nature and consists of roughly spherical voids. Many of the voids are joined together in clusters that extend mostly in the direction perpendicular to the shock direction. This cross section, a portion of which is shown in [1], was analyzed using image analysis software. A profilometer was used to measure the depths of the voids visible in the cross section. From these depth measurements, equivalent spherical voids were constructed using the equivalent circles of the cross section. In this fashion, full 3-D information was obtained for the voids intersecting the cross section. Equivalent void cross-sectional diameters were calculated, as well as the center position coordinates. We assume that the voids are spherical for our analysis, however the mean aspect ratio of the voids was 1.36.

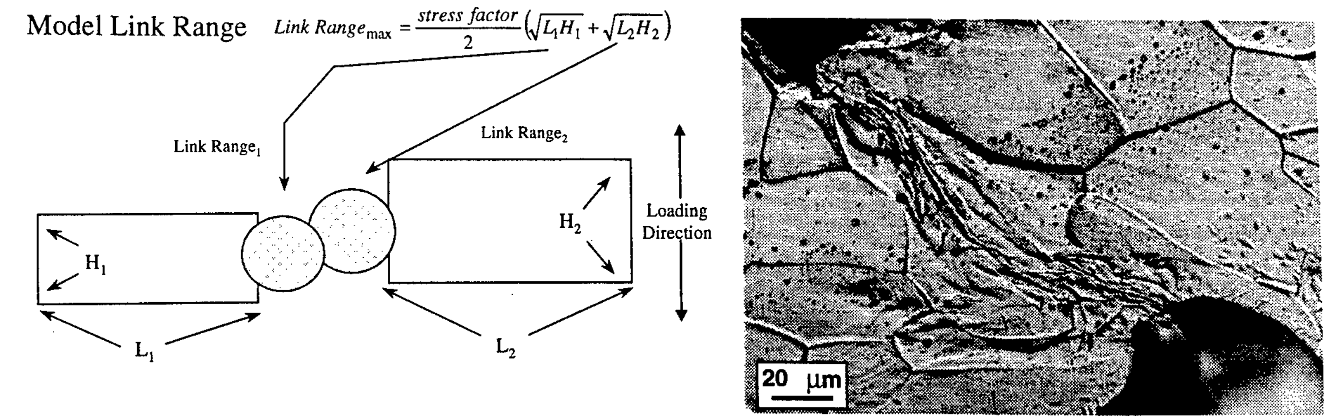
The void size, location, and porosity distributions are ideal for modeling efforts that focus on void growth. To investigate void coalescence, however, one must also examine the grouping of voids into clusters. There are many such clusters in the micrographs [1]. In addition, regions of localized plastic flow between voids are visible in the micrographs. This occurrence will be termed herein as void linking. These links play a role in the eventual fracture and must also be investigated. This paper discusses the implications of void clustering and void linking observed in this sample for micromechanical modeling of ductile fracture. A preliminary hydrocode calculation of the sample free surface particle velocity from the gas gun shot is also presented.

The investigation of void clusters here is limited to analysis of only one cross section through the sample. The cluster sizes visible in the cross section are not representative for many clusters because the cross section will not cut through the mid-section of most of the clusters, but at some random plane through the cluster. In this paper we will assume that the true cluster sizes are represented by the cross sections. The results obtained here are probably still qualitatively correct, but must be taken as provisional.

2. THEORETICAL FRAMEWORK FOR VOID CLUSTERING AND LINKING

In earlier work on ductile damage modeling [2, 3], a qualitative understanding of void coalescence processes was achieved. The elements of this understanding are reviewed here to introduce the cluster and linking analysis of the tantalum cross section.

The formation of void clusters, *i. e.* the formation of regions of merged voids, occurs via local instabilities that thin out intervoid ligaments. This process, called void linking, is recognized throughout the metallurgy community as being the mechanism for void coalescence. The localized plastic flow in the intervoid ligaments proceeds faster than that in the matrix. The formation of the localized flow depends upon the ligament being thin enough and the driving stress in the ligament being great enough. Large clusters have an enhanced range for linking to additional voids because there is a stress and strain enhancement at the periphery of the large cluster. The greater linking range of a large cluster is limited at very high damage and void growth rates, however, because the stress and strain enhancement requires a critical time to form. The critical formation time for the stress enhancement is approximately the time required for a release wave to traverse the cluster. This is because the formation of the stress (and strain) enhancement comes as new voids join the cluster as release waves from failing intervoid ligaments sweep over the rest of the damage cluster. The release waves move at roughly the longitudinal sound velocity. If the cluster forms faster than this sweep time, the linking range will be retarded since the peripheral stress and strain fields would not yet have reached their maximum values. These ideas are outlined in references [2] and [3].



(a)

(b)

Figure 1: (a) 2-D geometry of the linking range model. The hatched regions are in plastic flow, the rectangles are void cluster cross sections. (b) A localized flow zone region in the intervoid ligament of the commercial purity tantalum shocked at ~7 GPa. The dark spots in the upper left and lower right corners are the evolving voids.

The localized flow region in the intervoid ligament shown in Figure 1b of the commercial purity tantalum is an example of the void linking process. Figure 1a illustrates the geometry assumed in Equation (1) for our model of void linking. The hatched regions indicate regions of localized plastic flow bounded above and below by unloaded, rigid, elastic material.

In this paper, the experimental void linking ranges will be compared with a model linking range that is loosely based on the results presented in [2-4]. The model gives the maximum linking range between two damage clusters as a function of the two dimensional cross sectional sizes of the clusters seen in the micrographs, *i. e.* the cluster height, H, and the cluster length, L. A stress dependent factor is also included. This model relation is expressed as follows:

$$Link\ Range_{max} = \frac{stress\ factor}{2}\left(\sqrt{L_1H_1} + \sqrt{L_2H_2}\right), \tag{1}$$

where the subscripts 1 and 2 refer to the two clusters (or voids) between which a local instability occurs. This equation is appropriate for low strain rates (about < 10^4 1/s) for which the linking range enhancement due to cluster size is not retarded. When loading rates are high enough (about >10^5 1/s) for retardation to be significant, that is, when the loading time and damage growth times are shorter than the critical loading time mentioned above, the cluster lengths L_1 and L_2 should be replaced in equation (1) by the "effective cluster length". The effective cluster length is the critical loading time mentioned earlier multiplied by the longitudinal sound velocity. The stress factor in equation (1) is roughly a function of the volumetric tension divided by the matrix plastic flow stress. The link range given by equation (1) is the maximum that can occur. Actual link distances for the same geometry can be smaller.

The maximum link range can be described as the product of a stress factor and a geometry factor given by:

$$\textit{geometry factor} = \left(\sqrt{L_1 H_1} + \sqrt{L_2 H_2}\right)/2 \cdot \qquad (2)$$

In the analysis to come, the stress factor is assumed to be constant for all the data so that the geometry factor carries all of the variation in the modeling of link range from the data.

In equation (1) the assumption of two-dimensional symmetry is made where the 2-D cluster shape in the micrographs is assumed to extend infinitely in the direction perpendicular to the micrographs. It is unknown how well the clusters in our data fulfill this requirement. Equation (1) is also appropriate for cross sectional cluster shapes in the micrographs that are long or ellipsoidal where the long dimension is perpendicular to the shock direction. This cross sectional shape and orientation is realized for most of the clusters in our data.

3. RESULTS

In the data, voids are defined to be members of a cluster if the edge-to-edge distance between the voids is less than one-tenth the diameter of the smaller void. The cluster length is defined to be the projection of the center-to-center distance (in the micrographs) between the two end voids along the axis perpendicular to the loading direction in the metallographic plane, plus the sum of their radii.

Figure 2 shows a plot of measured link distance, *i. e.* the distance over which localized plastic flow is seen to occur in the micrographs, versus the geometric factor of the model link distance obtained from equation (2). Because of the etching used, the local instability is observable in the original micrographs as a narrow band of texture different from the matrix. The linking range is formed between two voids, but these voids are usually members of larger clusters of coalesced voids. These coalesced voids still retain enough of their original spherical shapes to be recognizable as voids. The cluster dimensions used in equation (2) are from the clusters to which the linking voids belong. The measured linking distances used are the 3-D edge to edge separations of the linking voids; the data cluster lengths, L, used are those defined earlier; and the cluster heights used are the average 3-D diameter of the voids in the clusters.

The test of the suitability of equation (1) is whether a clear boundary appears in Figure 2. According to the theory, the data can fall anywhere below a model maximum link range (the boundary), but not above it. As shown in Figure 3, there does seem to be a clear boundary, *i. e.* a straight line with a slope of roughly unity. This would suggest that the value of stress factor is roughly unity.

One uncertainty in our interpretation is that different clusters have seen different stress loading histories, the particular history depending upon the cluster position along the shock direction. Further resolution of this issue will require information from future hydrocode calculations investigating the stress history. The results here seem strong enough to suggest that the model link equation (1) has at least a measure of validity.

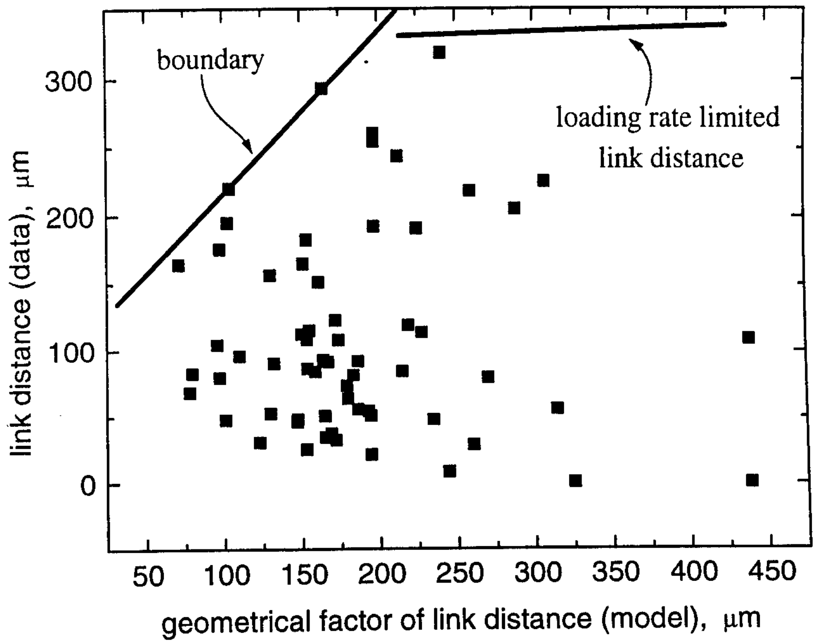


Figure 2 : Link distance data versus the geometrical factor part of the model link range.

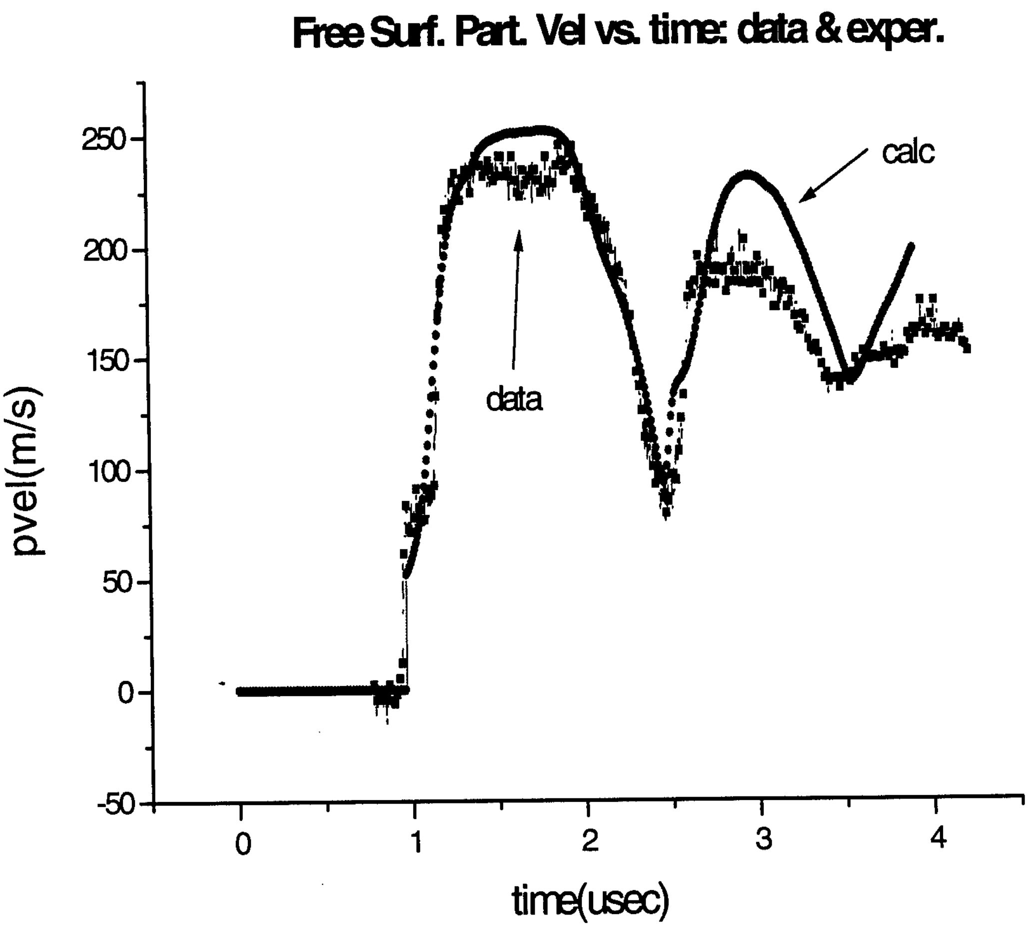


Figure 3. Observed free surface particle velocity (squares) versus a hydrocode calculation for the rolled Ta specimen, 255 m/s flyer velocity.

Figure 3 above shows the observed free surface particle velocity and a simplified hydrocode calculation for rolled Ta for the gas gun shot with a flyer velocity of 255 m/s. This is a different gas gun shot than the one used in the recovery, but the flyer velocities are almost the same. The calculation was done with the 1D characteristics code CHARADE with a simple void growth model. No clustering or linking effects were incorporated. The spall criteria was a porosity threshold of 5%. The calculation does not represent the damage growth portion of the data well, and, so, the simple damage model needs to be enhanced. The void clustering and linking effects described in this paper will be incorporated in the damage model to do this.

The VISAR free surface data of Figure 3 indicate that, once it started, void growth occurred very rapidly in this sample, in about 150 nanoseconds. This number is taken from the rise in the particle velocity data to the second peak of Figure 3, which results from the release due to void growth and damage evolution. The fall from peak particle velocity just prior to this rise marks the (extensive) tensile loading before void growth in the specimen near the spall plane. Hence, the void growth was delayed enough to allow significant initial volumetric tension to develop. The void surface of the larger voids grew at an average rate of about 1/3 the longitudinal sound velocity.

The absence of points in Figure 2 above the line labeled "loading rate limited link distance," for large geometrical factor values, has a possible explanation in the linking retardation due to the cluster size discussed earlier. These large geometrical factors correspond to large clusters, since the geometrical factor is related to the cluster cross sectional area. In Figure 2, geometrical factors larger than about 250 μm are seen not to produce correspondingly large linking ranges. For example, the largest geometrical factors near 350 μm are associated with maximum link distances of only 250 μm. One possible reason for this behavior is the linking retardation due to fast loading times and fast void growth rates, as mentioned earlier: the void growth and void linking occurred fast enough that the stress and strain enhancement at the cluster periphery did not have time to fully develop for the larger clusters. The "effective cluster size" is roughly, 300 μm, obtainable by multiplying one half of 150 nanoseconds by a longitudinal sound velocity of roughly 4 mm/μsec. The factor of one half is plausible because the void growth is just beginning at the time when damage growth begins. All of the void and damage growth happened within 150 nanoseconds, as mentioned earlier. The largest clusters in our sample is about 800 μm in length, so their effective cluster size for linking was limited by the high loading rate to 300 μm. This effective cluster size, together with a typical void size of ~250 μm for the larger clusters, can be inserted into equation (2) for the geometrical factor to obtain a value of about 275 μm, which is about where the effect begins in Figure 2.

4. CONCLUSIONS

This paper has interpreted digitized void data from micrographs of incipient spall experiment in commercial purity tantalum in terms of void clustering. Many of the results here are preliminary and will be improved in the future. However, the results so far seem promising and indicate the power of image analysis combined with optical profilometry for extracting meso-scale damage evolution information useful for modeling purposes. The VISAR free surface data and a preliminary hydrocode calculation provide some information on damage growth rates which helps explain a feature of the experimental linking distances. Damage cluster modeling will be added to the hydrocode simulation in the future.

Acknowledgments

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