Quantitative Analysis of Damage Clustering and Void Linking for Spallation Modeling in Tantalum

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Abstract. In a companion paper in this volume by Zurek et al, micrographs of incipient spallation damage in rolled tantalum were numerically analyzed using image analysis techniques. Void sizes, locations, and overall porosity were measured and tabulated. In this paper, we extend this analysis to include void clusters and examine the correlation between cluster size and the ranges of local instabilities between voids visible in the micrographs. The implications for spallation modeling will be given.

French. Abstract

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, image analysis of features at the grain size length scale produces the needed quantitative information for mesoscale micromechanical damage modeling.

In a companion paper by Zurek et al [1], computer image analysis results are presented for a complete cross section taken by optical microscope through a rolled tantalum plate exhibiting incipient spallation. The shock strength was about 8 Gpa. The cross section shows a narrow damage band about 800 microns wide normal to the shock direction. The damage is ductile in nature, i. e. it 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 image, which is composed of a montage of several optical microscope images, was analyzed using image analysis software. Equivalent void cross sectional diameters were calculated, as well as the center position coordinates. 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 cross section equivalent circles. In this fashion, full 3D information was obtained for the voids intersecting the cross section. This is important, since without the depth information, one could only guess about the true size of the voids. The practice used here of extracting equivalent spherical shapes should be reliable since the voids are observed to be roughly spherical in shape.

This information is 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 micrograph [1]. Also visible in the micrograph are regions of localized plastic flow between voids. This occurrence will be termed herein as "void linking". These will undoubtedly play a role in the

eventual fracture and, thus, must also be investigated. In this paper, we extend the work to include the clustering and void linking.

The investigation of void clusters is hampered by having only a cross section through the sample to look at. The cluster sizes visible in the cross section are undoubtedly not representative for many clusters. For want of more information, however, in this paper we will assume 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-dymat,tonks] [3-explomet tonks], a qualitative understanding of void coalescence processes was achieved. The elements of this understanding are reviewed here to introduce the cluster and linking analysis to follow of the tantalum cross section.

The formation of void clusters, i. e. the formation of regions of merged voids, comes about through local instabilities that thin out intervoid ligaments. This process, called void linking herein, 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 up 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 at the periphery takes a certain time to form. The formation time for the stress enhancement is greater than the time required for a release wave to traverse the cluster, since the formation of the stress (and strain) enhancement comes about as release waves from failing intervoid ligaments in the cluster sweep over the rest of the damage cluster. The release waves move at roughly a 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 potential values. These ideas are outlined in references [2] and [3].

The localized flow regions in the intervoid ligaments of the rolled tantalum micrograph are examples of the void linking process described above. Their extent and the size of the damage clusters participating in these regions of flow offer a means of further understanding this process. In this paper, the experimental void linking ranges will be compared with a model linking range that is loosely based on the results of references [2] and [3]. This model can also be inferred from reference [4-Melander & Stahlberg]. The model gives the maximum linking range between two damage clusters as a function of the two dimensional cross sectional sizes of the clusters, 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:

$$\text{Link Range}(\max) = (\text{stress factor})(1/2)(\sqrt{L_1 H_1} + \sqrt{L_2 H_2}) \quad (1),$$

where the subscripts 1 and 2 refer to the two clusters between which a local instability occurs. This equation is appropriate for slow loading times for which the linking range enhancement due to cluster size is not retarded. When loading rates are fast enough for retardation to matter, i. e. when the "effective cluster length" or loading time multiplied by a sound velocity, is smaller than the cluster lengths, L_1 and L_2 , they should be replaced in the formula by the effective cluster length. The stress factor in equation (1) is roughly a function of the volumetric tension divided by the matrix plastic flow stress.

Note that the link range given by equation (1) is the maximum that can occur. Actual link distances for the same geometry can be smaller.

The quantity plotted later will be the right hand side (rhs) of equation (1) without the stress factor. This part of the rhs will be called the "geometry factor". It is assumed that the stress factor is constant for all the data.

Model Link Range

$$\text{Link Range (max)} = (\text{stress factor})(1/2)(\sqrt{L_1 H_1} + \sqrt{L_2 H_2})$$

Figure 1. 2D geometry of linking range model. The dark areas are in plastic flow. The rectangles are void cluster cross sections.

Equation (1) is appropriate for two dimensional symmetry where the 2D cluster shapes represent the cross section of infinitely long cylinders. It is unknown how well the clusters in our data fulfill this requirement and the reader should remember that our results depend on this assumption. Equation (1) is also appropriate for cross sectional cluster shapes that are long or "cigar shaped" where the long dimension is perpendicular to the shock direction. This cross sectional shape and orientation obtains for most of the clusters in the data.

Figure 1 illustrates the geometry assumed in writing Equation (1). The dark regions indicate regions of localized plastic flow surrounded by unloaded, rigid material, i. e. not in plastic flow.

3. RESULTS

Figure 2 shows a histogram of cluster lengths, i. e. bin population versus cluster length. The figure gives some idea of the distribution of cluster sizes. The length was chosen in plotting since most of the clusters consist of strings of single voids linked along the perpendicular shock direction (the direction perpendicular to the shock direction). The cluster length is defined here to be the 3D center to center distance between the two end voids of furthest extent in the perpendicular shock direction plus the sum of their radii. This length lies approximately, but not strictly in the cross section. Single voids are also included here. The central region extending 400 microns above and below the nominal spall plane was used to include only clusters and voids with a similar stress loading history. A log log plot is used to show that for the larger clusters a linear dependence is roughly evident. This is evidence for "critical behavior"

Figure 2. Population of cluster lengths (extent of cluster in transverse shock direction)

[5-stauffer] in which clusters of all sizes are beginning to appear and there is no average cluster size. In reference [1], the maximum porosity was measured to be about 0.26, which is quite close to the porosity of 0.30 at which ductile spall is commonly modeled to occur [6-jnj,1982]. The linear dependence is not perfect, but other choices for axes scaling, e. g.; linear x and $\log y$, produced more curvature in the plot. It is definitely clear that more large clusters are present here than in an exponentially decaying cluster size distribution.

Figure 3 shows a plot of measured link distances, i. e. the distance over which the localized plastic flow is seen to occur in the micrographs, versus the geometric factor of the model link distance obtained from equation (1). The linking areas occur 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 (1) were those of the clusters to which the linking voids belong. The measured linking distance used is the 3D edge to edge separation of the linking voids; the cluster lengths, L , used are those defined earlier; and the cluster heights used are the average 3D diameter of the voids in the clusters.

The test of the suitability of equation (1) is whether a clear envelope appears in figure 3. According to the theory, the data can fall anywhere below a model maximum link range, but not above it. There does seem to be a rough envelope, i. e. a straight line of slope roughly unity. This would suggest that the value of stress factor is about unity.

One uncertainty in the whole interpretation is that different cluster may have seen different stress loading histories, the particular history depending upon the cluster position along the shock direction. In fact, most of the links seen experimentally are located within a few hundred microns of the nominal spall plane of maximum porosity and probably all experienced similar stress histories. Further conclusions must wait for hydrocode calculations investigating the stress history that are not yet complete. The results here seem strong enough to suggest that the model link equation (1) has at least a measure of validity.

Figure 3. Link distance data versus the geometrical factor part of the model link range

The geometrical factor has a possible explanation in retardation of the cluster size effect in linking at high loading rates. The largest geometrical factors come from the largest clusters, and it is these, as seen in figure 3, that are lacking in producing equally large linking ranges. The VISAR free surface data, together with preliminary hydrocode calculations, (not presented here) indicate that the void growth occurred for the sample here in about 150 microseconds. One can multiply one half this time by a longitudinal sound velocity of roughly 4 mm/ μ sec to obtain an effective (loading time limited) cluster size of, roughly, 300 μ m. The factor of one half is reasonable because the void growth is just beginning at the initial time. The largest clusters in our sample are about of size 800 μ m so it seems reasonable that their linking was limited by the high loading rate. The size of geometrical factor where this effect would begin should be, roughly, the square root of the effective cluster size, 300 μ m, times an average void size for the larger clusters of, roughly, 250 μ m, which equals about 275 μ m. This is about where the falloff occurs in figure (3).

Figure 4 shows a plot of void diameter of all voids versus the size of the cluster of which a void is a member. The plot should show any dependence of void growth on cluster size, i. e. voids in bigger clusters should grow faster than single voids. (The voids in clusters are coalesced with their neighbors but still show recognizable spherical shapes in the data here.) The straight line of points in figure 4 consists of single voids, which are a special case of clusters. For the rest of the points, if a cluster size correlation exists, the "center of mass" of points above a given cluster size should shift upward with larger cluster size. There does seem to be a trend of this sort, until cluster sizes of about 500 microns are reached. This is near the value 300 microns of the "effective cluster size" for loading rate limiting of void linking, as discussed earlier. The underlying considerations here should be the same, so loading rate limiting of the effective cluster size is a possible explanation for the lack of increase of void size with cluster size for the largest clusters.

4. CONCLUSIONS

Figure 4. Void diameter versus length of parent cluster

This paper has interpreted digitized void data from micrographs of incipient spallation damage in tantalum in terms of micromechanical processes. This information is useful for modeling the ductile damage process in spallation. Many of the results here are preliminary and will be improved upon in the future. However, the results so far seem promising and indicate the power of the image analysis technique for extracting useful modeling information. This work will be followed in the future with more extensive investigations of this sort, together with 1D hydrocode calculations of spall plate impact data. The 1D calculations will use the enhanced ductile spall model that is being created from the experimental results.

Acknowledgments

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