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Expansion into Vacuum of a Shocked Tungsten Carbide-Epoxy Mixture

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Abstract

The behavior of a shocked tungsten carbide / epoxy mixture as it expands into a vacuum has been studied through a combination of experiments and simulations. X-ray radiography of the expanding material as well as the velocity measured for a stood-off witness plate are used to understand the physics of the problem. The initial shock causes vaporization of the epoxy matrix, leading to a multi-phase flow situation as the epoxy expands rapidly at around 8 km/s followed by the WC particles moving around 3 km/s. There are also small amounts of WC moving at higher velocities, apparently due to jetting in the sample. These experiments provide important data about the multi-phase flow characteristics of this material.

In addition to the experiments, two-dimensional mesoscale simulations of the shock and expansion processes were conducted. These simulations give results that are in reasonable agreement with experimental results. More importantly, they provide insight into the physics of the problem and can be used to explore sensitivities. In particular, they suggest that energy release by epoxy plays an important role in the expansion process.

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CONTENTS

1. Introduction.....	7
2. Experimental Techniques	9
2.1. Material	9
2.2. Experimental Setup	9
3. Experimental Results.....	13
3.1. Determination of the shock Hugoniot state	13
3.2. X-rays of Expansion Experiments.....	14
3.3. Witness Plate Measurements	20
4. Mesoscale Modeling Results	23
5. Discussion and Conclusions	31
Distribution.....	34

FIGURES

Figure 1. SEM images of (a) WC powder and (b) WC-epoxy.....	9
Figure 2. Schematic for EOS experiments.....	11
Figure 3. Target configuration for expansion experiments. The rod and piece of plastic extending to the right of the sample were used to hold the PDV probe.	11
Figure 4. Schematic for expansion experiments with a witness plate. All dimensions are to scale for experiment WCE-15 except the height of the witness plate, which is about twice as tall as shown.....	12
Figure 5. Velocity histories measured with VISAR for experiment WCE-6.....	13
Figure 6. Stress-strain relationship for WCE in shock experiments. Line represents quadratic fit to data below 20 GPa.....	14
Figure 7. X-ray radiograph of WCE-17 taken at 4.007 μs after impact.	14
Figure 8. X-ray radiograph of WCE-14 taken at 7.829 μs after impact.	15
Figure 9. X-ray radiograph of WCE-8 taken at 10.326 μs after impact.	16
Figure 10. Expanded view of the X-ray radiograph for WCE-8 showing “jets” of WC emerging from the target.....	16
Figure 11. X-ray radiographs of the WC expanding from experiments WCE-17, 14, and 8 at 4.007, 7.829, and 10.326 μs after impact, respectively. Also shown is a WCE sample prior to impact.	17
Figure 12. X-ray radiograph of WCE-18 taken at 64.017 μs after impact.....	18
Figure 13. First and second X-ray radiographs from experiment WCE-14 shown to scale and with the proper spacing between images. The images were taken at 7.829 and 90.717 μs , respectively.	19
Figure 14. Positions along the centerline of the back of the Lexan along with the left and right edges of the WC cloud for all experiments relative to time of impact. Also shown is the width of the WC cloud, ΔX	20

Figure 15. Velocity history records along the centerline of the witness plate for WCE-15 at 47.8 mm behind the target.	21
Figure 16. Velocity history records of the witness plate for WCE-16 at 91.5 mm behind the target.	22
Figure 17. Velocity history records along the centerline of the witness plate for WCE-15 and WCE-16 at 47.8 mm and 91.5 mm, respectively, behind the target.	22
Figure 18. Mesoscale simulations shown at 0, 0.22, 0.7 μ s after impact. The solid colored region in (a) represents the impactor. The top part of each image shows contours of pressure, while the bottom part shows contours of velocity.	24
Figure 19. Mesoscale simulations shown at 0.7, 1.0, and 1.7 μ s after impact. The top part of each image shows contours of velocity, while the bottom part shows contours of density. The lowest contour of density shown is 0.01 g/cm ³	25
Figure 20. Density averaged vertically across the mesoscale simulation at t = 0, 2, 4, and 6 μ s relative to impact. Also shown.....	26
Figure 21. Density averaged vertically across the mesoscale simulations using non-reactive and reactive models for PMMA at t = 2, 3, and 4 μ s relative to impact.....	27
Figure 22. Density averaged vertically across the mesoscale simulations using non-reactive and reactive models for PMMA at t = 2, 3, and 4 μ s relative to impact.....	28
Figure 23. Velocity histories from the back of a 1.5 mm thick aluminum witness plate for experiment WCE-15 and one-dimensional simulations at varying density and velocity conditions.	29

TABLES

Table 1. Summary of Experimental Configurations.....	10
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1. INTRODUCTION

The phenomenon of multi-phase flow is important in a variety of applications. This report is intended to document the results of a series of high-velocity experiments performed on a tungsten carbide-epoxy (WCE) mixture. This material is also being studied as an alternative to the alumina-filled epoxy (ALOX) used in Sandia systems. The results of that investigation, which focuses on the low-pressure regime, will be reported elsewhere [Vogler *et al.*, 2009].

The experiments consist of impacting a WCE sample at approximately 6 km/s with a Lexan slug launched using Sandia's two-stage light gas gun. The impact should be sufficient to vaporize the epoxy matrix of the sample as well as the Lexan impactor. Following impact, the sample expands into the vacuum of the catcher tank. Because of the dramatically different densities between WC and epoxy, the two materials are expected to expand at very different velocities.

The expansion process is probed through flash X-ray radiography as well as through witness plates whose back surface is monitored with VISAR interferometry. Multiple X-ray locations and individual experiments with different delay times allow the expansion of the shocked WCE to be monitored. Results from two-dimensional mesoscale simulations performed with CTH are also presented to provide insight into the early-time expansion process.

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2. EXPERIMENTAL TECHNIQUES

2.1. Material

The WCE studied was fabricated using the same WC powder from Kennametal, Inc., studied by [Vogler *et al.*, 2007]. Individual particles consist of single WC crystals produced through a melt process [Lassner & Schubert]. The particles were sieved to give nominal particle sizes in the range of 20-32 μm as shown in Fig. 1a. Epon 828 resin and Epi-Cure Z curing agent were used at a ratio of 5:1 by mass. A nominal volume fraction of WC particles of 45.3% was used. Based on a density of 1.20 g/cm^3 for the epoxy and 15.7 g/cm^3 for WC, one expects a density of approximately 7.77 g/cm^3 . The mixture was vacuum outgassed before and after pouring into molds. The molds were heated to 93° C over 10 hours, then held at that temperature for 10 hours before cooling to room temperature over an hour. After curing, approximately 1 mm was machined from the top and bottom of each WCE billet to remove resin-rich and resin-poor regions, and then samples were machined from the billets. The material produced consists primarily of isolated WC particles surrounded by epoxy with few, if any, voids present as shown in Fig. 1b. Samples were machined to be flat and parallel to approximately 13 μm . Contact surface profilometry indicates an average roughness value, R_a , of approximately 1 μm with isolated low points on the order of 10 μm deep that are suggestive of WC particles that have pulled out of the surface.

Figure 1. SEM images of (a) WC powder and (b) WC-epoxy.

After fabrication, each sample disk was characterized for nominal density based on volume and mass, and the longitudinal and shear wave speeds of the material were measured at the center and four points between the center and edge distributed around the disk. The average density was 7.77 g/cm^3 , while the average longitudinal and shear wave speeds were 2.04 and 1.12 km/s, respectively.

2.2. Experimental Setup

Experiments were conducted in three formats: Hugoniot state measurement, expansion with X-rays, and expansion with witness plate. Specifics for the experiments are given in Table 1.

Each configuration provides different information about the behavior of the material. However, since the impact velocities for all experiments were within 1% of the average, the experiments can be considered identical except for variability in density between samples.

Table 1. Summary of Experimental Configurations

Shot	Velocity (km/s)	ρ_0 (g/cm³)	Sample Thick. (mm)	Instrumentation	X-ray Times¹ / Witness Plate Configuration
WCE-6	5.953	8.162	3.06	VISAR / LiF window	N/A
WCE-17	5.924	7.707	4.08	X-rays	4.007 μ s, N/A
WCE-14	5.976	8.177	4.08	X-rays	7.829 μ s, 90.717 μ s
WCE-8	5.976	7.626	4.06	X-rays, PDV	10.326 μ s, N/A
WCE-18	5.830	7.760	4.07	X-rays	N/A, 64.017
WCE-15	5.960	7.607	4.07	203 mm x 1.5 mm witness plate / VISAR	47.8 mm from back of sample
WCE-16	6.008	7.716	4.06	254 mm x 1.5 mm witness plate / VISAR	91.52 mm from back of sample

¹ Times given with respect to impact

In the first configuration, standard shock physics techniques were used to measure the Hugoniot (shock) state in the WCE sample. Two small holes were drilled through the WCE sample opposite the centerline from one another and toward the edge of the impacted zone, and a small LiF window (6 mm diameter) was placed in each hole such that it was flush with the front face of the WCE sample. The WCE sample was backed by a larger 19 mm diameter window. A thin layer (approximately 3000 angstroms) of aluminum was vapor plated onto the front of the LiF windows. The experimental configuration is shown schematically in Fig. 2. Coaxial shorting pins on the back surface of the sample (not shown in figure) provided the required instrumentation trigger upon impact as well as a measurement of projectile tilt. Typically, tilt was less than 8 mrad. The velocity of the plated surfaces was then monitored using VISAR diagnostics. The measurements at the front of the sample provide the time of impact, while the VISAR on the back of the sample give the time for the shock to travel through the sample. This information can be used to determine the Hugoniot state as described in Section 3.1.

Figure 2. Schematic for EOS experiments.

In the second configuration, a 25 mm diameter sample is held between three piezoelectric pins at the end of an aluminum cylinder mounted on the two-stage gas gun as shown in Fig. 3. The three pins provide a trigger for the instrumentation with minimal contamination of the experiment. The sample was impacted with a Lexan cylinder then allowed to expand into the vacuum of the gun's tank. Two 150 kV flash X-rays oriented perpendicular to the axis of the gun were placed about 200 mm apart. Times for the X-ray flashes relative to impact are given in Table 1; each X-ray pulse was approximately 24 ns long. In one experiment (WCE-8), an attempt was made to use a photon Doppler velocimetry (PDV) system [Jensen *et al.*, 2007] to measure the velocity of the sample's back surface. It was hoped that this would provide information on the velocity during expansion. However, no useful data was obtained with that instrument. It is not clear if that is because the instrument is not suitable to the application or if it merely needs to be optimized for these experiments. To-date, no additional attempts to use the PDV have been made because the system has not been available.

Figure 3. Target configuration for expansion experiments. The rod and piece of plastic extending to the right of the sample were used to hold the PDV probe.

The third configuration is similar to the second except that a 1.5 mm thick witness plate was used instead of X-rays to probe the expansion process. The witness plates were placed at 48 and 92 mm from the back of the sample. The back of the witness plate was monitored with five independent VISAR beams along the centerline and radially away from the center at 8.6, 17.3, 25.9, and 34.5 mm.

Figure 4. Schematic for expansion experiments with a witness plate. All dimensions are to scale for experiment WCE-15 except the height of the witness plate, which is about twice as tall as shown.

3. EXPERIMENTAL RESULTS

3.1. Determination of the shock Hugoniot state

Experiment WCE-6 was performed to determine the shock state for the experiments reported herein. Two VISARs at the edge of the sample monitoring the impact plane and a third monitoring the back of the sample were used to determine the shock velocity. Records from these three probes are shown in Fig. 5. The difference of about 24 ns in the shock times for the two edge records is due to tilt of about 7 mrad in the impactor. The difference between the average time for the edge records and the center record of about 471 ns gives a shock velocity U_s of 4.32 km/s. By impedance matching with the Lexan impactor, the Hugoniot state is found to be $u_p = 1.34$ km/s, $\sigma = 47.2$ GPa, and $\rho = 11.83$ g/cm³. This analysis assumes that the shock wave is steady as it traverses the sample, which may not be correct if significant amounts of energy are being released during that process and the wave is growing in amplitude in a process similar to a detonation process.

Figure 5. Velocity histories measured with VISAR for experiment WCE-6.

When the results of WCE-6 are compared to other shock experiments on WCE, the result appears significantly stiffer than for the lower pressure regime as shown in Fig. 6. Here, the solid line is a quadratic fit to the low-pressure data; the data point for WCE-6 falls significantly above this line, though it is a large extrapolation from 20 GPa to 46 GPa. Previous studies of epoxy have shown that it disassociates at a shock pressure of around 25 GPa [Kerley, 1999]. Thus, the epoxy is expected to be completely disassociated in this experiment. The epoxy may also be releasing significant amounts of energy as suggested by the stiffer response in Fig. 6.

Figure 6. Stress-strain relationship for WCE in shock experiments. Line represents quadratic fit to data below 20 GPa.

3.2. X-rays of Expansion Experiments

X-ray radiography was conducted on four experiments with somewhat different positioning and timing of the two X-ray flashes.

For experiment WCE-17, the first X-ray 4.007 μs after impact is shown in Fig. 7. A significant amount of the Lexan projectile has expanded radially and flowed around the target. The WC particles in the WCE sample form a very dark region that is relatively uniform in the center and curls around at the outer edges. Recall that the X-ray is a 2-D projection of an axisymmetric event. The left edge of the WC has moved about 8 mm, while the right has moved about 14 mm at this point. It appears that the central region (about 14 mm tall) of the WC is expanding in a 1-D manner and now has a thickness of around 6 mm compared to its initial thickness of 4 mm. The right edge of the X-ray corresponds to a velocity of approximately 7.5 km/s.

Figure 7. X-ray radiograph of WCE-17 taken at 4.007 μs after impact.

Low-density material can be seen above and below the WC and to the right of it. It appears that the Lexan projectile has flowed past the WCE target, which is not surprising given initial diameters of 30.2 mm for the projectile and 25.4 mm for the WCE target. Thus, the Lexan initially flows unimpeded past the sample, but as the WC expands laterally it pushes the Lexan outward.

In experiment WCE-14, the first X-ray was taken at 7.829 μs after impact and is shown in Fig. 8. The additional delay allows greater time for both the target and the impactor to move right relative to their original position. More of the impactor has “splatted” against the WCE target and flowed outward radially. The left boundary of the WC has moved about 18 mm. Comparing WCE-14 to WCE-17 gives a velocity of around 3 km/s for the left boundary of the WC. There is no longer a distinct flat region in the center of the WC, indicating that deformation is no longer 1-D. At the very center, the WC region is about 6.5 mm wide, indicating minimal expansion in the horizontal direction there. Much of the Lexan that flowed around the sample can still be seen in the field of view, but some of it has traveled outside the region of the X-ray. Ahead of the main region of WC particles, a region of sparse WC particles that appear to be jets of some kind can be seen. The jets will be discussed further shortly.

Figure 8. X-ray radiograph of WCE-14 taken at 7.829 μs after impact.

In experiment WCE-8, the first X-ray was taken at 10.326 μs after impact and is shown in Fig. 9. Both the target and impactor have moved farther to the right relative to their original position. Surprisingly, though, the distance from the back of the remaining impactor to the left edge of the WC is actually greater in this experiment than in the X-ray for WCE-14 that is taken earlier. It is not clear what has caused this since the impact velocities and impactor dimensions are essentially identical for these two experiments. It is possible that this is caused by a reaction in the Lexan or by part of the impactor bouncing off of the target.

As seen in WCE-14, there is not a distinct flat region in the center of the WC, indicating that deformation is no longer 1-D. At the very center, the WC region is about 8 mm wide, indicating somewhat greater expansion than seen previously. The Lexan that flowed around the sample has developed further, but much of it has traveled outside the region of the X-ray.

Figure 9. X-ray radiograph of WCE-8 taken at 10.326 μ s after impact.

The presence of a few WC particles ahead of the main WC group can be seen best in this experiment as shown in close-up in Fig. 10. The origin of these faster-moving particles is not clear. They may be due to ejection of particles from near the surface of the original sample, or they might be caused by non-uniformities in the material leading to jetting of material out the back of the sample. While it is difficult to distinguish the details of the jets, they appear to be spaced at an interval of 2-3 mm. The leading edge of this material is about 7 mm ahead of the right edge of the dense WC, suggesting an average velocity of approximately 4 km/s.

Figure 10. Expanded view of the X-ray radiograph for WCE-8 showing “jets” of WC emerging from the target.

To better illustrate the evolution of the WC region, the images from the three experiments are shown together in Fig. 11. The images are well placed in time to show the expansion process without overlapping one another. The radial expansion of the WC at a nearly constant rate is evident, as is the horizontal expansion in the central region. Unfortunately, the first X-ray of WCE-18, which would have been later than the three shown here, did not function properly. Nevertheless, the pattern of evolution is evident. The central region of the WC initially flows in a 1-D manner, but edge release allows increasing amounts of radial expansion, so that by about 8-10 μs the entire sample has transitioned from 1-D flow and the rate of radial expansion is approximately constant. The width of the WC region also increases, but the increase is not necessarily uniform due to the transition from 1-D flow. The region at the edge of the sample is curled over due to the flow of the Lexan impactor around and past the target. Finally the material ahead of the main group of WC appears to be increasing in density, but this may be a shot-to-shot variation in the X-ray exposure.

Figure 11. X-ray radiographs of the WC expanding from experiments WCE-17, 14, and 8 at 4.007, 7.829, and 10.326 μs after impact, respectively. Also shown is a WCE sample prior to impact.

The expansion process illustrated in Fig. 11 continues beyond the images shown. The second X-ray of experiment WCE-18 was taken $64.017\ \mu\text{s}$ after impact, a time sufficient to allow much greater expansion as shown in Fig. 12. Unfortunately, the first X-ray of this shot malfunctioned. In the second X-ray, the region of WC has expanded further both horizontally and vertically. In fact, it has spread out enough in certain regions that structures in the WC cloud can be distinguished. Distinct non-uniformities can be seen on both the front and the back, though the jets observed earlier seem to have spread out too much to be distinguished. To the left of the WC, the remains of the Lexan impactor can be seen.

Figure 12. X-ray radiograph of WCE-18 taken at $64.017\ \mu\text{s}$ after impact.

The rear edge of the Lexan impactor was imaged in the second X-ray of WCE-14 at $90.717\ \mu\text{s}$ after impact as shown in Fig. 13. The back edge of the Lexan has traveled about 275 mm since impact (impactor length is approximately 38 mm), giving an average velocity of approximately 3.0 km/s, though the velocity history will not be uniform as it is initially traveling at 5 km/s until the shock wave from impact travels through the Lexan slowing it down. If one compares the

Plotting positions versus time as shown in Fig. 14 illustrates that most of the changes in velocity occur in the first 8 μs after impact. The horizontal expansion of the WC at late time could be extrapolated reasonably well based on the data from 7.8 and 10.3 μs , as could the position of the back of the Lexan impactor. Additional data between 20 and 60 μs would fill in the details of the expansion, but would probably not change the general picture of what is occurring.

Figure 14. Positions along the centerline of the back of the Lexan along with the left and right edges of the WC cloud for all experiments relative to time of impact. Also shown is the width of the WC cloud, ΔX .

3.3. Witness Plate Measurements

In two experiments, WCE-15 and WCE-16, 1.5 mm thick aluminum witness plates were placed 47.8 and 91.5 mm, respectively, from the back of the WCE sample. The motion of the free surface (right side in Fig. 4) of the witness plate was then monitored using VISAR. The velocity history for the centerline VISAR probe is shown in Fig. 15. Initial motion at about 6.7 μs corresponds to material moving at about 8 km/s, probably vaporized epoxy that expands from the back of the target. Such material was not visible in the X-rays, but witness plates are better suited to capturing this low-density material. The velocity history in Fig. 15 can be used to infer the density of the material from the back of the sample, though that analysis is complicated by the radial expansion inherent in the problem. At about 10 μs after impact, the VISAR record becomes jagged, perhaps due to impact of a few WC particles. Eventually, at about 13.7 μs , the light returned by the VISAR drops to a negligible level. Examination of Fig. 14 indicates that the right edge of the main WC arrives at 13.8 μs after impact.

In contrast to the centerline measurement, the probes positioned radially lose light much earlier. The probe at 17.3 mm shows an initial response similar to the centerline probe but then loses light at about 7.5 μs , while the 25.9 and 34.5 mm probes lose light at about 8.0 and 8.5 μs , respectively. This suggests the witness plate in that region is being struck by something more substantial than vaporized epoxy. It is likely that the Lexan projectile outside of the sample diameter is impacting the witness plate and causing light to be lost prematurely. Loss of light at 7.5 μs would indicate a velocity of 7.0 km/s (accounting for the thickness of the target). Although this is somewhat higher than the projectile velocity of 6 km/s, it still appears to be the most likely explanation for the loss of light.

Figure 15. Velocity history records along the centerline of the witness plate for WCE-15 at 47.8 mm behind the target.

In experiment WCE-16, the witness plate was positioned farther behind the target at a distance of approximately 91.5 mm. Velocity histories for three of the probes positioned along the centerline, at 8.6 mm, and 34.5 mm from the center are shown in Fig. 16. Initial motion along the centerline suggests a velocity of about 8.4 km/s for the leading edge of the gases from the target, consistent with the previous experiment. No well-defined increase in jaggedness is observed in the centerline measurement, though. It is possible that any particles ahead of the main mass of WC are either more dispersed than in WCE-15 or that not many hit the witness plate near the centerline. Light is lost about 21 μ s after impact, somewhat sooner than would be expected based on the right edge of the WC shown in Fig. 14. It may be that light is lost due to deformation and roughening of the Al plate rather than impact of a mass of WC.

The probes positioned radially outward detect motion later than the centerline probe. In this case, though, the light is returned for longer. Light is lost first for the 25.9 mm probe (not shown) at around 15.8 μ s, which indicates a velocity of around 6.0 km/s. Light for the 17.3 mm probe (not shown) is lost next at around 17 ms, followed by the 34.5 mm and 8.6 mm probes. This pattern is indicative of the radial expansion of the Lexan projectile after it passes the WCE target. Future studies of this type should utilize larger samples or shields of some type to ensure that the impactor does not pass around the target.

Figure 16. Velocity history records of the witness plate for WCE-16 at 91.5 mm behind the target.

The VISAR records along the centerline for the two experiments are shown in Fig. 17. If time shifted appropriately, the two overlay one another to a velocity of about 0.06 km/s. Above that, the velocity climbs more slowly for the plate that is farther away. This is due to the velocity gradient of the expanding material that leads to lower density the farther it travels.

Figure 17. Velocity history records along the centerline of the witness plate for WCE-15 and WCE-16 at 47.8 mm and 91.5 mm, respectively, behind the target.

4. MESOSCALE MODELING RESULTS

In order to gain additional insight into the behavior observed in the experiments, two-dimensional mesoscale simulations of the experiments were conducted using CTH. Similar simulations have been performed for WC powder [Borg & Vogler, 2008b], sand [Borg & Vogler, 2008a], and WCE [Vogler *et al.*, 2009]. The simulations performed here consist of 32 μm diameter circles of WC randomly distributed in the domain to give the proper volume fraction. Surrounding the WC particles was an epoxy matrix. A simple Mie-Grüniesen EOS is used for the WC, and it is assumed to behave in an elastic-perfectly plastic manner with a yield strength of 8 GPa. A tabular EOS, Sesame 7602, was used for the epoxy, and the Lexan impactor was assumed to have the same EOS.

The impactor was assumed to be in contact with the target at time $t=0$ was assigned an initial velocity of 6 km/s. Dimensions for the baseline simulations were a sample 3 mm wide and 1 mm tall, with the impactor 6 mm wide and 1 mm tall. Periodicity conditions were applied to the top and bottom of the simulation domain so that the simulation behaves as if it is infinitely tall. Part of the simulation domain is shown in Fig. 18. The first image shows the domain at the beginning of the simulation; the solid colored region to the left is part of the impactor. The second image shows the simulation after 0.22 μs . A shock wave is seen about 1 mm into the sample. Some non-uniformity is observed in the wave front, and the wave itself is seen to have a finite thickness. By 0.7 μs , the wave has traversed the sample and has started to emerge from the back surface of the sample.

The expansion process is illustrated in Fig. 19. The first image shown is at the same time as Fig. 18c, 0.7 μs , but the perspective is shifted to the right. At 1.0 μs , the WC particles have moved nearly a millimeter, but the epoxy material has moved nearly two millimeters. Material with a density of less than 0.01 g/cm^3 are omitted from the lower part of the model, leaving the tendrils of material shown in Fig. 19b. These tendrils would look somewhat different for different choices of this lowest contour value. By 1.7 ms, the edges of the expanding epoxy have moved beyond the field of view, and almost all of the WC is visible. In fact, one particle has already exited the field of view. At the right of Fig. 19c, one can see three regions where particles are moving faster than elsewhere. These regions, as well as the single particle off the field of view, seem consistent with the apparent jetting seen in Fig. 10. At this point, the width of the main body of WC particles is approximately 3.4 mm, so it has already expanded somewhat and will expand further at later times. The leading edge of the epoxy, based upon the 0.01 g/cm^3 contour, travels at approximately 6.3 km/s, though choosing a lower value for the contour is expected to result in a higher velocity.

Figure 18. Mesoscale simulations shown at 0, 0.22, 0.7 μ s after impact. The solid colored region in (a) represents the impactor. The top part of each image shows contours of pressure, while the bottom part shows contours of velocity.

Figure 19. Mesoscale simulations shown at 0.7, 1.0, and 1.7 μs after impact. The top part of each image shows contours of velocity, while the bottom part shows contours of density. The lowest contour of density shown is 0.01 g/cm^3 .

Densities were extracted from the mesoscale simulations at specific times and averaged vertically through the domain. These average density profiles are shown in Fig. 20. At the beginning of the simulation, there are some fluctuations in the density due to small variability in the positioning of the particles. At 2 μs after impact, the WC region is still compressed somewhat due to the initial shock, but it is now expanding. At 4 μs , the WC region has expanded to about 4.4 mm if we look at a density of about 3.2 g/cm^3 , which is somewhat lower

than the width measured in WCE-17 of 5.7 mm. However, examination of the width for lower densities gives a greater width; it is not clear what to what density the boundary in the simulation corresponds. It is also worth noting that any misalignment between the WC region and the axis of the X-ray tube will make the WC appear wider than it really is, though that problem appears to be relatively small in WCE-17. The leading edge of that dense region has moved about 9.1 mm in the simulation, while in WCE-17 the leading edge has moved about 9.8 mm. Thus, the results of the mesoscale simulations agree quite well with the experimental results at 4 μ s. At later times, radial expansion effects become more significant and the lack of that expansion in the simulations makes the comparison between the experiments and simulations less valid.

Figure 20. Density averaged vertically across the mesoscale simulation at $t = 0, 2, 4,$ and 6μ s relative to impact. Also shown

Attempts to include witness plates in the simulations, either at the far distances used experimentally or closer to the target, were not successful. Thermodynamic problems, presumably arising due to the EOS of the matrix material, always resulted in premature termination of the simulation. It is possible that this problem could be overcome by discarding a small amount of material without affecting the simulation results significantly.

The Hugoniot results in Section 3.1 suggest that the epoxy matrix may release significant energy in these experiments. Also, once a polymer such as epoxy is heated sufficiently, it is important to account for the condensation products properly [Mulford *et al.*, 2007]. Unfortunately, there is no reactive model available in CTH for epoxy. To assess the effects of reactivity, simulations were performed with PMMA (Sesame 7750) substituted for epoxy. The two polymers have similar initial densities, and a reactive model is available for PMMA that utilizes the HVRB model to link the EOSs of PMMA and the reaction products [Kerley, 1999]. The EOS for the PMMA reaction products is denoted as Sesame 7752.

Mesoscale simulations were conducted using a non-reactive EOS for PMMA as well as a reaction model. Simulations with non-reactive PMMA are quite similar to those shown in Figs. 18, 19, and 20. However, the non-reactive and reactive models behave differently, at least in the leading edge of the expanding material for densities below about 1 g/cm³ as can be seen in Fig. 21. The leading edge for the reactive model is moving noticeably faster than that of the non-reactive model for low densities.

Figure 21. Density averaged vertically across the mesoscale simulations using non-reactive and reactive models for PMMA at $t = 2, 3$, and $4 \mu\text{s}$ relative to impact.

Plotting the densities on a logarithmic scales as shown in Fig. 22 highlights the differences between the non-reactive and reactive models for densities typical of gases, $\sim 0.001 \text{ g/cm}^3$. The front of the reactive model at that density is moving significantly faster than the non-reactive model, with the difference increasing for lower densities. Comparing the profiles for 2 and 3 μs at a density of 0.001 g/cm^3 , the velocity for the non-reactive and reactive models are 6.3 and 6.7 km/s, respectively. Thus, the reactive model gives results closer to those seen experimentally, though the velocities from the simulations are somewhat slow. This may be due to differences between PMMA and epoxy in the reaction regime.

Low-density gases are not visible in the X-rays, but the witness plate experiments record an integrated measure of density and velocity. In order to estimate the density of the gas hitting the witness plate, one-dimensional simulations were conducted in which a 1.5 mm thick layer of aluminum was impacted with a thick layer of low-density material traveling at 8 km/s. The first EOS utilized for the low-density material was air with an initial density of 0.001 and 0.0001 g/cm³. Velocity histories from the simulations (shifted 6 μs) are compared to those from experiment WCE-15 in Fig. 23. The simulation results show a stair step pattern as waves reverberate in the aluminum plate, accelerating it at a nearly constant rate. The fall-off after about 10 μs is an artifact relating to the finite size of the simulation. The acceleration caused by

Figure 22. Density averaged vertically across the mesoscale simulations using non-reactive and reactive models for PMMA at $t = 2, 3$, and $4 \mu\text{s}$ relative to impact.

10^{-4} g/cm^3 air is relatively low, while that due to 10^{-3} g/cm^3 air is similar to that seen experimentally. Thus, it seems likely that the leading edge of the expansion detected with the VISAR is on the order of 0.001 g/cm^3 . Densities lower than that are unlikely to accelerate the witness plate enough to be detected. In order to examine higher densities than air at ambient pressure, PMMA at low densities was used instead. For a small value of pressure, the temperature of the PMMA was adjusted until the desired density was achieved. PMMA with an initial density of 0.001 g/cm^3 gives results quite similar to those for air at the same density. Thus, the most important parameters for the expanding material are its density and its velocity, with the composition and temperature of secondary importance.

Following the initial acceleration, the witness plate accelerates more rapidly after about $7.5 \mu\text{s}$. Using 0.003 g/cm^3 PMMA gives a velocity history quite similar to that seen experimentally. If the same simulation is performed with an initial velocity of 6 km/s , then the acceleration is significantly reduced. Of course, the actual behavior in the experiment is much more complicated than these simulations. First, there is expected to be a gradient in density with the lowest density material moving fastest and the denser material moving slower. Second, the actual experiments include lateral expansion of material during the expansion process and after it impacts the witness plate. Nevertheless, these simulations provide insight into the nature of the expanding material as it strikes the witness plate. Material at about 0.001 g/cm^3 represents the leading edge detected by the VISAR. Following that, the material is increasingly dense and moving more slowly. Densities on the order of 0.003 to 0.01 g/cm^3 probably account for most of the measurements from the VISAR. In principal, one could utilize a more complex distribution of densities and velocities to recover the velocity histories seen in WCE-15 and WCE-16. However, unless radial expansion is accounted for, such an exercise is probably of limited value.

Figure 23. Velocity histories from the back of a 1.5 mm thick aluminum witness plate for experiment WCE-15 and one-dimensional simulations at varying density and velocity conditions.

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5. DISCUSSION AND CONCLUSIONS

In this investigation, we have studied the behavior of a mixture of tungsten carbide and epoxy as it is shocked to nearly 50 GPa and then allowed to expand into a vacuum. This expansion process is monitored using flash X-rays and stagnation on a witness plate at a distance behind the WCE target.

Following traversal of the shock, Lexan from the projectile flow around the outer edge of the target, complicating interpretation of the X-ray images somewhat. This material from the projectile also adversely affects the witness plate measurements. The shocked WCE expands into the vacuum when the shock wave reaches the back of the sample. Gas from disassociated epoxy travels out from the sample at around 8 km/s, followed by the WC particles. The front edge of these particles moves at 2.5-3 km/s, with jetting material moving even faster, on the order of 4 km/s faster. The back edge of the particle group moves more slowly, resulting in a gradual broadening of the WC particle region. As late as 64 μ s after impact, the WC particles continue to be grouped fairly closely, though that grouping has expanded both longitudinally and radially. Nonuniformities also develop at such late times.

Two-dimensional mesoscale simulations of the experiments provide valuable insight into the physics of the experiments and give good quantitative agreement with the experiments. The simulations show nonuniformities in the initial shock, expansion of low density matrix material ahead of the WC particles, and the presence of non-uniformities in the WC particle distribution that are similar to the apparent jets seen experimentally. The width of the WC region and the velocity of the expanding material is somewhat lower than the experiment, however, probably because of an inadequate description of the behavior of epoxy during the shock / release process. In particular, the potential release of energy by epoxy when it is shocked to the levels seen here may play an important role in the expansion process. Finally, one-dimensional simulations suggest that the initial expanding material that reaches the witness plate at 8 km/s has a density on the order of 0.001 g/cm³. The material gradually increases in density and decreases in velocity to somewhat less than 0.01 g/cm³ traveling at 4-5 km/s.

The following recommendations are offered for future work in this area:

- Larger samples or shielding material of some type should be utilized to prevent projectile material from traveling past the sample at high velocities. This should make it easier to interpret the X-ray images and improve the quality of the witness plate measurements.
- Additional X-rays should be fielded on the experiments to better capture the expansion process. Two X-rays oriented vertically and timed to image shortly after impact (10 μ s or less) and at an intermediate time (20-40 μ s) would help us understand the expansion process better.
- PDV has the potential to provide valuable information about the expansion process. Its use in experiments of this type should be explored further.

- Experiments performed under different conditions would serve as a stronger constraint on the development of multi-phase models. In particular, different impact velocities could be utilized to obtain scaling relationships for the expansion process. Also, WCE impactors could be used instead of the bare Lexan projectile. This would concentrate the kinetic energy in a smaller region of the impactor so that the Lexan projectile itself plays a smaller role in the experiment.
- In addition to varying experimental conditions, it would be interesting to explore modifications to the WCE itself. For example, the WC particle size could be varied, which should affect the interaction between the epoxy matrix and the particles. Another property that could be varied is the loading fraction of WC in the mixture. However, lower volume fractions of WC will lead to further difficulties in the fabrication process.
- Shocked samples could be allowed to expand into an atmosphere. An existing atmosphere would likely significantly affect the initial expansion of gases, but it probably would not affect the motion of the particles, at least initially.
- These initial mesoscale simulations show great promise for understanding the processes occurring in the experiments. Additional study is merited to understand the sensitivities of the simulations, as well as to explore potential modifications to the experiments. In this process, it will be important to identify ways in which the simulations can be validated against experimental data. One shortcoming that has already been identified is the need to model polymeric materials such as Lexan and epoxy in the regime of high temperatures and pressures as well as in the expanded state.
- Finally, a complimentary continuum multi-phase modeling effort should be undertaken, both to guide the experimental effort and to benefit from this set of experimental data.

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