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Dynamic Ductility of Zr

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Abstract

In order to create comprehensive models of mechanical deformation, it is important to observe the effect of high strain on materials. Often times this type of high strain and high strain rate deformation is examined in high symmetry, cubic metals, but less is known about the behavior of lower symmetry and highly textured metals. Dynamic extrusion is a mechanical test platform for examining this type of mechanical response. In this initial study, the influence of extrusion velocity on the dynamic tensile extrusion behavior of high purity, textured hexagonal closed packed (HCP) Zr will be examined. In this experiment, bullets of the sample material will be fired in a Taylor series gas gun into an extrusion die. It is expected that twinning and slip will both be observed as deformation mechanisms as well as grain elongation. For this study, the impact orientation will remain constant and the bullets will all be taken from the same sheet of stock material with a clock rolled texture. Increasing the velocity continuously increases elongation to failure. Additionally, the microstructural and texture evolution of Zr as a function of extrusion velocity have been examined, thereby allowing the observation of the effect of high strains on the microstructure and deformation of zirconium.

Introduction

As a hexagonal close packed (HCP) metal, zirconium lacks the symmetry exhibited in cubic materials. This anisotropy creates unique challenges in modeling deformation in the material. In order to accurately create such a model, extensive characterization of mechanical response must be performed to develop a standard understanding of the metal's deformation behavior. Zirconium has been the subject of significant research related to twinning and slip deformation as well as the effect of texture on deformation[1]. Even so, significant data on the effect of high strain and high strain rates on zirconium has not been established. Vogel et al.[2] have macroscopically observed the effect of high hydrostatic pressure on zirconium, but it is necessary to understand the microscopic effect of such abnormal conditions.

For this study, high strain and high strain rates will be established using dynamic extrusion. Dynamic extrusion is a method for observing the effect of high strain as it can create far higher strains than achievable in traditional uni-axial tests[3]. The amount of strain is also easily varied with velocity.

The initial portion of the study will focus on the effect of varying velocity, and therefore varying strain and strain rate. Given prior understanding of zirconium, both twinning and slip can be expected as modes of deformation. Twinning has been found to be crucial in deformation of HCP metals as they have far fewer slip systems than cubic materials (Song and Gray[4]). zirconium has three prominent twinning modes $(1\bar{1}02)$, $(11\bar{2}1)$, and $(11\bar{2}2)$, and extensive twinning is expected to be observed in each at high strains (Tome et al.[5]).

Study of dynamic extrusion on other materials such as Cu and Ta, has also found that considerable grain elongation as well as shear localization leading to void formation accommodates deformation at these high strains (Cao et al.[6]). Instability develops and the material fragments as it is extruded.

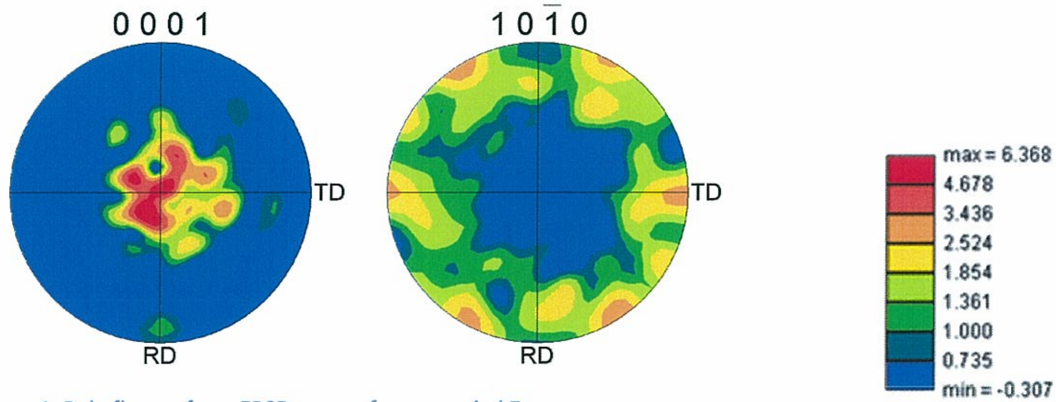

Figure 1. Pole figures from EBSD scans of as-annealed Zr

Experimental Method

This investigation examines high-purity, alpha zirconium which has been clock rolled. The average grain size is 35 µm, as measured by the Heyn method. Using Electron Back Scatter Diffraction (EBSD) a strong 0001 basal texture was observed as shown in Figure 1, which is characteristic of the plate having been clocked rolled during processing. The plate had been annealed at 550ºC for one hour and as such the initial dislocation density is very low. Bullet shaped specimens of approximately .29" in diameter and .31" in length were obtained from this plate and were machined in the In Plane (IP) direction. The actual dynamic extrusion tests were performed using a Taylor series gas gun which fired the bullets at velocities ranging from 200 m/s to 600 m/s. The spheres impacted a high strength steel extrusion die with an extrusion angle of 81 degrees.

High speed photography was used to observe the actual extrusion process on a macroscopic level (See Figure 2).

The extruded pieces were soft captured and collected. The portion of the bullet which remained caught in the die was removed by cutting the die near enough to the sample to substantially weaken the die thus allowing specimen removal. The soft recovered pieces as well as the piece from the die were weighed and this value was compared to the initial weight of the sphere. This ensured that no pieces had been lost. The total elongation was established by measuring the total length of each soft recovered piece and adding the values.

Individual soft recovered pieces were examined using scanning electron microscopy before being prepared for optical microscopy. These pieces were then prepared using standard preparation techniques and chemically polished and etched with a solution of 45 ml H_2O, 45 ml HNO_3, and 10 ml HF for 20-25 seconds.

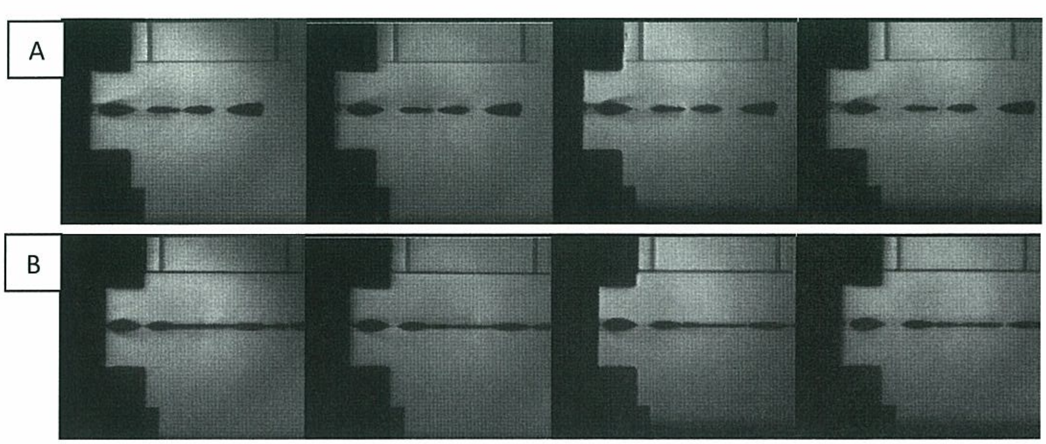

Fig 2. High speed photography of Dynamic Extrusion: a) 479.8 m/s and b) 654.6

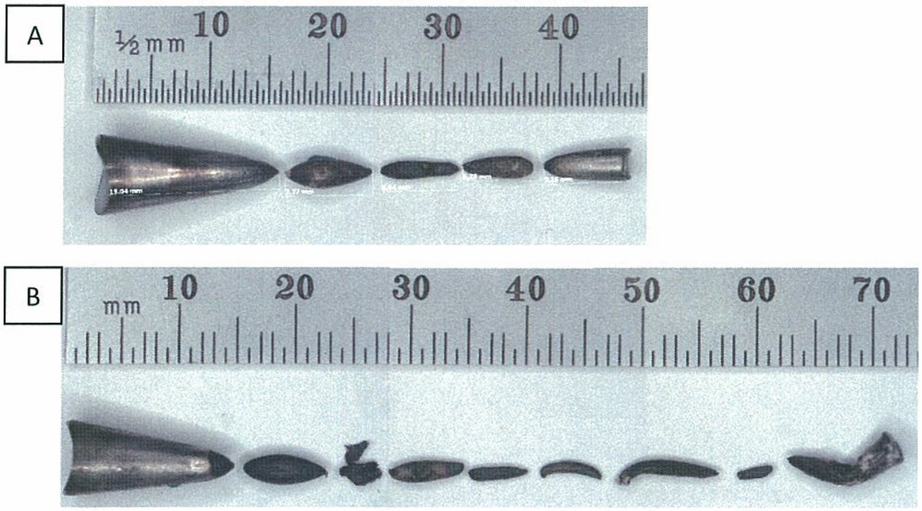

Fig. 3 Reassembled soft captured fragments of extruded Zr a) 479.8 m/s and b) 654.6 m/s

Optical microscopy was then performed on the samples using a microscope equipped with polarized light.

Results and Discussion

Thus far, dynamic tensile extrusion tests have only been performed in the IP orientation at velocities from 400-600 m/s at room temperature.

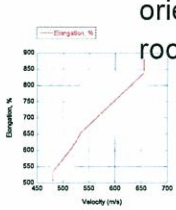

Fig 4. Percent elongation as a function of velocity for IP specimens

The high speed photography as captured at the lowest and highest velocities, is shown in Figure 2. Although in all tests the metal was not fully extruded, velocity is seen to strongly affect the fragmentation and elongation of the specimen. Total elogation was measured after reassembling the fragments in the extrusion order according to the high speed photography. Figure 3 clearly shows the effect of velocity on the macroscopic appearance of the sample, in that the number of fragments varies greatly. It is important to note that the specimen shot at 479.8 m/s fragmented into 5 pieces whereas the specimen shot at 654.6 m/s fragmented into 9 pieces. At higher velocities fragments were more drawn out and less uniform in shape than at lower velocities. The percent elogation as a function of veocity was plotted revealing a strong correlation between velocity and the elongation of the material (Figure 4).

Scanning electron microscopy(SEM) was used to observe the surface appearance of the soft recovered segments as well as the tips of the first and last piece in order to observe the manner in which

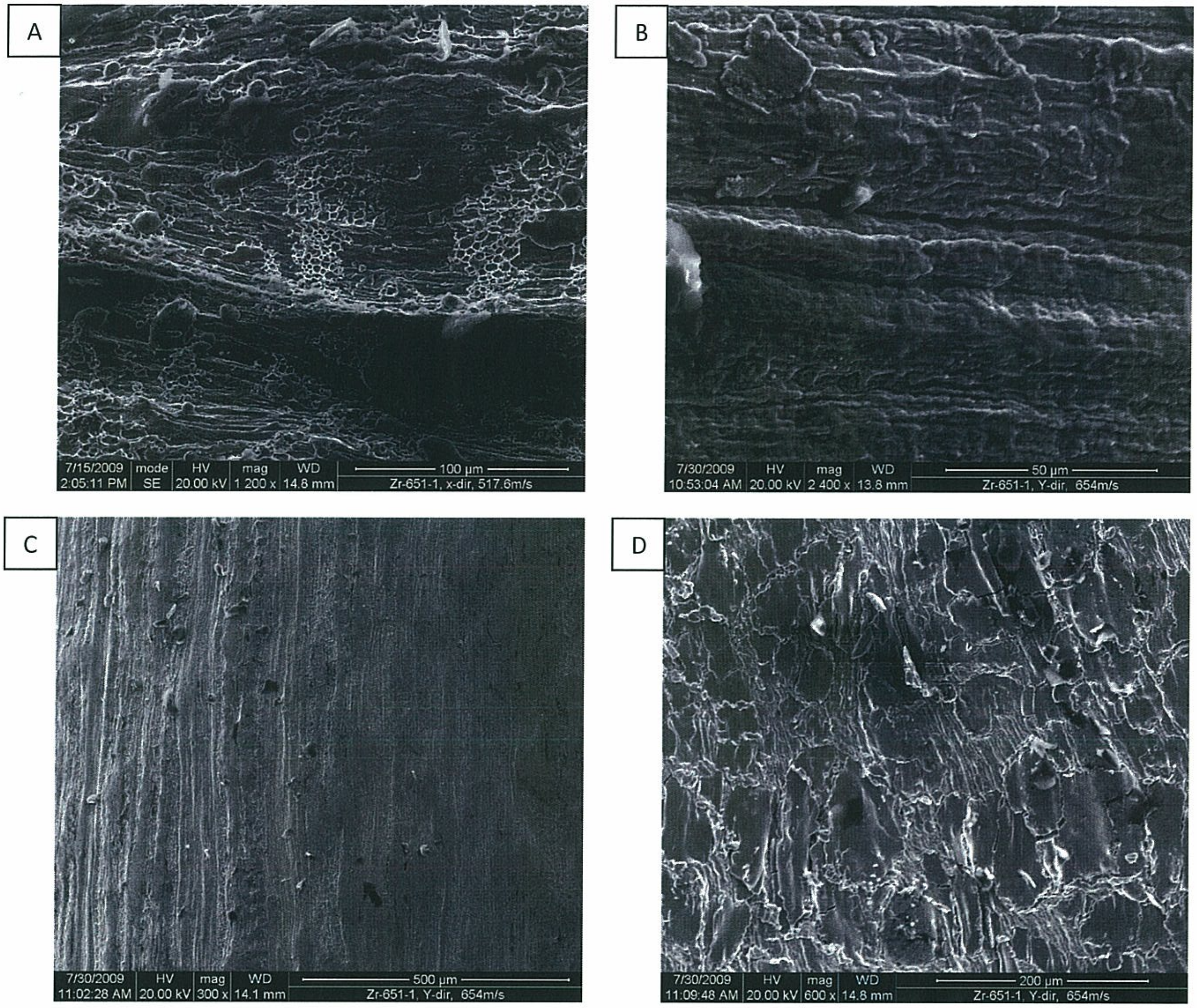

Fig. 5 Surface morphology a) 517.6 m/s –ductile tearing b) rivulet in 654.6 m/s c)general surface appearance of 654.6 m/s sample and d) cracking in 654.6 m/s sample

fragments came apart. This analysis revealed that rather than having sheared apart as seen in previous studies of cubic materials, the ends of the fragments showed a fracture surface similar to that seen in tensile tests. Figure 5 shows representative high magnification images of the surface morphology of both the specimen shot at 517.6 m/s and 654.6 m/s. Surface morphology was found to vary with velocity. The surface of low velocity shots shows ductile tearing as well as a high roughness.

In comparision, the high velocity specimen shows cracking both in rivulets and what apears to be at the grain boundaries in some regions, although in general the surface is smoother. Additionally, the Figure 6 shows the fracture surface as seen on the specimen deformed at 533.6 m/s.

Optical microscopy was performed on the specimen deformed at 479.8 m/s and 517.6 m/s. Rather than the expected grain elongation, both samples showed complete

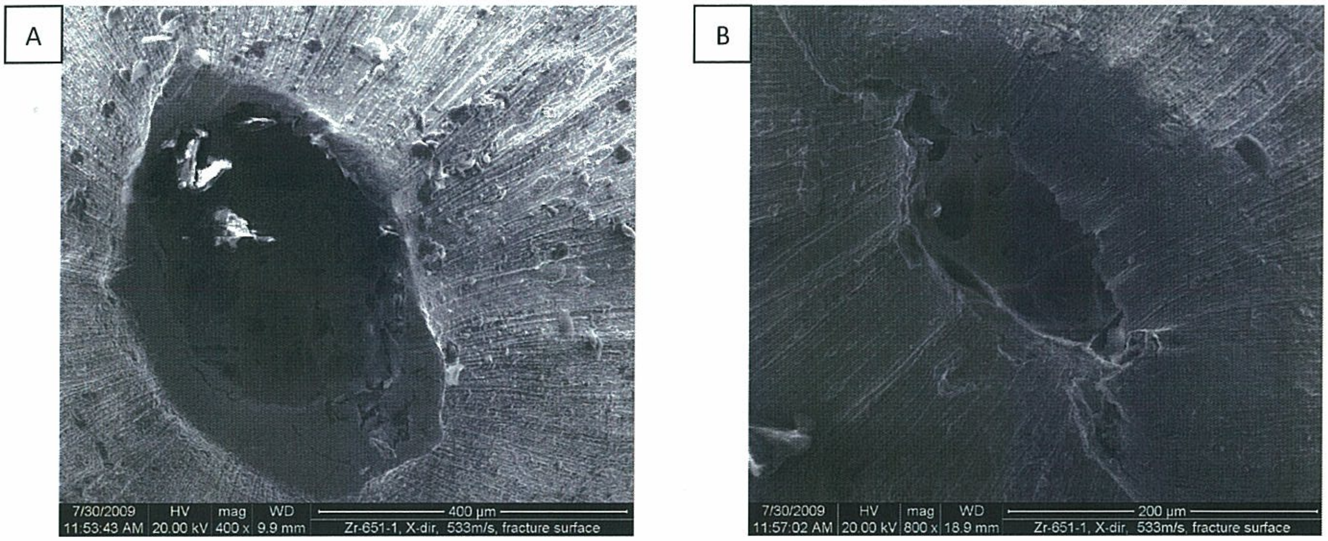

Fig. 6 Fracture surface on 533.6 m/s specimen a) piece remaining in die and b) first piece extruded

recrystallization in the extruded fragments (Figure 7). Grain elongation was visible in the middle of the piece not fully extruded from the die as shown in Figure 8, although the tip of this piece showed recrystalization as well as void formation. These voids were found in the tips of fragments where in previous studies shear has been seen to be the primary mode of fragmentation.

Finally, there is an unexpected end geometry both in the first piece extruded from the die and the piece remaining in the die which is not seen in the high symmetry cubic materials previously studied materials. In the cubic materials, the ends are convex[5] whereas in the zirconium, the end is concave and asymmetric. A comparision between the end geometry of the current study and previous work is shown in Figure 9.

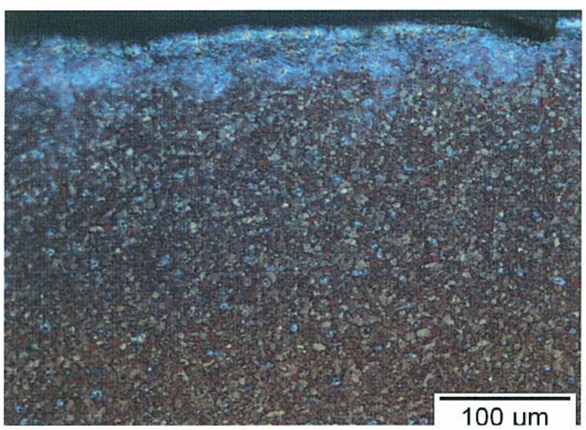

Fig. 7 Grain recrystallization in 517.6 m/s specimen

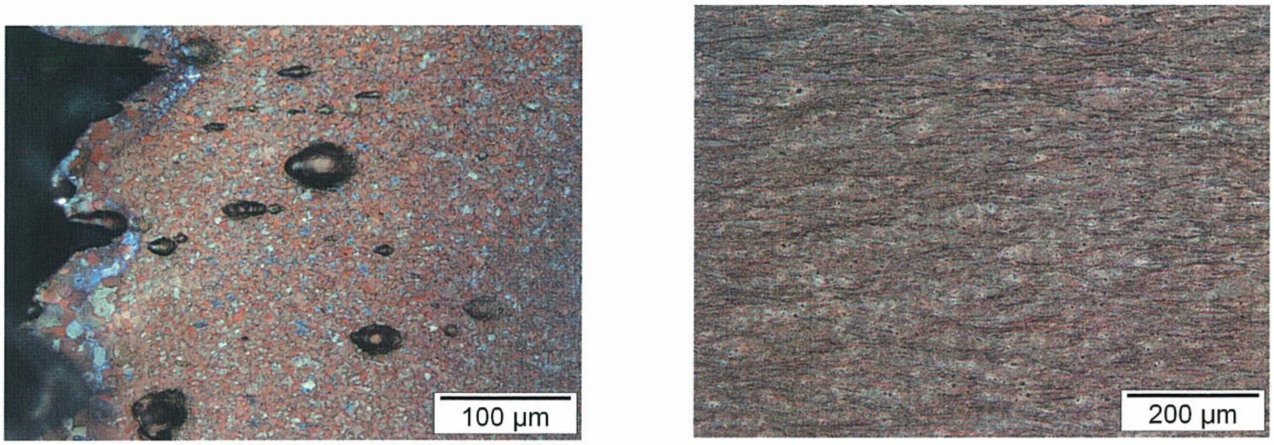

Fig. 8 Left: Tip of piece left in die (517.6 m/s) and Right: middle of piece left in die (517.6

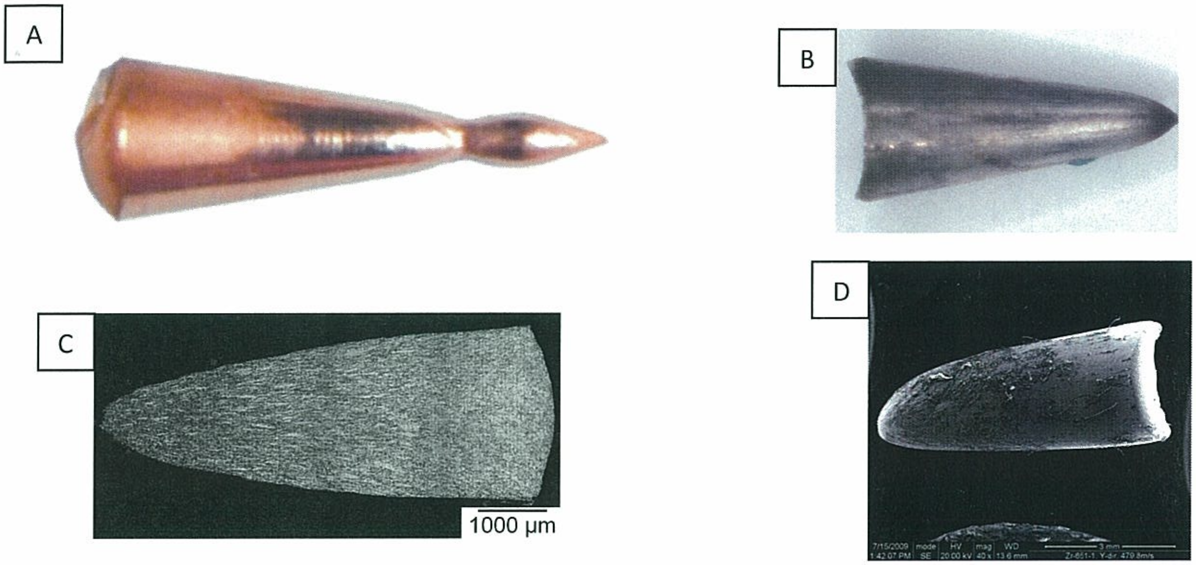

Fig. 9 End geometry a) piece in die in a copper specimen, b) piece in die of Zr, c) first piece extruded in Ta, d) First piece extruded in Zr.

Conclusions

Thus far, we can conclude from this study the following about the dynamic tensile extrusion response of Zr:

1. Impact velocity strongly influences the large-strain tensile ductility of Zr and thus elongation.
2. Impact velocity influences the number of fragments that occur during the extrusion process such that higher velocity produces more fragments.
3. Microstructural evolution of zirconium is significantly different than that observed in cubic metals, Cu and Ta

Future Plans

1. Continue microsturctural and texture analysis of samples
2. Test additional IP samples at more velocities within the experimental range.
3. Test TT samples in order to observe the effect of orientation

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References

1. Kaschner, G. C., and G. T. Gray III. "The Influence of Crystallographic Texture and Interstitial Impurities on the Mechanical Behavior of Zirconium." *Metallurgical and Materials Transactions A* 31A (200): 1997-2003. Print.
2. Vogel, Sven C., Helmut Reiche, and Donald W. Brown. "High Pressure Deformation Study of Zirconium." *Powder Diffration* 22.2 (2007): 113-17. Print.
3. Gray III, G. T., E. Cerreta, C. A. Yablinsky, L. B. Addessio, B. L. Henrie, B. H. Sencer, M. Burkett, P. J. Maudlin, S. A. Maloy, C. P.

Trujillo, and M. F. Lopez. "Influence of shock Prestraining and grain size on the dynamic-tensile-extrusion response of Copper: Experiments and Simulations." *Shock Compression of Condensed Matter* (2006): 725-28. Print.

4. Song, S. G., and G. T. Gray III. "Influence of Temperature and Strain Rate on Slip and Twinning Behavior of Zr." *Metallurgical and Materials Transactions A* 26A (1995): 2665-675. Print.
5. Tome, C. N., P. J. Maudlin, R. A. Lebensohn, and G. C. Kaschner. *Acta Metall.* 49 (2001): 3085-096. Print.
6. Cao, F., E. K. Cerreta, C. P. Trujillo, and G. T. Gray III. "Dynamic Tensile Extrusion Response of Tantalum." *Acta Materialia* 56 (2008): 5804-817. *ScienceDirect.* Elsevier Ltd, 14 Sept. 2008. Web. <http://www.sciencedirect.com>.