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Eulerian Hydrocode Modeling of a Dynamic Tensile Extrusion Experiment

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Abstract

Eulerian hydrocode simulations utilizing the Mechanical Threshold Stress flow stress model were performed to provide insight into a dynamic extrusion experiment. The dynamic extrusion response of copper (three different grain sizes) and tantalum spheres were simulated with MESA, an explicit, 2-D Eulerian continuum mechanics hydrocode and compared with experimental data. The experimental data consisted of high-speed images of the extrusion process, recovered extruded samples, and post test metallography. The hydrocode was developed to predict large-strain and high-strain-rate loading problems. Some of the features of the features of MESA include a high-order advection algorithm, a material interface tracking scheme and a van Leer monotonic advection-limiting. The Mechanical Threshold Stress (MTS) model was utilized to evolve the flow stress as a function of strain, strain rate and temperature for copper and tantalum. Plastic strains exceeding 300% were predicted in the extrusion of copper at 400 m/s, while plastic strains exceeding 800% were predicted for Ta. Quantitative comparisons between the predicted and measured deformation topologies and extrusion rate were made. Additionally, predictions of the texture evolution (based upon the deformation rate history and the rigid body rotations experienced by the copper during the extrusion process) were compared with the orientation imaging microscopy measurements. Finally, comparisons between the calculated and measured influence of the initial texture on the dynamic extrusion response of tantalum was performed.

Keywords: Hydrocode, MTS Strength Model, Eulerian, Extrusion, Particulation.

1. Introduction

Eulerian hydrocode (MESA [1]) simulations utilizing the Mechanical Threshold Stress flow stress model [2] were performed to provide insight into a dynamic extrusion experiment. The experimental concept [3] was developed by George T. Gray, III of Los Alamos National Laboratory to evaluate the behavior of selected material when subjected to large plastic strain deformation at a relatively high-

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strain-rate process without the need for a high-explosive type launch system. The objectives of the computational study were to perform quantitative and qualitative comparisons between the hydrocode simulation output parameters and the available experimental data to determine if this experiment was a useful indirect hydrocode validation experiment where material strength is an important modeling component.

2. Extrusion Experiment Description and Data

2.1 Experiment Description

Spherical Cu and Ta projectiles were accelerated in a high-pressure helium (He) gas gun to velocities ranging between 350 and 700 m/s and extruded through a high-strength steel die. High-speed optical imaging revealed the extruded topologies, individual necking rates, and extruded material leading edge velocity. Metallographic analyses were performed on the recovered extruded particles. The die exit diameters for the Cu and Ta dies were different to allow the stronger Ta material to be extruded without fracturing the die. In the high-speed images, a spray or "ejecta cloud" of the lubricant used in the die was observed preceding the exit of the sphere's leading edge. Grain size sensitivity to extrusion was investigated for Cu, while the effect of initial texture (material anisotropy) in Ta was investigated by controlling the sphere's orientation during launch.

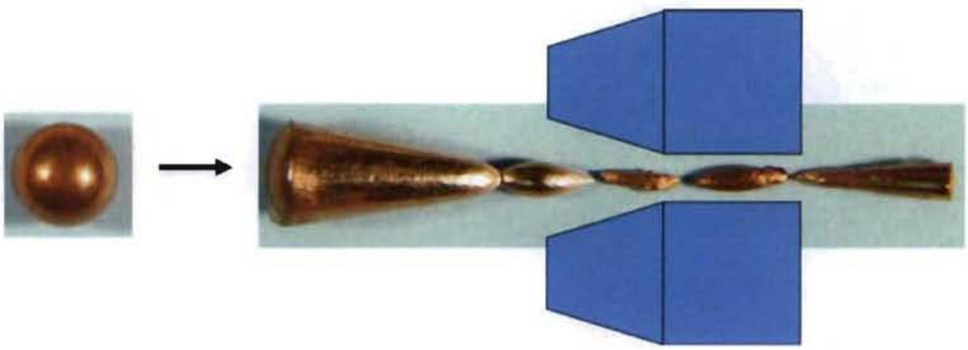

Fig. 1. 7.62-mm spherical Cu spherical projectiles of three different grain sizes were accelerated in a He-gas launcher to velocities of ~400m/s and extruded through a steel die.

2.2 Copper Extrusion Data Summary

The texture evolution in Cu deformed during dynamic tensile extrusion loading was found to display a strong grain size dependency. The texture evolution in Cu during tensile extrusion is seen to be nearly 2x stronger in the 63 μm grain size Cu than in the 118 μm grain size Cu. Increased <111> + <100> fiber texture in the 63 μm Cu is seen to correlate with a reduced propensity for strain localization / shear localization during the dynamic tensile extrusion loading.

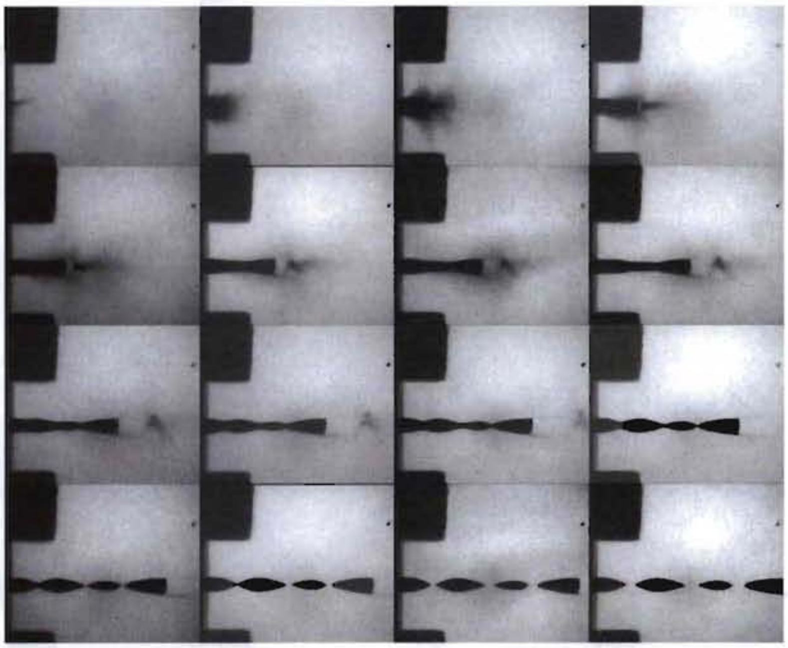

Fig. 2. High-speed imaging showing the deformation topology of an extruded Cu sphere which entered the die at ~400 m/s. Images advance in time from the upper left to lower right at 4 μs intervals.

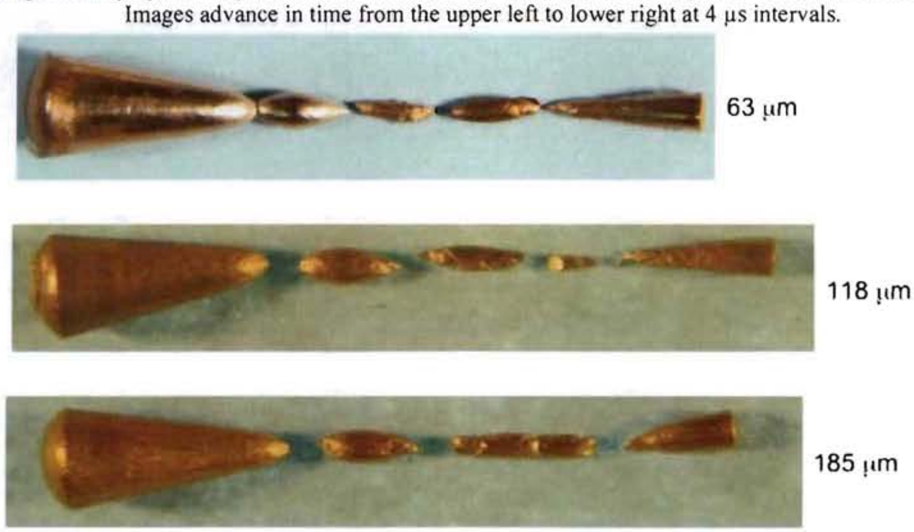

Fig. 3. The propensity for shear / strain / localizations is seen to increase with increasing grain size thereby reducing the overall dynamic ductility was observed in the recovered samples.

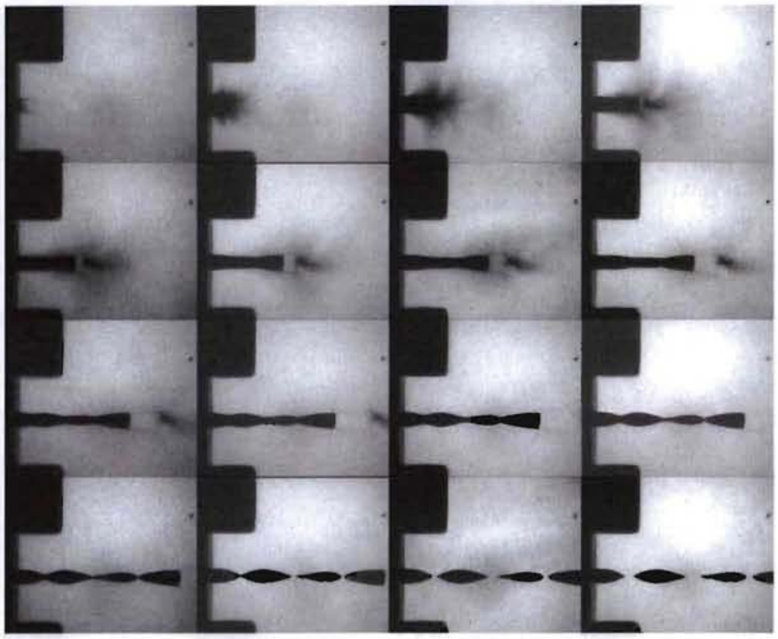

Fig. 4. Ta sphere extrusion at ~390 m/s with as-received material with TT orientation.

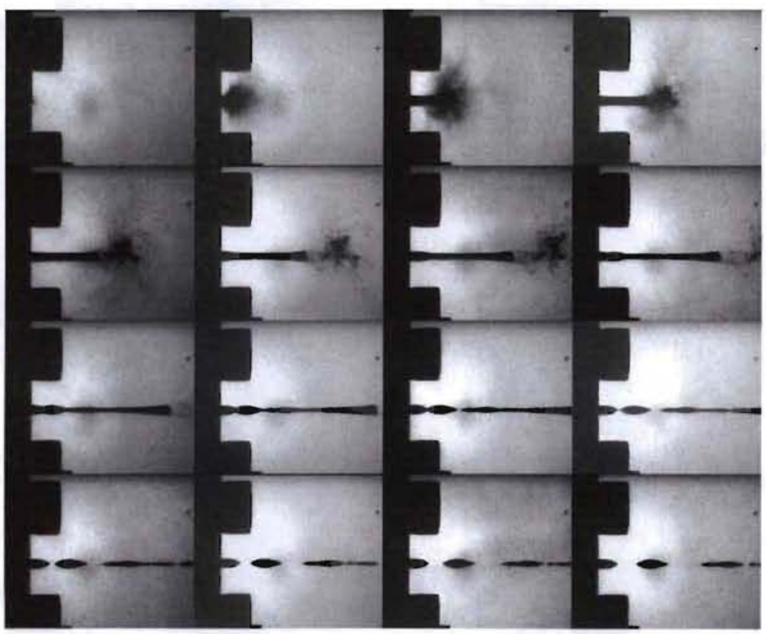

Fig. 5. Ta sphere extrusion at ~530 m/s with as-received material with TT orientation.

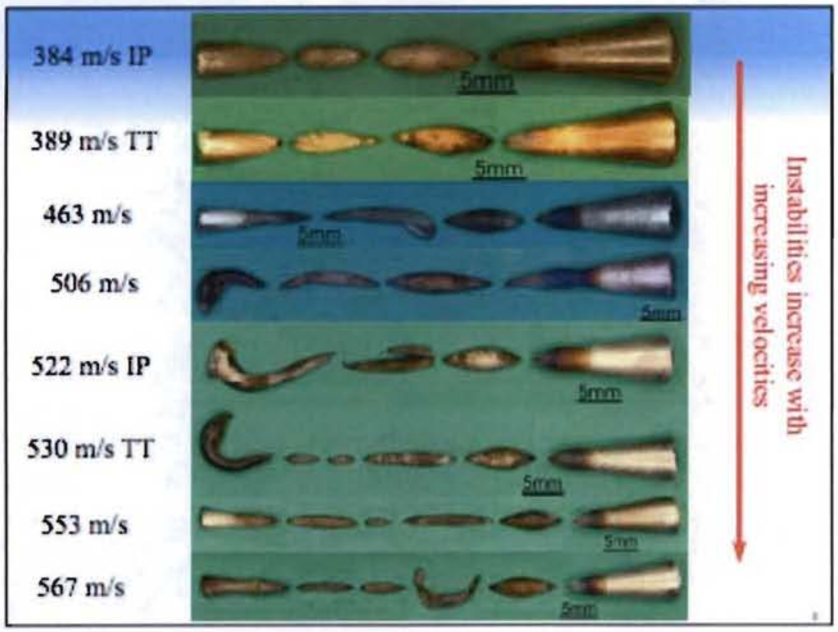

Fig. 6. Topology comparison of recovered extruded Ta spheres.

2.2.1 Tantalum Extrusion Data Summary

Analysis of the Ta data [4] revealed that particle elongation is mainly affected by velocity. Larger elongations and propensity for instability were achieved at higher velocities. Effect of starting texture of the spheres is exhibited at velocities lower than 400 m/s and becomes insignificant at higher velocities. Significant reorientation of the texture due to dynamic extrusion process was identified. Similar shear textures and hardness increments were developed in segments recovered at all velocities, regardless of the starting textures. No shear bands were observed for dynamically extruded Ta.

3. Eulerian Hydrocode and Strength Model Description

3.1 MESA 2D Eulerian Hydrocode

MESA is a two-dimensional Eulerian hydrocode that executes in a serial mode. The code has several key features that minimize advection errors including a Young's interface reconstruction algorithm and a Van Leer advection limiter. Several common hydrocode strength and damage models and standard equation of state options are available. Commercially available post-processing software can be utilized to perform analyses of simulations.

3.2 Selected Hydrocode Modeling Details

The Mechanical Threshold Stress model was used to approximate the plastic deformation behavior of Cu and Ta. Additionally, for the Ta, a two-dimensional axisymmetric anisotropic strength approximation was utilized. A uniform zoning of ~18 computational cells was employed to discretize the extrusion exit (the reduced end of the die) region. Also, the fine zoning was an important factor in allowing the projectile to "slip" through the computational mesh at the projectile/die interface. If a coarse mesh is selected, the projectile can realize numerical "drag" at this interface and affect the predicted extrusion rate and extruded material exit velocity. Finally, the die was assumed to be rigid structure.

3.3 Mechanical Threshold Stress (MTS) Strength Model as Implemented in Hydrocode

The Mechanical Threshold Stress (MTS) yield model is a physically based constitutive model based on dislocation mechanics (Ref. 25). The accumulative flow stress, also known as yield strength Y, is calculated as follows:

$$\sigma = \hat{\sigma}_a + \left(\mu / \mu_o \right) \sum_{i=1}^{N} \hat{\sigma}_i S_i \, , \tag{1}$$

where $\hat{\sigma}_a$, μ_o, and N are user-defined parameters. Currently, three terms are used in the above equation. The summed product in the above equation separates the contribution from interaction i into a structure evolution term $\hat{\sigma}_i$ modified with a constant-structure deformation S_i that is mainly a function of temperature and strain rate. The index i is either *1* or *2* or *3*, where they represent dislocation, interstitial atomic, and solute atomic terms, respectively. The athermal threshold stress $\hat{\sigma}_a$ represents dislocation interactions with long-range barriers, such as boundaries, and is assumed to be constant. The shear modulus μ, also written as G, is

$$\mu = \left(b_1 - \frac{b_2}{e^{b_3/T} - 1} \right) \left(1 + p_{hard} P \right) \tag{2}$$

where b_1, b_2, b_3, and p_{hard} are user-defined parameters. The pressure and temperature, P and T, are calculated from the equation of state. Generally, p_{hard} has a value of 0.7 for copper and 0.0 for most other materials. The $\hat{\sigma}_i$, described above, is obtained from the structure evolution equation, which is a differential hardening law:

$$\frac{\partial \hat{\sigma}_i}{\partial \varepsilon} = \theta_o [1 - F(X_i)], \tag{3}$$

where the expression $\partial \varepsilon$ is just $\dot{\varepsilon} \partial t$, with ε and $\dot{\varepsilon}$ being the total strain and total strain rate, respectively. The equation for the dislocation rate θ_o varies according to the material.

There are four different possibilities:

$$\begin{aligned}
&1)\quad \theta_o = a_1 - a_2(kT/\mu b^3)\ln(\dot{\varepsilon}_{s0}/\dot{\varepsilon}) \\
&2)\quad \theta_o = a_1 + a_2\ln\dot{\varepsilon} + a_3\dot{\varepsilon} \\
&3)\quad \theta_o = a_1 + a_2\ln\dot{\varepsilon} + a_3\sqrt{\dot{\varepsilon}} \qquad , \\
&4)\quad \theta_o = a_1 - a_2 T \\
&5)\quad \theta_o = \theta_{os}(\dot{\varepsilon}_{s0}/\dot{\varepsilon})^{-kT/A\mu b^3}
\end{aligned} \tag{4}$$

where a_1, a_2, and a_3, are the three user-defined parameters. The $F(X_i)$ and X_i are defined as

$$F(X_i) = \frac{\tanh(\alpha X_i)}{\tanh\alpha} \tag{5}$$

and

$$X_i = \frac{\hat{\sigma}_i}{\hat{\sigma}_s}, \tag{6}$$

respectively. The saturation threshold stress at 0K is

$$\hat{\sigma}_s = \hat{\sigma}_{so}\left(\frac{\dot{\varepsilon}_{s0}}{\dot{\varepsilon}}\right)^{-kT/(\mu A b_3)} - \hat{\sigma}'_a . \tag{7}$$

In this equation, $\hat{\sigma}_{so}$, $\dot{\varepsilon}_{so}$, b_3, and A are user-defined parameters, and k is the Boltzmann constant. The last term in the above equation, $\hat{\sigma}'_a$, is usually nonzero for copper and zero for all other materials. It should be noted that the relationships for θ_o, $F(X_i)$, $\hat{\sigma}_{so}$, and α are material specific. Finally, a constant-structure deformation term S_i, which is a function of temperature and strain rate, is defined to be

$$S_i = \left[1 - \left(\frac{kT\ln(\dot{\varepsilon}_i/\dot{\varepsilon})}{\mu b^3 g_i}\right)^{1/q_i}\right]^{1/p_i}, \tag{8}$$

where b is the magnitude of Burgers Vector (the interatomic distance in the slip direction), and g_i is a normalized activation energy for a given dislocation/obstacle interaction.

The flow stress σ and the shear modulus μ are set to zero when the temperature is greater than the melt temperature. Currently, the SESAME [5] equation of state must be used with this yield model. The form requires both the maximum yield strength and initial and maximum shear modulus. A von Mises yield criterion is used for Cu that results in a "radial return" to the yield surface. Ann associated flow stress formulation incorporating a yield function is solved using a geometric normal return method [6].

4. Computational Findings and Conclusions

Hydrocode output variables were used to provide comparisons with the experimental data. Material plots provided extrusion trajectories and shape(s) and extrusion exit velocity, while pressure response (in Cu), MTS flow stress model sensitivity (saturation stress magnitude), plastic strain, and texture effects (Ta) were extracted from the computational cell-centered variables.

Peak pressures of ~120 MPa (~12 kbar) were realized in the Cu sphere and are significantly below pressures experienced in a explosively driven extrusion-like configuration

In all the simulations and experiments, the extruded projectile material that exits the die originates in the leading edge of the sphere and experiences minimal rigid body rotations induced by geometry of the die (Fig. 8). The hydrocode predicted that leading edge of the sphere is accelerated as it exits the die and the exit velocity is dependent upon the MTS saturation threshold stress parameter magnitude (sigsat0). The saturation stress value sets the upper limit for flow stress magnitude at large plastic strains. Additionally, especially for Cu, there was good agreement between the predicted and measured characteristics of the leading particle's front surface contour and the rear contour of the sphere segment reaming in the die. The leading particle's leading surface was flattened after exiting the die, while the rear surface of the portion of the sphere lodged in the die maintained it's initial curvature. In general, good qualitative agreement was found between the predicted and measured particulation (material necking) behavior as a function of launch velocity. More particles and smaller diameter particles were predicted and observed at higher launch velocities and fewer necks and less elongated particles were predicted and observed at the lower launch velocities.

4.1 Cu Simulations

Predicted extruded Cu sphere topology and exit velocity was found to be highly dependent upon the saturation flow stress (at 0^{o}K) magnitude. A lower saturation flow stress (implying a coarser grain size based upon stress-strain data at higher strain rates) and at higher impact velocity (400 to 450 m/s) produced more ductile extrusions (no. of particles increased and the particle lengths generally increased). Variation in flow stress magnitude does not fully explain the differences (measured flow stress sensitivity to grain size is weakly coupled) in the observed deformation topology indicated by the recovered particles. More ductile extrusions were observed in simulations and experiment (independent of grain size) at the 450 m/s projectile velocities. Plastic strains >300% and strain rates on the order of 10,000 1/s were calculated. While the sphere was being extruded in the die, peak pressures of ~120

MPa (~12 kbar) were realized.

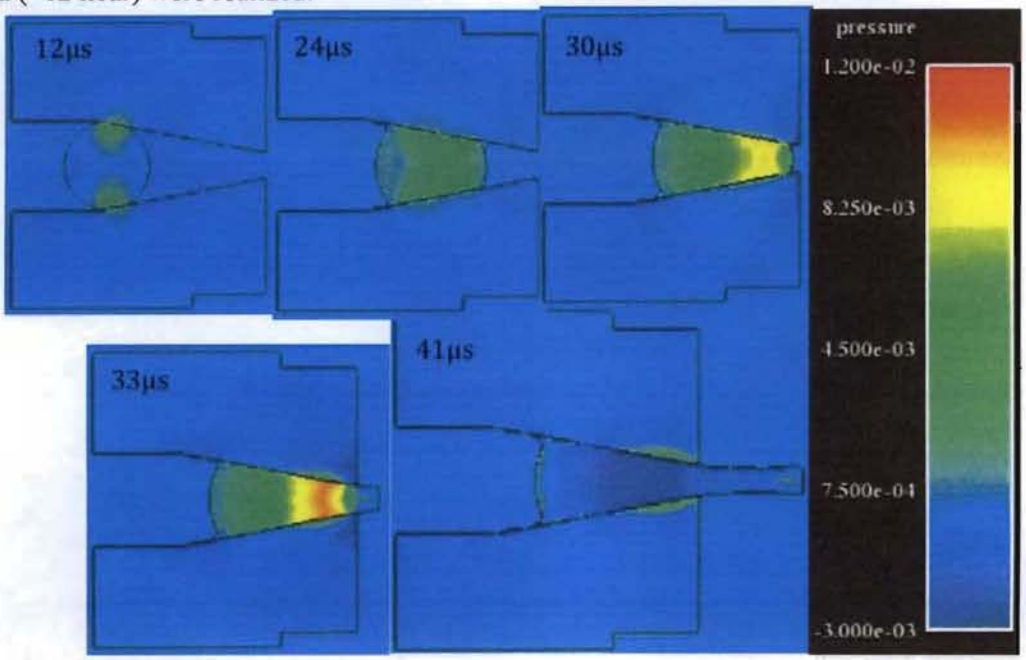

Fig.7. Predicted Cu Extrusion Pressure as a Function of Time. A few μs after the initial impact with the die, the sphere remains in compression during transit through the die until the sphere's leading edge begins to exit the die. At this time, the sphere unloads and remains in tension as the extrusion process develops.

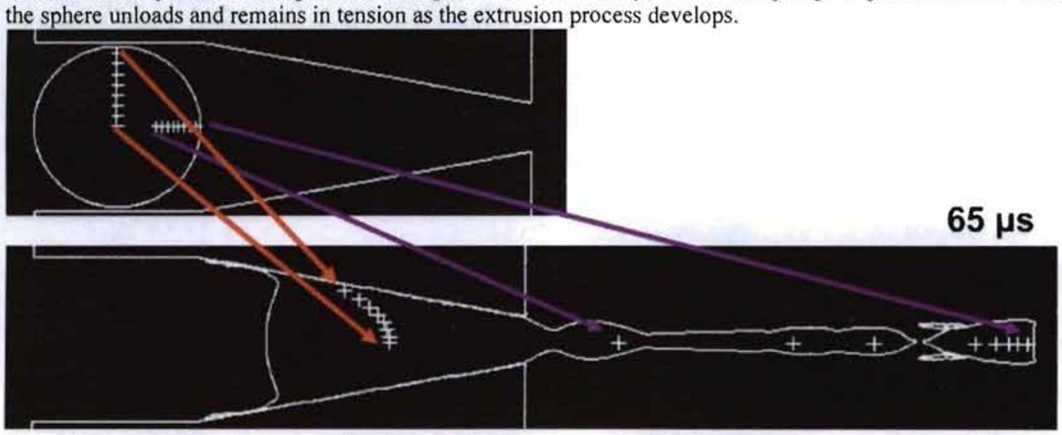

Fig. 8. The portion of the computational mesh depicting the projectile and die is shown. Lagrangian tracer particles (+) are shown in the projectile and were used to establish material extrusion trajectories.

4.1.1 Cu Exit Velocity Predictions and Sensitivities

For the Cu sphere entering at ~400 m/s, an avg. exit velocity of ~708 m/s was measured while a calculated exit velocity of ~650 m/s (for sigsat0 = 650 MPa) and ~706 m/s (for sigsat0 = 500 MPa) were predicted.

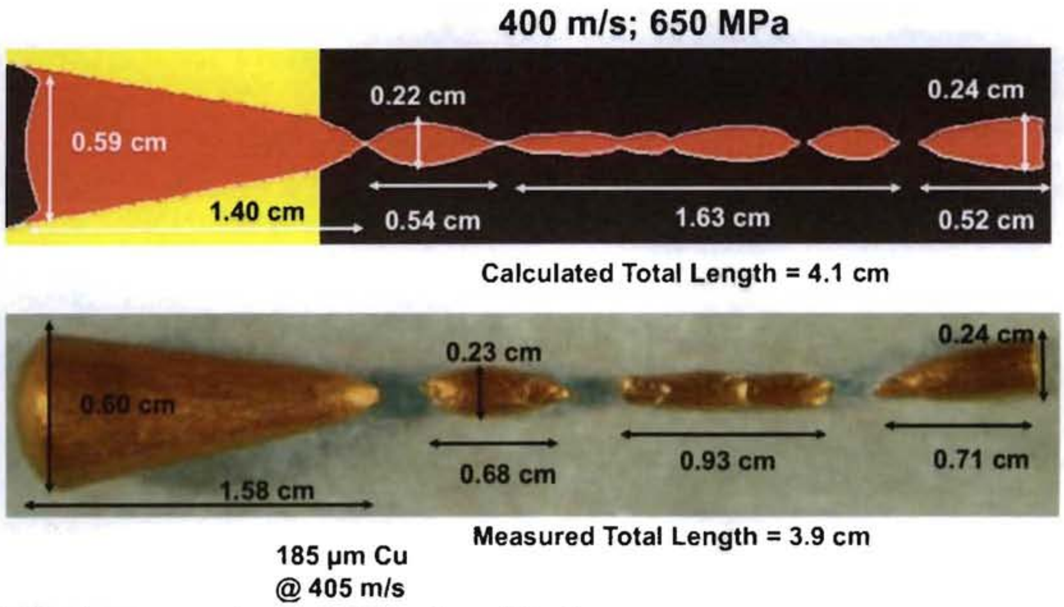

Fig. 9. Topology comparison for 185 µm Cu at 400m/s.

4.2 Ta Simulations

Ta spheres were launched with two different orientations: thru-thickness (TT) and in-plane (IP). The TT orientation is referred to as the "strong" direction while, the IP orientation is referred to as the "weak" direction. The TT is defined as "strong" because the flow stress magnitude in this direction is significantly higher than the value in the IP direction. In general, the predicted topologies and no. of particles were in poor agreement with the experimental data. Predicted anisotropic effects on Ta particulation was found to be minimally sensitive for low velocities (~385 m/s) and indicated a slight sensitivity at higher velocities (~525 m/s).

4.2.1 Ta Exit Velocity Predictions and Sensitivities

For Ta sphere entering at ~527 m/s, an avg. exit velocity of ~894 m/s was measured - a calculated exit velocity of ~651 m/s (for sigsat0 = 650 MPa) and ~779 m/s (for sigsat0 = 275 MPa) were predicted. For Ta sphere entering at ~385 m/s, an avg. exit velocity of ~532 m/s was measured - a calculated exit velocity of ~387 m/s (for sigsat0 = 650 MPa) and ~499 m/s (for sigsat0 = 275 MPa) were predicted. Plastic strains ranging between 500 - 800% were calculated in Ta while, strains up to 800% were measured during the metallographic analyses.

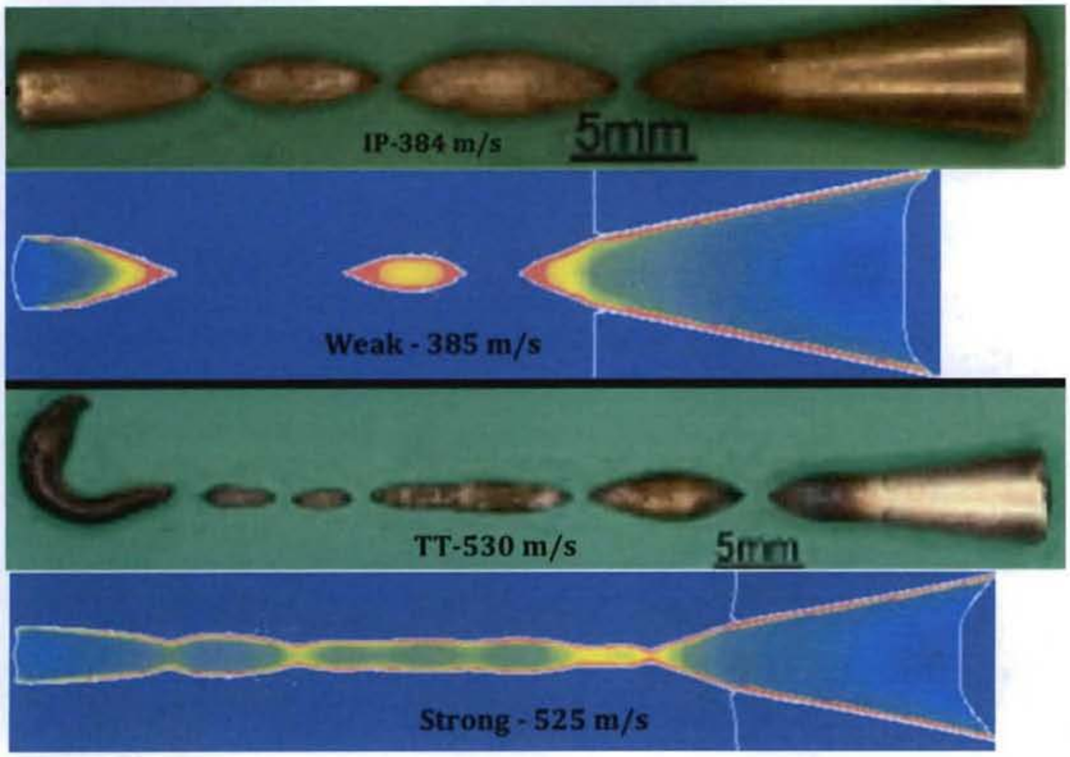

Fig. 10. Ta qualitative topology comparisons for TT and IP textures at launch velocities of 385 and 525 m/s.

5. Discussion and Possible Follow-on Computational Studies

The dynamic extrusion experiment is conceptually simple and efficient for evaluating and comparing the deformation behavior of numerous materials under-going large plastic strains at elevated strain rates while controlling the initial conditions of the material prior to processing. However, approximating the projectile "slip" through the die computationally is an important modeling detail that affects the predicted extrusion process characteristics and introduces additional complexity in validating the hydrocode and strength models. Additional experiments are being planned to measure the projectile transient time in the die to compare with the predicted transient time. If the measured and predicted times are found to be in agreement, the influence of the saturation stress magnitude may be an sensitivity that should examined further. These preliminary Eulerian hydrocode simulations have been able to provide insights into the material processing in the extrusion experiment and have compared well qualitatively. However, the extruded particle topologies and no. of particles for Cu and Ta, the texture evolution and grain size sensitivity observed for Cu and the anisotropic effects observed in Ta at lower velocities were either not in quantitative agreement, addressed in the modeling assumptions, or predicted by the simulations.

Further computational studies are required to investigate the effects of mesh resolution, possible three-dimensional effects in the deformation topologies induced by texture evolution and damage evolution (porosity and shear localization development by direct application of TEPLA model [7]). Additional simulations of Ta at higher velocities and comparisons of MTS results with other strength models like, Johnson-Cook [8] and PTW [9] would be beneficial.

Acknowledgements

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