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ScienceDirect

Procedia Engineering 00 (2017) 000–000

SAND2017-3686C
Procedia Engineering
www.elsevier.com/locate/procedia

14th Hypervelocity Impact Symposium 2017, HVIS2017, 24-28 April 2017, Canterbury, Kent, UK

Characterizing In-Flight Temperature of Shaped Charge Penetrators in CTH

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Abstract

With the increasing use of hydrocodes in modelling and system design, benchmarking of software against experiments has become even more vital. While substantial work has been done in this regard, comparisons with temperature data within dynamic experiments are sparse due to experimental limitations. However, novel developments in measurement techniques has enabled the in-flight acquisition of hypervelocity projectile temperature, providing a new source for validation. This is achieved by tracking the decay of an induced magnetic field which is related to conductivity and further correlated to material temperature. As such, an AC-14 bare shaped charge with a copper lining is simulated using CTH, and benchmarked against experimental temperature results observed by Uhlig and Hummer. Particular attention was given to the slug temperature profiles after separation, and the effect of varying equation-of-state and strength models. Simulations are in agreement with experimental results, with a best case of under 2% error between the observed and simulated temperatures for this shaped charge setup. This varied notably (around 20% variance) depending on strength model. Jet structures compare well with radiographic images and are consistent with ALEGRA simulations previously conducted.

Keywords: Shaped Charge, CTH, Transient Temperature Response

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1. Introduction

Computational approaches are becoming more and more prevalent in system modeling. Due to this, significant effort has been given to validating and benchmarking software against a range of experimental data. The rigor of these comparisons corresponds directly to the abundance of data available. With respect to dynamic experiments taking place over small time scales (micro to milliseconds), temperature data is among the most difficult to acquire given limitations of measurement devices. Recently developed experimental techniques, however, have allowed for in-situ measurement of temperature within hypervelocity projectiles.

Developed by Uhlig and colleagues, experiments are designed such that the projectiles of interest pass through a series of inductance coils and are therefore saturated with a detectable, material dependent, magnetic field. Downrange, the decay of magnetism is tracked via passive sensing coils [1-4]. The decay time of the projectile's magnetic field is directly proportional to the material conductivity, which can be further correlated to in-situ temperature [5]. A schematic setup can be seen in Figure 1. Measured projectiles included slugs from both shaped charges and explosively formed projectiles.

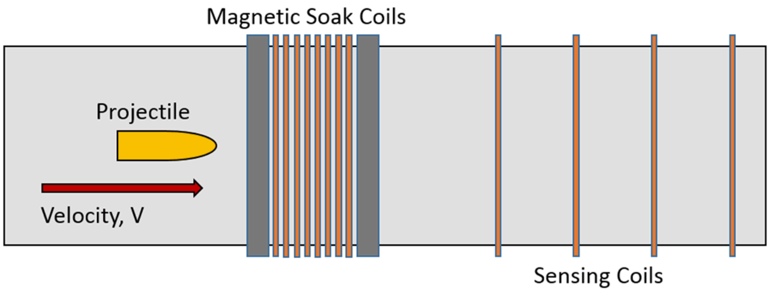

Fig. 1. A representative schematic of the temperature diagnostic used by Uhlig [1]. The projectile of interest is saturated with a magnetic field via soak coil, the decay of which is measured via the inductance down range. Measurements were made at standoff of 45 and 65 cm respectively for shaped charge experiments.

Reported here are shaped charge jet experiments that were modeled using the CTH hydrocode, in an effort to benchmark computationally calculated projectile temperature against experimental measurements [6, 7]. A mesh resolution study was performed, with projectile velocity and slug radial temperature profile serving as convergence criteria. The strength model utilized was varied to quantify the sensitivity of jet temperature to mechanical work. Other factors, such as the environmental effects of air versus vacuum conditions, were additionally explored. While experiment temperatures were indirectly calculated based on magnetic field decay and related conductivity, simulations will extract temperature calculations directly for comparison, in contrast to previously done studies using ALEGRA in which the magnetic field was compared directly [4].

2. Computational Setup

A two dimensional cylindrical domain was selected, allowed by axial symmetry, and enabling greater computational efficiency. An AC-14 bare shaped charge was modeled, reflecting the experimental study, with a copper liner diameter of 6.5 cm, liner thickness of 1.2 mm, giving an overall shaped angle of 22 degrees. The jet is formed via an LX-14 explosive driver.

Throughout the initial detonation, jet formation, and jet motion, the copper liner experience drastic change in temperature and pressure, and as such the chosen equation of state (EOS) must be robust enough to incorporate such variations up to and including melting. For this reason, a Sesame table was chosen over alternatives such as a Mie-Gruneisen EOS. More straightforward in selection, the LX-14 explosive required the use of a burn model and was therefore the Jones-Wilkins-Lee (JWL) model was implemented with a programmed burn for the rate law.

Because of the large stresses and deformations undergone, hydrodynamic behavior of the liner is expected and has been observed experimentally. However, the strength contributions cannot be neglected and have a fundamental role in the formation of the jet slug. This being the case, various constitutive models are implemented for comparison including Johnson-Cook (JO) [8], Steinberg-Guinan-Lund (SGL) [9], Preston-Tonks Wallace (PTW) [10], and Mechanical Threshold Stress (MTS) [11]. More concisely, computational models used are included in Table 1.

Table 1. Computational models used in the simulation of an AC-14 shaped charge.

Material	Copper Liner	LX-14
Equation of State	Sesame Table	Jones-Wilkins-Lee
Strength Model(s)	JO, SGL, PTW, MTS	None

The experiment was conducted within a near vacuum (~4 Pa), contained by polycarbonate tubing), in order to isolate jet temperature behavior from atmospheric effects, however this was noted to cause inconsistencies in experiments. Corresponding with this, simulations were conducted with both atmospheric air (Sesame EOS) and vacuum conditions with any effects noted. After the effects of varying strength model were explored, the additional factor of the polycarbonate tubing was included.

Prior to simulating the entire parametric space, a mesh resolution study was conducted to evaluate at what grade vital behaviors, in this case jet velocity and temperature, converged. This was done with the same setup described above with SGL arbitrarily chosen as the strength model. Starting at 0.03 cm/cell (flat mesh), the grade was incrementally refined to 0.01 cm/cell.

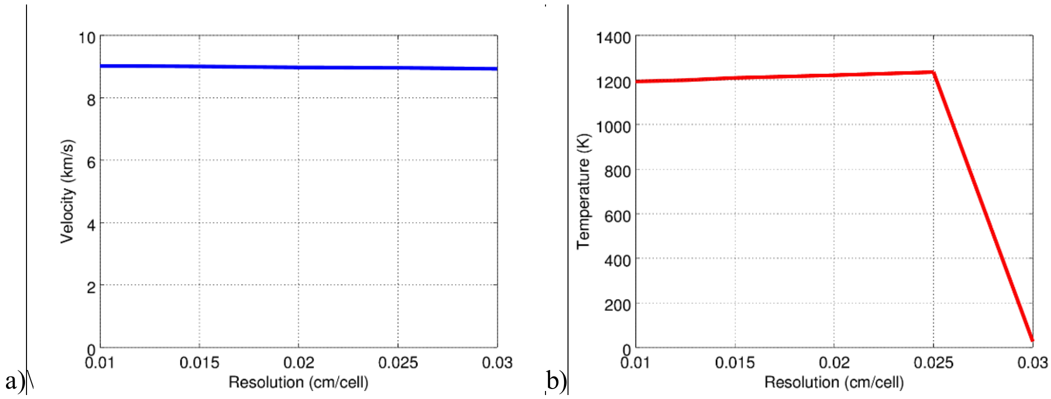

Fig. 2. (a) Jet velocity convergence with increased mesh refinement. (b) Temperature convergence with increased mesh refinement.

As shown in Figure 2, projectile velocity behavior converges to 9.02 km/s, comparable to the experimentally determined 9.15 km/s. Temperature converges in a similar manner, though at a higher mesh. Properties were evaluated using a tracer fixed to the shaped charge jet, evaluated once steady projectile velocity had been achieved. Previously done simulations using comparable setups concluded 0.0125 cm/cell to be sufficient [4]. This in mind, and being corroborated by the Figure 2, 0.0125 cm/cell was considered adequate, allowing for direct comparison to previous computational studies while still accurately capturing jet velocity. Note: this allowed a total of 10 cells through the thickness of liner.

3. Results and Discussion

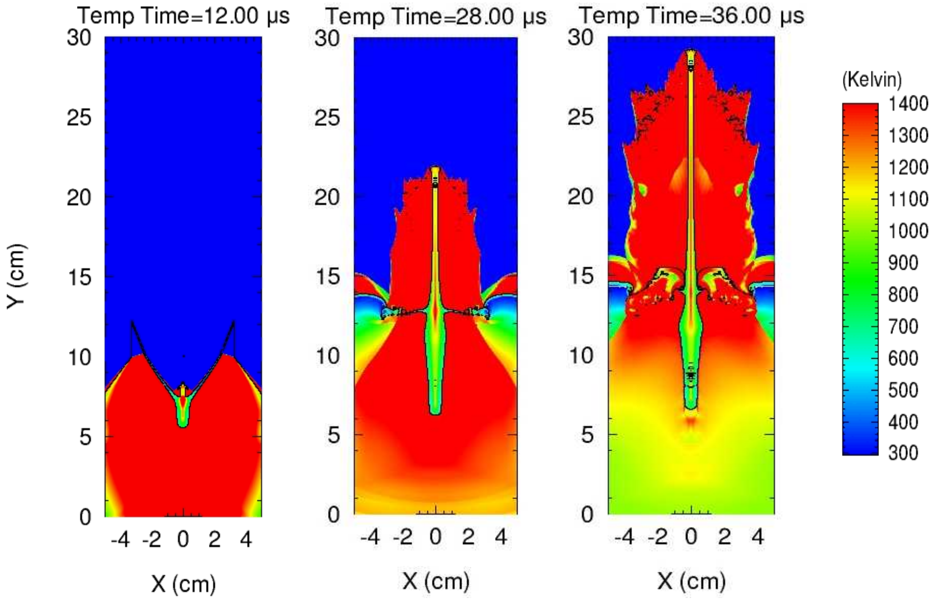

Fig. 3. Representative frames of the simulated shaped charge at times 12, 28, and 36 microseconds after detonation. Setup shown includes air and copper strength is modeled with SGL.

The bare shaped charge initiated by an LX-14 explosive was simulated in CTH using the aforementioned parameters (Table 1). As would be expected, the blast wave propagating through the explosive, impinges the copper liner onto itself forcing a jet penetrator outward at 9.02 km/s in good agreement with the measured ~9.15 km/s seen experimentally. While the time and location of jet separation varied with the constitutive model used, due to direct implications in plastic deformation, overall jet structure was consistent and compared well with experiment, despite variations between strength model being evident in both structure and temperature (Figure 4).

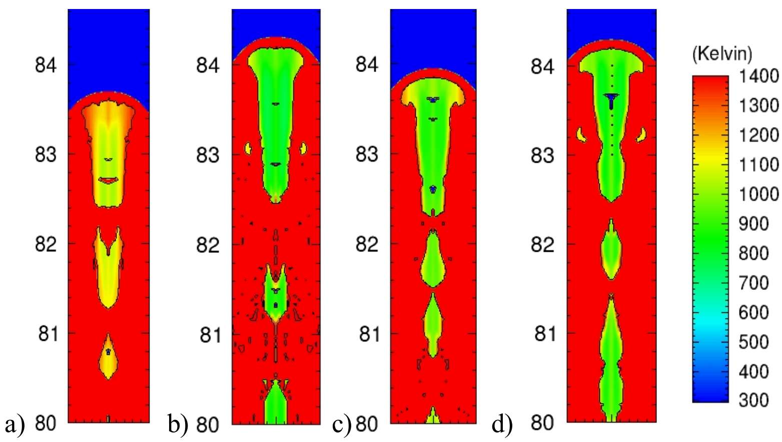

Fig. 4. Shaped charge jet structure and temperature post separation at approximately 70 cm standoff. a) SGL, b) JO, c) PTW, d) MTS.

With the interest specifically being in resolving jet temperature for comparison to experiment, a radial temperature profile of the slug was extracted. Several were taken longitudinally, along the y-direction, of the foremost jet tip. The average of all profiles were compared directly to the bulk values experimentally measured. Simulations using the SGL strength model for the copper liner showed temperature consistently within a few percent of the experimentally observed 1190K (± 60). In contrast, JO runs cooler, almost 30% less than the experimental measurements (Table 2, Figure 6). This trend corresponds well with previous simulations done in ALEGRA by Uhlig and Niederhaus [4]. The underestimations in the numerical trials using JO, are in some ways expected given its strong dependence on melt temperature [8].

At high temperatures, near material melt ($T_{melt} \cong 1350K$), the Johnson-Cook model predicts yield stress to become negligible regardless of other factors, which can lead to inaccuracies. For a shaped charge, the microsecond time scale suggests the major contributor to material temperature is the large amount of plastic work rather than traditional heat transfer mechanisms from blast heat. Minimizing material yield, reduces this work and therefore the corresponding temperature. Instead the material begins to behave hydrodynamically, which deviates from no melt behavior generally observed in jet formation [2].

This expectation of lower calculated temperatures does not extend to the Preston-Tonks-Wallace model, in which temperature dependence is not so simplistic. However, it has been seen to be unreliable with regard to strain rates below 10^8 s^{-1}, where shaped charges are generally around 10^5 s^{-1} [10]. Additionally, there could be variation in material parameters, which do not account for slight variations in copper composition found in experiment. With this in mind, this could infer an inaccurate contribution of stress to temperature increase, accounting for the observed underestimation of the temperature profile. Bulk jet temperature results are reported in Table 2, where radial, one-dimensional, temperature profiles of the jet were averaged to find the bulk copper temperature. Note: percent errors are taken with respect to the average experimental value and not the deviations.

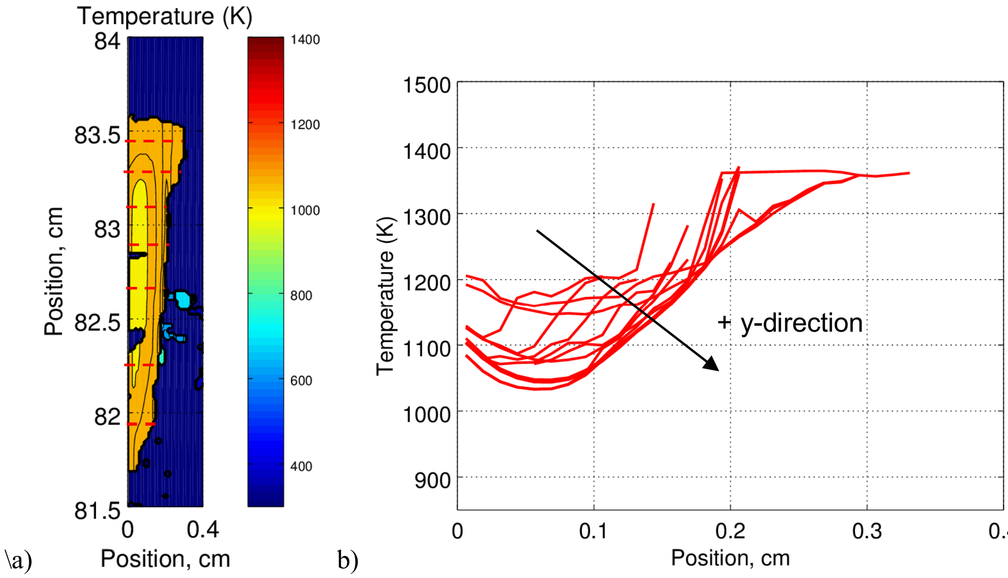

Fig. 5. a) MATLAB contour plot, used to analyze bulk jet temperature, note only the temperature of copper is considered. Red lines signify how radial profiles are generated. b) Radial jet temperature profiles start from 81.9 cm up to 83.5 in increments of 0.125 cm.

Table 2. Comparison of CTH simulated bulk jet temperature against experimental data and ALEGRA simulations [3].

Software	Strength Model	Temp. (K)	Experimental Temp. (K)	Percent Error
CTH	Johnson-Cook	958	1190±60	22%
	Steinberg-Guinan-Lund	1167		1.9%
	Preston-Tonks-Wallace	1012		15%
	Mechanical Threshold Stress	964		19%
ALEGRA	Johnson Cook	850		29%
	Steinberg-Guinan-Lund	1260		6%

The Steinberg-Guinan-Lund model was developed specifically for metals in this regime of strain rates. Instead of reducing yield stress based on temperature directly, the model derives a thermal yield contribution from strain rate – proposed as an inverse exponential relationship [9]. In these simulations, this allows the copper liner to retain strength near melting temperature, resulting in a more accurate estimate of plastic behavior and thus jet temperature.

Comparing to the Mechanical Threshold Stress model, MTS decouples strain rate sensitivity due to microstructure and microstructure evolution separately along with the incorporation of an Arrhenius temperature dependence [11]. Temperature contributes in the same form to both constant structure and structural evolution portions of stress, scaled by the log of the ratio of initial strain rate to current strain rate. In addition, the athermal stress is not scaled by change bulk modulus which is a function of temperature. Despite a more complex relationship between stress and temperature, they are still decoupled to a degree.

While models vary in their accurate prediction of jet temperatures, additional observations can be made about simulated jet structure. Synthetic radiographs generated in CTH compare well with X-ray's taken during experiments as can be seen in Figure 6.

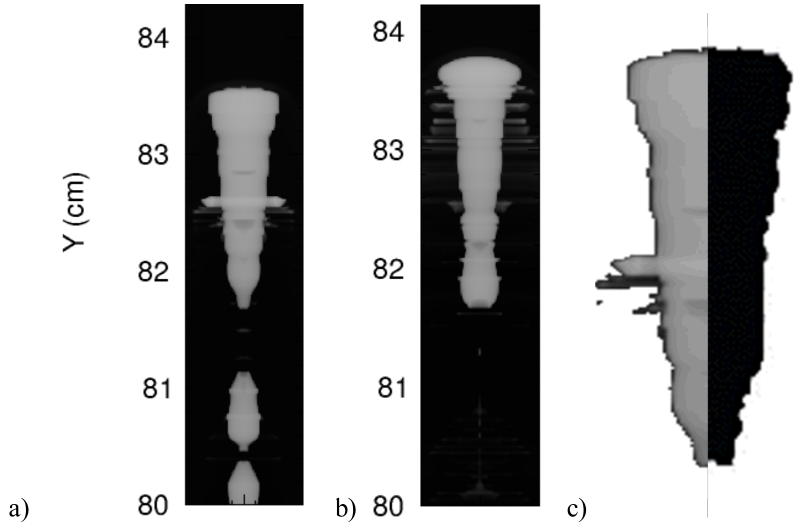

Fig. 6. a) CTH radiograph SGL. b) CTH radiograph PTW. c) Experimental X-Ray (right) compared to the CTH radiograph (SGL).

The explosive is the only source of energy into the system. Neglecting heating mechanisms such as conduction and convection due to the time scale, the only source of internal energy and so temperature rise is that of the mechanical work and material deformation. This infers that any inconsistencies in temperature are directly associated with problems capturing precise material deformation. So, as the Steinberg-Guinan-Lund model has the closest approximation of experimental temperature, then it should also best match the experiment jet shape, confirmed by the radiographs in Figure 6.

All strength models were initially simulated with only the shaped charge in an air environment, as was done in previous computational work, a simplification of the experimental setup. With Steinberg shown to most accurately model this setup, additional parameters were only altered for that case. The experimental setup was more precisely replicated including a vacuum chamber contained by polycarbonate (Figure 7). Implementing the vacuum chamber does increase jet temperature overall, especially closer to the core. It should be noted, that it is typical within CTH simulations for the axis of symmetry (in a 2D cylindrical setup) to artificial inflate thermodynamic values like temperature, specifically on the nearest cell or two. Overall, this slight skew is assumed to be averaged out by the rest of the profile.

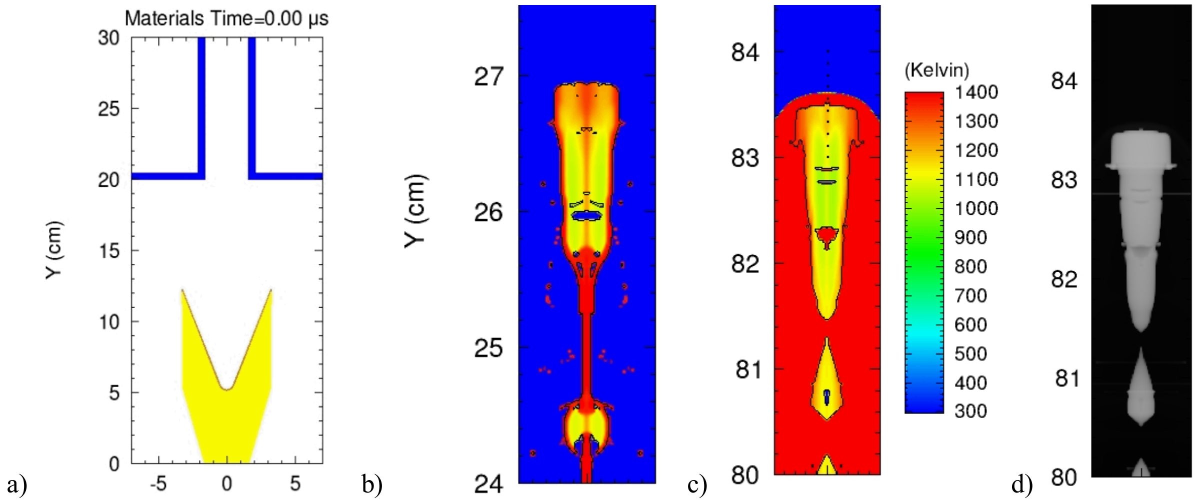

Fig. 7. a) Computational domain including vacuum containment. b) Jet temperature under vacuum, note the shift in axis values as the domain follows the jet in this case. c) Jet temperature with a JO fracture model. d) Radiograph with JO fracture included. (All use SGL strength)

Consider the temperature profiles of a vacuum simulation compared to a jet in atmosphere, as can be seen side by side in Figure 7. It is apparent that the air around the jet quickly reaches temperatures in excess of 1300-1400K due to the explosion. In contrast to aforementioned suggestions, with energy not going into heating air, more is available to increase the internal energy of the jet itself and therefore the higher temperatures seen. In addition, the air could have large implication of pressure-volume work within the copper, altering temperature. It has been observed experimentally that while the inner core of the jet may reach melt conditions, while the outer shell remains solid [2]. Contradictory to this and indicating a partial lack in capturing some heating phenomena, vacuum simulations show an outer layer which does attain melt conditions. While vacuum conditions are unique in this way, the outer layer is warmer across the board.

An alternative to simulating vacuum conditions, a fracture model was also added to evaluate the role added plastic mechanisms would play in copper temperature, with Johnson-Cook fracture used for simplicity [12]. Allowing fracture, introduces another option for the dissipation of energy, which further changes the bulk jet temperature when added to the original SGL simulation. However, fracture parameters were developed for a 3D orientation, so while the addition of a fracture model does allow for a more comprehensive physics model, the choice of a 2D axisymmetric domain does limit the effectiveness of include fracture conditions.

Table 2. Comparison of CTH simulated bulk jet temperature against experimental data, with the additional factors of vacuum conditions and the inclusion of fracture model considered.

Software/Strength Model	Added Factor	Temp. (K)	Experimental Temp. (K)	Percent Error
CTH/SGL	Vacuum/Contained	1204	1190±60	1.2%
	JO Fracture	1158		2.6%

Overall, bulk jet temperature varies greatly with chosen constitutive model. Given the range of strain-rates experienced by the liner throughout deformation, the relation between mechanical work is certain to change. Over various regimes temperature stress relationships can change from being best modelled by linear (JO), nonlinear exponential (SGL), and Arrhenius (MTS) models, as the physical mechanisms at play change over varying strain-rate regimes. Comparing all tested models, SGL captures the deformation and temperature with the highest accuracy in modelling this shaped charge jet formation.

4. Concluding Remarks

Shaped charge jets are a critical application in which proper modeling of both strength and thermodynamic characteristics are vital in accurately predicting formation. With recent developments in in-situ temperature measurement of hypervelocity projectiles, data is now available to aid in the validation of analytical and computational models describing the plastic formation of the jet.

Variations in strength model are particularly important given the large amount of plasticity seen in jet formation, as well as unique behavior at observed strain rates of 10^5 s^{-1}. Assuming equal system energy at detonation, each strength model budgets differing amounts of energy to varies strain, and mechanical work phenomena, and thus calculation of internal energy and so temperature change. In this study, Johnson-Cook, Steinberg-Guinan-Lund, Preston-Tonks-Wallace, and Mechanical Threshold Stress models are used to simulate an AC-14 bare shaped charge with a copper liner using CTH. Comparing across the board, SGL most accurately predicts bulk temperature to under 2% error with experimental observations. All other models are approximately 20% cooler than observed, though these deviations align with previous simulations done in ALEGRA.

Additional factors were considered such as vacuum conditions versus open air, and fracture included in strength modeling. These effects were tested on Steinberg, being the best performing thus far, and showed minimal impact on overall observed temperature (bulk), though the vacuum surroundings resulted in temperatures near and around melt for the outer shell of the copper jet.

In conclusion, CTH was shown to adequately simulate the described shaped charge experiment aligning with experimental observations. Strength model was shown to be critical for accuracy, giving changes in temperature stress relations and the high strain rate conditions.

Acknowledgements

The authors would like to thank Dr. Casey Uhlig of the U.S. Army Research Laboratory, who performed the experimental basis of this work, for answering our many questions to ensure an accurate computational model. Sandia is a multi-program Laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94-AL85000.

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