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Auspices Statement

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FY09 LDRD Final Report

Plasticity at High Pressures and Strain Rates using Oblique-Impact Isentropic-Compression Experiments

LDRD Project Tracking Code: 07-ERD-039

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Abstract

Part of LLNL's national security mission is reliant on accurate simulations of high strain-rate plastic flow (nonreversible deformation) under conditions of high hydrostatic pressures. In an effort to help advance the predictive capability of LLNL's multiscale modeling program a new experimental technique has been developed to provide strength properties under conditions of high strain rate (10^4 -10^6 s^{-1}) and high hydrostatic pressure (1- 100 GPa). The oblique-impact experiments allow for the shearing response of the material to be independently measured while the material is under pressure. The strength of the material is then inferred by conducting 2-D hydrodynamic simulations to match to the experimentally measured velocity profiles. Utilizing this technique, Cu and V experiments have been conducted that establish the utility of this technique to measure strength under dynamic conditions.

Introduction/Background

Understanding and simulating the plastic deformation of materials at high rates under pressure is a major component of LLNL's Stockpile Stewardship Program and is intended to simulate future NIF experiments. While progress has been made in recent years, especially for individual extremes of pressure and strain-rate [1], there is still an uncertainty in understanding the strength of materials under conditions of combined high strain-rate (10^4 – 10^6 s^{-1}) and high pressure (1-100 GPa).

Current strength models used in simulations include some physically based models such as the Mechanical Threshold Stress formulation [2], which has over 20 parameters. The uncertainty in the values for these parameters as well as values for the parameters in other physically based models is under question due to the inherent difficulties in conducting and extracting high-quality experimental data in the high pressure and high strain rate regimes. The experimental studies of material strength at these pressure and strain rate regimes further the understanding of the underlying physical strength mechanisms needed for accurate material strength models.

The goal of this project is to develop an oblique-impact compression experiment using windowed interferometry to measure the strength of materials under a condition of combined high strain-rate (10^4 – 10^6 s^{-1}) and high pressure (1-100 GPa). The oblique impact allows for a measurement of the strength properties under pressure [3], and by using windowed interferometry [4], the pressure is maintained during the measurement and higher pressures can potentially be achieved. The strength data will then be used to refine and enhance current strength models.

Overview of Project and Research Path

While this project was originally slated to be a three year project, due to budget constraints and losses of personnel, the 3rd year of funding was reduced from $640k to $75k (88% reduction), effectively making this a 2-year project. In addition, during the middle of the 2nd year, the co-investigator on this project, David Lassila, as well as the main developer of the graded density impactors, L. Peter Martin, both left LLNL. Therefore, most of the higher pressure work was not completed, and only a limited number of materials and variables could be tested.

The first step in this research plan was to establish a contract with Prof. Rodney Clifton at Brown University since he has the appropriate gas guns (keyed-barrel) and diagnostics to perform these experiments. Since these experiments were different from the traditional pressure-shear experiments that Prof. Clifton pioneered, some experimental development of the sample preparation and diagnostics were needed. Once the experimental issues were resolved, experiments were conducted on polycrystalline Cu and V samples to determine their strength under conditions of high strain rate and pressure. In addition, a simulation capability was developed to help guide and interpret the experimental results.

Results/Technical Outcome

The oblique-impact experiment developed in this LDRD, Fig. 1, involves the use of a gas gun to propel an impactor at the sample at high velocities (100's to 1000's m/s). The impactor is connected to a key-way in the barrel of the gas gun to prevent rotation during flight. This key-way allows for the impactor to strike the sample at an oblique angle (5° – 25°) while still maintaining a planar impact (the faces at impact are still flat and parallel to each other). The oblique impact sends both longitudinal and transverse (shear) waves into the sample, which can be measured using interferometric techniques. By using a transparent window material, the response of the material can be measured at the sample/window interface, when the sample is still under pressure. The longitudinal wave, which has both hydrostatic and deviatoric components, puts the material in a state of pressure and strain. The transverse wave, which runs slower than the longitudinal wave, probes the shear response of the material.

Utilizing this technique, the strength of Cu and V samples have been measured. The following sections describe the results and accomplishments from the sample preparation, modeling and simulation, and experimental efforts during this project.

I. Sample preparation

In this experiment the main diagnostics are the measurement of the particle velocities that pass through the sample. Most experiments measure the normal or longitudinal wave velocity, which contains both the hydrostatic and deviatoric information about the material. While the normal velocity is rich with information it can be difficult to interpret and is not very sensitive to the strength. For the oblique-impact experiment both the longitudinal and transverse (shear) particle velocities are measured. The normal velocity is typically measured with a normal displacement interferometer (NDI) which requires a reflective surface. The transverse wave is measured using a transverse displacement interferometer (TDI) and requires a diffraction grating in order to measure the shear waves [5].

For typical pressure shear experiments, the diffraction grating is applied at the back of a hard anvil material, like WC, or tool steel. The grating spacing is usually 600 lines/mm (line widths and spacings of 0.8 microns) and is created in a layer of photoresist using standard microelectronic photolithography techniques. For the experiments in this LDRD, a window is used to keep the pressure on the sample as the slower travelling shear wave arrives, and the wave velocities are measured at the sample/window interface. Because the velocities at a free surface or twice as large as those measured at the interface, a finer grating is needed to help increase the velocity resolution. In addition, the grating must be applied at the sample/window interface.

Under this LDRD, a process was developed to etch a 1200 lines/mm grating into the sapphire windows. Sapphire is chosen because it is optically transparent and has a shock impedance close to Cu and V.

The gratings were created by utilizing the laser lithography techniques that have been developed to produce diffraction gratings for advanced optics applications. Once the grating patterns were developed in photoresist, the sapphire was etched using a dry plasma etching process. The depth of the lines is 85 nm and was determined by using a commercial code to find the optimal depth to maximize both the diffraction and reflected signal as shown in Fig. 2.

After gratings are created, they are filled with thin layer of the sample material using sputter deposition. For the Cu and V tests, 120 nm of Cu or V were deposited into the gratings groves to provide a reflective surface. The samples are then attached to the film side of the sample by applying epoxy on the circumference of the sample/window interface. Any small gaps that exist in this configuration will be closed by the longitudinal wave well before the shear wave arrives at the grating.

II. Initial experiments

Since the initial proposal included using graded density impactors (GDI) to control the loading or strain rate, the first experiments conducted were aimed to characterize the GDI's by impacting them against a hard elastic anvil. The GDI's are fabricated by joining many thin layers of material with increasing longitudinal impedance. The resultant longitudinal and transverse waves from the experiments are shown in Fig. 3. The longitudinal wave shows the expected ramp loading, and the transverse wave is a measurement of the strength of the layers in the GDI. While the rise in the longitudinal

wave can attributed to the change in the impedance of the materials (which are well characterized), the transverse wave is complicated by the varying strengths from all of the individual layers in the GDI. Nanoindentation was performed on the GDI impactors to get a sense of the varying strength of the individual layers, and the results are shown in Fig. 4. Since there appears to be a significant difference in strength between the different layers in the GDI impactor, it may make it more difficult to interpret the resulting transverse wave that is generating from this impactor.

III. Simulation development

Both 2-D and 3-D simulations capabilities to model these experiments were developed in both ARES and ALE3D hydrodynamic codes. The results were compared between the two codes to ensure consistency. ALE3D was the code used for most of the simulations due to its larger library of strength models.

The simulations are an invaluable tool in the design of the experiments and in interpreting the experimental results. In order to extract the strength from the experiments, simulations were performed with several strength models and parameters. The strength was then inferred from the simulation that best matched the experiment. While there might be questions as to the uniqueness of the answer, it was found that the simulations were very sensitive in matching the transverse wave data, and that even if different strength models were used, a similar strength was needed to reproduce the experimental data.

IV. Cu experiments

Once the GDI impactors were characterized, experiments were conducted on Cu because it is a well characterized material and has a good impedance match with sapphire. The results of an experiment on Cu with a graded density impactor are shown in Fig 5. The longitudinal wave shows the expected result that there is a gradual rise in the longitudinal wave. The transverse wave shows an initial large rise that cannot be predicted using the strength models. In addition, the transverse wave abruptly ends due to the longitudinal wave arriving at the back of the sapphire window, which causes an unexpected loss of the transverse signal.

Given this result it was decided at this point to concentrate on obtaining a larger and reproducible transverse signal by using a thicker sapphire window and a using a monolithic target, such as Ta10W, instead of the GDI impactors. The reasons for foregoing the use of the GDI's and instead concentrating on measurement and analysis of the shear waves were made for the following reasons:

1) The current impact velocities produced strain rates in the range of interest (10^4-10^5) without the need of GDI's.
2) Cost of GDI's (roughly $100k per set of 5) are prohibitively expensive.
3) The shear wave results with the GDI experiments were inconclusive and the GDI was possibly adding to the complication of the interpretation of the waves.
4) While an effort was made to create lower cost GDI's, the primary investigator for that effort left LLNL.

An experiment with a Ta10W impactor and a larger sapphire window is shown in Fig. 6. The yield stress extracted for this Cu is 180 MPa under a pressure of 4 GPa. The results of this experiment are summarized in a proceedings document to the Society of Experimental Mechanics Conference (LLNL-PROC-426022). While the shear wave in this experiment can be matched using a strength model, there is considerable amount of noise in the shear wave measurement. Since the Cu has relatively low strength, the transverse velocity is low, meaning that the TDI measures only a few fringes during the duration of the test. With only a few fringes, the noise associated with the measurement increases, making it difficult to reproduce the results.

V. Vanadium experiments

Experiments on V were also conducted utilizing this technique. Since V is a stronger material it should produce more fringes in the TDI data which should produce more reproducible results. A summary of the V results including our effort to extract the strength using the strength models is contained in a paper published in the proceedings of the APS conference on Shock Compression of Condensed Matter [6] (LLNL-PROC-417930).

Exit Plan

The experimental technique developed in this LDRD will provide strength data on materials at high strain rates and high pressures. Since WCI's "Dynamics of Metals Program" is interested in understanding the strength of materials under dynamic conditions, they are applying this technique to materials of programmatic interest. There is currently a funded project that utilizes this technique to explore the role of the shear wave on the phase transformation in materials. In addition, the technique will be used to measure the strength near the transformation.

Conclusions

Under this LDRD, an oblique-impact with windowed interferometry technique has been developed to measure the strength of materials under conditions of combined high strain rates and high pressures. The technique has been used to measure the strength of polycrystalline Cu and v, and a description of the technique is contained in a proceedings paper. The V data has also been used to compare with the multiscale models developed in the ASC program. This technique is currently being applied to materials of programmatic interest.

A summary of the publications and presentations under this LDRD are as follows:

Presentations

2008 TMS Annual Conference, New Orleans, LA (March 2008) LLNL-PRES-405229.

2009 TMS Annual Conference, San Francisco, CA (March 2009) LLNL-PRES-410970.

2009 APS Conference on Shock Compression of Condensed Matter, Nashville, TN (June 2009) LLNL-PRES-414194.

Publications

2009 APS Conference on Shock Compression of Condensed Matter Proceedings. LLNL-PROC-417930.

2010 Proceedings of the Annual Conference of the Society for Experimental Mechanics LLNL-PROC-426022.

Acknowledgements

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3. R.J. Clifton and R.W. Klopp, ASM Handbook 9th ed., **8**, p230 (1985).
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5. Kim, K.S. st. al, J. of Applied Physics 48, p.4132, (1977).
6. J.N. Florando et. al, Shock Comp. of Cond. Matt., 1195, p. 723 (2010).

Figures

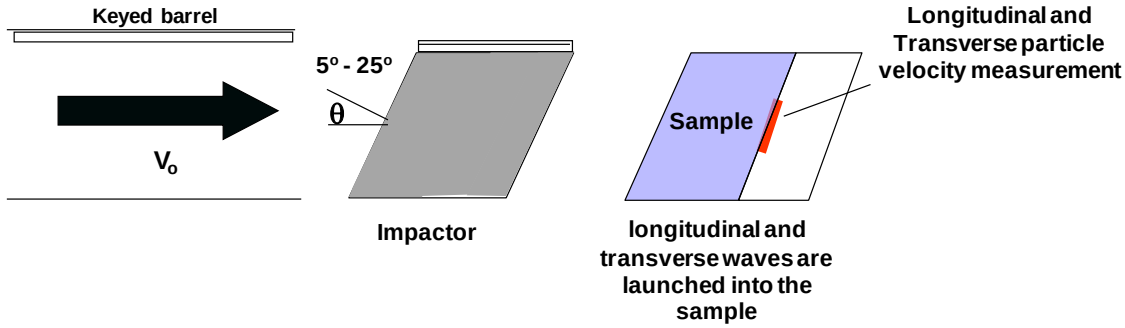

Figure 1- Schematic of the oblique-impact compression experiment

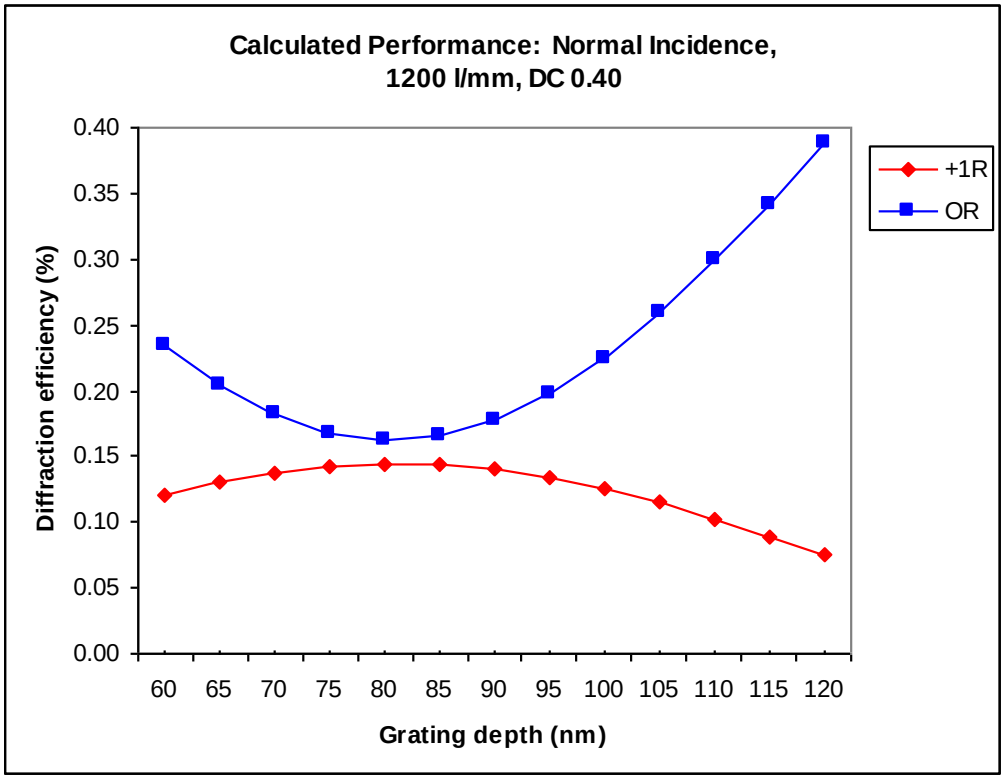

Figure 2- Calculation results of the efficiency of the reflected light with respect to depth of the gratings. The diffraction signal (red) is maximized near 85 nm.

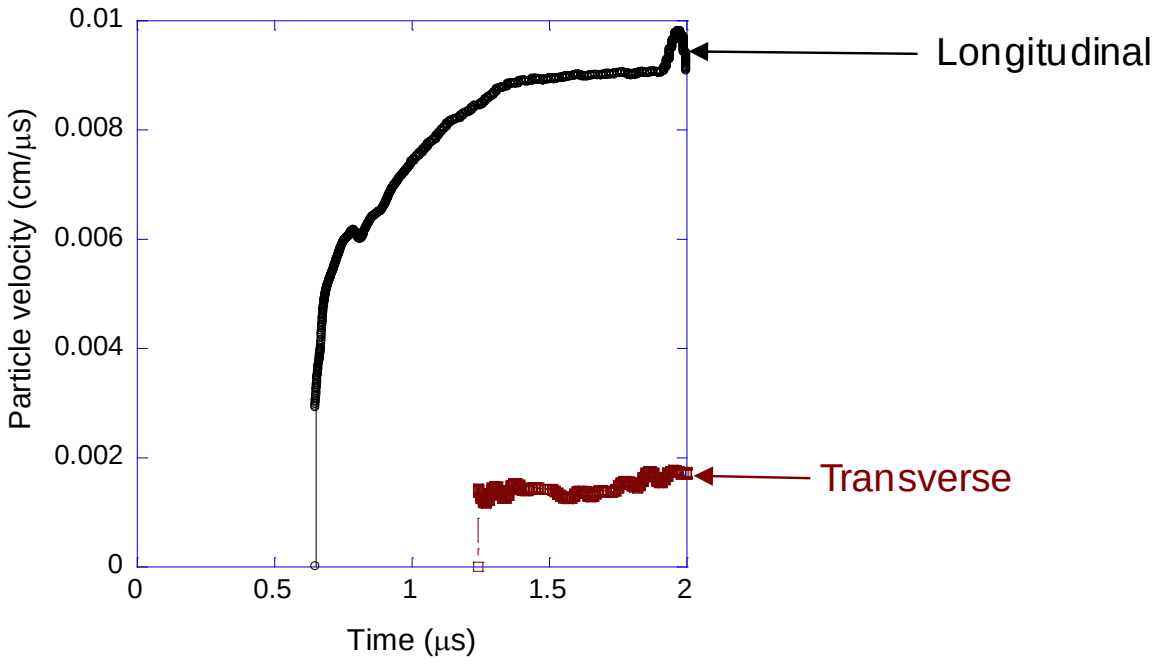

Figure 3- Longitudinal and transverse waves from the impact of the graded density impactor (GDI) against a steel anvil.

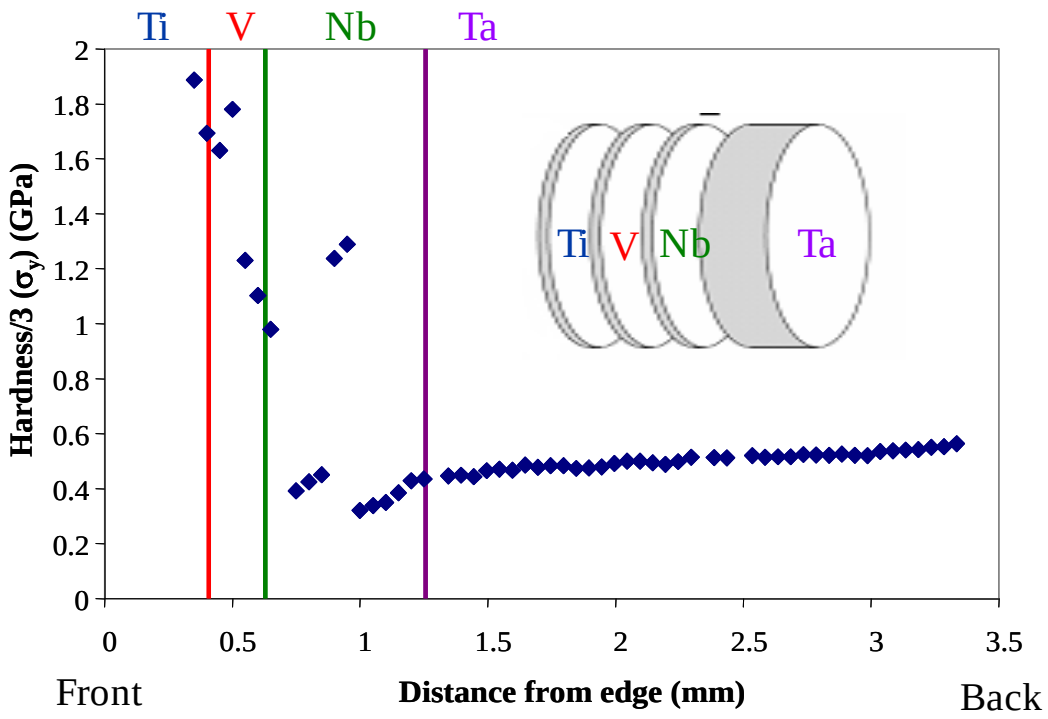

Figure 4- Nanoindentation results on the different layers in a GDI. The results show a large variation of yield strengths within the impactor.

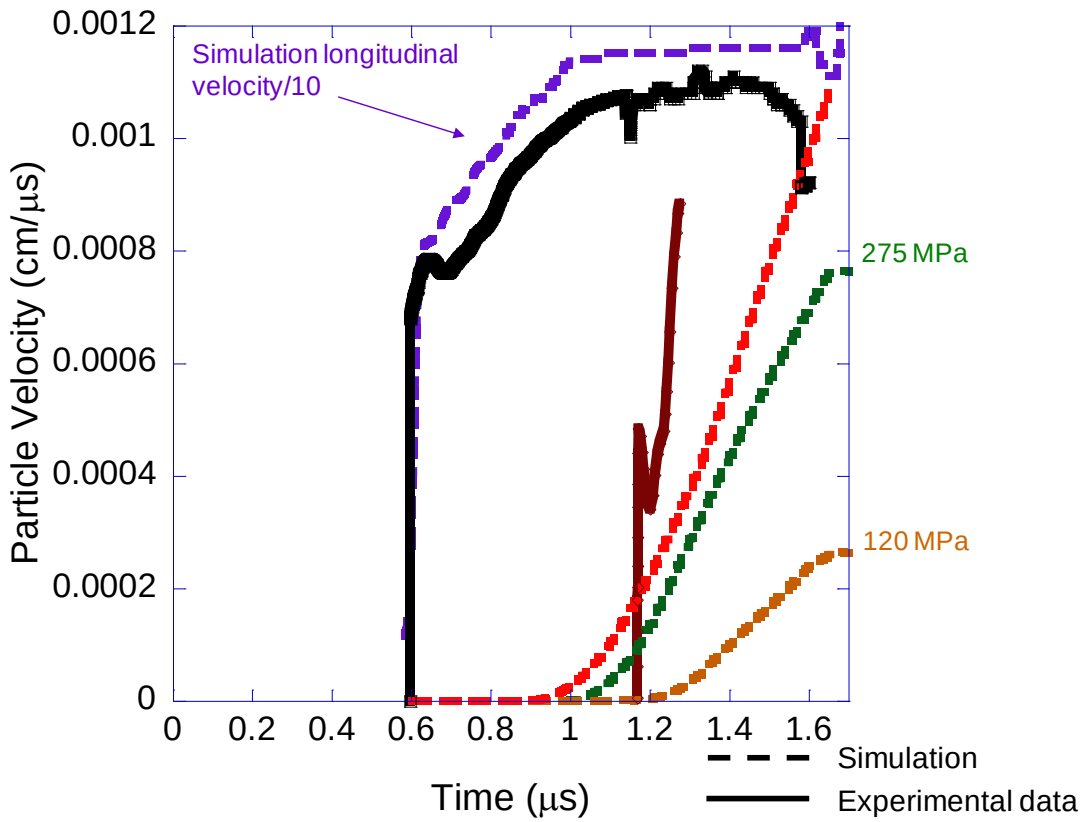

Figure 5- Experimental results with a GDI impactor and a Cu sample. The sharp rise in the transverse wave cannot be matched using the current strength model (dashed lines)

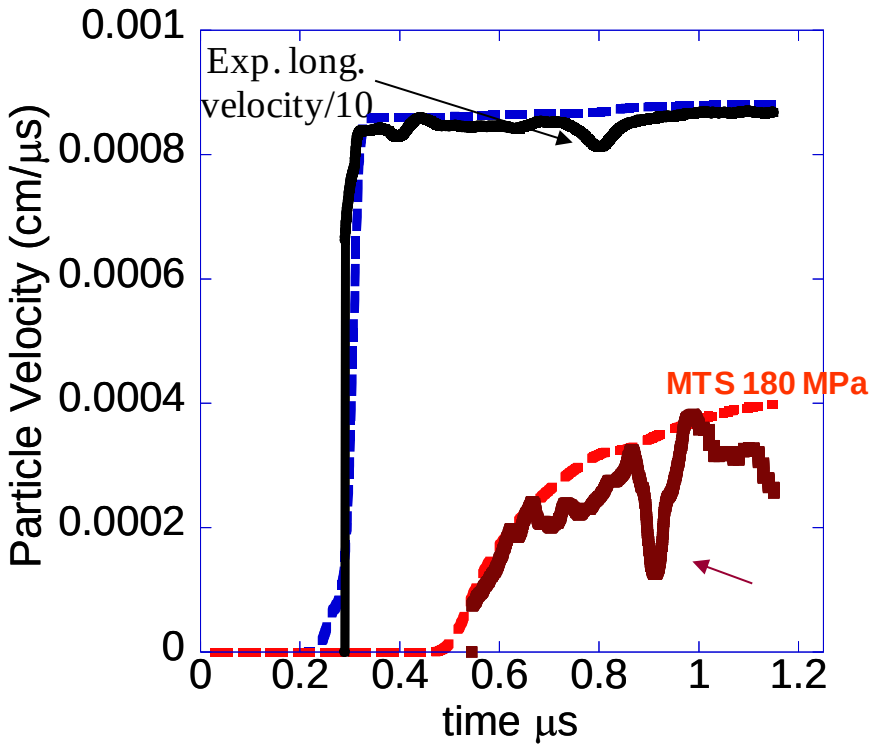

Figure 6- Comparison of experimental and simulation particle velocities on a Cu sample. The experimental transverse wave (solid line), can be matched using with a predicted yield stress of 180 MPa (simulation dashed lines) from the MTS model.