Pressure pulse shape effects on spall determined through direct numerical simulation

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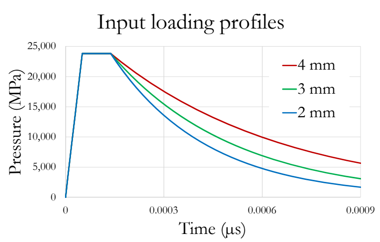
Introduction

Modern material failure studies rely on various mathematical models to determine failure patterns in ductile metals. A simple model for ductile material failure was proposed by A. L. Gurson (Gurson, 1977). Since the model's introduction, it has served as a basis for many other failure models. However, the Gurson model predicts different failure patterns than experiments. The intent of this research was to determine corollary effects between pressure loading profiles on a copper plate and failure evolution. The correlations were then compared to the Gurson model, providing insight regarding the locations where the model's inaccuracies arise. Through the use of finite element analysis on High Performance Computers (HPC's), ductile material failure was simulated directly and studied to make improvements to the Gurson Model. The full models were impossible to use in full armor system simulations as they require thousands of computer processor hours for small scale simulations. Improvements to the Gurson model will enhance the predictive capability of full system simulations used by Army Research Laboratory (ARL). This study assumes accuracy of the current full models.

Materials and Methods

This study utilized Arbitrary Lagrangian-Eulerian 3D Multi-Physics Code (ALE3D) to model failure in a 0.1 mm square representative cross section of a 2 mm thick copper plate. The modeled region was populated with 4762 void nucleating particles, each spherical, with a radius of 1 µm. The square surface of the copper was loaded with a dynamic pressure profile as shown below. Since the leading edge of a pressure front decays as the front propagates through material, a plateau at peak pressure was added to ensure that the peak pressure of the front was held constant with each simulation. The plateau has entirely decayed as the wave front reaches the rear free surface. The standard 3 mm curve was modified to produce five unique pressure decay rates, three are shown below.

The loading profile and material properties were input into ALE3D and run on 768 processors for 42.6 hours on HPC's Haise and Thunder. State files were saved every 200 ns for post-processing in VisIt software. Pressure, stress, strain rate, and volumetric void fraction were averaged over 20 µm lengths of the material.



Graph 1 (above): The three primary pressure loading profiles used in the simulations.

Materials and Methods (cont.)

These values were compared against Gurson's 1977 Yield function for simple flow field in spherical geometry as shown below.

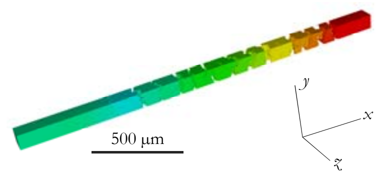
$$\phi = \left(\frac{\sigma_{vm}}{\bar{\sigma}}\right) + 2f\cosh\left(-\frac{3P}{2\bar{\sigma}}\right) - (1+f^2)$$

Equation 1 (above): The equation from which the yield surface and flow potential curves are derived.

The peak stress and strain rates of the different simulations at each time state are analyzed for indicators of failure. The failure patterns of each simulation were visually analyzed to determine spall plane similarities between simulations.

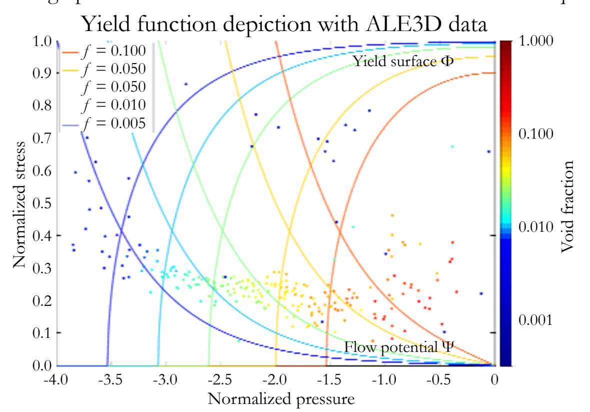
Results

Figure 1 (right): The specimen from the 3mm simulation at 1.2 µs showing multiple spall planes. These spall planes were constant across all simulations. The color of the material indicates the velocity, the red moving faster in the *x*-direction than the blue. All of the material is moving in the positive *x*-direction.



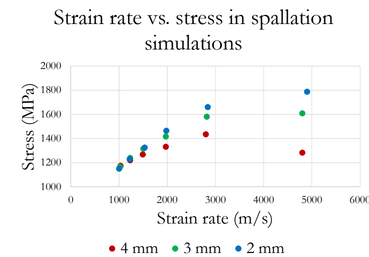
The failure patterns for each specimen were similar across simulations. There was one location which had only incipient spall in the 4 mm and 3 mm samples but exhibited complete spall in the 2 mm sample.

Equation 1 provides both a yield surface and a flow potential equation. In this instance the flow potential is the derivative of the yield function. These equations are plotted in graph 2 with five volumetric void fractions filled into the equation.



Graph 2 (above): Effective stress with pressure as a function of void fraction. The color of the curve or data point indicates the void fraction of the material with a value of 1 being entirely void, and a value of 0 having no void. The black line running through the middle is the predicted intersection point for the equations. It is at $1-\sqrt{2}$.

Results (cont.)



Graph 3 (left): The peak stress as a function of peak strain rate at various time steps. A positive correlation indicates that the material has begun spalling, while a negative correlation indicates that the material has resisted failure. Only the 4 mm simulation indicates time states after the wave reaches the free surface with no failure.

Conclusion

The purpose of this study was to determine which parts of the 1977 Gurson model need improvement to better match actual material failure. The study also served to discover commonalities between simulations with different ramp-release rates. The notion that spall planes are functions of the defect distribution of a specimen is supported as indicated by the common spall planes between the simulations. The scab length at the free surface was found to be primarily a function of decay rate where a quicker decay lead to a shorter scab length. It should also be noted that the plateau length was directly related to the scab length as found in other similar simulations run during the course of this study.

There is a relationship between pressure, stress, and volumetric void fraction that is common among the various pressure decays and opening rates as demonstrated by the common trend of data in Graph 2. The standard models assume that flow potential is the derivative of yield surface. The flow potential currently appears farther off of the data than the yield surface does. This supports the argument for use of a nonassociative flow potential. Determining a new flow potential is left for further investigation.

There are likely inertial effects contained within the void growth which are not yet known. Preliminary investigation has indicated that there is non-zero stress deriving from inertial effects, although the full extent is not yet understood and serves as an area of further study. The expectation is that inertial affects are significant at these strain rates.

References

Gurson, A. L. (1977). Continuum theory of ductile rupture by void nucleation and growth: Part I yield criteria and flow rules for porous ductile media. *Journal of Engineering Materials and Technology, 99*(1), 2. doi:10.1115/1.3443401