Deformation Criterion and Residual Life of Low Carbon Structural Steel Subjected to Blast Loading

W. Visser[1], Y. Sun[1], O. Gregory[2], H. Ghonem[1]

[1]Department of Mechanical Engineering, [2]Department of Chemical Engineering, University of Rhode Island , Kingston, RI, 02881, USA

Abstract

Effects of impact loading on microstructure of low carbon steel have been studied. Shock loading tests have been carried out on specimens using a gas gun with projectile velocities up to 500 m/sec. A Johnson-Cook constitutive model was employed to simulate the material behavior and obtain the particle velocity at the impact surface. This was coupled with an analytical approach to determine the twin volume fraction as a function of impact load. Tensile tests of post-impact specimens revealed an increase in yield and UTS, and a decrease in the hardening and strain energy as a function of impact load. Serrated flow characteristics of stress-strain curves suggest microstructure instability and twin-dislocation interactions.

Relevance

An integrated multidisciplinary program to develop a fundamental understanding of the mechanisms of deformation response of structural steel subjected to blast loading. Such understanding will be used to 1) identify the force limit for blast mitigation designs suitable for resistance to single and multiple blasts; 2) provide the material dynamic deformation flow characteristics required for the microstructure development of a blast resistant reinforcing metal phase.

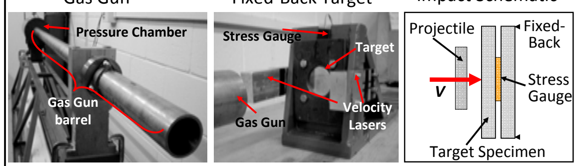
Accomplishments Through Current Year

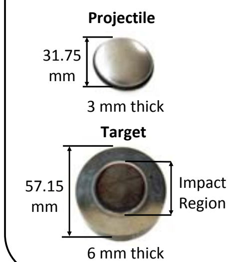
1) A series of blast experiments was carried out to establish a blast deformation criterion for low carbon structural steel in terms of twin volume fraction (TVF) as a function of blast load.
2) A combined numerical/analytical model capable of determining TVF as a function of impact stress has been developed.
3) Post-blast residual life has been measured experimentally and correlated with TVF as a function of impact stress.

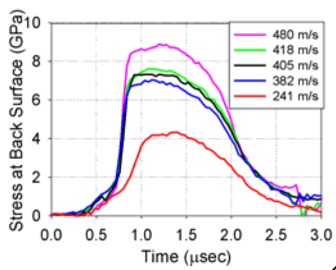
Technical Approach

- **Objective:** Establish a quantitative deformation criterion for blast loaded low carbon steel in terms of twin volume fraction and use the criterion to asses the residual life as a function of impact loading.
- **Approach:** A physically based deformation criterion developed by integrating three studies: **i-** Experimental program to determine twin volume fraction as a function of impact load, **ii-** A mechanistic based deformation criterion associated with high loading rates, and, **iii-** An experimental methodology to determine post blast residual life in terms of ductility reduction and available fracture energy.

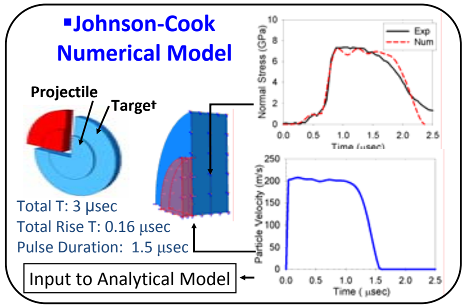
Experimental Plate Impacts







Johnson-Cook Numerical Model



Analytical Model

Conservation of Mass & Momentum Equations

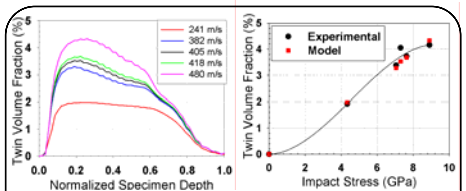
$$\frac{\rho_0}{\rho^2}\frac{\partial \rho}{\partial t}+\frac{\partial u}{\partial X}=0,\quad \rho_0\frac{\partial u}{\partial t}+\frac{\partial \sigma}{\partial X}=0$$

ρ_0 - initial density; ρ- current density; u – particle velocity; σ- current stress

Volume Fraction of Twins and Twin Growth Rate

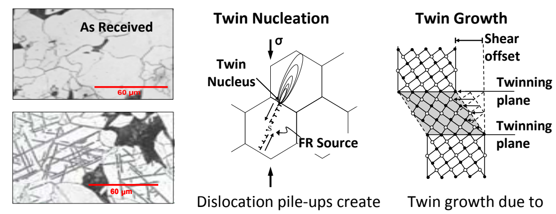
$$\alpha=\left(\alpha_0^{1/m}+\frac{1}{t_c}\int_0^t v(\tau)dt\right)^m,\qquad v(\tau)=\begin{cases}\tau/\tau_{tw}-1, & \tau\ge\tau_{tw}\\ 0, & \tau<\tau_{tw}\end{cases}$$

τ_{tw} - shear stress for twinning; m - twin growth parameter



Coupled model results of TVF are validated by comparison with Experimental results

Post-Impact Microstructure (Twin Formation)

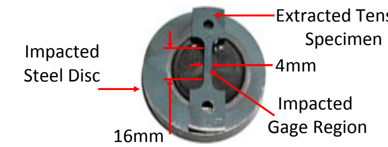


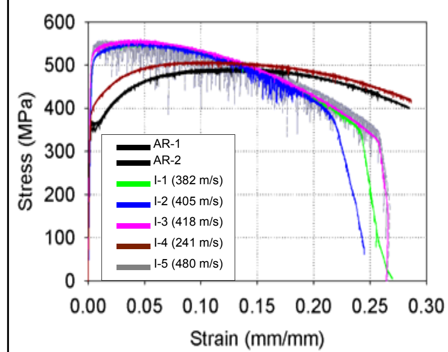
Velocity: 480 m/s
Peak Stress: 8.9 GPa
Twin VF: 4.4 %

Dislocation pile-ups create stress concentrations at GB result in twinning in neighboring grain

Twin growth due to progressive directional shear of atoms within twinning planes

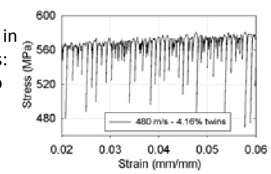
Post-Impact Residual Life



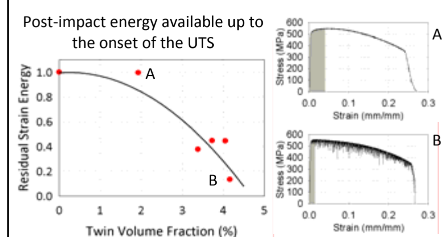


Post-Impact yield & UTS increase with impact stress

Type-C Serrations in post-Impact tests: instability due to twin-dislocation interactions



Post-impact energy available up to the onset of the UTS



Residual strain energy decreases with TVF

Future Work

Design and construct a new gas gun capable of extending the impact load experiments to a range beyond that of conventional TNT blast energy in order to examine deformation mechanisms and residual life corresponding to single and multiple severe blast loading of structural steel and cast iron materials as well as new structural alloys capable of absorbing high energy impact loads.

Publications

W. Visser, Y. Sun, O. Gregory, and H. Ghonem, **Deformation Criterion for Blast Loading in Low Carbon Steel**, *Int. J. Material Science and Eng.*, December 2010

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