Deformation quantification in steel plates following impact at a velocity of 2.6 km/s

J D Hogan\textsuperscript{1}, R J Rogers\textsuperscript{2} and J G Spray\textsuperscript{3}

\textsuperscript{1} Hopkins Extreme Materials Institute, The Johns Hopkins University, Baltimore, Maryland 21218, USA
\textsuperscript{2} Department of Mechanical Engineering, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada
\textsuperscript{3} Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada

E-mail: jd.hogan@jhu.edu

Abstract. Micro-scale damage processes during hypervelocity impact into steel targets have been evaluated using image analysis and electron backscatter diffraction techniques. The targets were 50 mm thick and the impact velocity was 2.6 km/s. Image analysis of the pearlite grains shows localized pockets of strain upwards of 55% occurring at depths associated with penetrator geometry. Electron backscatter diffraction (EBSD) shows that inter-granular ferrite grain orientations become less uniform, with deformation being primarily two- and three-dimensional. Mobilized micro-ferrite textures aligned in the shot direction were also identified with EBSD. These are formed as a result of significant plastic deformation and frictional shearing of the small volume of material.

1. Introduction

The characterization of the dynamic response of ductile materials has been primarily accomplished through mechanical property testing \cite{1}, as well as under ballistic testing \cite{2} and orthogonal machining \cite{3}. This work has provided insight into the strain rate effect on material properties \cite{4} and bulk failure processes (e.g., shear band formation in nitrogen alloyed steels \cite{4}), and has led to improvements in continuum material model development for numerical simulation.

Further attention to micro-structural aspects of deformation is needed in order to develop the next level of mechanism-based constitutive equations \cite{5}. The objective of this work is to quantify micro-structural aspects of extreme deformation during hypervelocity impacts in 50 mm thick steel plates. Image analysis and electron backscatter diffraction methods are used to quantify the behaviour of the pearlite and ferrite phases in the steel.

2. Experimental Setup and Sample Preparation

An electromagnetic railgun at the French-German Research Institute of Saint-Louis, France was used as the launch platform for an impact velocity of 2,660 m/s. The projectiles were made of a glass fibre reinforced composite with a mass of 600 g (figure 1b), within which are embedded four pairs of copper brushes and four pairs of copper rods (figure 1b). Copper brushes are used to launch the projectile via the Lorentz force, while rods are placed to implement damage to
the target. Copper pairs are spaced at 15 mm apart. The target material was St 37 steel, a German convention for a carbon steel with a tensile strength of 370 kip/mm$^2$ (yield strength of 235 MPa). The targets had dimensions of 330 mm x 330 mm and were 50 mm thick.

The steel plates were sectioned and four regions were removed (highlighted as rectangles in figure 1a). The impact direction is noted. The specimens were cold mounted and polished using 9 $\mu$m, 6 $\mu$m, and 3 $\mu$m disks and diamond suspension compounds for approximately 5 minutes at each size. A sub-micron silica polish was used in the final stage, and the samples were then etched using a 4% Nital etch. An Axiovision microscope with Zeiss Imager (resolution of approximately 2 $\mu$m per pixel) with an automated stage was used to image the steel microstructure. Secondary electron (SE) images of the steel sample were obtained using an Hitachi SU-70 analytical Field Emission Scanning Electron Microscope (FESEM) system equipped with an Oxford Instruments electron backscatter detector.

3. Image Analysis Applied to Undeformed Sample

Image analysis software written in Matlab [6] was used to convert the image to black and white and to extract size and orientation features of the well-defined pearlite grains. Shown in figure 1 is the image analysis process for an undeformed region highlighted in figure 1a (labelled sample 4-186). A 10 by 10 group of images is taken and stitched. This is repeated until the entire sectioned sample is documented (figure 1c). Note the near-horizontal and near-vertical boundaries between stitched images in the figure 1c.

Shown in figure 1d (left) is a representation of the pixel resolution of the steel microstructure. Each pixel corresponds to 2 $\mu$m. The dark ellipsoids are the pearlite grains and the lighter regions comprise of ferrite grains. The microstructure has a preferred orientation (horizontal) as a result of the rolling direction, with grain planes being parallel to the impact surface. The image is converted to black and white (figure 1d (right)), then gridded by 500 $\mu$m by 500 $\mu$m and the median pearlite grain orientation and size tabulated. Plotting contours of the results at each grid centre (figure 1e and f) allows results to be better visualized and trends extracted.

Next, the variation of grain size in the undeformed sample is examined. Shown in figure 1e is the contour plot of the ratio of the major axis dimension (taken as the largest spanning dimension of a pearlite grain) to the median value of the entire undeformed sample ($\Delta L/L_0 = (L_i - L_0)/L_0$, where $L_i$ is the median value of the gridded region and $L_0$ is the median value of the entire undeformed sample and equal to 23 $\mu$m). For an undeformed sample, $\Delta L/L_0$ represents the variation in grain size, while for a deformed sample, this is a measure of residual plastic strain. For the undeformed sample, values commonly range between -2% and 2%, with regional extremities of -5% to 8% (both are indicated in figure 1d).

Show in figure 1f is the contour map of gridded median orientations for the undeformed sample. The orientation co-ordinate system is defined in the top left, with 0° being parallel with the impact surface and the inherent micro-structure rolling orientation, and positive orientation taken in convention as counter-clockwise. Note that orientations at 45° also includes those at 225° (180° + 45°). Similarly, angles at -45° also includes those at 135° (180° - 45°). Little orientation variation exists, with median orientations between -1° and 3° for the undeformed sample (figure 1f). Combined, a baseline for grain variation and strain will allow an improved interpretation of the deformed areas.

4. Strain and Grain Orientation of Highly Deformed Regions

A strain contour map for the 2,660 m/s impact is shown in figure 2a. The upper and bottom lips of the sample are mainly uniform at 35% strain, with pockets of 45% at the bottom surface. Local pockets of 45%, 55% and 30% are observed below the impact surface (right surface). These occur at depths of 15, 30 and 60 mm from the top surface, corresponding to the spacing
Figure 1. Image analysis methods for determining pearlite grain size and orientation: (a) photograph of a steel plate cross-section for impact velocity of 1,350 m/s with undeformed region highlighted, (b) composite projectile with four pairs of copper brushes and four pairs of embedded copper rods, (c) compilation of stitched microscope images of undeformed region with boundaries left for visualization, (d) magnified region to demonstrate pixel resolution of dark pearlite grains (left) and resulting black and white image (pearlite grains are white) with centres of gridded regions used to determine median size and orientation, (e) contour map of gridded median major axis strain values, and (f) grain orientation contour of undeformed sample with coordinate system. Note the impact direction in (a) is vertical and the cold rolling in (c) is horizontal.

of the copper rods/brushes in the projectile. The remaining bulk of the sample is strained to approximately 10%.

Also highlighted in figure 2a are regions I to III, which show deformation in the pearlite grains. The pearlite grains are initially lighter than the darker ferrite grains in I. The pearlite grains become increasingly aligned in the shot direction (from horizontal to a vertical orientation) and the colour becomes more uniform closer to the impact edge (from region I to III). This suggests that the ferrite and pearlite grains are blending at the fine scale through plastic deformation. The majority of the pearlite grains become more elongated as well, with the exception of those which are circular (observable in III). The preservation of circular pearlite grains, and the elongation of the others, highlights characteristics of shock deformation and the importance of initial grain shape in multi-phase material modelling.

Shown in figure 2b is the orientation contour map for the deformed 2,660 m/s sample. Orientations alternate between large negative and positive angles along the impact edge. The pockets of large positive angles are spatially correlated with the regions of large plastic strain in figure 2a. The bottom surface orientations are less complicated than their strained counterparts. A microscope image of region i highlights a rapid change of positive to negative orientation of a small region (2.5 mm). This has implications for numerical modelling, where an element size selection of 0.25 mm may be suitable to capture pearlite grain deformation and orientation processes.
Figure 2. Image analysis results for a deformed region for an impact velocity of 2,660 m/s: (a) strain contour map with SEM images of regions I to III: pearlite orientation, size and grayscale colour. (b) Orientation contour map with electron microscope image of deformed region i (near top). Note the scale.

5. Electron Back Scatter Diffraction Methods and Results

Electron back scatter diffraction (EBSD) techniques are used to investigate localized ferrite grain deformation by characterizing its microstructure and crystallographic orientation. EBSD patterns are obtained by focusing the electron beam on a crystalline specimen. Diffracted electrons produce patterns, which are recorded by software. An orientation map (inverse pole figure) of an undeformed region is shown in figure 3b. Dark green regions correspond to unmapped pearlite grains. The corresponding SEM image is shown in figure 3a. Crystallographic orientations of the cubic ferrite structure is defined, where 001 (red) corresponds to crystallographic orientations aligned in the shot direction. Boundaries are placed for misorientation angles of more than 20° between adjacent measurements. Grain orientations for the undeformed sample are primarily uniform (i.e., a single colour) and have no preferred orientation (i.e., there is no spatial distribution pattern to the colours). The grain boundaries are well defined.

An orientation map for a deformed region of the 2,660 m/s sample is shown in figure 3d. The SEM image of the region is shown in figure 3c. Grains are multi-coloured, indicating
Figure 3. (a) Scanning electron image and (b) crystal orientation map of undeformed region. (c) Scanning electron image, (d) orientation map for deformed 2,660 m/s sample, with (e) evidence of ferrite mobilization. Orientations colour schemes for the cubic ferrite structure are defined and impact directions noted.

inter-granular twisting, and appear to have no preferred global orientation (figure 3d). The deformation is primarily two- (green in colour) and three-dimensional (blue in colour). Boundaries, which have misorientation angles of at least 20°, are not well-defined between adjacent grains, suggesting adjacent grains deform together, rather than distinctly. Grain boundaries may be molded together.

Also highlighted in figure 3d is a region of mobilized ferrite. Individual ferrite-rich zones are approximately 0.4 μm in size, crystalline (as it can be defined by EBSD), and aligned in the shot direction (i.e., 001). Temperatures approaching 1400°C [7] are needed to mobilize ferrite. Significant plastic deformation and frictional shearing of the small volume of material are the likely mechanisms for high temperature generation. These temperatures are realistic in large plastic deformation processes [8].

6. Concluding Remarks
Micro-deformation processes during impacts into 50 mm thick steel plates have been examined for an impact velocity of 2,660 m/s. Pearlite grains become increasingly aligned in the shot direction and become more elongated closer to the impact edge. Pearlite and ferrite grains
were observed to become more uniform in colour, suggesting that their crystal structures are becoming less distinguishable. Correlated pockets of local strain of 45%, 55% and 30% occurring at spacings of the copper rods embedded in the projectile were observed to be correlated with positive orientation angles (opposite to impact direction).

Electron back scatter diffraction has revealed that grain orientations become less uniform and deformation is primarily two- and three-dimensional as the penetration cavity is approached. EBSD was also used to identify crystalline micro-ferrite zones aligned in the shot direction. These are formed from significant plastic deformation and frictional shearing of small volumes of material.

This work enables a better understanding of deformation mechanisms during hypervelocity impact in metals. This is important in the development of high rate mechanistic material models. Future work will include expanding results for intermediate impact velocities and refining EBSD measurements to better understand superplastic features.

Acknowledgments
This work is partially funded through the Canadian Natural Science and Engineering Research Council PGS D scholarship and a student scholarship for the APS-SCCM/AIRAPT conference.

References
[1] Lambert D E and Ross C A 2000 Int J Impact Eng 24 985 – 998
[2] Awerbuch J and Bodner S 1974 Int J Solids Struct 10 671 – 684
[3] Merchant M 1945 J Appl Phys 16 267–275
[4] Lach E, Anderson C, Schirm V and Koerber G 2008 Int J Impact Eng 35 1625 – 1630
[5] Lesuer D, Syn C, Whittenberger J, Carsi M, Ruano O and Sherby O 2001 Mater Sci Eng: A 317 101 – 107
[6] 2013 Matlab user manual Simulink
[7] Kenkmann T, Trullenque G, Deutsch A, Hecht L, Ebert M, Salge T, Schafer F and Thoma K 2013 Meteorit Planet Sc 48 150–164
[8] Lewandowski J J and Greer A L 2006 Nat Mater 5 15–18