HIGH STRAIN RATE STUDIES OF ARMOR METALS

Ghaznafar Nazimuddin
Department of Mechanical Engineering
University of Manitoba
Winnipeg, Manitoba, Canada
umnazimu@cc.umanitoba.ca

Ioannis Polyzois
Department of Mechanical Engineering
University of Manitoba
Winnipeg, Manitoba, Canada
umpolyzo@cc.umanitoba.ca

M. Bolduc
Department of National Defense of Canada,
DRDC,
Valcartier, Quebec, Canada

M. N. Bassim, P. Eng
Department of Mechanical Engineering
University of Manitoba
Winnipeg, Manitoba, Canada
bassim@cc.umanitoba.ca

ABSTRACT

This paper investigates the dynamic stress strain response of armor metals subjected to high strain rate loading and large strains. These armor metals, supplied by the Canadian Department of National Defense (CDND), namely maraging steel 300, high hardness armor (HHA) and aluminum 5083-H131 alloy, are used in armor plating for military vehicles. Specimens were tested in compression using a Direct Impact Split Hopkinson Pressure Bar (SHPB) at multiple impact momenta. Dynamic stress strain response data are collected to study the plastic deformation behavior. Specimens are observed under optical microscopy, Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) to study the occurrence of adiabatic shear bands which are the primary source of shear failure under these conditions. The effects of impact momentum on the dynamic response and adiabatic shear failure are analyzed to evaluate the materials capability of withstanding conditions similar to those observed in the field.

INTRODUCTION

High strain rate investigations of materials using the Split Hopkinson Bar deal with strain rates in the range of 10^3 s^{-1} to 10^4 s^{-1}. The strains and strain rates are large enough to cause plastic deformation and subsequent fracture that is different from quasi-static loading conditions. Plastic deformation of many metallic materials at high strain rate produces localised shear strain within a narrow region in a material. These regions of extreme strain localization are known as Adiabatic Shear Bands (ASBs). The presence of ASBs is considered undesirable as they are microstructural defects that lead to failure at high loading rates. ASBs have been identified in a variety of materials including steel and aluminum alloys that are commonly used in service for many engineering applications.

During high strain rate plastic deformation at large strains, the heat generated within the metal is retained in narrow localized regions. The term adiabatic heating is referred to the entrapment of heat that leads to a significant rise in temperature and causes mechanical instability in the microstructure. The thermal softening effect in the microstructure leads to stress collapse in the material and contributes to extreme strain localization in the narrow regions. These narrow bands are referred to as either deformed bands or white-etching bands (transformed bands). The appearance of deformed bands consists of highly distorted and elongated grains in the microstructure than the rest of the bulk material. The white-etching bands when viewed under an optical microscope appear as a fine and narrow white region. The characteristics of ASBs are generally associated with increased hardness than the surrounding material and thus a material becomes brittle at high loading rates.

High strain rate loading conditions are often encountered in high velocity projectile impact and plate used for armour protection in military vehicles. It is very important to make design consideration for materials used in such tough service conditions. There are many factors that affect the formation of ASB that includes strain rate, hardness, microstructure and presence of imperfections such as precipitates and inclusion [1]. Therefore, understanding these material variables is crucial to better mechanical design of materials used in military applications.

This investigation focuses on three armour metals, namely maraging steel 300, high hardness armor (HHA) and aluminum 5083-H131 alloy—provided by the Department of National Defense, Defense Research and Development Canada (DRDC) Valcartier, to evaluate the dynamic mechanical response at high strain rate loading. This paper investigates the behavior of these materials at high strain rate loading conditions taking into account the factors that contribute to the formation of ASB and subsequent failure.

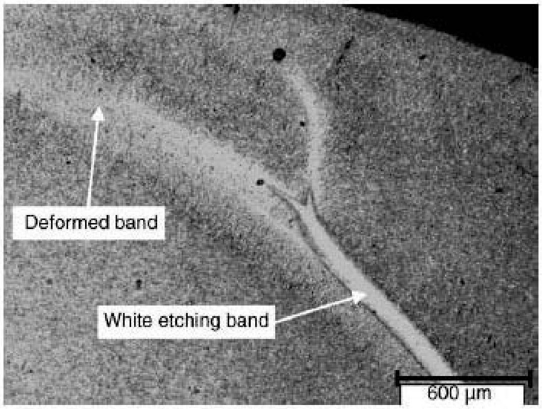

Fig. 1. Optical micrograph showing a white etching (transformed) band and a deformed band in the microstructure of a steel specimen after impact **[2]**.

EXPERIMENTAL PROCEDURES

The presence of ASBs in a material is undesirable because they act as preferential sites for failure, either by ductile void nucleation followed by growth and coalescence, or by crack growth. Understanding the behaviour of the microstructure is important in high strain rate studies to better design armour applications.

In this investigation, specimens of maraging steel 300, high hardness armour, and aluminum 5083-H131 alloy were tested under impact at various momentums using the Direct Impact Split Hopkinson Pressure Bar built at the University of Manitoba. This apparatus is a modification of the traditional two bar system developed from the Bertram Hopkinson Bar by Kolsky in 1949, removing one bar and allowing direct impact of the projectile onto the specimen, achieving greater strain rate deformation (10^3-10^4 s^{-1}) at larger strains.

Fig. 2. Direct Impact Split Hopkinson Pressure Bar at The University of Manitoba

Cylindrical specimens machined for Split Hopkinson Pressure Bar Impact testing were 10.5 mm in length and 9.5 mm in diameter. Maximum strain and strain rate are achieved with these dimensions during impact loading, based on earlier work by Bassim [3].

The range of firing pressure for maraging steel 300 was 100 – 200 kPa, for HHA was 100 – 200 kPa and for Aluminum 5083 – H131 Alloy was 60 – 150 kPa. The high strain rate investigation of dynamic mechanical loading has a direct relation between the firing pressure and the response through the impact momentum of the projectile. The relationship between firing pressure and impact momentum of the projectile were based on previous experiments conducted at the University of Manitoba [4]. All SHPB experiments were conducted at atmospheric pressure and room temperature.

MICROSTRUCTURAL INVESTIGATION USING OPTICAL MICROSCOPY

All specimens prepared for microstructural examination were studied using the Zeiss optical microscope with Clemex Vision Analyzer. Specimens from impact experiments were thoroughly examined for defects in microstructure such as micro-cracks, shear bands and cracks. A detailed specimen examination consisted of imaging a section of the microstructure at a magnification of 50x to 200x or 500x depending on the resolution and clarity of the image. Most valuable information such as deformation, reorientation of grains, and presence of shear bands were evaluated using the optical microscopy technique.

MICROSTRUCTURAL INVESTIGATION USING ATOMIC FORCE MICROSCOPY

The Atomic Force Microscopy (AFM) is an advanced technique to produce high resolution and three-dimensional images from examining the surface of a material. It is performed by the Dimension 3100 Scanning Probe Microscope by scanning a sharp tip over the specimen surface [5]. The process involves the tip (flexible cantilever) mounted on one end of a cylindrical piezo-electric tube which in turn is mounted near the top of the microscope. The piezo-electric tube contains X, Y and Z electrodes to detect the applied voltages. The X and Y electrodes on detecting the voltage, deflect the tube horizontally while the Z electrode upon the applied voltage detects the vertical height of the tip. There is a stepper motor attached to a lead screw that moves the specimen and a separate motor drive to control the height of the microscope and tip with respect to the material surface.

A TappingMode AFM with etched silicon cantilever substrates was utilized to perform the scans. When the cantilever comes near the material surface, the piezo stack continues to excite the cantilever substrate with the same energy and causes the tip to deflect on contact with the surface.

The reflected laser beam provides information such as height and characteristic of the material in a specified region. Scans are performed by selecting a region (inside or outside the shear band) 100µm x 100µm and optimizing the set point amplitude that increases the force at which the scan tip performs the TappingMode. The scan rate is also optimized so that it does not skip a region due to uneven surface texture. AFM scans were performed with both etched and unetched specimen (Mars 300) to study the characteristic of the microstructure. Due to the size of the tip, it was not possible to perform AFM scans on a deformed banded region (HHA and Al 5083 specimens).

EXPERIMENTAL RESULTS AND DISCUSSION

Dynamic impact tests at high strain rates on the three armour metals were performed. Stress-strain data was collected and compared. Deformation behaviour of the specimens as well as strain localization and occurrence of ASBs were investigated using optical, atomic force, and scanning electron microscopy. Results from the mechanical tests were compared with microstructural analysis.

The stress-strain curves for maraging steel 300 subjected to impact loading are shown in Fig. 3. It could seen clearly that as the impact momentum is increased from 32.91 kg.m/s to 40.04 kg.m/s, the maximum flow stress increases from 1200 MPa to 1600 MPa. The maximum stress decreases as the impact momentum further increases due to early formation of adiabatic shear bands. Referring to Fig. 4, it is observed that an increase in impact momentum increases the maximum flow stress for maraging steel 300.

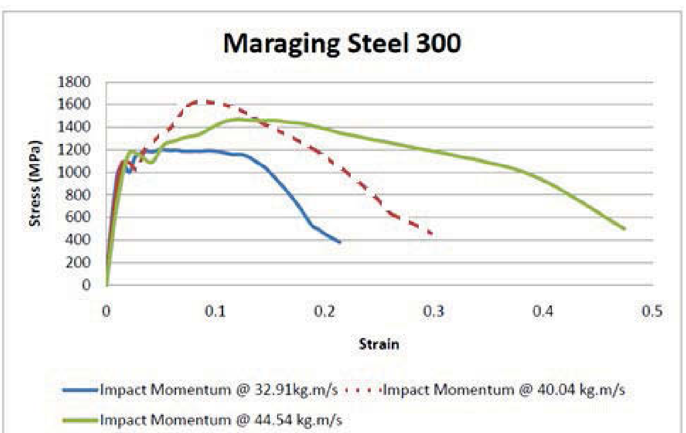

Fig. 3. Typical dynamic stress-strain responses for maraging steel 300 specimens at different impact momenta

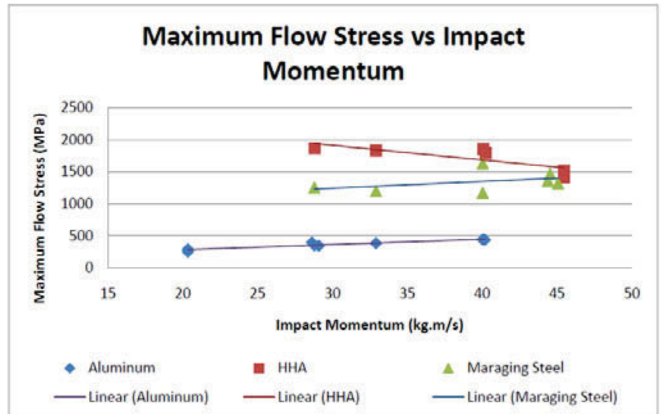

Fig. 4. The effect of impact momentum on maximum flow stress for all three metals

MICROSTRUCTURAL INVESTIGATION USING OPTICAL MICROSCOPY

Specimens from impact loading (SHPB) experiments were investigated for evaluation on the formation of ASBs. The specimens were investigated using optical microscopy for microstructural study and occurrence of ASBs. Advanced microscopic techniques such as Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) were used for detailed analysis on the microstructure.

A. Maraging Steel 300

Observation on optical microscopy images for maraging steel 300 specimens showed no shear bands between impact momentums of 32.91 kg.m/s and 40.04 kg.m/s. As the impact momentum is increased to 44.54 kg.m/s, ASBs were found. Fig. **5** shows the microstructure of maraging steel 300 with the presence of deformed bands and white etching bands at a magnification of 100x.

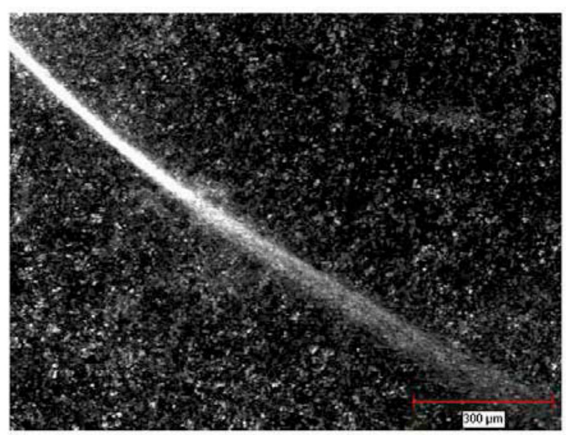

Fig. 5. Maraging steel 300 specimen impacted at 44.54 kg.m/s showing deformed and white etching bands

B. Aluminum 5083-H131 Alloy

A select few samples subjected to impact loading experiments were prepared for microscopic analysis. Fig. 6 shows the presence of deformed bands in Aluminum 5083 – H131 Alloy specimen subjected to impact momentum of 28.63 kg.m/s. The deformed bands from plastic flow were observed at the edge of the circular specimen. The optical microscopy images show clear evidence on reorientation of grains in the region of deformed bands.

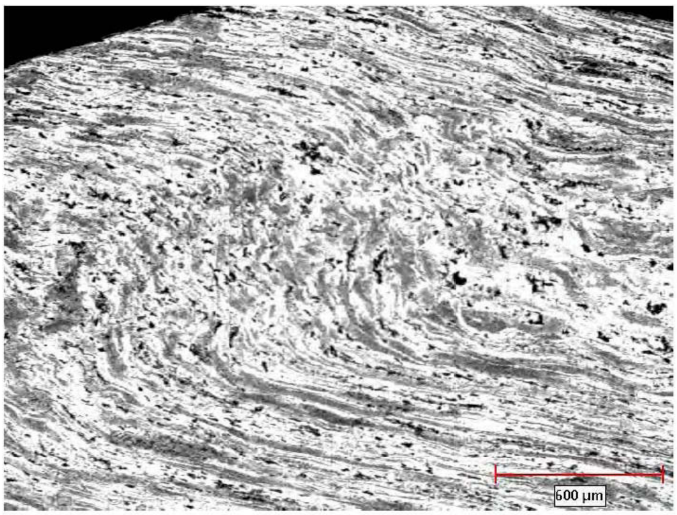

Fig. 6. Aluminum specimen impacted at 28.63 kg.m/s showing deformed band

MICROSTRUCTURAL INVESTIGATION USING ATOMIC FORCE MICROSCOPY

Microstructural observation of Maraging steel 300 (Mars 300) specimens subjected to an impact momentum of 44.54 kg.m/s revealed the presence of adiabatic shear bands by optical microscopy. As the shear band in Mars 300 appeared thin and more distinctive than HHA samples, using AFM to study the characteristics of such shear band was carried out. The 30μm wide scanning tip of AFM was able to scan sections of the ASB (deformed and white-etching bands). The nital etched specimen was studied at the sections containing deformed and white-etching bands. AFM scans present the topography of the specimen that gives very high accuracy on the surface condition. The uneven surface roughness shows densely packed mass in the regions of shear band than in the adjacent regions. The location containing shear bands is marked by hardness indentation and followed by removal of the etching layer using polishing with 30nm colloidal silica solution.

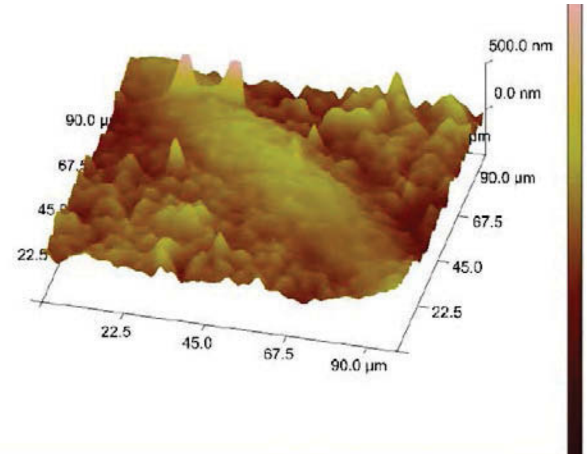

Fig. 7. A 3-dimensional surface view on white-etching band region in maraging steel 300

Similar shear bands were observed in ballistic tests done at DRDC Valcartier, which value the high strain rate approach considering the influence of momentum in the failure process.

ACKNOWLEDGMENTS

The work reported in this paper was sponsored by The Canadian Department of National Defense.

REFERENCES

[1] M. N. Bassim and A. G. Odeshi, "Microstructural Model for Occurrence of Adiabatic Shear Bands," AES-Advanced Engineering Solution, 2007.

[2] M. N. Bassim, A. G. Odeshi, S. Al-Ameeri, and Q. Li, "Dynamic shear band propagation and failure in AISI 4340 steel," *Journal of Materials Processing Technology*, no. 169, pp. 150-155, 2005.

[3] M. N. Bassim, "Study of the formation of adiabatic shear bands in steels," *Journal of Materials Processing Technology*, no. 119, pp. 234-236, 2001.

[4] S. Mirfakhraei, "Deformation of High Strength Alloys at High Strain Rates," Department of Mechanical and Manufacturing Engineering, The University of Manitoba, Winnipeg, Masters Thesis 2008.

[5] Veeco Metrology Group, Dimension 3100 Manual: Vol. Version 4.43C, Digital Instruments, 2003.