Deformation Criterion of Low Carbon Steel Subjected to High Speed Impacts

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Abstract

A study has been carried out to examine effects of blast loading on the microstructure deformation response of A572 Grade 50 low carbon structural steel. Symmetrical planar impact experiments have been carried out using a single stage gas gun to drive projectiles to velocities between 200 and 500 m/sec resulting in low to moderate shock loading of disc type steel specimens. Longitudinal stress histories of the impacted specimens were captured at the back face of the loaded specimens with the use of manganin gages. A constitutive model was employed to numerically simulate the particle velocity at the impact surface as well the pressure distribution across the specimens as a function of impact duration. An analytical approach utilizing a deformation model was used to link twin volume fraction to blast severity. Post-mortem analysis was carried out on the impacted specimens with the use of optical and scanning microscopy in order to correlate the severity of the impacts with development of twinning within the microstructure. A comparison between the analytically calculated and experimentally measured twin volume fraction was used to optimize the material and deformation models and establish a correlation between impact pressure and deformation response of the steel under examination.

Introduction

Impact loading of steel is a subject that has been studied widely for structural applications and material characterization. It has been established that high strain rate loading of steel will result in a change of both microstructural and mechanical properties which individually affect the residual life of the material. Vast amounts of research has been done in order to assess blast loading and deformation effects, much of it being on steel as it is a primary reinforcing phase of structures. Research in blast analysis, while in general utilizes the finite element technique to provide solutions for the dynamic response of the structures [1], requires implementation of microstructure constitutive models is required to accurately capture changes in mechanical properties during high strain rate loading.

In order to replicate the pressure profile and high strain rate deformation caused by explosive loading and recover large intact specimens, various techniques exist of which Field et al. [2] provide a detailed review. To achieve the highest velocities, above 1km/s, two and three stage gas guns are used. These techniques are typically used for obtaining Hugonoit curves, measuring spall strength, post-impact mechanical testing, and measuring phase change, the latter of which is the concern of the work presented herein.

The phase change of the material is of particular interest in material investigation and has been incorporated into analytical modeling in order to predict deformation response. De Resseguier and Hallouin [3] studied iron disks of different thickness submitted to shock loading by means high-power laser pulses. Post shock studies of the iron microstructure revealed significant twin formation. Using a constitutive twinning model proposed by Johnson and Rohde [4] accurate predictions of twin volume fraction and elastic-plastic response of the material have been made. Johnson and Rohde [4] proposed a mathematical model to describe deformation by slip and twinning based upon the laws of mass and momentum conservation. Plate impact experiments were used to examine shock-loaded iron and analytically predict twin volume fraction in recovered specimens as a function of impact stress.

The objective of this study is to establish the effect of moderate shock loading up to strain rates of 10^5 s^{-1}, on the microstructure deformation mechanisms of low carbon steel. This objective will be achieved by identifying a deformation criterion based on microstructure response to blast loading. This will be examined by subjecting discs of low carbon steel to high velocity impact loading using a light gas gun. Impact specimens will be analyzed by measurement of microstructural variations and mechanical properties. Attempts will be made to study the deformation pattern in steel using material and deformation models. Results of this analysis will be linked with the experimental work in order to asses the validity of the approach. In this paper, we present the experimental procedure used to impact the steel specimens and experimental observations of microstructure. In addition, numerical methods and analytical modeling of dynamic deformation based on slip and twinning are described, and results are compared with experimental findings.

Material and Experimental Procedure

The as received microstructure of A572 grade 50 low carbon steel is body center cubic structure which consists of primarily α-ferrite phase with colonies of pearlite; Figure 1. Preparation of all specimens was done by mechanical polishing to 1 micron and chemical etching using 5% nital solution for 8 seconds. [5]

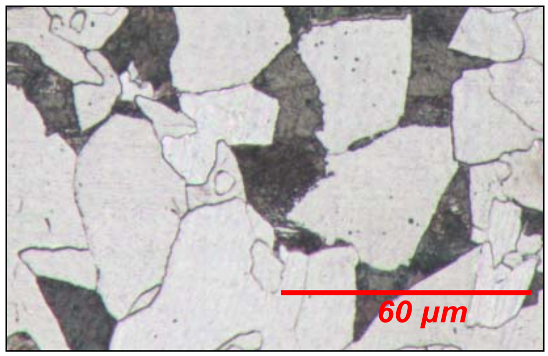

Figure 1. Micrograph of as received A572 grade 50 structural steel.

This material was prepared into round discs by electro discharge machining (EDM) and tested by subjecting it to different impact loads using a single stage light gas gun.

A series of five plate impact experiments have been carried out using a single stage light gas gun. Fixed back conditions were employed in order to minimize energy loss and provide means for recovering post impact specimens. Figure 2 provides an illustration of the experimental gas gun and target set up. The projectile measurements are 31.75mm diameter and 3mm thick, while the target disk and backing plate measurements are 57.15mm diameter and 6mm thick. The target dimensions allowed for tensile specimens to be machined from deformed specimens for post impact mechanical testing.

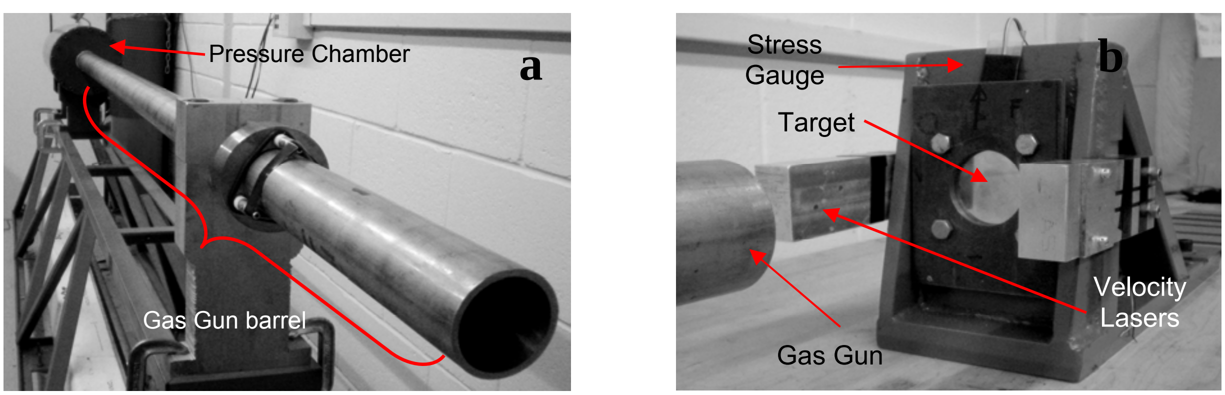

Figure 2. Photograph of a.) the experimental light gas gun and b.) the target and fixed back holder

Projectile velocities ranging from 200 to 500 m/sec were measured using two lasers which were mounted perpendicular to the projectile and in front of the target. Input pressure was used to control projectile velocities and magnitude of impact loads. Longitudinal stress histories were recorded using manganin stress gauges bonded centrally between the back surface of the target disk and a steel backing plate. Figure 3 shows a typical stress vs. time record obtained from the back surface of the target disk during an impact.

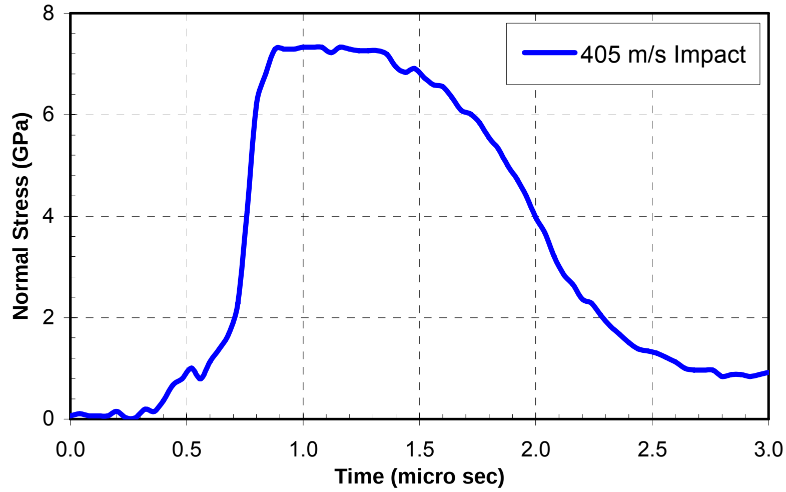

Figure 3. Impact Stress recorded with manganin gauge at the back surface of target disk during a 405 m/s impact

The curve from figure 3 will be compared to numerical results and used as a reference for optimizing simulation parameters. As a reference, particle velocity profiles of the target impact surface will be used as an input into analytical constitutive equations.

Experimental Results

Post impact target specimens revealed plastic deformation in the impacted area and back surface as well as increase in total diameter. The area of impact was discolored suggesting a large and rapid increase in temperature on the front surface during impact; Figure 4.

Figure 4. Impacted steel target specimen and deformed projectile

Specimen surfaces were ground flat using a surface grinder under coolant, and polished and etched. Optical microscopy was conducted on post impact test specimens and the results show the presence of mechanical twins within the α-ferrite grains; see Figure 5. Micrographs of the cross-section just below the impact surface showed a lack of twins, which is evidence that temperature rise was high enough to suppress twin formation in the contact region.

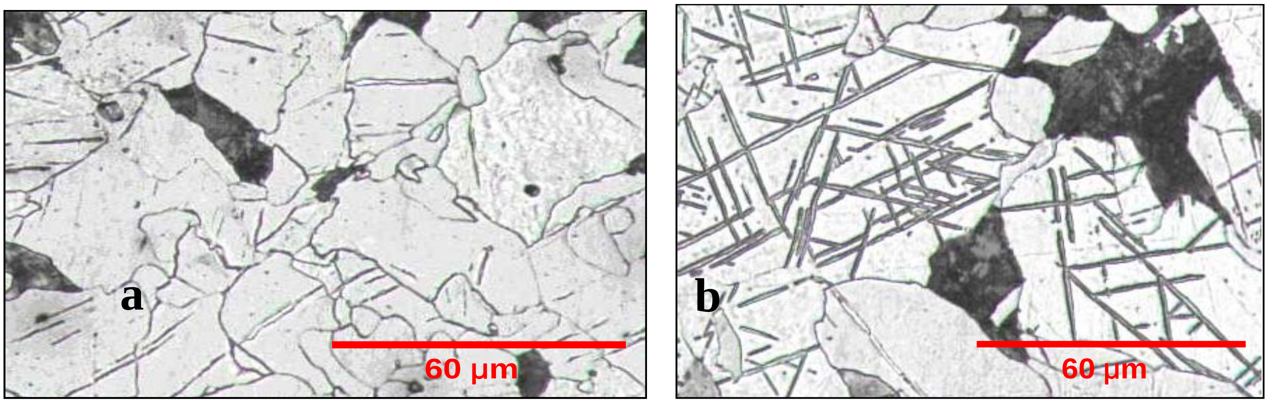

Figure 5. Example of optical micrographs of post impact steel specimens a.) 7 GPa peak stress yielding 3.4% twins, b.) 9 GPa peak stress yielding 4.3% twins.

Results of these optical micrographs show that all of the twins are of lenticullar shape, which is indicative of the mechanism by which the twins form. The majority of the grains have parallel twins extending between grain boundaries. However, there are also large amounts of twin-twin interaction in which twins terminate at other twins, or continue through the intersections, which suggests formation on multiple planes. Volume fraction of the twins was calculated using ASTM E562-05, standard test method involving systematic manual point count method. This count provides an average estimation of twin volume fraction which was correlated to impact stress, as illustrated in Figure 6. Figure 6 and Figure 8 show that twin volume fraction and macro hardness are both positively correlated to impact stress.

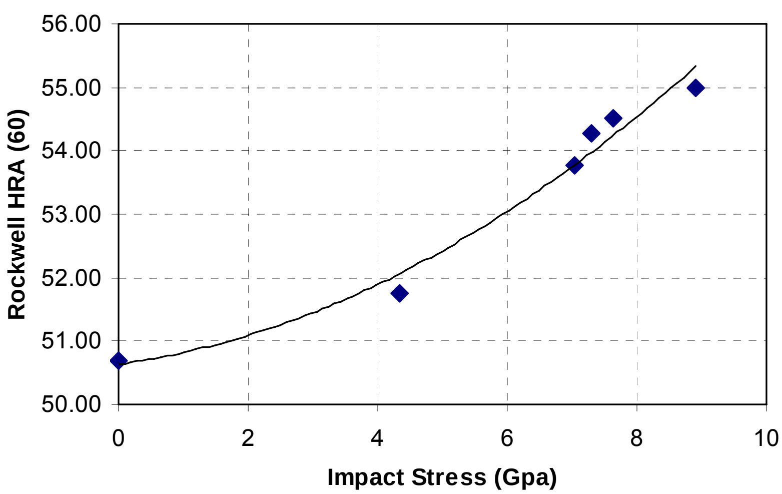

Figure 6. Post-impact macro hardness as a function of impact stress

The increase in hardness, which indicates an increase in yield strength of the material, can be attributed to strain hardening, as described by Maciejewski [5], and to twin-matrix interfaces, which provide additional barriers for further dislocation slip. There may exist a unique relationship between the twinning and hardness properties, however since hardness also increases in the absence of twinning, no attempt has been made from this study to examine the unique relationship between hardness and twinning.

Numerical and Analytical Analysis

Finite element simulation using Abaqus dynamic explicit analysis was used to model plate impacts. Simulation of impact conditions provides knowledge of impact wave parameters as well as a description of the blast related stress distribution within the impacted steel. Inputs parameters for boundary and loading conditions are obtained from experimental procedures. From the simulation, the longitudinal stress distribution is matched with experimental stresses recorded. Once good correlation exists between numerical and experimental outputs, particle velocity history at the impact surface is extracted from numerical results and used as an input for analytical modeling of twin volume fraction as a function of impact loading. In order to obtain stress histories in accordance with experimental results, parameters for a rate dependent model were required. The built in Johnson-Cook material model [6] was used to express the equivalent Von-Mises tensile flow stress as a function of the equivalent plastic strain, strain rate, and temperature. Values for constants were optimized using a room temperature stress-strain curve of the as received material [5]. Numerical stress history of the target specimen during impact show comparable profiles to experimental impact results. In this profile, three important components which must be captured accurately, pressure rise time, impact duration, and maximum stress, all exhibit good fits with experimental data. Figure 7 shows a numerically generated stress profile during impact at the back surface of the target specimen compared with experimental results.

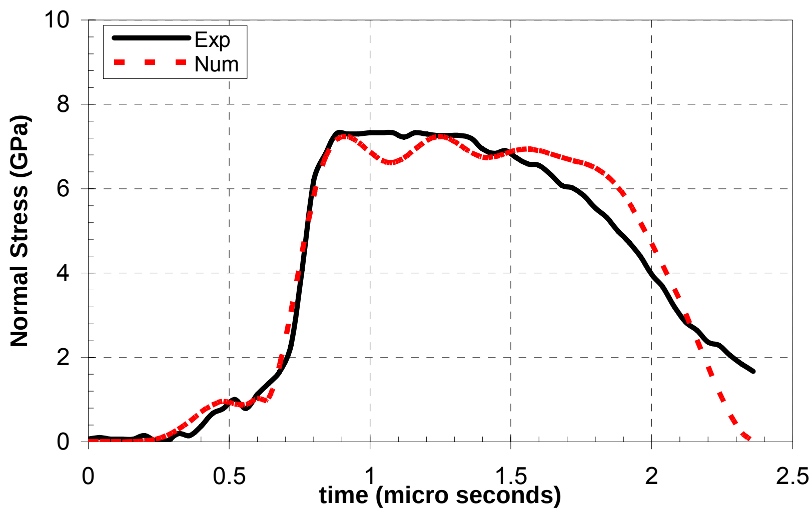

Figure 7. Experimental and numerical stress history at the back of the target specimen.

Cross slip and dislocation coalescence proposed by Sleeswyk provides a basis for a mechanistic model governing twin formation and has been confirmed by Mahajan [8]. The model proposed by Johnson and Rohde [4] incorporates slip and twinning mechanisms described [7,8] and accurately calculates twin volume fraction of low carbon b.c.c. steel for the given loading conditions. In order to analytically predict twin volume fractions, a modified form of a model based on the work of Johnson and Rohde [4] was applied here. Lenticullar shape of twins suggests formation by progressive shear of the lattice [7] in which slip must be present in order for twin formation to occur [8]. Johnson and Rohde [4] examined shock-loaded iron in order to analytically predict twin volume fraction in recovered specimens. They state that twin formation is based upon proportional shear of the lattice rather than local shuffling of the atoms and twin formation is preceded by corresponding dislocation multiplication. The assumptions and observation from this study are described in the constitutive model in which total plastic strain is composed of both dislocation slip and deformation twinning, and the twin volume fraction and growth rate are functions of corresponding shear stress. The dynamic response and deformation twinning of low carbon steel under impact loading is described by the laws of mass and momentum conservation. Analytical twin volume fractions were calculated using this model for each impact condition using a critical shear stress criterion. An average bulk material value was determined and compared to experimental results; see Figure 8.

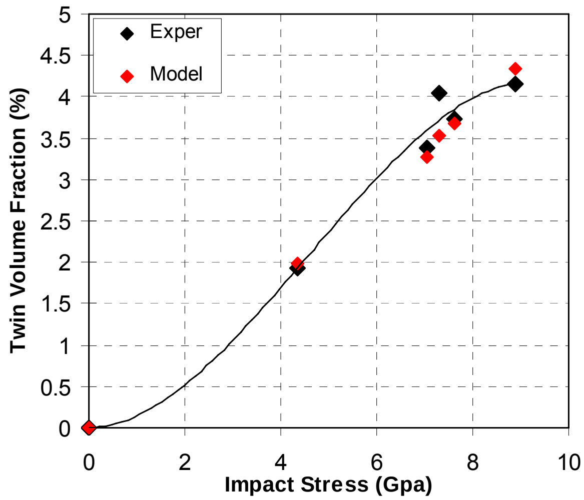

Figure 8. Comparison of experimentally measured and analytically computed twin volume fraction as a function of impact stress.

Analytical model predictions show similar trends to experimental measurements for the given stress range. The linearity of the experimental and calculated data in Figure 8 apparently deviates from this trend at higher stresses as the twins begin to saturate in the material, or other deformation mechanisms begin to play a role. While the relationship between impact stress and twin volume fraction may be satisfied within the given conditions, shear banding and phase transformation have been observed to occur at extremely high pressures [9,10], and the criteria may no longer be valid. Further study of the material at higher stresses and strain rates are needed to develop the relationship further and set limits for its accuracy.

Conclusions

The objective of the study is to present a correlation between high rate impact and microstructure variation of low carbon steel. Five plate impact experiments were carried out and post impact microscopy shows deformation mechanisms occurring during shock loading of low carbon b.c.c. steel. The coupling of numerical simulations and the analytical constitutive model act as a tool for defining impact history and predicting post-impact microstructure. Results of this study can be briefly summarized as follows:

1. Impact experiments indicated that slip and mechanical twinning are two competing deformation mechanisms occurring during high rate loading of b.c.c. low carbon steel.
2. A direct and unique relationship between impact stress and volume fraction of twins has been experimentally established.
3. Microscopic observations of lenticullar deformation twins formed on multiple planes within each grain indicate the twinning mechanism. This formation mechanism was used as a basis for selection of an analytical model aiming at predicting twin volume fraction.
4. The analytical model incorporates both slip and twinning mechanisms and accurately calculated twin volume fraction. This model was coupled with a rate dependent model implemented into numerical procedures and was capable of capturing deformation response and twin formation during impacts for the given stress range.

Acknowledgements

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