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ON ADIABATIC SHEAR BAND DETERMINATIONS BY SURFACE OBSERVATIONS

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ABSTRACT

Two cracking mechanisms, adiabatic shear band cracking and ductile dimpled shear cracking, have been observed in hollow, right circular cylinders of AISI 4340 steel, which were explosively expanded in a quick-stop containment apparatus. It is concluded that distinction of cracking mechanisms cannot be made without the use of metallographic sectioning, as the external appearances of both types of cracks are identical. These exploding cylinder results demonstrate the inaccuracies associated with determining the presence or density of adiabatic shear bands only from surface observations.

INTRODUCTION

Detonation of high explosives within hollow cylinders leads to fragmentation by several fracture modes.[1-5] Understanding these fragmentation processes can benefit the field of ordnance. Recent use of the "contained fragmenting round" technique[6,7] to study one of these fracture modes (adiabatic shear band formation and subsequent separation) has not focused on the criteria for the onset of adiabatic shear. A study of the adiabatic shear band mechanism should indicate how material properties influence both the onset and propagation of shear bands. The purpose of this paper is to report initial results of a study of the adiabatic shear band mechanism, where it was possible to distinguish two cracking mechanisms in the same alloy with different heat treatments.

MATERIALS AND EXPERIMENTAL PROCEDURE

Hollow, right circular cylinders of AISI 4340 steel (28.6 mm I.D., 41.3 mm O.D., 102 mm long) were used to study adiabatic shear band formation by means of the "contained fragmenting round" technique. Chemical composition in weight percent was 0.41 C, 1.84 Ni, 0.83 Cr, 0.26 Mo, 0.84 Mn, 0.26 Si, 0.15 Cu, 0.009 P, 0.012 S, balance Fe. The specimens were heat treated by austenitizing in a salt bath at 843 C for 1/2 hour, and oil quenched and tempered for 1 hour.

This quick-stop technique is described by Erlich et al.[6,7] but, briefly, it consists of a large, outer thick-walled containment cylinder surrounding the hollow right cylindrical specimen which is loaded with high explosive (C-4 at a density of 1.65 g/cc) and separated from the containment cylinder by a buffer layer of a castable polymerized methyl methacrylate (Figure 1). A cast-in-place lead cylinder surrounds the containment cylinder and acts as a trap to carry momentum radially away from the specimen. The compressive wave from detonation travels outward and enters the lead cylinder, but as reflection occurs at the outer diameter of the lead cylinder, the ingoing tensile wave stretches the lead cylinder and carries momentum away, minimizing damage to the specimen. As the specimen expands, the buffer layer is compressed, preventing an impact against the containment cylinder. The thickness of the buffer layer controls the amount of radial expansion of the specimen. Use of a tapered buffer layer allows a variation in strain within one specimen.

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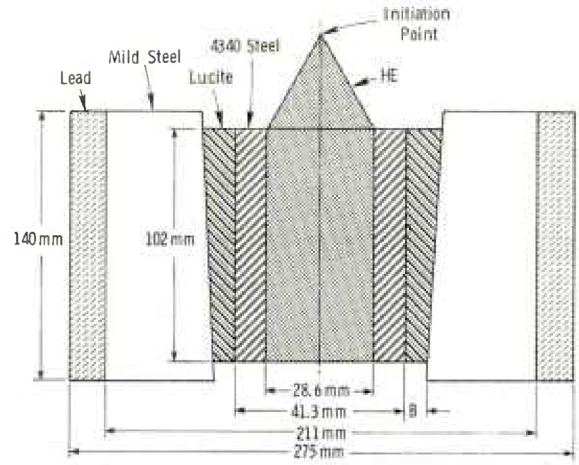

Figure 1. Cross-section diagram of contained fragmenting round experiments with 4340 steel specimen in place. The buffer layer thickness B is in the range of 1.5 mm, but varies from experiment to experiment, and may be double at the top.

Several material properties, including a range of hardnesses obtained by heat treatment, were investigated to explore the propensity for adiabatic shear band formation. AISI 4340 steel was used because of its potential for a variety of material properties obtainable by heat treatment, which are well documented in the literature. Of the two specimens in this study, one was tempered at 427 C (S-2) and one at 649 C (S-3). The final hardness for S-2 was HRC 43 and for S-3, HRC 27. Each specimen was explosively expanded in the containment fixture causing axial cracks to form.

RESULTS AND DISCUSSION

Two specimens with different heat treatments are shown in Figure 2 after explosive expansion in the contained fragmenting round fixture. The effect of the tapered buffer layer, to produce an end-to-end strain gradient, is evident in Figure 2a. Cracking can be seen on the inside surfaces of the specimens (Figure 2b). These cracks, when viewed from the surface, appear the same for both hardnesses. Sections through the wall thickness reveal cracking at approximately 45° to the radial and hoop directions for both specimens (Figure 2c). However, there are clear differences in the deformation and fracture mechanisms of each specimen. Specimen S-2, the harder material, exhibits white layering with cracking along this surface. This is taken as direct evidence of adiabatic shear deformation and has been called transformation adiabatic shear.[8,9] This is in contrast to S-3, the softer specimen, in which there is no evidence of white layering nor deformation adiabatic shear bands (Figure 2c). Flow lines concentrating to a curved narrow band would be evidence of deformation adiabatic shear.[8,9] This division of adiabatic shear bands into two types was proposed on the basis of etching characteristics and hardness. There is, at this time, not enough crystallographic evidence to indicate that they are different structures. They could both be highly deformed matrix structures, and the degree of deformation alone would account for the etching and hardness differences.

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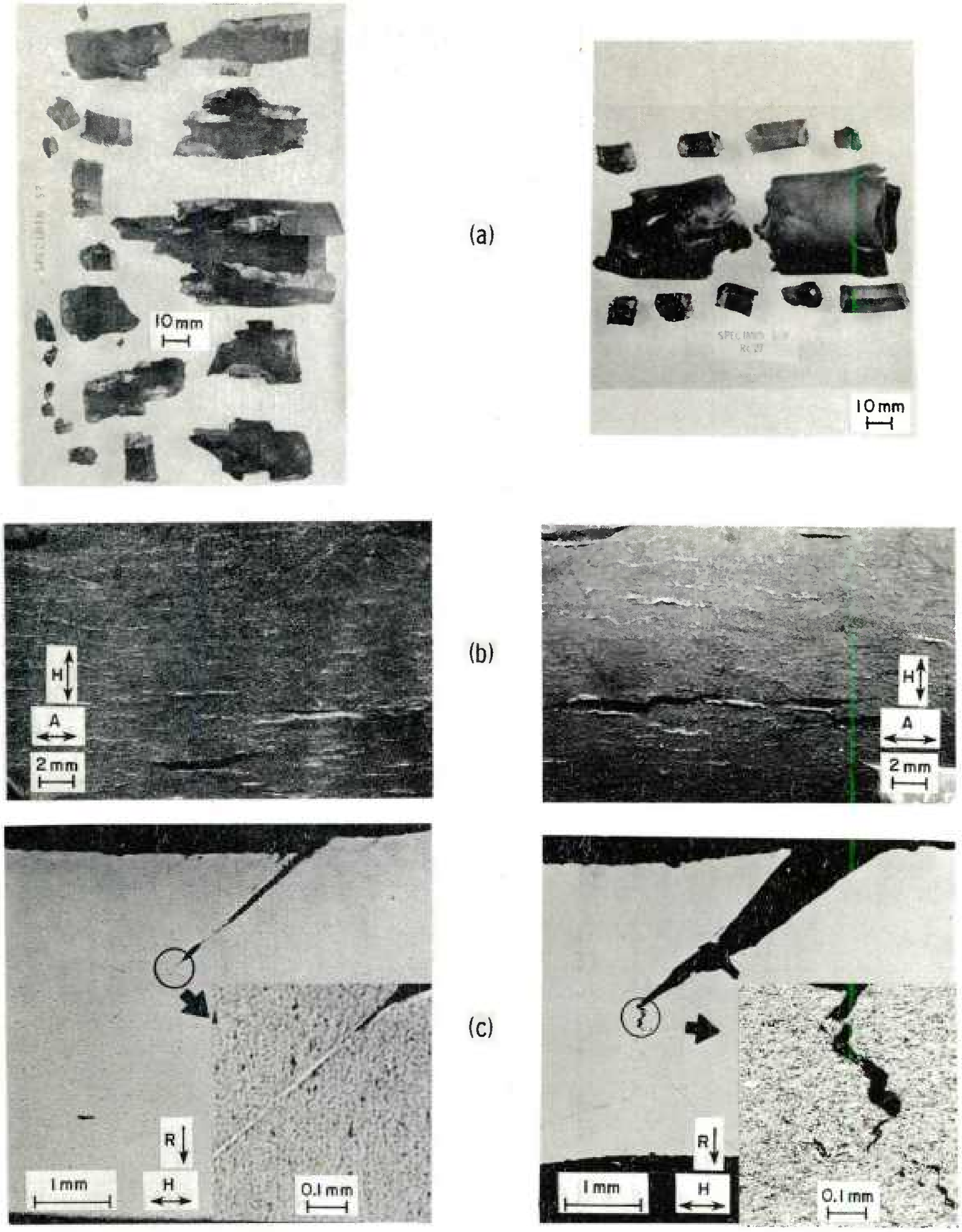

Specimen S-2 (Rc 43) Specimen S-3 (Rc 27)

Figure 2. Specimens after detonation showing (a) each specimen post mortem and (b) the inside diameter surfaces with cracking and (c) polished and etched cross sections of each wall. Specimen S-2 shows adiabatic shear bands and specimen S-3 shows ductile dimpled shear. The axial (A), hoop (H), and radial (R) directions are indicated.

Fracture in S-2 was by cracking along adiabatic shear bands (determined by metallographic sections) and S-3 shows ductile dimpled shear cracking (determined by metallographic sections and scanning electron microscopy). As can be seen from Figure 2b, both modes of cracking appear the same on the surface and therefore distinction must be made by sectioning and metallographic examination.

The orientation of both cracking modes is the same in both mechanisms, and no external appearances suggest any distinction. This lack of distinguishability by external appearance is in contrast to the two deformation mechanisms plugging and bulging, observed in 4340 steel by Mescall and Papirno[10] in ballistic penetration of targets by hard projectiles. Ballistic impact of their soft (HRC 15) target resulted in extensive bulging at the area of impact without any accompanying adiabatic shear. This is in contrast to their observations on the harder (HRC 52) target in which the bulging was replaced by localized deformation and white layering, leading to a shearing out of a plug roughly the diameter of the projectile. Unlike the exploding cylinder test, observations of the external geometry of ballistically impacted targets sometimes indicate whether adiabatic shear takes place.

These exploding cylinder results demonstrate the inaccuracies associated with determining the presence or density of adiabatic shear bands only from surface observations.[6,7] The nucleation criteria are expected to be different for ductile shear cracks and adiabatic shear bands. These two criteria are governed by different material properties and therefore vary in different functional relation to changes in these properties. Current theoretical analysis by the author shows adiabatic shear banding is governed by achievement of a critical true shear strain which, in turn, is a function of the temperature sensitivity of the flow stress of the alloy, its work hardening exponent, and the volume specific heat. The onset of ductile shear cracking is independent of temperature sensitivity of strength and volume specific heat.

CONCLUSIONS

1. Two cracking mechanisms, adiabatic shear band cracking and ductile dimpled shear cracking, have been observed in hollow, right circular cylinders of AISI 4340 steel, which were explosively expanded in a quick-stop containment apparatus.

2. Distinction of cracking mechanisms cannot be made without the use of sectioning and metallographic examination as the external appearances of both types of cracks are identical.

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