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UCRL-JC-151883

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February 19, 2003

THERMEC 2003 International Conference on Processing
and Manufacturing of Advanced Materials,
Leganes, Madrid, Spain, July 7-11, 2003

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HIGH STRAIN RATE – HIGH STRAIN RESPONSE OF AN ULTRAHIGH CARBON STEEL CONTAINING 1.3% C AND 3% SI

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Keywords: Ultrahigh carbon steel, high rate deformation, shear bands

Abstract. The mechanical response of a UHCS-1.3C material deformed at approximately 3000 s^{-1} to large strains (60%) has been studied. The influence of three different heat treatments, which resulted in pearlitic, martensitic and tempered martensitic microstructures, on the stress-strain response has also been examined. Failure, at both the macroscopic and the microscopic levels, and the ability of the material to absorb energy in compression have been evaluated. Failure for all heat treatments occurred due to shear localization. However, in the pearlitic condition, extensive buckling of the carbide plates was observed and the UHCS-1.3C material exhibited significant potential for compressive ductility (>60%) and energy absorption due to the distributed buckling of these plates. In the pearlitic condition, localization occurred due to adiabatic shear bands, in which austenite formed. Subsequent cooling produced a divorced-eutectoid transformation with associated deformation, which resulted in a microstructure consisting of 50 to 100 nm sized grains. The results show the large potential for use of UHCS in applications involving dynamic loading.

Introduction

Ultrahigh carbon steels (UHCS) are an emerging class of material with high strength, hardness, wear resistance and the opportunity for net shape forming via superplasticity [1]. The stress-strain and fracture response of UHCS at quasi-static strain rates has been well documented in the literature and the processing-structure-properties relationships have been reasonably well established under these conditions [2-4]. However, many of the potential applications for UHCS, including products in the automotive and military sectors, involve loading at high strain rates with the potential for large strain deformation. The response of UHCS at high strain rates has been largely unexplored [5]. In this paper, we report on a study concerning the mechanical response of a UHCS-1.3C material deformed at strain rates of approximately 3000 s^{-1} in compression to large strains (60%). Failure at both the macroscopic and the microscopic levels and the ability of the material to absorb energy in compression has been evaluated. The influence of three different heat treatments on the stress-strain response has also been examined.

Materials and Experiments

Materials and processing. The UHCS for this study had the composition 1.3%C, 3.0%Si, 0.5%Mn, 0.99%Cr and balance iron. A thirty-kilogram ingot was cast using vacuum induction

melting and forged at 1090°C from a square cross-section, 125 mm wide, to a plate 25 mm thick by 100 mm wide. The resulting microstructure had small discontinuous graphite stringers induced by the graphitizing influence of silicon. After casting, the plate was homogenized for one hour at 1125°C and air-cooled. This treatment produced a fully pearlitic structure (Fig. 1) with a reduced amount of rod-shaped graphite stringers that were oriented in the longitudinal direction of the plate. This fully pearlitic structure had a hardness of VHN = 355 ($R_c = 36$).

Fig. 1. Microstructure of as-processed UHCS in the pearlitic condition.

Compression samples were prepared in the form of right circular cylinders, 6.35 mm in diameter and 6.35 mm tall. All samples were deformed in the longitudinal direction. Samples were prepared for study in the pearlitic and martensitic condition. The samples with a martensitic microstructure were prepared in two conditions, quenched and quenched-and-tempered. The quenched state was obtained by heating the pearlite structure plate to 880°C for 20 minutes and water quenching. The hardness of the quenched sample was VHN = 770 ($R_c = 63$). The quenched-and-tempered state was obtained by tempering the quenched sample at 320°C for 30 minutes followed by air-cooling. The tempered sample had a VHN = 782 ($R_c = 63.5$).

Experiments. Dynamic compression tests were performed using the split Hopkinson pressure bar technique. The steel sample was placed between two long bars made of Ti-6Al-4V. A striker bar is propelled toward one of the pressure bars (the input bar). Upon impact, an elastic stress wave is introduced into the input bar. This stress wave travels down the bar and at the specimen-bar interface, a portion of this wave is transferred into the sample, causing the sample to deform. The strain histories for the incident and transmitted waves in the elastic pressure bars were measured and analyzed to determine the engineering stress, engineering strain and engineering strain rate response of the sample.

Dynamic Stress-Strain Response

The engineering-stress, engineering-strain curves for the three different heat treated samples are shown in Fig. 2. The average strain rates for each sample are documented in the figure, all exceeding 2500 s^{-1} . The pearlitic UHCS showed high compression ductility. The load began to decrease precipitously at about -0.55 strain and was terminated by a ring stop that limited the strain to -0.60. The quenched UHCS showed a compression ductility of -0.2 and the quenched-and-tempered UHCS showed the lowest ductility at -0.1. The compression ductility, surprising, was higher for the quenched material ($\epsilon = 0.2$) than for the quenched-and-tempered material ($\epsilon = 0.1$). Repeat tests

revealed identical results. This difference is attributed to a ductility-enhancing effect from the presence of some retained austenite in the quenched martensite sample.

Figure 2. Stress-strain curves in compression for UHCS-1.3C processed using three different heat treatments. Average strain rates are indicated in the figure.

All martensitic samples failed by the initiation and propagation of adiabatic shear bands. Compression tests were repeated for all structural conditions and the tests confirmed the reproducibility of the results. The increase in temperature during deformation up to the maximum stress was estimated by assuming that all the plastic work of deformation was converted to heat. The calculations yielded a temperature rise of 300°C for the pearlitic material, 160°C for the quenched-martensite material, and 80°C for the quenched-and-tempered material.

Fig. 3 shows the initial and deformed states of the pearlitic UHCS sample. The cross-section of the undeformed sample is given in Fig 3 (a). The matrix consists of a structure of fine pearlite containing a small amount of minute vertical graphite stringers. The stringers are oriented parallel to the lengthening direction during prior forging. Fig. 3 (b) shows a cross-section of the deformed pearlitic sample illustrating the two adiabatic shear bands oriented at about 45° to the compression axis. The deformed sample remained intact because of the ring stopper (sample strained to 0.6). Discontinuous cracks are observed within the two shear bands. The adiabatic shear-band widths were measured for the three heat treatment conditions by optical microscopy of polished-and-etched samples. The widths were 14 μm for the pearlitic UHCS, 8 μm for the quenched martensitic UHCS, and 4.5 μm for the quenched-and-tempered martensitic UHCS.

Figure 3. Cross-section of the UHCS-1.3C samples before (a) and after (b) testing to 60% deformation.

Failure Modes

Examination of the shear bands in the pearlitic sample provided valuable insight into the influence of microstructure and deformation on the development of instabilities during high rate deformation. Across the adiabatic shear band, a mixture of two structures appears. Segmented, broken-up (ultrafine) regions are mixed with oriented pearlite regions. The lamellar spacing in the pearlite remains about the same throughout this unique region. Significantly, the spacing of the pearlite in the shear band is about the same as the pearlite spacing away from the ultra-fine structure region. This mixed structure results from the two thermal events during and after deformation - adiabatic heating resulting from the large shear strain followed by subsequent rapid cooling. The microstructure in the shear band suggests that the temperature rise exceeds the A_1 transformation temperature. Most of the pearlite will transform to face-centered-cubic austenite. If the increase in temperature is only about 100°C above the A_1 not all the pearlite will dissolve. This is the temperature range where three phases co-exist, fine-grained austenite, and ferrite-plus-cementite as undissolved pearlite [6]. Upon rapid quenching at the completion of the shear-banding step, retransformation will take place. The formation of ultrafine ferrite-grains containing spheroidized cementite from the prior austenite will take place. This structure is favored over the formation of pearlite or martensite. This formation is known as the divorced eutectoid transformation (DET) [7, 8]. It is result of the dissolved carbon in austenite that is present in the form of embryonic clusters. The clusters are the result of insufficient time at temperature to be homogeneously distributed in austenite. These clusters are the nucleation sites for the formation of ultrafine ferrite grains containing spheroidized carbides. The embryonic clusters of carbon come together to reform the iron carbide. These former clusters form the ultra-fine ferrite structure interspersed with the un-dissolved pearlite.

It has been shown that the fine spheroidized structure obtained by DET processing [7, 8] is further refined if deformation accompanies the transformation. This process is called DETWAD (divorced eutectoid transformation with associated deformation). It is likely that a DETWAD-type transformation occurred during adiabatic shear band formation. This is because of the large amount of deformation taking place as austenite formed during shear banding. The ferrite grain size in the shear band is approximately 50 to 100 nm and the carbide particle size is believed to be approximately 10 nm. Nano-indentation hardness measurements gave values as high as 11.5 GPa.

Energy Absorption

Prior to the onset of shear localization during dynamic deformation, the pearlitic sample showed enormous potential for absorbing energy. Figs. 4 and 5 show the pearlitic sample after deformation to strains of 30% and 60% respectively. The figures show pronounced kinking of the carbide plates. The kinking is much more extensive in the sample deformed to 60% strain than the sample deformed to 30%. In both samples the kinking is highly distributed throughout the sample and is not associated with a specific region. This distributed kinking can absorb significant amounts of energy during deformation of the pearlitic UHCS material. Fig. 6 shows a region in the pearlitic sample deformed to 60% strain in which intense local shear was observed. The dominant shear band in the center of the micrograph is about 0.5 μm in width. Other shear bands in the figure are smaller but the spacing between bands is about 1 μm . The carbide plates in these bands are continuous and don't show any obvious fractures. It is important to note that these bands are significantly smaller

is size than the 14 μm shear band that was associated with the loss in load bearing capability of the sample.

(a)

(b)

Figure 4. Local instabilities in pearlite after 30% strain due to buckling of the carbide plates, low magnification (a) and high magnification (b).

(a)

(b)

Figure 5. Local instabilities in pearlite after 60% strain due to buckling of the carbide plates, low magnification (a) and high magnification (b).

Figure 6. Localized shear of the carbide plates in pearlite after 60% strain.

Kinking in pearlite plates, which were subjected to severe plastic deformation, has also been observed in steel-copper wires [9] during wire drawing. The kinking was believed to initiate in the carbide plates with the ferrite matrix “following” the kinking carbide. A similar mechanism is likely active in the pearlitic UHCS during high rate deformation. The stronger carbide is inherently expected to have a flatter stress-strain curve than the softer ferrite matrix. The flatter stress-strain curve for the carbide limits work hardening, which will encourage localization in the carbide and the development of an instability in the form of an initiating kink. Once the kink has initiated in the carbide, it will control the direction of kink propagate in the pearlite.

Summary and Conclusions

The mechanical response of a UHCS-1.3C material during high rate compression (approximately 3000 s^{-1}) has been studied for the steel with pearlitic, martensitic and tempered martensitic microstructures. The sample in the pearlitic condition was deformed to large strains (-0.55) without fracture and showed extensive ability to absorb energy. In the pearlitic condition, the carbide plates exhibited significant distributed kinking during deformation which results in significant amounts of energy absorption. For all three heat treatments, loss in load bearing capability was associated with the initiation and propagation of adiabatic shear bands. In the pearlitic condition, localization occurred due to adiabatic shear bands, in which austenite formed. Subsequent cooling produced a divorced-eutectoid transformation with associated deformation, which resulted in a microstructure consisting of 50 to 100 nm sized grains.

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Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.