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Evolution of adiabatic shear bands in a dual-phase steel at very high strain rates

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Abstract

Dynamic response to high velocity impact of a dual-phase and a martensitic steel that are obtained from heat treatment of 15V24 steel are evaluated. For the range of applied impact momentum of 40–50 kg m/s, which respectively corresponds to impact velocity of between 20 and 25 m/s for a projectile weighing 2 kg, deformation in the martensitic steel samples was relatively homogeneous while strain localization along shear bands was observed in the samples with dual-phase structure. The shear bands formed in the dual-phase steel contain finer grains and higher martensite content than the bulk material.

Keywords: Dual-phase steel; Inter-critical annealing; Impact test; High strain rate; Adiabatic shear band

1. Introduction

Dual-phase steels are characterized by a microstructure that consists of hard martensite embedded in a soft ductile ferrite matrix. Such microstructure can be obtained in low carbon–manganese–silicon steels such as 15V24 steel by partial austenitization before quenching, or by thermo-mechanical processing of the steel after inter-critical annealing. Dual-phase steels combine the high strength of martensite with the plasticity of ferrite and find useful applications in automobile components, where they may be exposed to deformation at high strain rates. Depending on its microstructure, strain rate, strain-rate sensitivity, strain hardening coefficient or thermal conductivity, the plastic deformation behaviour of a material at high strain rate may be characterized by the occurrence of extreme strain localization along narrow bands known as adiabatic shear bands. Results of previous investigations [1–5] have shown that material failure at high strain rate usually occurs along these shear bands.

Li et al. [5] observed that failure of titanium alloy Ti-17 at high strain rates is more sensitive to strain rate than to the applied stress levels. Odeshi et al. [4] reported that the susceptibility of adiabatic shear bands in martensitic steel to cracking and failure is influenced by the tempering condition of the steel. Using fine element modelling, Feng and Bassim [6] calculated the magnitude of stress resistance in the middle of adiabatic shear bands in AISI 4340 steel that is subjected to high strain-rate torsional loading and observed three stages of deformation: Stress resistance was constant at the initial stage, followed by a slight increase due to strain hardening and finally a rapid decrease due to excessive heating in the shear bands. They attributed initialization of ASB to the lower stress resistance and lower work hardening rate in the shear band regions.

In the current study, a comparative evaluation of the dynamic deformation behaviour of dual-phase and fully martensitic steel obtained from heat treatment of 15V24 steel is carried out. The effects of heat treatment variables, microstructure and loading conditions on the deformation behaviour are investigated and reported.

2. Experimental methods

Hot rolled 15V24 steel was machined into cylindrical compression specimens with 9.5 mm diameter and 10.5 mm in length. The steel contains 0.25% C, 1.48% Mn, 0.23% Si, 0.10% Ni, 0.045% Cr, 0.015% P and 0.028% S. The as-received test specimens were given an initial normalization treatment by complete austenitization at 900 °C for 30 min followed by air-

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Table 1
Experimental data sheet

Sample no.	Austeni- tization temperature (°C)	Predominant microstructure	Firing pressure (kPa)	Impact momentum (kg m/s)	Strain rate (s^{-1})	Total strain	ASB
A-1	750	Ferrite + martensite	180	41.0	4031	0.40	Yes
A-2	750	Ferrite + martensite	200	43.2	4311	0.43	Yes
A - 3	750	Ferrite + martensite	220	45.6	4512	0.45	Yes
A-4	750	Ferrite + martensite	240	47.7	4776	0.48	Yes
A-5	750	Ferrite + martensite	260	48.3	5079	0.51	Yes
B-1	800	Ferrite + martensite	180	41.4	2781	0.28	No
B-2	800	Ferrite + martensite	200	43.0	3008	0.30	No
B-3	800	Ferrite + martensite	220	45.1	3156	0.31	No
B-4	800	Ferrite + martensite	240	46.4	3345	0.33	Yes
B-5	800	Ferrite + martensite	260	49.5	3727	0.37	Yes
C-1	900	Martensite	180	40.8	2549	0.25	No
C-2	900	Martensite	200	43.2	2857	0.28	No
C-3	900	Martensite	220	45.4	2976	0.30	No
C-4	900	Martensite	240	46.5	3108	0.31	No
C-5	900	Martensite	260	49.0	3921	0.39	No

cooling. A total of 15 samples were investigated as shown in Table 1. Some of these specimens were inter-critically annealed at 750 and 800 °C for 15 min and subsequently oil-quenched to obtain dual-phase microstructures. The remaining samples were given full austenitization treatment at 900 °C for 30 min and oil-quenched to obtain a predominantly martensitic structure. The heat-treated steel samples were tempered at 315 °C for 1 h before high strain-rate testing.

High strain-rate testing of the samples was conducted using direct impact Hopkinson pressure bar as described in detail in earlier publications [7,8]. This testing method is very advantageous in that it can produce high strain rates and it is typical of extreme loading conditions as in ballistic impact or automobile crash. Test specimens were subjected to high strain-rate deformation by impacting with a high velocity projectile weighing 2 kg at a momentum ranging between 40 and 50 kg m/s. Variation in impact momentum was obtained by varying the firing pressure of the projectile between 180 and 260 kPa, which generates a projectile velocity that varies between 20 and 25 m/s respectively. Microscopic examination and Vickers hardness tests were conducted on the samples before and after impact to determine the effects of the heat treatment variables and impact velocity on microstructure and mechanical properties of the steels.

3. Experimental results

Typical optical micrograph of the obtained dual-phase steels showing the microstructure consisting of tempered martensites (dark) and ferrite grains (white) is shown in Fig. 1. The predominantly martensitic structure obtained from complete austenitization at 900 °C indicating the presence of a significant amount of retained austenite is shown in Fig. 2. The amount of martensites observed in the dual-phase structure is higher for those samples that were austenitized at 800 °C than for those which were austenitized at 750 °C (Fig. 3). More austenite is available for phase transformation into martensite during subsequent quenching hardening at inter-critical annealing tem-

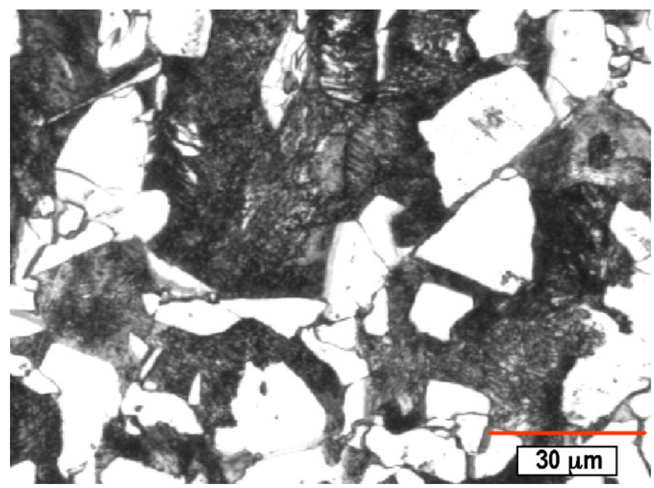

Fig. 1. Optical micrograph showing a dual-phase structure obtained from inter-critical annealing of 15V24 steel at 750 °C. The microstructure consists of dark martensite and white ferrite.

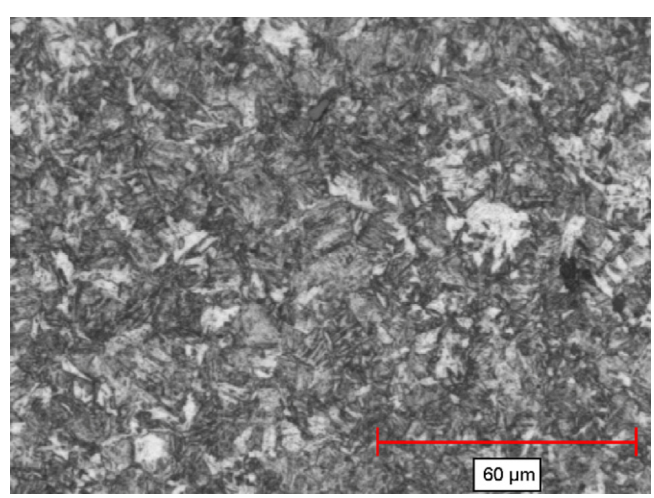

Fig. 2. A predominantly martensitic structure obtained from complete austenitization of 15V24 steel at 900 °C before impact test.