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Plastic instability at elevated temperatures in a TRIP-assisted steel

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ABSTRACT

An experimental investigation of plastic instability in a three-phase, TRIP-assisted steel prepared with a two-step quenching and partitioning heat treatment is presented. Testing conditions explored temperatures from 293 to 623 K at four quasi-static strain rates. Strain rate contours computed with stereo digital image correlation (DIC) showed propagating bands that resemble Type A Portevin–Le Châtelier (PLC) bands and are indicative of plastic instability. Negative strain rate sensitivity (nSRS), noted in the 333 to 623 K range, with flow curve serrations occurring within 373–523 K, suggested dynamic strain aging as the underlying mechanism for plastic instability. Band propagation speed and peak strain rate are dependent on strain rate but not temperature. Based upon the steel chemistry and band nucleation and kinetics analyses, plastic instability in the QP980 steel is attributed to C diffusion. The activation energy for band propagation is estimated to be 160 ± 16 kJ/mol, in excess of 84.1 kJ/mol for C diffusion. The effect of carbide precipitation in lath martensite on plastic instability is investigated with transmission electron microscopy at selected temperatures.

1. Introduction

The so-called TRIP-assisted steels [1] (TRIP = transformation induced plasticity) are distinct from first generation TRIP steels [2] by virtue of a higher retained austenite volume fraction (RAVF) and Mn content ~2 wt.% (or greater) [3], and have attracted considerable attention in transportation industries [4–6]. Of particular significance is the potential improvement in sheet formability at higher strength levels that is needed for complex body component geometries in the automotive industry. Macroscopic-scale properties are largely controlled by the multiphase microstructures which may consist of combinations of a ferrite matrix, bainitic ferrite, martensite, and retained austenite (RA). Diffusionless shear transformation of RA into martensite during plastic straining with the associated volume expansion leading to plastic deformation of other phases, i.e. the TRIP-effect [7], delays necking and fracture via localized work hardening and leads to exceptional ductility and strength. Additions of Al and Si [8,9] suppress carbide formation in these low alloy steels. Examples of TRIP-assisted steels are high Mn (>10 wt.%) TRIP steels [10–12], medium Mn (e.g. 3–10 wt.%) TRIP steels [13–17] and TRIP-assisted steels with a bainitic ferrite matrix (TBF steels) [18–21]. Most high Mn TRIP steels are fully austenitic steels, where the austenite is stabilized through high Mn content. In the course of deformation of high Mn TRIP steels, the TRIP effect is always accompanied with twinning induced plasticity (so called TWIP effect) due to a larger stacking fault energy of the high Mn austenite [12]. Medium Mn TRIP steels are produced through intercritical annealing in the ferrite–austenite region. Austenite is stabilized through enrichment with Mn and the initial microstructure contains no martensite. A TBF microstructure is produced by cooling to just above the martensite start temperature thereby allowing bainitic ferrite to form with C partitioning to the remaining austenite. Another novel type of TRIP-assisted steel results from a quenching and partitioning (QP) heat treatment [22–24]. This involves heating to a temperature above the austenitization temperature, AC_3, which can be followed by an immediate quench to a temperature (QT) between the martensite start and finish temperatures. Another path involves first cooling to a temperature just below AC_3, at which a portion of the austenite will transform to proeutectoid ferrite, and then quenching to QT. After quenching, the material is heated to a partitioning temperature (PT) intermediate to the AC_3 and QT which increases carbon mobility and allows greater carbon enrichment of austenite while minimizing carbide precipitation. The steel undergoes a second and final quench to room temperature after partitioning which results in some of the austenite transforming to martensite, with the remaining austenite being retained in the microstructure. Xiong et al. [25] identified both film-like and blocky forms of austenite in their room temperature investigation of austenite transformation in a Q&P steel. The larger, blocky austenite, with higher C content relative to film-like austenite, was found to transform to twinned martensite at 2% strain and was completely consumed at 12% strain. However, most of the smaller and lower C content film-like austenite had yet to transform at 12% strain. Park et al. [26] found similar behavior in a TRIP steel

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produced with intercritical annealing and isothermal bainitic transformation. However, the C content of the more stable film austenite was found to be higher than that of the less stable blocky austenite [27].

Elevated temperature effects (post-heat treatment) on plastic instabilities associated with dynamic strain aging (DSA) and serrated flow in TRIP-assisted sheet steels under different strain paths have received minimal attention in the literature. Alloying agents responsible for DSA are C and N, a consequence of the greater diffusivities of these interstitial elements relative to substitutional solutes [28,29]. Heat from plastic deformation leads to a considerable temperature increase in high strength steels [30,31]. Strain rates in automotive stamping processes (for example) can reach 1 s^{-1}–10 s^{-1} in ~0.1 s with minimal heat dissipation over such a short time. Hence, stamping is generally regarded as an adiabatic process with local temperatures reaching or exceeding ~550 K [31]. Under hood temperatures in automobiles have been reported to be as high as 423 K under normal operating conditions [32] with paint bake temperatures reaching 463 K [33]. Previous studies of TRIP steels have reported a temperature sensitivity of the TRIP effect as well as tensile properties [33–38]. In general, heat increases slip activity and decreases the driving force for the TRIP effect, thereby having a stabilizing effect on RA [39–41]. Wang et al. [42] observed that the total elongation of a Si–Al–Cr TRIP steel reached a maximum at 333 K. They found that 353 K was the temperature above which the TRIP effect no longer occurs. In their study of tensile property variations with temperature of a QP980 steel, Coryell et al. [33] found that the TRIP effect was minimized at 423 K. The ultimate tensile strength (UTS) was found to decrease from −173 K until 423 K. Over this temperature range, the UTS value decreased by 300 MPa. Similar decreases have been seen in other TRIP steels [42,43]. Dynamic strain aging (DSA), the mechanism that underlies the Portevin–Le Châtelier (PLC) effect and flow curve serrations, has been reported in high Mn content (Mn content 15–30 wt.%) [44,45] low stacking fault (fully austenitic) TWIP steels. The PLC bands, which can propagate, appear beyond a critical strain if the diffusion rate of C atoms is comparable to that of dislocation slip [46]. Serrated flow has also been linked to interactions between C-Mn bonds and mobile dislocations [47]. The PLC effect is typically accompanied by the loss of elongation of the specimen; however, reduced elongation is primarily associated with negative strain rate sensitivity (nSRS) of the flow stress rather than the PLC effect, although nSRS is a necessary but insufficient condition for the PLC effect [48]. The work of Gibbs et al. [15] is notable for reporting serrated flow in a 0.1C–7.1Mn (wt.%) medium Mn TRIP-assisted steel. No additional references pointing to DSA and serrated flow in TRIP-assisted steels could be located at any temperature.

This paper presents an experimental investigation of the elevated temperature deformation behavior of a QP980 TRIP-assisted steel in uniaxial tension. During the course of the investigation, plasticity instability in the form of serrated flow was noted over 373 to 523 K which covers much of the temperature range for adiabatic deformation in stamping. Stereo digital image correlation, which was used to investigate serrated flow over this temperature range, revealed propagative instabilities with phenomenological characteristics resembling Portevin–Le Châtelier bands and a negative strain rate sensitivity of the flow stress within 373–523 K. The principle aim of this study was to understand the effects of temperature and strain rate on the mechanical behavior and plastic instabilities of the QP980 steel. The effect of carbide precipitation in lath martensite on plastic instability is investigated with transmission electron microscopy at selected temperatures. The paper concludes with a summary of the major experimental observations and the mechanisms that affect elevated temperature plastic instabilities in the QP980 microstructure.

2. Experimental details

2.1. Materials

The steel investigated in this study is a 980 MPa grade TRIP-assisted steel, with a 1.2 mm nominal thickness subjected to a two-step QP heat treatment, hereinafter referred to as the QP980 steel [2,22–24,49]. Xiong et al. [25] present additional details of the QP heat treatment process. Each straight gage tensile specimen (ASTM E8/E8M-11, 2008) was prepared with water jet cutting using a very fine abrasive. The water jet was advanced at a slow feed rate to ensure smooth edges of the reduced gauge sections of all tensile specimens and hence to avoid machining defects. Tensile specimens were cut along the rolling direction since orientation does not have a significant effect on the mechanical properties of the QP980 steel [33]. The chemical composition of the QP980 steel is listed in Table 1. The as-received microstructure, shown in Fig. 1, consists of martensite (~53 vol.%), ferrite (~35 vol.%) and RA (~12 vol.%), as confirmed by X-ray diffraction measurements.

2.2. Experimental procedure

Tensile specimens were elongated on an Instron 5568 universal testing machine with an environmental chamber at $T = 293$, 333, 373, 423, 473, 523, 573 and 623 K until fracture. All specimens were air cooled after testing concluded. The broad range of test temperatures was selected since it was not known a priori if or when plastic instability would occur in the QP980 steel. The crosshead speeds used at each temperature were 0.1, 1, 10 and 100 mm/min, with nominal, quasi-static strain rates $\dot{\varepsilon}_N = 5 \times 10^{-5}$, 5×10^{-4}, 5×10^{-3}, and 5×10^{-2} s^{-1} (four orders-of-magnitude), respectively. The temperature variation during testing was less than ±5 K as monitored by a thermocouple. Three QP980 specimens were tested under each temperature/strain rate combination to confirm reproducibility of the measured mechanical properties. Rate sensitivity of the QP980 steel in the sub-Hopkinson range of strain rates ($10\ s^{-1} \le \dot{\varepsilon}_N \le 5 \times 10^2\ s^{-1}$) [50] (at room temperature) from a servo-hydraulic tester is detailed by Yang et al. [51].

The Instron environmental chamber included a transparent window through which two digital cameras were directed to view tensile specimen deformation. The cameras were part of a stereo digital image correlation (DIC) system used to measure displacement fields during deformation and then calculate strain fields. Fig. 2a shows the window in the environmental chamber with the two 4-megapixel digital cameras (in a stereo system) focused on a QP980 tensile specimen gauge section surface through the glass window. The camera framing rates were set to 0.2, 2, 20 and 30 frames/s (f/s) for the 0.1, 1, 10 and 100 mm/min crosshead speeds, respectively. Fig. 2b shows a digital image of a tensile specimen at the outset of a test captured from one of the two cameras in Fig. 2a. The “0 mm” and “32 mm” labels in Fig. 2b are proximate to the stationary and moving gripper ends, respectively. The 32 mm (*x*-axis or axial direction denoted by the red line) × 6 mm (*y*-axis or width direction) DIC area of interest (AOI) is positioned about the center of the reduced section of each tensile specimen, over which strains and strain rates were computed in the post-processing step using the Vic-3D software from Correlated Solutions, Inc. A contrast pattern, consisting of black spray paint droplets randomly distributed over a uniform, thin layer of white spray paint, was applied to each tensile specimen prior to testing after cleaning the surfaces with an organic solvent. Each black droplet was no more than ~33% of the chosen square pixel subset

Table 1
Chemical composition (wt.%) of the QP980 steel.

C	Si	Mn	Al	P	N	S
0.195	1.38	1.90	0.036	0.009	0.0045	0.0005