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Characterization of the spatiotemporal behavior of the PLC bands in austenitic steel during deformation at elevated temperature

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A B S T R A C T

The digital image correlation technique was used in situ during tensile testing to investigate the behavior of the Portevin–Le Chatelier (PLC) bands in a Fe–18Cr–8Ni–2.8Cu austenitic steel at a temperature of 680 °C. Effect of the strain on characteristics of the PLC bands, namely velocity, its intensity and the distance propagated by the bands was studied. New data of the spatiotemporal behavior of the PLC bands at elevated temperature were obtained. The PLC bands propagate continuously along the entire gauge length of the sample. The cause for such behavior of the PLC bands was discussed.

1. Introduction

S304H austenitic stainless steel has been widely used in different applications at elevated temperatures [1]. However, it is known that at such temperatures this steel susceptible to Portevin–Le Chatelier (PLC) instability [2,3]. On the microscopic scale, the cause of the PLC instability is dynamic strain aging (DSA), i.e. the dynamic process of dislocations pinning by solute atoms during their blocking on obstacles [4]. The macroscopic manifestation of this phenomenon is observed as serrated flow stress related to strain localizations in the form of shear macro bands [5] which leads to surface roughness as a result of their propagation [6].

There are a few common methods to investigate the PLC bands behavior, but recently the most widely used method is the digital image correlation (DIC) mapping the strain and local strain-rate distributions on surface of specimens [7,8]. However, due to the difficulties associated with image acquisition at elevated temperatures, there are very few works that would investigate the behavior of PLC bands in metallic materials at elevated temperatures, including austenitic steels [3,9]. As an example, a recent study of the PLC bands behavior in austenitic steel has been carried out in the temperature range from 450 to 550 °C although higher temperatures are of special interest [10]. Thus, it is necessary to investigate the PLC band characteristics at elevated temperatures to understand the behavior of these bands in austenitic steels.

The aim of this study was to identify the characteristics associated with spatiotemporal behavior of the PLC bands in a Fe–18Cr–8Ni–2.8Cu austenitic steel at a temperature of 680 °C by the digital image correlation method. The PLC bands characteristics, i.e. the band velocity, its intensity and the distance propagated by the bands, and the effect of strain on those characteristics were investigated.

2. Experimental

Austenitic stainless steel with the chemical composition of Fe–18Cr–8Ni–2.8Cu (wt.%) was studied. The steel specimens were annealed at 1150 °C for 1 h and then quenched in water. After heat treatment the average grain size of ~ 14 μm; dislocation density of approximately 2.7×10^{12} m^{-2}; and discovered Nb(C,N) particles with a spherical shape and average size of 174 nm were observed [11].

Tensile tests were performed at a constant strain rate of 10^{-3} s^{-1} and a temperature of 680 °C using an Instron 5882 testing machine equipped with a special furnace allowing temperature fluctuations within ± 5 °C until rupture. Three specimens with a size of 16 × 3 × 1.4 mm^3 were subjected to tensile tests. The PLC bands were observed using the digital image correlation (DIC) method. This method makes it possible to record the change in the distribution of local strain fields on the surface of the sample during testing by correlating successive images of the speckle pattern. The calculations were performed using the Vic-2D correlation program. Local strain rate values were determined by numerically, differentiating strain data with respect to time. More details about the DIC method are described in previous works [5,8].

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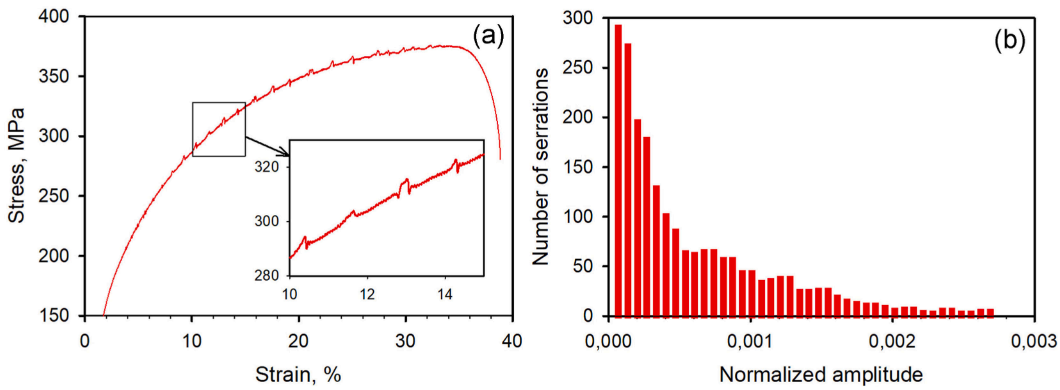

Fig. 1. The stress–strain curve (a) and the distribution of stress serrations (b) for an Fe–18Cr–8Ni–2.8Cu austenitic steel deformed at 1×10^{-3} s^{-1} at 680 °C.

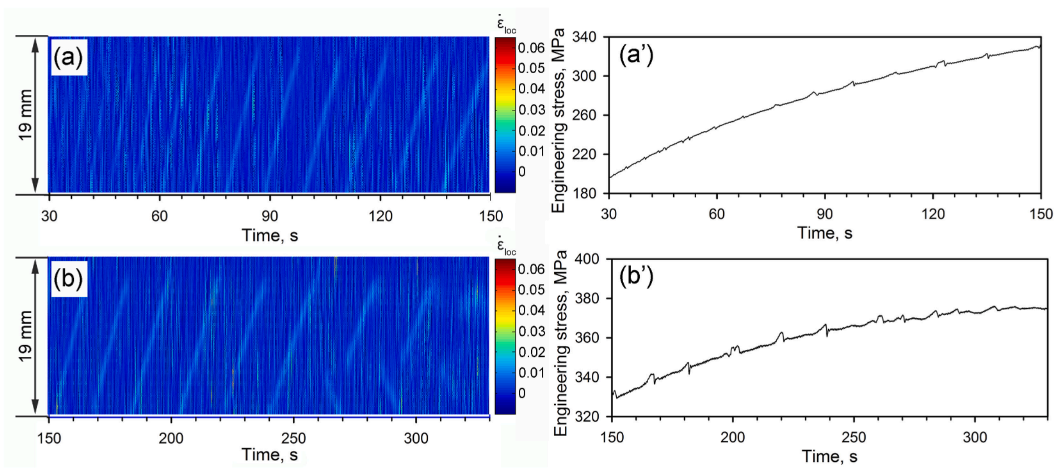

Fig. 2. The local strain rate maps (a, b) and the corresponding sections of the stress-time curve (a′, b′) of an Fe–18Cr–8Ni–2.8Cu austenitic steel obtained at a strain rate of 1×10^{-3} s^{-1} and a temperature of 680 °C. Color legend shows the local strain-rate scale.

3. Results and discussion

Fig. 1a shows the deformation curve for the studied Fe–18Cr–8Ni–2.8Cu austenitic steel deformed at a strain rate of 1×10^{-3} s^{-1} and a temperature of 680 °C. The PLC effect manifestsitself as the serrated flow stress on deformation curve.

The shape of the deformation curve recognized as increase in the flow stress followed by a drop to or below the general stress level is identified as type A behavior [12]. As can be seen in Fig. 1b illustrating distribution of stress serrations, the histogram has asymmetrical monotonically decreasing shape corresponding to the type A instability [12].

The local strain rate maps (Fig. 2a, b) and the corresponding sections of the deformation curve (Fig. 2a′, b′) for the sample of the studied austenitic steel tested at a strain rate of 1×10^{-3} s^{-1} and temperature of 680 °C show the change in the distribution of the local strain rate along the vertical center line of the sample (along the tensile direction) with the test time. The appearance of a new band is observed at every corresponding stress drop, while its propagation occurs during an increase in the flow stress.

It can be seen that PLC bands nucleate at the end of the sample and then continuously propagate to the opposite side (Fig. 2a, b). According to the well-known classification, this behavior is typical for the type A bands [6]. Continuous propagation along the entire gauge length of the sample is observed up to 260 s (Fig. 2b) which approximately corresponds to the maximal stress. The average distance over which the bands propagate continuously during strain hardening stage is 16.2 mm. After 260 s, PLC bands began to propagate over a short distance of 6.9 mm. At this stage the deformation curve shows the apparent “steady state” (Fig. 2b′).

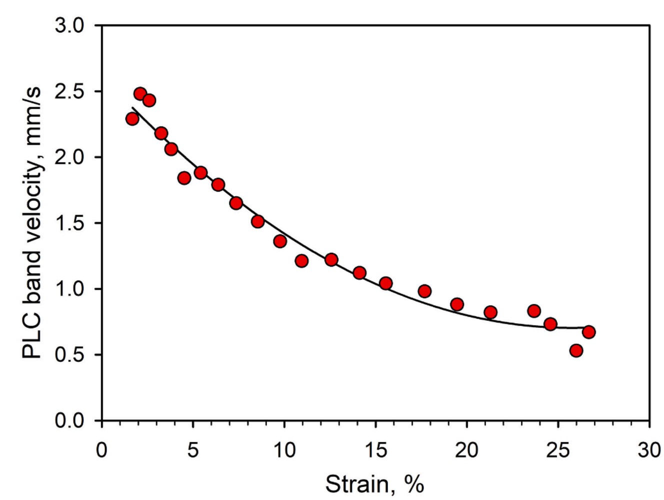

Fig. 3. Evolution of the band velocity with strain for an Fe–18Cr–8Ni–2.8Cu austenitic steel tested at a strain rate of 1×10^{-3} s^{-1} and a temperature of 680 °C.

As can be seen on the local strain rate maps presented in Fig. 2a, the first deformation bands are not clearly seen as compared with well-identified bands illustrated in Fig. 2b. This is due to rising intensity of the bands with strain [3,5].

The kinetic characteristics of the deformation bands were determined from the local strain rate maps. The velocity of PLC bands is determined as the speed of the displacement of the areas corresponding to the maximum local strain rate within the band [5]. Fig. 3 shows the evolution in the band velocity for the austenitic steel. It can be seen that the values of band velocity gradually decrease with increasing the strain (Fig. 3). The reduced ability of the band to propagate is associated with an increase in the number of obstacles to the dislocation motion with strain. Thus, the deformation band kinematics persists at different strain hardening stage.

According to [3] for austenitic steel, an increase in test temperature from 450 to 550 °C leads to a decrease in the distance continuously propagated by the bands, wherein the behavior of the bands shows some characteristics of the type B behavior. However, the results obtained in this study at even higher temperature (680 °C) using DIC did not confirm the observed tendency to decrease the distance continuously propagated by the bands with increase in temperature. Conversely, the behavior of PLC bands at temperature of 680 °C shows clearly different tendency. It should be noted that increase in the distance continuously propagated by the bands may be due to the overstress contributing to the transfer of plastic strain to neighboring regions of the sample [8]. There are several known causes leading to an increase in local overstress [8]. It is assumed that the cause of the observed PLC band behavior in the Fe–18Cr–8Ni–2.8Cu austenitic steel at temperature of 680 °C is the microstructural changes occurring in the material at temperature about 650 °C [10], namely, formation of the second phase particles. Nevertheless, this issue remains uncertain and will be considered in detail in the following works.

4. Conclusion

Serrated flow of an Fe–18Cr–8Ni–2.8Cu austenitic steel deformed at a strain rate of 1×10^{-3} s^{-1} and a temperature of 680 °C exhibits type A instability. The spatiotemporal behavior of the PLC bands is characterized by the continuous propagation along the entire gauge length of the sample. Straining leads to increased intensity of PLC bands while velocity and the distance continuously propagated by the bands tend to decrease with increase in the strain.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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