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Investigation using digital image correlation of Portevin-Le Chatelier Effect in Hastelloy X under thermo-mechanical loading

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ABSTRACT

The plastic behavior of Hastelloy X subjected to thermo-mechanical loading was investigated in this work, and the phenomenon of dynamic strain aging was studied under isothermal conditions, using digital image correlation (DIC). The material of interest, Hastelloy X a Ni-based superalloy, is widely used in high temperature applications. It was seen that Hastelloy X exhibits serrated plastic flow behavior between temperatures of 300 °C and 700 °C, as a consequence of the dynamic strain aging effect, which, depending on temperature, manifests as type A/B or A and B oscillations on the uniaxial tension stress–strain curve, and is characterized by strain concentration bands propagating along the length of the specimen. The characteristics of Portevin-Le Chatelier (PLC) band internal strain distribution in uniaxial tension experiments were also investigated. The bands themselves were seen to have internal (sub)bands of two or three smaller strain jumps. An analysis of the strain increments induced by these bands was performed and clearly illustrates the inhomogeneous nature of the deformation – both spatially and temporally. In addition to the uniaxial behavior, biaxial stress states were investigated by studying PLC band formation near a notch in a double notched tensile geometry. Similar macroscopic results to the uniaxial case were seen while the strain bands themselves were seen to initiate in the notch region and travel away from the notches.

1. Introduction

The demand for high performance materials for structural applications in extreme environments has driven the development of new materials like superalloys. To allow realization of functional designs such as structural thermal shields for space vehicles or pressure vessels for nuclear reactors using advanced materials, an understanding of their mechanical response is needed. In the case of metallic materials, it is of particular interest to study their behavior in the plastic regime, and uncover factors causing the observed material response. Many engineering metals exhibit irregular plastic flow, usually manifested as stress serrations ("jerky flow") or strain jumps ("strain staircase") in their uniaxial tensile response. Such irregular macroscale plastic flow, observed only in limited regimes of strain rate and temperature and sometimes above a critical strain

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(Wagenhofer et al., 1999), is caused by inhomogeneous deformation within various localization bands that can be either static or propagating along a specimen. The Portevin-Le Chatelier (PLC) effect is characterized by such instabilities in plastic flow and strain localizations, attributed primarily to a dynamic strain aging effect in which diffusion of solute atoms and dislocation motion occur over comparable time scales therefore necessitating the dislocations to continuously overcome the obstacles. Several factors, such as temperature and strain rate influence the occurrence of the PLC effect, which is also affected by the possible presence of precipitates (Thevenet et al., 1999; Argon, 2008; Liang et al., 2009). The presence of precipitates can cause rapid plastic flow upon reaching a critical strain energy, thus influencing the strain needed for the onset of a PLC effect. Extensive studies on the PLC effect and dynamic strain aging have been carried out by, among others, Kubin and Estrin (1990), Clausen et al. (2004), Benallal et al. (2006, 2008), Tong and Zhang (2007), Zavattieri et al. (2009) and Feng et al. (2012). The PLC effect has been associated with the relative mobility of dislocations and pinning obstacles in a metal (Cottrell, 1953; McCormick, 1971; van Den Beukel, 1980). For example, Clausen et al. (2004) showed the association between this serrated flow and localized shearing failure of precipitates in aluminum alloys. Corby et al. (2004) and Zhang et al. (2013), explained the PLC effect in Magnesium alloys. Though a complete understanding of the factors affecting the behavior of serrated plastic flow has not been established, the reason for serrated flow in the stress–strain curve has been attributed to negative strain rate sensitivity, which has been observed in different aluminum alloys (McCormick, 1988; Shabadi et al., 2004; Ranc and Wagner, 2005). There has also been an effort to study instabilities as a consequence of Portevin-Le Chatelier effect and Lüders bands in ferritic steels (Nikulin et al., 2010; Wenman and Chard-Tuckey, 2010; Chan et al., 2012; Hallai and Kyriakides, 2013).

Most structural components also possess geometrical features such as holes, corners or gaps that are necessitated by design to accommodate fasteners, joints, or for weight reduction. Under the influence of combined thermal and mechanical loads, such stress concentration sites may become initiation sites of the dynamic strain aging bands (Swaminathan et al., 2014). The local strain fields can be highly inhomogeneous in such biaxial, or in general triaxial, loading situations. The effect of dynamic strain aging in components with geometric features has received far less attention in the literature. Dynamic strain aging in aluminum alloys with stress concentrators has been studied by Benallal et al. (2008) and Tong et al. (2011). Both works presented a qualitative analysis of the PLC band formation in the presence of U-notches and V-notches at room temperature. Additional study in this area is needed to fully characterize the dynamic strain aging effect in conditions other than uniaxial loading.

Hastelloy X was chosen for the present study as a "simple" high-temperature alloy, with well-known behavior under isothermal high temperature mechanical loading (United States. Dept. of Defense, 2002). Hastelloy X is strengthened by solute hardening and its response is affected by dynamic strain aging. However, its plastic behavior is actually quite complex, as the hardening response under certain thermo-mechanical loading cycles was found to be unbounded by the isothermal stress–strain behaviors at the same test temperatures, *i.e.*, when applying one loading–unloading cycle at elevated temperature followed by one loading–unloading cycle at lower temperature the resulting response does not fall between the lower and higher isothermal stress–strain curves (Miner and Castelli, 1992; Swaminathan et al., 2014). In addition, chromium carbide precipitation in many Ni-based alloys can produce dynamic strain aging effects during deformation. Sakthivel et al. (2012) presented the stress–strain curves for Hastelloy X in the temperature range of 300–1023 K, at three different strain rates. They observed serrated flow at temperatures between 523 K and 927 K. Similar results were seen in Mo et al. (2013) for Ni-based superalloy 617 and Gao et al. (2013) for Ni–Co superalloy TMW.

The main objective of this work is to investigate the PLC effect that is present during plastic deformation of Hastelloy X using both far-field measurements based on load and displacement and near-field measurements using two-dimensional, *i.e.*, single camera, digital image correlation (DIC), and to do so for both homogeneous and nonhomogeneous stress states. Uniaxial tension samples were used for studying nominally uniaxial stress states, and double notched specimens were used to induce a bi-axial stress concentration in order to investigate PLC band formation under multi-axial stress states. The DIC technique allows greater understanding of dynamic strain aging effects as it can provide a wealth of information (*e.g.*, Tong and Zhang (2007) and Renard et al. (2010)), and has not been used at all in the observation of the phenomenon at high temperatures as is done here. More information about DIC, which uses digital images taken before and after deformation to extract in-plane displacement and strain on the sample's surface, can be found in Sutton et al. (2009). From an experimental point of view characterizing dynamic strain aging and PLC band morphology and behavior (Tong and Zhang, 2007) is made possible with DIC, at multiple scales and with suitable spatio-temporal resolution. It may then be possible to understand the micromechanical behavior that affects the continuum scale response of a material that exhibits a PLC effect (Tong, 2005; Abuzaid et al., 2012). Using DIC it is also possible to determine the behavior in extreme environments where other optical techniques may be limited due to complex experimental setups or experimental conditions. This work discusses the response of Hastelloy X at various test temperatures, extends the PLC band formation visualization to temperatures up to 700 °C, and offers an explanation on the interaction between the load history and strain behavior. It also provides some insight on the PLC behavior of Hastelloy across a range of temperatures in the plastic regime.

2. Experimental methods

2.1. Material and sample preparation

The material used in this study is Hastelloy X which is a solution heat treated Nickel-based superalloy with superior strength and oxidation resistance up to 1100 °C, making it a material of choice for combustion zone components in aircraft