International Journal of Plasticity 61 (2014) 32–48

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Experimental and numerical analysis about the cyclic behavior of the 304L and 316L stainless steels at 350 °C

Lakhdar Taleb [a,*], Georges Cailletaud [b], Kacem Saï [c]

[a] INSA, GPM, CNRS UMR 6634, BP 08 avenue de l'université, 76801 St. Etienne du Rouvray Cedex, France
[b] MINES ParisTech, Centre des Matériaux, CNRS UMR 7633, BP 87, 91003 Evry Cedex, France
[c] UGPMM Ecole nationale d'ingénieurs de Sfax, B.P. 1173, Sfax, Tunisia

ARTICLE INFO

Article history:
Received 11 December 2013
Received in final revised form 7 May 2014
Available online 9 June 2014

Keywords:
A. Fatigue
B. Cyclic loading
B. Elastic-plastic material
B. Metallic material
Ratcheting

ABSTRACT

In a previous study, we have demonstrated that cyclic accumulation of the inelastic strain exhibited by 304L SS at room temperature under tension–compression stress control is mostly due to creep (Taleb and Cailletaud, 2011). The same result in the same conditions is pointed out for 316L SS (Taleb, 2013a). In the present paper, the cyclic behavior of both 304L and 316L stainless steels at 350 °C is investigated. Creep is not significant at this temperature. In addition to tension–compression tests, the effect of non-proportional loading paths (axial-torsion) is considered for both stress and strain controlled conditions. The study suggests that ratcheting is very small with the different mean stress and amplitude used remaining into the assumption of small strains; this observation may be linked to the large cyclic hardening exhibited by both materials. However ratcheting seems more important under non-proportional loading path compared to the equivalent tension–compression conditions. A multi-mechanism model has been used to simulate the whole experimental data base. After the identification process of the material parameters conducted by considering only strain controlled experiments, its predictive capabilities have been evaluated on the stress controlled tests. The model presents a very good quantitative agreement with the quasi absence of ratcheting. However, the model fails in describing the over-hardening (mostly isotropic) observed under monotonic loading when the maximum strain is large (about 4%).

1. Introduction

The cyclic behavior of metallic alloys has been extensively investigated during the last decade, in one-dimensional or more complex conditions for different classes of materials. Specifically, austenitic stainless steels have retained the attention of researchers, due to their complex cyclic behavior. Ratcheting combined with cyclic hardening can be observed under proportional and non-proportional loading paths (Abdel Karim, 2010; Bari and Hassan, 2002; Bocher et al., 2001; Hassan et al., 2008; Jiang and Zhang, 2008; Kang et al., 2004; McDowell, 1987; Moosbrugger, 1993, etc.). The strain memory effect (Belattar et al., 2012; Chaboche, 2008; Chaboche et al., 1979; Nouailhas et al., 1985; Ohno, 1982; Taheri et al., 2011, etc.) introduces a strong influence of the loading history on hardening.

The interaction between creep and ratcheting has also been evaluated at room temperature since a long time (Krempl, 1979, 1990; Yoshida, 1990, etc.). Nevertheless, the process is not well understood yet. It has been recently demonstrated that the cyclic

* Corresponding author. Tel.: +33 2 32 95 97 65; fax: +33 2 32 95 97 10.
E-mail addresses: lakhdar.taleb@insa-rouen.fr (L. Taleb), Georges.Cailletaud@ensmp.fr (G. Cailletaud), kacemsai@yahoo.fr (K. Saï).

http://dx.doi.org/10.1016/j.ijplas.2014.05.006
0749-6419/

accumulation of the inelastic strain under tension–compression stress control is mostly due to creep (Taleb and Cailletaud, 2011; Taleb, 2013a). This result suggests that ratcheting (as rate-independent phenomenon) is not significant for austenitic stainless steels in these conditions. The process of progressive deformation can then be better understood by considering conditions where creep is not significant like 350 °C (even if dynamic strain aging is present at this temperature). Out of recent works, one can advocate the study of Kang et al. (2006) dealing with the cyclic behavior of 304L SS under stress and strain control at different temperatures (20, 350, 700 °C). In this work, it is shown that contrary to 350 °C, the behavior of the material is clearly rate-dependent at 20 and 700 °C. The ratcheting is studied in different conditions of loading and temperature. Hence, it is concluded that at 20 °C and 700 °C, ratcheting is more important in a reference tension–compression test, if compared to a test at the same equivalent loading under non-proportional loading path. However, this result may be influenced by two main factors: the interaction with creep at these temperatures and; the geometry of the specimens used (solid in uniaxial tests versus tubular in multiaxial tests). A comparison of the tests performed at a temperature where creep is not significant (350 °C) and using the same geometry of the specimens for uniaxial and multiaxial tests would bring more accurate results. At 350 °C, ratcheting under tension–compression seems very small and stabilizes quickly during the first cycles (Kang et al., 2006). However this result is based on one multi-step test only and deserves confirmation for other loading conditions with different mean stresses and amplitudes. A study of the cyclic plasticity at 350 °C is also performed in (Kang et al., 2006) but only one amplitude in tension–compression is considered (0.5%) without any investigation of non-proportional loading conditions. As the material is sensitive to the amplitude as well as to the loading path, it is necessary to investigate these phenomena under different conditions. It is also worth studying the way results on 304L SS at 350 °C may be extended to 316L SS.

Yu et al. (2012) have studied the cyclic behavior of 316L SS under tension–compression at different temperatures (20, 150, 250, 350, 450 and 550 °C) but for only one amplitude (0.6%) close to Kang's one (0.5%) (Kang et al., 2006). They confirm the rate dependence of the behavior at room temperature and point out the strong influence of dynamic strain aging between 250 °C and 550 °C. The important strain hardening obtained at high temperature is explained by the latter phenomenon. Stress controlled tests under repeated loading were performed in which no significant plastic flow is observed during the unloading branch of the cycles. This makes these tests inadequate for the study of ratcheting.

In a recent study, we have carried out cyclic tests on 304L and 316L stainless steels at 350 °C (Taleb, 2013b). At small amplitudes, the stress controlled experiments produce a very small ratcheting, confirming the results of (Kang et al., 2006) under tension–compression. However, for large amplitudes, the cyclic accumulation of the inelastic strain becomes small but significant under one-dimensional loading, and even larger under non-proportional loading. This observation deserves verification, since it contradicts the results of (Kang et al., 2006) at room temperature. The tests performed under strain control show a serrated flow during the loading in the first cycle which is due to dynamic strain aging phenomenon (Yu et al., 2012). Very significant strain hardening is observed; however this observation is only based on tension–compression tests as no test is performed under non-proportional loading.

In this work, the behavior of both 316L and 304L stainless steels is investigated experimentally at 350 °C under proportional and non-proportional loading paths using strain as well as stress control. Most of the questions advocated above are considered: (a) we use the same specimen geometry (tubular) for both uniaxial and multiaxial tests in order to minimize the influence of this parameter; (b) we use different amplitudes for the stress as well as strain controlled tests; (c) different tests under stress control were performed for the comparison between the cyclic accumulation of the inelastic strain in tension–compression and its equivalent non-proportional loading; (d) assessment of the importance of the extra hardening under non-proportional loading path. In addition to experiments, some numerical simulations have been conducted in order to check the capabilities of the multi-mechanism model (Taleb and Cailletaud, 2010) in the prediction of the test responses obtained considering both steels.

In the next section, the details about the experimental investigations are described including the presentation of the materials, the specimens, the experimental device and the list of the tests performed under stress as well as strain control. The third section is devoted to the presentation of test results and their discussion. The numerical simulations of the tests performed are described in the fourth section that shows successively the constitutive equations of the model, the procedure used to calibrate the material parameters and finally, the comparison between the test responses and their simulations. Some concluding remarks are given in Section 5 meanwhile the response of the MM model in the absence of the dynamic recovery term in the kinematic hardening variables is discussed in Appendix A.

2. Experimental investigations

2.1. Materials

Two austenitic stainless steels (304L and 316L) have been considered in this study. Their average chemical compositions are given in Table 1a and b.

2.2. Specimen and experimental device

Thin-walled tubular specimens have been used in this study. The gage length is equal to 46 mm where a central part of 25 mm is used for the extensometry; the outer and inner diameters are equal to 20 mm and 17 mm respectively (Fig. 1).