Materials Science and Engineering A 534 (2012) 580–587

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

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

Effect of temperature and strain rate on serrated flow behaviour of Hastelloy X

T. Sakthivel[a,*], K. Laha[a], M. Nandagopal[a], K.S. Chandravathi[a], P. Parameswaran[a], S. Panneer Selvi[a], M.D. Mathew[a], Sarwan K. Mannan[b]

[a] Mechanical Metallurgy Division, Indira Gandhi Centre for Atomic Research, Kalpakkam – 603 102, India
[b] Special Metals Corporation, Huntington, WV 25705, USA

ARTICLE INFO

Article history:
Received 14 August 2011
Received in revised form 1 December 2011
Accepted 2 December 2011
Available online 13 December 2011

Keywords:
Hastelloy X
Serrated flow
Activation energy
Phase precipitation

ABSTRACT

Serrated flow behaviour of Hastelloy X has been examined over a wide range of temperature (300–1023 K) and strain rate ($3 \times 10^{-3}s^{-1}$ to $3 \times 10^{-5}s^{-1}$). The alloy exhibited different types of tensile serrated flow in the intermediate temperature range of 473–923 K. Normal portevin-Le Chatelier effect (PLE) exhibiting type A and B serrations were observed at temperatures less than 823 K and inverse PLE exhibiting type C serrations was noticed at temperatures above 823 K. The average activation energy value of 106 kJ mol^{-1} for the A and B types of serrated flow has been evaluated. The evaluated activation energy value revealed that the migration of molybdenum in the nickel matrix has been found to be responsible for the occurrence of serrated flow in the alloy.

1. Introduction

Hastelloy X also known as HX alloy is a solid solution strengthened Ni-based superalloy. It derives its mechanical strength mainly by solid solution strengthening from Mo, Co and W. A few M_6C precipitates rich in molybdenum are also reported in this alloy. It is widely used for gas turbine engine combustors, tail pipes, and being considered as a candidate material for high temperature gas cooled reactor components because of its good oxidation resistance and strength at high temperatures [1–7]. Mechanical properties of superalloy materials are strongly dependant on deformation parameters such as temperature and strain rate [6]. Deformation and dynamic recrystallisation behaviour of Hastelloy X superalloy using hot compression experiments over a wide range of temperature and strain rate has been investigated by Aghaie-Khafri et al. [6,7]. The alloy as in several Ni-based superalloys and steels exhibits complicated yielding behaviour in the intermediate temperature range [8–14]. This has been attributed to dynamic strain aging (DSA) behaviour. The DSA is a phenomenon of serrated or jerky flow that occurs after a certain amount of critical plastic strain due to the dynamic interaction between mobile dislocations with solute atoms [8–14]. In general, the critical plastic strain (ε_c) decreases with increasing test temperature (normal behaviour). However in some cases increase in critical plastic strain (ε_c) with increasing temperature (inverse behaviour) has been observed in austenitic stainless steels and Ni-based superalloys at relatively higher temperatures and lower strain rates [8–14].

The measurement of critical plastic strain (ε_c) for the onset of serrated flow and its dependence on strain rate ($\dot{\varepsilon}$) and temperature (T) is essential to understand the underlying mechanisms for serrated flow [11–15]. This dependence is generally expressed as

$$\varepsilon_c^{(m+\beta)} = K\varepsilon' \exp(Q/kT) \quad (1)$$

where m and β are the respective exponents for the variation of vacancy concentration ($C_v \propto \varepsilon^m$) and mobile dislocation density ($\rho_m \propto \varepsilon^\beta$) with plastic strain, K is a constant, Q is the activation energy for serrated flow, k is the Boltzman constant and T is the absolute temperature. The exponent $(m+\beta)$ can be obtained from the slope of the plot of $\ln \dot{\varepsilon}$ vs $\ln \varepsilon_c$ at constant temperature. Methods for evaluating activation energy associated with serrated flow are described as follows [11–15]:

Method I: The quasi-static aging (McCormick) model, relates the concentration dependence of solute causing serrated flow with critical plastic strain (ε_c) for onset of serrated flow as

$$\varepsilon_c^{(m+\beta)}/T = (C_1/\Phi C_0)^{3/2}(\varepsilon' kb/LNU_m D_0)[\exp(Q/kT)] \quad (2)$$

where C_0 is the initial concentration of solute in the alloy, C_1 is the local concentration of solute at the dislocation required for locking, L is the obstacle spacing, U_m is the maximum solute-dislocation interaction energy, D_0 is the frequency factor, b is the Burger's vector and N and Φ are constants. Using the above equation, Q can be evaluated for a given $\dot{\varepsilon}$ value from the plot of $\ln[\varepsilon_c^{(m+\beta)}/T]$ vs $1/T$, as Q = slope $\times$ k. In this method the individual values of $(m+\beta)$ obtained at different temperatures have been used [11,13,15].

* Corresponding author. Fax: +91 44 27480075.
E-mail address: tsakthivel@igcar.gov.in (T. Sakthivel).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.12.011

Method II: Solute drag (Cottrell) model, from Eq. (1), the slope of a plot of $\ln \varepsilon_c$ vs $1/T$ at constant strain rate ($\dot{\varepsilon}$) can be used to evaluate Q, as Q = slope $\times$ $(m+\beta) \times k$. This method uses an average value of $(m+\beta)$ obtained over a range of strain rate ($\dot{\varepsilon}$) and temperature (T) values [11,13].

In the present investigation, the influence of temperature and strain rate on tensile serrated flow behaviour has been investigated. Both the above-mentioned methods were used to determine the activation energy for serrated flow.

2. Experimental details

The chemical composition of Hastelloy X is given in Table 1. The alloy was solution heat treated at 1450 K for 0.5 h followed by water quenched. The button head cylindrical tensile specimen had 4.0 mm gauge diameter and 28.6 mm gauge length. The tensile tests have been performed at various test temperature ranging from 300 to 1023 K and at constant cross-head speed with nominal strain rate of 3×10^{-5} s^{-1}, 3×10^{-4} s^{-1} and 3×10^{-3} s^{-1} in air. Prior to tensile testing, specimen has been heated to test temperature using electrical resistance split type furnace having three heating zones. Separate temperature controllers are used to maintain constant temperature across the different zones of the furnace. K-type thermocouples have been used to monitor the temperature of the testing specimen. The specimen was held for 15 min at test temperature to ensure uniform temperature along the specimen within $\pm$2 K. Activation energy for serrated flow has been evaluated using methods I and II, which have been described in Section 1. Specimen for microstructural investigation was extracted from gauge portion of the tensile specimen. Metallography was carried out by scanning electron microscope (SEM). Standard metallography techniques were used to prepare the specimen for microstructural investigation. The specimen was etched with Kalling's solution (50 ml methanol, 50 ml hydrochloric acid and 2.5 g of cupric chloride) for microstructural observation. Fractured surfaces of the tensile specimens tested at various temperatures have been investigated using SEM.

3. Results

3.1. Microstructure of solution treated Hastelloy X

Microstructure of Hastelloy X in the solution treated condition is shown in Fig. 1. It consists of equiaxed grain structure with average grain size of around 200 μm. A few Mo-rich M_6C carbides were found both on the grain and twin boundaries. The particles were identified by energy dispersive X-ray (EDX) analysis of chemical composition.

3.2. Serrated flow behaviour

Stress–strain curves for the alloy tested in the temperature range of 300–1023 K at the strain rate of 3×10^{-3} s^{-1} are shown in Fig. 2(a). Similar behaviour was observed in other two strain rates. Stress–strain curves were smooth at room temperature for all the strain rates employed. Serrated tensile flow was observed on the stress–strain curve at temperatures in between 523 K and 923 K at the strain rate of 3×10^{-3} s^{-1}. Occurrence of serrated flow in the stress strain curve shifted towards at lower temperature with further decrease in strain rate. The height of serrations in the stress–strain curve was found to increase with the increase in temperature and deformation and with the decrease in strain rate. Serrations of A, A + B, B and C types were noticed as shown in Fig. 2(b).

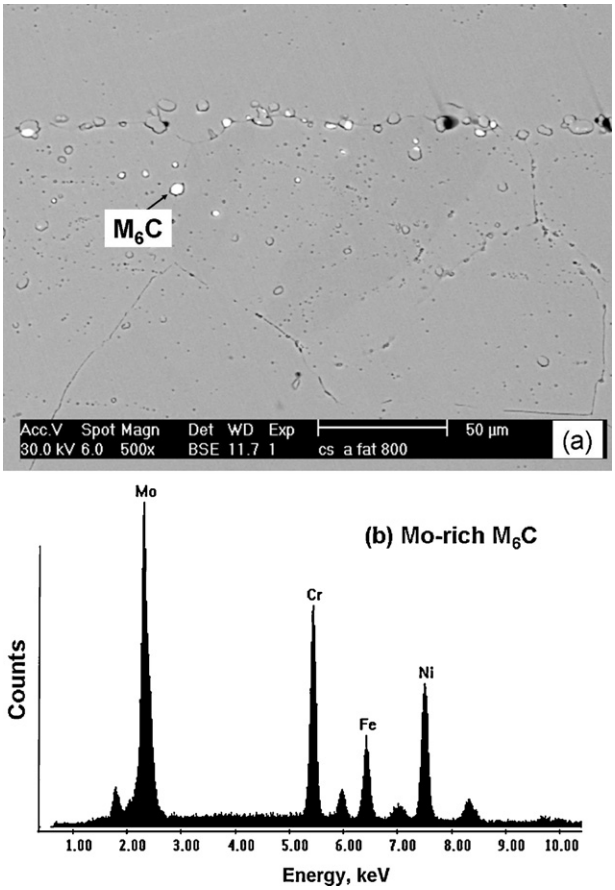

Fig. 1. Back scattered electron micrograph of Hastelloy X showing (a) Mo-rich M_6C precipitate, (b) EDX spectra of Mo-rich M_6C after solution treatment at 1450 K for 0.5 h.

Occurrence of serrated flow and its types at various temperatures and strain rates investigated are summarized in Fig. 3. Type A, type A + B, type B and type C serrations were observed at relatively low, intermediate, high and very high temperatures respectively in all the strain rates employed (Fig. 3). At lower strain rate of 3×10^{-5} s^{-1}, type A and B serrations were observed at temperature 773 K and below, whereas type C serration was observed at temperatures above 773 K. Further increase in strain rate, the occurrence of serrations of different types shifted towards at higher temperature (Fig. 3). In general, the frequency of serrations decreased with progressive deformation. The behaviour of type C serrations observed at relatively lower temperature was different from that observed at higher temperature. At 823 K, 873 K and 923 K, the type C serrations of small amplitude appeared initially and disappeared after certain percentage of elongation at the strain rates of 3×10^{-5} s^{-1}, 3×10^{-4} s^{-1} and 3×10^{-3} s^{-1} respectively. However, at larger progressive deformation regular type C serrations of large amplitude and frequency have been observed and continued up to fracture (Fig. 2a). No serrations were noticed at temperature below 473 K and above 823 K at the strain rate of 3×10^{-5} s^{-1}. However, increase in temperature for the onset and termination of serrations with increase in strain rates 3×10^{-4} s^{-1} and 3×10^{-3} s^{-1} have been observed.

Analysis of critical plastic strain (ε_c) for the onset of serration at different strain rates and temperatures were carried out to understand the mechanism responsible for serrated flow. The stress drop of 3 MPa in the stress–strain curve was used as a criterion for the measurement of critical plastic strain for onset of serrated flow. Similar procedure was adopted by other investigators [13]. The