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Temperature and Strain Rate Effects on Dynamic Strain Aging Behaviour of Hastelloy X

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---ABSTRACT---
Hastelloy X is a solid solution strengthened Ni-base high temperature alloy. It is widely used for gas turbine engine combustors and is considered as a candidate material for high temperature nuclear gas cooled reactors. Hastelloy X experience serrated flow behaviour in the intermediate temperature range of deformation which is referred to as dynamic strain aging (DSA). In this investigation the effects of test temperature and strain rate on DSA behavior of Hastelloy X was studied. Tensile testing was first performed over a temperature range of 22-700 ℃ and strain rate of 10-3 s-1. The alloy exhibited features of dynamic strain aging represented by well-defined serrations in the stress-strain curves at 550 and 650℃. No serrations were noticed at temperatures below 550 °C and above 650 °C at a strain rate of 10-3s-1. The frequency of serrations increased with progressive deformation up to the point of failure at each temperature. In order to test out the strain rate effect, additional tensile tests were performed at a slower strain rate of 10-5 s-1 at 550 and 650 ℃. The increase in test temperature from 550 to 650 ℃ and the decrease in strain rate from 10-3 to 10-5s-1 decreased the amount of both the flow stress and strain of the material. The intensity, frequency, and amplitude of the serrations increased with the decrease in strain rate and increase in temperature. The type of serrations was associated with the applied temperature and strain rate. Fracture surface examination indicated a change from ductile dimpled rupture at room temperature into ductile-brittle mixed mode at 650 ℃.

KEYWORDS - Hastelloy X, dynamic strain aging, tensile testing

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I INTRODUCTION

Hastelloy X is a solid solution strengthened Ni-based superalloy. It derives its mechanical strength mainly by solid solution strengthening from the alloying elements Mo, Co and W. It is widely used for gas turbine engine combustors 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]. Mechanical properties of superalloy materials are strongly dependent on deformation parameters such as temperature and strain rate. Deformation and dynamic recrystallization behavior of Hastelloy X has been investigated over a wide range of temperature and strain rates [2]. The alloy as in several Ni-based superalloys and steels exhibits complicated yielding behavior in the intermediate temperature range [3]. This has been attributed to the occurrence of dynamic strain aging (DSA) behavior which is referred to as the Portevin- Le Chatelier (PLC) effect [4]. The DSA is a phenomenon of serrated flow that occurs after a certain amount of critical plastic strain (εc) due to the dynamic interaction between mobile dislocations with solute atoms [5]. In general, the critical plastic strain decreases with increasing test temperature. This study presents the influence of test temperature and strain rate on dynamic strain aging behavior of Hastelloy X.

II EXPERIMENTAL

The chemical composition of Hastelloy X is given in Table 1. The alloy was solution heat treated at 1200°C for 0.5 h followed by water quenching. Cylindrical tensile specimens of 4.5 mm gauge diameter and 28 mm gauge length were tensile tested over a tensile test temperature of 22 to 700°C and a strain rate of 10^{-3} s^{-1}. Additional tensile tests were performed at 550 and 650 °C at a slower strain rate of 10^{-5} s^{-1}. Prior to tensile testing, each specimen was heated up to the required test temperature using electrical resistance split type furnace having three heating zones. Each specimen was held for 15 min at test temperature to ensure uniform temperature distribution along the specimen. Fractography was carried out using scanning electron microscope (SEM), (JOEL, JSM-400).

Table 1: Chemical Composition (wt.%) of Hastelloy X

C	Cr	Mo	Si	Mn	P	S	Fe	Co	W	Ni
0.0 7	21	8.59	0.24	0.51	0.014	0.00 1	19.4	0.5 5	0.5 9	48.9

III RESULTS

Figure 1 shows stress–strain curves of Hastelloy X after tensile testing over a temperature range of 22-700 °C and strain rate of 10−3 s−1. Stress–strain curves displayed smooth appearance at room temperature and up to 450°C and at 700°C. Serrated tensile flow was observed in the stress–strain curves at temperatures of 550 and 650 °C indicating the onset of dynamic strain aging which is referred to as the Portevin- Le Chatelier (PLC) effect. The frequency of serrations increased with the progress in deformation both at 550 and 650 °C. The amplitude of serrations in the stress strain curve increased with the increase in temperature from 550 to 650°C. In general, a decrease in the mount of flow stress and strain can be observed with the increase in test temperature from 22 to 700 °C. The value of the yield stress dropped 40% from 322 to 192 MPa whereas the ultimate tensile strength value only dropped 35 % from 710 to 460 MPa. The total elongation decreased from 63 % to 43% i.e. by about 30%.

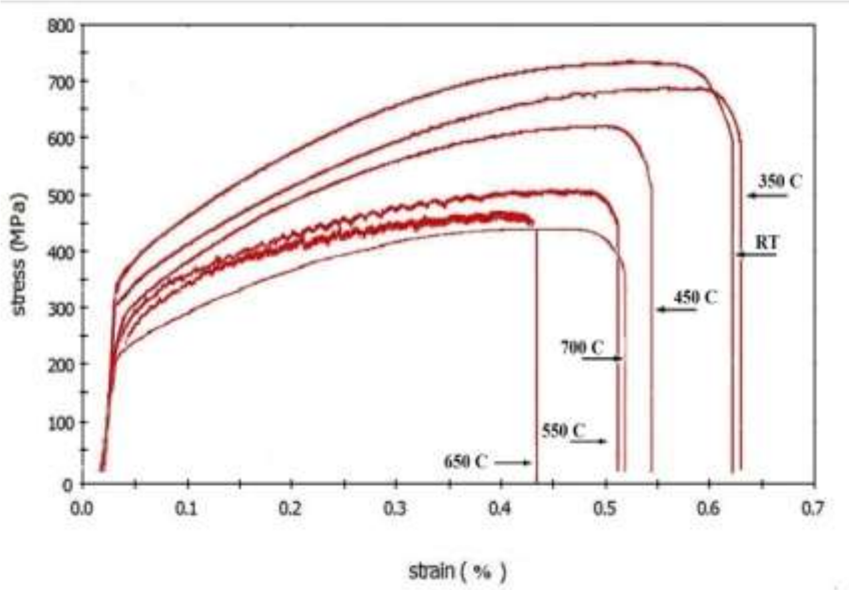


Fig. 1: Stress- Strain Curves at A Strain Rate of 10-3 s-1 at Various Test Temperatures

The effect of temperature and strain rate on the dynamic strain aging behaviour of Hastelloy X is shown in Figs. 2 and 3. In Fig. 2, testing at a strain rate of 10-3 s-1 shows that the rise in temperature from 550 to 650 °C resulted in a reduction in the flow stress and strain. The yield and ultimate stress values dropped 20 and 10 %, respectively whereas the strain decreased by 18 %. The strain hardening exponent (n) decreased as well from 0.51 to 0.48. Fig.3 shows results of testing at strain rate of 10-5s-1. The increase in test temperature from 550 to 650 °C decreased the yield stress and the ultimate tensile strength values by 30 and 15%, respectively. The elongation decreased by 15%. The corresponding strain hardening exponents were 0.42 and 0.38, respectively. The results of the tensile properties at a strain rate of 10-3 and 10-5 3s-1 of Figs. 2 and 3 are summarized in Table 2. As can be shown in Figs. 2 and 3 the frequency and the amplitude of serrations in the stress–strain curves increased with the increase in temperature and decrease in strain rate.

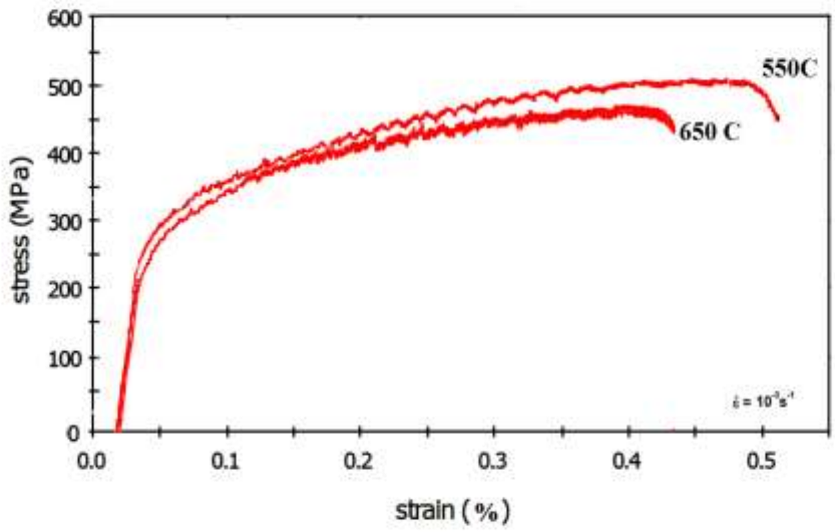


Fig.2: Stress-Strain Curves of Hastelloy X Tested at 550 And 650 °C at A Strain Rate of 10-3s-1

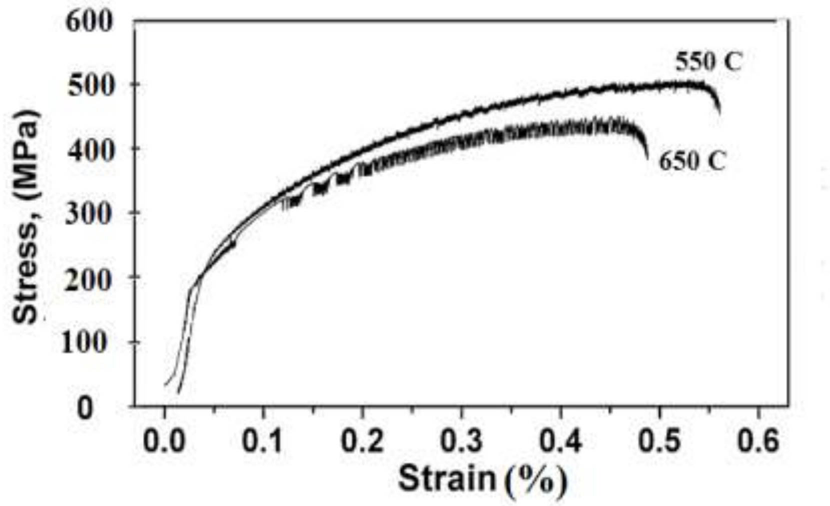


Fig.3: Stress-Strain Curves of Hastelloy X Tested at 550 And 650 °C at A Strain Rate of 10-5s-1

Table 2: Tensile Properties of Hastelloy X at 550 and 650 °C

Strain rate s^{-1}	Temp. °C	Yield stress MPa	UTS MPa	Elongation %	n
10^{-3}	550	230	510	0.52	0.51
	650	192	460	0.43	0.48
10^{-5}	550	210	480	0.45	0.42
	650	170	420	0.38	0.38

As can be seen in Fig. 2 the type of serrations changed from type A at 550 to type B at 650 °C whereas in Fig. 3 the serrations changed from type B at 550 to type C at 650 °C.

The serrations associated with repeated yielding during plastic deformation have been classefied as three different types A, B and C. They are characterized in Fig. 4. All these types of serrations can be produced by a suitable combination of strain rate and test temperature. Type A serrations show a rise and fall in stress above the general level of the stress-strain curve and is usually observed at low aging temperatures or high strain rates. Type B serrations are usually observed at intermediate temperature and strain rates and are characterized by an increase and drop in stress around the general level of the stress-strain curve. Type C serrations show reduction and increase in stress below the general level of the stress- strain curve and are referred to as unlocking serrations. They are observed at high temperatures or low strain rates [4].

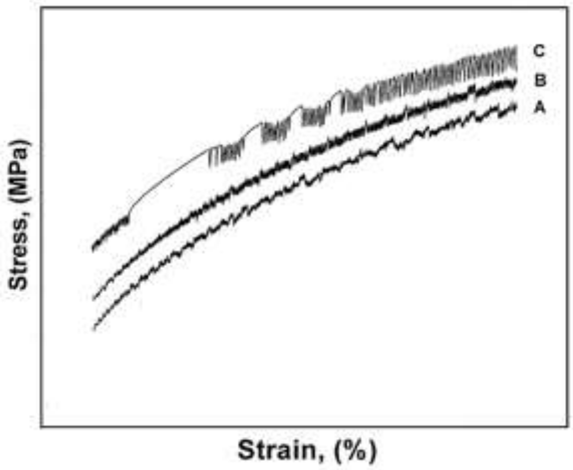
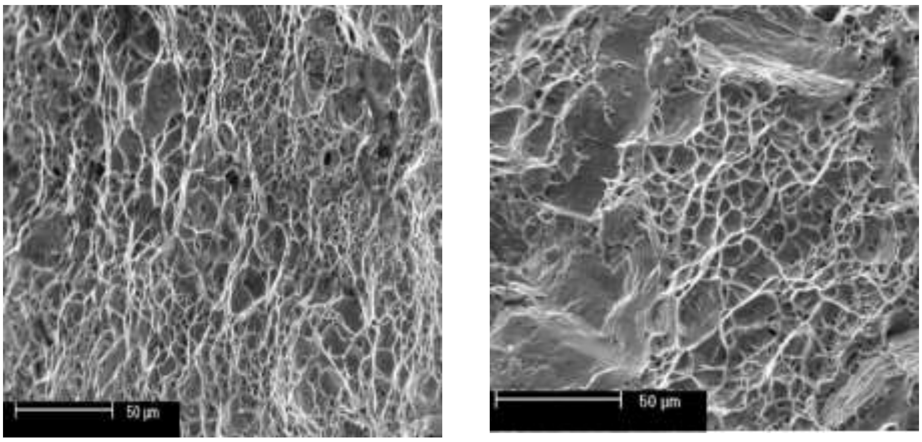


Fig. 4: Schematic Representation of Different Types of Serrations

The effect of serrated flow on the fracture behaviour of tensile specimens was examined by scanning electron microscopy (SEM). Figure 5 views SEM fractographs of specimens tested (a) at room temperature and (b) at 650 °C. As can be seen there is transition from ductile mode (Fig.5a) into a mixed mode of fracture (Fig. 5b). This demonstrates that the occurrence of serrated flow at 650 °C was accompanied by introduction of brittle fracture features characterized by cleavage facets alongside the ductile mode of dimpled rupture (Fig.5b).



(a) (b)

Fig. 5: Fracture Surfaces of Tensile Specimens Tested at (a) RT (ductile mode of failure) at strain rate of 10-3 s-1 and (b) 650°C (mixed mode of failure) at strain rate of 10-5 s-1

IV DISCUSSION

The alloy exhibited serrated flow during tensile deformation in the intermediate test temperature range (550 and 650 °C). The results showed that the increase in test temperature and decrease in strain rate resulted in a reduction in both the amount of flow stress and strain. This was accompanied by an increase in both the frequency and amplitude of the resulting serrations. In addition, there was a change in the type of serrations with the increase in temperature and decrease in strain rate. Similar kind of serrated flow has been reported in the literature [6]. The increase in stress drop with increasing strain as observed for type A, B and C serrations is assumed to be due to progressivly longer arrest time (waiting time of mobile dislocations at

forest dislocations) as the mobile dislocation density increases with increasing strain [6]. The increase in the frequancy and amplitude of serrations with increasing test temperature (Fig. 2) and with decreasing strain rate (Fig. 3) could be due to the increase in the activation energy and aging time required for the aging process to be complete [6].

In recent years, it has become accepted that dynamic strain aging is controlled by the diffusion of solute atoms. The two main models that could interpret the dynamic strain aging behavior are the dislocation-solute interaction model (DSI) [7] and dislocation-dislocation interaction model (DDI) [8]. Both models are based on a more realistic view of dislocation motion than the original solute drag model [9].The "solute drag model" suggested that dynamic strain aging results from the interaction of solute atoms with moving dislocations. This interaction takes place when the drift velocity of the solute is similar to the dislocation velocity. This type of interaction is responsible for the occurrence of serrations observed at low aging temperatures where interstitial solutes (basically carbon and nitrogen) result in repeated locking and releasing mechanism of dislocations. The chemical composition of the Hastelloy X under investigation shows reduced amount of carbon (0.07) and absence of nitrogen. This indicates a diminished role of carbon and nitrogen in the process of serrated yielding at low aging temperatures [10].

The conclusion is that dynamic strain aging (serrated flow behavior) of the studied Hastelloy X is achieved by the interaction of mobile dislocations with diffusing substitutional solutes (Mo, Cr) which have slower rates of diffusion at relatively higher temperatures than interstitial solutes [11]. The disappearance of serrated flow at test temperature of 700 °C in the stress strain curve (Fig. 1) might have occurred due to the larger critical plastic strain required for the onset of serrations. Precipitation of M6C, M23C6 and Cr-rich σ-phase has been observed in tensile specimens tested at high temperatures where the disappearance of serrations occurred [12].

Figure 6 displays the phase precipitation and time- temperature transformation diagram of Hastelloy X. As can be shown Hastelloy X in the solution treated condition consists of the face-cantered cubic (γ) solid solution matrix and a few of Mo-rich carbides. The M6C carbide is unstable with respect to the Cr-rich carbide M23C6 during aging at intermediate temperatures [13]. The existence of M6C and M23C6 carbides in the microstructure of Hastelloy X could have played a significant role in the occurrence of type C serrations with its intense frequency and high amplitude at 650 °C and strain rate of 10-5 s-1 (Fig.3). Moreover, these types of carbides could also contribute in the variation of the fracture type from ductile mode at room temperature to a mixed mode at 650 °C (Fig. 5).

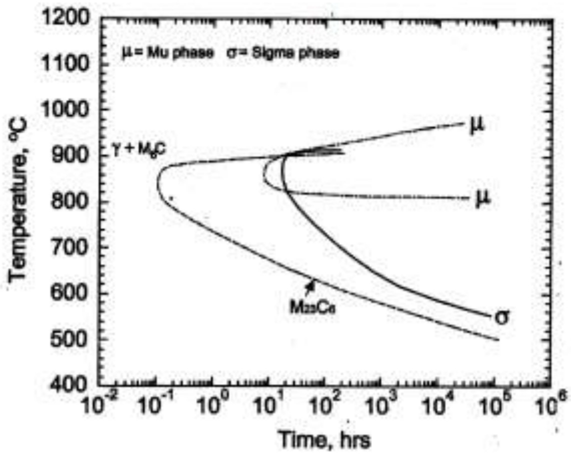


Fig. 6: Phase Precipitation and Time- Temperature Transformation Diagram of Hastelloy X [13]

V CONCLUSION

Tensile tests have been performed on Hastelloy X over a temperature range of 22-700 °C and a strain rate of 10-3s-1. The alloy exhibited features of dynamic strain aging represented by well-defined serrations in the stress-strain curves at 550 and 650°C. No serrations were observed at temperatures below 550 °C and above 650 °C at a strain rate of 10-3 s-1. Separate tensile tests were also conducted at a slower strain rate of 10-5 at 550 and 650 °C. The flow stress and strain decreased while the frequency and amplitude of serrations increased with the increase in test temperature from 550 to 650 °C and the decrease in strain rate from 10-3 to 10-5 s-1. The types of serrations changed from type A→B→C with the increase in test temperature and decrease in strain rate. The fracture surface demonstrated a change from ductile dimpled rupture at room temperature into ductile-brittle mixed mode at 650 °C.

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