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# Thermo-mechanical cyclic hardening behavior of 304 stainless steel at large temperature ranges: Experiments and simulations

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## ABSTRACT

Thermo-mechanical cyclic experiments on 304 stainless steel were performed at several temperature ranges with  $T_{\min}$  (minimum temperature) of 150 °C and  $T_{\max}$  (maximum temperature) ranging from 350 °C to 1000 °C. Corresponding isothermal cyclic experiments were also performed at several temperatures. Temperature-history dependent cyclic hardening was thus observed to significantly occur under thermo-mechanical cyclic loading when  $T_{\max}$  was around 600 °C. In contrast, almost no cyclic hardening occurred when  $T_{\max}$  was 1000 °C. The observed, thermo-mechanical cyclic hardening behavior was then simulated using a cyclic viscoplastic constitutive model with a cyclic hardening parameter. The simulation focused on the saturated state of cyclic hardening, leading to the following findings. The saturated thermo-mechanical cyclic hysteresis loops were not predicted well by simply taking into account temperature dependence in the cyclic hardening parameter. Then, by assuming the cyclic hardening parameter to be dependent on  $T_{\max}$ , the saturated thermo-mechanical hysteresis loops were simulated well. These mean that the cyclic hardening parameter of 304 stainless steel should not change with temperature but depend on  $T_{\max}$  in the saturated state of cyclic hardening under thermo-mechanical cyclic loading.

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## 1. Introduction

The elastic-plastic cyclic behavior of metallic materials usually depends on temperature. The temperature dependence necessarily makes the thermo-mechanical cyclic hysteresis loops of stress and mechanical strain different from the isothermal hysteresis loops of stress and strain. It is a *usual thought* that the thermo-mechanical cyclic behavior can be simulated well if temperature dependence is simply taken into account in the material parameters in a constitutive model so as to fit isothermal cyclic experiments. This usual thought was shown to be valid for copper [1], 2.25Cr-1Mo steel [2], P91 steel [3], and so on.

The usual thought mentioned above, however, is not appropriate for 304 and 316 stainless steels [4–6]. For example, Ohno et al. [4] observed the following on 304 stainless steel under thermo-mechanical cyclic loading with temperature cycling between 200 °C and 550 °C: the saturated peak stress at 200 °C under this thermo-mechanical cyclic loading was much larger than that under isothermal cyclic loading at 200 °C. This result was out of the expectations of the usual thought. The thermo-mechanical cyclic hardening of 304 stainless steel was thus shown to be temperature-history dependent, and was predicted well on the assumption that the evolution of cyclic hardening at  $T_{\max}$  (maxi-

mum temperature) occurred at lower temperatures as well under the thermo-mechanical cyclic loading.

It is well-known that 304 and 316 stainless steels exhibit noticeable cyclic hardening under isothermal cyclic loading around 500 °C [4,7]. This phenomenon is a consequence of dynamic strain aging, which most significantly occurs around 500 °C [8–10]. The above-mentioned finding by Ohno et al. [4] implies that the microstructure having developed under the influence of dynamic strain aging around 500 °C remains almost unchanged at lower temperatures under thermo-mechanical cyclic loading with temperature cycling between 200 °C and 550 °C, resulting in much larger peak stresses at 200 °C than those under isothermal cyclic loading at 200 °C. For a nickel-base superalloy, the microstructure was observed to be mainly influenced by  $T_{\max}$  under thermo-mechanical cyclic loading [11].

It is also well-known that metallic materials may exhibit thermal recovery in addition to strain hardening at high temperatures [12–15]. Obviously, thermal recovery affects cyclic hardening. For 304 and 316 stainless steels, thermal recovery markedly occurs at temperatures higher than about 600 °C [13,14]. It is worth investigating the effect of thermal recovery on the cyclic hardening behavior under thermo-mechanical cyclic loading in the presence of dynamic strain aging.

In this study, the cyclic hardening behavior of 304 stainless steel under thermo-mechanical cyclic loading at large temperature ranges

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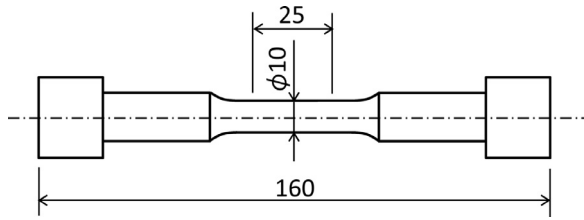


Fig. 1. Shape of specimens; size in mm.

**Table 1**  
List of isothermal cyclic experiments.

$T$ (°C)	150	350	500	600	700	850	1000
$\dot{\epsilon} = 10^{-4} \text{ s}^{-1}$ , $\Delta\epsilon = 0.01$	○	○	○	○	○	○	○
$\dot{\epsilon} = 10^{-5} \text{ s}^{-1}$ , $\Delta\epsilon = 0.01$	–	–	–	○	–	○	–

was investigated. Both thermo-mechanical and isothermal cyclic experiments were performed at temperatures ranging from 150 °C to 1000 °C. The observed, cyclic hardening behavior was simulated using a cyclic viscoplastic model with a cyclic hardening parameter. The simulation focused on the saturated state of cyclic hardening. The cyclic hardening parameter was thus assumed to be dependent on either temperature  $T$  or  $T_{\max}$  under thermo-mechanical cyclic loading. This assumption was much more straightforward and comprehensible than that in [4], in which an evolution equation was considered to represent cyclic hardening. We thus found that the saturated thermo-mechanical hysteresis loops were simulated well using the  $T_{\max}$  dependent cyclic hardening parameter in the presence of dynamic strain aging and thermal recovery.

Throughout this paper, a superposed dot indicates differentiation with respect to time  $t$ , a colon stands for an inner product between tensors (e.g.,  $\sigma:\epsilon = \sigma_{ij}\epsilon_{ij}$  and  $\mathbf{D}:\epsilon = D_{ijkl}\epsilon_{kl}$ ),  $\|\cdot\|$  denotes the Euclidean norm of second rank tensors (e.g.,  $\|\sigma\| = (\sigma:\sigma)^{1/2}$ ), and  $\langle \cdot \rangle$  indicates the Macaulay brackets (i.e.,  $\langle x \rangle = x$  if  $x > 0$  and  $\langle x \rangle = 0$  if  $x \leq 0$ ).

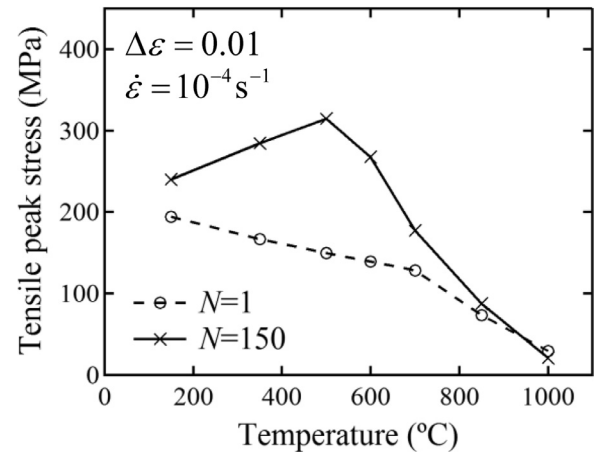
## 2. Experiments

### 2.1. Tested material, specimens, and testing machine

The material tested was 304 stainless steel, which was subjected to a solution heat treatment at 1080 °C. Solid bar specimens with the shape illustrated in Fig. 1 were used in all experiments, which were uniaxial. The experiments were performed using an electric-hydraulic servo-type material testing machine, Shimazu servo-pulser EHF-ED10T-20 L, equipped with a radio-frequency heating apparatus, a forced-air cooling apparatus, and a computer-control system. The temperature of each specimen was measured using a platinum-platinum-rhodium thermocouple spot-welded on the specimen surface in the gauge section. The axial strain in the gauge section was measured using a differential transformer type extensometer with two alumina rods, which were pushed onto the specimen surface in the gauge section. The gauge length was 20 mm.

### 2.2. Isothermal cyclic experiments

Isothermal cyclic experiments were performed up to 200 cycles to attain almost saturated hysteresis loops under the condition of  $\Delta\epsilon = 0.01$  and  $\dot{\epsilon} = 10^{-4} \text{ s}^{-1}$  at several temperatures ranging from  $T = 150$  °C to 1000 °C (Table 1), where  $\Delta\epsilon$  and  $\dot{\epsilon}$  denote uniaxial strain range and strain rate, respectively. The strain rate of  $10^{-4} \text{ s}^{-1}$  is considered to be slow enough to ignore the internal heat production due to viscoplastic deformation, as suggested by the cyclic experiments on 316 L stainless steel [16].

Fig. 2. Temperature dependence of tensile peak stresses at  $N=1$  and 150 in isothermal cyclic experiments.

**Table 2**  
List of thermo-mechanical cyclic experiments;  $T_{\min} = 150$  °C in all experiments.

$T_{\max}$ (°C)	350	500	600	700	850	1000
$\Delta\epsilon^m = 0.01$	○	○	○	○	○*	○**

\* rupture at  $N = 190$ , \*\* rupture at  $N = 125$

The tensile peak stresses thus obtained at  $N=1$  and 150 in the isothermal cyclic experiments are plotted against  $T$  in Fig. 2. From here on,  $N$  denotes the number of cycles. The hysteresis loops at  $N=1$  and 150 and the tensile peak stress variations with the increase in  $N$  are shown in Figs. 3 and 4 for some temperatures. It is seen from these figures that cyclic hardening significantly occurred around  $T=500$  °C whereas cyclic hardening was negligible at  $T=850$  °C and even cyclic softening slightly occurred at  $T=1000$  °C.<sup>1</sup>

Strain-rate dependence was examined by performing cyclic experiments at  $\dot{\epsilon} = 10^{-5} \text{ s}^{-1}$  at  $T=600$  and 850 °C in addition to those at  $\dot{\epsilon} = 10^{-4} \text{ s}^{-1}$  (Table 1). Monotonic tensile experiments at  $\dot{\epsilon} = 10^{-4} \text{ s}^{-1}$  and  $10^{-5} \text{ s}^{-1}$  were further performed at  $T=600$ , 700, 850 and 1000 °C. Strain-rate dependence was thus found to be more significant when  $T$  was higher in this temperature range, as shown in Fig. 5, in which the tensile peak stresses at  $N=150$  and the monotonic tensile stresses at  $\epsilon=0.005$  are plotted.

### 2.3. Thermo-mechanical cyclic experiments

Thermo-mechanical cyclic experiments were performed up to 200 cycles to attain almost saturated hysteresis loops under the condition of  $\Delta\epsilon^m = 0.01$  by prescribing temperature range  $[T_{\min}, T_{\max}]$  (Table 2), where  $\Delta\epsilon^m$  denotes the range of mechanical strain. In the thermo-mechanical cyclic experiments, minimum temperature  $T_{\min}$  was taken to be the same ( $T_{\min} = 150$  °C), maximum temperature  $T_{\max}$  ranged from 350 °C to 1000 °C, and  $T$  and  $\epsilon^m$  were varied in an out-of-phase condition as illustrated in Fig. 6. As shown in the figure,  $\epsilon^m$  was cyclically varied in a compressive range by considering the fact that hot regions are usually compressively strained in structures with non-uniform temperature profiles. The time period on the tension side (i.e., cooling process) was chosen to be twice larger than that on the compression side. This difference was introduced for enabling the constant change rate of temperature in the cooling process using the forced-air cooling apparatus. Since  $\Delta\epsilon^m = 0.01$ ,  $\epsilon^m$  was  $8.33 \times 10^{-5} \text{ s}^{-1}$  and  $4.17 \times 10^{-5} \text{ s}^{-1}$  on the compression side.

<sup>1</sup> Significant cyclic hardening around 500 °C can be ascribed to the increase in dislocation density and the enhancement of planar slip that were microscopically observed in the regime of dynamic strain aging in 316L stainless steel [9, 10].

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