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KINETICS OF $\alpha'$-MARTENSITE FORMATION DURING FATIGUE DEFORMATION IN METASTABLE AUSTENITIC STAINLESS STEEL

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Abstract.-

The effect of applied total strain range on the critical condition necessary for the onset of $\alpha'$-martensitic transformation kinetics during the fatigue deformation was studied in AISI type 304 metastable austenitic stainless steel at room temperature. In the case of fatigue deformation, the $\alpha'$-martensite formation was observed even in the condition that the saturated stress amplitude of austenite phase is smaller than the critical applied stress for the onset of $\alpha'$-martensite formation for the monotonic tensile deformation. Furthermore, the amount of $\alpha'$-martensite increased with the number of cycles even in the saturated stage of austenite phase in which the stress amplitude of austenite phase is almost constant during the fatigue deformation. The $\alpha'$-martensite formation was enhanced as the applied total strain range was increased. Such an enhancement of transformation was closely related with the increase in saturated stress amplitude of austenite phase due to the increase in applied total strain range. It was emphasized that the $\alpha'$-martensite was preferentially induced in the near-surface layer of the specimen by the increase in local concentrated stress due to the increase in number of piled-up dislocations with the number of cycles even in the saturated stage of austenite phase.

I. Introduction

Several investigations for the influence of deformation-induced martensitic transformation on the fatigue properties in metastable austenitic steels have been performed. These investigations showed that there is a remarkable difference in the fatigue life between the strain-controlled and stress-controlled tests. The stress-controlled fatigue tests showed that the martensitic transformation is beneficial to the fatigue life. However, the martensitic transformation shortens the fatigue life in the strain-controlled tests. These trends were covered in the paper by Olson et al.[1], and they pointed out that the deformation-induced martensite plays an important role in the fatigue behavior. It has been reported [2] that the influence of deformation-induced martensite on the fatigue life is closely related with the critical number of cycles for the onset of martensite formation. Therefore, it is important to make clear the critical condition necessary for the martensite formation and the transformation kinetics during the fatigue deformation. However, such critical condition and kinetics during the fatigue deformation are not yet well understood in comparison with those during the monotonic tensile or compressive deformation.

The purpose of present study was thus to make clear the effect of total strain range, $\Delta \varepsilon_T$, on the kinetics of $\alpha'$-martensite formation in metastable austenitic stainless steel during the total strain-controlled fatigue deformation at room temperature. The effect of $\Delta \varepsilon_T$ on the critical stress and strain for the onset of $\alpha'$-martensite formation was also examined. Furthermore, the critical condition and the kinetics during the monotonic tensile deformation were studied for the comparison.
II. Experimental Procedure

AISI type 304 (18Cr-9Ni) and type 310 (25Cr-20Ni) austenitic stainless steels were used. These steels were selected, because type 304 is metastable austenitic at room temperature and type 310 is stable. The specimens for fatigue and tensile tests, which had a gage section with 12 mm in length and a constant diameter with 5 mm, were machined from hot swaged bars with 20 mm in diameter. Specimens were solution-treated in vacuum at 1473 K for 3.6 ks and then quenched into oil. The average austenite grain sizes in type 304 and type 310 steels were about 200 pm and 250 pm, respectively. The total strain-controlled fatigue (tension-compression) and the monotonic tensile tests were carried out at room temperature (299-301 K) with a servo-mechanics and electrohydraulic closed-loop systemed machine. The strain rate, \( \varepsilon \), employed was setted as \( 3.3 \times 10^{-3}/s \). The total strain range, \( \Delta \varepsilon _T \), used in the fatigue tests was changed from 0.5% to 2.5%. The fatigue and the tensile tests were stopped at several periods, and the volume fraction of \( \alpha' \)-martensite was measured with a commercial "ferrite scope" which measures the magnetic permeability of specimens.

III. Results

3.1 \( \alpha' \)-martensite formation during the monotonic tensile deformation

True stress-strain curves of type 304 and type 310 steels at room temperature are shown in Fig. 1. The volume fraction of \( \alpha' \)-martensite, \( V_{M} \), in type 304 steel induced during the tensile deformation was also piloted in Fig. 1. It is seen that \( V_{M} \) increases with increasing the stress or strain. The critical applied stress and strain for the onset of \( \alpha' \)-martensite formation were recognized to be about 290 MPa and 6%, respectively. From the above results, it is clear that room temperature (= 300 K) is in the temperature range between \( M_S \) and \( M_D \) for type 304 steel and is above \( M_D \) for type 310 steel.

3.2 Effect of total strain range on the change in stress amplitude

Fig. 2 shows the effect of the applied total strain range, \( \Delta \varepsilon _T \), on the change in stress amplitude in tension side (cyclic tensile stress), \( \sigma _T \), with the number of cycles, \( N \), during the fatigue deformation in type 310 steel. In all the tests, \( \sigma _T \) reaches respective saturated stress levels after the cyclic strain hardening in an initial period. The saturated stress level scarcely changes with \( N \) up to fracture. The saturated stress level increases with increase in \( \Delta \varepsilon _T \). These results are in good agreement with the results of previous investigations in annealed stable austenitic metals and alloys [3]. The stage where \( \sigma _T \) increases with \( N \) is hereafter referred to as "strain hardening stage", and that where \( \sigma _T \) scarcely changes with \( N \) is referred to as "saturated stage".

On the other hand, in type 304 steel two distinct kinds of \( \sigma _T-N \) curves were observed as shown in Fig. 3. In cases of higher \( \Delta \varepsilon _T \) than 1.5%, \( \sigma _T \) continuously increases with \( N \) up to fracture. However, in cases of lower \( \Delta \varepsilon _T \) than 1.0%, the saturated stage can be observed after the initial strain hardening stage. After the saturated stage, \( \sigma _T \) again increases with \( N \). The start of such a secondary hardening is delayed as \( \Delta \varepsilon _T \) is decreased. The total strain ranges where the saturated stage was observed are hereafter referred to as "low \( \Delta \varepsilon _T \) region", and those where \( \sigma _T \) scarcely changes with \( N \) is referred to as "saturated stage".

Although \( \sigma _T \) is gradually increased with \( N \) after the onset of \( \alpha' \)-martensite formation as shown in Fig. 3, the stress amplitude which is applied to austenite phase (\( \sigma _T \) of \( \gamma \)) is essentially important for the analysis of kinetics of martensitic transformation. In order to estimate the change in \( \sigma _T \) of \( \gamma \) with \( N \) after the onset of \( \alpha' \)-martensite formation, the hardness change of austenite phase with \( N \) was measured in type 304 steel. The applied \( \Delta \varepsilon _T \) was setted as 1.5% which is in the high \( \Delta \varepsilon _T \).
region. The results are shown in Fig. 4. The overall hardness of specimen irrespective of structure (i.e., the mixture of martensite and austenite) and VM are also shown in Fig. 4. It is noted that γ keeps the hardness almost constant above about 100 cycles, while the overall hardness continuously increases with N. This result clearly indicates that even in the case of high Δε region, the austenite phase itself reaches the saturated stage after the strain hardening stage. In the case of low Δε region, σf of γ is considered to be also almost constant after the start of secondary hardening. Thus, it is concluded that the change in σf of γ with N in type 304 steel is essentially same as that in type 310 stable austenitic steel which was shown in Fig. 2. Moreover, it should be emphasized that VM increases with N even in the saturated stage of austenite phase. This result suggests that the local concentrated stress in austenite phase increases with N even in the saturated stage of austenite phase. This will be discussed later.

3.3 Effect of total strain range on the critical applied stress and strain for the onset of α'-martensite formation

The effect of applied Δε on the critical applied tensile stress for the onset of α'-martensite formation, σCa, during the fatigue deformation is shown in Fig. 5. σCa is equal to σf at the N indicated by arrows (6) in Fig. 3. The solid and the open circles in Fig. 5 (also in Fig. 6) indicate the respective data of the low Δε region and the high Δε region which were defined in 3.2. It is seen that in the case of high Δε region, σCa is almost constant and is about 290 MPa which is the same as that for the monotonic tensile deformation shown in Fig. 1. On the other hand, in the case of low Δε region, σCa decreases with decrease in Δε, and the respective σCa were consistent with the respective saturated stress amplitudes of austenite phase. It is emphasized that the α'-martensitic transformation takes place during the fatigue deformation even in the condition that the saturated stress amplitude of austenite phase is lower than σCa for the monotonic tensile deformation. This result indicates that in the case of fatigue deformation, the critical condition for the onset of α'-martensite formation cannot be explained only by the applied stress even when temperature and strain rate are fixed.

The effect of applied Δε on the critical cumulative plastic strain for α'-martensite formation is shown in Fig. 6. The cumulative plastic strain is the sum of the plastic strain range, Δεp, observed in the stress-strain hysteresis loop of each cycle, namely Δεp. The broken line indicates the critical strain observed in the monotonic tensile test, 6%. In the case of high Δε region in which the α'-martensite formation starts from the strain hardening stage of austenite phase like the monotonic tensile deformation, the critical cumulative plastic strain, Δεpc, is about 15%. This value is about three times larger than the critical strain for the monotonic tensile deformation. It is considered that such an increase in Δεpc from that for the tensile deformation is due to the Bauschinger strain which is contained in the plastic strain of the fatigue (tension-compression) deformation. It is noted that Δεpc in the low Δε is much larger than that in high Δε region, and Δεpc markedly increases with decrease in Δε.

3.4 Effect of total strain range on the α'-martensite formation behavior

The increase in volume fraction of α'-martensite, VM, with N in type 304 steel is shown in Fig. 7. The α'-martensitic transformation was observed in all the tests performed in the present study. VM increases with N in all the cases. The tendency of increase in VM with N for each Δε was consistent with that in σf, as shown in Fig. 3.

The effect of applied Δε on the α'-martensite formation behavior with Δεp during the fatigue deformation is shown in Fig. 8. Fig. 8 is the VM vs (Δεp - Δεpc) plot. In this figure, the results of the monotonic tensile test are also shown. It should be noted that VM at a given (Δεp - Δεpc) increases with increase in Δε, indicating that the value of VM/Δεp increases with increase in Δε. It is clear that VM during the fatigue deformation is not only the function of plastic strain, but also the function of Δε.
IV. Discussion

The kinetics of deformation-induced martensitic transformation has been usually treated as a function of strain. However, since the martensitic transformation is essentially assisted by shear stress, the theoretical treatment of the transformation kinetics should be based on the stress rather than the strain. It has been recognized that at the temperatures above Mg the martensitic transformation during the monotonic tensile or compressive deformation is induced by the local concentrated stress due to the plastic deformation [4,5]. It has been also considered that the martensitic transformation starts when the local concentrated stress reaches the true critical stress for the onset of martensite formation. It is reasonable that $V_m$ increases with increases in local concentrated stress or concentration sites of the stress. Thus the local concentrated stress in austenite phase ($\gamma$) must be also considered for the fatigue deformation. It can be assumed that the local concentration of stress is caused by the piled-up dislocations. For simplicity, we considered the concentrated stress at the position of top dislocation of the piled-up ones, $\sigma_d$, and such a stress can be generally expressed as $\sigma_d = n\sigma_o$ where $n$ is the number of piled-up dislocations in a slip plane and $\sigma_o$ is the applied stress.

Present results showed that $\alpha'$-martensitic transformation was observed during the fatigue deformation even in the condition that the saturated stress amplitude of $\gamma$ is lower than $\sigma_o$ for the monotonic tensile deformation. Moreover, $V_m$ increased with $N$ in the saturated stage of $\gamma$. These results suggest that the local concentrated stress, $\sigma_d$, increases with $N$ even in the saturated stage of $\gamma$. Since the stress amplitude (i.e., $\sigma_o$) of $\gamma$ is almost constant in the saturated stage, it is considered that $\sigma_d$ increased with $N$ due to the increase in $n$. Therefore, the pile-up mechanism of dislocations in the saturated stage is important for the $\alpha'$-martensite formation behavior during the fatigue deformation. It has been reported that in the saturated stage during the fatigue deformation the applied total strain range, $\Delta e_t$, is accommodated by dipole flipping and the shutting of dislocations between cell walls [6]. According to the above model, the increase in $n$ with $N$ can not be expected, because the dislocation motion is reversible. However, it has been frequently reported that the well-known extrusion and intrusion are observed in the surface of fatigued specimen. Such extrusion and intrusion have been explained by the irreversible movement of dislocations in near-surface layer of specimen. Pangborn et al.[7] reported that the dislocation density in the surface layer of fatigued specimen increases with $N$ up to fracture. Then it is considered that in the saturated stage of $\gamma$, $n$ in the near-surface layer of specimen increases with $N$ due to the irreversible movement of dislocations, while in the bulk (i.e., center region of specimen) $n$ scarcely changes. Therefore, it can be expected that the $\alpha'$-martensite formation in the saturated stage of $\gamma$ takes place preferentially in the near-surface layer. Actually, in the present study, it was confirmed by the optical microstructure observation that most of $\alpha'$-martensite formed in the near-surface layer of specimen. Luther and Williams [8] have also reported in the stress-controlled fatigue (tension-tension) deformation of type 321512 metastable austenitic steel that the $\alpha'$-martensite was present throughout the surface and the near-surface layers to a depth of about 30-60 $\mu$m. Therefore, it can be considered that in the fatigue deformation $n$ increases with $N$ in the near-surface layer of specimen even in the saturated stage of $\gamma$, so that the $\alpha'$-martensite is induced even in the condition that the saturated stress amplitude of $\gamma$ is lower than $\sigma_o$ for the monotonic tensile deformation, and $V_m$ increases with $N$ even in the saturated stage of $\gamma$.

It was shown in Fig. 6 that $\Delta e_{\gamma}$, in the low $\Delta e_t$ region was much larger than that in the high $\Delta e_t$ region. In the case of high $\Delta e_t$ region, the $\alpha'$-martensite formation starts from the strain hardening stage of $\gamma$ where $\sigma_d$ is increased with $N$ by increases in both of $n$ and $\sigma_o$. However, in the case of low $\Delta e_t$ region, the $\alpha'$-martensite formation starts from the saturated stage of $\gamma$ where $\sigma_d$ is increased only by increase in $n$. In such a situation, much larger $\Delta e_{\gamma}$ than that in the high $\Delta e_t$ region is required to obtain $\sigma_d$ necessary for the onset of $\alpha'$-martensite formation.

In the case of fatigue deformation, most of $\alpha'$-martensite formed in the saturated stage of $\gamma$, as shown in Fig. 4. Then $\sigma_d$ in Eq.(1) can be replaced by the saturated stress amplitude of $\gamma$, $\sigma_o$. Since $\sigma_d$ increases with increase in $\Delta e_t$, it is clear that $V_m$ during the fatigue deformation is the function of $\Delta e_t$ through $\sigma_o$ and the $\alpha'$-
martensite formation is enhanced as $\Delta c_T$ is increased, as shown in Fig. 8. Thus, it is concluded that the $\alpha'$-martensite formation behavior during the fatigue deformation can be qualitatively explained by the local concentrated stress in the near-surface layer of specimen.

Reference

Fig. 5 Effect of $\Delta e_t$ on $\sigma_{ca}$ during the fatigue deformation. See the text for the meanings of solid and open circles.

Fig. 6 Effect of $\Delta e_t$ on $\Sigma \Delta e_{pc}$ during the fatigue deformation. See the text for the meanings of solid and open circles.

Fig. 7 Effect of $\Delta e_t$ on the $\alpha'$-martensite formation with $N$ in type 304 steel.

Fig. 8 $V_M$ vs $(\Sigma \Delta e_p - \Sigma \Delta e_{pc})$ plot to show the effect of $\Delta e_t$ on the $\alpha'$-martensite formation with increase in $\Sigma \Delta e_p$. 

Type 304 
$\varepsilon = 9.3 \times 10^{-3}$s$^{-1}$ 
Temp = 300K 

Type 304 
$\varepsilon = 3.3 \times 10^{-3}$s$^{-1}$ 
Temp = 300K 

Type 304 
$\varepsilon = 3.3 \times 10^{-3}$s$^{-1}$ 
Temp = 300K 

Total Strain Range. $AE_t (\%)$ 

Total Strain Range. $AE_t (\%)$ 

Total Strain Range. $AE_t (\%)$ 

Critical Applied Stress. $0-300$ MPa 

Critical Applied Stress. $0-300$ MPa 

Volume Fraction of $\alpha'$. $V_{\alpha'}$ 

Volume Fraction of $\alpha'$. $V_{\alpha'}$ 

Volume Fraction of $\alpha'$. $V_{\alpha'}$ 

Number of Cycles, $N$ 

Number of Cycles, $N$ 

Number of Cycles, $N$ 

$\Sigma \Delta e_p - \Sigma \Delta e_{pc} (\%)$ 

$\Sigma \Delta e_p - \Sigma \Delta e_{pc} (\%)$ 

$\Sigma \Delta e_p - \Sigma \Delta e_{pc} (\%)$