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KINETICS OF α' -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 α' -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 α' -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 α' -martensite formation for the monotonic tensile deformation. Furthermore, the amount of α' -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 α' -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 α' -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 α' -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 α' -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 μm and 250 μm , 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 syssyemed machine. The strain rate, $\dot{\epsilon}$, employed was setted as $3.3 \times 10^{-3}/\text{s}$. The total strain range, $\Delta\epsilon_t$, 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 α' -martensite was measured with a commercial "ferrite scope" which measures the magnetic permeability of specimens.

III. Results

3.1 α' -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 α' -martensite, V_M , in type 304 steel induced during the tensile deformation was also plotted 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 α' -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^0 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, $\Delta\epsilon_t$, on the change in stress amplitude in tension side (cyclic tensile stress), σ_t , with the number of cycles, N , during the fatigue deformation in type 310 steel. In all the tests, σ_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 $\Delta\epsilon_t$. These results are in good agreement with the results of previous investigations in annealed stable austenitic metals and alloys [3]. The stage where σ_t increases with N is hereafter referred to as "strain hardening stage", and that where σ_t scarcely changes with N is referred to as "saturated stage".

On the other hand, in type 304 steel two distinct kinds of σ_t - N curves were observed as shown in Fig. 3. In cases of higher $\Delta\epsilon_t$ than 1.5%, σ_t continuously increases with N up to fracture. However, in cases of lower $\Delta\epsilon_t$ than 1.0%, the saturated stage can be observed after the initial strain hardening stage. After the saturated stage, σ_t again increases with N . The start of such a secondary hardening is delayed as $\Delta\epsilon_t$ is decreased. The total strain ranges where the saturated stage was observed are hereafter referred to as "low $\Delta\epsilon_t$ region", and those where the saturated stage was not observed are referred to as "high $\Delta\epsilon_t$ region". Arrows (\blacktriangleright) shown in Fig. 3 indicate the number of cycles at which α' -martensite formation starts. It is noted that the start of secondary hardening in low $\Delta\epsilon_t$ region corresponds to the onset of α' -martensite formation. Then it is clear that the secondary hardening is attributed to the α' -martensitic transformation. In the case of high $\Delta\epsilon_t$ region, the α' -martensite formation already started in the strain hardening stage; so that the saturated stage was not observed.

Although σ_t is gradually increased with N after the onset of α' -martensite formation as shown in Fig. 3, the stress amplitude which is applied to austenite phase (σ_t of γ) is essentially important for the analysis of kinetics of martensitic transformation. In order to estimate the change in σ_t of γ with N after the onset of α' -martensite formation, the hardness change of austenite phase with N was measured in type 304 steel. The applied $\Delta\epsilon_t$ was setted as 1.5% which is in the high $\Delta\epsilon_t$

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 V_M 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 $\Delta\epsilon_t$ region, the austenite phase itself reaches the saturated stage after the strain hardening stage. In the case of low $\Delta\epsilon_t$ region, σ_t of γ is considered to be also almost constant after the start of secondary hardening. Thus, it is concluded that the change in σ_t 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 V_M 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 $\Delta\epsilon_t$ on the critical applied tensile stress for the onset of α' -martensite formation, σ_{ca} , during the fatigue deformation is shown in Fig. 5. σ_{ca} is equal to σ_t at the N indicated by arrows (\blacktriangle) in Fig. 3. The solid and the open circles in Fig. 5 (also in Fig. 6) indicate the respective data of the low $\Delta\epsilon_t$ region and the high $\Delta\epsilon_t$ region which were defined in 3.2. It is seen that in the case of high $\Delta\epsilon_t$ region, σ_{ca} 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 $\Delta\epsilon_t$ region, σ_{ca} decreases with decrease in $\Delta\epsilon_t$, and the respective σ_{ca} 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 σ_{ca} 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 can not be explained only by the applied stress even when temperature and strain rate are fixed.

The effect of applied $\Delta\epsilon_t$ 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, $\Delta\epsilon_p$, observed in the stress-strain hysteresis loop of each cycle, namely $\Sigma\Delta\epsilon_p$. The broken line indicates the critical strain observed in the monotonic tensile test, 6%. In the case of high $\Delta\epsilon_t$ 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, $\Sigma\Delta\epsilon_{pc}$, 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 $\Sigma\Delta\epsilon_{pc}$ 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 $\Sigma\Delta\epsilon_{pc}$ in the low $\Delta\epsilon_t$ is much larger than that in high $\Delta\epsilon_t$ region, and $\Sigma\Delta\epsilon_{pc}$ markedly increases with decrease in $\Delta\epsilon_t$.

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

The increase in volume fraction of α' -martensite, V_M , 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. V_M increases with N in all the cases. The tendency of increase in V_M with N for each $\Delta\epsilon_t$ was consistent with that in σ_t , as shown in Fig. 3.

The effect of applied $\Delta\epsilon_t$ on the α' -martensite formation behavior with $\Sigma\Delta\epsilon_p$ during the fatigue deformation is shown in Fig. 8. Fig. 8 is the V_M vs ($\Sigma\Delta\epsilon_p - \Sigma\Delta\epsilon_{pc}$) plot. In this figure, the results of the monotonic tensile test are also shown. It should be noted that V_M at a given ($\Sigma\Delta\epsilon_p - \Sigma\Delta\epsilon_{pc}$) increases with increase in $\Delta\epsilon_t$, indicating that the value of $V_M/\Sigma\Delta\epsilon_p$ increases with increase in $\Delta\epsilon_t$. It is clear that V_M during the fatigue deformation is not only the function of plastic strain, but also the function of $\Delta\epsilon_t$.

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 M_g^0 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 (γ) 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, σ_d , and such a stress can be generally expressed as $\sigma_d = n\sigma_a$ (1), where n is the number of piled-up dislocations in a slip plane and σ_a is the applied stress.

Present results showed that α' -martensitic transformation was observed during the fatigue deformation even in the condition that the saturated stress amplitude of γ is lower than σ_{ca} for the monotonic tensile deformation. Moreover, V_M increased with N in the saturated stage of γ . These results suggest that the local concentrated stress, σ_d , increases with N even in the saturated stage of γ . Since the stress amplitude (i.e., σ_a) of γ is almost constant in the saturated stage, it is considered that σ_d increases with N due to the increase in n . Therefore, the pile-up mechanism of dislocations in the saturated stage is important for the α' -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, $\Delta\epsilon_t$, is accommodated by dipole flipping and the shuttling 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 γ , 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 α' -martensite formation in the saturated stage of γ takes place preferentially in the near-surface layer. Actually, in the present study, it was confirmed by the optical microstructure observation that most of α' -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 321S12 metastable austenitic steel that the α' -martensite was present throughout the surface and the near-surface layers to a depth of about 30-60 μm . 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 γ , so that the α' -martensite is induced even in the condition that the saturated stress amplitude of γ is lower than σ_{ca} for the monotonic tensile deformation, and V_M increases with N even in the saturated stage of γ .

It was shown in Fig. 6 that $\Sigma\Delta\epsilon_{pc}$ in the low $\Delta\epsilon_t$ region was much larger than that in the high $\Delta\epsilon_t$ region. In the case of high $\Delta\epsilon_t$ region, the α' -martensite formation starts from the strain hardening stage of γ where σ_d is increased with N by increases in both of n and σ_a . However, in the case of low $\Delta\epsilon_t$ region, the α' -martensite formation starts from the saturated stage of γ where σ_d is increased only by increase in n . In such a situation, much larger $\Sigma\Delta\epsilon_p$ than that in the high $\Delta\epsilon_t$ region is required to obtain σ_d necessary for the onset of α' -martensite formation.

In the case of fatigue deformation, most of α' -martensite formed in the saturated stage of γ , as shown in Fig. 4. Then σ_a in Eq.(1) can be replaced by the saturated stress amplitude of γ , σ_s . Since σ_s increases with increase in $\Delta\epsilon_t$, it is clear that V_M during the fatigue deformation is the function of $\Delta\epsilon_t$ through σ_s and the α' -

martensite formation is enhanced as $\Delta\epsilon_t$ is increased, as shown in Fig. 8. Thus, it is concluded that the α' -martensite formation behavior during the fatigue deformation can be qualitatively explained by the local concentrated stress in the near-surface layer of specimen.

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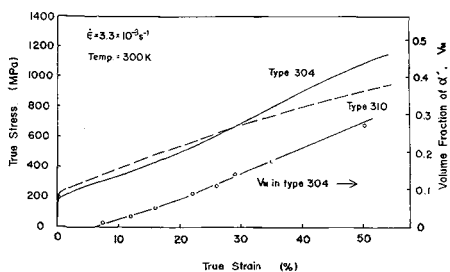


Fig.1 True stress-strain curves of type 304 and type 310 steels in the monotonic tensile test.

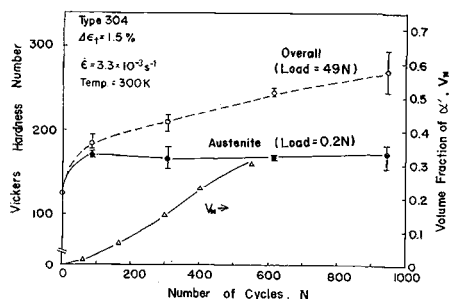


Fig.4 Change in hardness of austenite phase with N in type 304 steel.

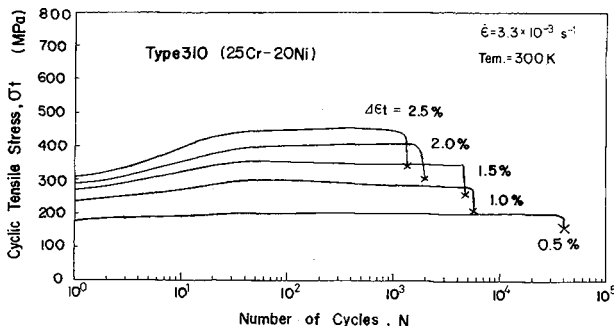


Fig. 2 Effect of $\Delta\epsilon_t$ on the change in σ_t with N in type 310 steel.

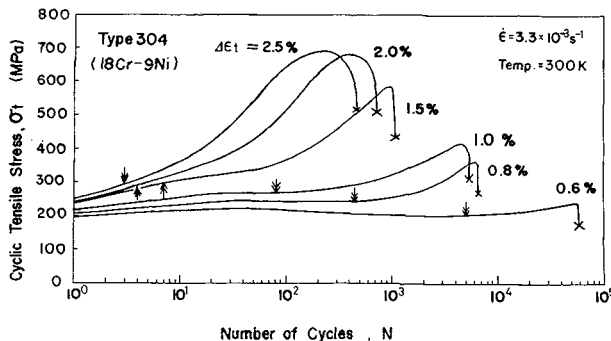


Fig. 3 Effect of $\Delta\epsilon_t$ on the change in σ_t with N in type 304 steel. See the text for the meaning of arrows (↗).

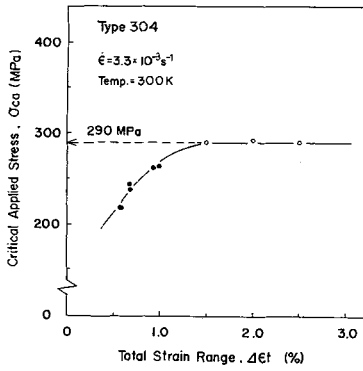


Fig. 5 Effect of $\Delta\epsilon_t$ on σ_{ca} during the fatigue deformation. See the text for the meanings of solid and open circles.

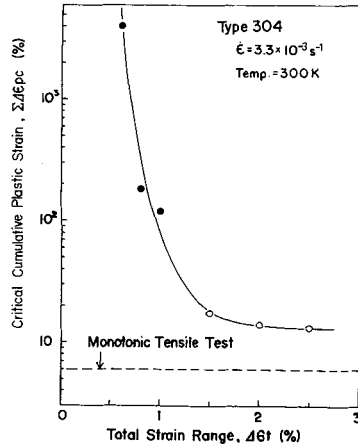


Fig. 6 Effect of $\Delta\epsilon_t$ on $\Sigma\Delta\epsilon_{pc}$ during the fatigue deformation. See the text for the meanings of solid and open circles.

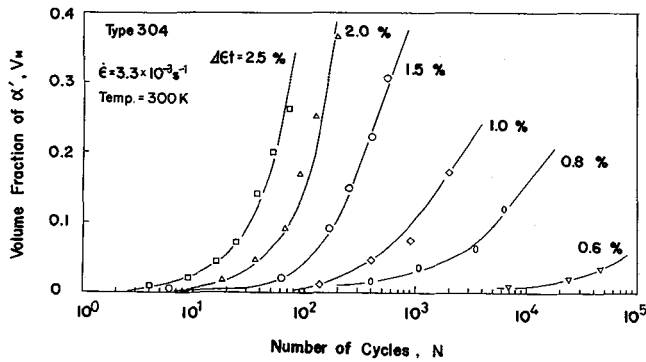


Fig. 7 Effect of $\Delta\epsilon_t$ on the α' -martensite formation with N in type 304 steel.

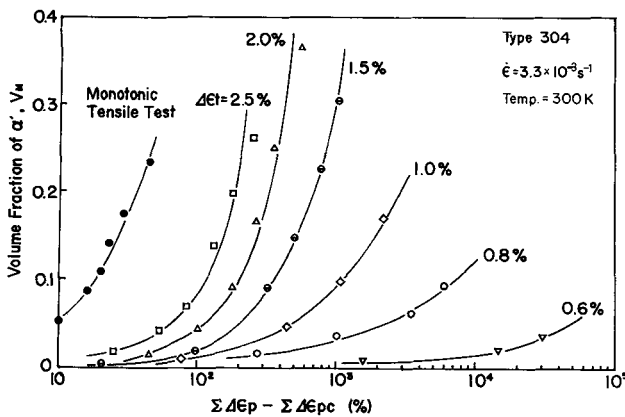


Fig. 8 V_M vs $(\Sigma\Delta\epsilon_p - \Sigma\Delta\epsilon_{pc})$ plot to show the effect of $\Delta\epsilon_t$ on the α' -martensite formation with increase in $\Sigma\Delta\epsilon_p$.