Fatigue Behavior of Metastable and Stable Austenitic Steels*

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Synopsis

An attempt has been made to survey the fatigue behavior of three different austenitic steels. The materials tested are Fe-30Ni alloy as metastable austenite, Fe-38Ni alloy as stable austenite and Fe-25Ni-16Cr alloy of low stacking fault energy. It was found that at low stress amplitudes the fatigue life of the metastable steel was longer than that of the stable ones, while at high stress amplitudes the metastable steel was inferior to the stable ones. This is probably attributed to the differences of the rate and period of martensite formation. The fatigue life of the Fe-25Ni-16Cr alloy was less than that of the Fe-38Ni alloy only at high stress amplitudes. The Fe-30Ni alloy showed a remarkable hardening with martensite formation, but its cyclic strain behavior except for the hardening due to the martensite formation was extremely similar to that of the Fe-38Ni alloy, that is, at high stress amplitudes a remarkable hardening occurred and at low stress amplitudes softening occurred slightly. Fatigue crack propagation property of the Fe-30Ni alloy was also better than that of the Fe-38Ni alloy at a low ΔK level, but at a high ΔK level the former was inferior to the latter.

I. Introduction

The effects of retained austenite on fatigue behaviors of steels have been discussed by several investigators.¹⁻⁸⁾ In some reports the retained austenite is cited as beneficial for fatigue strength,^{1,6-8)} but in others it is reported to be rather harmful.^{2,3)} The effects of retained austenite on the fatigue behavior are presumably dependent on the alloy compositions, volume fraction and stability of retained austenite, and experimental methods. Because of these complicated situations, this problem has not been sufficiently studied and contains many difficult matters awaiting solution.

There has been relatively little research conducted concerning the fatigue behavior of austenitic steels, but in recent years such studies⁹⁻¹²⁾ has steadily increased with an increasing demand for austenitic stainless steels.

In the present paper Fe-30Ni alloy as metastable austenite, Fe-38Ni alloy as stable austenite and Fe-25Ni-16Cr alloy of low stacking fault energy were tested so that (1) fatigue properties (fatigue damage, crack initiation, and crack propagation), (2) effect

of martensite transformation on the fatigue behavior and (3) effect of stacking fault energy (S.F.E.) on the fatigue behavior were established from the microstructural point of view.

II. Experimental Procedure

1. Materials and Heat Treatment

Materials were vacuum melted, annealed at 1 150°C and rolled to 6 mm plates and 10 mm diameter rods. Tensile specimens and fatigue specimens were machined to the same size as that described in the previous papers.^{13,14)} The chemical composition of materials are given in Table 1.

All specimens were heated at 900°C for 1 hr and cooled in a vacuum furnace. The austenite grain size was 35.2 μm in Fe-30Ni alloy, 47.2 μm in Fe-38Ni alloy and 33.6 μm in Fe-25Ni-16Cr alloy. For the purpose of obtaining the same grain-sized specimens, other annealing conditions were adopted —1 hr at 935°C for Fe-30Ni alloy and 1 hr at 950°C for Fe-25Ni-16Cr alloy. The grain size of these heat treated specimens was approximately equal to that of the Fe-38Ni alloy.

2. Tensile Test and Fatigue Test

Tensile tests were conducted at -196°, -70°, 20° and 98°C in order to obtain the data of conventional mechanical properties and stability of austenitic phases in each specimen.

Fatigue tests were conducted at 20°C. Fatigue damage tests were carried out in fully reversed bending using a Schenck type fatigue machine, the frequency of which was 450 cpm. The variation of strain amplitudes under constant applied stresses was measured dynamically.¹³⁾ To provide a quantitative estimate of the martensite formed in Fe-30Ni alloy during fatigue cycling, X-ray diffraction method was used. The amount of austenite V_γ was calculated by Eq. (1);¹⁵⁾

Table 1. Chemical composition of materials. (wt%)

	C	Si	Mn	P	S	Ni	Cr	Al	N
Fe-30Ni	0.005	0.003	0.002	0.004	0.003	30.14	—	0.018	0.0012
Fe-38Ni	0.004	0.006	0.001	0.004	0.003	37.89	—	0.015	0.0014
Fe-25Ni-16Cr	0.002	0.007	0.002	0.004	0.006	24.39	15.63	<0.001	0.0048

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$$V_r = 1.4I_r/(I_a + 1.4I_r) \quad \dots\dots\dots(1)$$

where I_r was the average of integrated intensity from $(220)_r$ and $(311)_r$, and I_a was the integrated intensity from $(211)_a$. The microstructure for each specimen was studied by optical microscopy to establish the morphological changes of the specimen surface and site of crack initiation. The specimens that had failed due to fatigue were examined by transmission electron microscopy.

Fatigue crack propagation tests were conducted on notched specimens at a frequency of 1 000 cpm by applying in-plane bending stress (stress ratio $R=0.06$). The notch length d_0 was 2 mm. Fatigue fractured surface was observed by scanning electron microscopy.

III. Experimental Results

1. Tensile Test

Figure 1 presents the tensile properties of three alloys with five different microstructures at a temperature range of -196° to 98°C . In Fe-30Ni alloy M_s temperature is about -20°C , and M_d temperature seems to be approximately room temperature (RT), so the elongation is maximum near RT and extremely low at -70°C and -196°C . The tensile strength increases with decreasing test temperature, but in the specimens tested below -70°C , they fracture almost without elongation because of the martensite formation prior to the deformation. Although it is reported that M_d temperature and M_s temperature of Fe-38Ni alloy are approximately -150°C and below -196°C ,¹⁶⁾ respectively, deformation-induced transformation martensite was not detected by optical or electron microscopy in the present experiment. In Fe-25Ni-16Cr alloy whose stability in Schaeffer's diagram is equal to that of Fe-38Ni alloy, the elongation is minimum at RT . Breedis and Robertson^{17,18)} reported that the Fe-25Ni-16Cr single crystal did not transform to martensite either by cooling to -269°C or by deforming at -196°C , and the martensite formation was not detected in the present experiment. Thus, it is considered that the increase of the elongation in the low temperature range originates from factors other than the transformation induced plas-

ticity,^{19,20)} although this question is unresolved in this report.

2. Fatigue Test

1. S-N Curves

Figure 2 exhibits the S-N curves in three steels, i.e., Fe-30Ni alloy (900), Fe-38Ni alloy (900) and Fe-25Ni-16Cr alloy (950) which are of approximately the same strength level. The metastable austenite Fe-30Ni alloy has a favourable fatigue resistance as compared with other alloys in a low stress amplitude range of $\sigma_a < 33 \text{ kg/mm}^2$, however the fatigue property of this alloy deteriorates remarkably with the increase of the applied stress and consequently becomes inferior to other alloys in a high stress amplitude range of $\sigma_a > 38 \text{ kg/mm}^2$. Fatigue resistance of Fe-25Ni-16Cr alloy is inferior to that of Fe-38Ni alloy at high stress amplitudes because the proof stress of this alloy is low, but the difference in the fatigue life in both alloys becomes less pronounced at low stress amplitudes.

2. Cyclic Plastic Behavior

The variations of plastic strain amplitudes in Fe-30Ni alloy (900, 935) are presented in Figs. 3 and 4. Comparison of the figures shows that the cyclic plastic behaviors do not depend so much on the austenite grain size. At high stress amplitudes, strain amplitudes of both specimens decrease remarkably

Fig. 2. S-N curves of austenitic steels.

Fig. 1. Relationship between mechanical properties and test temperature.

(hardening) and at a low stress amplitude ($\sigma_a = 14 \text{ kg/mm}^2$), strain amplitude increases slightly (softening) until 3×10^3 cycles and decreases afterwards. It is considered that the hardening is attributed mainly to martensite formation, but presumably other factors are also related to the hardening. The martensite formation process in this alloy was examined from

Fig. 3. Variation of plastic strain amplitude during testing: Fe-30Ni(900).

Fig. 4. Variation of plastic strain amplitude during testing: Fe-30Ni(935).

this point of view (Fig. 5). Surface martensite is easily formed in this alloy, and in fact 6~7% surface martensite was detected on the specimen surface prior to cyclic deformation. When this alloy was tested at high stress amplitudes ($\sigma_a = 25$ to 30 kg/mm^2), martensite was rapidly produced for up to 10^3 cycles, and then martensite formation rate gradually decreased. When it was tested at a low stress amplitude ($\sigma_a = 20 \text{ kg/mm}^2$), the martensite was formed relatively slowly in early cycles, but even in the last stage martensite transformation tended to occur gradually.

The transmission electron micrographs of specimens after being fatigued at $\sigma_a = 48 \text{ kg/mm}^2$ and 25 kg/mm^2 are shown in Photos. 1 (a) and (b), respectively. The morphology of the induced martensite does not seem to depend on these different stress levels and consists of lath type martensite with twin type martensite rarely seen.

The variation of the strain amplitudes in Fe-38Ni alloy (900) is presented in Fig. 6. In this alloy no such remarkable decrease of strain amplitude as that observed in Fe-30Ni alloy was detected since martensite transformation did not occur during cycling at RT. However, even this alloy revealed a tendency of hardening at an extremely high stress amplitude

Fig. 5. Change of the volume fraction of martensite during testing: Fe-30Ni(900).

- (a) Fe-30Ni(900): $\sigma_a = 48 \text{ kg/mm}^2$
- (b) Fe-30Ni(900): $\sigma_a = 25 \text{ kg/mm}^2$
- (c) Fe-38Ni(900): $\sigma_a = 25 \text{ kg/mm}^2$
- (d) Fe-25Ni-16Cr(950): $\sigma_a = 25 \text{ kg/mm}^2$

Photo. 1.

Transmission electron micrographs of specimens fatigued to failure.

($\sigma_a=37.5 \text{ kg/mm}^2$). At a medium stress amplitude ($\sigma_a=30 \text{ kg/mm}^2$) the alloy initially hardened a little, and kept strains constant or softened slightly in the range of 3×10^2 to 3×10^3 cycles. Below 0.2% proof stress the softening continued until 3×10^3 cycles followed by hardening. The dislocation structures of this steel after fatigue are shown in Photo. 1 (c).

The variation of strain amplitudes in Fe-25Ni-16Cr alloy (Fig. 7) reveals that this alloy hardens throughout its entire life. This tendency was remarkable at high stress amplitudes. The plastic behavior of this alloy did not depend on the grain size. Photograph 1 (d) shows the structure of the specimen that failed at the same cycles as Fe-38Ni alloy (Photo. 1 (c)), and noticeable morphological differences in both specimens have been observed.

3. Change of Surface Morphology

Photographs 2 to 4 exhibit the surface of three alloys fatigued to failure. In Fe-30Ni alloy fatigue cracks initiated preferentially in pre- γ boundaries at high stress amplitudes, whereas at low stress amplitudes they nucleated, in addition to these sites, along the interface of the austenite and the martensite that had existed prior to cycling or that was formed in

Fig. 6. Variation of plastic strain amplitude during testing: Fe-38Ni(900).

Fig. 7. Variation of plastic strain amplitude during testing: Fe-25Ni-16Cr(900).

early cycles. In Fe-38Ni and Fe-25Ni-16Cr alloys fatigue cracks initiated along γ boundaries at higher stress amplitudes. However, with a decrease of applied stress, the number of these crack initiations

Photo. 2. Slip bands and fatigue cracks on the surface of Fe-30Ni(900).

Photo. 3. Slip bands and fatigue cracks on the surface of Fe-38Ni(900).

decreased remarkably and the number of cracks along the slip bands increased.

4. Fatigue Crack Propagation

Figure 8 presents fatigue crack propagation rate as a function of stress intensity factor range ΔK for each structure. This stress intensity factor was calculated by using Gross's equation.²¹⁾ The coefficient C and the exponent m in the fatigue crack growth equation, $da/dN=C(\Delta K)^m$, are given in these figures. This result indicates that crack propagation properties do not depend on the grain size.

The comparison of the crack propagation prop-

erties for each alloy shown in Fig. 9 reveals that the crack propagation rate of Fe-30Ni alloy is lower than of Fe-38Ni alloy at low ΔK level, but it is opposite at high ΔK level, and that the propagation property of Fe-25Ni-16Cr alloy is superior to that of Fe-30Ni alloy or Fe-38Ni alloy over the entire ΔK range. Micrographs of the fatigue fractured surfaces are shown in Photos. 5 to 7.

IV. Discussion

1. Fatigue Properties of Metastable Austenite (Fe-30Ni)

Figure 10 shows the interrelationship between the variation of cyclic strain amplitude in Fig. 3 and that of martensite formed on the specimen in Fig. 5. The abscissa is the rate of the martensite formation, $dV_a/d(\log N)$, and the ordinate is the rate of hardening, $d\epsilon_p/d(\log N)$. Both values were plotted at each number of cycles. On each curve lower-right plots are of low cycles and upper-left plots are of high cycles. If the hardening is due to the martensite

Photo. 4. Slip bands and fatigue cracks on the surface of Fe-25Ni-16Cr(950).

Fig. 9. Comparison of fatigue crack propagation rate as a function of stress intensity factor range.

Fig. 8. Fatigue crack propagation rate as a function of stress intensity factor range.

(a) $\Delta K = 60 \text{ kg/mm}^{3/2}$ (b) $\Delta K = 28 \text{ kg/mm}^{3/2}$

Photo. 5. Fatigue fractured surface of Fe-30Ni(900).

Photo. 6. Fatigue fractured surface of Fe-38Ni(900): $\Delta K = 47 \text{ kg/mm}^{3/2}$.

formation only, these plots should produce an approximately straight line. We call this hardening, corresponding to this straight line, HDM (hardening due to martensite formation). The deviation from this line (upward deviation indicates softening and downward deviation hardening) suggests that some factors other than martensite formation also affect the cyclic behavior. But it should be noted that martensite formation also indirectly affects these factors (*e.g.*, the martensite transformation induces stress fields so that it causes softening or hardening).

As shown in this figure, when a stress of 30 kg/mm^2 was applied to Fe-30Ni alloy, it hardened by other factors in addition to HDM in early cycles (for up to 210 cycles), and then softened until 2×10^3 cycles. Further cyclic deformation led to the tendency of only HDM until failure. The behavior at an applied stress of 25 kg/mm^2 was similar to that at 30 kg/mm^2 . However, with the decrease of the applied stress the

Photo. 7. Fatigue fractured surface of Fe-25Ni-16Cr(950): $\Delta K = 47 \text{ kg/mm}^{3/2}$.

Fig. 10. Relationship between $dV_\alpha/d(\log N)$ and $d\varepsilon_p/d(\log N)$: Fe-30Ni(900).

transition in the number of cycles from hardening to softening became shorter and the amount of softening increased. The specimen under an applied stress of 20 kg/mm^2 showed not hardening but softening if HDM were excluded.

The remarkable hardening in early cycles at high stress amplitudes should be interpreted as a work hardening by interaction of dislocations inside or around the induced martensite. Subsequent softening process is attributable to the rearrangement of dislocations, but from this data it is not accurately determined whether it occurred in the austenite phase or in the martensite phase. It was, however, observed by transmission electron microscopy that the dislocation cell structures were produced in austenite phase after cyclic deformation, which might suggest that softening was related to the dislocation rearrangement in austenite phase.

2. Fatigue Properties of Stable Austenite (Fe-38Ni)

Fe-38Ni alloy hardens at high stress amplitudes, and the plastic behavior changes from hardening to

softening with a decrease of applied stress amplitudes. This applied stress dependence of the plastic behavior should be understood by the difference in the introduction and rearrangement of dislocations. Although at high stress amplitudes many dislocations are rapidly introduced in early cycles, they do not rearrange sufficiently in f.c.c. alloys, and the alloys subsequently tend to harden by the interaction of dislocations. Meanwhile at low stress amplitudes dislocations introduced are gradually accumulated and rearrange by the coalescence and annihilation of positive and negative dislocations. Subsequently, these alloys soften slightly as in the cases of b.c.c. alloys.^{13,14)}

It is noteworthy that such plastic behavior in this alloy is closely analogous to the behavior of Fe-30Ni alloy except HDM. From these results it is considered that at least the softening of Fe-30Ni alloy should also be affected by the dislocation rearrangement in austenite, although it is not clear whether the softening is related to the rearrangement in martensite.

Photograph 1 (c) shows the dislocation structure of Fe-38Ni alloy after fatigued. The cell formation was observed over the specimen, especially near the grain boundaries where stress is concentrated.

3. Effect of Stacking Fault Energy

The effects of S.F.E. on the fatigue behavior may be clarified by comparing Fe-38Ni alloy (900) with Fe-25Ni-16Cr alloy (950) that have almost the same austenite grain size and the same ultimate tensile strength. The low S.F.E. alloy continued to harden during cyclic deformation and the softening occurred only after the crack initiation (Fig. 7). It seems difficult that the cyclic deformation rearranges the linear dislocations and forms the cell structures in this alloy (Photo. 1 (d)).

As the proof stress of this alloy (950) is 10 kg/mm² lower than that of Fe-38Ni alloy (900), a large plastic strain is produced in the former. Therefore, a large strain in early cycles during cyclic deformation is fatal for the low S.F.E. materials.

4. Initiation of Surface Cracks

As mentioned above, the initiation sites of fatigue cracks depend upon the applied stress amplitudes in Fe-30Ni alloy, that is, the cracks initiate preferentially in pre- γ boundaries at high stress amplitudes and mainly along the interface of austenite/martensite at low stress amplitudes.

This may be explained as follows. The cyclic deformation at high stress amplitudes rapidly produces a large amount of martensite on the surface in the early stage, while the martensite formation is quite small in the subsequent stage when the fatigue cracks are initiated. It is presumable that in this later stage the stress-induced transformation has no relation with the crack initiation which takes place in the pre- γ grain boundaries where the martensite lath bundles intersect to generate the stress concentration. On the other hand, at low stress amplitudes both the stress concentration and crack initiation occur at the interface of the austenite phase and the mar-

tensite bundles that were produced prior to or subsequent to the early cycling rather than at the pre- γ grain boundaries. In this case martensite formation is so moderate that it may strengthen the regions and facilitate the deformation of the surrounding area. As the results, the crack initiation is considerably delayed although the cracks finally initiate in these regions. It is reasonable, therefore, that the fatigue life of this alloy is shorter than that of the stable austenitic alloy of the same strength at high stress amplitudes, whereas it is longer at low stress amplitudes.

In Fe-38Ni alloy or Fe-25Ni-16Cr alloy the cracks initiate preferentially at the grain boundaries or twin boundaries at high stress amplitudes, and this may be attributed to the stress concentration at the grain boundaries where the cell structures are well developed (Photo. 1 (c)). On the other hand, the cyclic deformation at low stresses seems to intensify the extrusion-intrusion on the specimen surface and causes cracks to initiate along the slip bands rather than the boundaries.

5. Fatigue Crack Propagation Properties

As shown in Fig. 9, fatigue crack propagation property of Fe-30Ni alloy is superior to that of Fe-38Ni alloy at low ΔK level, but this tendency is reversed at high ΔK level. This is similar to that of the S-N curves (Fig. 2) of both alloys, and suggests that the S-N curves of these alloys are affected not only by the crack initiation but also by the propagation (See IV. 4). Fractography (Photo. 5) exhibits that Fe-30Ni alloy fractures transgranularly at low ΔK , but intergranularly at high ΔK . That is the reason why the crack propagation property of this alloy is poor at higher ΔK levels. The dependence of fracture morphology on the ΔK level resembles the applied stress level dependence of the surface crack initiation sites. This is probably related to the rate and period of martensite formation near the crack tips. At low ΔK the preferred crack paths are along the gradually formed martensite bundles, whereas at high ΔK levels they are rather along the most stress-concentrated grain boundaries since martensite transformation near the crack tips has been completed.

In Fe-38Ni alloy the intergranular fracture is predominant over the entire ΔK range, which presumably explains that the crack propagation rate of this alloy is higher than that of Fe-30Ni alloy at low ΔK level. On the other hand, it is rational that propagation rate of Fe-38Ni alloy is lower than that of Fe-30Ni alloy although the predominant mode of crack growth is intergranular in both alloys, as the latter alloy has already transformed to martensite.

The crack propagation property of Fe-25Ni-16Cr alloy is superior to that of other alloys in all the ΔK range. The fractographic analysis of this alloy in Photo. 7 shows that the cracking occurs in the ductile mode which is characterized by striations and dimples, especially in extremely high ΔK range.

V. Conclusions

An attempt has been made to investigate the fatigue

behavior of three different austenitic steels. The materials tested are Fe-30Ni alloy as metastable austenite, Fe-38Ni alloy as stable austenite and Fe-25Ni-16Cr alloy of low stacking fault energy. The results obtained are as follows.

(1) Comparing the fatigue life of these alloys, it is found that the metastable austenitic alloy is superior to stable alloys at low stress amplitudes, but it is inferior at high stress amplitudes. This tendency seems closely related to the rate and period of martensite formation.

(2) From the relationship between cyclic plastic behavior and martensite transformation in Fe-30Ni alloy, the cyclic plastic behavior except for the hardening due to martensite formation is clarified. This behavior resembles that of Fe-38Ni alloy, that is, at high stress amplitudes hardening is remarkable and at low stress amplitudes softening is predominant.

(3) Fe-25Ni-16Cr alloy of low S.F.E. hardens remarkably during cyclic deformation, especially under high stress amplitudes.

(4) In Fe-30Ni alloy, surface cracks preferentially initiate in pre- γ boundaries at high stress amplitudes. At low stress amplitudes, in addition to these sites, they nucleate along the interface of austenite phase and martensite phase. The crack propagation paths also depend on ΔK level.

(5) The fatigue cracks in Fe-38Ni alloy and Fe-25Ni-16Cr alloy are initiated preferentially at austenitic grain boundaries or twin boundaries at high stress amplitudes, whereas mostly along slip bands at low stress amplitudes.

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