Audio-Frequency Internal Friction Characteristics Associated with the $\gamma \rightarrow \epsilon$ Martensitic Transformation in Fe-Mn-Si Based Alloys

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Audio-frequency internal friction and elastic modulus (square of frequency) of Fe-Mn-Si based shape memory alloys were measured as a function of temperature from 150 to 600 K using an electrostatic audio-frequency internal friction instrument. The internal friction characteristics of the martensitic and its reverse transformations have been investigated. The results show that the mechanisms of $\gamma \rightarrow \epsilon$ martensitic and $\epsilon \rightarrow \gamma$ reverse transformations may be different. The elastic modulus softening does not occur during these transformations, implying that the spontaneous nucleation by stacking faults would not need the lattice softening. The changes in modulus during the transformations are due to the fact that the modulus of the ϵ phase is higher than the γ phase. The amount of the ϵ martensite after the $\gamma \rightarrow \epsilon$ transformation decreases with the number of thermal cycling between 150 and 600 K.

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I. Introduction

The Fe-Mn-Si-based shape memory alloy is a potentially worthy material for practical application. In recent years, the materials scientists of different countries have paid much attention to this alloy both practically and theoretically⁽¹⁾⁻⁽⁴⁾. However, these alloys possess a rather low value of reversible strain, usually about 2%⁽³⁾. In addition, the knowledge of the semithermoelastic martensitic transformation⁽⁵⁾ associated with the shape memory effect (SME) in Fe-Mn-Si based alloys is far from the point reached with the thermoelastic martensitic transformation accompanying SME in typical shape memory alloys, such as NiTi and Cu-based alloys. It is recognized that the nucleation of the $\gamma \rightarrow \epsilon$ martensitic transformation in Fe-Mn-Si based alloys occurs by means of stacking fault, and there are two different mechanisms of the nucleation of ϵ martensite, *i.e.*, the pole dislocation mechanism⁽⁶⁾ and the stacking fault mechanism⁽⁷⁾⁻⁽⁹⁾. Vitek⁽¹⁰⁾ once calculated the stacking fault energy on {111} planes in the fcc using an interatomic interaction potential, and the result shows that the intrinsic stacking fault is a configuration of low energy which provides the conditions of the spontaneous nucleation occurring directly through the stacking fault. Hsu has pointed out that the nucleation of the $\gamma \rightarrow \epsilon$ martensitic transformation in Fe-Mn-Si based alloys⁽¹¹⁾, Co-Ni and Co-Cu alloys⁽¹²⁾ may not occur through the pole mechanism, and occur directly through the stacking fault and may not strongly depend on the soft mode.

The internal friction property of solids is known to be highly structure-sensitive. In the case of crystalline materials, the study of the internal friction can yield

many valuable informations, for example, the mobility of atoms and behavior of point defects, dislocations, grain boundaries, and phase transformations, etc. Sato *et al.*⁽¹³⁾ have studied the low-frequency internal friction associated with the $\epsilon \rightarrow \gamma$ reverse transformation in which the hcp (ϵ) martensite was induced by pre-deformation in an Fe-Mn-Si-Cr alloy. The effects of heating rate and frequency on the internal friction peak were investigated and the result meets the equation: $Q^{-1} \propto \dot{T}/f$, but the modulus variations corresponding to the internal friction peaks were not discussed thoroughly. Yoshida and Otsuka⁽¹⁴⁾ have measured changes in internal friction and modulus as a function of temperature from 100 to 500 K in an Fe-Mn-Si-Cr alloy using a low-frequency inverted torsion pendulum with Ke's type. The results show that the cooling/heating rate and frequency dependence of the peak height nearly conformed with Delorme's model $Q^{-1} \propto \dot{T}/f$. Corresponding to the peak, a stepwise modulus change was observed, which was inconsistent with the Delorme's model and was explained by the difference in the modulus of both phases. Pérez-Sáez *et al.*⁽¹⁵⁾ have investigated the internal friction and modulus in a temperature range from 110 to 600 K in an Fe-Mn-Cr-Si-Ni alloy with an inverted torsion pendulum at about 1 Hz. Two internal friction peaks and modulus changes associated with the martensitic and reverse transformations were measured. The effect of thermal cycling on the martensitic and reverse transformation was studied and they showed that the M_s decreases and the amount of ϵ martensite increases with a thermal cycling⁽¹⁵⁾. Lin *et al.*⁽¹⁶⁾ measured the internal friction and modulus related to $\gamma \rightarrow \epsilon$ martensitic and its reverse transformations in an Fe-30Mn-6Si alloy using a low-frequency inverted torsion pendulum instrument. They did not find the occurrence

of lattice softening during the $\gamma \rightarrow \epsilon$ martensitic and its reverse transformations, and did not discuss the mechanism of $\gamma \rightarrow \epsilon$ martensitic and its reverse transformation. Because of the difference in material compositions and in the conditions of testing, the experimental results are not perfectly consistent with each other.

In order to understand the internal friction characteristics of $\gamma \rightleftharpoons \epsilon$ transformation in Fe-Mn-Si based shape memory alloys, in this paper, the changes in internal friction and modulus are measured in a temperature range from 150 to 600 K with an electrostatic audio-frequency internal friction instrument. The experimental results are discussed so as to enrich our knowledge about the transformation mechanism.

II. Experimental Procedure

The alloys studied were prepared by induction furnace melting, using high-purity iron, manganese, silicon, chromium and casting under an argon atmosphere. After homogenization at 1373 K for 15 h, the ingot was hot forged and hot rolled into plate with 1–2 mm thickness. Specimens of dimensions 5 mm $\times$ 30 mm for internal friction measurement were cut from the sheet by a spark cutter and were annealed at 1173 K for 10 min to avoid any influence from rolling texture. In order to remove the demanganization layer and to obtain thin internal friction specimens, all specimens were ground and chemically polished to 0.2–0.3 mm in thickness. The compositions of the alloys studied and the critical temperatures T_N , M_s , A_s and A_f determined by the electrical resistivity method are shown in Table 1.

The internal friction value was measured by means of an electrostatic audio-frequency internal friction instrument with the audio-frequency of 190 to 340 Hz. The measurements were made during thermal cycling between 150 and 600 K. The cooling and heating rates were 2–4 K/min. The recording of data was completely automatic, and the data on internal friction and frequency versus temperature were plotted by a computer. Sato *et al.*⁽¹³⁾ pointed out that the variation of the ω^2 during the $\epsilon \rightarrow \gamma$ transformation can be attributed to the size change of the strained specimen but not to an actual or effective change in elastic constants. The specimens in the present work were in an annealed state, and the shape change was very small during cooling and heating. For this reason, we may regard the changes in the square of frequency as the changes in modulus since the elastic modulus is proportional to the square of frequency. In order to get steady data, the measurement of the Fe-Mn-Si-Cr alloy starts from the second thermal cycling. The effects of thermal

cycling on the $\gamma \rightarrow \epsilon$ martensitic and its reverse transformation were measured at a wide temperature range of 150–600 K. In order to get the effect of the frequency on the internal friction, the specimen was installed again to raise the testing frequency after the third cycling. The fourth thermal cycling starts at room temperature. For the same purpose, the specimens of the Fe-Mn-Si alloy were first heated for 5 min at 573 K in the internal friction instrument to clear up stress-induced martensite which may be formed in machining or installing course. The measurement of the internal friction and modulus starts upon cooling from 573 K.

III. Results and Discussion

1. $\gamma \rightarrow \epsilon$ martensitic transformation

The changes in internal friction and modulus of the Fe-Mn-Si-Cr alloy upon heating and cooling in the range of temperature from 150 to 600 K were measured as shown in Fig. 1. There are two stepwise variations on the F^2 - T curves. The first stepwise increment corresponds to a large sharp internal friction peak at about 303 K, and the second stepwise decrease corresponds to another small peak around 206 K. The results of resistivity measurement (Table 1) indicate that the M_s and T_N temperatures of martensitic and antiferromagnetic transformations are 323 and 223 K, respectively. Thus, in Fig. 1, the first peak represents the $\gamma \rightarrow \epsilon$ martensitic transformation, and the second peak relates to the paramagnetic-antiferromagnetic transition. It is very noticeable that a large stepwise increment in modulus associated with the $\gamma \rightarrow \epsilon$ transformation can be found on the F^2 - T curve in Fig. 1. The modulus of the alloy increases rapidly with the increase of the amount of ϵ phase during continuous cooling. It indicates that the modulus of the ϵ phase is larger than that of the parent (γ) phase. The modulus of ($\epsilon + \gamma$) during heating is larger than that of (γ) during cooling at the same temperature between 323 and 423 K, which also indicates significantly that the modulus of the ϵ phase is

Fig. 1 Changes in internal friction (Q^{-1}) and elastic modulus (F^2) with temperature in an Fe-Mn-Si-Cr alloy, the second cycle, testing frequency 220 Hz.

Table 1 Compositions (mass%) and transformation temperatures (K) of the alloys studied.

Alloy	Mn	Si	Cr	T_N	M_s	A_s	A_f
Fe-Mn-Si	30.30	6.10	—	273 K	323 K		
Fe-Mn-Si-Cr	26.4	6.02	5.2	223 K	323 K	393 K	453 K

larger than that of the γ phase. The result of the present work is consistent with the results obtained by Yoshida and Otsuka⁽¹⁴⁾ as well as Perez-Saez *et al.*⁽¹⁵⁾.

It should be noted that the modulus variation range of the $\gamma \rightarrow \epsilon$ martensitic transformation on the F^2 - T in Fig. 1 is wide, from 298 K to the Néel temperature, but the internal friction peak related to the $\gamma \rightarrow \epsilon$ martensitic transformation does not exactly correspond to the change of the modulus. The internal friction change has definitely appeared before the onset of the change in the modulus. In other words, the variation of the modulus is not observed till the internal friction peak appears. The internal friction lowers to the background value at about 273 K, implying that the $\gamma \rightarrow \epsilon$ transformation seems to stop. This phenomenon can be explained as follows. The changes in the modulus can not be observed for small amount of the ϵ phase in the initial stage of the $\gamma \rightarrow \epsilon$ transformation, while the internal friction change related to the transformation could be clearly observed. With decreasing temperature, the amount of ϵ phase increases rapidly, then the change in the modulus can be observed, and the internal friction decreases gradually to the background. From this phenomenon, it seems that the change in internal friction mainly relates to the nucleation process of the $\gamma \rightarrow \epsilon$ transformation, and the height of the internal friction associated with the $\gamma \rightarrow \epsilon$ transformation decreases with the decrease of the nucleation rate. The modulus variation seems to be related to the amount of the ϵ phase, *i.e.* the modulus increases with the increase of the amount of the ϵ phase.

A small internal friction peak can be observed upon cooling between 373 and 423 K, which is about 50–60 K above M_s in Fig. 1. It indicates that a change in the microstructure appears in the temperature range of 373 to 423 K. There are two possibilities for appearance of this phenomenon. (1) it may be related to a formation of intermediate phase before the $\gamma \rightarrow \epsilon$ transformation. The significant change in the modulus can not be observed corresponding to this peak on the F^2 - T curves in Fig. 1, indicating that the elastic modulus of the intermediate phase is close to the modulus of the γ phase. The formation of an intermediate phase may be advantaged to decrease the energy of the $\gamma \rightarrow \epsilon$ transformation. Liu⁽¹⁷⁾ recently found an intermediate phase with an 8R structure in an Fe-Mn-Si based alloy by the electron microscopy, which may be related to the present result. (2) it may be associated with a pre-transformation behavior of the $\gamma \rightarrow \epsilon$ transformation. A further investigation is in need.

Figure 2 shows the changes in internal friction and modulus of an Fe-Mn-Si alloy with temperature from 150 to 600 K, revealing that the changes in internal friction and modulus in the Fe-Mn-Si-Cr alloy (Fig. 1) are different from that in the Fe-Mn-Si alloy (Fig. 2). There is a stepwise decrease in the F^2 - T curve upon cooling in Fig. 2. We know that the Néel temperature of the Fe-Mn-Si alloy is 273 K by the resistivity measurement, thus the abnormal modulus corresponding to T_N is related to the antiferromagnetic transition. There is not an internal friction peak corresponding to the abnormal modulus,

Fig. 2 Changes in internal friction (Q^{-1}) and elastic modulus (F^2) with temperature in an Fe-Mn-Si alloy, testing frequency 190 Hz.

but there is a small peak at 225 K with further cooling below the Néel temperature. This small peak associates with the $\gamma \rightarrow \epsilon$ transformation, which can be verified during the $\epsilon \rightarrow \gamma$ transformation. Comparison between Figs. 1 and 2 show that the height of the internal friction peak of the Fe-Mn-Si-Cr alloy is ten times as great as that of the Fe-Mn-Si alloy during the $\gamma \rightarrow \epsilon$ transformation. For the higher Néel temperature in the Fe-Mn-Si alloy, the $\gamma \rightarrow \epsilon$ transformation is partly inhibited and the internal friction peak of the $\gamma \rightarrow \epsilon$ transformation is depressed to a lower temperature (Fig. 2). Because the amount of the ϵ phase resulting from the $\gamma \rightarrow \epsilon$ transformation in Fe-Mn-Si is very small, the increment of modulus related to the $\gamma \rightarrow \epsilon$ transformation can not be observed.

In Figs. 1 and 2, we can see that the modulus corresponding to the internal friction peak of the $\gamma \rightarrow \epsilon$ transformation does not decrease, in other words, the softening of the γ phase does not occur. It indicates that the nucleation of the $\gamma \rightarrow \epsilon$ martensitic transformation in the Fe-Mn-Si based alloys may not need the soft mode. Vitek⁽¹⁰⁾ once calculated the stacking fault energy on {111} planes in the fcc by the interatomic interaction potential and the result shows that a great number of stacking faults exist stably on {111} planes in the fcc phase. The intrinsic stacking fault is a configuration of low energy. The stacking fault energy is relaxed perpendicular to the planes adjacent to the stacking fault. It implies that the stacking fault may not produce a long range stress field. The low energy of the configuration provides the condition of the spontaneous nucleation occurring directly through the stacking fault. It has been observed that a large amount of intrinsic stacking fault often existed in Fe-Mn-Si based alloys with low stacking fault energy.

Hsu has pointed out that the nucleation of the $\gamma \rightarrow \epsilon$ martensitic transformation in Fe-Mn-Si based alloys⁽¹¹⁾, Co-Ni and Co-Cu alloys⁽¹²⁾ may not strongly depend on the soft mode, and the strengthening of the parent phase will not markedly affect the M_s . The critical driving force for the $\gamma \rightarrow \epsilon$ transformation in an Fe-Mn-Si based alloy can be expressed as⁽¹¹⁾⁽¹²⁾:

$$\Delta G_c = A\gamma + B \quad (1)$$

where γ refers to the stacking fault energy, A is a constant and B nearly equals to the strain energy, and $A\gamma > B$. With the decrease of the temperature, the stacking fault energy in the alloy decreases⁽¹⁸⁾, and the critical driving force decreases too. Thus the nucleation of the $\gamma \rightarrow \varepsilon$ transformation occurs spontaneously through the stacking fault, and in an Fe-Mn-Si based alloy, the soft mode is not necessary for the nucleation of the $\gamma \rightarrow \varepsilon$ martensitic transformation. The result of the present work is consistent with the previous works⁽¹²⁾, and Li and Wayman⁽⁸⁾ supports Hsu's point of view⁽¹²⁾.

2. $\varepsilon \rightarrow \gamma$ transformation

In Fig. 1, there are two stepwise changes on the F^2 - T curve upon heating from 150 to 600 K in the Fe-Mn-Si-Cr alloy. The first abnormal increment of modulus corresponds to an internal friction peak around 238 K, the T_N^γ of the antiferromagnetic transition determined from the electrical resistivity measurement. The second abnormal modulus, a large decrease in the F^2 - T curve appears around 423 K, corresponding to a wide internal friction peak (417–500 K) associated with the $\varepsilon \rightarrow \gamma$ transformation. As the elastic modulus of the γ phase is lower than that of the ε phase, the modulus of the Fe-Mn-Si-Cr alloy would markedly decrease during the $\varepsilon \rightarrow \gamma$ transformation. The modulus decreases to the same value as the cooling magnitude on the F^2 - T curve upon cooling after the $\varepsilon \rightarrow \gamma$ transformation, which indicates that the whole microstructure is the γ phase. As seen in the F^2 - T curve, the modulus in the initial stage of the $\varepsilon \rightarrow \gamma$ transformation does not visibly decrease, so we can conclude that the modulus softening does not occur during the $\varepsilon \rightarrow \gamma$ transformation.

As shown in Fig. 2, there are two internal friction peaks, at 298 and 420 K, related to the antiferromagnetic and $\varepsilon \rightarrow \gamma$ transformation respectively on the internal friction curve upon heating. By comparison of Figs. 1 and 2, we can see that the height of the internal friction is much lower and the lowering of modulus in the Fe-Mn-Si alloy is less than those in the Fe-Mn-Si-Cr alloy during the $\varepsilon \rightarrow \gamma$ transformation, which implies that the amount of the ε phase in the Fe-Mn-Si alloy is very small after cooling to 200 K.

Comparing the $\gamma \rightarrow \varepsilon$ transformation with the $\varepsilon \rightarrow \gamma$ transformation in Fig. 1 we can find that the change in the internal friction keeps pace with the change in modulus during the $\varepsilon \rightarrow \gamma$ transformation, but it is not the case during the $\gamma \rightarrow \varepsilon$ transformation. It indicates that the mechanism of the $\varepsilon \rightarrow \gamma$ transformation may be different from that of the $\gamma \rightarrow \varepsilon$ transformation.

From the above discussion, we know that the nucleation of ε martensite occurs directly through the stacking fault and makes growth by the movement of Shockley partial dislocations in the $\gamma \rightarrow \varepsilon$ transformation. In the $\varepsilon \rightarrow \gamma$ transformation, on the other hand, two mechanisms may coexist, *i.e.*, the reverse movement of Shockley partial dislocations and the nucleation in the ε phase occurring through the stacking fault.

3. Paramagnetic $\rightarrow$ antiferromagnetic transition

We can observe an internal friction peak corresponding to the abnormal modulus around Néel temperature during heating or cooling in Figs. 1 and 2. The internal friction peak near T_N^γ may originate from the motion of domain walls during the antiferromagnetic transition, which displays the internal friction characteristic of the first-order phase transformation. The abnormal changes in modulus near T_N^γ point appear in different temperature ranges during heating and cooling and the initial point of the abnormal changes in modulus upon heating or cooling is denoted as the T_N^γ temperature⁽¹⁹⁾. Thus we recognize that the peak temperatures of the internal friction near T_N^γ are not the same during heating and cooling in Fig. 1, showing the characteristics of the first-order phase transformation due to the motion of domain walls. For the same reason, the peak temperature of the internal friction related to the antiferromagnetic transition is at 298 K, but is not at the T_N^γ point (273 K). The abnormal modulus appears at 273 K in the Fe-Mn-Si alloy (Fig. 2), and at 225 K in the Fe-Mn-Si-Cr alloy (Fig. 1) upon heating or cooling. So the initial points of the abnormal modulus are the T_N^γ points, 273 K in the Fe-Mn-Si alloy and 225 K in the Fe-Mn-Si-Cr alloy respectively, which are consistent with the results of the electrical resistivity measurement.

As the T_N^γ temperature is about 80 K below M_s and the effect of the antiferromagnetic transition on the $\gamma \rightarrow \varepsilon$ transformation is very small, the $\gamma \rightarrow \varepsilon$ transformation occurs adequately during cooling in the Fe-Mn-Si-Cr alloy. Near T_N^γ , the microstructure consists of a large amount of the ε phase and a small amount of the residual γ phase, the abnormal decrease of the modulus related to the antiferromagnetic transition of γ phase is small too (Fig. 1). The $\gamma \rightarrow \varepsilon$ transformation is partly suppressed during cooling as the T_N^γ is slightly below the M_s in Fe-Mn-Si alloy. The microstructure of the Fe-Mn-Si alloy is mainly the γ phase near T_N^γ , so a large decrease of the abnormal modulus related to the antiferromagnetic transition of the γ phase appears near T_N^γ .

4. The effect of thermal cycling on the $\gamma \rightarrow \varepsilon$ and $\varepsilon \rightarrow \gamma$ transformation

Figure 3 shows changes in internal friction (Q^{-1}) and elastic modulus (F^2) with temperature in the Fe-Mn-Si alloy during the third, fourth and fifth thermal cycling after the second thermal cycling (Fig. 1). In Fig. 3(b) the measurement in which the specimen was cooled to 173 K in the former thermal cycle started from the room temperature. From the results of measurement with the different frequency, the changes in the internal friction and modulus in Fig. 1 are found to be consistent with that in Fig. 3. But the height of the internal friction peak decreases with the increasing frequency from which it may be concluded that the height of the internal friction peaks is inversely proportional to the frequency.

By comparison between Figs. 1 and 3, we can find that the heights of internal friction peaks of the $\gamma \rightarrow \varepsilon$ and $\varepsilon \rightarrow \gamma$

Fig. 3 Changes in internal friction (Q^{-1}) and elastic modulus (F^2) with temperature in the Fe-Mn-Si-Cr alloy, (a) the third cycle, testing frequency 220 Hz. (b) the fourth cycle and (c) the fifth cycle, testing frequency 340 Hz.

transformations decrease with the increase of the number of thermal cycling, implying the marked effect of the thermal cycling on the $\gamma \rightarrow \varepsilon$ and $\varepsilon \rightarrow \gamma$ transformation. According to Belko's model⁽²⁰⁾, the volume of the reversible martensite is approximately proportional to the integration of the transient component Q^{-1} with respect to temperature T from A_s to A_f in reverse martensitic transformation, under the conditions of the constant heating rate, the constant testing frequency and the variation of the shear modulus below 5 per cent. Thus, the volume of reversible martensite V_m^0 can be expressed as

$$V_m^0 = \frac{\omega k T_p}{2G\beta\alpha^2} \int_{A_s}^{A_f} Q^{-1} dT \quad (2)$$

in which k is Boltzmann's constant, β is the size of the critical nucleus, α is the transformation strain of martensite, $T_p = (A_s + A_f)/2$ is the temperature of the internal friction peak, ω is the testing frequency and G is the shear modulus.

From eq. (2), the volume of martensite in $\varepsilon \rightarrow \gamma$ transformation is proportional to the area of the internal friction peak ($\int_{T_1}^{T_2} Q^{-1} dT$, T_1 and T_2 are the bottom temperatures of the internal friction peak). The decrease of the modulus corresponding to the internal friction peak of the $\varepsilon \rightarrow \gamma$ transformation is about 5%, which can be considered as consistent with the conditions in eq. (2) for qualitative analyses. The areas of the internal friction peaks of the

$\varepsilon \rightarrow \gamma$ transformation were calculated by a computer with Microcal software, as shown in **Table 2**.

Table 2 shows that the amount of the ε martensite in the $\varepsilon \rightarrow \gamma$ transformation remarkably decreases with the increase of the number of the thermal cycling. For example, the decrease of the height of the internal friction peak of the $\gamma \rightarrow \varepsilon$ transformation from second to third thermal cycles is about 28.88%, and 11.45% from fourth to fifth thermal cycles. A probable interpretation is that the transformation and thermal stresses are induced during the wide temperature range of the thermal cycling, and these stresses increase as the A_s increases with the number of cycling⁽²¹⁾. These stresses may result in the formation of lattice defects. In addition, the lattice defects also easily induce near Néel temperature due to the softening of the γ phase. These sessile lattice defects impede the motion of the partial dislocations on interfaces. As a consequence, an additional driving force is required to produce a certain amount of martensite. The $\gamma \rightarrow \varepsilon$ trans-

Table 2 The effect of thermal cycling on the areas ($\int_{T_1}^{T_2} Q^{-1} dT \times 10^{-3}$) of the internal friction peaks of the $\varepsilon \rightarrow \gamma$ transformation.

Number of thermal cycling	2	3	4	5
Area of the $\varepsilon \rightarrow \gamma$ peak	1634.92	1214.77	384.78	374.70
Testing frequency, Hz	220	220	340	340

formation is partly suppressed, and the amount of the ε martensite decreases. Thus the amount of the reverse martensitic transformation decreases. The result is contrary to the result gotten by Tsuzaki *et al.*⁽²²⁾ in an Fe-Mn-Si alloy. Because the thermal cycles are between 307 and 573 K in the work of Tsuzaki *et al.*, the transformation and thermal stresses are lower, and the number of lattice defects resulting from the $\gamma \rightarrow \varepsilon$ transformation are smaller than that in present work. The present results are also contrary to the result gotten by Pérez-Sáez *et al.*⁽¹⁵⁾ in an Fe-Mn-Si-Cr alloy. This may be due to the different composition of alloys.

From the Belko's model⁽²⁰⁾, the volume of reversible martensite is approximately proportional to the area of the internal friction. So we can also consider that the area of the internal friction peak of the $\gamma \rightarrow \varepsilon$ transformation is proportional to the volume of the ε martensite. The calculated integration of the area of the $\gamma \rightarrow \varepsilon$ transformation peak (303 K) in Fig. 1 is 423.46×10^{-3} , that is one-fourth of the area of the $\varepsilon \rightarrow \gamma$ transformation peak (472 K) in Fig. 1, indicating the area of the internal friction peak of the $\gamma \rightarrow \varepsilon$ transformation is markedly smaller than that of the $\varepsilon \rightarrow \gamma$ transformation. The internal friction associated with the martensitic and reverse transformations is considered to be a static hysteresis loss associated with the stress-induced motion of the coherent interfaces⁽²³⁾. Since there are a larger number of coherent interfaces between γ and ε phases in the $\varepsilon \rightarrow \gamma$ transformation than that in the $\gamma \rightarrow \varepsilon$ one, the area of the internal friction peak of the $\varepsilon \rightarrow \gamma$ transformation is larger than that in the $\gamma \rightarrow \varepsilon$ transformation.

IV. Conclusions

(1) The modulus softening does not occur during the $\gamma \rightarrow \varepsilon$ martensitic transformation as well as the reverse transformation, so the nucleation of ε -martensite does not need the soft mode in Fe-Mn-Si based alloys. The change in modulus during the transformations is due to the difference in the modulus of both phases. The modulus of the ε phase is greater than that of the γ phase.

(2) The change in the internal friction keeps pace with the change in modulus in the $\varepsilon \rightarrow \gamma$ transformation, but it is not the case in the $\gamma \rightarrow \varepsilon$ transformation, which implies that the mechanism of the $\varepsilon \rightarrow \gamma$ transformation may be different from the $\gamma \rightarrow \varepsilon$ transformation. The nucleation of ε martensite occurs directly through the stacking fault in the $\gamma \rightarrow \varepsilon$ transformation. The $\varepsilon \rightarrow \gamma$ transforma-

tion is a combined process of the reverse movement of the partial dislocations and the nucleation occurring directly through the stacking fault in the ε phase.

(3) The amount of the ε martensite after the $\gamma \rightarrow \varepsilon$ transformation decreases with the increase of the number of thermal cycles between 150 and 600 K. It may be attributed to lattice defects which impede the motion of the partial dislocations on interfaces.

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