Effect of magnetic field on TTT diagram of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation in SUS304L stainless steel

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Abstract. We have investigated the effect of magnetic field on TTT diagram of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation in a solution-treated SUS304L stainless steel in order to clarify kinetics of the successive martensitic transformation. The TTT diagram of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation shows a C-curve with a nose temperature located at 103 K. Incubation time of the successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation shortens with increasing the strength of magnetic field. However, the nose temperature does not change significantly under the magnetic field. An in-situ optical micrograph suggests that the successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) transformation probably proceeds by isothermal \( \gamma \rightarrow \varepsilon' \) martensitic transformation followed by athermal \( \varepsilon' \rightarrow \alpha' \) martensitic transformation.

1. Introduction

Martensitic transformations are usually classified into two groups from a view point of kinetics: athermal and isothermal ones [1]. The former transformation occurs instantaneously when a definite temperature (\( M_s \)) is reached, while the latter occurs after some finite incubation time during isothermal holding. Although the two kinds of transformation kinetics are now basically explained by a universal phenomenological theory [2], the number of the alloys exhibiting an isothermal transformation is small. For this reason, most of the isothermal transformations studied so far are the \( \gamma \rightarrow \alpha' \) ones observed in Fe-Ni-Cr and Fe-Ni-Mn alloys. The isothermal transformation in these alloys is characterized by a C-curve in time-temperature-transformation (TTT) diagram [3-4].

Recently, however, we found a new type of isothermal transformation in a solution-treated SUS304L stainless steel. In the steel, the successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation proceeds by isothermal holding in the temperature range between 70 and 170 K [5]. As far as the authors are aware, this was the first finding of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation by isothermal holding. However, the TTT diagram has not been constructed in previous studies. Also, the kinetics of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation has not been clarified yet.

In the present study, therefore, we have constructed the TTT diagram of the successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation in a solution-treated SUS304L and examined the effect of magnetic field on the TTT diagram in order to obtain information about kinetics of successive \( \gamma \rightarrow \varepsilon' \rightarrow \alpha' \) martensitic transformation.
2. Experimental Procedure

The material used in the study is SUS304L austenitic stainless steel with a composition of 0.023C-0.48Si-1.07Mn-0.005S-8.47Ni-18.20Cr-Bal.Fe (mass %). From the sheet, specimens of 3 × 3 × 1 mm in size were cut out, and were solution-treated at 1323 K for 0.5 h in vacuum followed by quenching into iced water. Then the oxidized surface layer was eliminated by electropolishing in an electrolyte composed of 85% C2H5OH and 15% HClO4 in volume. Isothermal holding was carried out under magnetic fields of 0 and 0.8 MA/m in the temperature range between 70 and 170 K. The volume fraction of the α′-martensite, \( f_{α′} \), formed by an isothermal holding was evaluated by a magnetization measurement at 300 K (= \( T_R \)). That is, \( f_{α′} = M_0(T_R) / M_0^{α′}(T_R) \), where \( M_0(T_R) \) and \( M_0^{α′}(T_R) \) are the spontaneous magnetization of the specimen and that of the α′-phase, respectively, at \( T_R \). Here, the magnetizations of γ-phase and ε′-martensite are neglected because they are nonmagnetic [6]. The value of \( M_0^{α′}(T_R) \) is roughly approximated to be the value at 0 K, \( M_0^{α′}(0) \), which is estimated to be 1.79 μB/atom considering the Slater-Pauling curve and their valence electron concentration [7-8].

Morphology of the martensites was observed by in-situ optical microscopy during an isothermal holding process.

3. Results and Discussion

Isothermal holding experiments for constructing the TTT curve under magnetic fields have been carried out at several temperatures in the temperature range between 70 and 170 K under magnetic fields of 0 and 0.8 MA/m. Figure 1 shows typical magnetization curves at room temperature (\( T_R \)) after isothermal holding in the absence of magnetic field at 103 K for 50 s (a), 170 s (b), 520 s (c), 1660 s (d), 5200 s (e) and 10400 s (f). We can evaluate the volume fraction of α′-martensite (\( f_{α′} \)) from the spontaneous magnetization as described in experimental procedure. As an example, the spontaneous magnetization obtained from curve (f) is indicated with an arrow in figure 1. Obviously, the spontaneous magnetization increases with increasing isothermal holding time. It means that the \( f_{α′} \) increases with increasing the isothermal holding time.

The \( f_{α′} \) obtained from the figure 1 is shown with solid circles as a function of holding time in figure 2. The same holding experiments at 103 K have been made under magnetic field of 0.8 MA/m, and the result is also shown with opened circles in figure 2. From the linear relation shown in figure 2, the time required for the formation of 0.5 vol.% of α′-martensite is obtained. It is 6.1 and 3.6 ks at 103 K under magnetic fields of 0 and 0.8 MA/m, respectively, as shown by arrows. We know from the result that the \( f_{α′} \) obviously depends on magnetic field as well as holding time.

**Figure 1.** Magnetization curves at 300 K of the solution-treated SUS304L after isothermal holding at 103 K for (a) 50 s, (b) 170 s, (c) 520 s, (d) 1660 s, (e) 5200 s and (f) 10400 s.

**Figure 2.** Relation between holing time and volume fraction of α′-martensite during the isothermal holding at 103 K under magnetic fields of 0 and 0.8MA/m.
The same experiments have been made at some temperatures under magnetic fields of 0 and 0.8 MA/m, and the TTT diagram of 0.5 vol. % of \(\alpha'\)-martensite has been constructed as shown in figure 3. It should be noted in this result that TTT diagram of successive \(\gamma\rightarrow\epsilon'\rightarrow\alpha'\) martensitic transformation clearly forms a typical C-curve, and nose temperature (indicated by an arrow) is about 103 K. Moreover, incubation time shortens by the application of magnetic field. However, nose temperature of C-curves does not change significantly. This result is different from that of Fe-Ni-Cr and Fe-Ni-Mn alloys, whose incubation time shortens and nose temperature decrease with increasing the strength of magnetic field [3-4]. This difference should be ascribed to the difference in kinetics of martensitic transformation between them.

In order to know how the isothermal \(\gamma\rightarrow\epsilon'\rightarrow\alpha'\) martensitic transformation proceeds, we have made in-situ optical microscope observation. Figure 4 shows a series of optical micrographs showing isothermal \(\gamma\rightarrow\epsilon'\rightarrow\alpha'\) martensitic transformation at 103 K. After isothermal holding of \(3.0 \times 10^2\) s, banded plates of the \(\epsilon'\)-martensite appear in the \(\gamma\)-phase in figure 4 (a). The number of \(\epsilon'\)-plates gradually increases with increasing holding time, and moreover the constant of certain area enclosed by banded \(\epsilon'\)-plates (indicated by a dashed rectangle in figure 4 (b)) also increases with increasing the holding time. Such a change in contrast will be due to the gradual growth of banded \(\epsilon'\)-martensites. This result suggests that the \(\gamma\rightarrow\epsilon'\) martensitic transformation is isothermal transformation. On the other hand, figure 4 (d) shows that wedge-shaped plates, which are characteristics of \(\alpha'\) martensite [9],
instantaneously formed in the banded $\varepsilon'$-plates. This result implies that the $\varepsilon'\rightarrow\alpha'$ martensitic transformation is athermal one. We confirmed from figure 4 that the successive $\gamma\rightarrow\varepsilon'\rightarrow\alpha'$ martensitic transformation proceeds by an isothermal $\gamma\rightarrow\varepsilon'$ martensitic transformation followed by an athermal $\varepsilon'\rightarrow\alpha'$ martensitic transformation. Probably, the athermal nature of $\varepsilon'\rightarrow\alpha'$ martensitic transformation is the reason why the nose temperature does not change by the application of magnetic field as seen in Figure 3.

4. Conclusions
We have investigated the effect of magnetic field on TTT diagram of successive $\gamma\rightarrow\varepsilon'\rightarrow\alpha'$ martensitic transformation in a solution-treated SUS304L stainless and the following results have been obtained.
(i) TTT diagram of the successive martensitic transformation shows a C-curve, whose nose temperature is about 103 K.
(ii) Incubation time of the successive $\gamma\rightarrow\varepsilon'\rightarrow\alpha'$ martensitic transformation shortens with increasing the strength of magnetic field. However, the nose temperature does not change significantly under the magnetic field.
(iii) Successive $\gamma\rightarrow\varepsilon'\rightarrow\alpha'$ martensitic transformation probably proceeds by isothermal $\gamma\rightarrow\varepsilon'$ martensitic transformation followed by athermal $\varepsilon'\rightarrow\alpha'$ martensitic transformation.

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