Effects of High Magnetic Field and Tensile Stress on Martensitic Transformation Behavior and Microstructure at 4.2 K in Fe-Ni-C Alloys

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Effects of high magnetic field and tensile stress on martensitic transformation behavior and microstructure at 4.2 K have been studied in Fe-31Ni-0.4C and Fe-27Ni-0.8C (wt%) shape memory alloys. In order to make clear the difference of the effects of high magnetic field and tensile stress on the amount of martensite, two types of experiments were conducted, that is, the magnetic field of 10 T was applied first and then the tensile stress of 220 MPa was applied in constant magnetic field in one type of experiment and the tensile stress of 220 MPa was applied first and then the magnetic field of 10 T was applied under constant tensile stress in the other type of experiment. The amount of martensite formed in these two experiments were compared. It was found that the critical magnetic field to induce martensitic transformation is between 7.5 T and 10 T. In the case of Fe-27Ni-0.8C, martensitic transformation is stress-induced at lower level of stress in magnetic field than in the case no magnetic field is applied. The amount of martensite formed by increasing the magnetic field under constant stress is larger than that formed by increasing the stress in the constant magnetic field, which shows that the effect of tensile stress on the number density of martensite is larger than that of magnetic field in this experimental condition.

key words: high magnetic field, tensile stress, martensitic transformation at 4.2K, transformed structure, Fe-Ni-C alloys,

I. Introduction

Austenitic stainless steels become unstable under the stress or the magnetic field, and as a result, the mechanical properties change. The effects of stress on martensitic transformation were studied in detail[1,2] and the stress-induced martensitic transformation start temperature can be calculated quantitatively as a function of applied stress. The effects of high magnetic field on martensitic transformation have also been studied by some researchers[2-17]. Among these, Kakeshita et al.[5-15], Emura et al.[16] and Kurita et al.[17,18] have been studying the effects of magnetic field on martensitic transformation quite systematically. However, very few works[16] have ever been done on the combined effects of high magnetic field and stress on the martensitic transformation. In this study, effects of high magnetic field, tensile stress and the combined effects of high magnetic field and tensile stress on martensitic transformation behavior and microstructure at 4.2 K have been investigated in Fe-Ni-C shape memory alloys. In order to clarify the difference of the effects of high magnetic field and tensile stress on the martensitic transformation behavior, two types of experiments were conducted, that is, the magnetic field of 10 T was applied first and then the tensile stress of 220 MPa was applied in

constant magnetic field in one type of experiment and the tensile stress of 220 MPa was applied first and then the magnetic field of 10 T was applied under constant tensile stress in the other type of experiment. The amount of martensite formed in these two experiments were compared.

II. Experimental

The alloys used in this study are Fe-31Ni-0.4C and Fe-27Ni-0.8C(wt%) shape memory alloys. Kajiware and Kikuchi[19] showed that thin-plate type martensites are stress-induced at 77 K and the A_f temperatures are 600 K and 750 K for Fe-31Ni-0.4C and Fe-27Ni-0.8C, respectively. Alloys were made by vacuum melting, and ingots of 3 kg with 45X45X70 mm size were obtained. The ingots were hot-forged and hot-rolled into sheets 20-mm thick. Tensile specimens with parallel portion of 3X3X20 mm were cut from the sheets, sealed in evacuated silica capsules. These were solution-treated at 1473 K for 3.6 ks, and quenched to room temperature by breaking the capsules in the brine. The specimens were chemically polished by 0.1 mm in a hydrofluoric acid solution to remove any decarburized surface layer. These specimens were used for the four kinds of experiments shown schematically in Fig. 1. In this figure, all the tensile

Fig. 1 Schematic illustration for the application of high magnetic field and/or tensile stress.

tests with or without the high magnetic field have been conducted at 4.2 K using the super conducting magnet equipped with tensile machine which can apply maximum load of 1 t. The effect of high magnetic field on martensitic transformation was studied by increasing the magnetic field from 0 up to 10 T in about 10 min (the rate of increasing and decreasing magnetic field is constant in all the experiments in this study), kept it constant for 5 min and then decreased to 0 (a). The effect of tensile stress on martensitic transformation was studied by increasing the tensile stress from 0 up to 220 MPa (which is about 1/3 of the maximum tensile stress of Fe-27Ni-0.8C), kept constant for 5 min and then decreased to 0 (b). The effect of stress applied in high magnetic field on martensitic transformation was studied as shown in Fig. 1(c). First, the magnetic field was increased up to 10 T and kept constant, and the tensile stress was increased up to 220 MPa and kept constant for 5 min. Then the stress was decreased to 0, and then the magnetic field was also decreased to 0. The effect of high magnetic field applied under tensile stress was studied as shown in Fig. 1(d). First, the tensile stress was increased up to 220 MPa and kept constant. Then the high magnetic field was increased up to 10 T, and kept constant for 5 min. Then the magnetic field was decreased to 0 and then the stress was decreased to 0 as well. The

stress-strain curves were measured during these experiments. The specimens after these experiments were chemically polished by 0.1 mm in a hydrofluoric acid solution and etched by a 5% nital, and then observed by an optical microscope.

The specimens of 2X2X2 mm size were used for the measurement of magnetization curves by VSM in order to determine the transformation temperature under magnetic field. The specimens were sealed in evacuated silica capsules and solution-treated at 1473 K for 3.6 ks, and quenched to room temperature by breaking the capsules in brine and supplied for the experiment.

III. Results and discussion

It was found by the optical microscopic observation that more than 50% martensite were formed by applying high magnetic field of 10 T in the experiment indicated in Fig. 1(a). In order to determine the transformation temperature under magnetic field, the magnetization curves were measured by VSM as shown in Fig. 2. The curves saturate at around 1 T in both specimens. There is no indication of martensitic transformation on these curves. The maximum magnetic field is about 7.5 T in this experiment. Therefore the critical magnetic field is between 7.5 T and 10 T.

Fig. 2 Magnetization curves at 4.2 K for solution-treated Fe-31Ni-0.4C and Fe-27Ni-0.8C alloys.

Figures 3 and 4 show the results of experiments indicated in Fig. 1 (b)-(d). The results of (a)-(c) in each figure were obtained by the experiments shown in Fig. 1(b)-(d), respectively. Figs. 3 and 4 show the stress-strain curves of Fe-31Ni-0.4C and Fe-27Ni-0.8C, respectively. Figs 3(a) and 4(a) are the stress-strain curves obtained by applying the tensile stress of 220 MPa. In the figure, no magnetic field was applied. Serrations due to the stress-induced martensitic transformation are observed on both curves, more clearly in Fe-27Ni-0.8C. Figs 3(b) and 4(b) show the stress-strain curves obtained by applying the tensile stress of 220 MPa in high magnetic field of 10 T as indicated in Fig. 1(c). Serrations due to martensitic transformation are observed on both curves. In the case of Fe-27Ni-0.8C, the transformation proceeds at very low stress level in the early stage of deformation. The driving force for martensitic transformation is raised with the application of magnetic field, and the nucleation of martensite becomes easier in magnetic field. As a result, the martensitic transformation is stress-induced at lower level of stress in magnetic field than that without magnetic field. Figs 3(c) and 4(c) show the stress-strain curves obtained by applying the high magnetic field of 10 T under tensile stress of 220 MPa as indicated in Fig. 1(d). The left half part of curve is obtained during the stress-induced martensitic transformation without magnetic field. The right half part of curve is obtained during the transformation induced by increasing the magnetic field under constant tensile stress. Many clear serrations were generated on the curve because the stress is accommodated when a bunch of martensite plates are formed by stress-induced transformation and the stress level is lowered, but the stress is controlled to be kept constant in this experiment and is increased to 220 MPa, and this procedure occurs repeatedly to form the serrations. The elongation of the specimen shown in the right half part of the curves in Figs. 3(c) and 4(c) is indicated as a function of time and magnetic field in Figs. 5 and 6. Figure 5 and 6 are the results obtained for Fe-31Ni-0.4C and Fe-27Ni-0.8C, respectively. Figs 5(a) and 6(a) show the elongation of specimen and magnetic field as a function of time. The elongation and magnetic field were measured while the magnetic field was increased under constant tensile stress. As seen in Figs. 5(a) and 6(a), the elongation increases with increasing magnetic field and is almost constant while the magnetic field is constant. The abrupt increase of elongation during the increase of magnetic field is considered to be caused by the martensitic transformation. Figs 5(b) and 6(b) shows the elongation of specimen as a function of magnetic field. The elongation is increased with increasing magnetic field and almost constant while the

Fig. 3 Stress-strain curves for Fe-31Ni-0.4C. (a) Only the stress of 220 MPa was applied. (b) The stress was increased up to 220 MPa in the constant magnetic field of 10 T. (c) The magnetic field was increased up to 10 T under the constant stress of 220 MPa.

Fig. 4 Stress-strain curves for Fe-27Ni-0.8C. (a) Only the stress of 220 MPa was applied. (b) The stress was increased up to 220 MPa in the constant magnetic field of 10 T. (c) The magnetic field was increased up to 10 T under the constant stress of 220 MPa.

Fig. 5 Elongation of Fe-31Ni-0.4C as a function of time (a) and magnetic field (b) when the magnetic field was increased up to 10 T under the constant stress of 220 MPa.

Fig. 6 Elongation of Fe-27Ni-0.8C as a function of time (a) and magnetic field (b) when the magnetic field was increased up to 10 T under the constant stress of 220 MPa.

magnetic field is decreased. The elongation is larger in Fe-27Ni-0.8C than in Fe-31Ni-0.4C.

The elongation obtained by applying the magnetic field under constant stress is larger than that obtained by applying the stress in constant magnetic field as shown in Figs. 3 and 4. This means that the amount of martensite formed in the former case is larger than that formed in the latter case because the elongation is proportional to the amount of martensite formed. The total increase of driving force for the martensitic transformation is the same in both cases because both the high magnetic field and the tensile stress are applied at the same time in the middle of each experiment. However, the combined effects of the high magnetic field and the tensile stress on the amount of martensite are different if the sequence of the application of high magnetic field and tensile stress is different. It is considered that the reason for these experimental results is that the high magnetic field increases the potency for the nucleation of martensite, but the influence of high magnetic field on the number density of nucleation site for martensite is relatively small compared with that of stress, and much more nucleation sites of martensite are formed when the maximum stress is applied in the very early stage of transformation than in the case stress is increased in the magnetic field during the transformation, and therefore larger amount of martensite is formed by increasing magnetic field under constant stress due to the larger amount of nucleation sites for martensite.

IV. Conclusion

The effects of high magnetic field and tensile stress on martensitic transformation behavior and microstructure at 4.2 K have been studied in Fe-31Ni-0.4C and Fe-27Ni-0.8C alloys. The main results obtained are as follows;

- (1) The critical magnetic field to induce martensitic transformation is between 7.5 T and 10 T.
- (2) In the case of Fe-27Ni-0.8C, martensitic transformation is stress-induced at lower level of stress in magnetic field than in the case no magnetic field is applied.
- (3) The amount of martensite formed by increasing the magnetic field under constant stress is larger than that formed by increasing the stress in the constant magnetic field.

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REFERENCES

- [1] L. Kaufman and M. Cohen: *Prog. Met. Phys.*, **7**(1958), 165.
- [2] J.R. Patel and M. Cohen: *Acta Metall.* **1**(1953), 531.
- [3] V.D. Sadovsky, L.V. Smirnov, YE.A. Fokina, P.A. Malinen and I.P. Soroskin: *Fiz. metal. metalloved.* **24**(1967), 918.
- [4] YE.A. Fokina, L.V. Smirnov, V.N. Olesov, V.M. Schastlivtsev and V.D. Sadovsky: *Fiz. metal. metalloved.* **51**(1981), 160.
- [5] T. Kakeshita, K. Shimizu, T. Sakakibara, S. Funada and M. Date: *Trans. JIM*, **24**(1983), 748.
- [6] T. Kakeshita, K. Shimizu, S. Funada and M. Date: *Acta Metall.* **33**(1985), 1381.
- [7] T. Kakeshita, K. Shimizu, S. Kijima, Z. Yu and M. Date: *Trans. JIM*, **26**[1985], 630.
- [8] T. Kakeshita and K. Shimizu: *Proc. ICOMAT-86. Jpn. Inst. Metals, Sendai*, (1986), 230.
- [9] T. Kakeshita, S. Furikado, K. Shimizu, S. Kijima and M. Date: *Trans. JIM*, **27**(1986), 477.
- [10] T. Kakeshita, H. Shirai, K. Shimizu, K. Sugiyama, K. Hazumi and M. Date: *Trans. JIM*, **28**(1987), 891.
- [11] T. Kakeshita, H. Shirai, K. Shimizu, K. Sugiyama, K. Hazumi and M. Date: *Trans. JIM*, **29**(1988), 553.
- [12] T. Kakeshita, K. Shimizu, T. Maki, I. Tamura, S. Kijima and M. Date: *Scripta Metall.*, **19**(1985), 973.
- [13] T. Kakeshita, K. Shimizu, M. Ono and M. Date: *Materials Trans. JIM*, **33**(1992), 461.
- [14] T. Kakeshita, K. Kuroiwa, S. Shimizu, T. Ikeda, A. Yamagishi and M. Date: *Materials Trans. JIM*, **34**(1993), 415.
- [15] T. Kakeshita, K. Kuroiwa, S. Shimizu, T. Ikeda, A. Yamagishi and M. Date: *Materials Trans. JIM*, **34**(1993), 423.
- [16] S. Emura, K. Fujita, Y. Kurita and K. Shibata: *Proc. of Int. Conf. on Stainless Steels*, 1991, Chiba, ISIJ., p.441.
- [17] Y. Kurita, K. Fujita and K. Shibata: *Annual Report of the Engineering Research Inst. 8 Faculty of Engineering, Univ. of Tokyo*, **51**(1992), 167.
- [18] Y. Kurita, S. Emura, K. Fujita, K. Nagai, K. Ishikawa and K. Shibata: *Proc. of ICOMAT-92. Monterey Institute for Advanced Studies*, 1993, Monterey, California, U.S.A. p. 457.
- [19] S. Kajiwara and T. Kikuchi: *Acta metall. mater.*, **38**(1990), 847.