Magnetic properties of SUS 304 austenitic stainless steel after tensile deformation at elevated temperatures

LEFU ZHANG*
School of Material Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
E-mail: lefu_zhang@tom.com

SEIKI TAKAHASHI, YASUHIRO KAMADA, HIROAKI KIKUCHI, KATSUYUKI ARA, MASAYA SATO
NDE and Science Research Center, Faculty of Engineering, Iwate University, Morioka 020-8551, Japan

TAKASHI TSUKADA
Department of Nuclear Energy System, Japan Atomic Energy Research Institute, Shirakata Shirane 2-4 Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan

Austenitic stainless steels are widely used in a variety of hostile environments applications, such as nuclear reactors and chemical plants, where the combination of good corrosion resistance with high strength, stiffness, and toughness is required. However, one of the most widely used austenitic stainless steel SUS 304 contains metastable austenitic phase, which is easily transformed into martensitic phase due to deformation and change of temperature. With the increase of martensitic transformation, the strength of material increases, while ductility and corrosion resistance decreases. Detecting the martensitic phase is one way to evaluate the degradation process of austenitic stainless steels. The austenitic phase in stainless steel is fcc structure, and is paramagnetic at room temperature. The martensitic phase is bcc structure, and is a ferromagnetic phase. There is current interest in the use of magnetic measurement as a nondestructive evaluation (NDE) technique for monitoring the degradation of stainless steels [1, 2].

Martensitic transformation in austenitic stainlesssteels, especially strain induced martensitic transformation (SIMT) at temperature below 50 °C, has been studied for a very long time [3–7]. The mechanism is quite complex. Temperature, stress, and plastic strain are the main external factors; chemical composition, grain size, and dislocation density are the internal factors that affect the amount of martensitic transformation. The reports about magnetic changes during SIMT at elevated temperature above 100 °C are less excessive. In our group, we have studied SIMT in SUS 304 by compression test at elevated temperature up to 450 °C [2]. In this paper, we briefly present the change of saturation magnetization and coercive force due to martensitic transformation in SUS 304 after tensile deformation at temperatures from room temperature up to 200 °C.

The material used for this investigation was a low carbon austenitic stainless steel type SUS 304 provided by Japan Atomic Energy Research Institute. The chemical compositions of the stainless steel are given in Table I. The material was annealed at 1100 °C for 30 min in as-received state and the grain size was determined to be about 80 μm. There was 0.6% residual martensitic phase after annealing. The initial purpose of this material was for study of radiation-induced segregation. Some of its magnetic properties have been studied and presented in Zhang *et al*. [8].

Deformation to the material was introduced by tensile test. Tensile specimens were cut from the material by wire spark cutting into dimensions given in Fig. 1. Tensile tests were carried out by using a Shimadzu Autograph AGS-10KNB testing machine with a heating system. Test temperatures were room temperature (RT—23 °C), 50, 100, 150, and 200 °C. Before each tensile test started, the temperature was held for 10 min after the setting temperature became stable. The fluctuation of testing temperature was ±0.3 °C for room temperature, ±0.2 °C for 50 °C and ±0.1 °C for above 100 °C. The cross head speed was 2 mm/min (strain rate at gauge was about 0.0625/min).

After tensile tests, small specimens were cut by wire cutting from the center of the tensile test specimens for subsequent magnetic measurements. Magnetic properties were measured by using a superconducting quantum interference device (SQUID) magnetometer, Quantum Design MPMS XL, and a vibrating sample magnetometer (VSM), TOEI VSM-P7. The dimensions of specimens for SQUID and VSM measurements were 3 mm×3 mm×1 mm.

True stress–true strain curves obtained at different temperatures are shown in Fig. 2. The yield strength at every temperature falls into a range between 155 and 175 MPa. The slopes of true stress–strain curves of RT and 50 °C are much steeper than those of 100, 150, and 200 °C in stage C. The increase of the slope indicates the strengthening contributed by martensitic transformation.

Saturation magnetization was measured by using SQUID magnetometer at the temperature of 300 K

*Author to whom all correspondence should be addressed.

0022–2461

TABLE I Chemical compositions of SUS 304 austenitic stainless steel

	C	Si	Cr	Ni	Mn	P	S	Fe
Wt%	0.034	0.48	18.1	8.1	1.01	<0.001	<0.001	Bal.

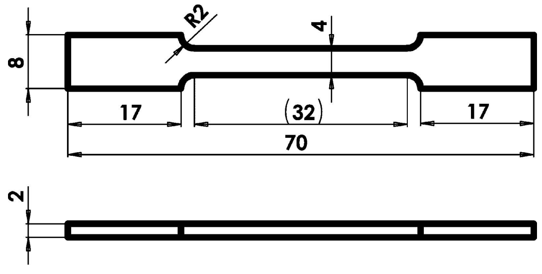

Figure 1 Dimensions of tensile specimen.

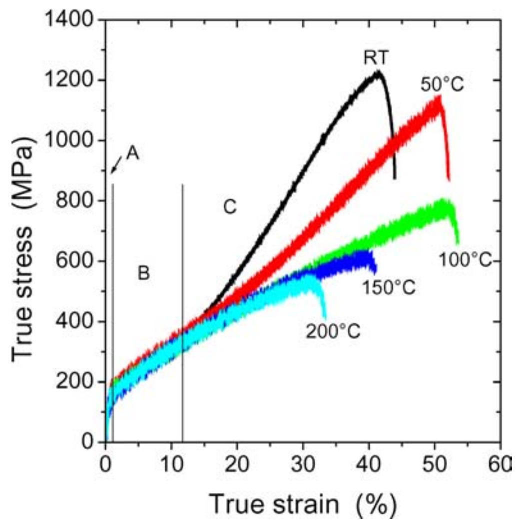

Figure 2 True stress–true strain curves of tensile deformation at different temperatures.

(27 °C) with applied field from 0 to 30 kOe. The changes of saturation magnetization with true strain at different temperatures are shown in Fig. 3. The results show that deformation at RT and 50 °C yield large amount of martensite, while above 100 °C, the transformation rate versus strain decreases greatly.

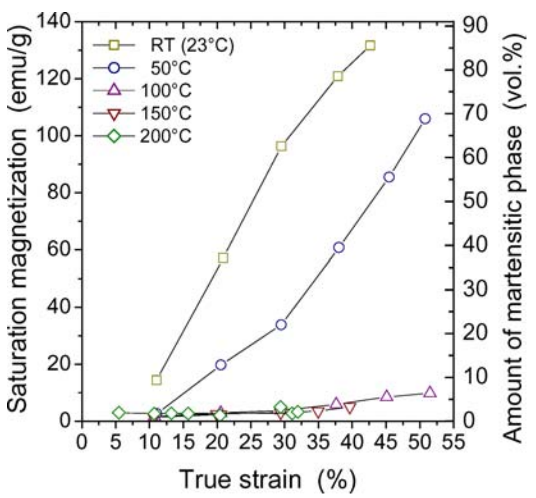

Figure 3 Dependence of saturation magnetization on true strain.

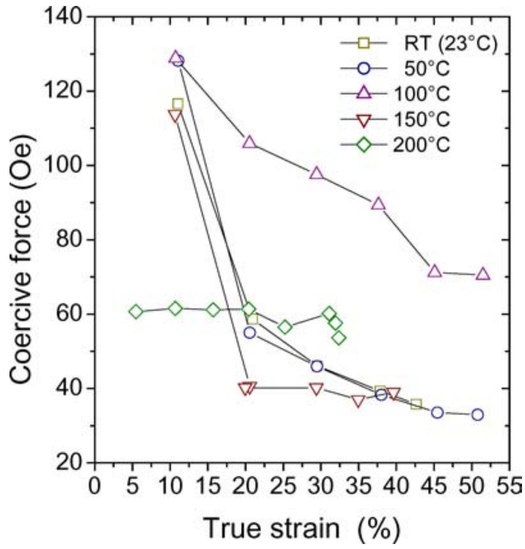

Figure 4 Dependence of coercive force on true strain.

The martensitic phase is the only ferromagnetic phase in SUS 304 after deformation-induced transformation at temperature above RT [2]. We usually take that the saturation magnetization of 100% martensite is about 154 emu/g for the material compositions as SUS 304 [9]. Saturation magnetization is a structural insensitive magnetic property, and therefore can be used to evaluate the percentage of martensitic phase in stainless steels. From the results shown in Fig. 3, we can observe that SIMT is very easy to occur at temperature below 50 °C, and the maximum percentages of SIMT are about 85 and 68% for RT and 50 °C, respectively. When temperature is increased to 100 °C and above, the percentage of martensitic transformation is not sensitive to true strain, and the amount is near 5%. The slopes of the curves that saturation magnetization changes with true strain Fig. 3 are about 3.8, 2.6, 0.2, 0.1, and 0.04 for RT, 50, 100, 150, and 200 °C, respectively.

The coercive force H_c was measured along the loading direction of tensile test by using VSM in the applied magnetic field of 20 kOe and the results are shown in Fig. 4. H_c decreases with the increase of true strain for samples deformed at every temperature.

H_c is a structural sensitive magnetic property. As we have already known that H_c usually increases with the increase of dislocation density and the reciprocal of grain size [10], dislocation density increases with the increase of plastic strain. The decrement of H_c with strain as shown in Fig. 4 implies that dislocation density is not a dominant factor that affects H_c of stainless steel. The size of strain-induced martensite increases with the increase of saturation magnetization [4]. The change of H_c with saturation magnetization is given in Fig. 5. H_c decreases with the increase of saturation magnetization. The results show that H_c is mainly affected by the average size of martensite. When the strain level is relatively low, the shape of strain-induced martensitic phase is usually thin needle or plate [4–7], here we call them particles. In macroscale, these particles distribute uniformly in austenitic phase. With the increase of strain level, newly transformed small particles cluster together and become martensite islands in austenitic

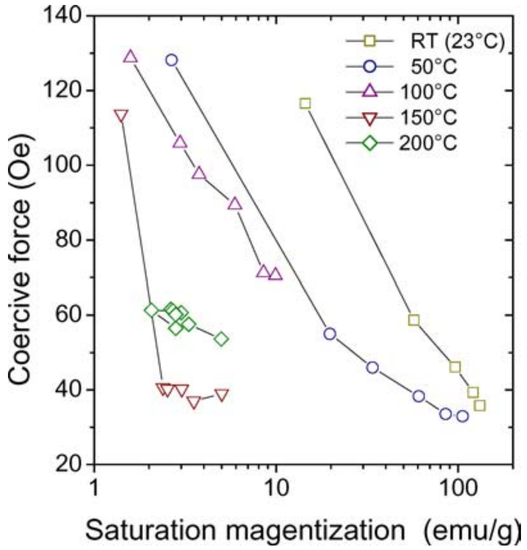

Figure 5 The change of coercive force with saturation magnetization.

phase. The martensite particles or islands are magnetized in magnetic field, and behave like small magnets. The magnetic properties of the stainless steel are the statistic summation values of those small martensite magnets. A high applied field is needed to overcome the demagnetizing field in order to obtain saturation magnetization and H_c. For ferromagnetic materials, H_c is sensitive to the average grain size due to the balance of crystal anisotropy and magnetic exchange energy. When strain-induced martensite particles are small, the pinning effect of grain boundaries is strong for domain wall movement, and causes a high H_c. Whereas, the movement of domain walls becomes easier, and the coercive force decreases with the increase of the size of martensite islands.

The results of this work show that, it is possible to detect the strain-induced martensitic transformation by magnetic measurement. We can use saturation magnetization and coercive force to predict the volume percentage and the size of the martensite. A detailed explanation will be presented in a full paper.

Acknowledgments

This research was supported by a grant-in-aid for Scientific Research on Priority Areas, from the Ministry of Education, Culture, Sports, Science and Technology of Japan under the contract of Scientific research (S) No. 141020345, and by a grant-in-aid for postdoctoral fellow from Japan Society for the Promotion of Science (JSPS), under the fellow ID P02350.

References

1. S. TAKAHASHI, J. ECHIGOYA, T. UEDA, X. LI and H. HATAFUKU, *J. Mater. Proc. Tech.* **108** (2001) 213.
2. K. MUMTAZ, S. TAKAHASHI, J. ECHIGOYA, L. F. ZHANG, Y. KAMADA and M. SATO, *J. Mater. Sci.* **38** (2003) 3037.
3. F. LECROISEY and A. PINEAU, *Metal. Trans.* **3** (1972) 387.
4. R. P. REED and C. J. GUNTNER, *Trans. Metal. Soc. AIME* **230** (1964) 1713.
5. G. B. OLSON and MORRIS COHEN, *J. Less-Common Metals* **28** (1972) 107.
6. H. C. SHIN, T. K. HA and Y. W. CHANG, *Scr. Meter.* **45** (2001) 823.
7. PAT L. MANGONON, JR. and G. THOMAS, *Metall. Trans.* **1** (1970) 1577.
8. L. ZHANG, Y. KAMADA, H. KIKUCHI, K. MUMTAZ, K. ARA, S. TAKAHASHI, M. SATO and T. TSUKADA, *J. Magn. Magn. Mater.* **271** (2004) 402.
9. M. B. STEARNS, *Phys. Rev.* **13** (1976) 1183.
10. H. KRONMÜLLER and M. FÄHNLE, in "Micromagnetism and the Microstructure of Ferromagnetic Solids" (Cambridge University Press, 2003).

Received 8 June
and accepted 14 October 2004