Microstructure, Magnetic Permeability and Electric Resistivity of High Manganese-Chromium-Nickel Steel*

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Synopsis

In order to develop the austenitic steel with the nonmagnetic characteristics, microstructures, mechanical properties, magnetic permeability and electric resistivity of Mn-Cr-Ni steels with much amount of manganese as an austenitizing element have been examined. The results obtained are as follows.

It was found that composition range showing stable austenite phase lays on the higher content side of the line connecting approximately 10%Mn-10%Cr and 20%Mn-0%Cr in Mn-Cr-1%Ni phase diagram. This composition range moved to the line connecting approximately 20%Mn-10%Cr and 23%Mn-0%Cr in the case of cold-rolled steel plate. High toughness and magnetic permeability (μ) under 1.01~1.02 were obtained in the steel with complete austenite phase. Magnetic permeability markedly increased by small amount of martensite in austenite phase. Therefore, it is necessary that nonmagnetic steel have complete austenite phase. The relationship between electric resistivity (ρ) and alloying elements; manganese, chromium, nickel, silicon in austenite phase, can be written as

$$\rho = 1.27[\% \text{Mn}] + 0.66[\% \text{Cr}] + 1.62[\% \text{Ni}] + 5.90[\% \text{Si}] + 36 (\mu\Omega\text{-cm})$$

From the above results, 25Mn-5Cr-1Ni steel may be selected as an optimum composition from the view points of stable austenite, high toughness, nonmagnetism and suitable electric resistivity.

I. Introduction

Austenitic steels not only have excellent corrosion and heat resistance as represented by the 18-8 stainless steel, but also possess good low-temperature toughness characteristic of the austenite phase and are nonmagnetism. The authors^{1,2)} already conducted basic research on the cryogenic applications of Mn-Cr-Ni steels by focusing attention on their good low-temperature toughness and small thermal expansion coefficient, and found the 25%Mn-5%Cr-1%Ni steel as grade of the optimum chemical composition for cryogenic service. This steel has a stable austenite phase and thus may be applicable as a nonmagnetic steel.

As austenitic manganese steels are now highlighted as steels to meet a growing demand for nonmagnetic steels to be used, for example, in magnetically levitated transports,³⁾ the authors have investigated on the basis of the previously reported cryogenic application research results various Mn-Cr-Ni steels for their composition range that exhibits the stable austenite phase and for their magnetic permeability and electric resistivity as physical properties that indicate their

toughness and nonmagnetism, and studied their applicability as nonmagnetic steels.

II. Overview of Past Research Results

Works on the use of Mn-Cr austenitic steels for cryogenic service are summarized in the previous reports.^{1,2)} It should be especially noted that high-Mn-Cr steels have recently been studied by researchers the world over, particularly in the United States and the Soviet Union.⁴⁾ Research on austenitic manganese steels as nonmagnetic steels is mainly concerned with the practical use of already known nonmagnetic steels. Ishida *et al.*,⁵⁾ investigated the effects of working and heat treating conditions on the magnetic permeability of the 15%Mn-1.2%Ni steel as base composition steel and studied the practical applicability of the steel. Ohno *et al.*,⁶⁾ conducted research concerning reinforcing bar applications, while Nishimura *et al.*,⁷⁾ investigated Mn-Cr base composition steels with large additions of nickel, molybdenum, vanadium, cobalt and other alloying elements as nonmagnetic tool steels. Nonmagnetic steels must have a microstructurally stable austenite phase. The authors^{1,2)} found the 25%Mn-5%Cr-1%Ni steel of optimum chemical composition in this sense and demonstrated that the steel exhibits a stable austenite phase at subzero temperatures down to the liquid-helium temperature and can be used at that temperature. This work can become the basis for research on austenitic steels or nonmagnetic steels. On the basis of these research results, the authors then investigated the effects of manganese, chromium, nickel and other elements on austenitization as well as magnetic permeability and electric resistivity. This paper summarizes the details of that study. Ohtani and Okada⁸⁾ subsequently conducted similar investigations on steels with the base composition ranges of 10 to 12 % Mn, 0 to 15 % Cr and 0.05 to 0.45 % C.

III. Experimental Method

The magnetic permeability μ varies with the structures of austenite γ and martensite α' .[†] Based on the past study results,^{1,2)} therefore, the test steels in the

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† For the sake of brevity, magnetic permeability, electric resistivity, austenite, ferrite and martensite are sometimes signified hereinafter by μ , ρ , γ , α and α' , respectively. The ϵ phase in the γ phase is difficult to distinguish from streaks due to stacking faults or twin boundaries in optical microstructures. As a result, it is treated as a kind of stacking fault in the γ phase and is described as the γ phase even if it exists.

present work had the manganese, chromium, nickel and silicon contents widely varied so as to clarify the composition boundary of the nonmagnetic region or γ region. The composition ranges studied are given in Table 1.

10 to 20 kg of each test steel were melted in an argon atmosphere, cast into ingots 10 to 20 kg in weight, reheated to 1 473 K, rough rolled, finish rolled at 1 193 K into 13-mm thick plates, and cooled in air. To investigate how cold working would change the stable γ region in terms of composition, some of these test steel plates were additionally cold rolled by 5, 12.5 and 25 %, respectively.

From these test steel plates of different chemical compositions were prepared specimens for chemical analysis, specimens for optical microscopy, JIS No. 4 tensile test specimens for determining tensile strength at ambient temperature, JIS No. 4 2-mm V-notch Charpy impact test specimens for determining impact strength, 9-mm diameter by 120-mm long round specimens for measuring magnetic permeability, and 5-mm diameter by 120-mm long round specimens for measuring electric resistivity.

Optical microstructures were observed at the magnification of 200X. Tensile tests determined 0.2 % proof strength (PS) and tensile strength (TS), and impact tests were conducted at an ambient temperature of 293 K and liquid-nitrogen temperature of 77 K. The amount of α' in each specimen for optical microscopy was measured with a ferrite indicator.* Some of the amounts of α' thus determined were verified by the X-ray diffraction technique. The magnetic permeability μ was measured with a bal-

listic galvanometer according to ASTM A342-64. The electric resistivity ρ was measured with a potential difference gauge length of 50 mm on the above-mentioned specimens, using a standard resistance of 0.01 Ω .

IV. Experimental Results and Discussion

1. Microstructure and Mechanical Properties

Figure 1 shows changes in microstructure (herein-after referred to as the Mn-Cr constitution diagram) and mechanical properties when the nickel content is fixed at 1 % while the manganese and chromium contents are varied. The analyzed chemical compositions of typical test steels are given in Table 2.

The Mn-Cr constitution diagram of Fig. 1 was derived from the microstructures observed with an optical microscope and the amounts of α' measured with the ferrite indicator, and is almost the same as that presented in the previous report.¹⁾ Microstructures of representative test steels are shown in Photo. 1. Steel exhibits the γ phase at ambient temperature when the manganese and chromium contents are

Fig. 1. Strength and toughness of Mn-Cr-Ni steel.

Table 1. Chemical composition range of experimental steels. (%)

(1) For the influence alloying element	(2) Other element
Mn: 5.0~26.0	C: 0.09~0.16
Cr: 0~15.0	P: 0.002~0.046
Ni: 0~6.0	S: 0.002~0.013
Si: 0.1~5.2	Nb: Tr.~0.17
	Al: 0.008~0.31
	N: 0.049~0.086

Table 2. Typical example of chemical composition in experimental steels.

Marks	Alloying system	C	Si	Mn	P	S	Cr	Ni	Al	N
A	11Mn-5Cr-1Ni	0.14	0.31	10.78	0.005	0.011	5.13	0.96	0.03	0.059
B	16Mn-3Cr-1Ni	0.15	0.31	16.30	0.026	0.008	2.99	1.09	0.03	0.072
C	20Mn-0Cr-1Ni	0.15	0.31	20.40	0.002	0.008	—	0.82	0.03	0.035
D	20Mn-3Cr-1Ni	0.13	0.31	19.60	0.026	0.010	2.90	1.09	0.04	0.013
E	23Mn-0Cr-1Ni	0.14	0.30	23.10	0.002	0.009	—	0.98	0.03	0.028
F	25Mn-5Cr-1Ni	0.15	0.40	25.50	0.046	0.010	5.00	1.10	0.02 Nb 0.09	0.086
G	25Mn-5Cr-1Ni-5Si	0.16	5.13	25.00	0.019	0.009	4.73	1.08	0.03 Nb 0.10	0.079

* An instrument that determines the amount of α or α' by utilizing the characteristic that steel becomes a ferromagnetic material when the α or α' phase is formed in the γ phase. The ferrite indicator used in the present experiments was made by Helmut Fischer GmbH of F.R. Germany.

Photo. 1. Microstructure of Mn-Cr-Ni steel. ($\times 200$)

above the boundary line (dotted line) that connects 10%Mn-10%Cr and 20%Mn-0%Cr in the constitution diagram.

When steel has manganese and chromium contents below the boundary line (for example, steel A of the 11%Mn-5%Cr system), it shows a high tensile strength. As the manganese content increases or the steel enters the γ phase region, the tensile strength decreases. The proof strength remains unchanged or increases slightly. Virtually the same tendencies are observed with chromium as well. As the chromium content increases in the γ phase region, both tensile strength and proof strength increase slightly. This is probably due to the solid solution hardening of chromium. The effect of chromium content in excess of 15 % is not investigated here, because it was made clear by Binder *et al.*,⁹⁾ that the α' phase appears when the chromium content exceeds 15 %.

The test steels F and G in the γ phase region are 25%Mn-5%Cr-1%Ni steels with different silicon contents. The addition of 5 % silicon increases the 0.2 % proof strength and tensile strength by about 100 and 150 MPa, respectively. With these high manganese, chromium and nickel contents, the γ phase is so stable than no α or α' phase is detected even when silicon, a ferrite former, is added 5 %.

Charpy impact test values vE_{293} and vE_{77} at ambient temperature and liquid-nitrogen temperature are examined as toughness properties. The vE_{293} value is considerably high even if α' is present in some amount, but the vE_{77} value drops under the increasing influence of α' . The relation of toughness with steel composition is opposite to that of strength with steel composition. This means that steels of optimum chemical composition for toughness must be particularly within the stable γ phase region. The 25% Mn-5%Cr-1%Ni steel for cryogenic service reported previously, for example, shows very good toughness.

2. Microstructure and Magnetic Permeability μ

The relationship between the Mn-Cr constitution diagram and magnetic permeability μ is shown in Fig. 2. The magnetic permeability μ is below 1.01

Fig. 2. Magnetic permeability of Mn-Cr-Ni steel.

to 1.02 when the manganese and chromium contents are above the boundary line (dotted line) that connects 10%Mn-10%Cr and 20%Mn-0%Cr and indicates the γ phase. As α' appears in the region below the boundary line, the magnetic permeability μ increases. The relationship between the magnetic permeability μ and the amount of α' may be plotted as shown in Fig. 3. The magnetic permeability μ sharply increases even when the amount of α' is extremely small. As evident from these results, nonmagnetic steels must have an extremely stable γ phase free of any α' phase.

When nonmagnetic steels are put to practical use, they are generally cold worked. Accordingly, the effect of working on the amount of α' (that is, μ) was investigated. Working was cold rolling and the degree of working was denoted by the ratio of reduction. The investigated results are shown in Fig. 4.

When the as-hot-rolled plate is cold rolled 5 %, the stable γ phase region (whose boundary is indicated by a dotted line) shifts toward about 3 % higher

manganese and chromium contents. The reduction of 12.5 % moves the stable γ phase region toward still higher manganese and chromium contents. When the as-hot-rolled plate is cold rolled 25 %, the stable γ region does not shift to a large degree. This shift of the stable γ region toward higher manganese and chromium contents by cold rolling indicates that the stress-induced martensite transformation point M_d is present within the range bounded by the 0 % and 25 % cold reduction lines in the Mn-Cr constitution diagram. According to these results, the manganese and chromium contents must be above the line that connects about 20%Mn-10%Cr and about 23%Mn-0%Cr if the stable γ phase is to be obtained despite heavy working. The previously reported 25%Mn-5%Cr-1%Ni steel^{1,2)} that shows a stable γ phase and high toughness in cryogenic service in this composi-

tion region.

3. Composition and Electric Resistivity ρ

The electric resistivity ρ of the test steels was measured and the effects of the alloying elements manganese, chromium, nickel and silicon were investigated. The results are shown in Figs. 5 to 8.

The effect of manganese content is discussed first (Fig. 5). When the 5%Cr-1%Ni steel has a manganese content in excess of about 19 % (region that indicates a complete γ phase), ρ increases at a slope of $1.48 \mu\Omega\text{-cm}/\%$ (the unit of slope is omitted hereinafter) as the manganese content increases. In the low-manganese region (12 % and 16 % Mn), ρ somewhat deviates from this slope as indicated by δ in the diagram. This is probably because some α' is formed. Since there must be a complete γ phase when nonmagnetic steels are considered as mentioned earlier, the results are arranged here by the γ phase region. When the electric resistivity ρ of the 25% Mn-5%Cr-1%Ni steel that is developed for cryogenic service and found optimum for nonmagnetic application according to the magnetic permeability measurements described above is measured, it is about $73 \mu\Omega\text{-cm}$ and is practically the same as that of the 18-8 stainless steel. The effect of manganese on the electric resistivity ρ of the 5%Cr-5%Ni base composition steel changes along the slope of 1.06. Although the former 5%Cr-1%Ni steel and latter 5%Cr-5%Ni steel differ in base composition, their average slope is 1.27 and may be considered as the effect of manganese on ρ .

The effects of chromium, nickel and silicon contents on ρ are similar to that of manganese (Figs. 6 to 8). The average slope of each element is 0.66 for chromium, 1.62 for nickel and 5.90 for silicon, with silicon exerting the largest effect on ρ .

The effect of these alloying elements on ρ resembles

Fig. 3. Relation between magnetic permeability and amount of martensite (α') in austenite of Mn-Cr-Ni steel.

Fig. 4. Relation between amount of martensite [α'] and ratio of cold rolling reduction in Mn-Cr-Ni steel.

Fig. 5. Influence of manganese content on electric resistivity in Mn-Cr-Ni steel.

Fig. 6. Influence of chromium content on electric resistivity in Mn-Cr-Ni steel.

Fig. 7. Influence of nickel content on electric resistivity in Mn-Cr-Ni steel.

their effect on iron (α phase)¹⁰⁾ but is smaller in degree. This may be attributed to the difference in crystal structure between the γ phase and α phase.

As the alloying elements increase in content, ρ also increases in magnitude, probably because the periodicity of atoms is disturbed and free electrons are scattered in the same way as free electrons are scattered as metal temperature rises, for example. The

Fig. 8. Influence of silicon content on electric resistivity in Mn-Cr-Ni steel.

Fig. 9. Relation between electric resistivity and alloying elements in Mn-Cr-Ni steel.

reason for the difference in the degree of effect of the respective alloying elements is not clear. Within the composition ranges studied by the present work, silicon most greatly affects ρ . This appears related in some way to the fact that silicon has the smallest atomic weight and specific gravity among the four elements.

An empirical formula was derived for the effect of the four elements on ρ within the composition ranges given in Table 1. The calculated results are shown in Fig. 9. The electric resistivity ρ is given by

$$\rho = 1.27[\%Mn] + 0.66[\%Cr] + 1.62[\%Ni] + 5.90[\%Si] + 36 (\mu\Omega\text{-cm})$$

When the empirical formula is applied to the 18-8 stainless steel, for example, the abscissa of Fig. 9 becomes about 33 and ρ becomes $72 \mu\Omega\text{-cm}$. As evident from this example, the empirical formula has a considerable degree of applicability to austenitic steels.

When the α' phase appears, ρ deviates from the empirical formula as shown by open circles in Fig. 9.

V. Summary

Since high-Mn-Cr-Ni austenitic steels have the possibility of being used for cryogenic service as well as for nonmagnetic and many other applications, the authors have investigated the microstructure, mechanical properties, magnetic permeability and electric resistivity of the 25%Mn-5%Cr-1%Ni base composition steel selected as the optimum one for cryogenic service and other grades with varying manganese, chromium, nickel and silicon contents. The findings obtained may be summarized as follows:

(1) To obtain the γ phase at ambient temperature, the manganese and chromium contents must be above the line that connects 10%Mn-10%Cr and 20%Mn-0%Cr in the Mn-Cr constitution diagram with the base nickel content of 1%. In the region of lower manganese and chromium contents, the α' phase forms to increase strength but to decrease toughness.

(2) In the above γ phase region, μ is under 1.01 to 1.02. As the α' phase appears, μ sharply increases in magnitude. Steels to be used for nonmagnetic applications, therefore, must have the stable γ phase.

(3) When the steel that exhibits the γ phase at ambient temperature is cold worked, the α' phase appears. If the steel is to retain the stable γ phase under heavy working (cold reduction of 12 to 25%), its manganese and chromium contents must be above the line that connects 20%Mn-10%Cr and 23%Mn-0%Cr in the Mn-Cr constitution diagram.

(4) The effects of the alloying elements manganese, chromium, nickel and silicon on the electric resistivity ρ of the steels that exhibit the γ phase have been investigated. As a result, the following empirical formula has been obtained:

$$\rho = 1.27[\% \text{Mn}] + 0.66[\% \text{Cr}] + 1.62[\% \text{Ni}] \\ + 5.90[\% \text{Si}] + 36 \text{ } (\mu\Omega\text{-cm})$$

The electric resistivity ρ increases in magnitude as the content of each alloying element increases. Of the four elements, silicon most greatly affects ρ .

(5) When the above results are taken into account together with the results described in the previous reports,^{1,2)} the 25%Mn-5%Cr-1%Ni steel that shows the stable γ phase and has good low-temperature toughness, stable nonmagnetism and electric resistivity comparable to that of the 18-8 stainless steel is considered as optimum nonmagnetic steel.

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REFERENCES

- 1) H. Yoshimura, N. Yamada, H. Yada, H. Honma and T. Ito: *Trans. ISIJ*, **16** (1976), 98.
- 2) H. Yoshimura, T. Shimizu, H. Yada and K. Kitajima: *Trans. ISIJ*, **20** (1980), 187.
- 3) Y. Kyotani: *Chemical Economy & Engineering Review*, **6** (1974), No. 12, 22.
- 4) J. M. Morris, Jr., S. K. Hwang, K. A. Yushchenko, V. I. Belotzerkovetz and O. G. Kvensnevskii: *Advances in Cryogenic Engineering*, **24** (1978), 91; Proc. the 2nd Int'l Cryogenics Materials Conf., Colorado, August 1977.
- 5) T. Kato, M. Fujikura, S. Yakagi and M. Ishida: *Denki-Seiko (Electric Furnace Steel)*, **49** (1978), 90.
- 6) T. Ohno, N. Kato, M. Takahashi and K. Aihara: *Sumitomo Metals*, **30** (1978), No. 2, 54.
- 7) T. Nishimura, H. Kikuchi and M. Imamura: *Denki-Seiko (Electric Furnace Steel)*, **48** (1977), 65.
- 8) Y. Ohtani and Y. Okada: *Tetsu-to-Hagané*, **64** (1978), S859.
- 9) R. Franks, W. O. Binder and J. Thompson: *Trans. ASM*, **47** (1955), 231.
- 10) R. M. Bozorth: *Ferromagnetism*, (1951), 40.