Development and Production of 18Mn-18Cr Non-magnetic Retaining Ring with High Yield Strength

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Retaining ring for electric generator is required to have non-magnetism, high strength, high ductility and stress corrosion cracking (SCC) resistance. Several kinds of materials for non-magnetic retaining ring have been developed and recently 18%Mn-18%Cr austenitic steel which has been developed to improve susceptibility to SCC of 18%Mn-5%Cr austenitic steel has begun to use. 18%Mn-18%Cr steel contained high nitrogen content has been investigated as the material with high strength, high ductility and SCC resistance. On the base of the fundamental studies of chemical composition and cold work on increasing yield strength of 18%Mn-18%Cr steel, a trial 18%Mn-18%Cr retaining ring with yield strength 1400 MPa was successfully manufactured and mechanical properties, fatigue strength, fracture toughness and SCC were investigated for the trial ring material.

KEY WORDS: austenitic; non-magnetic; strength; ductility; toughness; stress corrosion cracking; retaining ring.

1. Introduction

For improvement of the susceptibility to SCC of 18%Mn-5%Cr austenitic steel (18-5)^{1,2)} which has been widely used for non-magnetic retaining ring (R/R) material, 18%Mn-18%Cr austenitic steel (18-18) have been investigated. In order to avoid SCC caused by grain-boundary carbides which are associated with 0.4 to 0.6 wt% carbon content of 18-5 specified in ASTM A 289 class B, carbon content of 18-18 was reduced to maximum 0.13 wt% as specified in ASTM A 289 class C. 18-5 and 18-18 are austenitic steels, so their strengthening is due to solution and cold worked hardening. Reducing carbon content of 18-5 will result in lower austenite stability and solution hardening. This can be offset by the replacement of carbon with another interstitial element, nitrogen. The chromium content has been increased in order to increase nitrogen solubility³⁾ and improve corrosion resistance. In this way, 18-18 material for R/R has been developed.

Recently there is a great demand for higher strength 18-18 R/R. The specified 0.2 % yield strength has increased as maximum unit capacity of generator increases, as shown in Fig. 1. For increasing of unit capacity, the diameter of generator and R/R increase. As a result, 0.2 % yield strength required for R/R increases, because stress occurred in R/R is directly proportional to multiplying by diameter.⁴⁾

Effects of chemical composition of 18-18 on mechanical properties have been studied. This paper describes that a trial R/R with yield strength 1400 MPa (YS 1400 MPa) was manufactured by 18-18 which material was fundamentally studied on the

effect of chemical composition and cold work ratio on mechanical properties and SCC resistance, additionally various properties of the trial R/R material are investigated.

2. Fundamental Studies—Chemical Composition & Cold Work—

2.1. Experimental Procedure

One of important requirements for non-magnetic R/R materials is stable austenite structure without magnetic structure of delta ferrite. Effects of chemical composition on austenite stability of high Mn-Cr austenitic steels were studied using 20 heats which were made from 50 kg VIM-ingots, forged by hammer to 40 mm square block (forging ratio approx. 12S) and then solution-treated at 1050°C, 2 h. Delta ferrite contents were determined by magnetic method.

Strengthening method of 18-18 was studied on solution hardening due to nitrogen and carbon elements and cold work hardening. Effects of nitrogen and carbon content of 18-18 on mechanical properties have been investigated by 5 heats which were made from 50 kg VIM-ingots. Chemical compositions of the heats are shown in Table 1. Test samples were forged in 25 mm thickness, solution treated at 1040 °C, 2 h and water cooled. 14 mm diameter and 50 mm gauge length specimens are used for tensile test of solution treated specimens. Cold working were performed by stretched round specimens using tensile test machine up to specified cold work ratio at room temperature.

Mechanical properties were determined by the tensile specimens with 10 mm diameter and 50 mm gauge length which were made from the stretched

Fig. 1. The transition of maximum specified 0.2 % yield strength and maximum unit capacity of generator which have been manufactured in JSW.

Table 1. Chemical compositions of experimental heats for examination of mechanical properties and stress corrosion cracking properties.

No.	C	Mn	Cr	N	Material
1	0.045			0.576	Key
2	0.050			0.840	Effect of N
3	0.047	19.42 19.81	19.33 20.01	0.719	
4	0.150			0.555	C
5	0.250			0.575	

round specimens. For studies of anisotropy of tensile properties, plate specimens which size are 70 mm width and 10 mm thickness are stretched by tensile test machine and small tensile specimens which size are 6 mm diameter and 30 mm gauge length, are used for longitudinal and perpendicular direction tests.

2.2. Results and Discussion

2.2.1. Stability of Austenitic Structure

The austenite stability is estimated with Cr equivalent ($Cr_{eq.}$). Fig. 2 shows the relationship between $Cr_{eq.}$ and delta ferrite content of 18-18 after solution treated at 1050°C. $Cr_{eq.}$ shall be calculated by Newhouse equation⁵⁾ as shown below.

$$Cr_{eq.} = Cr + 6Si + 4Mo + 1.5W + 11V + 5Nb - (40C + 2Mn + 4Ni + 2Co + 30N)$$

From these results, $50 + Cr_{eq.}$ should be less than 13 to avoid delta ferrite. Hsiao and Dulis studied the austenitic stability by means of high Mn-Cr steel which were contained up to 0.8 wt% C, 5 to 28 wt% Cr, 12 to 28 wt% Mn, 0.1 to 0.8 wt% N and reported precipitations of delta ferrite for high Cr steel, so the results correspond with our investigation.⁶⁾ Additionally, delta ferrite content is influenced by solution temperature. Fig. 3 shows the effect of solution temperature and chemical composition on delta ferrite content. Adding nitrogen more than 0.576 wt% is effective for stability of austenitic structure.

Though vanadium and niobium are effective for high strength because of grain fining element, those are not suitable for complete austenitic structure because of forming delta ferrite. Typical photographs of delta ferrite obtained on 18-18-0.502wt% N, solution treated at 1050°C are shown in Fig. 4 in comparison with complete austenitic structure of 18-18-0.840wt%N solution treated at 1050°C.

2.2.2. Mechanical Properties

Mechanical properties in the solution treated state as a function of nitrogen and carbon content are plotted in Figs. 5 and 6, respectively. Tensile strength (TS) and 0.2 % yield strength (YS) increase with

Fig. 2. Relationship between chromium equivalent and delta ferrite content of 18%Mn-18%Cr material after solution treated at 1050°C.

Fig. 3. The effect of solution temperature and chemical composition on delta ferrite content.

Fig. 4. Typical photographs of delta ferrite obtained on 18%Mn-18%Cr-0.502 wt%N as compared with uniform austenitic structure on 18%Mn-18%Cr-0.840wt%N.

nitrogen and carbon content, respectively. Elongation (EL) are almost independent of nitrogen and carbon content. Normally high nitrogen content brings out increasing strength and decreasing EL . In this investigation on nitrogen content of such small variation, effect of nitrogen content on EL is not detected. On the other side, reduction of area (RA) decreases slightly with carbon content and is almost independent of nitrogen content. Consequently, it is clear that nitrogen is effective for solution hardening without remarkable decreasing EL and RA .

Figs. 7 and 8 show the effect of nitrogen and carbon content on mechanical properties of cold worked material, respectively. YS increases with cold work ratio and its tendency is obviously on high nitrogen and carbon content material. EL decreases as cold work ratio increases. However, EL values of cold worked material are almost identical for either nitrogen or carbon content. This is because EL in the solution treated state is almost independent of nitrogen or carbon content as shown in Figs. 5 and 6.

The effect of nitrogen or carbon content on cold work response is explained schematically in Fig. 9. YS in high nitrogen or carbon content material is higher than YS in low nitrogen or carbon content material at same cold work ratio.

The anisotropy of tensile properties was investigated on cold worked 18-18-0.576wt%N and 18-18-0.840wt%N. Ratio of longitudinal YS ($YS-T$) for cold worked direction and perpendicular YS ($YS-R$) slightly decreases as cold work ratio increases, as shown in Fig. 10. Tensile properties anisotropy of higher nitrogen content and lower cold worked material is smaller than one of higher cold worked and lower nitrogen content material. Consequently, if nitrogen or carbon content of 18-18 increase, YS after cold working increases remarkably and EL is not influenced. Accordingly, in order to manufacture high YS 18-18 R/R it is effective industrially to be

Fig. 5. Mechanical properties in the solution treated state as a function of nitrogen content.

Fig. 6. Mechanical properties in the solution treated state as a function of carbon content.

Fig. 7. The effect of cold work ratio and nitrogen content on elongation and yield strength.

Fig. 8. The effect of cold work ratio and carbon content on elongation and yield strength.

Fig. 9. Schematic explanation of the effect of nitrogen or carbon content on stress-strain curve of 18%Mn-18%Cr steel.

small anisotropy and to obtain high strength with lower cold work ratio by high nitrogen and carbon content.

Fig. 10. The relationship between radial and tangential yield strength and cold work ratio.

Material	SCC test results
Key	○
0.15, 0.25 C	Pitting
0.840 N	○

○ : No crack after 400 h test
 Stress : 95 % YS
 Condition : 3.5 % NaCl, 80°C

Fig. 11. SCC test results for the 40 % cold worked materials by three point bend test at 80°C.

2.2.3. SCC

SCC susceptibility was investigated for the 40 % cold worked materials by three point bend test at 80°C in the 3.5 % NaCl solution loaded on applied stress of 95 % YS. As the results of the above test, pitting and cracking are detected in the material with 0.15 and 0.25 wt% carbon content by 400 h and no pitting and cracking detects on 0.840 wt% N material as shown in Fig. 11. Accordingly, high carbon content is not suitable to avoid SCC of 18-18.

3. Production of a Trial 18-8 R/R with YS 1 400 MPa and Its Material Properties

A trial 18-18 R/R with YS 1 400 MPa by high nitrogen content material was manufactured according to the basic experience of chemical composition and cold working. The R/R have typical size for steam power generator, outer diameter and inner diameter are ϕ 1 670 mm and ϕ 1 430 mm, respectively.

3.1. Manufacturing Sequence

Manufacturing sequence is shown in Fig. 12. The ingot was made with electroslag-remelting (ESR) process in which electrode was made with electric furnace (EF) and vacuum-oxygen-decarburization (VOD).

The composition of YS 1 400 MPa R/R is shown in Table 2.

Hot forging was performed by 3 000 and 10 000 t presses. In hot forging, it is important to obtain uniform and finer grain size in addition to give essential forging effect as compression of microporosity. The forged ring was then machined, examined by non-destructive test (NDT), solution treated, cold expanded by wedge method and stress relieved.

3.2. Mechanical Properties of a Trial YS 1 400 MPa R/R

Various material properties were investigated with test prolongation of 30 mm length.

Fig. 13 shows the mechanical properties of YS 1 400 MPa R/R through the ring thickness. *TS* and *YS* at mid wall which is usually used as typical strength specification of R/R are 1 432 and 1 427 MPa on an average, respectively. Strength of outer side is lower than that of inner side. The difference of strength between outer side and inner side depend on the difference of cold work ratio. Average value of *RA* and *EL* at mid wall is 53.8 and 18.3 %, respectively. Consequently, high ductility, toughness and uniform of mechanical properties were confirmed in the trial R/R.

3.3. Examination of Material Properties on a Trial YS 1 400 MPa R/R

3.3.1. Tensile Test Properties

There are clear differences in the mechanical prop-

erties of 18-18 and 18-5.

Figs. 14 and 15 show the relationship of *EL* vs. *YS* and *RA* vs. *YS* in tangential direction. At lower strength, *EL* is similar for 18-18 and 18-5. However, *EL* is higher for 18-18 in the important high strength region. Consequently, 18-18 has higher ductility and toughness than 18-5.

The variation of *TS* and *YS* of 18-18 and 18-5 with test temperature are illustrated in Fig. 16. *TS* and *YS* decrease as test temperature increases, as well

Table 2. Chemical compositions of a trial 18%Mn-18%Cr retaining ring.

C	Si	Mn	Cr	N
0.043	0.31	19.09	19.37	0.709

Fig. 13. Mechanical properties of a trial yield strength 1 400 MPa retaining ring through the ring thickness.

Fig. 12. Manufacturing sequence of 18% Mn-18% Cr retaining ring.

known. The TS and YS decrease of 18-18 is larger than that of 18-5 at the temperature from room temperature to about 200°C. The peculiar YS and TS decrease of 18-5 shall be explained by strain aging due to high carbon content of 18-5.⁷⁾

○: Actual results of the trial ring

Fig. 14. Relationship between tensile strength and yield strength.

○: Actual results of the trial ring

Fig. 15. Relationship between reduction of area and yield strength.

Fig. 16. The variation of tensile strength and yield strength with test temperature of 18%Mn-18%Cr and 18%Mn-5%Cr steels.

3.3.2. Anisotropy of Tensile Properties

Fig. 17 shows anisotropy of YS , that is, radial/tangential ratio of YS at mid wall of 18-18 R/R as a function of tangential YS . The ratio decreases as tangential YS increases.

The radial/tangential ratio of YS of high nitrogen content material is higher than one of low nitrogen material. So high nitrogen content material is good for the isotropy of higher strength 18-18 R/R.

3.3.3. Fracture Toughness

Fig. 18 shows comparison of fracture toughness of 18-18 and 18-5 which are determined by J_{IC} using 1TCT specimens. Fracture toughness of 18-18 is higher than that of 18-5. Anisotropy of fracture toughness is not observed, though fracture toughness decreases as YS increases. The fracture toughness of 18-18 is very high.

3.3.4. Fatigue Strength

Test results of low cycle fatigue of 18-18 as a function of test specimen direction and YS range are shown in Fig. 19 with 18-5 data. Fatigue strength increases with increasing YS , and fatigue strength of tangential direction are higher than radial direction which shall be explained by anisotropy of tensile strength.

Fig. 17. Anisotropy of mechanical properties of 18%Mn-18%Cr as a function of tangential YS .

Fig. 18. Fracture toughness and yield strength of 18%Mn-18%Cr and 18%Mn-5%Cr retaining ring materials.

Table 3. SCC initiation test results of the 18%Mn-18%Cr retaining ring material with yield strength 1 400 MPa.

Chemistry (wt%)				Direction	0.2 % YS (MPa)	SCC initiation test	
C	Mn	Cr	N			Applied stress (MPa)	Results
0.043	19.09	19.37	0.709	Tangential	1 427.8	999.5 (70 %)	5 162 h
						1 285.0 (90 %)	No crack
						1 356.4 (95 %)

Test method : Three point bend test
Environment : 3.5 % NaCl

YS grade	Chemical composition (%)					0.2 % YS (MPa)	
	C	Si	Mn	N		Radial	Tangential
18Mn-18Cr	1 088	0.08	0.30	18.72	0.522	961	1 088
	1 295	0.04	0.41	19.19	0.767	1 046	1 295
	1 427	0.04	0.31	19.09	0.709	1 065	1 427
18Mn-5Cr	967	0.50	0.5	17.99	0.093	—	967

Fig. 19. Low cycle fatigue strength of 18%Mn-18%Cr and 18%Mn-5%Cr as a function of test specimen direction and yield strength tested with 0 mean stress.

3.3.5. SCC

Test results of SCC initiation for a trial R/R are shown in Table 3. Cracks and pitting are not detected on specimen after 5 162 h under applied stress 1 356.4 MPa which means 95 % of YS at mid wall.

4. Conclusion

Retaining ring for electric generator is required to have non-magnetism, high strength, high ductility SCC resistance. Several kinds of materials for non-magnetic R/R have been developed and recently 18%Mn-18%Cr austenitic steel which has been de-

veloped to improve susceptibility to SCC of 18%Mn-5%Cr austenitic steel has begun to use. 18%Mn-18%Cr steel contained high nitrogen content has been investigated as the material with high strength, high ductility and SCC resistance. Following results were obtained on fundamental experience and manufacturing a trial ring.

(1) Yield strength of solution treated 18%Mn-18%Cr steel is higher as nitrogen content increases.

(2) 18%Mn-18%Cr steel with high nitrogen content offers higher yield strength with smaller cold work ratio.

(3) A smaller cold work ratio results in higher ductility and less anisotropy.

(4) High carbon content is not suitable to avoid SCC of 18%Mn-18%Cr-N retaining ring material.

(5) SCC of 18%Mn-18%Cr steel with yield strength 1 400 MPa shows good performance in a corrosion environment.

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