Development of Welding Wire for High-Purity Austenitic Stainless Steels

Welds produced with the developed filler metal possess equivalent corrosion and mechanical properties to high-purity stainless steel, in addition to good weldability

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ABSTRACT. High-purity austenitic stainless steels have been developed for nuclear fuel reprocessing applications. To produce nuclear fuel reprocessing facilities, *i.e.*, process vessels and pipeworks, welded joints are necessary, thus stimulating a need for filler metals. This paper discusses the development of a high-purity welding wire. As filler metal, such welding wire should provide not only good weldability, but should also be able to produce weldments having mechanical and corrosion properties equivalent to those of the base metal. According to these criteria, potential filler metals were evaluated. Based on this investigation, a high-purity austenitic stainless steel welding wire was developed that can be used to produce satisfactory weldments in terms of weldability, mechanical properties and, most importantly, corrosion properties.

Introduction

Since its discovery and development in 1910, stainless steel has played an important role in industrial development — particularly in the last few decades (Refs. 1–5). A variety of stainless steel grades have been developed to meet various design and operating requirements (Refs. 5–12). The special features of stainless steel are good corrosion resistance and mechanical properties. As new process environments become more corrosive, increased corrosion resistance of the materials is required. With new classes of stainless steel continuously being developed to improve corrosion resistance of specific equipment in severe corrosive environments, development of welding filler metals for stainless steels remains an important issue.

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Since nuclear fuel reprocessing facilities are generally operated with highly concentrated nitric acid solutions at elevated temperatures, stainless steels are the predominant materials used to construct these facilities. When operating conditions become severe, an upgrade of stainless steel is desirable to withstand the medium. For example, in the 1960s, Type 304L and 316L stainless steels were satisfactorily used for nuclear fuel reprocessing. Subsequently, Type 310LNb stainless steel was used in the '70s and early '80s. In all stages, welding filler metals (wires and electrodes) have been developed to meet operating requirements (Refs. 12, 13). Recently, in modern nuclear fuel processing facilities, stainless steels with improved corrosion resistance have become necessary. In such facilities, the operating mediums (which may be in the form of mixed acids) are complex. For example, they may contain not only concentrated nitric acid but also acids such as sulphuric acid with some additional corrosive ions. For this reason, a high-purity stainless steel (000Cr25Ni20) with excellent corrosion resistance has been developed (Ref. 14). The compositions of the base material are given in Table 1. Note that carbon, phosphorus and sulphur contents of the steels are lower than 0.01%, which is purer than the normal L-class stainless steels. In addition, Si content was also controlled to be less than 0.1% since Si and P were found to increase the intergranular corrosion in nonsensitized stainless steel (Refs. 14– 18). This steel has particularly excellent resistance to intergranular corrosion in high-oxidizing environments. For practical industry use, new steels need a suitable welding filler material because fabrication of most equipment requires some type of joint. In such cases, weldability of the material and properties of the joint become critical factors in controlling the range of application. As such, development of welding filler materials is imperative. The object of this research was to develop a welding wire that produced crack-free welds and matched the mechanical and corrosion properties of high-purity stainless steels.

KEY WORDS

High-Purity Stainless Steel
Corrosion Resistance
Welding Wire
Solidification Cracking
Mechanical Properties
GTAW
Filler Metal

Methodology

Two principles are normally applied to develop new corrosion-resistant stainless steels: 1) to use additional alloying elements to obtain desirable corrosion properties, and 2) to maintain a high level of purity in the steel by reducing impurity contents (*i.e.*, carbon, sulphur and phosphorus) to achieve the enhanced corrosion properties. In this case, the new high-purity austenitic stainless steels were developed based mainly on the second principle. When welding high-purity austenitic stainless steels, a fully austenitic weld metal is desirable to match the base metal's enhanced corrosion properties. Although a small amount of ferrite in the weld metal is of benefit in avoiding solidification cracking when welding austenitic stainless steels (Refs. 19–21), in this case, it is not recom-

Table 1 — Compositions of the Base Materials (wt-%)

	C	Si	Mn	Cr	Ni	P	S
000Cr25Ni20 (A)	0.01	0.1	0.5	24.20	20.20	0.009	0.009
000Cr25Ni20 (B)	0.005	0.05	—	24.52	19.33	0.005	0.008

mended for high-purity austenitic stainless steel. Although ferrite may not be detrimental to corrosion resistance in nitric acid, it may lead to selective corrosion in mediums such as sulphuric acid. In addition, the possible reduction of ductility and toughness of duplex weld metal is also a concern. Therefore, the object of this research was to develop a welding wire capable of producing fully austenitic weld metal. When developing filler materials for high-purity stainless steels, two major problems should be solved: solidification cracking and corrosion resistance. The methodologies used to solve these problems were based on adjusting alloying elements and/or reducing impurity levels.

Corrosion Properties

To increase corrosion resistance, a low level of impurity elements such as C, Si, S and P is desirable (Ref. 14). Therefore, the methodology was to develop a welding wire with low levels of impurities, *i.e.*, the P and S content was controlled at least as low as the base metal. Carbon content was also controlled to a level lower than 0.01%.

Solidification Cracking

The tendency to solidification cracking in stainless steels, particularly Type 310L, has long been recognized (Refs. 19–43). Austenitic stainless steels are usually susceptible to solidification cracking, due to their inherent characteristics. First, large deformation and tensile residual stresses can form in austenitic stainless steel weld metals during the local welding heat effect, due to the small thermal conductivity and large thermal expansion coefficient, as compared to other steels. Second, microstructure in the weld metal tend to be dendritic, with strong directionality that facilitates the segregation of impurities and formation of low-melting liquid films. Third, the complex composition of austenitic stainless steels facilitates the formation of low-melting phases from both impurities and some alloying elements, due to the limitation of dissolubility. In general, two measures can be used to reduce the hot-cracking sensitivity of austenitic stainless steels:

1) Reduce the level of impurities such as C, S and P. (This method can be widely used today due to advanced steelmaking technology.)

2) Add some useful alloy elements to reduce hot crack sensitivity, such as Mn, Mo, N, etc. The beneficial effect of Mn is to suppress the harmful effect of P and/or S by forming the high-melting compound MnS. In this way, it can prevent the formation of low-melting NiS-Ni eutectic and become the nucleus of solidification, thus speeding up weld solidification and reducing the brittleness temperature range (BTR) (Refs. 25, 33, 45). Molybdenum has a large solubility in Fe, Cr and Ni, which forms a solid solution with a melting temperature near that of the weld metal. Therefore, it can reduce BTR and become more crack resistant (Ref. 44). The methodology adopted in this research was to reduce the level of impurities while concurrently adding some useful alloy elements (such as Mn and Mo) in the filler metal, to avoid the occurrence of cracking in the weld metal.

Experimental Procedures

Materials

Base Material

High-purity austenitic stainless steels were melted via the vacuum induction furnace. The ingot was then forged and hot rolled into 6- and 12-mm-thick plates. The plates were subsequently solution heat-treated at 1050°C (1922°F) for 30 min, followed by water quenching. Sensitization treatment was carried out at 650°C (1202°F) x 1 h, followed by air cooling. The chemical compositions of the steels are given in Table 1.

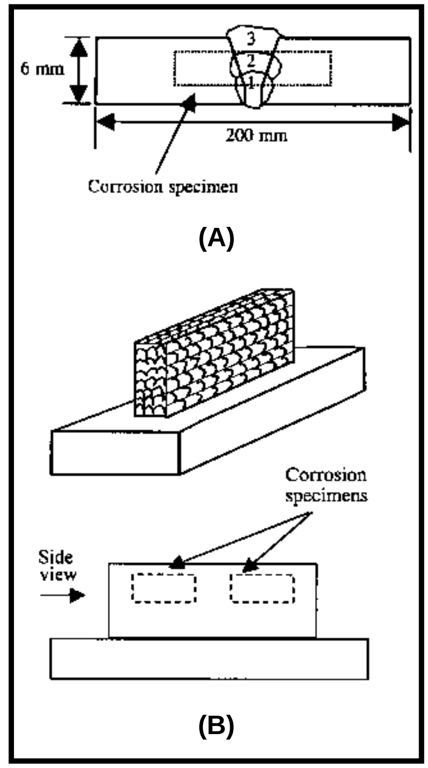

Fig. 1 — Schematic illustration of a welded joint and a weld deposit. Corrosion specimens size: A — Joint 80 x 20 x 3 mm; B — deposit 40 x 20 x 3 mm.

Welding Wires

The filler metals were produced by melting the high-purity raw materials with a low level of C, S, P and Si content in a 25-kg vacuum induction furnace. The ingot was first heated to 1140–1170°C (2084–2138°F) for 1 h and then forged into blocks. The blocks were rolled into 6.5-mm-diameter wire rods, which were then drawn into 1.6-mm-diameter wires through a few repeated steps (including solution treatment at

Table 2 — Compositions of the Filler Metals (wt-%)*

#	Filler Metal	C	Si	Mn	Cr	Ni	P	S	Mo	N
#1	000Cr25Ni22Mn4Mo2	0.008	0.22	4.47	24.83	22.2	0.007	0.007	2.17	0.05
#2	000Cr25Ni22MnMo2N	0.003	0.21	1.99	24.87	22.42	0.003	0.003	2.18	0.12
#3	000Cr25Ni22Mn4Mo2	0.006	0.22	4.4	25.08	22.30	0.008	0.006	2.8	0.05
#4	000Cr25Ni22Mn4Mo2N	0.006	0.14	3.79	24.66	21.81	0.005	0.006	2.38	0.12
#5	00Cr25Ni22Mn4Mo2N	0.023	0.14	4.8	24.99	21.99	0.005	0.006	2.5	0.12

*#5 is a commercially available wire.

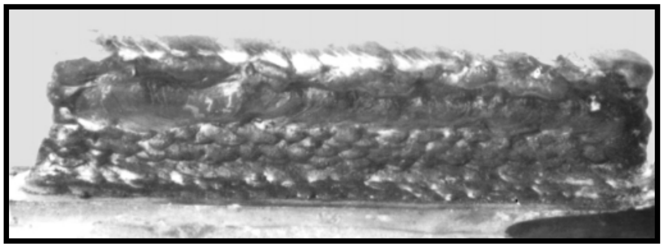

Fig. 2 — A sample from plate deposition testing.

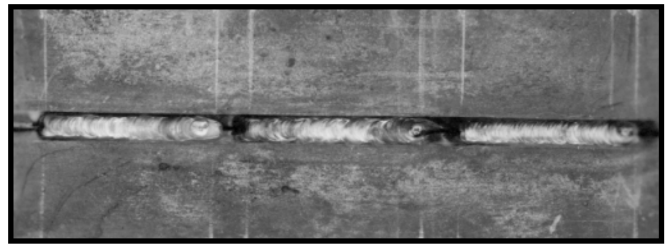

Fig. 3 — A sample from FISCO crack testing.

1050°C and pickling). To determine the effect of these elements, filler metals with several compositions were produced. The chemical analyses of the filler metals are given in Table 2. For comparison, in some tests, a commercial filler metal #5 was also used.

Corrosion Testing

Two types of welding samples were prepared for corrosion testing: welded joints and weld deposits — Fig. 1. The sizes and orientations of corrosion testing specimens are also shown in Fig. 1. The welding conditions used are given in Table 3. The corrosion specimens were prepared by machining the welded joints and weld deposits to the surface finish required by the testing specification (surface roughness Ra around 0.8 µm). The specimens were completely immersed in the corrosive solutions. Two specimens were used for each test; the corrosion rate is the average of the two specimens. The corrosion testing was arranged in two stages. First, initial selection of welding wires was conducted by corrosion testing in a boiling nitric acid containing hexavalent chromium ions ($HNO_3 + Cr^{+6}$). In the second stage, a selected wire with good corrosion resistance from the first stage was tested in simulated corrosion environments, such as evaporators and dissolvers, to determine corrosion matchability between the base metal and the filler metal. The major compositions of such corrosion mediums, which contain nitric acid and certain amounts of other corrosive elements, are given in Tables 7–9. Details about the corrosion testing mediums are given in (Ref. 14).

Weldability Tests

Since hot cracking was the major concern, two types of tests were used to examine the cracking sensitivity of the welding wires: 1) plate deposition test and 2) FISCO test (Refs. 46, 47). In the plate deposition test, filler metal was deposited onto a rigid plate by gas tungsten arc welding (GTAW). The size of the deposited weld was 150 x 30 x 10 mm — Fig. 2. Dye penetrant was used to check the surface crack in each pass, with the interpass temperature kept below 150°C (302°F). The deposit sample was then sectioned transversely to the welding direction for micro-examination at a magnification of 100X. When checking cracks in the deposit samples, both solidification cracks in the weld metal and liquation cracks in the reheated weld metal were included.

The FISCO testing sample was a 200 x 100 x 12-mm plate. The two base metal plates were secured in a FISCO fixture and welded using the conditions given in Table 3. Three 40–50-mm-long welds were produced with a 5-mm root opening between each. The space between the weld was 10 mm. The butt joint was removed from the fixture after cooling down to room temperature. The weld surface and weld metal were then microscopically checked to determine crack size. The heat-affected zone (HAZ) crack was also examined at the same time. Figure 3 shows a FISCO testing sample.

Mechanical Testing

Mechanical testing, including tensile, bending and Charpy V-notch toughness tests, were performed for the joints. Welding parameters are given in Table 3.

Table 3 — Welding Conditions Used in this Investigation

Process	Wire Diameter (mm)	Current (A)	Voltage (V)	Speed (mile/h)	Ar Gas Flow Rate (L/min)
GTA welding	1.6	80–100	12	14	8

Figure 4 shows the location and orientation of the testing samples. The tensile test samples were made from weld metal according to ASTM standards (Ref. 48). Specimens used were standard Charpy samples (10 x 10 x 55 mm) with a transverse-face bend.

Results and Discussion

Corrosion Properties

Since corrosion resistance was one of the most critical criteria for determining whether the filler metal developed would match the high-purity stainless steel, the first step in this work was to select suitable wires that possessed at least similar corrosion resistance as the base metal. In this stage, 000Cr25Ni20(A) base metal was used. Table 4 lists the corrosion test results for the wires and base metals in an 8N boiling $HNO_3 + 0.3gCr^{+6}/L$ medium.

It was noted that the joints and deposit samples made of high-purity filler metals (#1, #2, #3) had corrosion rates similar to the high-purity base metal. Although a slight corrosion trace in the weld metal could be visually observed, no intergranular corrosion was found by microscopic observation. Figures 5 and 6 show the micrographs of samples made with #1 wire for the deposit sample and joint, respectively. The effect of carbon content in the wires on the corrosion resistance was evidenced by the test results, *i.e.*, higher carbon content results in a higher corrosion rate (comparing #5 with #1, #2 and #3 wires in Table 4). It was also found that the deposit samples and joints with 2% Mn (#2) gave similar corrosion resistance to those with 4% Mn (#1 and #3). However, the deposit sample showed micro-cracks with low Mn wire — Fig. 7. No microcracks were found in deposit samples produced with higher Mn wire — Fig. 8. Based on these observations, a higher Mn wire is recommended to prevent cracking. Furthermore, the corrosion test results also show that there is no significant difference in corrosion resistance from wires with different N con-

Table 4 — Laboratory Corrosion Test Results in Boiling 8N HNO_3+0.3g Cr^{+6}/L Medium

	Welding Wire	Sample Type	Corrosion Rate ($g/m^2.h$)	Observation
#5	00Cr25Ni22Mn4Mo2N	Joint	1.00	Slight traces of corrosion in weld metal
#1	000Cr25Ni22Mn4Mo2N	Joint	0.778	No obvious traces of corrosion
#2	000Cr25Ni22MnMo2	Joint	0.747	Same
#3	000Cr25Ni22Mn4Mo2	Joint	0.779	Same
#1	000Cr25Ni22Mn4Mo2N	Deposit	0.772	Same
#2	000Cr25Ni22MnMo2	Deposit	0.7613	Same
#3	000Cr25Ni22Mn4Mo2	Deposit	0.801	Same
	000Cr25Ni20(A) base metal	Base metal	0.7596	Same

Table 5 — Laboratory Corrosion Test Results in 8N HNO_3+0.6g Cr^{+6}/L Medium

	Welding Wire	Sample Type	Corrosion Rate ($g/m^2.h$)	Observation
#5	00Cr25Ni22Mn4Mo2N	Joint	2.60	Corrosion in weld metal
#1	000Cr25Ni22Mn4Mo2N	Joint	1.953	No obvious traces of corrosion
#2	000Cr25Ni22MnMo2	Joint	1.673	Same
#3	000Cr25Ni22Mn4Mo2	Joint	1.786	Same
#1	000Cr25Ni22Mn4Mo2N	Deposit	1.883	Slight traces of corrosion in weld metal
#2	000Cr25Ni22MnMo2	Deposit	1.673	Slight traces of corrosion in weld metal
#3	000Cr25Ni22Mn4Mo2	Deposit	1.903	Slight traces of corrosion in weld metal
	000Cr25Ni20 (A) base metal	Solution treated	1.85	Slight traces of corrosion
	000Cr25Ni20 (B) base metal	Solution treated	1.66	No obvious traces of corrosion
	000Cr25Ni20 (B) base metal	Sensitized	1.66	No obvious traces of corrosion

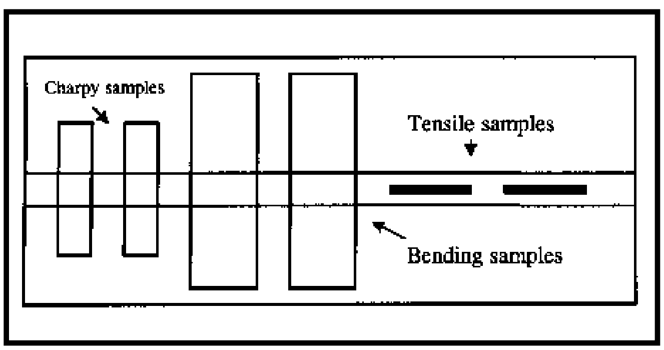

Fig. 4 — Schematic illustration showing locations and orientations of the mechanical testing samples from the joint (the plate thickness was 12 mm).

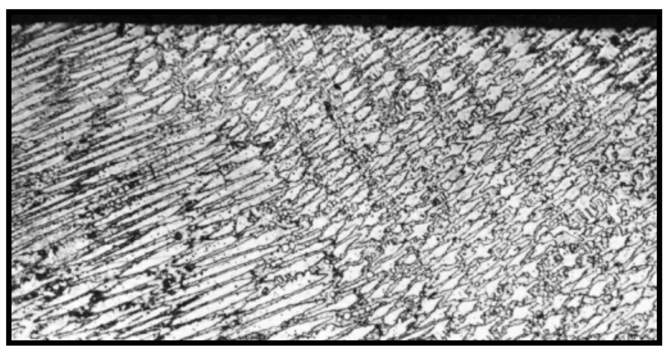

Fig. 5 — Deposit sample with #1 welding wire after corrosion testing (100X).

tents. The purpose of adding some nitrogen to the wire is to increase the stability of the austenite in the weld metal, although no ferrite was found in the welds. It was noted that no obvious traces of corrosion in the HAZ were observed for the samples from joints.

Table 5 lists the corrosion test results in a boiling 8N HNO_3 + 0.6gCr^{+6}/L medium having higher Cr^{+6} content than that in Table 4. In this test, 000Cr25Ni20(B) steel, in both solution-treated and sensitized states, was included for comparison. It can clearly be seen that the corrosion rate increased in all materials due to the higher Cr^{+6} content as compared to Table 4, but the corrosion tendency was the same. It can also be seen that 000Cr25Ni20(B) steel possessed better corrosion resistance than 000Cr25Ni20(A) steel, due to the purity difference. Based on the above results, a welding wire with the composition of #4 in Table 2 was proposed for further corrosion testing. This wire was modified from #1, #2 and #3 in consideration of reducing crack sensitivity and increasing the stability of austenite in the weld metal, *i.e.*, using high Mn content and additional nitrogen in the wire. Note that no ferrite was observed in the weld metals of #1, #2 and #3 wires.

In the second stage, various simulated mediums were used to further evaluate the corrosion resistance of the selected wire. All the deposit samples and joints in this stage were produced with #4 welding wire using the 000Cr25Ni20(B) steel. Results are given in Tables 6–9 in the various corrosion mediums. Since these mediums were selected based on specific applications, they are representative of the future service environments of the steel (Ref. 14).

The results in second-stage corrosion testing indicated that weldments produced with #4 wire showed equivalent corrosion rates to the base metal in either the solution-treated or sensitized states given in Tables 6 and 7. Therefore, the corrosion resistance of the wire is

Table 6 — Corrosion Rate (g/m^2.h) in Boiling 13N HNO_3 [106°C (222.8°F)] (5 x 48 h)

Base Metal	Solution Treated	Sensitized	Deposit Sample	Joints
000Cr25Ni20(B)	0.0535	0.0540	0.0640	0.0618

Table 7 — Corrosion Rate (g/m^2.h) in Boiling 8N HNO_3 with Certain Amount of Fe^{+++} + Na^+ + Al^{+++} Medium (106°C x 250 h)

Base Metal	Solution Treated	Sensitized	Joints
000Cr25Ni20(B)	0.0709	0.0670	0.0988

Table 8 — Corrosion Rate (g/m^2.h) in 1M HNO_3 with Certain Amount of $Hg(NO_3)^2$ +$Al(NO_3)_2$ Medium [100°C (212°F) x 240 h]

Base Metal	Solution Treated	Sensitized	Deposits	Joints
000Cr25Ni20(B)	0.00170	0.00240	0.000678	0.00443

Table 9 — Corrosion Rate (g/m^2.h) in 6.5M HNO_3 with Certain Amount of $Hg(NO_3)_2$ + $Al(NO_3)_2$ Medium [106°C (228°F) x 240 h]

Base Metal	Solution Treated	Sensitized	Deposits	Joints
000Cr25Ni20(B)	0.0140	0.021	0.0124	0.0155

Table 10 — Comparison of Hot Cracking Susceptibility of Various Austenitic Stainless Steels Using Transvarestraint Test Criteria

Material	BTR °C (°F)	E_{min} (%)	CST (x10^{-3}%°C^{-1})
000Cr25Ni20 [42]*	70 (158)	0.36	11.4
Normal 310 [25]	160 (320)	0.08	0.9
Normal 321 [25]	70 (158)	0.40	16
Normal 304 [25]	60 (140)	0.60	22

*Composition of 000Cr25Ni20 steel (wt-%): C-0.003, Si-0.25, Mn-1.22, S-0.004, P-0.007, Cr-24.95, Ni-19.78.

considered to be satisfactory in heavy-oxidizing mediums. Although corrosion rates of deposit and joint samples were higher than the base metal in some mediums (shown in Tables 8 and 9), they were still lower than the required technical specification (<0.05 – 0.1 g/m^2.h) (Ref. 14). Since a low level of Si in the steel was found to be more corrosion-resistant (Refs. 14, 15, 17, 18), it may also be beneficial to improving the corrosion resistance of the weld, if the wire has less than 0.1% Si. Further investigation is needed to verify this. Nevertheless, the current level of Si in the wire can still meet the requirements. Therefore, it can be concluded that 000Cr25Ni22Mn4Mo2N (#4) wire is a suitable filler metal to the 000Cr25Ni20 high-purity austenitic stainless steel, in terms of corrosion resistance.

Crack Sensitivity Evaluation

Although, in general, austenitic stainless steels are susceptible to solidification cracking, high-purity austenitic stainless steels have better crack resistance when compared to the same grade of steels. Table 10 lists some crack sensitivity evaluation data among several grades of austenitic stainless steels by using the Transvarestraint test (Refs. 25, 42). In the Transvarestraint test, the crack susceptibility was evaluated by determining the solidification BTR, the minimum augmented strain required to cause cracking (E_{min}) within the BTR and the critical strain rate (CST) for a temperature drop, defined as the inclination of the tangent to the ductility curve from the liquidus temperature. The larger the BTR, the more sensitive the material is to hot cracking. In contrast, the larger the values of E_{min} and CST, the less sensitive the material is to hot cracking. Studies indicate that the CST index is the most reliable one among the BTR, E_{min} and CST (Refs. 24, 25, 42). It can be seen from Table 10 that high-purity austenitic stainless steels have much better hot-crack resistance, when compared to normal Type 310 steels (although not as good as Type 304 steel). This is due to the low level of impurities, *i.e.*, the C, S and P content compared to normal Type 310 stainless steels. The good hot-crack resistance for Types 321 and 304 was due to the small amount of ferrite formation in the weld metal.

In this study, crack sensitivity was evaluated based on the corrosion testing results (*i.e.*, the evaluation was made only for those filler metals that could produce weldments with acceptable corrosion resistance). Therefore, welding wires #1, #2 and #3 were evaluated using the two weldability tests discussed above. The plate deposition test was used mainly to examine the hot-cracking sensitivity in weld metals, while the FISCO test was used for both weld metals and HAZs.

The results of the two weldability tests showed that there were no cracks found in #1 and #3 welding wires. However, microscopic observation of deposit samples in the plate deposition test revealed intergranular cracks for #2 welding wire — Fig. 7. Therefore, #4 welding wire, which was developed based on weldability test results of #1, #2 and #3 wires, was considered to be a good choice for this application, with satisfactory crack resistance. In fact, no cracks were found in welds produced with #4 welding wire.

Mechanical Properties

The mechanical testing samples were prepared by welding 000Cr25Ni20(B) steel with #4 welding wire. Results of the mechanical testing listed in Table 11 show that the weld metal and joints possessed satisfactory mechanical properties (Ref. 14). Therefore, #4 welding wire meets the specification requirements.

Welding Wire

Based on the above investigation, a wire with a composition of 000Cr25Ni22Mn4Mo2N (#4) was suc-

Table 11 — Mechanical Properties of the Weld Metal and Joints

	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Reduction in Area (%)	Charpy V Impact Energy (J)	Bending (D = 3a)
Sample 1	655	470	32.0	65.0	134	No crack
Sample 2	640	505	37.0	67.0	142	No crack

cessfully developed with corrosion resistance, mechanical properties and weldability. Currently, only a wire for GTAW can reach the high-purity criteria. It has been difficult to produce coated electrodes with such high purity. (The procedure for manufacturing such wire was described above.)

Conclusions

A high-purity austenitic stainless steel welding wire (000Cr25Ni22Mn4Mo2N) was developed, which can be used to produce satisfactory weldments with newly developed, 000Cr25Ni20 high-purity austenitic stainless steels in terms of weldability, mechanical properties and, most importantly, corrosion properties. Therefore, potential applications of the new high-purity austenitic stainless steels in the production of nuclear fuel reprocessing facilities (evaporators, dissolvers and waste containers) can be realized by using this filler metal.

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References

1. Streicher, N. A. 1978. Stainless steels — Past, present and future. *Proc. of the Intl. Conf. on Stainless Steel*, Climax Molybdenum Co., New York, N.Y., pp. 1–34.

2. Hooper, R. A. E. 1986. Stainless steels — Past, present and future. *Metals and Materials*, 12(1): 10–12.

3. Kiessling, R. 1990. Stainless steel — A versatile material in a competitive age. *Stainless Steel Europe*, 2(3): 26–31.

4. Schade, J. P. 1991. Present and future trends in the application of stainless steels. *Proc. of the Int. Conf. on Stainless Steels*, Chiba, Japan, ISIJ, pp. 1140–11475.

5. *ASM Handbook*, 10th ed., Vol. 1, 1990. Properties and selection: Irons, steels, and high-performance alloys. ASM International, Materials Park, Ohio.

6. Hodgson, P. D., and Jackson, R. 1981. Recent trends in the alloy development of stainless steel. *Met. Forum* 4(4): 192–208.

7. Pickering, F. B. 1984. Physical metallurgical development of stainless steels. *Proc. of the Intl. Conf. on Stainless Steel*, The Institute of Metals, London, England, pp. 2–28.

8. Widmark, H. 1993. Thirty years of stainless steel development. *Scandinavian Journal of Metallurgy* 22(3): 156–164.

9. Gooch, T. G. 1995. Welding recently developed stainless steels. *Proc. of the Intl. Conf. on Welding and Joining*, Institute of Metals and Materials Australiasia Ltd., Victoria, Australia, pp. 1–6.

10. Tuthill, A. H., and Avery, R. E. 1993. Corrosion behavior of stainless steel and high-alloy weldments in aggressive oxidizing environments. *Welding Journal* 72(2): 41-s to 49-s.

11. Gooch, T. G. 1993. Stainless steels: new alloys and welding processes. *Proc. of the Intl. Conf. on Processes & Materials*: *Innovation Stainless Steel*, Associazione Italliana di Metallurgia, Milano, Italy, pp. 3.221–3.230.

12. Roberts, T. 1994. Choosing materials for nuclear fuel reprocessing. *Materials World* 2(12): 628–631.

13. Gang, Y. M. 1994. Review of materials used in nuclear fuel reprocessing industry. Technical report, Central Iron and Steel Research Institute, Beijing, P. R. China.

14. Gang, Y. M. 1994. Development of high purity austenitic stainless steels — 000Cr19Ni15 and 000Cr25Ni20. Technical report, Central Iron and Steel Research Institute, Beijing, P. R. China.

15. Armijo, J. S. 1968. Intergranular corrosion of nonsensitized austenitic stainless steels. *Corrosion* 24(1): 24–30.

16. Briant, C. L., and Andresen, P. L. 1988. Grain boundary segregation in austenitic stainless steels and its effect on intergranular corrosion and stress corrosion cracking. *Metallurgical Transactions A* 19A(3): 495–504.

17. Watanabe, T., EI, K., and Nakamura, H. 1988. Intergranular corrosion of TIG welds of austenitic stainless steels. *J. High Temp. Soc. Japan* 14(4): 185–194.

18. Kuriki, Y., Tamura, M., Yamanouchi,

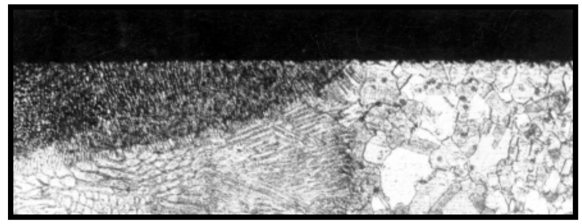

Fig. 6 — Weld joint sample with #1 welding wire after corrosion testing (100X).

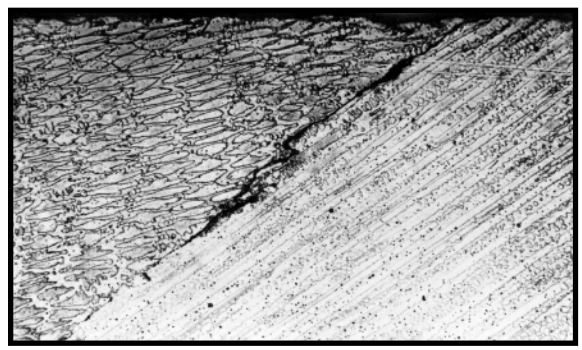

Fig. 7 — Microcracking in cross section of a deposit sample with #2 welding wire (400X).

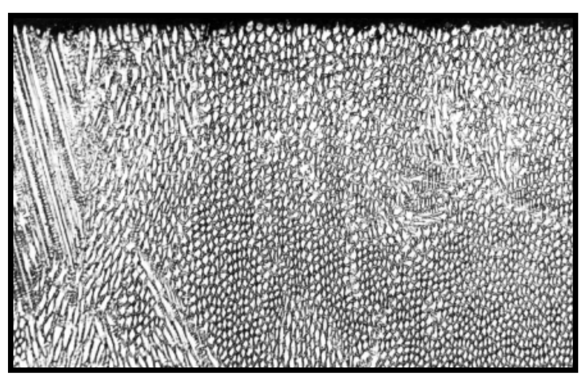

Fig. 8 — Cross section of a deposit sample with #1 welding wire (400X).

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N., and Kiuchi, K. 1991. Effects of silicon on the corrosion of AISI 304L steel in highly oxidizing nitric acid. *Proc. of the Intl. Conf. on Stainless Steel*, Iron and Steel Institute of Japan, Tokyo, Japan, pp. 295–300.

19. Hull, F. C. 1967. Effect of delta ferrite on hot cracking of stainless steel. *Welding Journal* 46(9): 399-s to 409-s.

20. Arata, Y., Matsuda, F., and Katayama, S. 1976. Fundamental investigation on solidification behaviour of fully austenitic and duplex microstructure and effect of ferrite on microsegregation. *Trans. JWRI* 5(2): 35–51.

21. Kujanpaa, V., Suutala, N., Takalo, T., and Moisio, T. 1979. Correlation between solidification cracking and microstructure in austenitic and austenitic-ferritic stainless steel welds. *Welding Research International* 9(2): 55–76.

22. Borland, J. C., and Younger, R. N. 1960. Some aspects of cracking in austenitic steels. *British Welding Journal* 71(1): 22–60.

23. Masumoto, I., Tamaki, K., and Kutsuna, M. 1972. Hot cracking of austenitic stainless steel weld metal. *Trans. JWS* 41(11): p. 1306.

24. Senda, T., Matsuda, F., Takano, G., Watanabe, K., Kobayashi, T., and Matuzaka, T. 1972. *Trans. Japanese Welding Society* 3(6): 709–723.

25. Arata, Y., Matsuda, F., and Katayama, S. 1977. Solidification cracking susceptibility in weld metals of fully austenitic stainless steels — Report 3, Effect of ferrite, P, S, C, Si, and Mn on ductility properties of solidification brittleness. *Trans. JWRI* 6(1): 105–116.

26. Backman, A., and Lundquist, B. 1977. Properties of a fully austenitic stainless steel weld metal for severe corrosion environment. *Welding Journal* 56(11): 23-s to 28-s.

27. David, S. A., Goodwin, G. M., and Braski, D. N. 1979. Solidification behavior of austenitic stainless steel filler metals. *Welding Journal* 58(11): 330-s to 336-s.

28. Matsuda, F., Nakagawa, H., Uehara, T., Katayama, S., and Arata, Y. 1979. A new explanation for role of delta-ferrite improving weld solidification crack susceptibility in austenitic stainless steel. *Trans. JWRI* 8(1): 105–112.

29. Lundin, C. D., Chow, C. P. D., and Sullivan, C. J. 1980. Hot cracking resistance of austenitic stainless steel weld metals. *Welding Journal* 59(8): 226-s to 232-s.

30. Matsuda, F., Katayama, S., and Arata, Y. 1981. Solidification crack susceptibility in weld metal of fully austenitic stainless steels. V — Solidification crack susceptibility and amount of phosphide and sulfide in SUS 310S weld metals. *Trans. JWRI* 10(2): 73–84.

31. Ogawa, T., Zaizen, T., and Tsunetomi, E. 1981. The hot cracking susceptibility of niobium-containing austenitic stainless steel welds. *J. Jpn. Weld. Soc.* 50(7): 680–688.

32. Ogawa, T., Nakamura, H., and Tsunetomi, E. 1981. Toughness at cryogenic temperature and hot cracking in austenitic stainless steel weld metals. *J. Jpn. Weld. Soc.* 50(12): 1203–1211.

33. Matsuda, F., Nakagawa, H., Katayama, S., and Arata, Y. 1982. Solidification crack susceptibility in weld metal of fully austenitic stainless steels. VII — Effect of manganese and nitrogen on solidification crack resistance. *Trans. JWRI* 11(2): 79–85.

34. Matsuda, F., Nakagawa, H., Katayama, S., and Arata, Y. 1982. Weld metal cracking and improvement of 25%Cr-20%Ni (AISI 310S) fully austenitic stainless steel. *Trans. Jpn. Weld. Soc.* 13(2): 41–58.

35. Lippold, J. C., and Savage, W. F. 1982. Solidification of austenitic stainless steel weldments. III — The effect of solidification behavior on hot cracking susceptibility. *Welding Journal* 61(12): 388-s to 396-s.

36. Ogawa, T., and Tsunetomi, E. 1982. Hot cracking susceptibility of austenitic stainless steels. *Welding Journal* 61(3): 82-s to 93-s.

37. Matsuda, F., Nakagawa, H., Katayama, S., and Arata, Y. 1983. Solidification crack susceptibility in weld metal of fully austenitic stainless steels. VII — Effect of nitrogen on cracking in 304 weld metal. *Trans. JWRI* 12(1): 89–95.

38. Ogawa, T., Suzuki, K., and Zaizen, T. 1984. The weldability of nitrogen-containing austenitic stainless steel. II — Porosity, cracking and creep properties. *Welding Journal* 63(7): 213-s to 223-s.

39. Cieslak, M. J., and Ritter, A. M. 1985. Precipitate formation in austenitic stainless steel welds. *Scr. Metall.* 19(2): 165–168.

40. Sun, Z., and Han, H. Y. 1990. Fractographic study of solidification cracking of niobium bearing stainless steel weld metal. *Proc. of the 2nd Intl. Conf. on Trends in Welding Research*, eds. S. A. David and J. M. Vitek, ASM International, Materials Park, Ohio, pp. 679–685.

41. Brooks, J. A., and Thompson, A. W. 1991. Microstructural development and solidification cracking susceptibility of austenitic stainless steel welds. *International Materials Review* 36(1): 16–44.

42. Sun, Z. 1992. A study of solidification crack susceptibility using the solidification cycle hot-tension test. *Materials Science and Engineering* A154: 85–92.

43. Sun, Z., and Han, H. Y. 1992. Hot ductility of simulated stainless-steel weld metals. *Journal of Materials Science* 27: 1311–1316.

44. Rabensteiner, G. 1989. The welding of fully austenitic stainless steels with high molybdenum contents. *Welding in the World* 27(1/2): 2–12.

45. Folkhard, E. 1988. *Welding Metallurgy of Stainless Steels*. Springer-Verlag, Wien, New York, p. 167.

46. Schnadt, H. M. 1957. *Oerlikon Schweissmitteilungen*, 15: 31–42.

47. Wu, S. C. 1983. *Weldability Tests for Metals*. Shanghai Science & Technology Publishing House, Shanghai, pp. 97–100.

48. ANSI/ASTM E185-79, *1980 Annual Book of ASTM Standards*, Part 10, Metals — Physical, Mechanical, Corrosion Testing. ASTM, Philadelphia, Pa.