Welding Consumable Development for a Cryogenic (4 K) Application

Research led to the development of a nitrogen- and manganese-modified, high-nickel stainless steel alloy for a demanding cryogenic magnet application

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ABSTRACT. This paper summarizes the development and qualification of an appropriate welding consumable for a demanding cryogenic magnet application. It begins with a review of the research conducted on cryogenic fracture toughness of wrought and welded austenitic stainless steels. This research shows that certain elements of the composition have a powerful effect upon the steel's fracture toughness at 4 K. In particular, the higher oxygen content in the weld manifests itself as inclusions, which have a severe detrimental effect upon the fracture toughness. This one factor accounts for most of the difference in toughness between wrought and weld materials of similar composition, and is a function of the weld process. Also, welds enriched with manganese and nickel have demonstrated improved fracture toughness. These discoveries were combined in the development of a nitrogen- and manganese-modified, high-nickel stainless-steel alloy. It produced gas metal arc welds with superior cryogenic mechanical properties (yield strength near 900 MPa at 4 K and a Charpy V-notch impact energy near 140 J at 76 K) when the procedures were modified to reduce the oxygen content.

Background

In 1983 and in 1989, the nuclear physics community prepared long range plans for the U.S. Department of Energy and the National Science Foundation. In both years, they identified the Relativistic Heavy Ion Collider (RHIC) as the highest priority for facility construction. In response, the U.S. Congress appropriated the first construction funds for the RHIC in fiscal year 1991. The construction of the RHIC, at the Brookhaven National Laboratory (BNL), will provide the United States with a world-class facility with a potential for unique discoveries. Specifically, the RHIC will be able to create matter at extremely high temperatures and densities — so extreme that scientists hope to observe phenomena that have not occurred in the natural universe since the original "Big Bang." These experiments cannot be conducted at existing high-energy accelerator facilities.

In the RHIC, two beams of heavy ions will speed in opposite directions inside a pair of rings in a tunnel almost 3.9 km in circumference. The beams will be bent and focused by more than 1700 superconducting magnets. The material and magnetic property requirements (material strength to resist the mechanical loads and the fracture toughness requirements at 4 K) of these magnets are very demanding. This paper concentrates on the weld design and materials to meet the design requirements of the superconducting magnet structures.

BNL Magnet Design Requirements

A superconducting magnet has the same basic structure as a traditional electromagnet — an iron core wound with an electrical cable. In the case of niobium-tin superconducting magnets, the electrical cable is superconducting and must be maintained at a temperature of less than 4.6 K. The cable and iron core are enclosed within a cryogenic pressure vessel to provide this cooling. The U.S. Department of Energy requires that all pressure vessels at its facilities comply with the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*. These requirements, coupled with the cryogenic system design and manufacturing cost parameters, require a weld yield strength of 900 MPa for the 4.8-mm-thick stainless steel magnet shells, a ferrite number (FN) less than 3 for weld processes other than gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) and a lateral expansion greater than 0.38 mm for a Charpy V-notch (CVN) impact test at the operating temperature. ASME Code paragraph UG-84 requires impact testing for applications operating at temperatures below 19 K, where the RHIC pressure vessels will be operating, yet impact testing at 4 K is complicated by the low heat capacity of materials at this temperature. The ASME Code (originally developed for applications near room temperature or above) had been applied to cryogenic temperatures without adjusting for the changes in the physics of heat flow and deformation. The standard Charpy impact test prescribed by the American Society for Testing and Materials (ASTM) Standard E 23 becomes questionable at extreme cryogenic temperatures. Recent studies show that a specimen cannot be transferred from a 4 K cooling bath to the test machine quick enough to avoid exceeding the test temperature by a large margin (Ref. 1). Furthermore, the adiabatic heating associated with deformation has such an influence on all materials at this temperature that the deformation preceding fracture often in-

KEY WORDS

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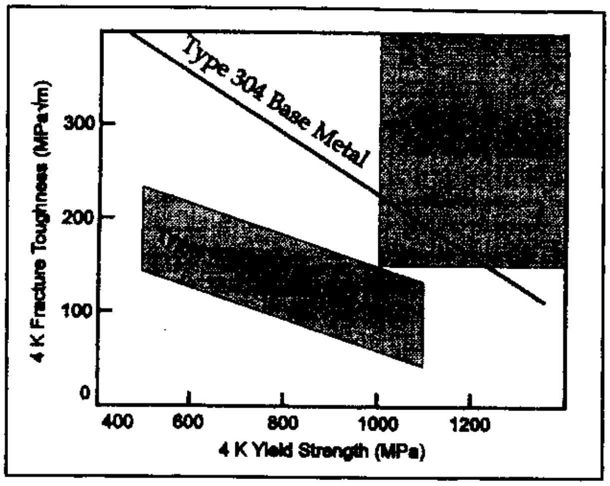

Fig. 1 — Comparison of the relationships for weld and base metal strength-toughness.

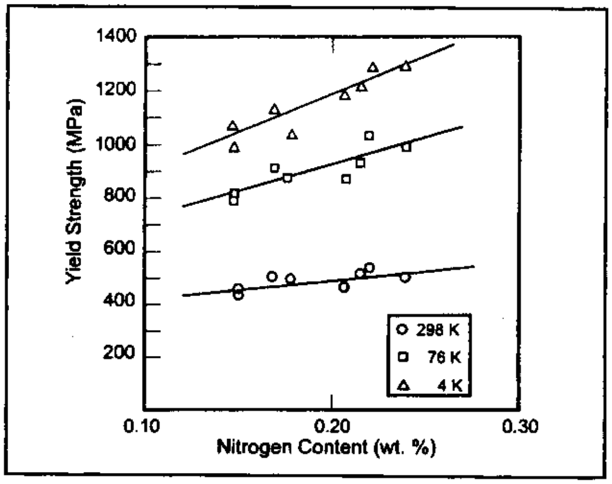

Fig. 2 — Yield strength vs. nitrogen content for Type 316LN welds.

creases the specimen temperature by 70 K or more. This means the specimen temperature might far exceed the test temperature during fracture even while using innovative techniques to keep the specimen cool until the instant of fracture (such as cooling the specimen while it is already sitting on the impact machine anvils). This testing may provide acceptable data for projectile impact tests, but cannot provide valid data for a large structure at 4 K. What we wanted was a large cryogenic structure with acceptable fracture toughness, not simply good impact data. The solution to this dilemma is engineered welds.

Engineered Welds

Fracture mechanics calculations conducted for several cases showed the fracture toughness (K_{Ic}) of the magnet should be at least 68 MPa $\sqrt{m}$ at 4 K. While this fracture toughness requirement appears relatively easy to achieve, it forms the minimum design requirement. Current data indicate a one-sigma scatter band of ±44 MPa $\sqrt{m}$ (Ref. 2). This indicates that the nominal fracture toughness value must be at least 156 MPa $\sqrt{m}$ to guarantee that a 95% confidence level is achieved. This requirement places the necessary fracture toughness at the upper boundary for commercially available weld metal, as shown in Fig. 1 (Ref. 2).

One complexity in designing for fracture resistance is that many published reports, including the ASME Code, specify qualitative CVN impact requirements as absorbed energy, in joules, or lateral expansion, in millimeters, while strict fracture-mechanical calculations use quantitative fracture toughness data, in MPa$\sqrt{m}$. These are significantly different approaches and we wanted to be certain that we fulfilled both needs. Therefore, we generated both types of data for our welds, then compared our data to both types of requirements.

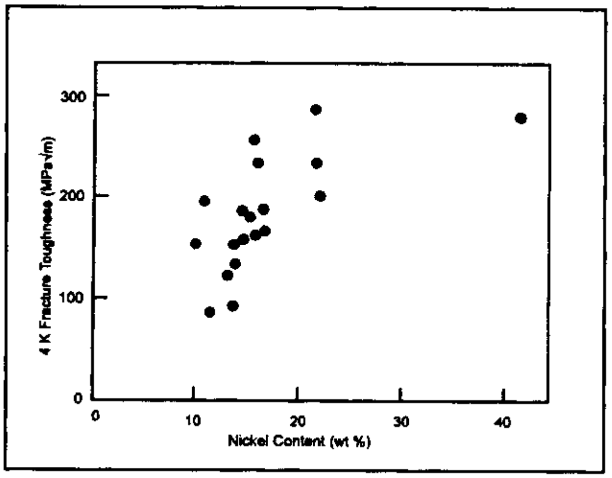

Fig. 3 — Fracture toughness vs. nickel content in welds.

Conventional wisdom says the weld should match the composition of the base material as much as possible. This general rule is very often useful in helping designers avoid problems due to differences in thermal expansion (residual stress and distortion), corrosion potentials and differences in strength. This structure will not be subject to a severely corrosive environment, but the other problems could be important, so we favored a matching composition. To guide our selection of the electrode composition, we found several studies of materials and joining processes for specific cryogenic magnet structures that provided very practical advice (Refs. 3, 4). In particular, Goodwin's 1985 paper (Ref. 3) describes the construction of large magnet cases of Type 316LN stainless steel (the large coil program) for 4 K service. Goodwin found an extremely wide range in reported mechanical properties for candidate welding consumables and described how they qualified electrodes that met their property requirements. For the RHIC, we wanted a margin between the requirements and typical properties that was wider than those listed in this study (for greater reliability). Therefore, we broadened our scope to include alternative compositions, especially compositions developed or evaluated since these reports, but kept the potential strength and thermal expansion differences in mind when evaluating their suitability.

Other published studies of material properties provide broader guidance on the effect of various elements and on the selection of a material to meet a set of mechanical properties (Refs. 5–18). Reference 14 shows that the strength of austenitic stainless steel at cryogenic temperature is controlled primarily by the nitrogen content. Predictive equations for weld strength have a relatively small scatter (standard deviation near 50 MPa, or about 6% for this application), and the range of strength data spans the 900-MPa goal of the RHIC. Figure 1 shows data for strength vs. toughness for Types 308L and 316L stainless steel compositions. Unfortunately, it shows as the strength increases (through nitrogen ad-

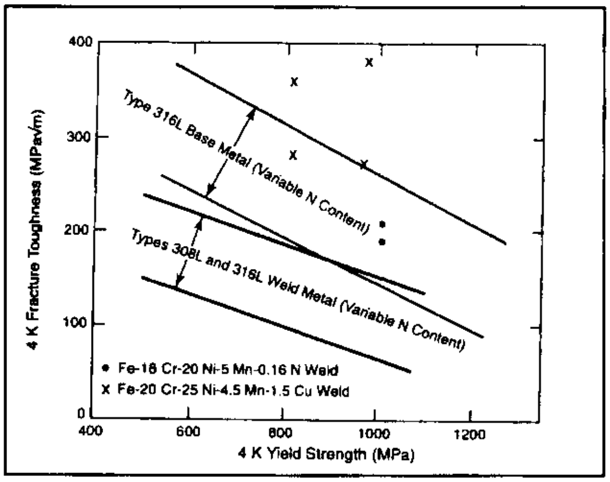

Fig. 4 — Fracture toughness vs. yield strength.

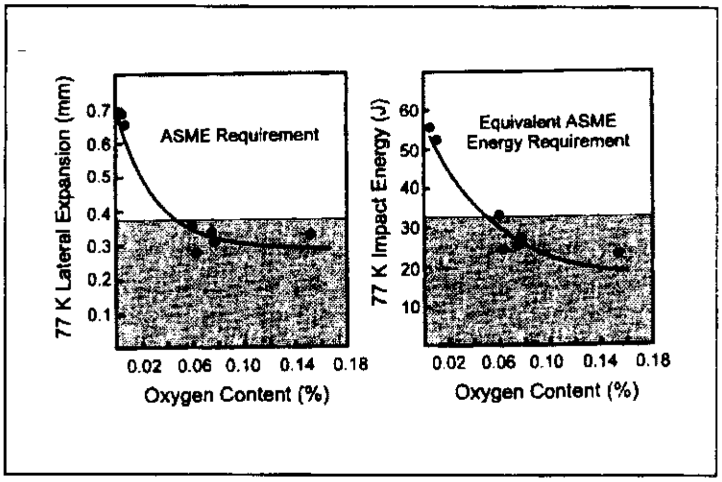

Fig. 5 — Results of oxygen content investigation (Ref. 6).

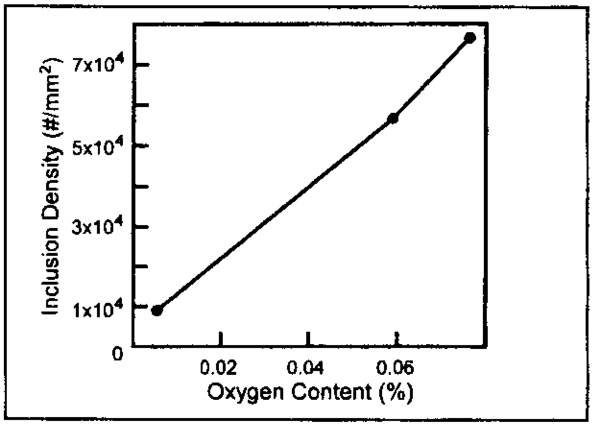

Fig. 6 — Linear relationship between inclusion density and oxygen content (Ref. 6).

ditions), the toughness decreases, so we were concerned about our ability to meet both the strength and the toughness requirements simultaneously. Figure 1 also shows the welds fall short of the base metal properties. This was of concern to the designers because welds usually have an uneven surface profile and contain high residual stresses that can grow still larger when cooled to cryogenic temperatures. The combination of lower toughness, surface roughness and residual stresses could make the welds a critical fracture path during unexpected tensile overload or propagation of fatigue cracks. We were looking for welds that could match both the strength and toughness of the 304L base material.

Factors Affecting Cryogenic Strength and Toughness in Weld Metal

Weld toughness is affected by many factors. One well-known metallurgical factor causing low toughness in weld metal is precipitates, such as carbides, nitrides and intermetallic compounds. The presence of delta ferrite and nonmetallic inclusions are also well-known detractors of toughness. Typical compositions (Types 308 and 316) used for cryogenic stainless welds generally fall about 40% below base metals in their σ_y vs. K_{Ic} performance (see also Fig. 1) (Ref. 2).

Ferrite

Delta ferrite is a residual phase present in some stainless steel welds that solidifies in a primary ferrite mode. Residual ferrite in small quantities is normally desirable in stainless steel welds because it inhibits the formation of compounds with low melting points (such as FeS and FeP) that promote hot cracking in fully austenitic alloys. However, ferrite should be minimized for best toughness in cryogenic service. Therefore, welding alloys for cryogenic service are either ferrite-free or very low in ferrite. The ferrite-free alloys are produced with very strict controls on the impurity contents that promote hot cracking. Also, welds with a FN greater than 7 show relatively low toughness, but welds with a lower FN are scattered within the one-sigma scatter band of ±44 MPa in Fig. 1. Thus, ferrite should be reduced to the lowest level consistent with cracking resistance.

Previous data from the National Institute of Standards and Technology (NIST) in Fig. 1 show an inverse relationship between yield strength and fracture toughness (Ref. 5). Test data available to date indicate eliminating delta ferrite, avoiding chromium carbides and reducing the width of columnar grains may increase the strength-toughness characteristics of welds. These actions will raise the trend line of the weld strength-toughness characteristics closer to that of wrought stainless steel.

Other research establishes that a Charpy absorbed energy of at least 32 J is necessary to meet the ASME minimum lateral expansion of 0.015 in. (0.38 mm) (Ref. 6). Reference 7 lists the following equation for 76 K CVN impact energy as a function of FN, calculated from the Schaeffler diagram (ferrite potential if negative), carbon content and nickel content:

$$\mathrm{CVN(J)} = 19 - 1.4\mathrm{FN} - 890\mathrm{C2} + 1.4\mathrm{Ni}$$

Of course, FN is determined by the composition, including C and Ni, so this equation should be used cautiously. However, it does indicate that toughness is increased as Ni is increased, as FN is decreased and as C is decreased. Quantitatively, it suggests that a CVN of 32 J requires a nickel content of no less than 11 wt-%, if the C were restricted to 0.05 wt-% and the FN was zero. To have a reasonable safety factor, the Ni would have to be substantially higher.

Nitrogen

The strengthening characteristics of nitrogen become more pronounced at lower temperatures. Figure 2 shows how the yield strength of 316L welds increases with increasing nitrogen content (Ref. 7). Yield strength at 0.20 wt-% N increases by a factor of 2 as temperature is decreased from 298 to 76 K, and in-

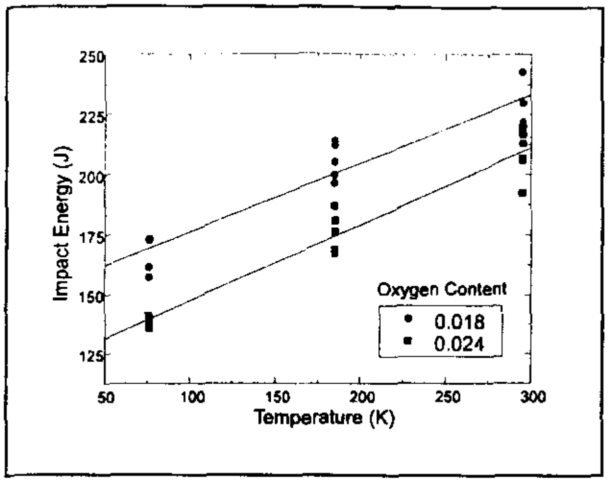

Fig. 7 — CVN impact energy.

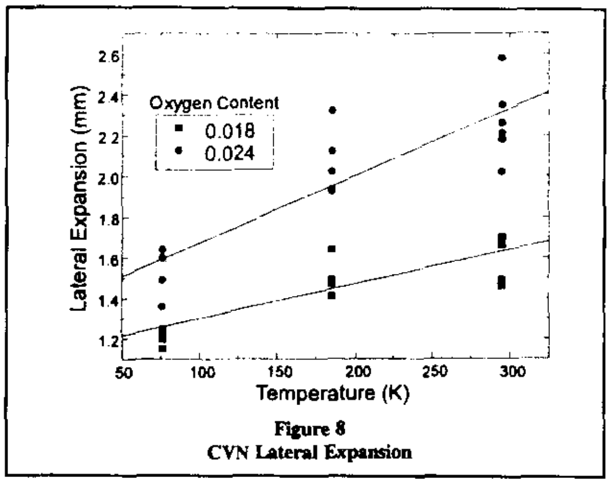

Fig. 8 — CVN lateral expansion.

creases by a factor of 2.5 when the temperature is decreased to 4 K. Studies also show that increasing the nitrogen from the typical weld nitrogen content of 0.05% to 0.20% yields a threefold increase in strength when cooled to 4 K.

Nitrogen cannot be added without limit. The upper limit is determined by the solubility of nitrogen in the microstructure. Weld porosity occurs above this limit. The solubility limit is a function of the composition, with certain elements (such as manganese) serving to increase the limit (Ref. 8). Manganese at a concentration above the 1.5 wt-% typical for austenitic stainless steels was added to provide greater protection from porosity formation and to act as a solid solution strengthener.

Nickel

Nickel also has a significant, though nonlinear, effect on toughness. Figure 3 shows that increasing nickel from 10 to 20% in the welds provides the greatest improvement in toughness. Thus, a weld with more than 20% nickel should exhibit the greatest attainable toughness for an austenitic stainless steel. Workers at NIST performed work to determine an optimum weld material for 316LN, which is a popular base material for demanding cryogenic applications (Ref. 7). Two commercially available compositions (18Cr-20Ni-5Mn-0.16N and 20Cr-25Ni-4.5Mo) were evaluated using GMAW. Shielding gases were more inert than normal to reduce oxygen content, and the gas used for the 20Cr-25Ni-4.5Mo electrode was augmented with nitrogen to increase the nitrogen content of the weld metal. Figure 4 shows the strength was comparable to that of 316LN base metal and the fracture toughness was equal to or greater than that of the 316LN base metal. This toughness clearly exceeds the toughness achievable with 308- and 316-based welding compositions and standard welding procedures.

Other research shows that higher nickel contents improve the toughness in two ways: nickel reduces the ferrite content of the weld metal (a magnetic mictrostructural phase and more brittle than austenite), and nickel additions increase the toughness in fully austenitic compositions (Refs. 9–12). Figure 3 shows how additions of nickel to stainless steel alloys generally increase the toughness, at least up to 20 wt-%. A secondary benefit is that nickel stabilizes austenitic structures against the formation of martensite (another magnetic phase) during deformation. The two references on the fabrication of the cryogenic magnet structures mentioned their search for these magnetic phases during qualification and control of the welding procedure (Refs. 3, 4).

Tramp Elements

Fully austenitic compositions may be subject to hot cracks, which are ruptures that form in the hot weld during solidification. Studies show this tendency can be controlled by careful control of "tramp" elements, phosphorus and sulfur, that produce a low-melting-point eutectic (Ref. 3). This problem is evident in electrode specifications where crack-sensitive compositions can be available in a special grade with stricter limits on the elements that promote hot cracking. Sometimes the fully austenitic grades can be made less sensitive to cracking by adding elements such as manganese, copper or carbon that change the solidification structure. These elements may change the shape of the solidification front or change the amount of terminal eutectic between adjacent dendrites.

Oxygen

Because of its reactivity, free oxygen is not found in the weld. Instead, it combines with other elements to form oxide inclusions. These inclusions have diameters near 1 µm and are spherical because they form in the liquid above the solidification temperature. As the weld cools, these inclusions are entrained in the solid and have little effect on mechanical properties until the weld is deformed. Inclusions are harder than the surrounding metal matrix and serve as impediments to dislocation motion during deformation. As a result, substantial stresses form in the vicinity of oxide inclusions, causing voids to initiate. These voids then link by void coalescence, leading to final fracture of the material. Since the voids nucleate at inclusions, reduction in the density and size of inclusions reduces the number of voids that form and is an obvious step in increasing the toughness of a weld. Stainless steel welds usually have lower toughness than wrought material. The primary difference between weld material and wrought material is the amounts of inclusions and ferrite. Welds will contain more inclusions because of the imperfect gas shielding of the metal while molten. Studies have shown that correlation of toughness with inclusion spacing is similar for wrought material, which suggests that the differences in fracture toughness can primarily be attributed to this one factor (Refs. 14, 15).

Research on the effects of the welding process and shielding gas on toughness has been conducted using 308, 308L and 316L filler metal; GTAW with 100%

Table 1 — Effect of Oxygen Content on Inclusion Density and Yield Strength

σ_y (MPa)	El (%)	RA (%)	K_{Ic} (MPa$\sqrt{m}$)	Oxygen (wt-%)	Inclusion (#x10^3/mm^3)	Inclusion Spacing (μm)
736	47.9	46.6	179	0.004	19.3	7.0
747	22.3	23.7	150	0.048	37.7	5.0
743	10.2	13.1	132	0.072	55.2	4.3

Table 2 — Electrode Specification (Ref. 19)

Element	Range (%)
Carbon	0.02 max
Manganese	7.0–7.2
Silicon	0.2–0.5
Phosphorous	0.018 max (desired as low as possible)
Sulfur	0.004 max (desired as low as possible)
Chromium	20.9–21.7
Nickel	24.75–25.25
Molybdenum	4.75–5.25
Copper	1.25–1.75
Nitrogen	0.17–0.21
Oxygen	0.015 max (desired as low as possible)
Other	< 0.50
Iron	Remainder

Fig. 9 — Fracture surface of Charpy specimen at 76 K (0.024% oxygen content; 1500X).

argon shielding or GMAW with Ar/2% O_2 and Ar/5% O_2 (Ref. 6). The results are shown in Fig. 5. Most of the elements in the chemical composition of the Type 316L weld metal were consistent for the different processes, but the oxygen content changed dramatically (0.005–0.076%). The study found the lateral expansion properties would meet ASME requirements at 173 K, but only the GTA weld shielded with pure argon would meet the requirement at 77 K.

The oxygen contents of the Type 308/308L weld metal ranged from 0.007 to 0.15%, and the weld metal properties were similarly affected by oxygen content, with steep declines in lateral expansion and impact energy. Impact properties began to stabilize when oxygen content reached 0.06% oxygen. Mechanical tests revealed a relationship between FN and oxygen content and the ability to meet the ASME lateral expansion requirement. However, the low-oxygen GTA weld could meet the ASME requirement easily, even with a relatively high FN, while the high-oxygen-content welds could not meet the lateral expansion requirement, even with a FN of 5. This accounts for the ASME recommendation for a FN lower than 3 for weldments produced by processes other than GTAW and GMAW (Ref. 6).

Kim's study also found an excellent correlation between lateral expansion (LE) and impact energy at 173 and 76 K (Ref. 6). This relationship is described by the following equation:

$$LE(mm) = 0.012 \times C_v(Joule)$$

Thus, the ASME lateral expansion requirement of 0.38 mm is equivalent to an impact energy of 32 J (23.6 ft-lb). Fractographic analysis of the 76 K Charpy V-notch specimens showed more brittle fracture of ferrite on the fracture surface of samples with decreased oxygen content. This is attributed to crack initiation and propagation for welds having retained delta ferrite and very low inclusion content. The fracture in this case is more likely to initiate in, and follow, the ferrite phase. The overall fracture process, however, still requires high energy because the ductile austenitic matrix prevents continuous brittle fracture in the weld. Fractures in welds with high oxygen content initiate by the formation of microvoids and propagate by microvoid coalescence. This proceeds so easily that the whole fracture occurs in a fully dimpled mode at low energy. Therefore, it is possible to increase impact toughness in low-oxygen welds by decreasing ferrite, but ferrite control would not be effective in high-oxygen welds because ferrite has a negligible role in the fracture process.

This effect also was studied by Whipple and Kotecki (Ref. 17), who produced a series of 316L welds using GTA, GMA and submerged arc welding (SAW). The toughness at 4 K was found to be inversely proportional to the inclusion content, with the highest toughness found in the GTA welds (181 MPa·√m). Other research found the K_{Ic} of Type 316L stainless steel weld composition increased significantly at 4 K when inclusion contents in GMA welds were decreased (Ref. 18). The study showed an increase in toughness of 18 MPa·√m/μm in average inclusion spacing.

Siewert and McCowan tested specimens made by varying shielding gas composition over 304 plate with 316L electrodes (Ref. 18). Material properties are shown in Table 1. Inclusion density had little effect on yield strength, which varied less than 4%, but fracture toughness increased by 35% as the inclusion content decreased by 65%. The wide scatter for toughness data of weld metals is attributed to the varying inclusion contents when several welding processes are used.

Finally, the inclusion density is linearly related to oxygen content, as shown in Fig. 6 (Refs. 6, 15). This is useful because oxygen content can be determined much more quickly and economically using standard procedures and equipment than inclusion density, for which standards have not yet been developed. Clearly, minimizing oxygen content, thus minimizing inclusion density, will ensure that a minimum toughness will be exceeded.

Final Electrode Composition

By combining the desirable ranges for the various elements listed above, we arrive at the following aim composition for our weld (and welding electrode):

- ◆ 25 wt-% nickel (to provide good toughness),
- ◆ 20 wt-% chromium (to develop the fully austenitic composition),
- ◆ 0.18 wt-% nitrogen (to provide a yield strength of 900 MPa at 4 K),
- ◆ 7 wt-% manganese (to increase the solubility of nitrogen, strengthen the weld and reduce the hot-cracking sensitivity),
- ◆ 1.5 wt-% copper (to reduce the hot-cracking sensitivity by modifying the solidification front substructure; copper is intentionally added to other austenitic alloys such as ER320, ER320LR, ER383 and ER385 [Ref. 16]),
- ◆ 5 wt-% molybdenum (to strengthen the weld),
- ◆ 0.005 wt-% upper limit on "tramp elements" phosphorus and sulfur (to re-

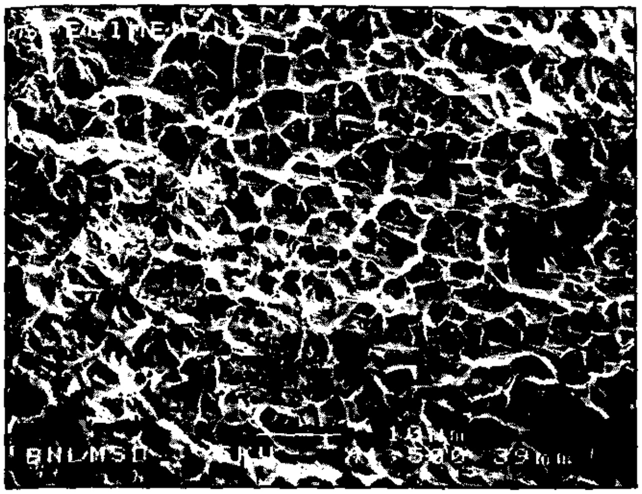

Fig. 10 — Fracture surface of Charpy specimen at 76 K (0.018% oxygen content; 1500X).

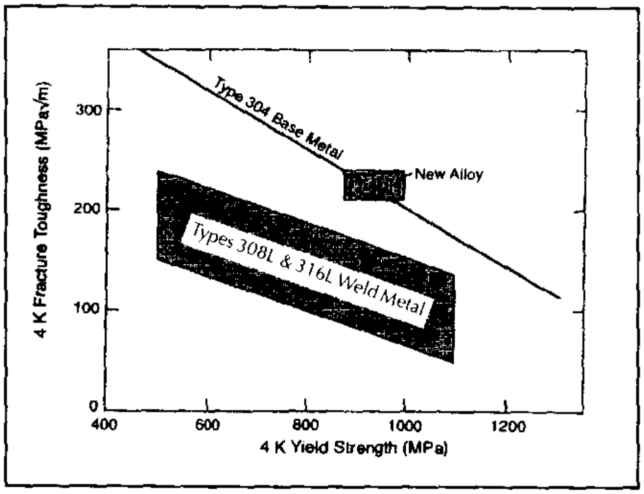

Fig. 11 — Test alloy mechanical properties.

duce the hot-cracking sensitivity) and

◆ 0.02 wt-% upper limit on oxygen (to produce higher toughness).

Working with electrode manufacturers, we adopted the composition specification detailed in Table 2. Because this composition does not match that of the Type 304L base metal, we need to consider the potential problems of nonmatching compositions. This composition is fully austenitic, as is the base material, so they should have closely matched coefficients of thermal expansion, and so develop only minor residual stresses. The strength has been matched, so there should be no problems with localized strain. The weld has a high nickel content, so it should have no ferrite and be very resistant to the formation of martensite under deformation at cryogenic temperatures. The low limits on phosphorous and sulfur should minimize the tendency for hot cracking, but we need to watch for poorer penetration due to a change in the weld pool convection.

Process Selection

The differences between weld materials and wrought materials are the inclusion and ferrite contents. Welds will have a higher inclusion content because of the imperfect shielding of the metal while molten. Therefore, choosing the welding process that produces the lowest inclusion content, or modifying the process to reduce inclusion content, is required to improve weld toughness. Welding processes such as laser, electron beam and GTA can produce welds with lower inclusion contents and with toughness at the upper side of the scatter band (Refs. 17, 20) — Fig. 1.

Initially, we considered a variety of welding processes — shielded metal arc (SMA), GTA, GMA and flux cored arc (FCA) — because they all are appropriate for base metals with a thickness near 5 mm and do not require special chambers, special alignment or expensive power sources. From this list, we eliminated SMAW because it is not amenable to automation and ranked GTAW lower than the others because it has a lower deposition rate.

The number of inclusions is a function of both the oxygen content of the welding electrode as manufactured and of the oxygen that is added during welding. Both sources of oxygen content must be controlled to produce the best toughness in the weld. We were unable to locate an FCAW electrode with a slag system that produced low inclusion contents, so this reduced our weld process choices to GMA and GTA welding.

GMAW is preferred for higher production rates, but the process might not produce adequate mechanical properties unless tightly controlled. Some of the newer, commercially available pulse power supplies provide excellent manual welding results. Other, older power sources are less flexible because their preset schedules are not applicable to the wide range of filler materials and gas compositions. BNL selected a modern weld power source employing a proprietary, constant-current power supply with a patented, pulse-width-modulated, constant-voltage control. This feature provides the ability to optimize the pulsed-spray arc and process characteristics using a set of direct unit controls. The full range of parameter controls on this system is far more complicated than the typical single-knob systems, but the process is more suitable for automated operation. More precise control over the arc and other process characteristics yield a cleaner weld with more consistent composition and microstructure.

Test Procedures

Materials and Welding Details

Workers at NIST ordered a small laboratory heat (100 kg) to evaluate the properties. After successful results with this laboratory heat, BNL ordered a production quantity and evaluated it in a similar manner. The chemical compositions used in this study, as received from the manufacturer, are shown in Table 3. The actual weld compositions varied from these heat compositions due to dilution by the 304 plate material and by some losses during welding. The dilutions were estimated to be as high as 30% in the root pass and near the fusion boundaries and as low as 5% near the center of the last pass. Small losses due to volatilization and oxidation are expected for the manganese, silicon and chromium. Still smaller changes are expected for the nickel and molybdenum. Little change is expected in the nitrogen level.

The testing was conducted in three increments. Workers at NIST determined the mechanical properties of the welds made with the first heat and the effect of oxygen on the weld metal. Workers at BNL first evaluated the NIST heat to establish a baseline for material properties, then evaluated their own heat to verify mechanical properties. All welds were deposited using the GMA process in single 60-deg V-grooves, as specified in AWS A5.4-81, on Type 304 base plates; 25 mm thick for all NIST testing, 12.7 mm

308 and 316 weld compositions usually specified for this application.

Conclusions

A high-nickel/high-nitrogen superaustenitic weld alloy provides exceptional mechanical properties for 4 K cryogenic welded structures using production-welding processes.

Oxygen content has a direct effect on inclusion density, fracture toughness and CVN energy. Weld metal oxygen analysis can serve as a convenient quality assurance tool to help predict toughness.

Size distribution and density of inclusions have a direct and significant effect upon weld metal fracture toughness. However, a procedure for determining inclusion density must be standardized before this can be used to predict fracture toughness.

Hot cracking has not been experienced with this superaustenitic weld alloy. This may be attributed to the low contents of phosphorus and sulfur in the test alloys, but hot cracking susceptibility for stainless steels with $(Cr/Ni)_{eq}$ ratio less than 1 needs additional investigation.

Adequate weldability was achieved with the addition of 1% CO_2 to the shielding gas and this addition did not adversely affect cryogenic material properties.

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