WELDING ASTUTE-CLASS SUBMARINES

Welding Astute-Class Submarines

Q1N steel was found to be the best material, while gas shielded flux cored arc and submerged arc welding were the predominant processes for constructing these first-of-class vessels

BY R.G. MURRAY

BAE Systems, Barrow-in-Furness, Cumbria, England, is currently fabricating the pressure hull for the first-of-class Astute submarine. This article describes the introduction of Q1N as the quenched-and-tempered steel selected for the submarine's pressure hull and current welding processes employed by the company in its fabrication.

Material Background

The first U.K. high-strength, quenched-and-tempered steel selected for use on submarines in the 1950s was QT35. The material was susceptible to lamellar tearing due to its inherent high sulphur (max 0.04 wt-%) and phosphorus contents (max 0.035 wt-%). High sulphur content produced a large amount of nonmetallic inclusions that were responsible for poor through-thickness properties. This created susceptibility to lamellar tearing. The high levels of sulphur and phosphorus were a consequence of the initial steel production route, i.e., the early QT35 steels were made in open hearth furnaces using silicon/manganese for deoxidation purposes. The high incidence in lamellar tearing occurring in the weld configurations assisted in the designation of pressure-hull-frame web to pressure-hull welds (and pressure-hull-frame web to table welds) as complete joint penetration with 100% ultrasonic examination were required to ensure sound welds. Major weld repairs were carried out throughout this period on the early QT35 steels because lamellar tearing on T-welds was common.

However, steelmaking practice for QT35 changed in the mid 1960s to use of the basic electric furnace, vacuum degassing, and aluminum deoxidization. These changes produced much cleaner steels and eliminated lamellar tearing problems. Also, the Ministry of Defense (Navy) (MOD(N)) decided in 1966 to replace QT35 with HY80; soon after, in 1969, a modified HY80 (named Q1N) was introduced by MOD(N) to replace HY80 (Ref. 1). The Q1N levels

of sulphur and phosphorus were limited to 0.015 wt-% max.

Fig.1 - The twin tandem submerged arc (SA) arrangement for joining the frame web to table joints.

Further developments and refinements in steelmaking practice of Q1N since 1980 have resulted in all production of Q1N by the basic oxygen steelmaking vacuum arc degassing (BOS-VAD) process. The net effect is very clean steels with extremely low inclusion contents (typical sulphur equals 0.002 wt-%). Consequently, Q1N has excellent through-thickness properties and is very resistant to lamellar tearing. Q1N plating has a 0.2% proof stress value in excess of 550 N/mm2 and onerous toughness requirements (i.e., for t ≤ 60 mm, the minimum average Charpy value equals 100 J at -84°C). Detailed chemical analysis of Q1N plate can be found in NES 736 part specification (Ref. 2).

Welding Consumable Approval

Q1N welding of pressure hulls is carried out in accordance with NES 770, parts 1 (Ref. 3) and 2 (Ref. 4) requirements. Welding consumables are approved via a series of tests that vary depending on the integrity of the Q1N joint being fabricated. The pressure hull envelope consists of Category 1 and 2 components that are of high integrity and are required to demonstrate both good strength, static toughness, and dynamic toughness into the plastic regime. For Category 1 and 2 components, welding consumable approval requires welding series A, B, and C test plates that incorporate crack tip opening displacement (CTOD) testing, flawed bulge explosion (FBE) testing (unique tests carried out exclusively at DRA, Dunfermline), and standard mechanical testing. This includes weld-metal Charpy impact testing matching 50 J at 50°C and Charpy crystallinity values less than 55%; the average 0.2% proof stress measurements must exceed 550 N/mm2. There is, historically, a good link between Charpy percent crystallinity values and FBE performance. Consequently, once a welding consumable is MOD(N) approved, series A panels (standard mechanical tests) can be used at MOD(N) discretion to qualify minor deviations, e.g., a slight change in heat input, wide root openings, and unconventional weld preps. Historically, due to strain-aging effects in weld-root regions, true single-sided Category 1 and 2 welding are not permitted because successful FBE testing of single-sided welds has never been achieved.

Current practice for Astute class is to combine series A panels with EN 288, part 3 weld procedure test for Group 3 material. These test plates are third-party witnessed.

Production Welding

Welding of Q1N requires close-heat input control and the application of preheat. The most common welding process, gas shielded flux cored arc welding (FCAW-G), operates within a heat input band that equals 1.02.0 kJ/mm. Preheat is 70°C minimum, except temporary attachments, which are 120°C minimum. Interpass temperature is set at 150°C max. Preheat is predominantly applied by electric strip elements or radiant panels. A gas torch is used as a supplementary heating method, but not on its own for major pressure-hull welds. The application of a temper bead is no longer necessary. However, the last bead must be placed away from the base plate (or passing member for T butt joints) for plate thickness exceeding 20 mm.

The contractual technical details are provided within approved welding procedure specifications (WPSs). Controlled copies are issued to production team leaders, managers, and QC personnel. A summary of the welding parameters, including bead width restrictions/run-out length (ROL) per process, is issued to each welder via a weld procedure card. No welding consumable can be issued to a welder without possession of this card.

The FCAW-G is used in both the semiautomatic and mechanized mode (ESAB RAILTRAC). BAE Systems is developing new FCAW-G consumables to join Dualshield 101TM, which was the principal consumable used on previous submarines. Currently, the most common welding consumables used on site are SAFDUAL 128V and ESAB 15.19. Both consumables are complemented with Argon 20 CO2 shielding gas. Regarding the pressure hull envelope, semiautomatic FCAW-G is used for welding the pressure-hull frame butt joints and table butt joints, pressure-hull subunit vertical joints, welding of penetrations into the pressure hull, joining of units as static circumferential butt joints, and root runs in submerged arc welds.

For Astute, the use of the mechanized FCAW-G process is more pronounced than for previous submarines. Nowadays, the majority of vertical welding of pressure-hull subunits and welding of static circumferential butt joints is by mechanized FCAW-G. An increase in productivity has been realized by the welding of longer block lengths and increased arc time compared to the semiautomatic mode.

Fig.2 - Rotated circumferential submerged arc welding shop.

The submerged arc (SA) process is employed wherever practical on the pressure-hull envelope. Both single-wire and twin-wire modes are utilized. Twin tandem SA is used for joining the pressure-hull-frame web to table T-joints - Fig. 1. Welding is carried out in the H/V (PB position) and both sides of the joint are welded simultaneously. The welding heads remain stationary while the T segments are rotated. The submerged arc consumables are 3.2-mm-diameter Oerlikon OES3NiMo1 wire and Oerlikon OP121TT flux. Typical heat inputs are 1.22.2 kJ/mm per tandem head. Travel speeds are within 8501000 mm/min. The equipment for this dedicated twin-tandem submerged arc unit was recently refurbished specifically for the Astute program. Another investment program for Astute involved the refurbishing and modernizing of the mammoth column and boom that is worked in conjunction with high-duty welding rotators for welding rotated subunit circumferential butt joints - Fig. 2. This is a tandem wire submerged arc (AC/DC) system using 4-mm-diameter wires and producing heat input levels of 1.18-3.2 kJ/mm for both the lead and trail wires. The lead wire is direct current electrode positive powered and has considerably higher current than the AC trail wire. Single-wire submerged arc welding is also used on the pressure hull, primarily for welding large penetrations into the pressure hull and for welding pressure-hull frames to the pressure hull using squirtmobile sets.

Welding procedures referring to shielded metal arc welding (SMAW) are still produced, but SMAW is not common at the Barrow site and is restricted to difficult-access welds only. The Fortrex NQ1 electrode is the preferred consumable.

BAE Systems has produced a unique set of welder qualifications relating to Q1N material. Welder qualification procedures have been produced that provide dual qualification to NES 770 and EN 287, part 1 (Group 3) specifications. Each welder is required to complete a butt-joint weld in each position separately for Category 1 and 2 welding. Completed welders' tests are examined by 100% visual, MP, UT, or RT to EN and NES 773 acceptance standards.

Design Issues

Fundamentally, the design of welds for Astute class remains similar to previous submarines. All major butt-joint welds are complete joint penetration, requiring 100% volumetric NDE (ultrasonics and radiography). Throughout Astute, there is an intention to progressively introduce digitized ultrasonics as a replacement for conventional ultrasonics and radiography (i.e., 100% digitized UT would replace 100% conventional UT and 100% radiography). Adoption of this technique will depend on its ability to detect defects that need to be recorded by type and/or size in order to validate weld integrity. Digitized UT benefits by providing a "fingerprint" of the examined welds that can be stored for off-the-job assessment and reviewed for comparison purposes during any subsequent through-life inspection.

One design change implemented on Astute class is the designation of pressure-hull-frame web to table welds (excluding containment frames) as partial penetration rather than full penetration, as was previously done. This rerating was instigated by reference to a comprehensive program of fatigue trials on partial penetration T-welds carried out by DERA at Dunfermline (Ref. 1). Some limited fatigue trial tests were carried out by BAE Systems at Barrow to complement this data. Cost savings have been realized by this rerating. Comprehensive ultrasonic examination of these welds has been replaced by random UT checks to see if the unfused portion of the root face does not exceed a maximum value.

QA Aspects

BAE Systems employs a custom-computerized system called the Weld Management System for individually recording all major structural welds, including all welds associated with the pressure hull. All weld details are recorded electronically from the designer's input of material, thickness, type of weld prep, and NDE requirements. Details are then sent to the welding engineers to annotate the applicable process, welding procedure specification, weld procedure card, welders' qualification required, and job type. This information is then sent electronically to the production team leader who, in conjunction with weld map drawings produced by the technical drawing office (DO), is presented with a detailed technical information summary pertaining to every weld. From there, production and NDE personnel post records of the welders' names/NDE results, which are sent to QC records, and a complete electronic package is compiled. The system has a built-in control that returns welds that have been repaired three times in the same region back to welding engineers.

Another unique system applicable to BAE Systems is the use of a welding engineer's technical instruction (WETI) to record any welding deviations applicable to Q1N welds. Typical use of a WETI is to record excessive root openings, all weld buildups or buttering of Q1N, rectification of unacceptable misalignment, weld repairs to castings, and weld repairs to correct misplaced holes. The WETI is mostly used as a stand-alone document, but can occasionally be used to complement technical queries or concessions for major deviations.

Regular QA audits are carried out by BAE Systems internal staff plus the BAE Systems prime contract office (PCO) who are contracted to carry out audits on behalf of the customer (MOD(N)). These audits ensure compliance with agreed working practices and systems is adhered to.

Further Work

Welding development work is ongoing to explore the relationship between sustained preheat and interpass temperatures and mechanical properties in the welded joint. Any changes introduced via successful trials will be implemented only with prior PCO and MOD(N) approval. Also, BAE Systems is currently customizing NES 770, parts 1 and 2 into one document that will reflect agreed reservations and current working practices at the Barrow site. This document will require PCO and MOD(N) agreement prior to issue.

References

1. A Review of DRA Work on Marine High-Strength Steels. 1997. Q1N History Extract, Health and Safety Executive Offshore Technology Report - OTO 97 066.
2. Requirements for Q1 (Navy) Quality Steel Plates. NES 736, part 1.
3. Requirements for the Welding and Fabrication of High-Strength Steels - General. NES 770, part 1.
4. Approval of Welding Procedures for Submarine Construction. NES 770, part 2.

R. G. MURRAY (gordon.murray@baesystems.com) is Principal Welding Engineer for BAE Systems, Barrow-in-Furness, Cumbria, England.