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REPORT 80-14E

THE CORROSION OF WELDS IN ICE-BREAKING SHIPS – A REVIEW

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PHYSICAL METALLURGY RESEARCH LABORATORIES

Energy, Mines and Resources Canada
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APRIL 1980

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Catalogue No. M38-13/80-14E   Canada: $1.25
ISBN 0-660-10700-7   Other Countries: $1.50

Price subject to change without notice.

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THE CORROSION OF WELDS IN ICE-BREAKING SHIPS - A REVIEW

by

J.B. Gilmour*

ABSTRACT

Literature related to the corrosion at the welds of ice-breaking ships has been reviewed. Two distinct types of corrosion - weld metal attack and weld heat-affected zone attack - are described. Both types of attack are the result of small differences in corrosion potential between the corroding metal and the hull plate. The use of welding electrodes containing copper and nickel will eliminate weld metal corrosion and special hull steels are available that are claimed to reduce heat affected zone attack. A research project to assist the Canadian marine industry to minimize this problem is proposed.

*Research scientist, Corrosion Science Section, Metals Development Laboratory, Physical Metallurgy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa

LA CORROSION DES PIECES SOUDEES DANS LES NAVIRES BRISE-GLACE - UNE ETUDE

par

J.B. Gilmour*

RESUME

La documentation ayant trait aux soudures sur des navires brise-glace a été étudiée. Deux genres distincts de corrosion sont décrits, la corrosion du métal de soudure et la corrosion de la zone affectée thermiquement de la soudure. Ces deux types de corrosion sont occasionnés par les différences minimes du potentiel de corrosion existant entre le métal corrodé et la plaque de la coque. L'utilisation d'électrodes de soudage contenant du cuivre et du nickel éliminera la corrosion du métal de soudure; des aciers spécialement conçus pour les coques de navires sont disponibles et prétendent réduire la corrosion des zones affectées thermiquement. Un projet de recherche est proposé pour aider l'industrie canadienne de la navigation à surmonter a problème.

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CONTENTS

TABLES

FIGURES

INTRODUCTION

Corrosion of welds in ice-breaking ships* has been a problem since the advent of welded hull construction. Because of the nature of the task required of these ships, it has generally been impossible to keep a conventional paint coating on the hull.

Cathodic protection using zinc anodes is sometimes used to protect the stern area from galvanic effects between the propellers and hull but the sacrificial anodes are often damaged or lost through ice abrasion. Impressed current cathodic systems are not used for the same reason.

Weld related corrosion, as discussed in the literature, takes two distinct forms. The first, shown schematically in Fig. 1(a), is the direct attack of the weld metal, the result of slight differences in corrosion potential between the deposited weld metal and the hull plate. This accelerated corrosion of the weld metal can be overcome by using an alloyed welding consumable that has a corrosion potential slightly noble to that of the hull plate. Welding electrodes are commercially available which are said to meet this requirement.

The second form of attack, shown schematically in Fig. 1(b), is the accelerated corrosion of the heat-affected zone (HAZ) of the weld. This corrosion is reported to result from the presence of low temperature transformation products formed during cooling after welding (1). These deleterious transformation products can be minimized by adjusting the chemistry of the steel and by controlling the welding conditions.

Two examples of weld related corrosion in Canadian ice-breaking ships have been examined at the Physical Metallurgy Research Laboratories, one from the C.C.G.S. Sir Humphrey Gilbert in 1967 (Fig. 2a) (2) and one from the C.C.G.S. John A. MacDonald in 1979 (Fig. 2b). Both of these samples showed extensive corrosion of the weld metal, but little or no accelerated attack of the HAZ.

This report briefly reviews the literature related to weld corrosion in ice-breaking ships and proposes an in-house research project to assist the Canadian marine industry to understand and to minimize this problem.

CORROSION OF WELD METAL

The corrosion of weld metal in ice-breaking ships appears to have been first investigated by Uusitalo in 1958 (3). Using corrosion potential measurements he showed that weld metal was often anodic relative to the hull plate under the conditions in which ice-breakers operate (cold water, high oxygen availability and rapid removal of corrosion products). This corrosion potential difference, combined with the unfavourable area ratio (small weld-metal anode and large hull cathode), results in accelerated attack of the weld metal.

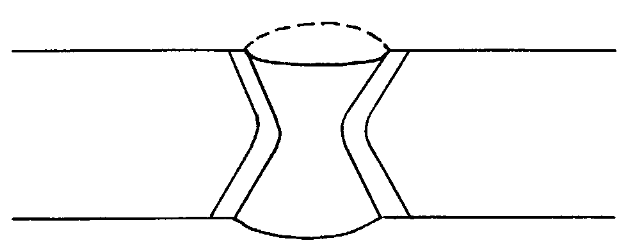

Fig. 1(a) - Schematic representation of the corrosion of weld metal

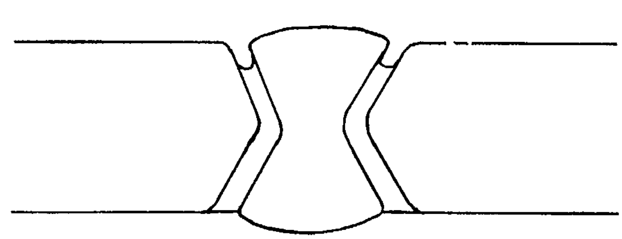

Fig. 1(b) - Schematic representation of the corrosion of the weld HAZ

*The term "ice-breaking ships" as used in this report includes all ships operating in ice conditions.

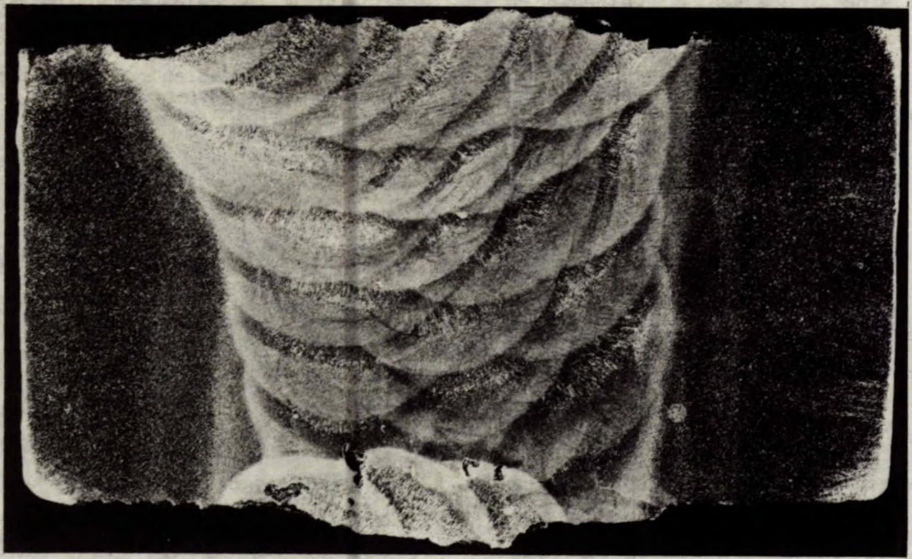

Fig. 2(a) - Sections from a hull weld of the C.C.G.S. Sir Humphrey Gilbert (2). The plate is 33 mm thick.

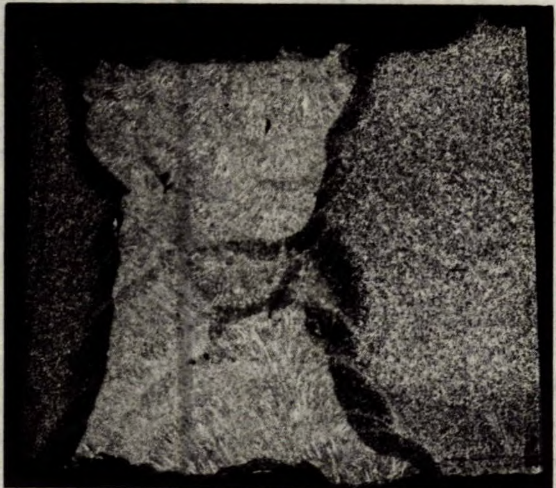

Fig. 2(b) - Section from a hull weld of the C.C.G.S. John A. McDonald. Sea water side is at the top. Interior weld has also been corroded, probably by sea water ballast. (Note that the original weld has been cut and the plate on the right hand side replaced). The plate is 40 mm thick.

In 1961, Valanti reported the results of an investigation of the corrosion of welds and ship plate (4). In his experimental program he used ship plate of ten different analyses, varying primarily in silicon, manganese and copper. Thirteen different welding consumables were used, again varying in silicon, manganese and copper. Valanti carried out a variety of experiments in both natural and synthetic sea water and showed that laboratory measurements of corrosion potential correlated with the degree of corrosion attack. In the course of this work Valanti developed a method of testing welded plate specimens by attaching the specimens to a wheel which was rotated continuously in synthetic sea water. This test, now often referred to as the Valanti or ESAB test (Valanti worked for ESAB, a Scandanavian welding electrode producer), is claimed to reproduce the type of corrosion attack found on the hulls of ice-breaking ships.

Also in 1961, Uusitalo (5) showed that the effect of sea water velocity was to shift the potential of weld metal and ship plate in the noble direction and to increase the difference in potential between the weld metal and the hull plate. In this work Uusitalo investigated the effect of silicon content on the corrosion potential of hull plate and weld metal in artificial sea water at 0°C.

Following the work of Uusitalo and Valanti, ESAB developed an electrode specifically designed to produce corrosion resistant welds in hulls of ice-breaking ships. This electrode, OK 48.23, has the chemical composition C $\backsim$ 0.08%, Si $\backsim$ 0.25%, Mn $\backsim$ 0.8%, Ni $\backsim$ 0.4% and Cu $\backsim$ 0.6%. Although references to this electrode appeared in 1970 (1,6) it was not until 1974 that experimental results of corrosion tests were published by Lundin (7). Wranglen in 1969 and 1971 reported on the weld HAZ corrosion of an ice-breaker welded with an electrode containing 0.6% Cu, presumably OK 48.23. (8,9)

CORROSION OF THE WELD HEAT-AFFECTED ZONE

The accelerated corrosion of the weld HAZ was first noted as a serious problem in ice-breaking ships in 1966 when severe damage was discovered on the hull of a new European ship after only "a few months at sea" (9). Some of the early work on this failure appeared to show that continuously cast steel was more susceptible to this type of attack than ingot cast steel and that this difference in corrosion susceptibility was the result of variations in inclusions in the steels cast by the two methods (9). However other workers have since concluded that the casting method used in steel production has no effect on HAZ corrosion (1,10). The experimental evidence and the arguments against the casting technique as a major contributing factor in HAZ corrosion were summarized by Adrian et al in 1977 (11).

Relander, Saarinen and co-workers at Rautaruukki Oy Research Laboratories in Finland have published a number of papers on the corrosion of the HAZ of welds in ship plate (1,6,10,12). They have presented convincing evidence that this corrosion is the result of differences in corrosion potential between the hull plate and the HAZ. The HAZ contains retained austenite formed during welding and low temperature transformation products formed during cooling after welding. Low temperature transformation products and retained austenite are anodic relative to the hull plate and, again because of the unfavourable area ratio (small anode, large cathode), corrode at an accelerated rate. These workers have further shown that the factors which increase the tendency to form these undesirable phases are increased manganese content of the steel and low heat input equivalent during welding. They have used a number of experimental techniques, including the Valanti or ESAB test, and the corrosion of simulated weld heat affected zones formed in Noren Weld Hardening (NWH) test bars (12).

In the NWH test a HAZ was produced by high frequency induction melting of the protruding end of a 10 x 10 x 50 mm test specimen immersed in water (Fig. 3). Various heat input equivalents were produced by varying the distance between the induction coil and the water level. Specimens were corroded potentiostatically at -500 to -550 mV_{SCE} at 20°C in de-aerated 3% NaCl solution. Figure 4 shows some of the results obtained by Saarinen and Onnela (12) on experimental steels.

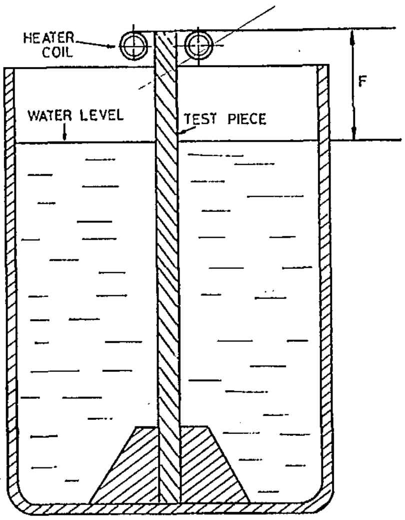

Fig. 3 - The preparation of NWH-bars in a high frequency induction heating unit (12)

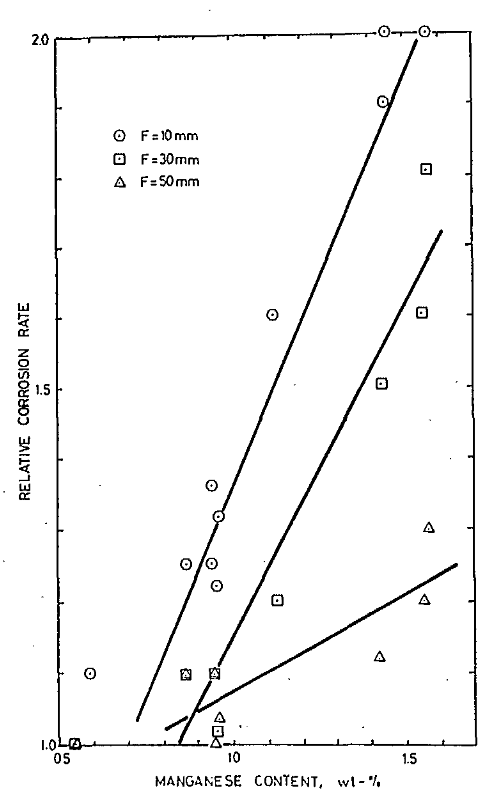

Fig. 4 - Results of Saarinen and Onnela showing the relative corrosion rate of the HAZ, determined using NWH test bars, as a function of manganese content at different values of F (Fig. 3). F can be related to the heat input equivalent of a weld. Composition of steel: ~0.16C, 0.30 Si, >0.02 Al (12).

Welded specimens of the same steels were tested for 3 months using the Valanti test. Figure 5 shows the results of these tests. It is obvious there is good agreement between the two sets of results.

Rautaruukki Oy, a Finnish steel producer, has marketed ship plate claimed to be resistant to HAZ corrosion. The development of these steels - RAEX 26 E POLAR and RAEX 32 E POLAR - was outlined by Rasanen and Relander in 1978 (14). They showed that by varying the silicon content of the plate the corrosion of the weld metal (OK 48.23) could be controlled (Fig. 6). The silicon content of the commercial plate has been limited to the range of 0.2 - 0.3%. To control the corrosion of the HAZ, manganese content is limited to 1.1% and the minimum energy input during welding is specified as shown in Fig. 7.

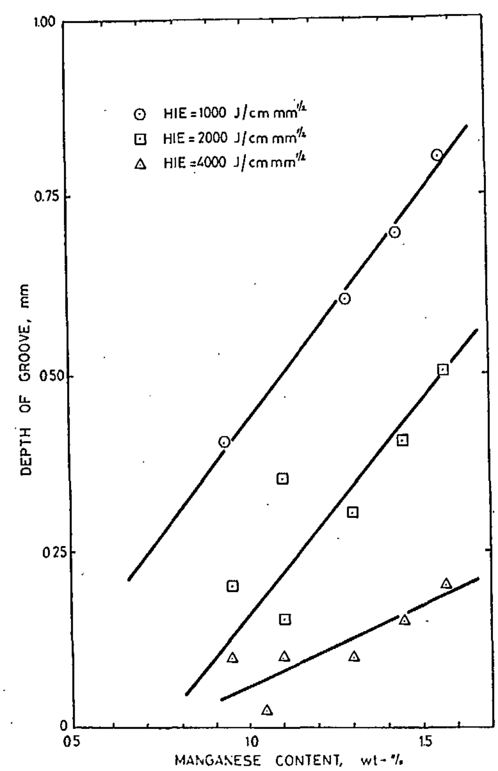

Fig. 5 - Results of Saarinen and Onnela showing the effect of Mn content on the corrosion rate of the weld HAZ in the Valanti or ESAB test after a period of three months. Composition of steel as specified in Fig. 4 (12).

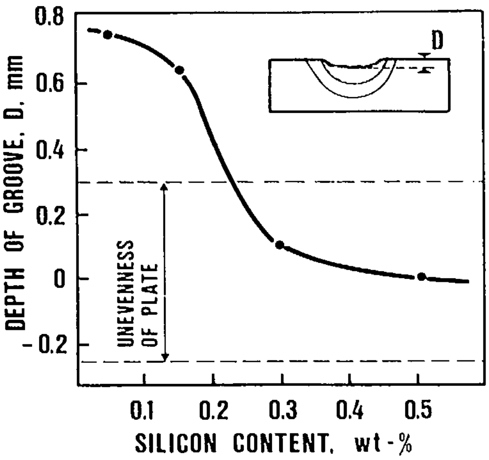

Fig. 6 - Depth of corrosion in weld metal OK 48.23 as a function of the silicon content of the ship plate after four months in the Valanti or ESAB test. Steel analysis C ∽ 0.15, Mn ∽ 1.0, Cu ∽ 0.18 [from Rasanen and Relander (14)].

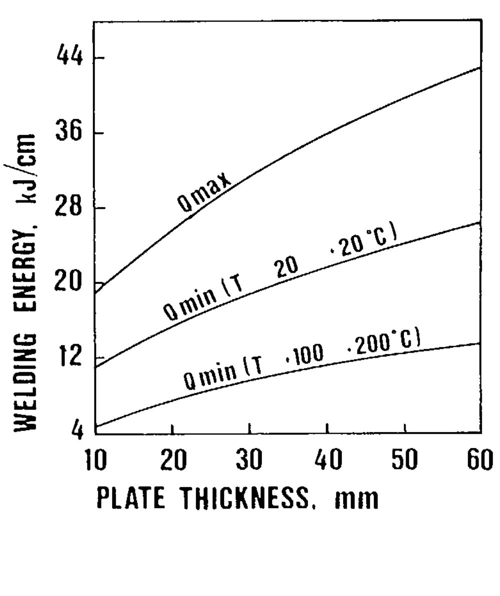

Fig. 7 - Permissible welding energy for Rautaruukki POLAR ship plate. Q max determined on the basis of HAZ toughness and Q min on the basis of corrosion resistance. T is the temperature of the plate before welding [from Rasanen and Relander (14)].

In addition to the HAZ corrosion discussed above, Rasanen and Relander (14) also describe a further type of attack at the weld fusion line shown schematically in Fig. 8 (12). They attribute this attack to the presence in the plate of low melting-point sulphides which may form a film on the grain boundaries of the austenite at the fusion line during welding. They state that the addition of alloying elements such as arsenic, antimony or tin, which decrease the austenite surface tension, or elements such as cerium, titanium or zirconium, which form high melting point oxysulphides, eliminate fusion line attack. In the commercially produced steel 0.02 - 0.06% cerium is added and the sulphur content limited to 0.015%.

Other foreign steelmakers are marketing steels for which they claim excellent corrosion resistance in marine environments but these steels have not been developed for ice-breaking ships and no data are available on the corrosion of the HAZ under ice-breaking conditions (15).

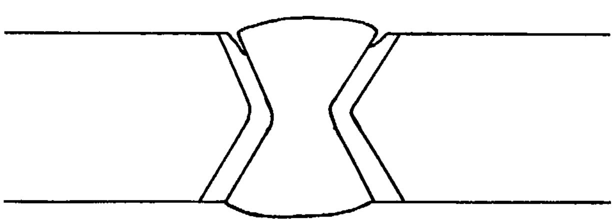

Fig. 8 - Schematic representation of fusion line corrosion [after Rasanen and Relander (14)].

CANADIAN PRACTICE

Ship plate is normally produced to the specification of one of a number of standards organizations (e.g. Lloyds, ASTM, ABS, Norski Veritas, etc.). Tables 1 and 2 reproduce part of the standards specified by the American Bureau of Shipping (16). In general, the standards of the various organizations are similar: Grade A is the most common and least specified plate and E

Table 1 - ABS requirements (1980) for ordinary strength hull structural steel*

Grades	A	B	D	E	DS	CS
DEOXIDATION	Any method except rimmed steel for plates over 12.5 mm (0.5 in.)	Any method except rimmed steel	Fully killed fine-grain practice(2) (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)	Fully killed fine-grain practice (See 43.3.2d)
Chemical composition (ladle analysis)	For all grades exclusive of Grade A shapes and bars the carbon content +1/6 of the manganese content is not to exceed 0.40%. The upper limit of manganese may be exceeded up to a maximum of 1.65% provided this condition is satisfied.					
Carbon, %	0.23 max.(1)	0.21 max.	0.21 max.	0.18 max.	0.16 max.	0.16 max.
Manganese, %	2.5x carbon min. for plates over 12.5 min. (0.5 in.)	0.80-1.10 0.60 min. for fully killed or cold flanging	0.70-1.35 0.60 min. for thickness 25 min (1.0 in.) and under	0.70-1.35	1.00-1.35	1.00-1.35
Phorphorus, %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Sulfur, %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Silicon, %		0.35 max.	0.10-0.35	0.10-0.35	0.10-0.35	0.10-0.35
Tensile test						
Tensile Strength	For all Grades: 41-50 kg/mm^2 (58,000-71,000 psi); for Grade A shapes 41-56 kg/mm^2 (58,000-80,000 psi). For cold flanging quality: 39-46 kg/mm^2 (55,000-65,000 psi)					
Yield point, min.	For all Grades: 24 kg/mm^2 (34000 psi); for Grade A over 25.0 mm (1.0 in.) in thickness 23 kg/mm^2 (32,000 psi). For cold flanging quality: 21 kg/mm^2 (30,000 psi)					
Elongation, min.	For all Grades: 21% in 200 mm (8 in.) (See 43.3.4d and 43.3.4e) or 24% in 50 mm (2 in.) (for specimen see Fig. 43.2) or 22% in 5.65 √A (A equals cross-sectional area of test specimen). For cold flanging quality: 23% min. in 200 mm (8 in.)					
Impact test Charpy V-notch Temperature		0°C (32°F) Over 25 mm (1.0 in.)	-10°C(14°F)	-40°C(-40°F)		
Energy, avg. min. longitudinal specimens or traverse specimens		2.8 kg-m(20 ft-lb) 2.0 kg-m(14 ft-lb)	2.8 kg-m(20 ft-lb) 2.0 kg-m(14 ft-lb)	2.8 kg-m(20 ft-lb) 2.0 kg-m(14 ft-lb)		
No. of specimens		3 from each 50 t	3 from each 50 t(3)	3 from each plate		
Heat treatment			Normalized over 35 mm (1.375 in.) thick(4)	Normalized		Normalized
Marking	AB/A	AB/B	AB/D(5)	AB/E	AB/DS	AB/CS

NOTES.

1. A maximum carbon content of 0.26% is acceptable for Grade A plates equal to or less than 12.5 mm (0.5 in.) and all thicknesses of Grade A shapes.
2. Grade D may be furnished semi-killed in thickness up to 35 mm (1.375 in.,) provided steel above 25.0 mm (1.00 in.) in thickness is normalized. In this case the requirements relative to minimum Si & Al contents and fine grain practice do not apply.
3. Impact tests are not required for normalized Grade D steel when furnished fully killed fine grain practice.
4. Control rolling of Grade D steel may be specially considered as a substitute for normalizing in which case impact tests are required for each 25 t of material in the heat.
5. Grade D hull steel which is normalized or controlled rolled in accordance with Note 4 is to be marked AB/DN.

*From Table 43.1 of "Rules for Building and Classing Steel Vessels", Copywright of the American Bureau of Shipping. Used with permission. These Rules are updated annually and the latest edition should be consulted to learn current requirements.

Table 2 - ABS requirements (1980) for higher-strength hull structural steel*

Process of Manufacture: Open Hearth, Basic Oxygen or Electric Furnace						
Grades(1)	AH32	DH32	EH32	AH36	DH36	EH36
Deoxidation	Semi-killed or killed(3)	Killed, fine-grain practice(4)	Killed, fine-grain practice(4)	Semi-killed or killed(3)	Killed, fine-grain practice(4)	Killed, fine-grain practice(4)
Chemical composition for all Grades (Ladle analysis)						
Carbon, %	0.18 max					
Manganese, %(2)	0.90-1.60					
Phorphorus, %	0.04 max					
Sulfur, %	0.04 max					
Silicon, %(3)	0.10-0.50					
Nickel, %	0.40 max	These elements need not be reported on the mill sheet unless intentionally added.				
Chromium, %	0.25 max					
Molybdenum, %	0.08 max					
Copper, %	0.35 max					
Columbium, % (Niobium)	0.05 max					
Vanadium, %	0.10 max					
Tensile test						
Tensile strength	48-60 kg/mm^2; 68,000-85,000 psi			50-63 kg/mm^2; 71,000-90,000 psi		
Yield point or yield strength, min	32 kg/mm^2; 45,500 psi			36 kg/mm^2; 51,000 psi		
Elongation, min	For all Grades; 19% in 200 mm (8 in.) or 22% in 50 mm (2 in.) (for specimen in Fig. 43.2) or 20% in 5.65 $\sqrt{A}$ (A equals area of test specimen)					
Heat treatment; See Table 43.4						
Impact test						
Charpy V-Notch						
Temperature	None required	-20°C(-4°F)	-40°C(-40°F)	None Required	-20°C(-4°F)	-40°C(-40°F)
Energy, avg min						
Longitudinal specimens or		3.5 kg-m(25 ft-lb)(5)	3.5 kg-m(25 ft-lb)		3.5 kg-m(25 ft-lb)(5)	3.5 kg-m(25 ft-lb)
Traverse specimens		2.4 kg-m(17 ft-lb)(5)	2.4 kg-m(17 ft-lb)		2.4 kg-m(17 ft-lb)(5)	2.4 kg-m(17 ft-lb)
No. of specimens		3 from each 50 t	3 from each plate		3 from each 50 t	3 from each plate
Marking	AB/AH32	AB/DH32(6)	AB/EH32	AB/AH36	AB/DH36(6)	AB/EH36

NOTES.
1. The numbers following the Grade designation indicate the yield point or yield strength to which the steel is ordered and produced in kg/mm^2 or psi.
2. Grade AH 12.5 mm (0.50 in.) and under in thickness may have a minimum manganese content of 0.70%.
3. Grade AH to 12.5 mm (0.50 in.) inclusive may be semi-killed in which case the 0.10% minimum silicon does not apply. Unless otherwise specially approved, Grade AH over 12.5 mm (0.50 in.) is to be killed with 0.10 to 0.50% silicon.
4. Grades DH and EH are to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirement (see 43.5.2d).
5. Impact tests are not required for normalized Grade DH.
6. The marking AB/DHN is to be used to denote Grade DH plates which have either been normalized or control rolled in accordance with an approved procedure.

*From Table 43.2 of "Rules for Building and Classing Steel Vessels", Copywright of the Amercian Bureau of Shipping. Used with permission. These Rules are updated annually and the latest edition should be consulted to learn current requirements.

is a high quality fracture resistant plate. (The Rautaruukki steels discussed above are said to meet the requirements for grade E regarding weldability and toughness (14)).

Two examples of hull plate from Transport Canada ice-breakers examined in PMRL (Fig. 2a, 2b) were specified to meet Grade C requirements, although new construction would probably require grade E or EH. As mentioned previously, both of these ships suffered severe corrosion of the weld metal but no accelerated attack of the HAZ. However, Grade C ship plate has an upper limit of 0.9% manganese whereas published data show that it is only at manganese contents over 1% that HAZ corrosion is a serious problem (12). In addition, the corrosion of the weld metal may significantly reduce the tendency of the HAZ to corrode.

If Scandinavian data are applicable to Canadian-produced ship plate, and there is no reason to believe they are not, then ships constructed of grade E plate with its higher manganese content and welded with corrosion resistant electrodes such as OK 48.23 may be more susceptible to HAZ corrosion than older ships constructed of grade C plate.

The welding electrodes used in ship construction in Canadian shipyards are usually E6011 and E7018 low hydrogen. Both of these electrodes are produced by a number of manufacturers to AWS specifications. The specification for the wire used in these electrodes is based on the mechanical properties of the deposited metal. Indeed there are no chemical specifications for the wire for E6011 and only a limited analysis specification for E7018 wire (17). There is no North American electrode similar to the ESAB OK 48.23, designed specifically to reduce weld corrosion of ice-breaking ships.

RESEARCH PROPOSAL

Continued and expanding activity in the Canadian Arctic, especially in the exploration for and development of energy resources, will require the construction of a number of large ships for use in ice-covered water (18). Even at present, ice-breaking ships used in petroleum exploration are being kept in the Arctic year round and repair of hull weld corrosion damage is made difficult and sometimes impossible by very limited facilities and inclement weather. Thus it seems obvious that improvements in the corrosion resistance of welds of ice-breaking ships developed in Europe over the past 20 years should be introduced without delay by the Canadian marine industry. In addition, Canadian specifications for ships operating in the Arctic should take into account the problems of weld corrosion.

However, to convince the Canadian marine industry that weld related corrosion can be minimized it is necessary to acquire first-hand knowledge of the problem, and to demonstrate that the causes of the corrosion are well understood and that practical solutions to the problem exist.

It is therefore proposed that a research project be initiated in the Corrosion Science Section of CANMET on weld-related corrosion of ice-breaking ships. In its initial stages the work plan should be designed as follows:

1. Using commercially available ship plate and welding consumables, of North American origin, determine if the type of weld-related corrosion observed in Canadian ice-breaking ships can be duplicated in the laboratory.
2. Demonstrate that the corrosion observed is the expected form of attack, given the corrosion properties of the weld metal and ship plate.
3. Determine if the higher manganese grade E ship plate would be more susceptible to weld HAZ corrosion than grade C ship plate.
4. Determine if ship plate and welding consumables available from foreign sources, claimed to reduce weld and weld HAZ corrosion, do in fact perform as stated.

At the conclusion of this phase of the project, discussions should be held with representatives of interested government departments (MOT, ITC, DND and EMR), the steel industry and the shipbuilding industry to determine the best method of introducing this technology to the Canadian marine industry.

SUMMARY

Literature relating to the corrosion of the weld metal and the weld HAZ of ice-breaking ships has been briefly reviewed. Weld metal corrosion as observed on Transport Canada ice-breakers is the result of galvanic effects between the weld metal and the ship plate. This preferential corrosion of the weld metal may be eliminated by using an alloyed welding consumable that has a corrosion potential in cold sea water noble to that of the ship plate. Corrosion of the weld HAZ may well become a problem with Canadian ice-breaking ships when the preferential corrosion of the weld metal is reduced or eliminated. Grade E plate containing high manganese may be especially susceptible to this type of attack. However steels that meet Grade E specification and that minimize HAZ attack are available from foreign sources. Similar steels could be developed and produced in Canada.

It is proposed that a research project be initiated at CANMET to investigate weld related corrosion with a view to assisting the Canadian marine industry to introduce modern technology that will reduce or eliminate this problem.

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