Welding of Stainless Steel in Cryogenic Applications

By S. Banerjee and S. K. Bardhan*

A. Introduction :

Cryogenics—a science dealing with the behaviour of materials at low temperatures has become a practical tool for industry, particularly in the field of low temperature process plant, atomic energy, rocketry and missiles, air-craft and space-craft. The physical properties of materials at a very low temperature differ so widely from those normally encountered that an engineer or a scientist cannot probably rely upon ordinary experience and so, an entirely new thriving industry with a new dimension has developed. However, due to the rapid growth of this branch of engineering in the last decade, many highly complex problems have arisen in low temperature technology.

Materials at low temperature acquire or lose whatever properties they have at normal temperature. A designer poised to develop such an equipment has to look deep into the metallurgical aspects in addition to other usual design parameters. This necessitates that he is in possession of correct and detailed data on behaviour of each material, whether ferrous or non-ferrous, at various sub-zero temperatures ; for, it is to be appreciated that because of this phenomenon, the welding and selection of material, particularly stainless steels of different variety, becomes naturally complicated.

B. Properties at Low Temperature :

Before going into the details of welding and fabrication, rather with a view to make these operations a success—technically and economically—, one has to study the properties and behaviour of a range of materials at low temperatures. The selection of materials quite naturally follows this study :

a) *Impact Strength :*

Normally, any temperature below minus 150°C (minus 238°F) is generally associated with cryogenic engineering. Many of the materials acceptable for service at normal temperature suffer such a decrease in impact resistance at sub-zero temperatures (according to ASME-VIII, below minus 20°F i.e. minus 29°C) as to be unable safely to resist shock loading, suden changes of stress or high stress concentration. Therefore, requirements and results of impact tests are of highly critical importance for safe design and operation (See Table I & Fig. 1).

b) *Transition Temperature :*

Transition temperature for any steel is the temperature above which the steel behaves in a predominantly ductile manner and below which it behaves in a predominantly brittle manner. Thus steel with high transition temperature is more likely to behave in a brittle manner during fabrication and in service. Carbon influences the

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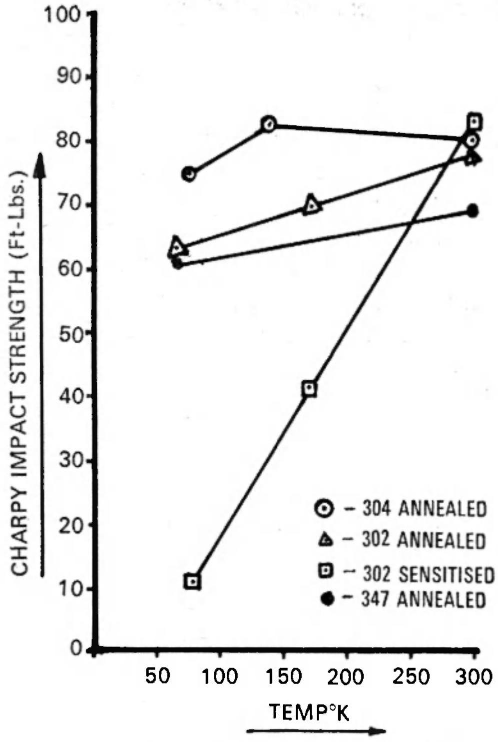


Fig. 1. Impact Strength of S.S.

TABLE—I

GENERAL REQUIREMENTS OF IMPACT STRENGTH

Size of Specimen, mm	Minimum Average Notched Bar Impact Value of each set of three specimens, ft/lb.	Minimum Notched Bar Impact Value of one specimen only of a set ft/lb.
10× 10	15	10
10×7.5	125	8.5
10×5	10	7.0
10×2.5	5	3.5

transition temperature unfavourably like most elements other than those used for deoxidation. Nickel is the notable exception and very widely used because it lowers appreciably the transition temperature. Austenitic Cr-Ni stainless steel and some high nickel steels do not show transition at temperatures as low as minus 325°F to minus 425°F. Austenitic stainless steels (say Type 304) with limited carbon content do not experience transition in impact strength from ductile to brittle fracture and therefore may be used for low temperatures without pressure rating penalities.

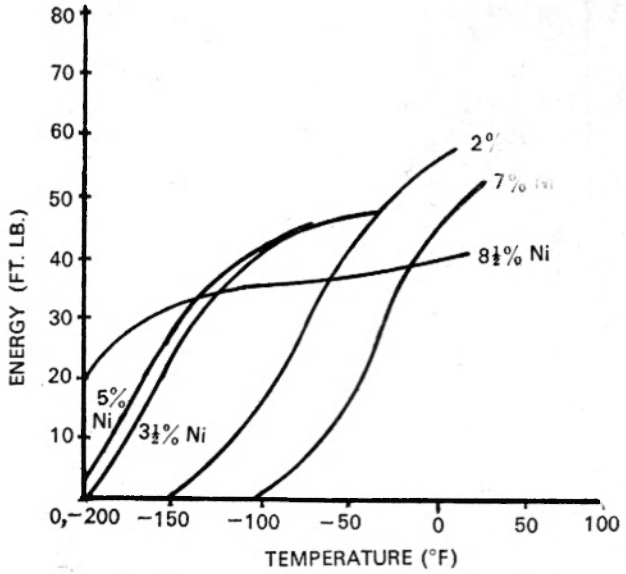


Fig. 2. Effect of Nickel at low temperature

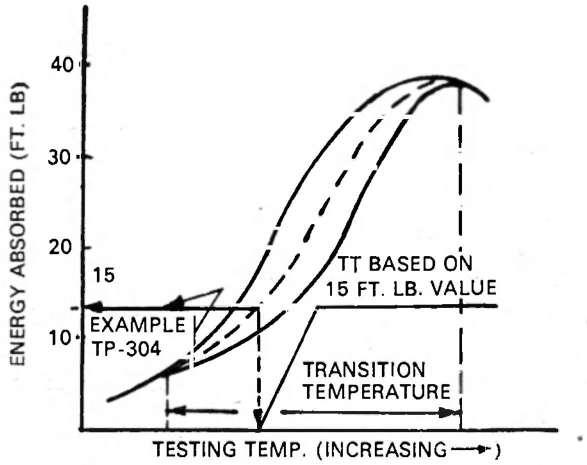


Fig. 3. Charpy keyhole energy curve

The general effect of nickel on notch toughness is shown in Fig. 2 and Charpy Keyhole Energy Curve is shown in Fig. 3.

c) *Notch Toughness :*

Notch toughness is a property of steel reflected in its resistance to brittle failure under condition of high stress concentration such as impact loading in presence of a notch. As we know, such conventional properties as tensile, yield and fatigue strengths increase whereas ductility and toughness decrease at low temperatures. The modulus of elasticity also generally increases at low temperatures.

Whereas the notch toughness of most ferritic steels decreases with decreasing temperatures, this factor is of

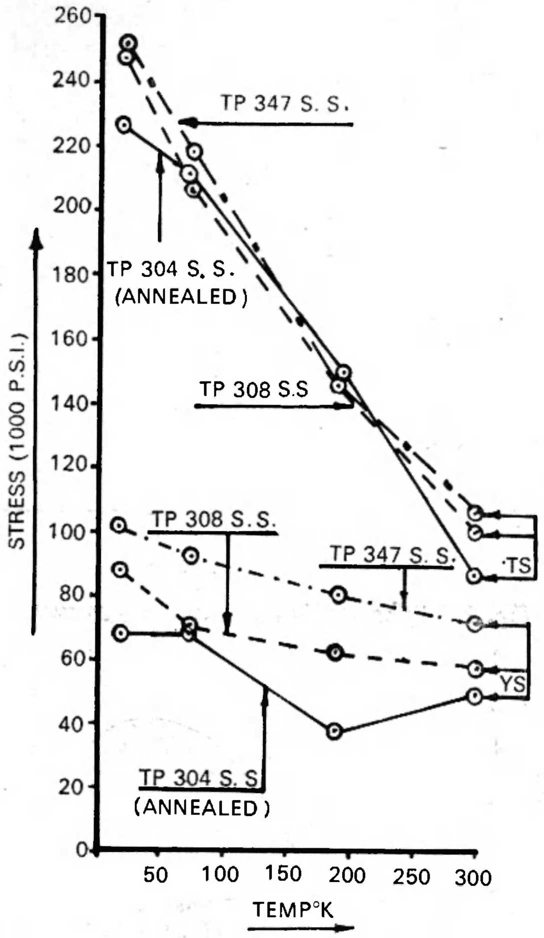


Fig. 4. Tensile & yield strength of stainless steel

critical importance in consideration of these materials for cryogenic applications.

Fig. 4 represents Strength—Temperature characteristics of Types 304, 308 & 347 stainless steels.

d) *Grain Structure :*

Austenitic stainless steel has a highly grain refined structure made by heat treatment. The composition, mechanical working, heat treatment cycle and the solidification rate in weld metal largely determine the degree to which ferrite, carbide and sigma phases are formed in austenitic stainless steels. The type of structure and the thermal and mechanical treatment it receives are determining factors in its ductility and toughness and in its resistance to crack susceptibility, intergranular corrosion etc. Existence of sigma phase in an austenitic stainless steel may reduce its ductility and toughness. Presence of ferrite, prior cold working, ferritizers (eg. Mo, Cb, Ti, etc.) are factors for formation of sigma phase. Sigma phase may be transformed into austenite and ferrite by suitable heating and quenching.

e) *Thermal Expansion & Contraction :*

This factor is important in sandwich construction of cryogenic vessels and in double-walled vessels that use different materials. In some cases, the thermal expansion might influence the decision to make the inner and outer tanks of a cryogenic vessel of the same material. For cryogenic service, the coefficients of expansion might be more aptly reported as coefficient of contraction, since it is the contraction during cooling-down operation that creates the major problems in design. Fig. 5 shows the thermal expansion properties of type 304 stainless steel, and Fig. 6, its coefficient of linear expansion.

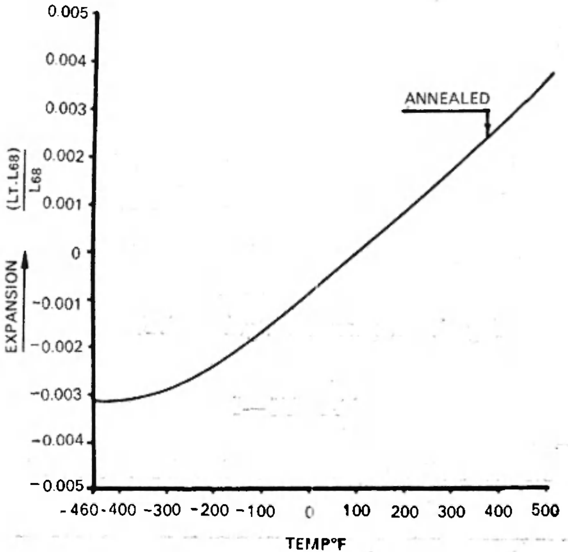


Fig. 5. Thermal expansion of AISI type 304 stainless steel

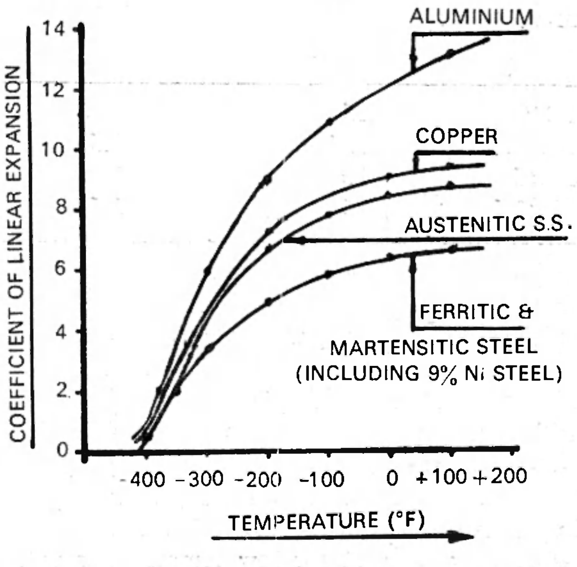


Fig. 6. Coefficient of linear expansion (IN/IN/°F × 10^{6})

f) *Thermal Conductivity :*

For support, piping, sensing lines etc., a material with low thermal conductivity would be preferred. A high conductivity reduces thermal gradients during the initial cooling-down but results in much higher heat gains through the piping when the equipment is in service.

g) *Experimental Results :*

Figs. 7 & 8 show microstructures of Types 308 & 310 SS at different low temperatures when broken in tension. The tests were carried out at NBS-AEC Cryogenic Engineering Laboratory and were reported by MC Smith of Colorado School of Mines, U.S.A. The tests also indicated the following :—

1) The yield and tensile strengths increased with decreasing temperature without serious decreases in ductility. In general, the tensile strength increased by a larger per cent, compared to the room temperature value, than does the yield strength. This is probably due to the increased strain hardening rate at low temperatures, which retards necking down of the specimens.

2) Measurements indicated that the room temperature metastable austenitic stainless steel (approx. 18% Cr & less than about 13—15% Ni) forms increasing amounts of martensite with decreasing temperature. A stable austenite (Type 310) does not transform appreciably even at low temperatures.

3) Repeated yielding has been observed at low temperatures in materials not having a definite yield point at higher temperatures. This has been observed in stainless steels including Type 310. The strain record for one specimen of Type 304 tested at 20°K showed 21 successive yield points.

4) Brittle and premature fracture at radii (fillets) and through scribe and punch marks indicate that at very low temperatures and high strain even the face centred cubic metals are quite notch sensitive.

C. Selection of Material & Design :

The speciality in design of a cryogenic element lies probably more in appropriate selection of base metal as well as weld metal electrodes than having to concentrate typically on other general considerations. Economical but efficient design—with a view to effecting a trouble-free performance of the element during operation is possible so long as a compromise is setforth between the code requirements and the grade of material demanded by the

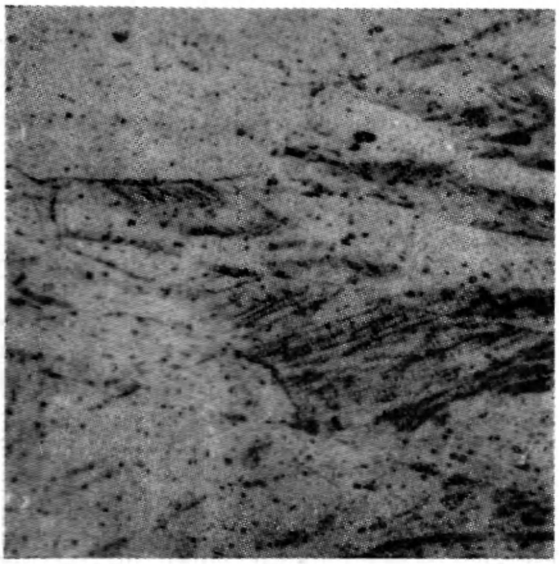


Fig. 7. Microstructure of type 310 stainless steel broken in tension at 297°K, 500X. Fine striations are evidently not martensite lamellae, since the specimen is not detectably ferromagnetic.

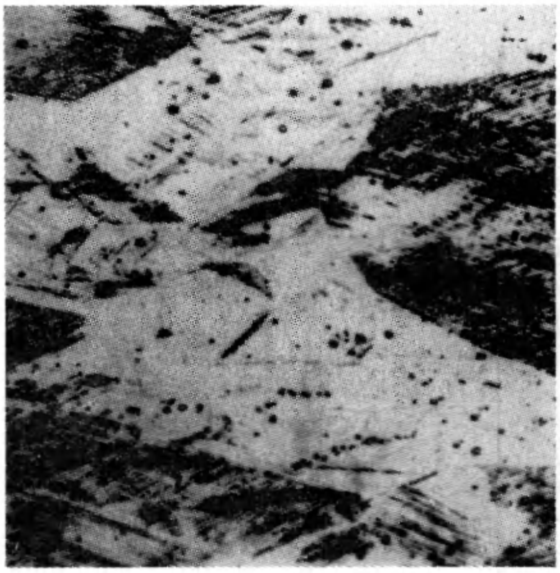


Fig. 8. Microstructure of type 310 stainless steel broken in tension at 760°K, 500X. Strain markings broader and more numerous, specimen not detectably ferromagnetic.

operating conditions. Accordingly, the code and the general requirements have been highlighted in the following paragraphs.

a) *Code Requirements :*

Quite often than not, the cryogenic equipment is required to be designed and manufactured to one of the various national or international codes. A few of the important requirements are :

(1) The allowable stress values to be used in design shall not exceed those specified for temperatures of, say as per ASME-VIII,—20°F to +100°F (—29°C to+38°C) for stainless steel.

(2) Welded vessels be post-weld heat treated in line with specified procedures. The equipment may be exempted from post-weld heat treatment if the material is exempted from impact test requirement.

(3) All materials, be it for base metal or weldment, must satisfy the minimum impact strength requirement at their corresponding sub-zero operating temperatures.

It may, however, appear somewhat disappointing to some that the design of code-regulated, low temperature equipment is based on tensile properties of material at ambient temperature and therefore does not take advantage of the higher strengths at lower temperatures. The design of space-craft and a few types of air-craft does deviate from this code with a view to enhance pay-load (See Fig. 9).

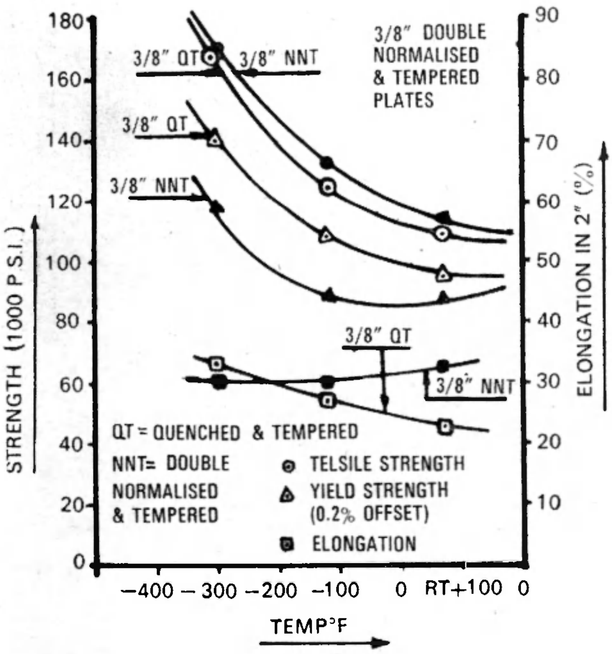


Fig. 9. Effect of low temperature on strength and Elongation of 9% Ni steel.

b) *General Requirements :*

(1) Notch toughness is a prime requisite of metals selected for cryogenic application. Design based upon conventional tensile test data gives no assurance that a pressure vessel or pipe section will not fail in brittle manner at low temperature ; nor can assurance be obtained by simply increasing the factor of safety. In presence of notches, increase in section size will most likely increase restraint and may even lead to failure at lower applied loads. The designer has to take into account the conditions which promote notch sensitivity and attempt to control these conditions so that the ductility transition temperature of tanks, piping etc. under condition of design and service will be below the temperature at which it operates. This may be accomplished by selecting the proper steel, by using generous radii, by limiting the extent of surface defects and by controlling welding and other fabrication procedures. When it is necessary to incorporate undesirable design features, or when economic considerations restrict selection of steel, the adverse factors may be at least partly off-set by using a low design stress and, where possible, avoiding shock conditions in service.

(2) As already discussed, thermal conductivity is also of considerable importance in the selection of materials for low temperature applications.

(3) Talking in terms of specification among the variety of austenitic stainless steels meant for cryogenic applications. Type 304 has been found most economical and the ideal material available for pressure vessels and piping in addition to providing excellent resistance to corrosive environments. Type 310 stainless steel will be surely a superior alternative but may off-set economy. Rest of the variety of cryogenic stainless steels, though they satisfy minimum requirement, have to undergo wider code restrictions, tests etc. and may not on the whole prove befitting.

Tables II, III & IV are expected to be quite useful in selection of material and design in particular and in cryogenic engineering in general.

Table—II: Physical Properties of Stainless Steels for Low Temperature and Cryogenic Service

PROPERTY	AISI Types 304, 304L	AISI Types 309, 309S	AISI Type 310	AISI Type 310S	AISI Types 316, 316L	AISI Type 321	AISI Types 347, 348	ASTM A 353 A 333 A 334 (9% Ni)
Density :								
Lb. per cu. in.	0.29	0.29	0.29	0.29	0.29	0.29	0 .29	
Gm. per cu. cm.	7.9	7.9	7.9	7.9	7.9	7.9	7.9	
Specific Electrical Resistance :								
Microhm—in.	28.4	30.8	30.8	30.8	29.2	28.4	28.6	
Microhm—cm.	72	78	78	78	74	72	73	
Specific Heat (Btu./lb/°F) :								
At + 80°F to + 700°F								0.119
At — 150°F to + 80°F								0.0878
+ 32 to 212°F	0.12	0.12	0.12	0.12	0.12	0.12	0.12	
Thermal Conductivity (Btu./hr./Sq. ft./°F/in.) :								
At — 320°F								91.3
At — 280°F	56.4							
At — 155°F	90.0							169
At + 70°F	117.6							189
At + 212°F		108	73.8	73.8	113	112	112	209
At + 600°F	120							
Mean Coefficient of Thermal Expansion (in./in./°F) :								
— 300°F to + 70°F	7.4 × 10^{-6}							
—200°F to + 70°F	7.7 × 10^{-6}							
— 100°F to + 70°F	8.2 × 10^{-6}							
+ 32°F to 212°F	9.6 × 10^{-6}	8.3 × 10^{-6}	8.8 × 10^{-6}	8.8 × 10^{-6}	8.9 × 10^{-6}	9.3 × 10^{-6}	9.3 × 10^{-6}	
+ 32°F to 600°F	9.9 × 10^{-6}	9.3 × 10^{-6}	9.0 × 10^{-6}	8.8 × 10^{-6}	9.0 × 10^{-6}	9.5 × 10^{-6}	9.5 × 10^{-6}	
At — 300°F								1.0 × 10^{-6}
— 300°F to 0°F								1.0 × 10^{-6}
— 300°F to 200°F								5.6 × 10^{-6}
+ 70°F to + 1300°F								5.8 × 10^{-6}

Table III. Typical specification numbers, nominal composition & minimum tensile properties for cryogenic stainless steel

ASTM AISI Type No. Specn No. and Grade	Nominal Composition Per Cent					Tensile Strength (Thousands of Lbs Per Sq. in.)	Yield Strength 0.2% Offset (Thousands of Lbs Per Sq. in.)	Elongation (Per Cent) in 2 in)	Lowest Usual Service Temp. (°F)
	C	Mn	Si	Ni	Cr				
201	0.10	6.0	0.60	4.5	17.0	95	45	40	— 320
202	0.10	9.0	0.60	5.0	18.0	90	45	40	— 320
302	0.10	1.50	0.60	9.0	18.0	75	30	40	— 452
304	0.06	1.50	0.60	10.0	19.0	75	30	40	— 452
304L	0.02	1.50	0.60	10.0	19.0	70	25	40	— 452
305	0.10	1.50	0.60	11.5	18.0	70	25	40	— 452
309	0.13	1.50	0.60	13.5	23.0	75	30	35	— 452
309S	0.06	1.50	0.60	13.5	23.0	75	30	40	— 452
310	0.10	1.50	0.60	20.0	25.0	75	30	35	— 452
316	0.06	1.50	0.60	12.0	17.0	75	30	40	— 452
316L	0.02	1.50	0.60	12.0	17.0	70	25	40	— 452
321	0.06	1.50	0.60	10.5	18.0	75	30	40	— 456
347	0.06	1.50	0.60	11.0	18.0	75	30	40	— 452
348	0.06	1.50	0.60	11.0	18.0	75	30	40	— 452
None	0.06	1.50	2.0	18.0	18.0	75	30	40	— 452
None	0.10	15.0	0.60	5.5	18.0	105	55	40	— 320

TABLE—IV

Room and Low Temperature Toughness of Several Annealed Austenitic Stainless Steels

Steel	Temperature (°F)	Energy Absorbed (ft/lb.)
AISI	80	220
Type	—320	61
201		
AISI	80	220
Type	—320	56
202	—425	49
AISI	80	154
Type	—320	87
304	—425	90
AISI	80	118
Type	—320	67
304L	—425	67
AISI	80	142
Type	—320	89
310	—425	86
AISI	80	120
Type	—320	66
347	—425	57

D. Welding Considerations

Having acquainted ourselves with the science of cryogenics, we have now the ticket to discuss the welding of and fabrication in cryogenic stainless steels.

Mandatorily, the weld deposit should be identical in mechanical properties and metallurgical aspects to the base metal.

In welded vessels and piping involving low-temperature service conditions—where notch brittleness is one of the basic considerations—it is desirable to keep the width of the HAZ (heat affected zone) as narrow as possible by means of ensuring low heat-input. When the layer thickness of the weld metal is held constant, faster rates of electrode travel reduce the width of the HAZ. This is desirable as transition temperatures tend to rise as the HAZ becomes wider, as shown in Fig. 10.

It may not be absolutely irrelevant to hover briefly on that welding at sub-freezing temperatures is not permitted by most of the codes. Such practice will produce weld deposits having reduced ductility and impact toughness. The drop in ductility becomes pronounced at welding temperatures below minus 50°F. The impact tests on specimens welded at minus 50°F are reported to have exhibited a toughness 15 or 20% lower than specimens welded at ordinary atmospheric temperature.

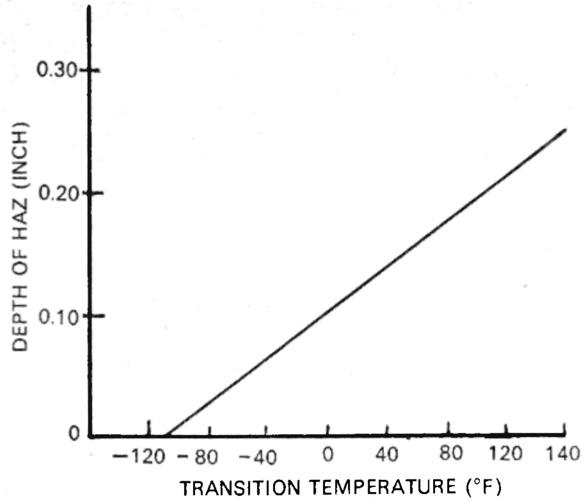


Fig. 10. Depth of HAZ against TT.

Typically, selection of electrode is a composite affair. Optimum is achieved when cost and quality are balanced as in other cases. The problem is that the conventional testing procedures have not been co-related with the service behaviour of the material after it has been welded. For example, one electrode may be preferred over another because the weld metal produced from it develops higher tensile strength. However, it might be well that an incipient surface crack will propagate readily in the weld deposit made from one electrode but not in the deposit from the other because the latter has the ability to adjust iteself plastically, even at low service temperature.

Titanium stabilized type 321 stainless steel is normally welded with Columbium stabilized type 347 stainless steel electrodes. If Ti were added in the electrode, most of it would be oxidised out in welding arc and there would be no stabilizing alloying element in the weld deposit. Columbium, on the other hand, is not lost in significant quantities during welding. Welding type 304 stainless steel with type 308 electrode may be vulnerable to corrosive environment which may attack the ferrite phase in type 308 in which case type 310, which is austenitic, will be the desired base metal.

E **Welding Defects** :

The following weld defects are detrimental to the construction of equipment for cryogenic services :—

(1) Arc strikes—Arc strikes represent any localised heat affected zone or change in the surface contour of the finished weld or base metal caused by an arc.

(2) Burn through—Burn through refers to a coalescence of weld metal beyond the root of the weld. Burn through, sometimes called as icicles may form a cavity through a backing ring.

(3) Cracks represent linear ruptures of metal under stress. Cracking in welded joints occurs in several forms :

(a) Hot cracking in weld deposit : It occurs at elevated temperatures during cooling after the weld metal has been deposited and has started to solidify from molten state.

(b) Cold Cracking : It occurs below 400°F usually near or at room temperature. It is also sometimes delayed, occurring hours or even days after the weldment has equalized in temperature. In general, cold cracking starts in the heat affected zone.

(c) Microfissuring : These are very small fissures not detectable at magnification less than ten diameters. Microfissures may be caused by hot or cold cracking. These defects are not detectable by "Radiographic" examinations.

(d) Base Metal Cracking : Welding also causes cracking in the adjacent base metal usually in the heat affected zone. It may be due to hot or cold cracking.

(4) Incomplete fusion : It involves lack of complete melting and coalescence of some portions of the metal in a weld joint.

(5) Lack of penetration : It involves incomplete penetration of the weld through the thickness of the joint. It usually applies to the initial weld pass or passes made from one or both sides of a joint.

(6) Porosity : Porosity is the presence of gas pockets or voids caused by the entrapment of gas evolved during the weld metal solidification. Porosities may occur in welds due to so many causes eg. damp electrodes, wrong polarity when welding, current too high or the improper welding technique.

Effects of porosity on ultimate strength, elongation and charpy V-notch impact toughness of submerged arc weld, are shown in Fig. 11.

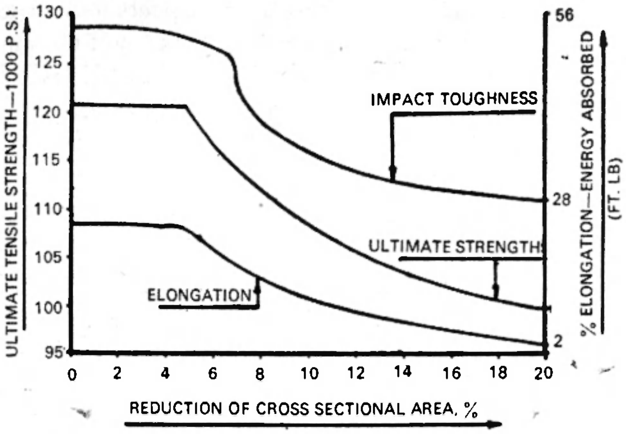


Fig. 11. Effect of porosity on ultimate strength, elongation, notch impact toughness of Submerged Arc Welds.

(7) Sink or concavity : Sink in a root weld bead refers to concavity. It is produced by gravity sink of the molten metal or by surface tension of the weld bevel pulling the molten weld metal into the bevel.

(8) Slag Inclusions : Slag represents non-metallic solid material entrapped in the weld deposit or between weld metal and base metal.

(9) Tungsten Inclusions : Metallic tungsten inclusions are particles which are deposited in the weld metal from a tungsten electrode used in the inert-gas tungsten arc welding process. Tungsten inclusions generally are not considered harmful, unless their size and number become excessive.

(10) Undercut : Undercut is the melting away of the side walls of the welding groove at the edge of a layer of weld metal. In service involving severe mechanical or thermal fatigue or pipe movement, undercut representing a sharp notch condition may result in cracking and failure specially at sub-zero temperature.

Welding Engineers and Inspectors are required to be very cautions about the above defects, particularly in cryogenic engineering.

F FABRICATION & INSPECTION PROCEDURE

1 Welding Procedure Qualification

Theoretical welding procedure is to be prepared. It is the test to establish the properties of the weldment. Welding properties are most important in the selection of materials for low temperature service; an improper weld can introduce critical notch defects which can be the starting points of fractures.

The theoretical procedure is tried out as per code on a test piece. The method of welding may be (i) S. M. A. W. (ii) T. I. G. (iii) Double-operated T.I.G. or (iv) S.A.W. Welding is carried out with the test pieces in fixed positions. Welds are subjected to the following examinations :

(i) Visual inspection.
(ii) Macro examination.
(iii) Radiographic examination.
(iv) Tensile Bend tests.
(v) Impact tests on H.A.Z. and weldment at minus 196°C.

Welding procedure is also made qualified before it is adopted in production. A few types of welding details are shown in Table - V. Also are shown mechanical test results of a set of welding procedures in Table-VI.

2 Qualification of Welders

Welding Performance Qualification Tests for welders are also required to be taken for commencement of actual production. It is the test for skill of the welder.

3 Setting up for Welding

The materials are identified and identification stamps are transferred, if necessary.

The edges of S.S. plates are prepared by Plasma cutting and/or edge planing machine and checked by Dye penetration test to find out any lamination.

The shell is rolled in cold condition; the dishes are formed in cold condition and the pipes are bent also in cold condition. In other words, no heating operation is allowed during any formation of material.

Set up of shell belts and dishes are made by qualified procedures and qualified welders. Joints set up are checked with tools and gauges for strict quality control.

Inspection is very important in ensuring that there is no notch on the dish and also that there is no abrupt change of section or thinning.

Cold bending is done on stainless steel tubing with relatively small diameter and wall thickness. Proper equipment and dies are essential to avoid wrinkling, excessive thinning and excessive ovality. Greater care

TABLE V

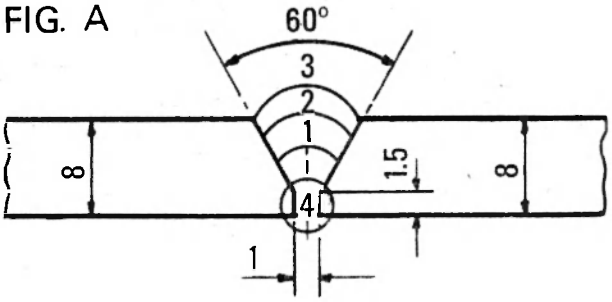
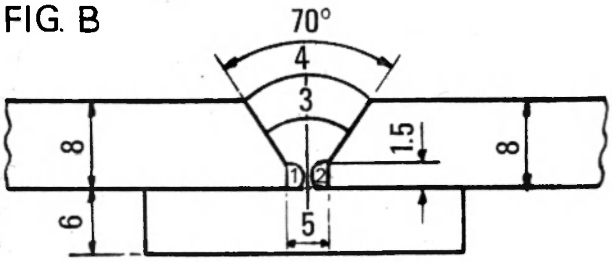
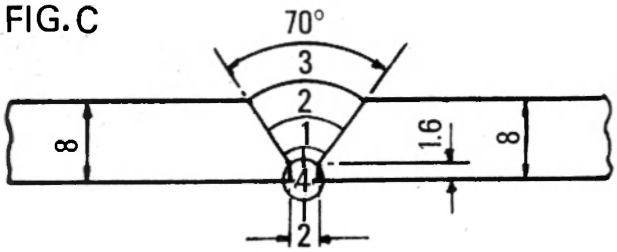
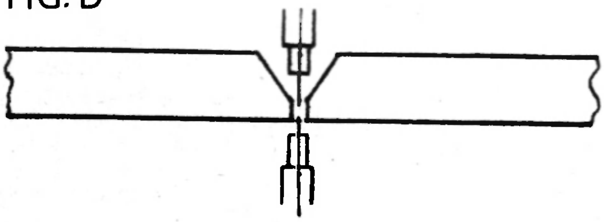
TYPE OF WELDING	PROCEDURE & ELECTRODE FILLER
FIG. A  	Position = 3G P No. = 8.1 F No. = 5 A No. = 8 AWS No. = E 308 — 16 Current = DC Polarity = + ive holder Welding Process — SMAW Amp. = 65 to 75 for 2.5 = 80 to 100 for 3.25 Volts = 80 ocv
FIG. B  	Position = 3G (Vertical Welding Process = 1st & 2nd run GTAW and 3rd & 4th run SMAW) P No. = 8.1 F. No. = 5 A. No. = 8 Current = DC Polarity = Straight —ive holder } GTAW +ive holder — SMAW Amp = 125 for 1.5 65 to 75 for 2.5
FIG. C  	Position = 3G P No. = 8.1 F No. = 5 Specn. No. = 5.9 AWS No. = ER 308 Current – DC Polarity = — ive electrode Amp = 90 — 125 Volts = 80 ocv Welding Process = TIG Shielding Gas = Argon
FIG. D 	Position = 3G P No. = 8.1 F No. = 6 AWS No. = ER 308 Others as in Fig. C Welding Process = Double Operated TIG.

Table - VI : Mechanical Test Results of Some Welding Procedure Tests

WPS	Material	Thickness	ASME Thickness Range	Type of Weld	Filler Metal	TEST RESULTS			
						UTS (PSI)	Bend	V-Notch Charpy (— 196°C)	
1.	S S to S S A 240 TP-304	8 mm to 8 mm	6 mm to 12 mm	SMAW	(E 308L-16)	(i) 81,100 (ii) 81,100	Satisfactory	HAZ Weld	—27 ft. lb. —22 ft. lb.
2.	S S to S S (Backing Strip)	8 mm to 10 mm	6 mm to 12 mm	GTAW (Root Run) + SMAW (Filling Runs)	ER-308L GTAW (E-308L-16) SMAW	(i) 78,900 (ii) 77,900	Satisfactory	HAZ Weld	—25 ft. lb. —23 ft. lb.
3.	S S to S S A 240 TP-304	6 mm to 12 mm	6 mm to 12 mm	GTAW	ER-308L	(i) 75,600 (ii) 75,000	Satisfactory	HAZ Weld	—30 ft. lb. —24 dft. lb.
4.	S S to S S	6 mm to 6 mm	6 mm to 12 mm	GTAW First run double operated. No back gouging	ER-308	(i) 81,790 (ii) 81,210	Satisfactory	HAZ Weld	--40.5 ft. lb. --30 ft. lb.
5.	S S to S S (Backing Strip)	6 mm to 8 mm	6 mm to 12 mm	GTAW (Root Run) + SAW (Filling Runs)	ER-308 GTAW ER-308 + OKI } SMAW ESAB Sweden (Flux)	(i) 77,500 (ii) 78,500	Satisfactory	HAZ Weld	—33 ft. lb. —18 ft. lb.
6.	S S to S S	6 mm to 6 mm	6 mm to 12 mm	SMAW (Root Run) + SAW Filling Runs)	(E-308) ER-308 +OKI of ESAB Sweden (Flux) } SAW	(i) 84,570 (ii) 85,380	Satisfactory	HAZ Weld	--27 ft. lb. --17 ft. lb.
7.	S S to S S	12 mm to 12 mm	6 mm to 24 mm	SAW	ER-308 + OKI of of ESAB Sweden (Flux)	(i) 90,000 (ii) 90,000	Satisfactory	HAZ Weld	—34 ft. lb. —30 ft. lb.

is required with decreasing wall thicknesses and smaller radii of bending. Uneven straining is considered responsible for the failure. Excessive ovality in cold-bent tubing has resulted in a number of failures caused by corrosion fatigue. In Germany, the maximum ovality permissible in the tube bend is determined on the basis of outside diameter and wall thickness as follows :

OD/ID Ratio	1.10	1.15	1.20	1.25	1.30	1.40
Max. ovality (%)	3.50	5.25	7.25	9.00	12.75	14.75

In American practice the maximum permissible ovality is considered to be 8%.

Proper joint fit-up is essential to the making of sound weld in pipes and plates. Improper fitting may result in lack of penetration notches. The weld joints may be butt joint, open or with backing rings. Backing ring type joints are usually considered necessary in order to ensure adequate penetration without forming undesirable protrusions which are difficult to avoid with open butt joints.

4 Welding and Quality Assurance

Welding is performed by qualified welding processes and welders as mentioned in detail earlier. Production test coupons are prepared as test samples and welded simultaneously. These test coupons are subjected to different physical tests and also Notch (Charpy Impact) test at minus 196°C. Inside surface of welding on the job is ground absolutely flush. Strict control is exercised so that there would be no notch or undercut left. If any of these are formed, immediately action to repair the same is taken.

After welding, radiography (X-Ray) is done to find out whether there are defects. Different techniques are employed as found suitable for the purpose. Adequate measure is taken so that radiographs are of highly sensitive quality. Forms in the grade of type-II is used, exposure selected so that density of the processed film corresponding to the area of interest, i.e., weldment is in between 1.7 and 2.2 (i.e. around 2). Sensitivity should range between 1% and 1.5% using DIN ISO type I.Q.I. ASME flat type Penetrameters are also used. Location markers are used on the job, letters are written by Mag ink so that cross reference is always possible. In this manner 100% radiographic examination is completed. Interpretation by viewing with a high power illuminator is done. The defects, if revealed, are rigidly scrutinised against a predetermined standard to determine acceptance. If not accepted, the defective location is marked and repaired by grinding and re-welding by qualified welder and procedure only. Re-shot is taken and re-examination is performed. The process continues as long as the defect is not completely removed or not removed to such a degree that it is within acceptable limit.

The vessel, now after completion of piping, is ready for tests such as pneumatic, hydraulic & halogen leak detection. Hydraulic test pressure is 1.5 times the design pressure and pneumatic test pressure is 1.25 times the design pressure. Halogen leak detection test helps to find out exact location of any existing through hole, however minute it may be.

For hydraulic test, the vessel is completely filled with water and prssure is raised to the required test pressure. Peening all over near the weld seams with wooden hammer on the pressurised tank and thorough visual inspection for locating any leaking water is performed. Two pressure gauges are used as is the standard method for any such test. The tank is kept under pressure for an hour. Initial and final readings on the indicating gauges must be the same ; otherwise, it becomes obvious that somewhere leakage is there.

Next, pneumatic test is undertaken which should be performed with greater care, since any leak may lead even to fatal results during the test. Pneumatic test consists of pressurising the tank with air to the required pressure and testing the weldments and joints with soap solution. Leak will be indicated by formation of bubbles. Similar to hydraulic test, two gauges are used and constancy of two readings taken at definite intervals are also checked.

Halogen leak detection test is another useful method which supplements the above two tests. The tank is pressurised, the probe is taken near the weldments and joints and moved all over and leaks are detected.

G. CONCLUSION

Welding of Cryogenic stainless steel is not a strange phenomenon to us in India; may be we are out of pace in the race. Study of Cryogenic stainless steel and its welding has a tremendous prospect to apply effectively and beneficially with the rapid growth in fertilizer, petro-chemical and other allied industries.

Cryogenics is an ever growing industry and shall remain perpetually so as long as mankind's quest for the exploration of solar and outer-solar system continues.

This perhaps sounds somewhat abstract or overambitious with respect to our economic conditions, and limited financial and material resources. Back on earth in India, however, minimum level of research work, discussions, communication and exchange of experiences, like the one we are having here right now, is essential for mutual benefit. And may this continue.

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