Scope of Welding Technology in the manufacture of Vessels for Cryogenic Services

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Introduction :

Manufacture of Pressure Vessels for Cryogenic Services is relatively a new field in India. The word "CRYOGENIC" was inherited from the Greek word "KRYOS" which means frost or ice and "Genes" means "born". Cryogenics is the branch of physics concerned with phenomena at very low temperatures, ranging below—100°C extending down to absolute zero, -273°C. In industry, many Cryogenic equipment are designed to work at service temperatures as low as -196°C or even lower. The Cryogenic science is being used in industries like Gas Separation, Deep sea oil extraction, Missile Launching, Biology, Food handling, Electronics etc.

In the air-separation plants for manufacture of gases like oxygen, nitrogen and argon, vessels and pipings are required extensively and fabrication of such vessels is being taken up recently. Besides that the vessels are fabricated under ASME Boiler and Pressure Vessels Codes, Section VIII, the welds have to be absolutely free from defects like pinholes and porosity to become leak tight in order to stand vacuum. Mechanical properties, specially impact property of the weldments and its heat-affected zones at sub-zero temperatures is another major factor that needs consideration. Role of welding technology starting from selection of materials to final testing would thus become an important area in manufacture of Cryogenic equipment which is the subject of this article.

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Materials Selection :

Selection of materials for Cryogenic vessels necessitates certain special considerations to physical and mechanical properties. Such mechanical property would include the familar yield and tensile properties, ductility, fatigue limit, impact and toughness properties. Ductility, the ability of material to deform plastically and toughness, resistance to brittle failure under specific conditions of stress concentrations, must be present in metals that are considered for use at low or Cryogenic temperatures. Selection of materials for Cryogenic services is also based on various physical properties like low heat conductivity, low co-efficient of thermal expansion and low emissivity. All such properties can be used to advantage in storage vessels, vacuum transfer lines and other components of low-temperatures or Cryogenic systems.

Of all the metals useful in construction for low-temperature applications, steels remain the most popular because they are more efficient, most readily available, most versatile and most economical. Austenitic Stainless Steel (which is non-hardenable by heat treatment) is an excellent material over the entire range of Cryogenic applications because of its toughness and high ductility at low temperatures and because it is highly corrosion resistant. In other words, the Austenitic Stainless Steels meet all the requirements for low-temperature service. They remain tough at liquid hydrogen and liquid helium temperatures and their co-efficient of thermal expansions and thermal conductivity are lower than those of non-ferrous Cryogenic structural materials.

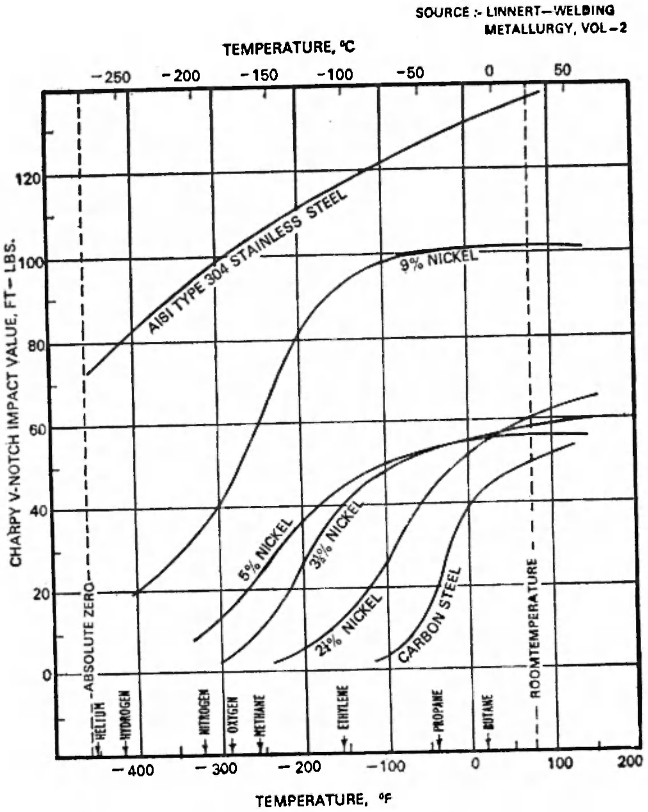


Fig. 1. Boiling points of gases are shown on ABSC ISSA. Impact properties of steels over a wide range of temperature showing the benifit of nickel in lowering toughness transition temperature, and superiority of austenitic stainless steel at all temperatures.

Fracture toughness of steels at low temperature is an important criteria for selecting right type of steel. Linnert[1] has mentioned about a few remedial steps in steel-making for securing good fracture toughness of which heat treatment and alloying with nickel are included. Heat treatment can improve fracture toughness, and extend its range of usefulness to about—60°C. By adding nickel in substantial amounts, the range of applicability can be extended as follows :-

Steel Composition	*Lowest Service Temperature*
2¼% Nickel	-60°C
3½ Nickel	-100°C
5% Nickel	-130°C
9% Nickel	-200°C

The service temperature limits listed above are based upon having a minimum charpy impact strength of at least 15 ft. lbs. Fig. 1 by Linnert indicates the impact properties of steels over a wide range of temperature and superiority of austenitic stainless steels at all temperatures. (15 ft. lbs=2.073 Kgf. m.)

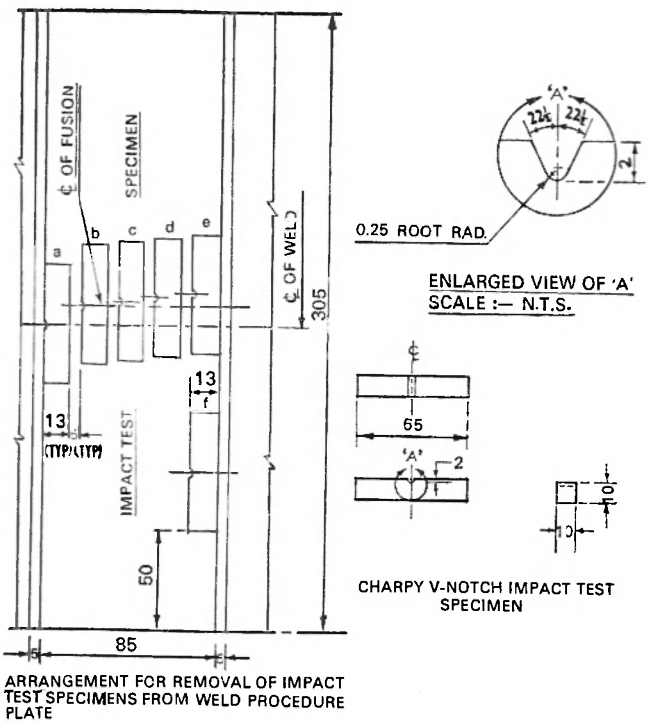
In addition to various types of steel mentioned, both copper and Aluminium Alloys are also extensively used in Cryogenic Plants and Vessels. However, use of copper is restricted to the low and medium capacity Air Separation Plants in columns and trays, while Aluminium Alloy (4.5% Mg.) is extensively used in tonnage plants. Selection of such material is based on factors like toughness, ductility and fatigue resistance. For the purpose of convenience, the present article would be restricted to the welding problems of S.S. and Nickel Steel only, while welding of Aluminium Alloy can be a subject of another article.

Welding Process & Procedures :

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 point of fractures. Besides that the welding procedure shall be laid down to produce weld joints with a high degree of integrity both in geometric form and metallurgical character, joints must be virtually free of design faults or defects like unfused root faces, severe undercutting & underbead cracking. Furthermore, the welding procedure must provide a notch-tough metallurgical structure in the weld metal and the heat-affected zone of the final weldment.

For this reason, fabricators should experiment with materials for Cryogenic applications to develop proper welding techniques. Experience gained in testing techniques for welding materials for Cryogenic service is likely to pay off in reduced production costs.

Many Cryogenic vessels are fabricated conforming to ASME Pressure Vessels Code Section VIII & IX and procedure qualification tests are conducted as per these codes before actual production welding is allowed to take place. Mechanical tests including low-temperature impact tests are conducted for the procedure test specimens. *Fig. 2* shows a typical arrangement for removal of test specimens from the procedure test plate and test specimen configurations. It can be noticed that notches for the impact test specimens were shifted from centreline of weld to fusion line and slowly to the heat affected zone. This technique of testing for impact strength is not new and is practiced in many Chekoslovakian and other East European Countries. The result can be plotted in a graph which will show the lowest impact strength at a particular point between



SPECIMEN	a	b	c	d	e	f
D	0	—	—	—	—	FROM PARENT PLATE AS SHOWN IN FIG. ABOVE
F	—	0	+1 mm	+3 MM	+5 mm	

Fig. 2. Weld procedure test. Charpy-V-notch impact test. Specimen for cryogenic vessels.

weld zone to HAZ. The acceptance of the impact test is based on the fact that the lowest impact value shall be equal to or more than 15 ft. lbs. for a 10×10 mm^2 standard charpy V-notch specimen at the lowest service temperature specified. (15 ft. lbs—2.073 Kgf. m).

Welding performance qualification test for welding operators are also required to be taken before commencement of actual production welding. Since 100% X-Ray radiography is required for the job, it is desirable that procedure and performance qualification test specimens are radiographed as per relevant ASTM standard before sectioning plates to make test pieces.

Type of Welding :

The three major types of welding processes used with low-temperature and Cryogenic vessels are shielded metal-arc welding, submerged arc welding and inert gas-shielded metal-arc welding. Shielded metal arc welding process, using coated electrodes, is predominant in manual operations, tungsten or non-consumable electrode welding is used in manual, semi-automatic or automatic operations. Submerged arc welding is used principally in automatic and semi-automatic operations.

Out of various types of steel used in Cryogenic services, carbon steels to spec. ASTM A516 and A517 are welded either with shielded metal-arc welding or submerged arc welding depending on thickness without much problem, since these steels possess good weldability. Out of all nickel steels used, weldability of 9% nickel steel to spec. ASTM 1A-353 needs certain consideration and would be outlined here. These types of steels have extensive use in low-temperature applications as can be seen from *Fig. 1* due to the excellent impact property at low-temperatures. Welding of Austenitic stainless steels is not unknown, but precautions while welding such steels for Cryogenic services are mentioned.

Welding of 9% Nickel Steel (ASTM A 353) :

a) *Cleaning :* Adequate cleaning of joints in 9% nickel steel is required to produce X-Ray quality welds. Mill and flame-cutting scales should be removed from the weld area by blasting, grinding, or power brushing; careful flux-removal between the weld passes followed by grinding the entire groove to bright metal, is required.

b) *Joint Design :* For grooved joint, wider included angle, compared to ordinary constructional steels, is recommended. Joint angles of 60°-80° in both single and double vee groove welds are necessary.

c) *Filler Metal :* Shielded metal-arc welding, when first applied to the 9% nickel steel using electrodes of similar metal composition gave rise to weld metal cracking. Besides, the weld metal exhibited charpy V-notch impact strength of 5 ft. lbs at -200°C, which was not adequate. Weldments made with "INCONEL" type filler wire as listed in Table (I) by Linnert[1] has shown adequate fracture toughness at low temperature as can be seen from Table (II), having tensile strength almost equal to base metal but having yield strength upto 55 ksi compared to 60 ksi in base metal (ASTM A-353, Gr. A). However, such filler metals provided good impact strength (*Fig. 3*). No difficulty was encountered in qualifying these electrodes for ASME Code requirements and hence these are widely used. Because the weld metal deposited by these electrodes has approximately 95% joint strength efficiency, the ASME allowable design stress is reduced for 9% nickel steel

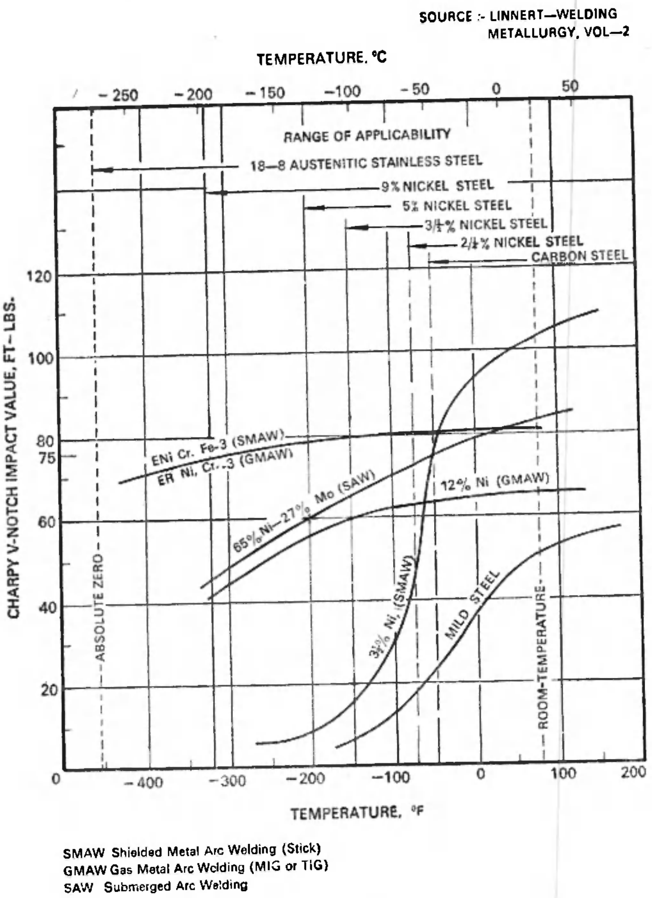


Fig. 3. Typical impact properties of weld metals in as diposited condition as affected by temperature.

in welded constructions.(5ft. lbs. -0.7 Kgf. m.) Riley & Plate[2] have reflected similar thoughts in their article "Welded Tanks for liquified gases". Another group of investigators, Carter & Harrison[3] in their paper 'Welding of 9% Nickel Steel" listed filler metal having 60% Ni 12% Cr with Mo/Ni addition, however claim that adequate tensile strength of the weldments was achieved at room temp. and also at -164°C. Besides tensile properties & impact strength at -196°C, C.O.D. test and wide plate testing were also carried out with satisfactory results.

Welding Technique :

In most cases, the nickel-based electrodes must be operated on D.C. reverse polarity. Where practical, positioners should be used which will enable all welding to be done down hand. Nickel base electrodes are difficult to use in vertical position, and welding in this position can result in porosity. Electrodes of 1/8" to 5/32" dia, should preferably be used for all root passes in down hand position. In case backing bar is required, copper may be used which should eventually be removed by grinding. A preheat temperature upto 100°C and interpass temperature not exceeding 200°C are recommended. A method of calculating preheat temperature from cooling rates etc. by the author[4] may be referred in this context. Electrodes may be used in their lower side of current ranges to minimise porosity but weaving may be necessary. Baking of electrodes prior to welding is essential upto 150°C for two hours. The suggestions listed above are not supposed to be exhaustive and would act as a guideline for experiments with welding of nickel steel.

Welding of Austentic Stainless Steels :

Tungsten Inert-Gas (TIG) arc welding is ideally suited to the most critical joining requirements of the austenitic stainless steels. The intense, concentrated heat of this arc permits the highest welding rates and the lowest heat input of any of the fusion joining methods. These characteristics of the tungsten arc minimise weld cracking and heat effects on corrosion resistance. Root passes laid down by TIG welding are always specified for X-Ray quality welds in large, heavy walled pipe or vessels. The root may be formed by direct fusion of specially prepared edges machined in parent metal, or by fusing a consumable metal ring inserted between the bottom ends of the pipe sections. TIG welding of stainless steel is done with D.C. straight polarity using 1% or preferably 2% thoriated tungsten electrodes.

Stick electrodes are widely used in stainless steel welding and quality of stainless steel electrodes of various types has shown remarkable improvements in our country in the recent years. In comparison with stabilised electrodes, use of low carbon variety (C-·03%) electrodes are mostly preferred. However, a real source of trouble with coated electrodes for S.S. comes from moisture pick-up due to atmospheric humidity. As received, the rods are normally packed in polythene bags inside hardboard box to keep them dry ; the coating materials are hygroscopic and absorb water depending on temperature, humidity and the coating composition. A "Wet" rod gives a sputtery arc and a porous weld deposit ; therefore, it is wise to put the unused electrodes in a drying oven at about 100°C. Three or four hour's exposure at high humidity can raise moisture content in coating to about 4 to 5% and thus cause poor welding performance. In vacuum insulated vessels used for cryogenic services, difficulty has been experienced very often to achieve, required degree vacuum due to presence of porosity, pinholes or piping.

Besides TIG, MMA, MIG and SA processes of welding are substantially used for stainless steel. The axial-spray type metal transfer in MIG gives a clean, sputter-free weld with good penetration and no problems of slag removal. Submerged are welding, both semi-automatic and automatic types with D.C. power sources, result in high speed, better control over arc starting and arc length, high deposition rates, good penetration. D.C straight polarity gives highest deposition rates and best arc stability with least penetration and is suitable for thinner materials. D.C reverse polarity gives greatest penetration and best bead shape. Flux removal is necessary between passes and current range of 700-800 amps is normally used. Economically, S.A welding is preferred compared to other welding processes mainly because of high deposition rates and superb quality. However, a problem of welding stainless steel by S.A process is that because of high heat input, notch impact values of weld zones are reduced until the weldments are normalised. This effect is more pronounced in thicker sections.

Inspection & Testing

Inspection of cryogenic vessels is presently carried out as per ASME Pressure Vessels code. Besides ASME, many companies manufacturing Cryogenic vessels set their own inspection standards in order to ensure stringent standards during manufacture. A high standard of welding is required with rigorous attention to weld procedure qualification of all the different forms of joints under welding conditions. All welds are subjected to 100% radiography to ensure satisfactory quality and leak tightness. The major areas of inspection required for Cryogenic vessels are :

a) *Plate Materials :* Carbon steel and stainless steel plates of certain types are being manufactured at our steel works in limited quantities and identity and or quality of many such plates are not well established. Besides, weldability of many such plates are still under controversy. Acceptance of plate materials as per ASME ASTM Codes thus poses a great problem in this country. Aluminium alloy and Nickel alloy steel plates for Cryogenic vessels are going to be used in huge quantity in the near future of which former type are available in limited quantity while the latter type are not manufactured in India. Copper sheets and plates used in air separation unit columns and trays are however available.

b) *Weld Inspection :* Visual, destructive, non-destructive testing and leak detection tests are extensively used. As already discussed, all notch-like defects including undercut etc. must be inspected carefully and repaired. Among all destructive tests, impact test at sub-zero temperature needs strongest attention. Inspection of notch for its position and geometry before breaking, should be done with the aid of "Shadowgraph" and tolerances as per ASTM should be observed. Liquid nitrogen may be used as coolant for the impact specimens and a test temperature of −196°C is envisaged. Radiography, preferably with X-Ray is extensively used for inspecting welds in the root run, final run and repair welds. Sensitivity of radiographs must be between 1% to 2% to detect minute defects and wire-type image-quality indicator DIN ISO type is recommended. Use of Ultrasonic testing should be made extensively before and after radiography for testing welds but since, in most of the cases, wall thicknesses of vessels are limited for access of ultrasonic equipment, easy interpretation of test results may not be possible. Dye-epnetrant method of testing is simple, inexpensive and when conducted carefully, gives lot of useful information of surface and sub-surface defects on welds. Leak-detection by use of halogen compounds and Freon-12 gas gives a qualitative information and exact location of leak is possible to be detected by this method. Halogen leak detection test is a powerful tool to achieve a leak-free tank or vessel.

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Book Review

WELDING IN OFFSHORE CONSTRUCTIONS by The Welding Institute, Abington Hall, Abington, Cambridge CBI 6AL, U. K. 1974. Price : for Members £10.00 and Non-Members £15.00

This is published in 2 volumes. Vol. 1 contains texts of 23 papers during the International conference organised by the WI at New castle 26-28 February 1974. Vol. 2 records discussions. The papers cover structural design and fatigue, steels, weld metals, fabrication procedure, pipelines and under-water welding and future requirements. The publication is a timely one, since fabrication activities are under way for deep sea oil-drilling platforms all over the world and especially in the North Sea. Experiences and problems have been discussed among experts from various advanced countries like the USA, UK, W. Germany, Sweden, Japan and France.