SPECIAL REQUIREMENTS FOR FABRICATION OF PROCESS EQUIPMENT FOR RADIO-CHEMICAL PLANTS OF NUCLEAR FUEL CYCLE FACILITIES

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ABSTRACT

Radio-chemical plants for various applications in nuclear fuel cycle facilities have been in existence for last many decades in India. They have complex nature of operations and problems associated with handling of large amount of radioactivity in dispersible forms. Most of the processes as carried out in radio-chemical plants use nitric acid based solutions. Highly oxidizing nature of nitric acid environment in such plants makes the equipment vulnerable to corrosion. In addition, equipment congestion, complex piping and high radiation fields in shielded cells pose challenges to carry out any contact maintenance. Accessing any equipment for maintenance or repair work inside the shielded cells needs massive decontamination efforts and high men-rem expenditure. Such maintenance work in process cells results into long shut-down of plants.

It is imperative to have a high degree of reliability for the process equipment to minimize maintenance work. Hence, appropriate and stringent fabrication requirements are laid to enhance the confidence level on structural integrity of these critical process equipment. Many special requirements to safeguard against probable reasons of mechanical failures are identified in addition to fabrication requirements specified in various applicable codes and standards. These requirements are dictated by the importance given to the equipment for radiological safety in the plant. This paper summarizes the special requirements being practiced for the fabrication of such equipment employed in the nuclear fuel cycle facilities.

INTRODUCTION

Nuclear fuel cycle facilities referred here cover nuclear recycle plants mainly fuel reprocessing and waste management facilities. These plants employ large number of different types of process equipment such as dissolvers, thermo-syphon evaporators, heat exchangers, extraction columns, conditioners, scrubbers, annular vessels, storage tanks, etc. They are designed and manufactured as per the provisions of ASME B&PV Code, Section III, Div. 1, Subsection NC [1] or ND [2] based on their nuclear safety class. The above equipment differ from nuclear power plant equipment largely by the process conditions prevailing in the plants and material of construction used for them. The design of nuclear power plant equipment is generally governed by strength considerations due to high pressure and temperature operations, while the design of these equipment is influenced by corrosion aspects. Nuclear recycle plant equipment is subjected to varied process conditions ranging from normal temperature to boiling condition operations and 0.1 M to 12 M of HNO3 concentrations in service. Also, they are housed inside the shielded concrete cells due to high radioactive inventory stored in them that result into inaccessibility of such equipment for any contact maintenance. Therefore, it is necessary to aim for failure-free service life of the equipment. After years of field experience and extensive studies on performance evaluations of the equipment in simulated conditions, some special requirements are identified for the fabrication and quality control which are included in the technical specifications [3] for fabrication of equipment. Typical equipment and their parts at various fabrication stages are illustrated in Figure 1 to Figure 5.

MATERIAL SPECIFICATION

Choice of material of construction to suit the process environment for such critical applications is vital in enhancing the structural integrity of the equipment. A special composition of austenitic stainless steel material conforming to ASTM A 240 grade 304L [4] has been developed. This special material, referred as SS 304L (NAG) [5] has lower impurity levels, controlled delta ferrite [6] and refined grain size. The material is tested for detecting susceptibility to intergranular attack as per ASTM A 262 [7] Practice ‘A’ and Practice ‘C’. Acceptable etch structures are ‘Step’ and ‘Dual’ when tested as per ‘Practice A’ and average corrosion rate shall be less than 10 mpy as per Practice ‘C’. Also, all the plates having thicknesses equal to or greater than 6 mm are tested for ultrasonic testing by straight beam and angle beam techniques as per ASTM A 578 [8] and ASTM A 577 [9] respectively. Fabrication of such a clean material needs special care during each stage of the construction. A comparison between standard ASTM grade SS 304L and modified SS 304L (NAG) is given in Table-1.

Table-1

Grade		C	Mn	Si	P	S	Cr	Ni	N
304L	min.	-	-	-	-	-	18.0	8.0	-
	max.	0.030	2.0	0.75	0.045	0.030	20.0	12.0	0.10
304L (NAG)	min.	-	-	-	-	-	18.0	9.0	-
	max.	0.02	1.8	0.35	0.025	0.018	20.0	11.0	0.05

Similarly welding consumable’s chemistry has been developed, which are used in welding of the SS 304L (NAG) materials. The filler wire material has controlled δ-ferrite content and conform to low corrosion rates, matching to parent materials. Typical composition of the filler wire is given in Table-2.

Table 2

Grade		C	Mn	Si	P	S	Cr	Mo	Ni	Cu
SFA 5.9 ER 308L	min.	-	1.0	0.3	-	-	19.5	-	9.0	-
	max.	0.030	2.5	0.65	0.03	0.03	22.0	0.75	11.0	0.75
SFA 5.9 ER 308L (spl.)	min.	-	1.0	-	-	-	18.0	-	10.0	-
	max.	0.025	2.0	0.4	0.02	0.01	20.0	0.20	12.0	0.1

SPECIAL FABRICATION REQUIREMENTS

To achieve the objective of trouble-free design life of the equipment, technical specifications for fabrications of these equipment is meticulously developed. Primarily because the equipment are associated with severe corrosive service conditions, hazard of radioactivity and inaccessibility for any maintenance during the service; it was considered necessary to look beyond the scope of code requirements for fabrication and quality control. Hence, many supplementary requirements are kept in addition to those specified in the code of construction to improve the overall quality. These requirements are also attributed to the special material of construction used with its controlled chemistry and metallurgical cleanliness. These equipment differ in construction from the conventional ones with respect to requirements of large no. of nozzle penetrations for decontamination sprays, instruments for monitoring of process parameters, passive agitation, transfer of the liquid lines, liquid sampling, cooling/heating purpose, etc. Major parts of the equipment are heads or dished ends, shells (body of the vessels), reducers, tubes, tube-sheets, jackets, attachments like nozzles, manholes, supports, agitators, cooling/heating coils, etc. The basic fabrication operations used for these manufacture of the equipment are cutting, forming, welding and expansion rolling. The important highlights of the specifications are briefly described here.

Prevention of Contamination

Avoiding of cross contamination of material during fabrication is an important aspect. Any contamination on stainless steel parts may deteriorate corrosion resistance property of the materials. Therefore, fabrication of the equipment needs to be carried out in a separate enclosed or barricaded area isolated from other general fabrication work. Contaminations from tools, consumables, tackles, grinding wheels, etc. should be avoided by making them available exclusive for stainless steel fabrication work. Stainless steel plates, pipes, tubes, rods, etc. for the fabrication are stored in a dry enclosed area to ensure contamination free material. Cleaning of the raw material prior to any fabrication process and finished/ semi-finished components after fabrication is carried out as per as per ASTM-A-380 [10] and approved procedures. Pickling and passivation is carried out for all the parts/assembly after heat treatment. Fabricated equipment undergo iron contamination and chloride contamination checks after pickling and passivation as per the approved procedures. Contamination control remains an important issue to be addressed throughout the fabrication work.

Forming

The basic manufacturing process that fall under forming operation specifically used here are pressing, spinning, and bending. The raw materials used for equipment fabrication are allowed to be formed by only cold working process to give finished shapes. Mechanical and corrosion properties of austenitic stainless steels are largely affected by cold working. The special requirements include care during forming, selection of forming operation, limits on cold working, heat treatment requirements, etc.

The direction of bending of the plates is maintained as far as possible, same as that of the original direction of plate rolling. The shell sections are rolled only after dish ends are formed so as to minimize the mismatch of fit-ups as a good engineering practice [11]. In the shell bending, conventionally called rolling of shells are essentially carried out after pre-pinging. Direct contact between the carbon steel roller surface and stainless steel plates is avoided by providing stainless steel lining on rollers or rubber padding. Dished ends are formed either by pressing or by spinning operations. Torispherical dished ends with minimum knuckle radius as 10% of the inside diameter of the skirt is used to limit the amount of cold work in the torus region. The pressing operation is usually adopted wherever the size of the part is relatively small. For the cold pressing of parts, the chances of surface cracks on the outer surface are high due to the effect of work hardening, hence it calls for thorough surface examinations.

Spinning operation for forming of dished ends are comparatively fast and generally requires initial hole drill at the centre and local pressing of crown region. Later, the hole is covered by plugging of plate with full penetration butt weld joint. The amount of cold work is restricted to maximum 10% to maintain corrosion properties within acceptable limits. Cold worked stainless steel parts are subjected to hardness checks on the surfaces. If the hardness exceeds beyond 200 Brinnel Hardness Number (BHN) limit, heat treatment is carried out. Also, as a general practice, all torispherical dished ends and pipe bends having bend radius less than 5 times pipe diameter, are solution annealed. For cold bending of pipes and knuckle region of the dished ends, minimum wall thickness after forming should not be less than the minimum design thickness plus corrosion allowances. The ovality of pipe bends is maintained below 5% and no ripples/wrinkles on pipe surfaces are allowed. The above parameters are established on procedure qualification samples prior to production.

Cutting of material

All material cutting operations are preferably carried out by mechanical means. For cutting of thick plates chain drilling (nibbling) operation is usually employed which are subsequently finished to size by grinding. Any unavoidable thermal cutting of the material is carried out only by plasma process with adequate edge allowances for complete removal of heat affected zone by grinding. During fabrication, the prepared edges of plates, pipes and other fittings are examined by liquid penetrant tests to detect open to surface unacceptable flaws. All defects are removed and area is repaired as per the approved procedure, if needed.

Fit-up

Since austenitic stainless steel material has higher coefficient of thermal expansion and lower thermal conductivity as compared to those of carbon steel material, distortion problems are relatively more during fabrication. This can be taken care of by proper fit-up, use of supports/fixtures, appropriate sequence of welding and minimum heat input. Proper fit-up is the key to sound fabrication of the equipment. During fit up, examination is carried out for proper weld-edge preparation, physical dimensions, surface examination of the weld edges, clamping and stiffening of the parts, and cleanliness of weld edge surfaces. Different types of jigs & fixtures have been developed to suit specific need to control distortion and misalignment. Tack welding on the seam or the use of clamps and wedges may be resorted to for holding the joint in position. Only qualified welder are employed for depositing tack welds, using a qualified welding procedure. As far as possible, mechanical clamping is used for making fit-ups. Temporary fittings such as tacking strips, cleats etc. are carefully removed to prevent any damage to the parent materials. Fit up brackets are used only on the vessel outside. Any blemishes on the parent material are rectified and the area is examined by liquid penetrant tests for detection of any defect, and if required, it is also be radiographed and inspected accordingly.

All shell sections are provided with spiders for maintaining the circularity while rotating the shells on rotators. At least four leg-spiders are used at both ends of the shell leaving the longitudinal seam area. Additional care is required to be taken with respect to cave-in of nozzles having large sizes. Some of the effective ways adopted to minimize the cave-in of nozzles are by providing temporary stiffeners/restraints during the fit-up and adopting staggered welding techniques with low current. The profile of the shells & dished ends are examined over the entire area, using templates. Local deformations are quantified, including over-crowning using taper gages. Thinning of the knuckle, pipe bends and other formed parts are checked using ultrasonic method. The straightness of the shell is measured and recorded by suitable means. Concentricity of reducers is checked by putting it on rotators. The maximum difference between observed diameters at any cross section of the shell is maintained much less than those specified in the code of construction. Similarly, much stricter tolerances are followed for deviation from true shape than those given in the construction codes for vessels subjected to external pressures.

All the supports, clamps, jigs and fixtures used for distortion control are of stainless steel material. If carbon steel members are used for aligning/restraining purposes, suitable stainless steel pad are employed to prevent contamination of stainless steel. Moreover, such steel parts are painted to avoid falling of rusts from them which will contaminate the surfaces. Hammering directly on plates or the use of excessive force is not permitted to achieve a fit up.

Welding

Manual Gas Tungsten Arc Welding (GTAW) process is adopted for construction of all process equipment here primarily because of its cleanliness. Welding is carried out with minimum heat input because of the associated problems of warping and distortion of stainless steel during welding. Necessary Welding Procedure Specifications (WPS), Procedure Qualification Records (PQR) and Welder Performance Qualifications (WPQ) are carried out in conformance with requirements of ASME Sec IX [12]. Additional qualification criteria for corrosion and ferrite content are kept for welding procedure qualifications. All welding filler wire used are conforming to ASME B&PV Code Section II, Part C, SFA-5.9 ER 308L [13] with special chemistry [14] to achieve low corrosion and control on ferrite content. For the shells of comparatively smaller diameter, the full circumference is made from a single plate. If two or more plates are used to make a circumference of the shell, weld reinforcement from both the sides are ground-off to parent metal level to facilitate smooth bending.

To the extent possible, all the welds are full penetration butt joints with back chipped and re-welded. Full penetration welds accessible from only one side is to be continuously back purged with argon gas during welding. Weld joints from inside of the equipment are finished smooth with uniform contour to eliminate any crevices. Reinforcement on welds is not allowed to exceed 10% of the material thickness. High purity argon gas of 99.995 % purity is employed with purging for root and subsequent successive layers. To avoid burn through of pipe nozzles, hollow bar nozzles are used. Haphazard striking of electrode on base metal for establishment of arc is not permitted. High Frequency unit is used for arc starting. In case inadvertent arc strikes occur, the affected area needs to be ground flush and the surface is examined by liquid penetrant test. Welding sequence is selected carefully to minimize distortion problems. Skip-welding, back-step welding, specially designed fixtures were used to avoid the distortion and control residual stress. Staggered welding is considered if the length of the seam is more than 2 m.

After every pass, the weld is cleaned using proper tools to remove spatters and surface defects before it can be taken for depositing subsequent beads. Inter-pass temperature is maintained strictly below 150° C to avoid longer residence time of chromium carbide precipitation temperature range. All defective areas as revealed by visual, liquid penetrant tests, radiographic and ultrasonic examinations, are to be repaired as per the approved procedures. All repairs are carried out as per the applicable subsections of ASME Section –III. Method of inspection used for the repaired area is same as the one used for the original area. Repair of welding at any spot is restricted to one time only. Weld seams are thoroughly cleaned from rust, grease, mill scale, or any other foreign material on groove and to a near surface on either side of the groove. The use of circular wire brush of stainless steel or grinding wheels is used for this purpose.

Heat Treatment

The mechanical as well as corrosion behavior of austenitic steel changes greatly whenever it undergoes cold working during manufacturing/fabrication. To avoid the adverse effects of cold work, they may need solution annealing heat treatment depending upon the amount of cold work and service duty of the equipment. The vessel as a whole needs no heat treatment. However, all dished ends, pipe bends with radius less than 5 times the outside diameter of the pipe and other formed or heavily machined (all hollow bar nozzles) components need solution annealing treatment after forming as per the approved procedure.

De-scaling of the heat treated part is carried out by chemical procedure i.e. pickling as per ASTM-A-380 standards. Representative test coupons are heat treated together with the formed components. The test coupons should have welds incase components with welds are solution annealed. The coupons need to be examined for microstructure, ferrite content, hardness and inter granular corrosion after the heat treatment to check its conformity with required values.

Quality Assurance

A detailed quality assurance plan, indicating schedule of fabrication and inspection stages is established and approved before the start of fabrication work. Various mock-up trials are performed to establish the required performance of the written down procedures rather than on actual jobs. All the non destructive testing and examinations are as per ASME Section V [15]. Acceptance criteria of NDEs/testing are developed judicially based on the safety role of the equipment in addition to the requirements given in the applicable ASME code. All the raw materials including welding consumables are inspected and tested to the requirements of appropriate material specifications/ standards. In case of non-availability of mill test certificates, separate tests need to be carried out for each material heat.

In addition to mechanical and bend tests as prescribed in the code, the weld test coupons are also required to be tested for accelerated corrosion tests and delta ferrite content. Corrosion test is performed for not only to detect the susceptibility to Inter Granular Corrosion (IGC) as per ASTM A 262, but also to evaluate the corrosion rate in accelerated conditions as per Practice 'C'. Acceptable average corrosion rate for 5 cycles as per the Practice 'C' of the standard should not be more than 2 mpy over the value of the base material. Delta Ferrite value of weld metals should be between 4FN to 10FN. All stainless steel surfaces which come in contact with chemicals, oils or other materials at any stage of fabrication are liable to be contaminated by halogens and are required to be checked for chloride contamination at suitable stages. All stainless steel surfaces are also examined for iron contamination at suitable stages after cleaning. Scales and oxide films developed during the welding and solution heat treatment are subjected to pickling subsequent to mechanical cleaning to achieve bright surface which is finally passivated.

Surface examination of weld seams and Heat Affected Zone (minimum 1/2″ on either side of the weld) are carried out using Liquid Penetrant Tests as per the code guidelines. But acceptance standards are made more stringent than they are specified in the ASME Code. Penetrant materials viz. penetrant, developer and cleaners are analyzed for sulpher/halogens content as per relevant ASTM standards. Volumetric examination is done for detecting internal flaws of full penetration butt weld joints by radiographic examination as per ASME Section V, Article 2 and in accordance with the requirements given in ASME Section III (NC/ND). X-rays source is preferably used for radiography on account of better quality. In addition to the acceptance criteria given in the code, any undercutting on inside or outside, oxidation, linear defects/indications, root concavities, etc. are also not acceptable. Ultrasonic examination is carried out in lieu of radiography when the later is not feasible in any of the full penetration butt weld joints or full penetration corner weld joints, as per the code guidelines. Acceptance criteria flaws are same as those for the radiographic examination.

CONCLUSION

Assurance of structural integrity of the process equipment in radio-chemical plants is extremely important. Therefore, it is essential to improve the quality of fabrication by employing additional requirements at various stages in order to avoid premature failures during service. Applicable codes/standards for construction of nuclear components provide set of rules for more generic services and do not address specific service conditions. These rules are not sufficient to address the distinctive problems of fuel cycle facilities equipment related to highly corrosive service conditions and difficulty in replacing the equipment for repair or maintenance. In order to enhance the reliability, supplementary requirements are worked out to realize the desired fabrication standards and quality levels.

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FIGURES

Fig. 1: Fabricated Vessel at final inspection

Fig. 2: Fabricated Annular Vessel at final inspection

Fig. 3: Thermo-syphon evaporator after fabrication

Fig. 4: Internal cooling coils in the vessels

Fig. 5: Hollow bar nozzle to avoid burn through of nozzle