Quality Assurance in Manufacturing of Valves for Nuclear Applications.

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Key words: Quality assurance, non-destructive examination, ultrasonic examination, liquid penetrant examination, Radiographic examination, helium leak testing, sealing surface, hard facing etc.

Abstract: Quality assurance (QA) commences with the design stage of the valves and covers entire manufacturing till packing of the valves for shipment. Quality assurance enhances the quality of the valves internally eliminates rejections, reduces cost and improves reliability resulting safe operations. Quality assurance involves destructive qualifications & non-destructive qualifications of mock ups, test coupons, welding & forming qualifications and finally non-destructive evaluation of product. Non-destructive examination is one of the constituent of quality assurance. The non-destructive examinations are performed at various stages of manufacturing for raw material qualification, in-process examinations and examination of finished valves. Nuclear valves discussed in the paper are manufactured with deployment of wide range of materials including various steels, bronze, hard facing consumables etc. Main materials of the construction are austenitic stainless steel forged bars and close die forgings. The sealing surfaces are hard faced with colmonoy hardfacing for creating surfaces to achieve leak tightness. Precipitation hardened (PH) stainless steel is deployed for stems connecting sealing plug and operating mechanisms. Predominantly ultrasonic examination is deployed for examination of raw materials, welds, hard facing for sealing surfaces. Liquid penetrant examination is deployed for detecting surface discontinuities on raw materials and on machined & welded surfaces as in-process inspection. Radiographic examination of cir-seam welds are performed in addition to ultrasonic examination wherever constrains are observed in ultrasonic examination limiting scope of examination. Finally helium leak testing is performed to determine leak tightness of pressure boundaries and sealing surface.

The paper covers some of the important stages of valve manufacturing, critical elements of quality assurance, selection of non destructive examinations at various stages of manufacturing, requirements of selected non destructive examinations, limitations observed during implementation of non destructive examinations and corrective measures to enhance the scope of non-destructive examinations.

1. Introduction:

Quality is a subjective term for which each person or sector has its own definition. Quality is defined by many scholars, some of the simple definitions are by Joseph Juran, "fitness for use" & according to Philip Crosby "conformance to requirements" ⁴. In both the definitions use or requirements are to be defined in specific terms to ascertain quality. The Quality Assurance can be defined in simple terms as act of guiding the processes involved in system to give confidence for achieving the specified requirements in the end product or service. The objectives of the Quality Assurance are product should be suitable for the intended purpose (i.e. Fit for use) and mistakes should be eliminated (i.e. Right first time). In the nuclear fabrication quality assurance is more critical as access to components is limited during the service due to radiations. In our view good quality assurance provides higher properties with respect to specified limits for each manufacturing operation, which makes final component with properties, which are well above specified limits and give confidence that product will serve intended purpose. For example quality assurance during melting & refining process produces defect free material with mechanical properties 20-30% higher
than specified limits. Effective quality assurance during fabrication produces weldment with zero defects and has extra margin over permissible size & number of discontinuities. Therefore the product manufactured with good quality assurance comprises characteristics much superior than permissible limits.

2. Quality Assurance in Manufacturing of Valves: The Valves discussed in the paper are manufactured for steam generation plant and some of the valves are installed in primary system. Design, materials qualification, fabrication and examinations are in line with American society of Mechanical Engineers (ASME) codes. ASME Sec III NB, ASME Sec V & ASME Sec IX are referred for formulation of non destructive examination requirements & welding qualifications. The quality assurance programme is devised right from design, raw material manufacturing, semi finished component manufacturing, bought out components evaluation, in-process inspections and final testing of valves. Quality assurance plans are formulated for each stage of manufacturing by listing inspection stages sequentially. Quality assurance plan constituents are process parameter that influences the product quality, relevant procedures, reference standards, acceptance criteria and involvement of various agencies. Quality assurance becomes more critical with subcontracting of the manufacturing activities as various agencies are involved.

2.1. Quality Assurance during Design Stage: In design stage requirements are finalized to satisfy the intended purpose. Care shall also be taken to avoid overdoing of requirements as it may increase the cost. Material selection, its melting route, inspection and testing requirements, material sampling and test plans (MSTP), non destructive qualification, fabrication processes, mock ups, production test coupon etc are finalized in design stage.

The objective of material selection, its manufacturing route and its evaluation parameter is to satisfy intended application requirements. Secondary remelting in addition to primary melting like Vacuum Arc Remelting (VAR) or Electro Slag Remelting (ESR) is envisaged for manufacturing of raw material. Secondary remelting processes produce cleaner material, which contains minimum non metallic inclusions. Presence of non metallic inclusions decreases the ability of metal to withstand high static loads, impact forces, cyclical or fatigue loading and sometimes corrosion and stress corrosion. Nonmetallic inclusions can easily become stress concentrators due to their discontinuous nature and incompatibility with the surrounding composition. This combination may very well yield flaws of critical size under suitable loading conditions and result in complete fracture of the forged part [2]. The austenitic stainless steels are solution annealed to develop corrosion resistance properties.

Inspection and testing requirements of raw materials are finalized on the basis of expected fabrication processes, service conditions, operating environment etc. Valve raw materials are subjected to set of metallurgical, mechanical and corrosion tests. Specimens for these tests are drawn as per specified material sampling & test plan. Material sampling and test plan are drawings showing location & orientation of various specimens. Material for testing is obtained by sacrificing few of the production items. Codes provide guidelines for locations of specimens for mechanical testing. Whereas specimens for corrosion testing should be located in such a way that it shall represent the most unfavourable location for the envisaged test. For example intergranular corrosion test specimen shall be located at a minimum distance greater than half of diameter from one heat treated surface & at centre of forged bars as heating or cooling occurs at last at these locations during solution annealing.

Non destructive examination methods are recommended on the basis of the product form (i.e. cast or wrought), discontinuities associated with the thermo mechanical process, expected type of discontinuities, location & orientation of discontinuities. Valves are mainly manufactured from forged bars & close die forgings. Surface & internal planner discontinuities are expected in these products. Ultrasonic examination is suggested for detecting internal discontinuities and liquid penetrant examination is envisaged for surface discontinuities. Radiographic examination and ultrasonic examination are recommended for evaluation of the welds during fabrication. Ultrasonic
examination is recommended for non-destructive evaluation of hard facing. Non-destructive examinations are covered in detail in paragraph 3.

2.2. Quality Assurance During fabrication: Some of the weld operations and hard facing are critical, defective welds may cause rejection of entire subassembly. Mock ups and production test coupons are planned in design stage to avoid rejections & to facilitate confirmation of critical parameters through destructive testing. Some of the important aspects of quality assurance during fabrication are mentioned below.

Halogen content in materials coming in contact with stainless steel during fabrication shall be controlled. Halogen content in coolant & liquid penetrant examination materials (penetrant, developers and cleaning agents) is restricted to 25 parts per million (PPM). Halogens penetrate the passive film of stainless and allow corrosion to occur. In addition to uniform corrosion attack, halogens cause stress corrosion cracking of stainless steel under tensile stress [3].

Iron contamination of stainless steels should be avoided during all storage, handling and fabrication stages and also during the service life of the stainless steel items. In case iron contamination is suspected then surface should be tested for contamination. If contamination is detected it should be removed & spreading of it should be avoided during the removal operation. Stainless steel items should not show rust staining, unless iron contamination is introduced. The use of non-stainless steel processing and handling equipment is a frequent source of contamination. Working in 'mixed-metal' fabrication shops, without taking segregation and cleaning precautions can result in contamination. Cutting or grinding debris from non-stainless steels should not be allowed to settle on stainless steel items [4].

Austenitic stainless steel bars and forgings are solution annealed to enhance corrosion resistance. It is observed that Furnace calibration is critical parameter for attaining the desired corrosion, mechanical & metallurgical properties. The furnace shall be calibrated with well defined working zone created with number of thermocouples specified in API 6A. The working zone greater than 10 ft² shall be calibrated with minimum nine thermocouples. In case of cuboid one thermocouple is place at each corner and one at centre. Calibration ensures temperature uniformity specified in API 6A (i.e. ±13°C) and facilitate soaking within specified temperature range. Soaking at non uniform temperatures results in varying grain sizes, it makes ultrasonic examination difficult & sometimes impossible with specified sensitivity.

Internal Cleanliness is another requirement for nuclear component to limit the activation of metallic particles during operation as it increases activity levels and increases dose to the plant personnel. Component internal surfaces are cleaned to wash away dust, dirt, lubricants and loose metallic particles. The sediments in the cleaning agents are checked for loose metal particles. Components are cleared for dispatch only after confirmation that internal surfaces are free from foreign particles.

2.3. QA during inspection & Testing:

Some of the important aspects related to inspection & testing are mentioned below.

The destructive testing is also performed during qualification of raw materials. It is very important to meticulously follow the standards and procedures formulated for testing. Stress rate is a critical testing parameter. Stress rate range (70 - 690MPa) for mechanical testing is specified in testing standards ASME SA 370 & ASTM E8. The stress rate can be converted into strain rate using modulus of elasticity of material under test. Ludwik first studied the effect of strain rate upon the stress at which metal fails in 1909. He found that the stress required for failure increased with an increase in the strain rate. Generally yield strength & tensile strength increases with increase in strain rate while elongation usually decreases [5].

Visual examination are performed at various stages of manufacturing, Light intensity specified for examination is 1000 Lux. Intensity of light should be maintained during examination and light glare from surface being examined should be avoided for meaningful examination.

Solvent removable dye penetrant technique is deployed for liquid penetrant examination. Precaution shall be taken to avoid flushing of penetrant with solvent during penetrant removal process and
before application of developer. Flushing of penetrant may result in either missing penetrant indications or smaller indication size.
Post examination cleaning after ultrasonic examination & liquid penetrant examination is very important especially for stainless steels as left out penetrant, oil and grease attract dust & metal particles available in shop floor. It may cause corrosion of stainless steel.


3.1. Raw Materials and Semi-Finished Components:
Austenitic stainless steel close die forgings SS321 is the major material used for valve body and bonnet. Rolled/forged bars are supplied as raw material for close die forgings. Aluminium Bonze is used for yoke sleeve & bushes. Precipitation hardened (PH) stainless steel is deployed for stems connecting sealing plug and operating mechanisms. The raw materials are of circular cross section wrought product. Raw materials are subjected to visual, liquid penetrant and ultrasonic examination. Table1 indicates the raw material, reference standard for examination, acceptance criteria and calibration sensitivity.

Table-1: NDE Requirements for Raw Materials [6, 7].

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Raw material NDE</th>
<th>Non-destructive Examination</th>
<th>Standard for examination</th>
<th>Acceptance criteria</th>
<th>Calibration Sensitivity [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>SA 182 F321 Forges/rolled bars, Close die forgings SA 564 Gr 630 (17-4 Ph steel) bars</td>
<td>Ultrasonic</td>
<td>Article – 5 SA 745</td>
<td>As mentioned in this Para 3.1.1.</td>
<td>•Φ10 to Φ40– FBH Ф2 •Φ40 to Φ75 –FBH Ф3 •Above Φ75- FBH Ф5. •Notch depth 3 % of finished thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.1.2.</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid Pentrant</td>
<td>Article – 6</td>
<td>NB 2546</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>SA 453 Gr 660</td>
<td>Ultrasonic (&gt; 50mm)</td>
<td>Article – 5 SA 745 / SA 388</td>
<td>As mentioned in Para 3.1.1.</td>
<td>•Φ10 to Φ40-FBHΦ1.5 •Φ40 to Φ75 –FBH Ф3 •Above Φ75- FBH Ф5. •Notch depth 3 % of finished thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual</td>
<td>Article - 9</td>
<td>NB 2582</td>
<td>0.8</td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td>Liquid Penitrant (up to 25mm)</td>
<td>Article – 6</td>
<td>NB 2584</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td>Liquid Penetrant (&gt;25mm)</td>
<td>Article – 6</td>
<td>NB 2584</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>Aluminium Bonze BS 2872 CA 104</td>
<td>Ultrasonic</td>
<td>Article – 5 SB -283</td>
<td>Thickness Up to 152 – FBH Ф3.2 •Thickness152 to 406 – FBH Ф6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.1.2.</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid Pentrant</td>
<td>Article – 6</td>
<td>NB 2546</td>
<td>-</td>
</tr>
</tbody>
</table>

3.1.1. Ultrasonic Examination:
Scanning directions: Ultrasonic examination is performed on finished bars & close die forgings however fasteners are examined before thread rolling. All the raw materials are scanned by straight
beam in two perpendicular directions and angle beam in axial and circumferential direction. Flat bottom holes (FBH) and V notches (in axial and circumferential directions) are used as reference reflector for straight and angle beam scanning respectively. Discontinuity sizing: 6 db drop method.

Acceptance criteria: Indication echo height exceeding the primary reference level is not permissible. Recordable indication having length more than 30 mm is not permissible. Two recordable indications shall be separated by at least the major dimension of the longer discontinuity, otherwise they will be considered as single discontinuity and shall be evaluated as per 30 mm limit. Drop of back wall echo amplitude by 50% or more of original amplitude is not permissible unless otherwise it is proved that this is not because of defect.

Exceptions: Forgings or sections of forgings which have coarse grains or configurations which do not yield meaningful examination results by ultrasonic methods shall be examined by radiographic methods in accordance with Section V, Article 2, using the acceptance standards of NB-5320. In addition, all external surfaces and accessible internal surfaces shall be examined by a liquid penetrant examination (NB-2546) [6].

3.1.2. Visual examination:
Visual examination is performed before liquid penetrant examination for discontinuities expected on the surface due to rolling and forging operations like seams, surface cracks, laps, embedded foreign particles etc. Visual examination is also performed during evaluation of macro specimens of the bars for internal discontinuities.

3.1.3. Liquid Penetrant Examination:
All the bars are subjected to solvent removable liquid penetrant examination after finish machining before shipment from mill. Bars for fasteners are subjected to liquid penetrant examination before thread rolling and after thread rolling. The acceptance of fasteners bars before & after thread rolling is in line with requirements of NB 2584.

3.2. In-Process Inspections:
Examination requirements for some of the in-process inspection stages are listed in table 2.

3.2.1. Examination of machined components:
All the machined parts (i.e. close die forgings, welded, hard faced subassemblies) are subjected to liquid penetrant examination & visual examination. Weld edge preparation on close die forgings are evaluated with respect to requirements of NB 2546, whereas machined welds & hard faced surfaces are evaluated in line with NB 5350 requirements. The visual examinations are performed to confirm absence of surface discontinuities like cracks, inclusions etc.

3.2.2. Examination of full penetration welds:
Cir-seam welds between body and flow bores are full penetration welds. ASME Sec III NB 5222 recommends a volumetric examination & surface examination of cir-seam welds. There were many joints where meaningful radiography is not feasible due to obstruction from valve internals and inaccessibility. ASME NB 5279 recommends substitution of radiography with ultrasonic examination and liquid penetrant examination in case radiographic examination is not feasible. However considering the application requirements radiographic examination and ultrasonic examination are envisaged for the welds in valves. Care is taken while devising the technique sheet to examine the weldment to maximum extent possible. Visual examination is performed to confirm absence of surface discontinuities like cracks, inclusion, undercuts etc.

3.2.3. Examination of fillets welds and seal welds:
These welds are of small size and only visual & liquid penetrant examination is feasible. Layaer be layer liquid penetrant examination is envisaged for seal welds. The visual examinations are performed to confirm absence of surface discontinuities like cracks, inclusions & undercuts etc.

3.2.4. Examination of Hard facing:
ASME NB 5173 recommends only liquid penetrant examination of hardfacing for valves with inlet connection size greater than NPS 4 (DN 100). In view of application requirements ultrasonic
examination is introduced as mentioned in table 2. Recording limit is 6db below the primary reference echo. Hard facing is mainly deposited on sealing surfaces of sealing plugs and seating surfaces. Echoes exceeding the recording limits are considered not acceptable. The visual examination of hard facing is performed after each layer deposition. Visual examination is performed to confirm absence of surface discontinuities like cracks, tungsten inclusion, undercuts etc.

**Table – 2 In-Process NDE Requirements [6, 7].**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>In-Process NDE stages</th>
<th>Non-destructive Examination</th>
<th>Standard for examination</th>
<th>Clause for acceptance</th>
<th>Calibration Sensitivity [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Examinations of machined components</td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.2.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid Penetrant</td>
<td>Article – 6</td>
<td>NB 2546 (Base metal) NB 5350 (welds)</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Examination of full penetration welds &amp; adjacent surface.</td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.2.2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid Penetrant</td>
<td>Article – 6 NB 5140</td>
<td>NB 5350 (welds) NB 2546 (base metal)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultrasonic</td>
<td>Article – 4 Figure T-434. 2.1</td>
<td>NB 5330</td>
<td>Thickness up to 25: SDH Φ2.5. Thickness 25 to 50: SDH Φ3.</td>
</tr>
<tr>
<td>3</td>
<td>Radiography</td>
<td>Visual</td>
<td>Article - 2</td>
<td>NB 5320</td>
<td>Table NB-5111-1</td>
</tr>
<tr>
<td>4</td>
<td>Examination of fillets welds and seal welds</td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.2.3</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Layer by layer liquid penetrant</td>
<td>Article – 6 NB 5140</td>
<td>NB 5350 (welds) NB 2546 (base metal)</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Examination of hard facing [8]</td>
<td>Visual</td>
<td>Article - 9</td>
<td>As mentioned in Para 3.2.4</td>
<td>0.8</td>
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<td></td>
<td>Liquid Penetrant</td>
<td>Article – 6</td>
<td>NB 5350</td>
<td>-</td>
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<td></td>
<td></td>
<td>Ultrasonic</td>
<td>Article – 4</td>
<td>KTA 3201 - 3</td>
<td>3 FBH</td>
</tr>
</tbody>
</table>
3.3. Final inspections:
Valves are subjected to Hydro Test, Internal Cleanliness Test and Helium Leak Test sequentially before shipment. Helium test is performed after hydro test to confirm integrity of pressure boundary after hydro tests.

3.3.1. Hydro Test:
Hydro tests of pressure boundary are performed at 1.25 times design pressure for 10 minutes to confirm the integrity of pressure boundary. Leak tightness tests of seat are performed at working pressure under the seat. Leak tightness test over the seat is performed for valves with non return function. There shall be no visible leak and no pressure drop for acceptance of valves.

3.3.2. Cleanliness Test:
It is important to verify cleanliness of internal surface of valves. Acetone is poured in the valves and shacked rigorously to wash out dust, dirt, oil, grease & metal particles. Acetone is poured into transparent beaker and visual check is performed for presence of sediments & suspended particles in acetone. In case of absence of sediments & suspended particles the valve is cleared for helium leak test. In case sediments and suspended particles are present the cleaning process is continued till the time no sediments and suspended particles are observed. Particles are filtered on filter paper and ferroxyl test (ASTM A 380) is performed to check iron particles. Presence of any foreign particle especially iron particles is not permissible.

3.3.3. Helium Leak Test:
Cleanliness test is performed prior to helium leak test & after hydro test to remove oily contaminates (if any) and to remove water droplets (if any) through acetone. Hot air is blown through the valves to dry the internal surfaces for helium leak testing. Valves are tested using Hood Technique in accordance with article 10 - Appendix IX of ASME Section V. helium Leak rate more than 1x10^-6 std cc/sec is not permissible.

4. Limitations & Corrective Measures:
Coarse grain austenitic stainless steels and aluminium bronze behave similarly in ultrasonic examination. It occurs due to variations in parameters during thermo-mechanical processes employed in raw material manufacturing. Non uniformity of temperature in heating furnace, exceeding the specified temperature or exceeding soaking time during hot working or solution annealing makes ultrasonic examination difficult and sometimes impossible. We faced grain non uniformity problems in large forged bars, close die forgings of SS 321 and forged bars of aluminium bronze. Some examples are mentioned below.

Grain coarsening of 15-20 mm observed in the circumference of Φ315 mm forged bars in macro etch test. The grain coarsening in the circumference is rectified by reworking (3% reduction in diameter) and subsequent solution annealing. It is concluded that grain coarsening at circumference can be corrected with reworking. Reduction ratio to eliminate circumferential grain coarsening may be finalized with trials and consultation with forge master.

Distinct recordable indications at certain locations & spread along circumference and section of the bar length were observed in circumferential scanning during ultrasonic examination of Φ320mm forged bar with 2MHz probes. Indications height was 80% at beam path of 37mm. Grain coarsening was also observed in macro specimen of same bar as shown in fig 1, it is predominantly scattered in a band about 30 to 80 mm from circumference. Macro specimen with uniform grains is fig 2 below for comparison purpose. The grain size in grain coarsening areas measured with liner intercept method and grain dimensions found 221 micron to maximum of 403 micron as shown in fig 3 & fig 4 below. Ultrasonic response from coarse grain at similar depth was found same as observed on the Φ320mm forged bar at same machine settings.

Further macro specimen is cut at the indication location & no discontinuity was observed in that location. Areas of indication are scanned with 1 MHz probe and it is found that indication height reduced much below recording level. In view of this, it is concluded that indications in Φ320mm bars are from grain coarsening.
Radiography examination of the non return valves cir-seam weld joint carried out with gamma source (Ir$_{192}$). Valve internals were interfering with radiographic image of the weld and internal sensitivity of the radiograph. The sensitivity achieved near to specified limit using double wall double image technique. Many trials are carried out with objective to reduce the geometrical unsharpness and improve the sensitivity. Trial could have been avoided with deployment of X-ray machine as focal spot is much smaller comparison to gamma source. The smaller source size results in lower geometrical unsharpness and better sensitivity.

5. Acknowledgement:
We acknowledge the guidance & support provided by Shri RS Yadav, Director RPG, BARC and Shri KN Vyas, Head Reactor Projects division, BARC during development & manufacturing of valves.

6. References:
[8] KTA 3201 - 3